IGS

INTERNATIONAL
GPS
SERVICE

TOWARDS REAL-TIME
NETWORK, DATA, AND ANALYSIS CENTRE 2002 WORKSHOP

Proceedings

Ottawa, Canada

April 8 - 11, 2002

IGS Central Bureau

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California U.S.A.

Edited by
P. Tétreault
R. Neilan
K. Gowey

Natural Resources Canada
Ressources naturelles Canada
Canada

Foreword

Almost ten years after the first IGS Analysis Workshop, the Geodetic Survey Division (GSD) of Natural Resources Canada had the pleasure to host the IGS community for a second time. The enthusiasm and large number of participants that convened in Ottawa April 8 to 11, 2002 for the first combined IGS Network, Data and Analysis Center Workshop are strong indications of the importance and vitality of the IGS. Both of which can only be strengthened by the willingness of all IGS contributors to respond to changing requirements as demonstrated by the adoption of the many workshop's recommendations in support of a path "Towards Real-Time".

I am thankful to all those who have contributed to the workshop's position papers, presentations and posters documented in the pages that follow. Their hard work was essential to stimulate the numerous discussions and support the recommendations agreed upon during the workshop. The valued help of all session chairs in organizing the technical programme and ensuring its smooth delivery is also gratefully acknowledged. Sponsorship of social events by Leica Geosystems, Nanometrics, NovAtel Inc., Thales Navigation, Topcon/Javad, Trimble Navigation Canada and Natural Resources Canada, was much appreciated. These events were quite successful in facilitating dialogue and nurturing relationships essential to the collegial IGS spirit. I am also thankful for the support received from the Natural Resources Canada, Earth Science Sector's management team and help provided by my many colleagues at GSD both of which were, of course, vital to the workshop's success.

Pierre Tétreault
Chair IGS Workshop 2002
Ottawa, February 2003

Abstract

An all-components - network, data and analysis centers - IGS workshop to address current and future IGS challenges was held in Ottawa, Canada, April 8-11, 2002. The programme, in addition to the planning needed to strengthen and improve the current Service, focused on the steps needed to develop a real-time component of the IGS. The four-day agenda was divided into eleven technical sessions:

- workshop opening addresses,
- real-time application and products,
- real-time data and products exchange,
- data center issues,
- network issues,
- posters,
- reference frame,
- receiver and satellite antenna calibrations,
- ground based GPS ionospheric estimation,
- low earth orbiters,
- review of IGS products.

These proceedings document the current status of IGS activities and proposed approach in moving towards real-time, a path that the IGS is evidently already embarking on through future collaboration and working group discussions.

Contents

Network, Data and Analysis Center Workshop 2002

Position Papers and Abstracts

Session 1: Review of IGS Analysis Products

Session 2: Real-Time Applications and Products

Session 3: Real-Time Data/Product Exchange

Session 4: Network Issues

Session 5: Ground-Based GPS Ionospheric Estimation

Session 6: Low Earth Orbiter

Session 7: Reference Frame

Session 8: Receiver and Satellite Antenna Calibrations

Session 9: Data Center Issues

Session 10: Working Group Reports

Session 11: Poster Abstracts

Presentations and Additional Papers

Session 1: Review of IGS Analysis Products

Testing of the Proposed IERS 2000 Convention Sub–Daily
Earth Rotation Parameter Model
J. Kouba

IGS/BIPM Pilot Project: GPS Carrier Phase for
Time/Frequency Transfer and Time Scale Formation
J. Ray, K. Senior

Extending the Standard Product 3 (SP3) Orbit Format
S. Hilla

Session 2: Real-Time Applications and Products

Session 3: Real-Time Data/Product Exchange

Session 4: Network Issues

Session 5: Ground-Based GPS Ionosphere Estimation

Session 6: Low Earth Orbiter

Session 7: Reference Frame

Session 8: Receiver and Satellite Antenna Calibration

Session 9: Data Center Issues

Session 10: Posters

CDDIS Update
C. Noll

CODE – Current Issues Relevant to the IGS: Part 1
U. Hugentobler

CODE – Current Issues Relevant to the IGS: Part 2
U. Hugentobler

ESA/ESOC IGS Activities
J. Dow et al

Use of the IGS Ultra-Rapid Orbits in the COST-716 NRT Campaign 2001 – Part 1
J. Dousa

Study of Different Analyzing Schemes for the Ultra-Rapid Orbit Determination Using the Bernese GPS Software
J. Dousa, U. Hugentobler

Global NRT Solution by the Geodetic Observatory Pecnỳ AC
J. Dousa

Geoscience Australia Activities Related to the International GPS Service
J. Dawson et al

Developments in Absolute Field Calibration of GPS Antennas and Absolute Site Dependent Multipath
G. Wübbena, M. Schmitz

Recent Results and Activities of the IGS Analysis Center at JPL
D. Jefferson et al

IGS LEO - CHAMP Orbit Campaign Status: Part 1
H. Boomkamp

IGS LEO - CHAMP Orbit Campaign Status: Part 2
H. Boomkamp

Continental Plate Rotations Derived from International GPS Service: Station Coordinates and Velocities, 1996-2002
D. Hutchison

NRCan Internet Global Positioning System Data Relay (iGPSDR)
S. Delahunt, K. MacLeod, M. Caissy and K. Lochhead

AGENDA

Date:April 8-11, 2002
Ottawa, ON, CA

Monday April 8th, 2002 - AM

8:30 a.m.	NRCan	Welcome
9:00 a.m.	G. Beutler	IAG Issues
9:20 a.m.	C. Reigber	IGS Strategic Planning
9:40 a.m.	G. Gendt	Troposphere Working Group
9:55 a.m.	J. Ray	Precise Time Transfer Project
10:10 a.m.	J. Slater	International GLONASS Pilot Project
10:25 a.m.		Coffee break

Real Time Applications and Products
Chairs: Yoaz Bar-Sever and John Dow

10:45 a.m.	Y. Bar-Sever and J. Dow	Introduction
11:00 a.m.	N. Romero et al.	Ultra-Rapid Orbits at ESOC, Supporting Real-Time Analysis
11:20 a.m.	R. Muellerschoen	JPL Real Time OD Products
11:40 a.m.	R. Pacione et al.	The Italian Near-Real Time GPS Fiducial Network for Meteorological Applications
12 noon	H. van der Marel	What about using GPS for Weather Forecasting?

Lunch

Monday April 8th, 2002 – PM

Real Time Applications and Products (cont'd)

1:45 pm.	E. Powers et al.	Real-Time Ultra-Precise Time Transfer to UTC Using the NASA Differential GPS System
2:10 pm.	B. Wilson	Near Real Time Ionospheric Products
2:20 pm.	P. Héroux	Real-Time Delivery of the Canadian Spatial Reference System - Strategy and Applications
2:40 pm	Y. Bar-Sever	Natural Hazard Applications
2:50 pm	J. Dow	Galileo Status
3:00 pm.	Bar-Sever / J. Dow	Discussion
3:15 pm		Coffee break

Real-Time Data/Products Exchange
Chairs: Mark Caissy and Ron Muellerschoen

3:35 pm	M. Caissy	Session Overview and what we hope to achieve
3:40 pm.	M. Caissy and R. Muellerschoen	Position Paper
4:10 pm	G. Weber	Real-Time Streaming of Differential Corrections via Internet
4:30 pm	K. MacLeod	Internet GPS Data Relay
4:50 pm	G. Hedling and R. Hanssen	Real-Time Permanent GPS Networks in Northern Europe
5:10 p.m.	Caissy/Muellerschoen	Discussions / Questions and Answers
6 pm		Reception Sponsors Leica Geosystems, Nanometrics, NovAtel Inc., Thales Navigation, Topcon/Javad, Trimble Navigation (Canada) and Natural Resources Canada

Tuesday, April 9, 2002 – A.M.

Real-Time Data/Products Exchange (cont)
Chairs: Mark Caissy and Ron Muellerschoen

8:50 a.m.	Caissy/ Muellerschoen	Formats Discussion
9:00 a.m.	Caissy/ Muellerschoen	Discussion / Recommendations
9:30 a.m.		Coffee Break

Data Center Issues
Chairs: Carey Noll and Loïc Daniel

9:50a.m.	C.Noll	Introduction and Overview of Data Center Issues
10:05 am	L. Daniel/E. Gaulué	Ideas and Perspectives for the Present and Future IGS Data Network Management
10:25 am	H. Habrich	Data Center Security Issues
10:45 am	Michael Scharber	GPS Seamless Archive Center (GSAC) - Streamlining data/metadata exchange in the GPS community
11:05 am	C. Noll/L. Daniel	Discussion
11:20 am		Network Issues (Vendors)

Lunch

Tuesday April 9th, 2002 - PM

Network Issues
Chairs: Angelyn Moore and Mike Schmidt

1:30 p.m.	A. Moore	Introduction
1:40 p.m.	L. Combrinck	Africa Update
1:50 p.m.	P. Zhang and H. Sun presented by P. Fang	China Update
2:05 p.m.	R. Neilan	GPS Modernization
2:15 p.m.	L. Estey and W. Gurtner	RINEX Readiness for GPS Modernization
2:25 p.m.	Discussion Panel Moore, Schmidt, Neilan, Estey and Gurtner	GPS Modernization Impact on IGS, RINEX and IGS Metrics
2:55 p.m.	Moore / Schmidt	Wrap-Up / Action Items

Poster Session

Chair: Pierre Tétreault

3:30 Poster Sessions

Wednesday, April 10, 2002 AM

Reference Frame
Chairs: Zuheir Altamimi and Rémi Ferland

8:30 a.m.	R. Ferland	IGS Reference Frame Coordinator Report
8:45 a.m.	S.Y. Zhu	Possible Reasons for the Scale Error in the GPS Frame
9:00 a.m.	R. Ferland	Regional Networks Densification
9:15 a.m.	H. Habrich and C. Bruyninx	EUREF Approach
9:30 a.m.	M. Craymer	NAREF Approach
9:45 a.m.	Z. Altamimi	ITRF2000 Summary and Some Regional Solutions Evaluation
10:10 a.m.		Coffee break

Receiver and Satellite Antenna Calibrations
Chairs: Gerry Mader and Markus Rothacher

10:30 a.m.	M. Rothacher and G. Mader	Satellite and Receiver Antenna Calibrations
10:45 a.m.	M. Schmitz et al.	Absolute Receiver Antenna Calibrations with a Robot
11:00 a.m.	G. Mader	Calibration of Satellite Antenna Offsets at the Ground

11:15 a.m.	R. Schmid and M. Rothacher	Estimation of Satellite Antenna Phase Center Variations
11:30 a.m.	P. Elosegui, K.-D. Park et al	Multipath Characteristics of GPS Signals as Determined from the Antenna and Multipath Calibration System: Preliminary Results
11:45 a.m.	Rothacher/Mader	Discussion

Lunch

Wednesday, April 10, 2002 PM

Ground-Based GPS Ionospheric Estimation
Chairs: Joachim Feltens and Brian Wilson

1:30 pm	J. Feltens	Ionosphere Working Group Report and Outlook
1:50 pm	S. Schaer	TEC Maps and DCBs Analyses, Comments on Combination Weights
2:00 pm	P. Héroux	NRCan Evaluation of IGS/IAAC TEC Maps
2:10 pm	B.Wilson	
2:20 pm	B. Wilson for G. Hajj	Assimilating Occultation Data into a Global Assimilative Ionosphere Model (GAIM)
2:30 pm	J. Feltens / B. Wilson	Discussion
2:50 pm	S. Schaer	Short COD Presentation
	P. Héroux	Short NRCan Presentation
2:55 pm.		
3:00 pm	J. Feltens	Current Status of ESOC Ionosphere Modelling and Planned Improvements)
3:05 pm.	B. Wilson	Investigation of the 1/f^3 Higher Order Ionospheric Effect and Planned Improvements
3:10 pm	J. Feltens for M. Hernandez-Pajares Et al.	UPC Ionospheric Activities: TEC Maps, Real-Time Corrections and Radio-Occultations Retrieval
3:15		Coffee break

Low Earth Orbiter
Chair: Henno Boomkamp

3:35 p.m.	H. Boomkamp	IGS LEO Pilot Project Status
3:50 pm.	S.Y. Zhu	The Usefulness of Combined GPS+LEO Processing
4:05 pm.	B. Schutz	LEO Activities at CSR
4:20	U. Hugentobler	LEO Processing Status at AIUB
4:35 pm	M. Rothacher	Comparison of Kinematic and Reduced Dynamic CHAMP Orbits Using Zero and Double Differences
4:50 pm	H. Boomkamp	LEO Processing at ESOC
5:00 pm	H. Boomkamp	Discussion

Thursday, April 11, 2002 AM

Review of IGS Products
Chairs: Jim Ray and Robert Weber

8:30 a.m.	J. Kouba	Sub-Daily EOP Effect
8:45 a.m.	J. Ray	Clock Issues, IERS Conventions
9:00 a.m.	Ken Senior	New Clock Alignment
9:20 a.m.	Robert Weber	Combination Issues, Product Latency
9:45 a.m.	Tom Yunck	Long-Term Consistency of IGS Products
10:00 a.m.	S. Hilla	SP3 Format Update
10:10 a.m.	J. Ray / R. Weber	Discussion
10:30 a.m.	Coffee	

Summary of Recommendations / Closing Discussion
Chairs: Angelyn Moore and Robert Weber

Thursday, April 11, 2002 PM

1:30 pm	Session Chairs/GB Members Wrap-Up Meeting

List of Participants

NAME	*ORGANIZATION*
Altamimi, Zuheir	IGN, France
Andersen, Per Helge	Forsvarets forskningsinstitutt, Norway
Bar-Sever, Yoaz	JPL, USA
Beck, Norman	NRCan/GSD, Canada
Beutler, Gerhard	University of Berne/CODE, Switzerland
Boomkamp, Henno	ESA/ESOC, Germany
Bouin, Marie-Noelle	IGN, France
Bourassa, Martin	NRCan/GSD, Canada
Bourdon, Michel	Leica Geosystems, USA
Bruyninx, Carine	Royal Observatory of Belgium, Belgium
Caissy, Mark	NRCan/GSD, Canada
Carter, Merri Sue	USNO/EO, USA
Chin, Miranda	NOAA/NGS, USA
Collins, Paul	NRCan/GSD, Canada
Combrinck, Ludwig	Hart RAO, South Africa
Craymer, Mike	NRCan/GSD, Canada
Daniel, Loïc	IGN, France
Dawson, John	Geoscience Australia/National Mapping Division, Australia
Delahunt, Stephen	NRCan/GSD, Canada
Dillinger, Bill	NOAA/NGS, USA
Donahue, Brian	NRCan/GSD, Canada
Dorsey, Arthur	LM Management and Data Systems, USA
Dousa, Jan	Geodetic Observatory Pecny, Czech Republic
Dow, John	ESA/ESOC, Germany
Dulaney, Bob	NOAA/NGS, USA
Duquesne, Louis	CNES, France
Elosegui, Pedro	Harvard-Smithsonian/Center for Astrophysics, USA
Estey, Louis	UNAVCO/UCAR, USA
Faccia, Roberto	Telespazio S.p.A., Italy
Fang, Peng	SIO/SOPAC, USA
Feltens, Joachim	ESA/ESOC, Germany
Fenton, Pat	NovAtel, Canada
Ferland, Rémi	NRCan/GSD, Canada
Galas, Roman	GFZ, Germany
Gallace, Joe	NRCan/GSD, Canada
Gaulué, Edouard	IGN, France
Gendt, Gerd	GFZ, Germany
Gurtner, Werner	University of Berne/Astronomical Institute,Switzerland
Habrich, Heinz	BKG/IFAG, Germany
Hanssen, Rune	Norwegian Mapping Authority/Geodetic Institute, Norway
Hedling, Gunnar	Lantmäteriverket, Sweden
Héroux, Pierre	NRCan/GSD, Canada
Hilla, Steve	NOAA/NGS, USA
Hothem, Larry	US Geological Survey, USA
Hugentobler, Urs	University of Berne/CODE, Switzerland
Huot, Caroline	NRCan/GSD, Canada
Hutchison, David	NRCan/GSD, Canada
Jefferson, David	JPL, USA
Khachikyan, Razmik	Raytheon/ITSS, USA
King, Robert	MIT, USA

Klatt, Calvin	NRCan/GSD, Canada
Kogan, Mikhail	Lamont-Doherty Earth Observatory, USA
Kouba, Jan	NRCan/GSD, Canada
Krügel, Manuela	DGFI, Germany
Lahaye, Francois	NRCan/GSD, Canada
Larson, Kristine	University of Colorado/Boulder, USA
Liwosz, Tomasz	Warsaw University of Technology, Poland
MacLeod, Ken	NRCan/GSD, Canada
Mader, Gerry	NOAA/NGS, USA
Madsen, Finn Bo	KMS, Denmark
Mannucci, Tony	JPL, USA
Marshall, John	NOAA/NGS, USA
Meindl, Michael	University of Berne/CODE, Switzerland
Miller, Kevin	JPL, USA
Mireault, Yves	NRCan/GSD, Canada
Moore, Angelyn	JPL, USA
Muellerschoen, Ron	JPL, USA
Nardi, Antonio	Telespazio S.p.A., Italy
Neilan, Ruth	JPL, USA
Niell, Arthur	MIT/Haystack Observatory, USA
Noll, Carey	GSFC/CDDIS, USA
O'Toole, Jim	NSWC, USA
Pacione, Rosa	ASI, Italy
Pagiatakis, Spiros	York University, Canada
Pesec, Peter	Space Research Institute, Austria
Piraszewski, Mike	NRCan/GSD, Canada
Popelar, Josef	NRCan/GSD, Canada
Powers, Edward	USNO/Time Service, USA
Ragsdale, Rob	Trimble Navigation, Canada
Ramatschi, Markus	GFZ, Germany
Ray, Jim	USNO/EO, USA
Rea, Carlo	Technel Engineering Inc., Canada
Reigber, Christoph	GFZ, Germany
Renfro, Brent	University of Texas/ARL, USA
Rohde, Jim	USNO/EO, USA
Romero, Nacho	ESA/ESOC, Germany
Roosbeek, Fabian	Royal Observatory of Belgium, Belgium
Rothacher, Markus	TU-Munich, Germany
Ruud, Oivind	UNAVCO/UCAR, USA
Schaer, Stefan	University of Berne/CODE, Switzerland
Scharber, Michael	SIO/SOPAC, USA
Schmid, Ralf	TU-Munich, Germany
Schmidt, Michael	NRCan/PGC, Canada
Schmitz, Martin	Geo++GmbH, Germany
Schutz, Bob	University of Texas/CSR, USA
Scott, Doug	NRCan/GSD, Canada
Senior, Ken	USNO/Time Service, USA
Slabinski, Victor	USNO/EO, USA
Slater, Jim	NIMA, USA
Smith, Morgan	Topcon/Javad, USA
Snow, Robert	Thales Navigation, USA
Spriggs, Neil	Nanometrics, Canada
Steblov, Grigory	Russian Academy of Sciences/RDAAC, Russia
Stevens, Joel	NIMA, USA

Stiles, Paul	NovAtel, Canada
Stowers, David	JPL, USA
Taylor, Peter	NRCan/GSD, Canada
Tétreault, Pierre	NRCan/GSD, Canada
van der Marel, Hans	TU-Delft, The Netherlands
van Loon, Danny	TU-Delft, The Netherlands
Vespe, Francesco	Agenzia Spaziale Italiana, Italy
Weber, Georg	BKG, Germany
Weber, Robert	TU-Vienna/AIUB, Austria
Weisse, Katrin	GFZ, Germany
Wilson, Brian	JPL, USA
Woppelmann, Guy	Université de La Rochelle, France
Yunck, Tom	JPL, USA
Zhu, Sheng Yuan	GFZ, Germany
Zumberge, James	JPL, USA

Workshop Recommendations
2002 IGS Network, Data and Analysis Center Workshop, Ottawa, Canada (April 8-11, 2002)

Compiled by A. Moore and R. Weber

Real-Time Products and Applications (J. Dow and Y. Bar-Sever)

A variety of applications including weather prediction, ionospheric weather monitoring, satellite and terrestrial navigation, earthquake and volcano monitoring, positioning of structures, surveying, timing and earth orientation would benefit from the availability of Real-Time (RT) GPS raw data products and from RT or Near Real-Time (NRT) products computed from them. In view of this trend towards real time, the relevant IGS elements should press ahead with the development of:

1. the infrastructure needed to transfer in real time raw GPS data from a sub-set of the stations of the global network to servers located at those IGS Analysis Centres interested in participating in this new activity;

2. the software needed to generate, quality check and disseminate RT and NRT orbit, clock and other products (Global Ionospheric Map (GIM), Total Zenith Delay (TZD), ...)

An appropriate project structure should be set up within the IGS to coordinate and execute this work (for example the Real-Time Working Group (RTWG)).

As an interim measure, the AC's and the AC Coordinator are encouraged to:

review the current latencies of the classical orbit and clock products (ultra-rapid, rapid, final) and assess whether it is appropriate to modify these in view of the increased availability of hourly stations and whether it is still necessary to maintain separate rapid and final products.

reduce as soon as feasible the latency of the ultra-rapid productsfrom the current 12 hours to 3 hours.

Real-Time Data/Products Exchange (M. Caissy and R. Muellerschoen)

It is recommended that the IGS community guided by the RTWG move forward on two fronts with the goal of completing phase 1 of the RTWG's charter.

1. Involve the broadest membership as possible from within the IGS community.

2. Move forward on the development of a prototype for data and product exchange incorporating the design presented in the position paper with the following additional recommendations based on discussions at the workshop:

    - It is recommended that the RTWG investigate the impact of using Transmission Control Protocol (TCP) in place of User Datagram Protocol (UDP) in order to assess the value of using TCP in the post-prototype phase of IGS real-time processes.

    - It is recommended that the RTWG investigate the impact that the choice of UDP may have on our ability to traverse firewall implementations at institutes where the use of UDP is discouraged or denied.

    - It is recommended that due to the demonstrated interest from global data centres, they be involved on a voluntary basis, at the prototype stage, in a demonstration of the concept of distributed data centres.

Data Center Issues (C. Noll and L. Daniel)

DAT1: A Subset of Data Centres (DC)s should participate in RTWG's prototype efforts

DAT 2: Establish a DC Working Group

- to evaluate metadata storage and exchange as well as monitoring and bug tracking
- to create and maintain the
    a) topology of data flow up to Global Data Centres (GDC)
    b) DC requirements and guidelines

DAT 3: GDCs and Regional Data Centres (RDC)s should participate in GPS Seamless Archive Centre (GSAC) effort

DAT 4: Integrate GPS/Glonass data flow into IGS paths

Network Issues (A. Moore and M. Schmidt)

NET 1: Form an IGS industry panel with representation from manufacturers of equipment used in IGS

NET2: Implement associate regional networks and associate applications networkers

NET3: ACs and Pilot Project (PP) / Working Groups (WG)s should communicate to the Network Coordinator (NC) recommended equipment guidelines (e.g. radome types, non DM antennas,...) and recommended degree of enforcement

NET 4: Reference Frame Working Group (RFWG) should recommend conventions for reporting time series discontinuities

NET5: IGS should keep abreast of and prepare for GPS modernization; When equipment and signal availability schedule is clear, a phased adoption at IGS sites should be coordinated

NET6: Form a RINEX task force

Reference Frame (R. Ferland and Z. Altamimi)

REF FR 1
Test in detail the various proposed combination/constraining approaches (fixing-minimum constraints-combined) to align regional solutions to the ITRF. Use various regions and time spans. Agree on one proposition to be recommended for all regions.

Antenna Calibration: (M. Rothacher and G. Mader)

CALIB 1
Review and adopt the new IGS Phase Centre Variation (PCV)-format for receiver and satellite antenna phase centre corrections. (envisaged date for adoption Jan, 1st, 2003).

CALIB 2
Adopt absolute antenna PCV for receiver antennas and new satellite antenna offsets and patterns after conducting a thorough test campaign (envisaged date for adoption Jan, 1st, 2003).

CALIB 3
Set up a so-called 'Antenna WG' to keep track of antenna issues in general and to organise the transition to absolute phase center variations in particular.

CALIB 4
Avoid to the extent possible any change in the antenna setup at IGS permanent sites. Whenever possible the same antenna type should be installed in case of replacement due to malfunctioning of older hardware.

Ground-Based Ionospheric Estimation (J. Feltens and B. Wilson)

ION 1:
Start with the delivery of a combined IGS Ionosphere Product (asap / when?)

ION 2:
Combined IGS Total Electron Content (TEC) maps should be produced with an overlap of one day to decrease jumps at the day boundaries.

ION 3:
Global Ionospheric Associate Analysis Centres (IAAC)s TEC maps should cover all parts of the world.

ION 4:
Explore the use of ENVISAT and JASON satellites for validation of IGS Ionosphere Products.

ION 5:
In view of NRT Monitoring of the Ionosphere the distribution of ground stations as well as the data flow (latency) has to be improved.

IGS-LEO (H. Boomkamp)

IGS-LEO 1:
Explore in detail the impact of GPS-LEO data on the classical IGS products in combination solutions.

IGS-LEO 2:
Explore the latency requirements for tracking data availability as well as delivery of current IGS products to support LEO data processing (e.g. for atmosphere sounding).

IGS-Products (J. Ray and R. Weber)

PROD 1 (Time Scale)
Adopt a new time scale for IGS Final and Rapid Products to achieve continuity at day boundaries and allow for a direct link to UTC. (envisaged date of adoption: July 1,2002)

PROD 2 (New SP3 format)
Review and adopt a new version of the SP3 format. To serve the user community keep both the old and the new format in parallel for a period of at least 1 year. (envisaged date of adoption: July 1,2002)

PROD 3: (GLONASS data processing)
Intensify the ability to process data from combined GPS/GLONASS tracking sites. ACs and AACs are encouraged to provide orbit and clock submissions in order to ensure a reliable combined IGS GLONASS orbit and clock product.

PROD 4: (IGU products)
In view of upcoming NRT- needs explore and implement a more frequent update of the IGU -Ultra Rapid Products. An update cycle of 3 hours (currently 12 hours) for IGU products is envisaged. Investigate the option of different update cycles for orbits (6 hours) and clocks (3 hours). In addition explore the possibility of decreasing the latency of IGU products from currently 3 hours to 2.5 hours as well as the submission of 5-minutes rinex-clock files.

Executive Summary

2002 IGS Network, Data and Analysis Center Workshop, Ottawa, April 8-11, 2002.

P. Tétreault, P. Héroux and J. Kouba

The workshop, re-scheduled from October 2001, was held at the Courtyard Marriott hotel in the heart of Ottawa's popular Byward market area. The 3.5 day workshop regrouped more than 100 participants and was organized around the central theme "Towards Real Time". The technical program included the following eleven sessions:

1. Opening
2. Real-time applications and products
3. Real-time data/products exchange
4. Data center issues
5. Network issues
6. Poster session
7. Reference frame
8. Receiver and satellite antenna calibrations
9. Ground based GPS ionospheric estimation
10. Low Earth Orbiters (LEO)
11. Review of IGS Products

Altogether nine position papers corresponding to the above sessions were presented and all but one were available at the workshop www site (http://www2.geod.nrcan.gc.ca/~pierre/igs_workshop.html) prior to the start of the workshop. The following contains brief summaries of each session, followed by a draft of workshop recommendations, which were compiled at the end of the workshop by the Network and Analysis Center Coordinators, A. Moore and R. Weber, along with the session chairs.

Opening Session

The workshop participants were welcomed by the Assistant Deputy Minister (ADM), Dr. Irwin Itzkovitch, of the Department of Natural Resources Canada (NRCan) who outlined Canada's approach to the national reference frame delivery and maintenance, which are inherently based on NRCan's Geodetic Survey Division (GSD) GPS and VLBI programs. NRCan's participation to IGS is viewed as crucial and mutually beneficial to both parties. After the ADM's introduction, there was a short welcoming address by Norman Beck, Chief of the Active Control Section. Professor Gerhard Beutler, the first chair of the IGS Governing Board (GB) and currently the first vice president of IAG, followed with a brief presentation reminding the workshop participants that it was in Ottawa, almost nine years ago, that many IGS initiatives and products were initiated. However, his main message was about the role the IGS and other IAG services will play within a new, reorganized, and increasingly multidisciplinary IAG and its IGGOS Pilot Project. He reminded us, in his usual witty way, that the workshop theme "Towards Real-Time" implied that there must also be some unreal-times. Professor Christoph Reigber, the current chair of the IGS GB, addressed the workshop on behalf of the board and summarized the recent strategic planning (SP) exercise. He confirmed that real time IGS data and products were likely to play an increasingly stronger role to satisfy various and important projects, like LEO missions, atmospheric monitoring, etc. The enhanced role of IGS Central Bureau (CB) was also envisioned in the IGS SP, which is currently available from IGS CB. The SP report was, for the first time, distributed during the workshop.

Following the opening remarks, three working group (WG) and pilot project (PP) status reports were presented since they were not assigned individual sessions during the workshop; namely the Tropospheric WG, Precise Time Transfer PP and the International GLONASS (IGLOS) PP. The Tropospheric WG, chaired by G. Gendt of GeoForschungsZentrum (GFZ), has been producing official IGS products of combined tropospheric zenith path delays for several years, but is now concentrating on near real-time (NRT) tropospheric products in conjunction with accelerated IGU orbit production and delivery. J. Ray of the United States Naval Observatory (USNO) who co-chairs the Precise Time Transfer PP, presented a status report (posted on the workshop www site). The objective of realizing an IGS time scale and aligning the IGS clock products to UTC has been reached and other goals such as timing receiver calibration and increased participation of timing labs in PP are progressing well. The plan calls for formal adoption of the IGS time scale and the correspondingly aligned IGS combined clock products by the end of 2002. The new improved alignment has helped to identify daily clock discontinuities at some stations, which represents a valuable and efficient quality check and provides an impetus for further investigation of some station installations. Finally, J. Slater of NIMA gave the status of the IGLOS PP. Currently, there are only 6-7 operational GLONASS satellites, and only 3 Analysis Centres (AC), are routinely computing the satellite orbits, which are combined by the AC Coordinator (Robert Weber) with a delay of one or two months. This is hardly acceptable, more GLONASS satellites, ACs and faster GLONASS combinations are needed. Ultimately, IGLOS should be integrated into the routine IGS operation and products.

Real-Time Applications and Products

Tropospheric and LEO applications have the most demanding requirements for IGS data and products within 1 to 3 hours. Initially, the session position paper called for IGS Ultra rapid orbit solutions with delays of no more then 1 hour. However, from the discussions following the position paper, it became clear that the proposed 1 hour delay was unrealistic, given the status of the current data delivery schedule as well as AC workload. ACs quickly compromised on a 3 hour-delay. A presentation on Ultra rapid processing given by N. Romero of ESA initiated discussion on the omission, by most ACs, of a relatively high number of satellites from the ultra rapid solution. This goes directly against the standing IGS policy adopted in 1998 specifying that the IGS orbit products should be as complete as possible and include even marginal satellites with appropriate accuracy codes. R. Muellerschoen of JPL gave an impressive presentation on the JPL real time orbit/clock solutions supporting NASA's wide area (worldwide) DGPS. The JPL/NASA system is designed to support all NASA navigation needs at or below 10 cm.

The NASA system can also be utilized for sub ns time transfers, provided that calibrated receivers are utilized as outlined in a presentation by E. Powers of USNO. Two European presentations on NRT tropospheric solutions, relying on IGU products, within the scope of the COST716 project (http://www.knmi.nl/onderzk/index.html), were given by R. Pacione and H. van der Marel. The real time needs for ionospheric TEC information were described by B. Wilson of JPL. P. Heroux of GSD outlined the Canadian approach to national reference system delivery/maintenance, which is also moving towards real time and relies on IGS and VLBI. Real time and near real time requirements for natural hazard monitoring were presented by Y. Bar-Sever of JPL. His presentation clearly showed the complementarily nature of seismic monitoring and continuous GPS precise positioning. Namely, GPS provides monitoring at low frequencies with periods of hours to days where seismology becomes biased or completely fails.

Real-Time Data/Products Exchange

This was the first opportunity for the newly created IGS Real-Time Working Group (RTWG) to share its initial findings and formulate future plans. The results of an initial investigation, which are summarized in the position paper, were presented by M. Caissy on behalf of RTWG. They suggested that IGS adopt UDP (User Datagram Protocol) for Internet real time GPS data streaming since it has been tested and successfully used by both JPL and NRCan. The UDP (unicast or multicast) protocols, unlike the more standard TCP/IP, do not require point to point connections, and consequently are more efficient than TCP/IP (no opening/closing connections, smaller packet size overhead etc.). This is true, in particular, for smaller intermittent packets typically seen in GPS real time data stream. On the downside UDP, unlike TCP/IP, does not include receipt acknowledgements and/or retransmission, which may be needed for product delivery. G. Weber of BKG and G. Hedling of Lantmateriverket demonstrated the use of TCP/IP in their presentation of an operational RT DGPS system in Europe. K. MacLeod of GSD described UDP operational tests at NRCan. Following these presentations, security issues and firewall problems were discussed quite extensively in this and the following DC session. In the end, there seemed to be general agreement that both the UDP and TCP/IP protocols for RT data exchange should be researched and prototypes developed by RTWG for IGS. A solid interest was shown by both IGS DCs and ACs since this development could lead to timely, robust and redundant near RT or RT data streaming directly to the interested DCs and ACs.

Data Center Issues (DC)

Overall DC statistics, performance and current issues, and the GSFC DC in particular, were summarized by C. Noll of GSFC. For example, most of the recent LEO (GPS) data are now available at the GSFC DC. The need for the establishment of a DC WG was also raised. (It was subsequently formalized by the IGS GB at its April 11 meeting, and will be chaired by C. Noll). Firewalls and security issues were discussed extensively as well as the somewhat confusing data management at DC (found to be inadequate in particular for new, uninitiated users). This was shown in a presentation by E. Gaulue of IGN. H.

Habrich and M. Scharber summarized status and new developments at the BKG and SIO DCs, respectively. The GPS Seamless Archive Center (GSAC) developments at SIO are maturing and look promising. It was also pointed out that the GLONASS/GPS data streams will soon be integrated at the RINEX level as previously planned and announced.

Network Issues

Following the DC session, the invited vendors, who also sponsored Monday night's ice-breaker reception, made short presentations on their latest GPS receiver and related hardware developments. Some of the current or new receivers are, or will be capable of stand-alone station monitoring and include internet (IP) communication software. Also discussed was the current IGS standard P1/P2 pseudorange pair, which poses some additional complications for some receivers, which observe C1 rather than P1 pseudoranges. As pointed out by some vendors, P1 observable would make their receiver more expensive. Perhaps, in the future, IGS should cooperate more closely with manufacturers when adopting standards such as the P1/ P2 pseudoranges. The P1-C1 differences, when used inconsistently with the fixed IGS orbit/clock product in undifferenced processing, will result in significant position and receiver clock errors.

The network issues session was introduced by the IGS CB Network Coordinator, A. Moore. Solid progress has been made on data availability, timeliness and integrity, though some improvements are still possible. With the continuous addition of tracking stations in dense regional networks, the concept of associated IGS network was put forward. This proposition, paralleling AACs, would allow inclusion of new stations in regions already saturated with IGS stations. It would ensure that IGS becomes open to new participation and provide a model for manageable growth of IGS networks. L. Combrinck gave an update on the situation in Africa. He reminded participants that, with the exception of very few nations (like South Africa), the African situation, particularly the communication/internet infrastructure, is very fragile and not likely to improve in the near future. P. Fang of SIO, on behalf of Chinese colleagues, gave an update on the situation in China. While there are many suitable stations and considerable interest in China, reflecting on all IGS components, the situation remains difficult, primarily stemming from political decisions/willingness to release/exchange appropriate data and information to IGS. R. Neilan, Director of IGS CB, summarized the status of the GPS modernization, including the new L2CS and L5 frequencies, which could potentially revolutionize GPS. Currently, there are 12 Block IIR with L2CS and 6 Block IIF satellites (with the additional L5 frequency) planned to be launched. The GPS modernization and the new GPS III benefit from healthy competition by GALILEO. J. Dow of ESA presented a status on GALILEO. Phase I, covering all system development and initial tests has been approved by EC. The system is quite complementary and designed to be interoperable with GPS as far as the broadcast frequencies are concerned, yet offers a satellite constellation different from GPS (e.g. 27+3 satellites with 14h22m orbits). The full operation is envisaged for 2008. IGS input into GALILEO design is ensured and considered important. L. Estey of UNAVCO, indicated in his presentation that RINEX is ready and flexible enough (thanks to the recent revisions), to accommodate the GPS modernization and its new frequencies. At the end of this session, participants were once again reminded that the promised integration of GPS/GLONASS observations for GPS/GLONASS stations would take effect shortly at all DCs. No integration of GPS/GLONASS orbits into a single sp3 file is being considered at this time, according to R. Weber, the current AC Coordinator.

Poster Session

The poster session was intended for ACs to exchange their recent experience and compare their approaches. Most ACs presented at least one poster, usually highlighting significant changes implemented since the last AC workshop, held in September, 2000 in Washington DC. In addition to the AC posters, there were also poster presentations on regional and global station solutions, near real time orbit and tropospheric processing, LEO (CHAMP) orbit comparisons as well as the latest information on the recently launched GRACE mission. During the poster presentation, which was held in the AGU poster tradition, i.e. with cold (Canadian) beer, there was also a demonstration of GPS.C - the Canadian RT DGPS system.

Reference Frame (RF)

The current IGS RF Coordinator, R. Ferland of GSD, gave a progress report on Reference Frame (RF) WG activity. The production of the IGS station combined products (both weekly and cumulative) is proceeding smoothly, though some AC solutions had to be excluded from geocenter monitoring due to problems with the removal of constraints from their SINEX submissions. This identified problem should be corrected as soon as possible. Nevertheless, the IGS geocenter solutions agree quite well with the independent SLR solutions. The recent switch (on December 02, 2001) to ITRF2000 and its IGS00 realization has been quite smooth. Currently, the IGS combination already includes about 200 stations and satisfies the target IGS Station Polyhedron of about 200-250 stations. The size of this globally distributed polyhedron network was derived independently and allows for precise relative determinations over baselines of about 2000 km. For these reasons, additional back substitutions to derive polyhedron stations, as originally envisaged, is no longer necessary. This goal, in fact, is already being met in a single combination step. The RFWG, on behalf of IGS, also took part in the IERS PP aimed at testing of EOP/ITRF alignment. Since the IGS orbit, clock, station and ERP combinations were designed to be consistent with the ERP/ITRF, it was not surprising to see a high degree of agreement in submitted solutions, with the IGS adopted minimum constrain approach showing one of the best consistency/results. S. Y. Zhu of GFZ looked into the apparent difference of a few ppb between GPS and ITRF scales. He concluded that it cannot be due to GM or a common satellite antenna offset, as in both cases the resulting scale effect is negligible in GPS global analyses. This has confirmed earlier tests done by various ACs. In terms of regional station integration, an unresolved and open question remains "what should be the recommended approach for continental AAC to integrate RNAAC solutions into the IGS realization of ITRF (i.e. the IGS station polyhedron)? R. Ferland addressed this problem in his scond presentation. The two main options considered ere: constraining (consistently with the IGS variance-

covariance matrix r even much higher constraints) and minimum constraints suitable for non-global networks, e.g. Blaha's inner constraining type (presented here by Z. Altamimi of IGN). The RFWG will need to perform some additional testing before consensus is reached and a specific method is recommended for integration of regional solutions into the IGS polyhedron. In many respects, EUREF's approach presented by its Director, C. Bruyninx of ROB, should serve as a model for such IGS/ITRF densification. The outline of the newly emerging NAREF initiative, given by M. Craymer of GSD was encouraging, in particular the clear commitment to commence regular submissions to IGS. Finally, M. Rothacher of TUM, the current IERS Analysis Center Coordinator, highlighted the result of the discussions related to the new SINEX
version of 2.0.

Receiver and Satellite Antenna Calibrations

M. Rothacher introduced the session with the position paper presentation. Very significant progress has been made since the 1999 and 2000 AC workshops. Namely, at the 1999 AC workshop, satellite antenna patterns were first identified as a potential cause for the mysterious and unexplained scale bias of about 15 ppb introduced when precise absolute calibrations of receiver antennas were included into global GPS solutions. The absolute (anechoic chamber) and relative antenna calibrations have been recently confirmed by independent, ingenious, and very precise absolute calibrations methods. One of these methods was developed by the Hannover group and uses a robot rotating and tilting a GPS antenna while observing real GPS signal. This method was well described in a presentation by M. Schmitz of Geo++. Calibrating satellite antennas on the ground, due to their size and electronic complexity/adjustment proved to be quite a challenge as seen from the presentation by G. Mader of NGS. However, solving for antenna phase pattern with respect to absolutely calibrated receiver antenna phase center variations (PCV), gave quite precise and repeatable results. Two distinct satellite antenna PCV's, namely for the Block II/IIA and Block IIR satellite types were obtained in that fashion. A separate presentation by R. Schmid of TUM showed that introducing the satellite and receiver antenna PCV's greatly diminishes the 15 ppb scale error. It is important to realize that both receiver and satellite PCV's are subject to an initial (and somewhat arbitrary) datum height (scale) offset, which is commensurate with a common antenna offset, or the scale of GPS. Consequently, the ITRF/VLBI scale can be used to solve/fix this antenna offset convention/datum problem, i.e. consistently with ITRF scale. Another approach to this antenna-offset/datum problem can be imposing the condition that a (weighted) sum of PCV variations, over a certain range of azimuths and elevation angles, be equal to zero. (NOTE: This is in fact how the current (DM) antenna offsets, used as a convention by IGS, have been derived, i.e. it is based on an early antenna chamber calibration, which assumed no elevation and azimuth variations and which gave the current conventional height L1/L2 offsets. It is quite remarkable that this old and crude antenna measurement, in fact, implies a scale that is correct within only 2-3 ppb of the ITRF scale convention.) Another, quite independent approach to antenna PCV calibration, presented by P. Elosegui of Harvard-Smithsonian/Center for Astrophysics, is based on comparing the precise phase observations obtained by the multi-directional GPS antenna under calibration with respect to a directional parabolic one. Since the reference parabolic antenna is virtually immune (once properly calibrated) to PCV and multipath, while common effects are canceled out through procedure (e.g. the short baseline, delays), the remaining difference is due to multipath as well as to antenna PCV (note any satellite antenna PCV is also eliminated here). The advantage of this method is that it is station specific, unlike the previous approaches, and thus also includes multipath. Potentially, it can also be used for mobile calibrations of IGS sites w/o any interruption or changes to the IGS operations (subject only to the requirement of an antenna splitter at each station).

As a first step towards a significant improvement over the current convention (which uses PCV relative to the DM antenna type), it was proposed that IGS adopt, by January 2003, a new IGS antenna convention (receiver, satellite antenna PCV's and the corresponding height offsets), subject to prior evaluation and testing by ACs. Also discussed during this as well as the Network session was an urgent need to develop clear IGS guidelines on equipment and antenna changes in particular, which should provide sufficient overlaps to ensure a long term continuities of the IGS times series. This is also imperative in view of equipment improvements and the future GPS modernization upgrades.

Ground Based GPS Ionospheric Estimation

The ionospheric group, headed by J. Feltens of ESA is a very active group that had already met earlier this year in Darmstadt, Germany. Consequently the agenda and recommendations were well focused. The most important goal, as outlined in the position paper, is an official production of ionospheric combined product, which has been long in preparation, and which has been maturing quickly as indicated by evaluations utilizing TOPEX TEC data. Currently, the yet unofficial IGS ionospheric combinations are as precise, reliable and complete as the best AAC contributions. There is a clear commitment, after some fine-tuning (e.g. global weighting) to launch this official IGS ionospheric combined product. S. Schaer of CODE AC presented an impressive (and real) ionospheric video. He has also compared station DCB's, furthermore he is also responsible for the official IGS P1-C1 bias estimations. He has also stressed the importance of minimizing discontinuities between daily ionospheric grid maps. An interesting presentation on validation using TOPEX TEC data as well as the assimilation of TOPEX ionospheric profiles into numerical ionospheric models was given by B. Wilson of JPL. He also reviewed past (and published) research on the significance of the neglected (3rd and higher) ionospheric and magnetic terms in two frequency GPS positioning. The effect, under extreme ionospheric conditions, could reach up to 2-cm phase range errors in precise GPS positioning. P. Heroux of GSD also presented a simple but effective approach for ionospheric map quality evaluation utilizing observed and computed P1-P2 delays at a selected set of IGS stations, preferably not included at the ionospheric grid map generation. During subsequent discussions and with regards to daily discontinuities, it was pointed out that it would also be equally beneficial to include the last epoch of each day (24:00) in all IGS daily orbit/clock files as well. This would also enable the detection/mitigation of any orbit/clock daily discontinuities.

Low Earth Orbiters (LEO)

Recently, the LEO WG has become very active with the availability of data from several LEO's already in orbit. Steady progress has been realized in CHAMP precise orbit determination (POD) such that the best CHAMP POD test results, based on reduced dynamic methods, are well below the 10 cm precision level. The best kinematic POD (independently determined epoch positions) is approaching the 10 cm precision level. This was shown in the LEO position paper presentation made by H. Boomkamp of ESA and in separate presentations on different LEO POD approaches by B. Schutz of CSR, M. Rothacher of TUM and U. Hugentobler of CODE. This is the first and necessary step of LEO WG. The subsequent goal/aim (as specified in its charter) is the investigation of possible improvements to the IGS core products (orbits/clocks) through simultaneous LEO and IGS data processing. An initial attempt to answer this difficult question was already presented by S. Y. Zhu of GFZ. Clearly, the LEO POD must have the highest possible precision before any meaningful contribution to the current IGS orbit/clock products is made. This is why it was suggested that the WG should concentrate, for the time being, only on one specific LEO satellite. Also benefit/effects and timeliness of the IGS Rapid versus IGS Final orbit/clock combination products were discussed. The question was also raised if IGS Final orbit/clock combination delays should be reduced from the current 2 weeks down to perhaps one week.

Review of IGS Products

Previous sessions and this session's position paper reviewed the IGS products in view of increasing demands on timeliness to satisfy the requirements of near RT applications for LEO POD, troposphere and precise positioning. The IGS core products of combined orbits/clocks and station coordinates aspire to be consistent and conform to current IERS standards. That is the reason for the adoption of the new ITRF2000 and that the official IGS ERP accumulated series (igs00p02.erp), which spans the ITRF94, ITRF96, ITRF97 and ITRF2000, has been transformed into the ITRF2000 realizations. Thanks to the minimum constraint approach adopted for IGS products since 1998, the ITRF96/97 and ITRF97/2000 transformations are nearly exact. A similar transformation of the IGS combined orbit products into the current ITRF realization was also proposed in this session's position paper. Apart from the already proposed 3-hour production cycle for IGU and tropospheric solutions, the main question that remains is the effect of the proposed IERS2000 Conventions on IGS products. J. Kouba of GSD, in his presentation, tested the new subdaily ERP model, which is already available from the IERS2000 Conventions www site, by using independent pole rate solutions. He concluded that the IERS 2000 subdaily ERP model could be adopted since it fits the IGS data as well, or perhaps slightly better, than the IERS96 subdaily ERP model. A detailed report on this testing is available from the workshop website. J. Ray of USNO reviewed the proposal for the new celestial pole (CP) definition which will be included in the new IERS 2000 Conventions. Since there still are some clarifications needed, and since IGS analyses are relatively insensitive to CP, as long as consistent transformations are used going to and from CP, he recommended a "wait and see" approach. There was also a question raised about the need for IGS satellite clock products at a time interval shorter than the current 5-min sampling. Linear interpolation of 5-min satellite clocks is precise at the 0.1 ns rms level, allowing precise kinematic positioning (at any interval) with about 5-10 cm (rms) precision. This represents only a slight precision decrease from the positioning obtained with the original, not interpolated, satellite clocks. Some participants felt that for the most precise LEO applications, this 5-10 cm precision level may not be acceptable. However, the significant effort and additional computational burden involved with clock determinations at higher rates need to be considered. The IGS time scale and the newly aligned IGS clock (including the sp3) products have reached a mature stage and are ready for adoption by IGS, as clearly and convincingly demonstrated by K. Senior of USNO, the developer of the IGS time scale. R. Weber of TU Vienna /AIUB, the current AC Coordinator summarized all three IGS orbit/clock combinations and also stressed the importance for ACs to include ALL satellites, including the marginal ones, but with proper accuracy codes. This is in particularly important for the IGU combined product, where a number of satellites are routinely excluded by ACs due to a lower accuracy. These missing satellites are badly needed by RT and near RT applications as it was indicated in several presentations during this workshop. T. Yunck of JPL gave an entertaining, but somewhat controversial presentation on the GPS scale and consistency. Finally, S. Hilla of NGS, who took on the challenge to update the SP3 orbit/clock format, presented his SP3 format update proposals. The latest variant, which allows accuracy codes for both orbits and clock at each epoch and is largely backward compatible, seemed to have received the widest acceptance. Though concerns were expressed that the proposed accuracy code exponential base of 1.25 is not compatible with the base of 2 used for the header accuracy codes, and that it did not allow for any x, y, z orbit correlations.

IGS

SESSION 1:

REVIEW OF THE IGS ANALYSIS PRODUCTS

REVIEW OF IGS ANALYSIS PRODUCTS

Robert Weber, University of Technology, Vienna
Jim Ray, U.S. Naval Observatory, Washington
Jan Kouba, Natural Resources Canada, Ottawa

A) Final Combined Products

The IGS Final Products are the definitive set of GPS results provided for the general user community. They are designed to be fully self-consistent, within the noise level, and also consistent with International Terrestrial Reference Frame (ITRF) and the Conventions of the International Earth Rotation Service (IERS). Below is a summary of their current status.

Summary of Current Status of IGS Final Products

Final	Update		Sample	
Product	Latency	Interval	Interval	Accuracy
GPS ephem.	~13 days	weekly	15 min	<5 cm
GLONASS ephem.	~4 weeks	weekly	15 min	30 cm
sat & sta clocks	~13 days	weekly	5 min	0.1 ns *
coords: horizontal	12 days	weekly	weekly	3 mm
vertical				6 mm
veloc: horizontal	12 days	weekly	weekly	2 mm/yr
vertical				3 mm/yr
polar motion	~13 days	weekly	daily	0.1 mas
polar motion rates	~13 days	weekly	daily	0.2 mas/d
length-of-day	~13 days	weekly	daily	0.020 ms $
zenith troposphere	<4 weeks	weekly	2 hours	4 mm
iono TEC grid		(under development)		

* w.r.t. IGS timescale which is linearly aligned to GPS time each day
$ VLBI results are used to calibrate long-term behaviour of LOD estimates

Issues/questions to consider:

* **Orbit accuracy** -- While the internal consistency of the IGS orbits is at about the 2-cm level, the agreement with SLR is around 5 cm (radial). Are there any new results or changes in this area? Have we reached the accuracy/consistency limit, more or less?

* **Orbit modelling** -- Are there any innovations or improvements to report related to modelling GPS orbits? What about for Block IIR spacecraft?

* **Long-term product consistency** -- Users would prefer to get products from the IGS that are fully self-consistent, over long times as well as for any particular epoch. The occasional changes in TRF realization and other such changes can cause discontinuities. Should/how can the IGS provide long-term consistency?

Several approaches could be considered:

- reanalyse/recombine the full history of GPS data -- huge burden but would give the best possible results (who will do this, e.g. SIO, TU-Munich?)
- recombine the previous solutions using ITRF2000, etc -- nearly equivalent to next approach but more work
- transform existing products to be consistent with ITRF2000 -- relatively simple to do although it is not fully effective

The IGS needs to consider this challenge and determine the best approach that is also realistic. Probably, the most feasible option is for all orbit, ERP, and station products to always be transformed into the official ITRF realization, whenever it is changed, starting with the ITRF2000 change. The original solution files could be moved into subdirectories ITRFxx, where ITRFxx is the ITRF realization used originally. The regular product directory WWWW would thus contain only the IGS combined products in the current ITRF. This way everything would be available and the readily visible products will be always in the currently official ITRF.

In order not to duplicate too much information another approach, also worthwhile to consider, should be mentioned:

- label and separate clearly products based on different TRF realization within the public wwww and ftp directories; provide in addition a PC- and UNIX software tool which easily enables the user to transform orbits, ERPs and station coordinates between the TRF realizations.

* **ERP series** -- Effectively two Final ERP series are available, one from the SINEX combination and one from the orbit/ERP combination. The latter is available for a much longer span. As with the long-term consistency item above, these series should be unified into a single long-term (consistent) time series for users.

This has been done by the NRCanada group. The accumulated ERP file igs00p02.erp (from the Final SINEX-based ERP file starting with GPS week 1013) has been augmented with the longer igs95p02 series (old Finals from the orbit combination process), after applying transformations to the current ITRF2000 realization. The only other official IGS ERP series is igs96p02 from the Rapid combination, which is to be used for the most recent epochs.

* **AC model changes** -- Changes in an AC data analysis strategy can have major unintended consequences for the IGS product combinations. Even though ACs generally test their changes thoroughly before implementing them operationally it is not always easy to detect certain types of problem. For this reason, ACs are strongly encouraged to submit a full suite of test products to the AC Coordinator (as well as coordinators for specific product lines) for evaluation before operational implementation. At least a brief information on the planned change should be forwarded to the ACC per email one day before the change becomes effective. Also, AC Analysis Strategy Summaries should be updated at the Central Bureau at least annually.

* **ITRF2000** -- [See also the separate ITRF session and position paper]. The Reference Frame working group recommended that the IGS change from the IGS97 realization of ITRF97 using a set of 51 RF sites to:

- IGS2000 realization of ITRF2000 using a set of 54 RF sites
- change already performed on 02 December 2001 (start of GPS week 1143)
- change the RS51 set of sites to RS54 by:
  - drop BRAZ,AREQ
  - add ASC1, CEDU, DGAR, LPGS, and RIOG
- for sp3 files, the alias for "IGS2000" is "IGS00"
- the transformation from IGS97/RS51 to IGS2000/RS54 (using those stations in common) were computed by Remi Ferland and reported in IGS Mail #3605.
- the only significant shifts were the T_z component of the origin and the scale, part of which is due to the general relativistic effect of changing from TCG (geocentric) time in ITRF97 to TDT/TT (terrestrial time) in ITRF 2000.

* **IGS geocenter & solution constraints**-- Remi Ferland has shown that the IGS combined geocenter estimates are rather consistent with long-term geocenter of ITRF2000 (but not consistent with the Z component of ITRF97); the mean offsets are 3.9, 0.0, and 5.3 mm for X, Y, and Z, respectively. Significant systematic variations remain (e.g., annual oscillations in Z), the reality of which needs to be investigated. Nonetheless, the prospects of GPS contributing usefully to monitoring variations in the geocenter (motion of the Earth's center-of-mass viewed from the ITRF) appear bright.

ACs are reminded that all constraints to the parameters in a SINEX file must be included in the “APRIORI” blocks. Currently, the geocenter estimates from GFZ are not used in the IGS combination due to strong constraints applied in their analysis. Even though the geocenter estimates of the other ACs are included, evidence exists that subtle analysis constraints may continue to influence the IGS combination. These effects needs to be studied more closely and resolved, not just for geocenter estimates but for all parameters.

* **IGS TRF scale** -- Compared to VLBI and SLR, the GPS frame scale is complicated by the effects of: partly understood non-hemispherical phase patterns for the tracking antennas; much less understood satellite transmit antennas (Blocks II,IIA,IIR, and in the future IIF); very easy and sometime frequent changes in antenna equipment/heights; and important but usually neglected effects due to multipath and other phenomena involving the antenna environments. What are the prospects for overcoming these difficulties/limitations to the level of VLBI and SLR (~0.5 ppb or better)? [This relates closely with the separate session on antenna calibration.]

* **Station coordinate residuals** -- Time series of station coordinate residuals from the weekly SINEX combination can be very useful for many users. These are available in weekly files at the IGS Data Centres. Continuously updated, station-based files would be more useful for most users. A service of this type is already provided by Tom Herring at his Web-site `http://bowie.mit.edu/~fresh/index2.html` . IGS should consider providing on official IGS service of this type, advantageously located at the IGS Reference Frame Coordinator Web-Site.

EUREF, for example, provides besides the ‘Standard Time Series’ so-called ‘Time Series for Geokinematics’ which are improved coordinate series, where the jumps, outlier periods are corrected and eliminated. Should IGS provide such a kind of product ? [This relates to the separate TRF session and results from Remi Ferland.]

* **Clock time scale** -- The new realigned clocks from Ken Senior are now available. It is recommended that these be adopted officially by the IGS to replace the previous clock products. The questions are when and how to do this, and whether to replace the prior clock files in the GLOBAL DATA Centers with the new product files.

* **Clock solution densification** -- What is the status of AC efforts to "densify" their clock submissions? It is really necessary to have at least two ACs do this on a reliable basis for a comprehensive set of tracking stations, but more ACs would be better. The current IGS coverage is not adequate to ensure that all stations with high-quality frequency standards and all BIPM timing labs are included.

* **High-rate satellite clocks** -- It has been suggested that high-rate satellite clocks (sampling at 30-s intervals rather than the current 5-min) might be needed to support LEO missions. This would place a heavy burden on the ACs. However, study of the actual random walk behaviour of the Cs and Rb clocks aboard the satellites shows that error from linear interpolation of 5-min clocks to the middle 2.5-min epochs is very close to the accuracy of the IGS clocks, namely ~0.11 ns. Rb clocks are somewhat better while Cs clocks are worse. There does not appear to be sufficient support now to justify recommending higher rate clock products.

* **Troposphere** -- What about "densifying" tropo solutions by asking the ACs to use precise point positioning for their tropo-products (in addition to densified clocks)?

* **Ionosphere** -- Based on the Ionosphere Working Group workshop, held during 17-18 January 2002, it is expected that combined IGS TEC maps can be produced as a routine product beginning in the near future. It is likely that the temporal resolution will be improved from 2 hours to 1 hour. When can this service begin? What about other ionospheric products, such as corrections for higher order effects?

* **Updated <P1-C1> biases** -- Given that the satellite biases vary significantly with time, these should probably be updated at least annually. The most recent set of biases was implemented on January 20th,2002. What is the proper update cycle for the future? This maintenance issue could be largely removed if the old cross-correlation receivers in the IGS network were replaced. Problems remain with some modern receivers that report C1 instead of P1 and with small inter-receiver biases.

* **Extended SP3 format** – Steve Hilla has drafted several proposals for adding new data type to the sp3 orbit files. Position and velocity errors would be possible each satellite and at each epoch, rather than the current single accuracy codes for each satellite. Clock errors would be entirely new, and various possible flags are suggested for specific types of orbit and clock events (e.g. manoeuvres and clock resets). The ACs should consider the options and prepare to adopt one of the extended formats in Ottawa.

B) Rapid Combined Products

The IGS Rapid Products are intended as a near-definitive set of products for users unable to wait for the Final Products. Generally, the accuracy is about 50% poorer than the Finals, but the difference is usually very small in absolute terms. Below is a summary of their current status.

Summary of Current Status of IGS Rapid Products

Rapid Product	Latency	Update Interval	Sample Interval	Accuracy
GPS ephemerides	17 hours	daily	15 min	5 cm
sat & sta clocks	17 hours	daily	5 min	0.2 ns *
polar motion	17 hours	daily	daily	0.2 mas
polar motion rates	17 hours	daily	daily	0.4 mas/d
length-of-day	17 hours	daily	daily	0.030 ms $

* w.r.t. IGS timescale which is linearly aligned to GPS time each day

$ VLBI results are used to calibrate long-term behaviour of LOD estimates

Issues/questions to consider

* **User requirements** -- Are rapid service user requirements being satisfied adequately, in terms of accuracy and product availability? What about the need of rapid tropo & iono products? Should these be considered?

* **Clock time scale & densification**—The issues for the IGS Rapids are the same as discussed above for the Final products.

C) Ultra-Rapid Combined Products

The IGS Ultra-Rapid Products are intended as a set of GPS products for high-accuracy real-time users. They are forward extrapolations using the latest and best observational results available. The goal is an orbit accuracy better than 30 cm, preferably better than 20 cm. Below is a summary of their current status (predicted part only).

Summary of Current Status of IGS Ultra-Rapid Products

Ultra-Rapid Product	Latency	Update Interval	Sample Interval	Accuracy
GPS ephemerides	real time	twice daily	15 min	~25 cm
sat clocks	real time	twice daily	15 min	~5 ns
zenith troposphere		(under development)		

Issues/questions to consider

* **User requirements** -- Are real-time user requirements being satisfied adequately, in terms of accuracy and product availability? Are more frequent updates needed? Robert Weber and his colleagues now provide diagnostic information on the Ultra-rapid combinations at their Web-site `http://luna.tuwien.ac.at/forschung/satellitenverfahren/igs/html` .

* **Integrity info** -- Should the IGS consider monitoring the real-time integrity of its Ultra-rapid products and start providing integrity alerts to users? [This relates to the separate session on real-time products and user needs.]

* **Near real-time troposphere** -- Gerd Gendt has proposed adding troposphere estimates for the observed half of the Ultra-rapids and to increase the update frequency to every 3 hours. This is under development. Is it adequate? Should these be "densified" using precise point positioning?

* **Predicted clocks** -- Are these worth providing? Not much effort is involved but they will probably never be at the 1 ns level, at least not until the entire constellation is replaced with Block IIR spacecraft or unless more frequent updates are made.

* **Clock time scale** -- When a satellite clock is reset, the current clock combination is corrupted. The algorithm should be changed (similarly to the IGS Rapid combination) to detect clock breaks and reject them from the time scale alignment. He combination could probably also be improved by identifying and rejecting poor submissions.

* **Missing satellites** – The Ultra-Rapid Orbit Combination usually suffers from a remarkable number of satellites missing in the AC-submissions (about 10-15%). How can we tackle that problem.

D) New IERS Conventions

The "IERS Conventions 2000" is near the final stages of preparation (for details see `http://maia.usno.navy.mil/conv2000.html`). As usual, ACs are encouraged to follow the Conventions to the greatest extent possible. Departures and innovations are should be noted in AC Analysis Strategy Summaries and should not compromise product quality. Based on the current draft, we can anticipate a number of areas of changes which will probably affect the IGS.

* **New celestial pole and nutation model** -- The 24th General Assembly of the IAU (2000) adopted a set of new definitions for the celestial pole and the ephemeris origin using a "non-rotating origin" no longer directly tied to the vernal equinox. In addition, a new nutation model was adopted. However, realization of the final version of the nutation model has been delayed many times and implementation of the new celestial formalism awaits appropriate user software and documentation. It is likely that GPS analyses will be only very slightly influenced by these model changes. Note that the IERS is planning a workshop on 18-20 April 2002 to focus on this topic and to consider plans for implementation.

* **New geopotential** -- This has been a very controversial area of the new Conventions. EGM96 is now recommended over JGM-3, but the high GPS orbits are probably not very sensitive to modest differences in these models.With data now coming from the CHAMP mission, we can expect other improved gravity fields (such as EIGEN-CH).

* **New solid Earth tide model** -- The model has been extensively modified but it is unclear what the practical effect is in terms of displacement accuracy. Further information is needed. ACs are encouraged to study this model and share their experiences.

* **New ocean loading service** -- Loading coefficients can be accessed at `http://www.oso.chalmers.se/~loading/` which is associated with the new IERS Special Bureau for Loading, within the Global Geophysical Fluids Center. Again, ACs are encouraged to try this service and share their experiences.

* **New EOP tidal model for periods >5 d** -- The previous model from Yoder et al. (1981) for periods greater than 5 days has been updated to account for mantle anelasticity and ocean effects. For users of tidally corrected EOP values, great care should be taken to describe precisely which tidal model has been used. To avoid such problems, ACs are urged to deliver products to the IGS with the long-period tides fully restored.

* **New subdaily EOP tidal model** -- A new subroutine is available to compute the effects of subdaily (near 12 and 24 hr periods) EOP tidal variations. The tidal model itself is unchanged from 1996 and the coefficients of the 8 main tidal constituents are nominally the same. However, a frequency- dependent admittance function is now used to account for a total of 71 diurnal and semidiurnal terms. Comparison of the 2000 and 1996 models for year 1997 shows peak differences of 0.1 mas for PM-x, more than 0.08 mas for PM-y, and about 0.012 ms for UT1. The RMS differences are 0.033 mas, 0.030 mas, and 0.0041 ms, respectively. These differences are large enough to justify adoption of the new model by the IGS.

E) Summary of Recommendations

IGS Reference System

* Long-term product consistency -- For user convenience, past orbit and ERP products of the IGS will be transformed into the official ITRF realization, whenever it is changed, starting with the ITRF2000 change. The original solution files will be moved into subdirectories ITRFxx, where ITRFxx is the ITRF realization used originally. The regular product directory WWWW will thus contain only the IGS combined products in the current ITRF.

The igs00p02.erp file (the Final SINEX-based ERP file) has been augmented with the longer igs95p02 series (old Finals from the orbit combination process) and transformed to the current ITRF. The Reference Frame coordinator (Remi Ferland) has kindly taken care of this.

* *IGS geocenter & parameter constraints*-- ACs are encouraged to work with the Reference Frame coordinator (Remi Ferland) to resolve outstanding questions concerning subtle constraints in their SINEX submissions. It is very desirable that all AC SINEX

submissions be usable for the IGS geocenter combination and that these be free of all over-constraints.

* *AC model changes* -- ACs should provide test solutions before making operational changes and should update their Analysis Strategy Summary annually.

New IGS Products

* *Ionosphere* -- What/when will Iono-products be offered? This relates to the separate Iono session. A summary of their product recommendations will be available after the Workshop.

* *Near real-time troposphere* -- The Troposphere Working Group chair (Gerd Gendt) has begun a trial service providing near real-time zenith troposphere estimates as part of the Ultra-rapid products. These have 3-hr latency and are updated every 3 hr. All ACs are encouraged to support this new product.

* *Integrity info* -- Should the IGS consider monitoring the real-time ? This relates to the separate real-time session. A summary of their product recommendations will be available after the Workshop.

* *Clock time scale* – The adoption of the new clock time scale at least for IGS Final products should take place end of 2002.

* *Extended SP3 Format* – The adoption of a new extended SP3-Format should take place not later than end of 2002.

IGS Analysis Products — Clock and IERS Convention Issues - J. Ray

- **Densification of station clock solutions**
  - IGS clock combination requires at least 2 AC submissions for each clock
  - highly desirable to include all stable clocks (~40 H-masers, ~25 Cs, ~15 Rb) & all timing labs (~18 now)
  - allows IGS clock products to be used for time transfer, including by the BIPM for TAI/UTC
  - improves the stability of the IGS internal time scale
  - can be done most efficiently using PPP method by each AC to densify own clock submission
  - currently done by CODE & USNO ($\gtrsim$100 stations each)
  - *need more ACs to participate*

- **High-rate satellite clocks ?**
  - previously suggested that 30-s satellite clocks needed for LEO applications, rather than IGS standard of 5 min
  - however, current Cs & Rb satellite clocks show interpolation errors near IGS accuracy (~0.11 ns)
  - *currently, no need seen for high-rate clock*
- **Maintenance of <P1-C1> biases ?**
  - *recommend continued updates based on CODE solutions, at least annually*
  - *eliminate cross-correlator receivers from IGS network*
  - *work with receiver makers to supply P1 instead of C1*

- **IGS internal time scale**

  - to overcome short-term instability due to GPS time
  - developed by K. Senior using dynamically weighted ensemble algorithm
  - *propose to implement officially ~30 June 2002, provided:*

    - * letter of institutional support/commitment submitted
    - * approval by Governing Board
    - * AC Coordinator is satisfied
    - * IGS Mail to be sent beforehand

  - *suggest replacing all old clock files in IGS Data Centers*

- **Future of IGS/BIPM Pilot Project**

  - *recommend end of pilot phase on 31 Dec 2002*
  - *propose permanent liaison between IGS & BIPM starting in 2003*

IGS Analysis Products — New IERS Conventions

- **Website:** http://maia.usno.navy.mil/conv2000.html

- **Implementation of new IAU Resolutions**
  - new ICRS celestial system, time scale transformations, nutation-precession model, & origin for intermediate geocentric frame
  - IERS Workshop on implementation issues being held 18-19 April at Paris Observatory
  - IERS publication will be prepared based on workshop
  - expect mostly tiny effects for GPS analyses
  - *propose no AC changes at this time*

- **Geopotential model**
  - EGM96 now recommended but newer/better models coming quickly
  - differences probably not significant for GPS altitude
  - *ACs encouraged to investigate and share results*

- **New solid Earth tide model**
  - extensive changes from earlier versions
  - no information on practical consequences or magnitude of differences
  - supposed to be accurate to 1 mm
  - *ACs encouraged to investigate and share results*

- **New zontal UT1 tidal model**
  - updates Yoder *et al.* (1981) using Defraigne & Smits (1999) Earth model with inelastic mantle
  - for periods longer than 5.64 d
  - *recommend ACs not apply tidal corrections to output products to avoid ambiguities*

- **New subdaily EOP tidal model**
  - extends previous model for 8 main tides to 71 diurnal & semidiurnal terms
  - differences at about accuracy level
  - if uncorrected, will affect EOP rates and alias into GPS orbits, mostly
  - *recommend ACs adopt IERS subroutine for routine processing as soon as possible*
  - *set date for uniform conversion ?*

IGS Analysis Products - Combination Issues

Robert Weber

Introduction

This paper reflects the summary of a talk given at the IGS Workshop in Ottawa in April 2002. The text is meant to be complementary to the position paper 'Review of IGS Analysis Products' presented by (Weber, Ray, Kouba) prior to the IGS Workshop.

IGS Final Products

The IGS Final Products are the definitive set of GPS results provided for the general user community. They are designed to be fully self-consistent, within the noise level, and also consistent with International Terrestrial Reference Frame (ITRF) and the Conventions of the International Earth Rotation Service (IERS).

The graphics below show the status of orbit and clock consistency of the submitted AC solutions covering (approximately) the past 60 weeks. Both graphics are regularly updated and can be obtained from the IGS-ACC web page at http://www.aiub.unibe.ch/acc.html

The WRMS-figure (Fig.1) shows the Weighted RMS (mm) of the individual AC solutions with respect to the IGS Final orbit. The CRMS-figure (Fig.2) shows the Clock RMS (ns) of the individual AC solutions with respect to the IGS Final clocks. For display purposes the values of the Final Combination summaries are shown after smoothing using a sliding 7 day window.

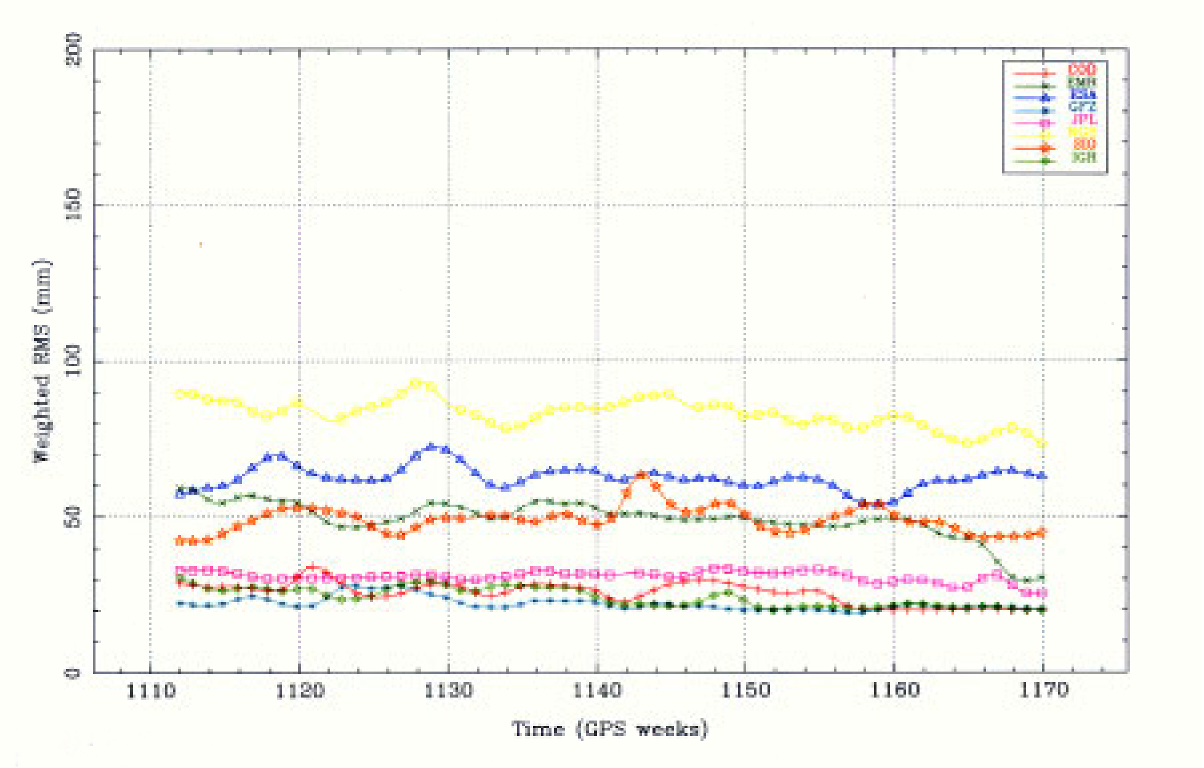


Figure 1

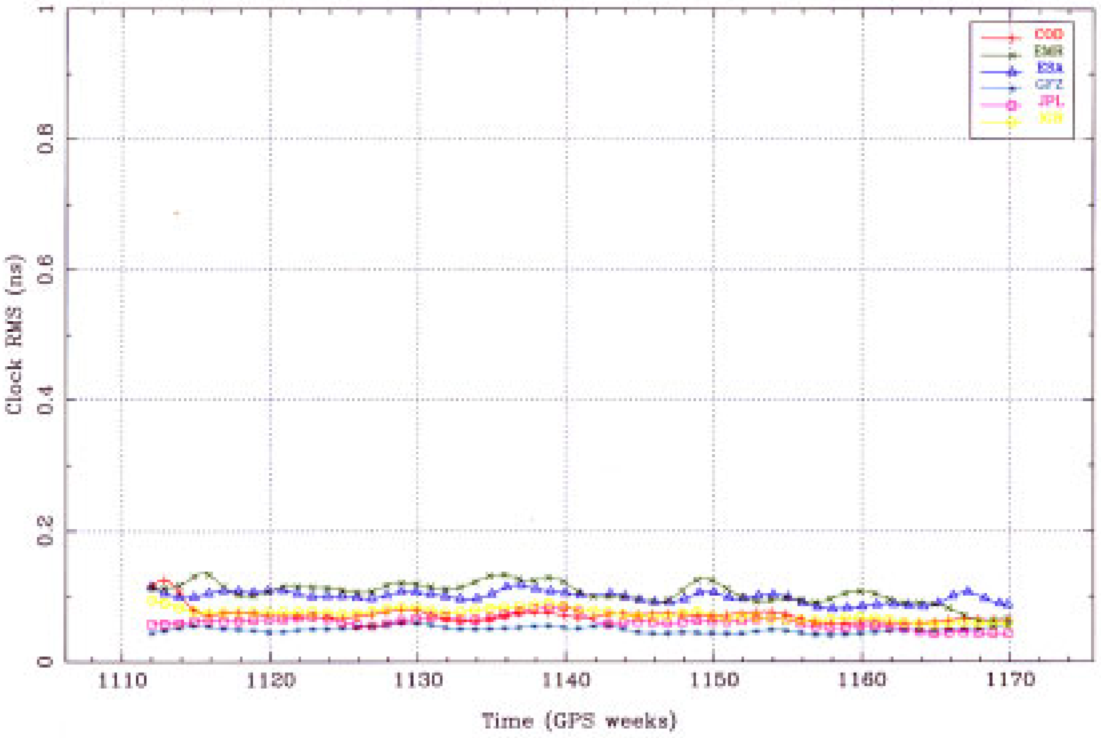


Figure 2

Both graphics show a quite satisfactory consistency of the submissions, below the 5cm level for the orbits and well below the 0.1ns level for the clocks.

A number of questions related to the igs-products were raised from individuals within the IGS and listed in various chapters of the position paper. In the sequence some of them should be discussed briefly. Comments reflect the discussion in Ottawa and are in accordance with the official list of workshop recommendations.

Questions related to IGS Final products

Question: Have we reached the accuracy limit for the orbits?
Answer: While the overall consistency of the IGS orbits is at the 2-cm level, the agreement with SLR is around 5 cm (radial). The consistency is very much dependent on the number of quite good orbit submissions. Up to 7 AC submissions are available and required each week to achieve this level of consistency. The bias between GPS and SLR observations has been investigated during the past 2 years by various groups without providing a satisfactory explanation. Another attempt will be made this summer in cooperation with SLR Analysis groups.

Question: Is 30s satellite clock sampling required for LEO mission support ?
Answer: Although there is no clear evidence that clock interpolation between 5 minutes time stamps is not sufficient, the IGS products will move towards providing 30 sec clocks. This will lay a huge computational burden on several ACs. Currently JPL is providing 30s clocks for the final product. LEO mission support usually asks for a low latency and therefore for 30s satellite clocks within the IGS Rapid and IGS Ultra Rapid (observed part) submissions.

Question: The new realigned clocks from Ken Senior are now available. Adopt the new clock time scale to serve BIPM?

Answer: It is recommended that these realigned clocks should be adopted officially by the IGS to replace the previous clock products. The questions, when (Jan. 2003 might be appropriate) and how to do this still remain. Another question is whether to replace the prior clock files in the GLOBAL DATA Centers with the new product files?

Question: What is the status of AC efforts to "densify" their clock submissions?

Answer: It is really necessary to have at least two ACs do this on a reliable basis for a comprehensive set of tracking stations, but more ACs would be better. The current IGS coverage is not adequate to ensure that all stations with high-quality frequency standards and all BIPM timing labs are included.

The current latency of about *14 days* in delivering the IGS Final products seems to be well accepted. Studying the delivery-time of the particular AC submissions shows a very heterogeneous picture ranging from 5 to 12 days. Thus, decreasing the latency of the IGS final combination seems to be feasible, but is currently not really requested by the community.

IGS Rapid Products

The WRMS-figure (Fig.3) shows the Weighted RMS (mm) of the individual AC solutions with respect to the IGS Rapid orbit. Figure 4 shows the Clock RMS (ns) of the individual AC solutions with respect to the IGS Rapid clocks. For display purposes the values of the Rapid Combination summaries are shown after smoothing using a sliding 7 day window.

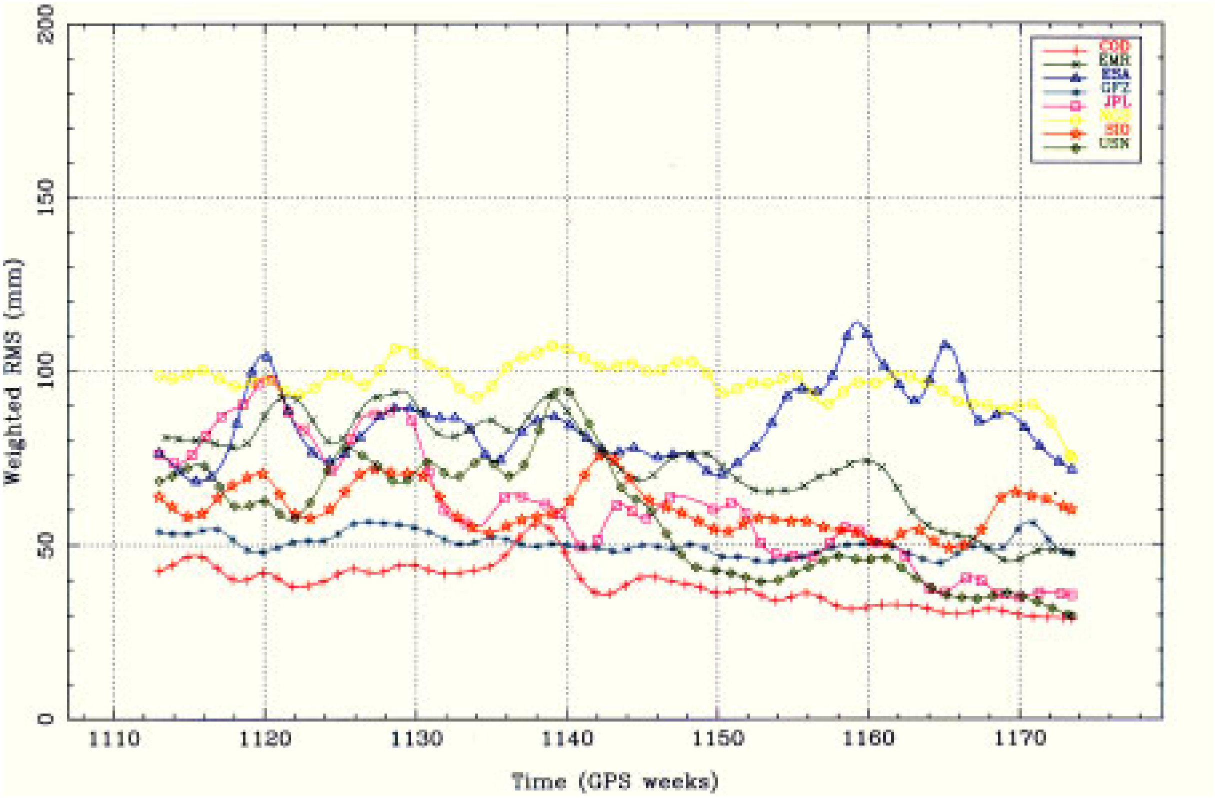


Figure 3

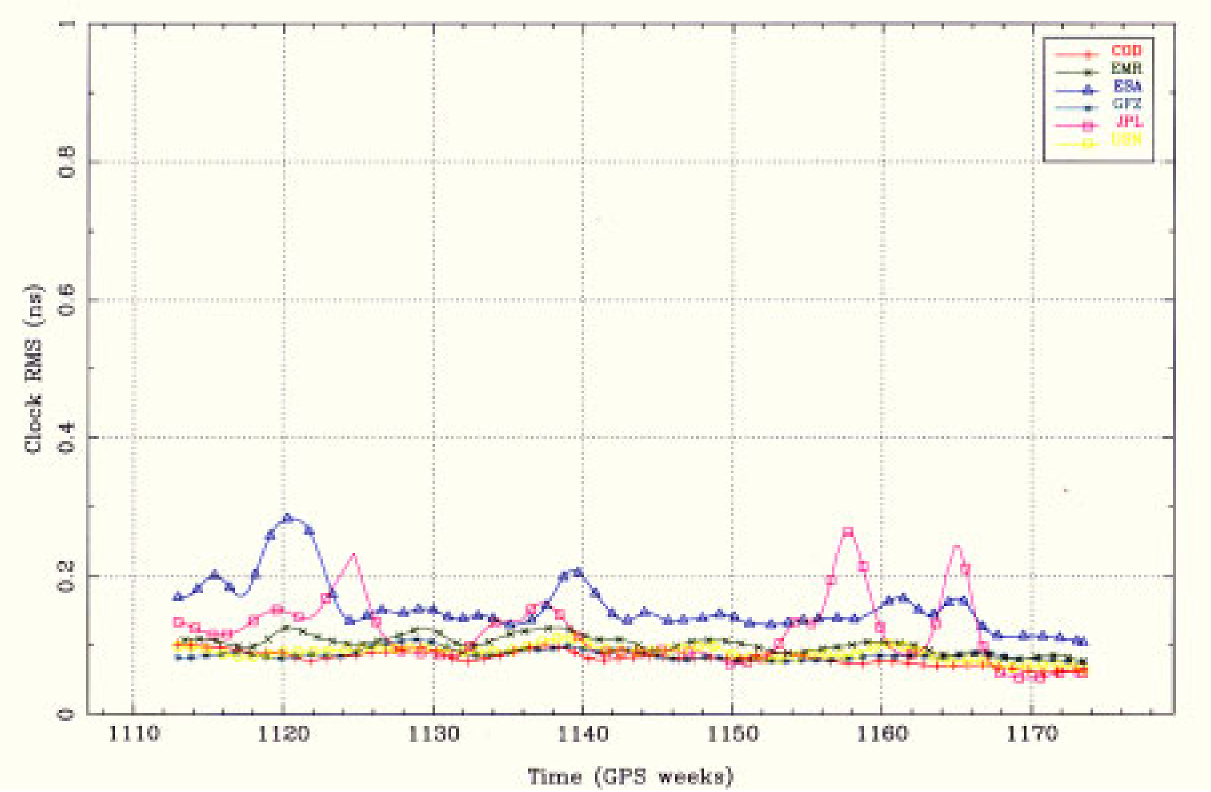


Figure 4

The next two figures show the difference between individual AC Rapid X-pole rate and Y-pole rate ERP solutions and the IGS Final ERP series. The individual series are shifted by 3 mas/day.

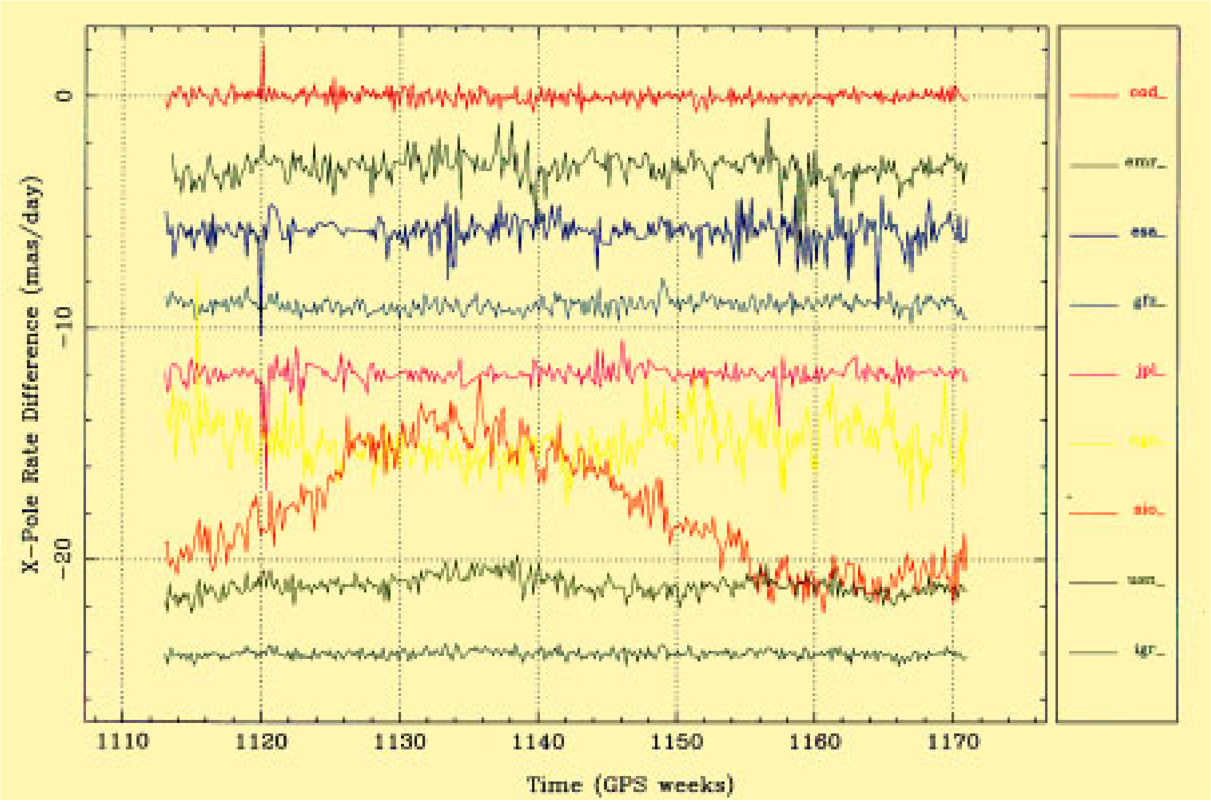


Figure 5

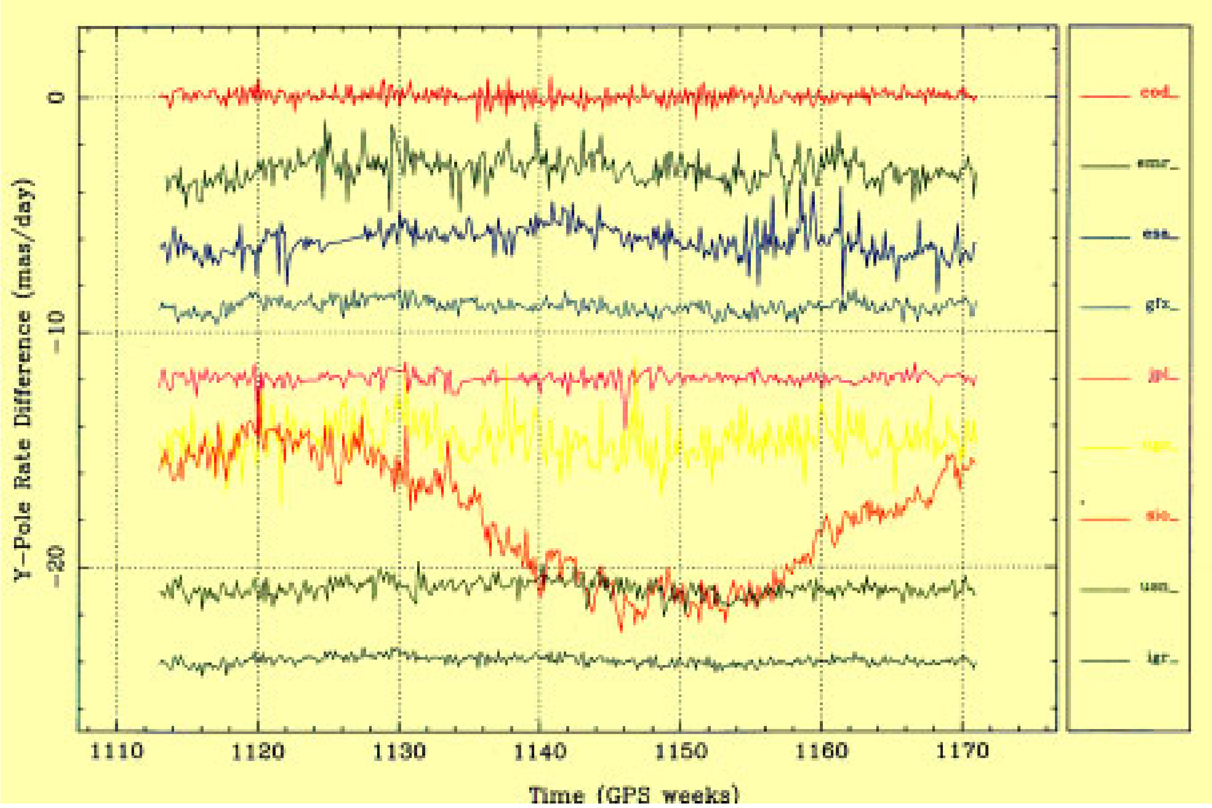


Figure 6

Please note the huge annual signal dominating the sio PM-rates. This signal has to be eliminated as soon as possible.

Questions related to IGS Rapid products

Question: Clock time scale & densification?
Answer: The issues for the IGS Rapids are the same as discussed above for the Final products.

The current latency of about *17 hours* in delivering the IGS Rapid products seems to be appropriate. Submissions to the IGS Rapid Combination are delivered by the ACs usually between 8 UTC and 17 UTC. Again decreasing the latency of the IGS Rapid combination seems to be feasible, but is currently not really requested by the community. People would prefer more frequent updates of the IGS Ultra-rapid combination, which will be discussed later.

IGS Glonass Products

Between January 1 and May 31, 2002, there have been 7-8 healthy, operational GLONASS satellites. They are all in the planes 1 and 3 of the constellation. The first new GLONASS-M satellite, GLONASS No. 711 in Plane 1/Slot 5, has not yet been designated as operational. It is not clear, if any problems may have been encountered after launch.

Microwave Technique / Tracking Status

The number of "permanent" IGLOS microwave tracking stations has grown slightly since December 2001. There are now 50 stations in the network, continuously tracking the GLONASS satellites and transmitting their data to the IGS Data Centers. Forty-five or more of these stations have been sending data to the data centers each week. Most of the receivers are Ashtech Z18 or JPS Legacy models. New stations that came on-line during the last three months include Frankfurt, Germany (FFMJ), Kourou, French Guyana (KOU1), and Zimmerwald, Switzerland (ZIMZ).

Orbit Determination

BKG, ESA and the Russian Mission Control Center (MCC) continue to compute and make available GLONASS orbits on a routine basis. The MCC orbits are based on SLR data. Figure 7 below demonstrates the daily coordinate rms. of the center submissions with respect to the combined orbit (1998.8-2002.2). The consistency among all contributed orbit submissions is at the 20cm level, regardless of the basic observable. MCC orbit rms. numbers are of course somewhat noisier, caused by the low number of satellites tracked by ILRS. The visible bump in summer 2001 is related to a mis-modelling of radiation pressure for satellite slot 8. Just after fixing that problem the rms. numbers decreased below the 20cm level.

In May 2002 the IGS-CB integrated all combined GPS/GLONASS tracking sites within their official data site pool, which was a long lasting request of the IGLOS-Pilot Project. This step should encourage all IGS Analysis Centers to make increased use of the GLONASS data in their processing schemes and come up with a number of new or improved products. In the first place precise GLONASS orbits with an increased orbit accuracy of 1-3 cm in the radial direction should be sufficient to study in detail the reason of the remaining bias of a few centimetres between microwave and laser tracking observations. Moreover, in case of a new GLONASS launch to plane II (elevation of sun above the orbital plane up to 88 degree) we are looking forward to learn more about reliable radiation pressure models for the GLONASS satellites.

Questions related to IGS Glonass orbits

Question: How many contributing ACs are necessary to provide a stable and reliable GLONASS orbit solution (orbit combination)?
Answer: The current number of 2 ACs calculating GLONASS orbits based on microwave observation data is far too small. We urgently need at least 2 more centers (or associated ACs) to provide a reliable solution !

Question: Why not providing combined GPS/GLONASS SP3 files?
Answer: That’s of course the goal to reach. But in fact the number of IGS-AC currently able to provide this product is only one (ESA). So, again, we urgently need more ACs to calculate precise GLONASS orbits.

The current latency of about *4-10 weeks* in delivering the IGS GLONASS orbits seems to be too long. We have to keep in mind that IGS-ACs usually align the GLONASS orbits to their center specific GPS orbit solutions. IGS-AACs solely calculating GLONASS orbits are forced to wait for the IGS final combination for this alignment. Thus, about 14 days are currently the shortest conceivable period for delivering precise GLONASS orbits, respectively a combined GLONASS orbit solution.

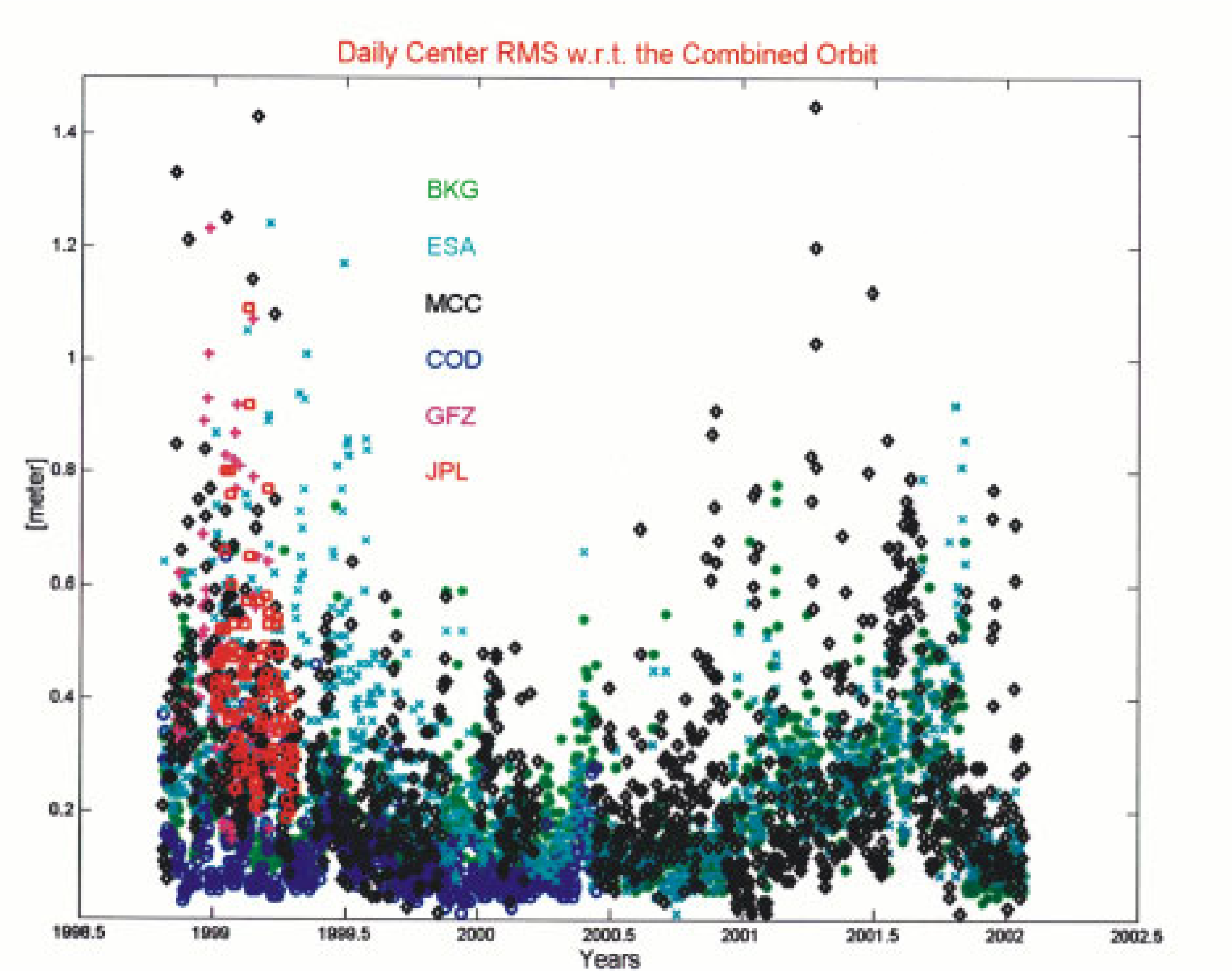


Figure 7

IGS Ultra Rapid Products

Figure 8 shows the Weighted RMS (mm) of the individual AC solutions with respect to the IGS Ultra Rapid orbits. For display purposes the values of the Ultra Rapid Combination summaries are shown after smoothing using a sliding 7 day window. The graphic shows a consistency of the submissions at the 20cm level. This number is quite comparable to the rms-differences between the Ultra Rapid combined orbit and the IGS Rapid orbit combination.

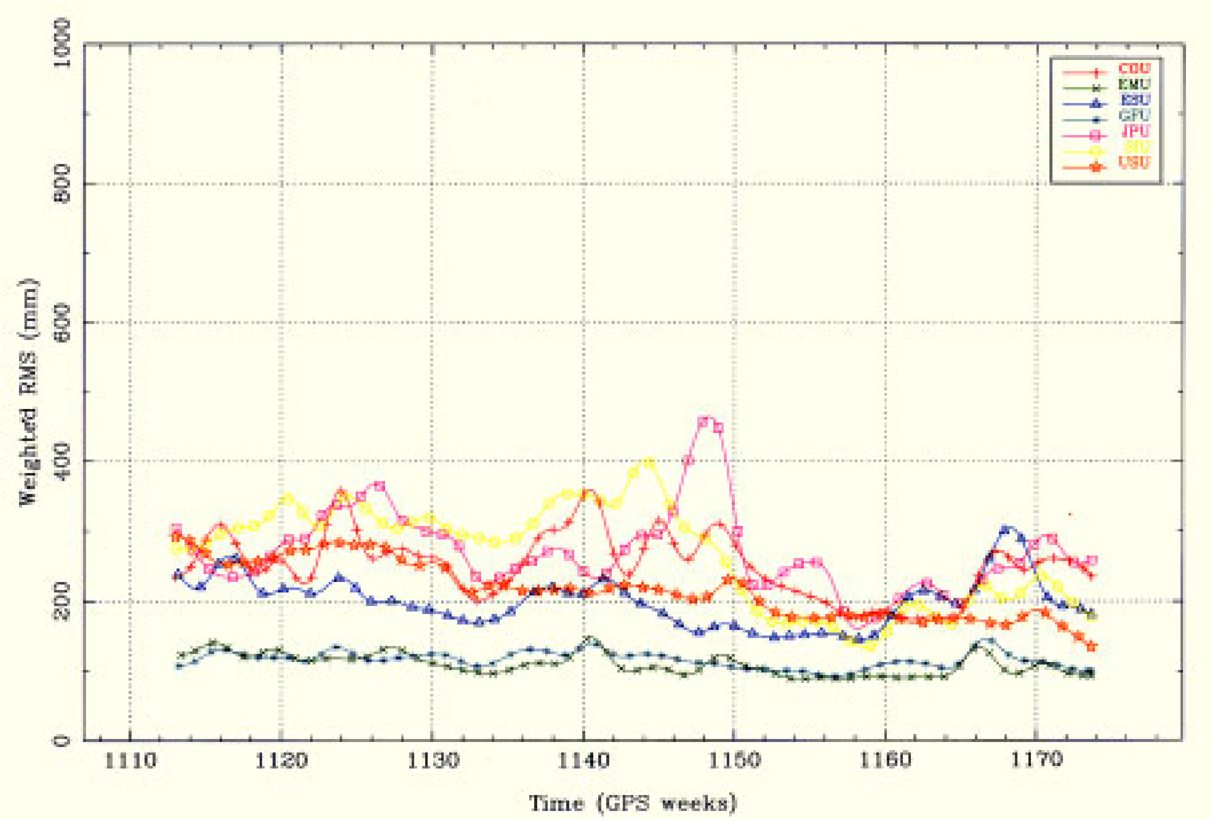


Figure 8

Questions related to IGS Ultra Rapid Products

Question: The IGS Ultra Rapid orbits are updated twice a day. Does the user community ask for more frequent updates? Which application may be served with more frequent updates?

Answer: Application which obviously would benefit from more frequent IGU updates are Near Real Time Troposphere Monitoring and LEO missions. This has been expressed in the relevant PROD4 recommendation of the Ottawa workshop, which is given below:

'In view of upcoming NRT-needs explore and implement a more frequent update of the IGU-Ultra Rapid Products. An update cycle of 3 hours for IGU products is envisaged. Investigate the option of different update cycles for orbits (6 hours) and clocks (3 hours). In addition explore the possibility of decreasing the latency of IGU products from currently 3 hours to 2.5 hours as well as the submission of 5-minutes rinex-clock files'.

In addition, Gerd Gendt has proposed to deliver troposphere estimates for the observed half of the Ultra-rapids and to increase the update frequency to every 3 hours. This is under development.

Question: The Ultra-Rapid Orbit Combination usually suffers from a remarkable number of satellites missing in the AC-submissions (about 10-15%; see also figures 12a,b). How can we tackle that problem?

Answer: ACs are asked to provide as much as possible satellites in their submissions. Make a more intensive use of accuracy codes to identify bad satellite position records (needs an SP3 format update) instead of removing satellites completely from the orbit file.

Question: Do we need clock-RINEX files (sampling 5 minutes or 30 seconds) complementary to the ultra rapid orbit files?

Answer: An adequate clock-interpolation asks for at least 5 minutes sampling. This holds especially for the observed 24 hours. Predictions are usually based on more or less simple analytical representations. A 5 minutes sampling is therefore not a must for the predictions. The whole issue has not decided up to now but there is another pro for providing clock rinex files: When a satellite clock is reset, the current clock combination is corrupted. The combination algorithm, based on clock rinex files, can (similarly to the IGS Rapid combination) detect clock breaks and reject them from the time scale alignment. The combination could probably also be improved by identifying and rejecting poor submissions.

Ultra Rapid Clock Comparisons

Since Wk 1151 a regularly updated Web-site

http://luna.tuwien.ac.at/forschung/satellitenverfahren/igs_ultrarapids_products.htm

provides weekly comparisons of the submitted ultra-rapid clock solutions, both for the observed and the predicted 24 hours. The plots are grouped per day and AC and show basically raw clock differences per satellite to the IGS Rapid clock solution as well as the offset and trend reduced clock-rms again with respect to the IGS Rapid clock solution. As a nice additional feature the clock rms numbers for the predictions are available for 3,6,9,12 and 24 hours time slots after start of the prediction.

A number of examples (3) is given below:

Example 1 (Figures 9a-d):
GFU-IGR , week 1156, day 3 observed, day 4 predicted

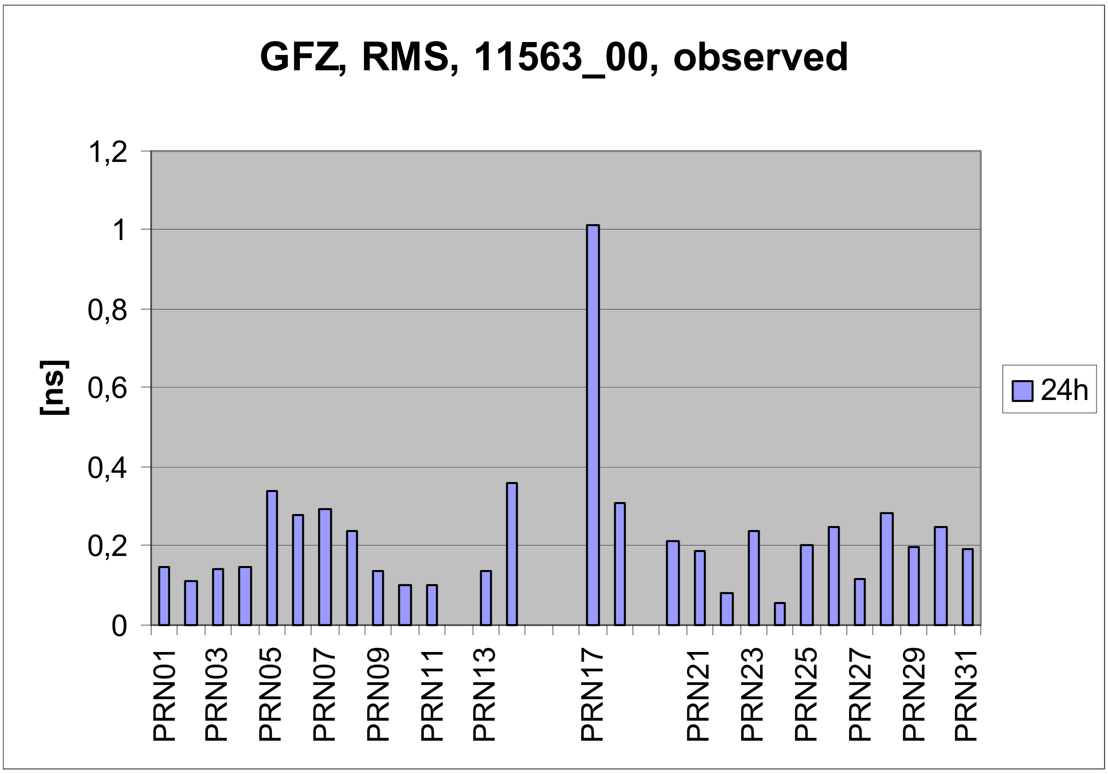


Figure 9a: clock-rms, day 3 , 00 UTC; offset+trend reduced

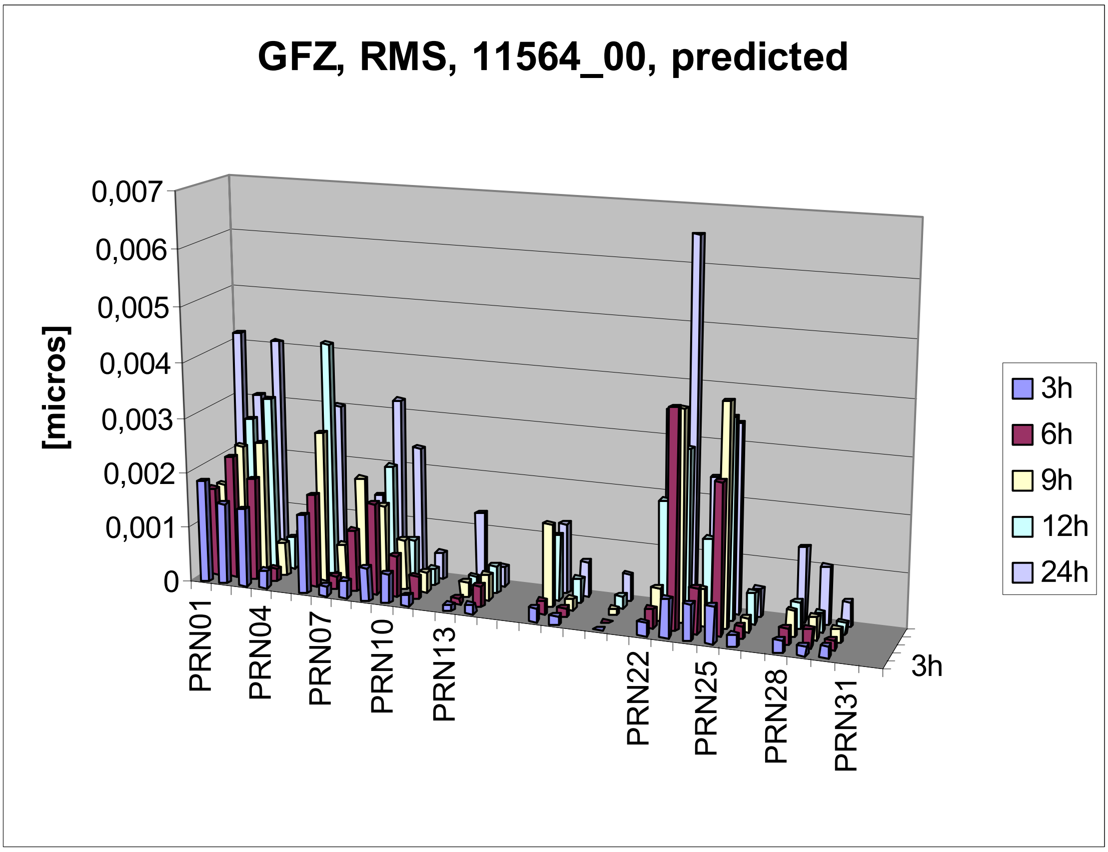


Figure 9b: clock-rms, day 4 , 00 UTC; offset+trend reduced; 5 time slots

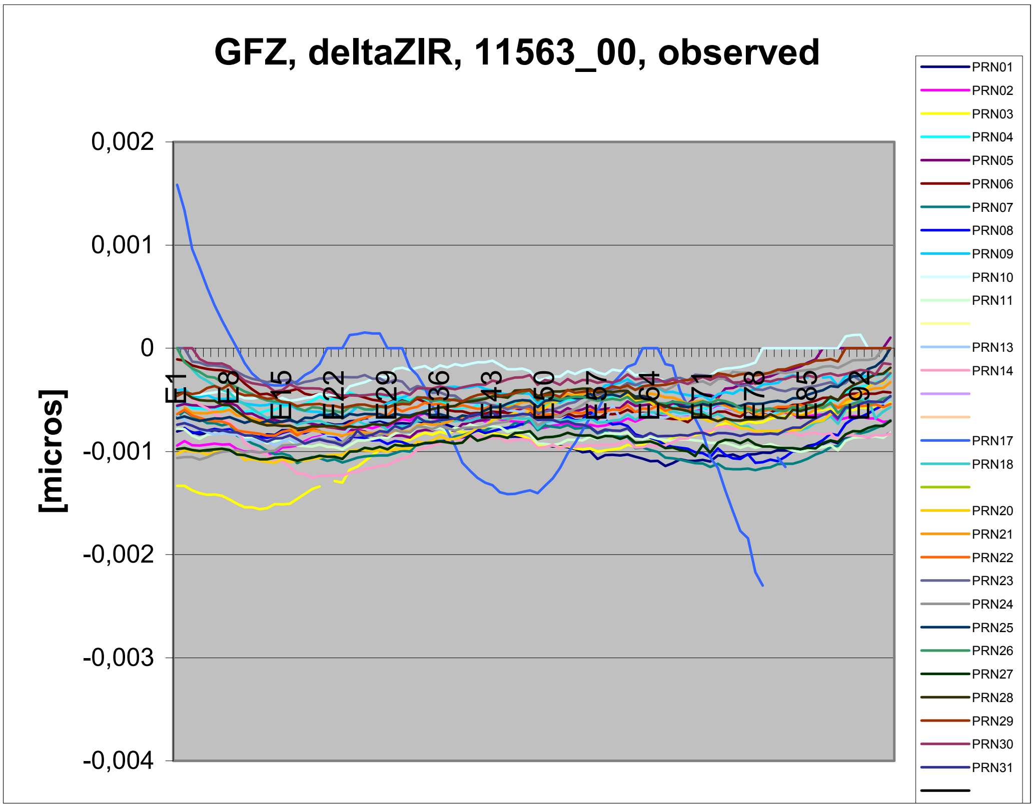


Figure 9c: raw clock difference, day 3 , 00 UTC

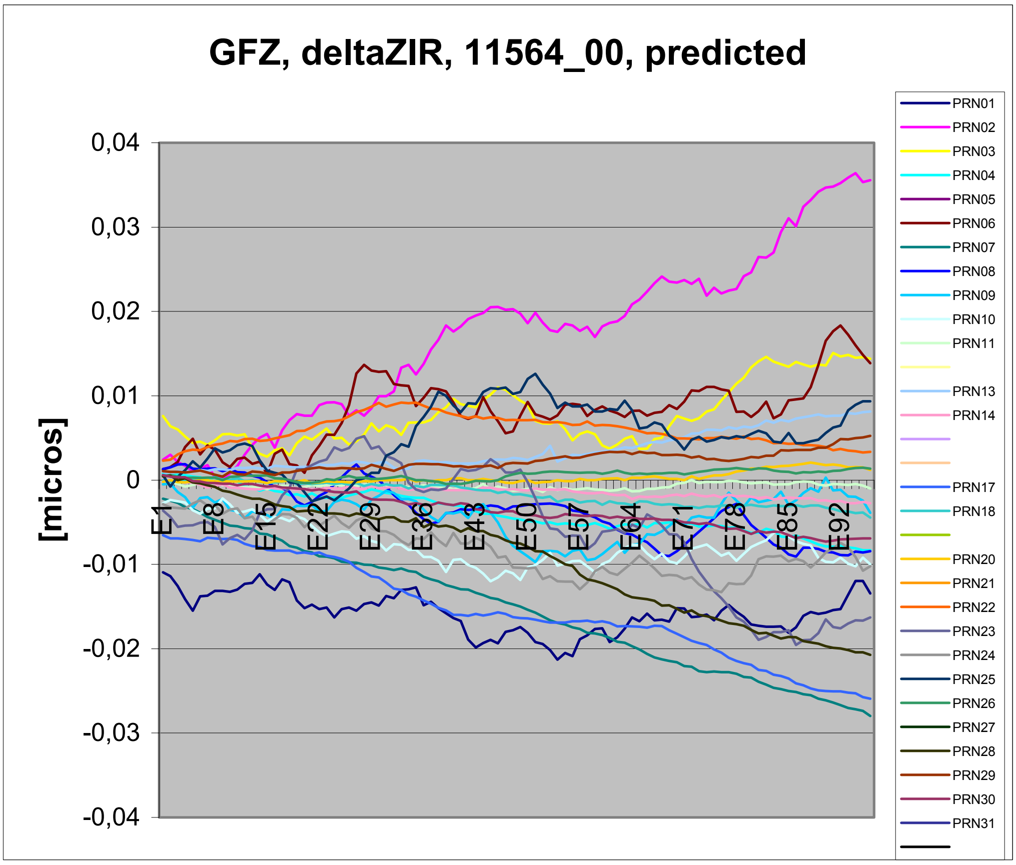


Figure 9d: raw clock difference, day 4 , 00 UTC

Example 2 (Figures 10a-d):
USU-IGR , week 1156, day 3 observed, day 4 predicted

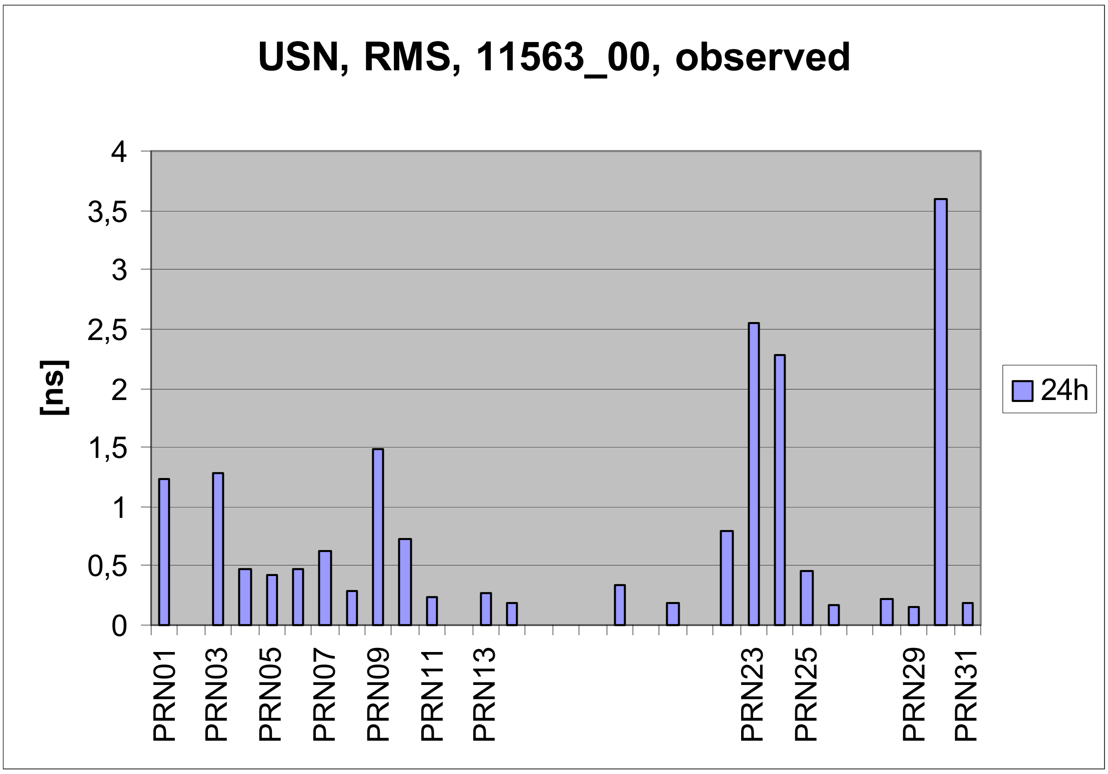


Figure 10a: clock-rms, day 3 , 00 UTC; offset+trend reduced

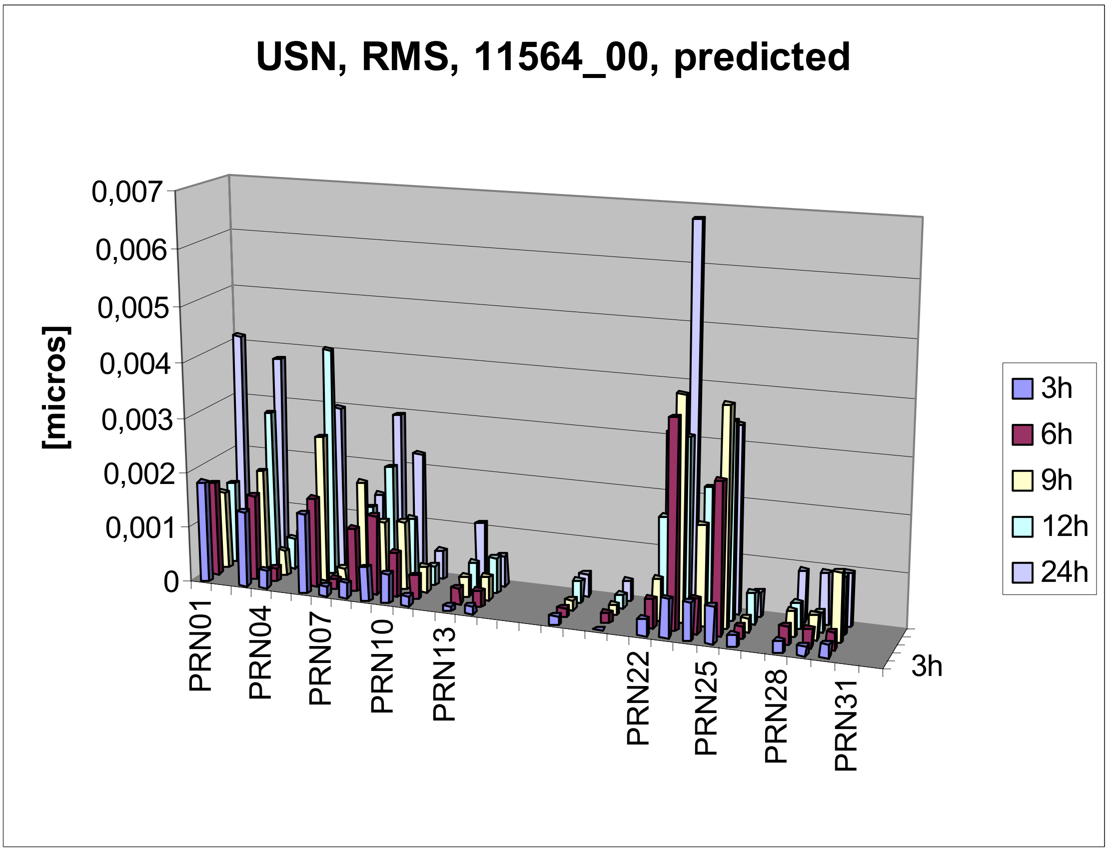


Figure 10b: clock-rms, day 4 , 00 UTC; offset+trend reduced; 5 time slots

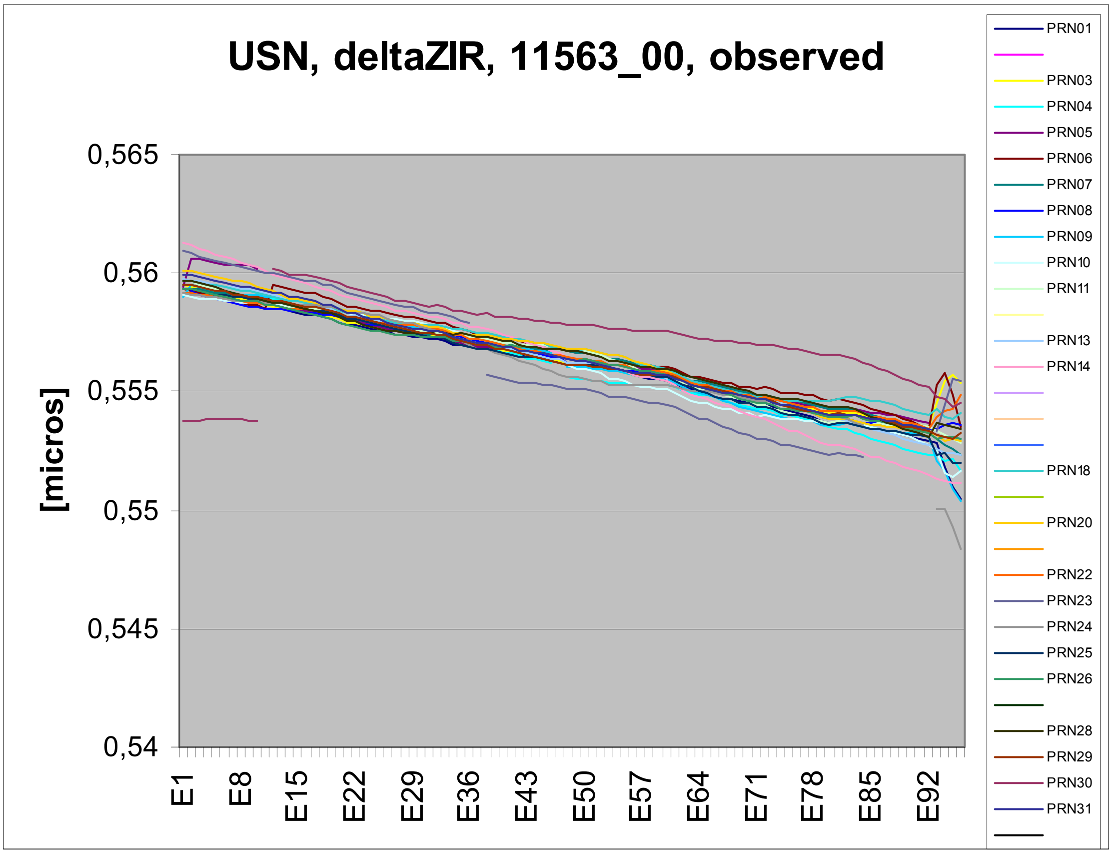


Figure 10c: raw clock difference, day 3 , 00 UTC

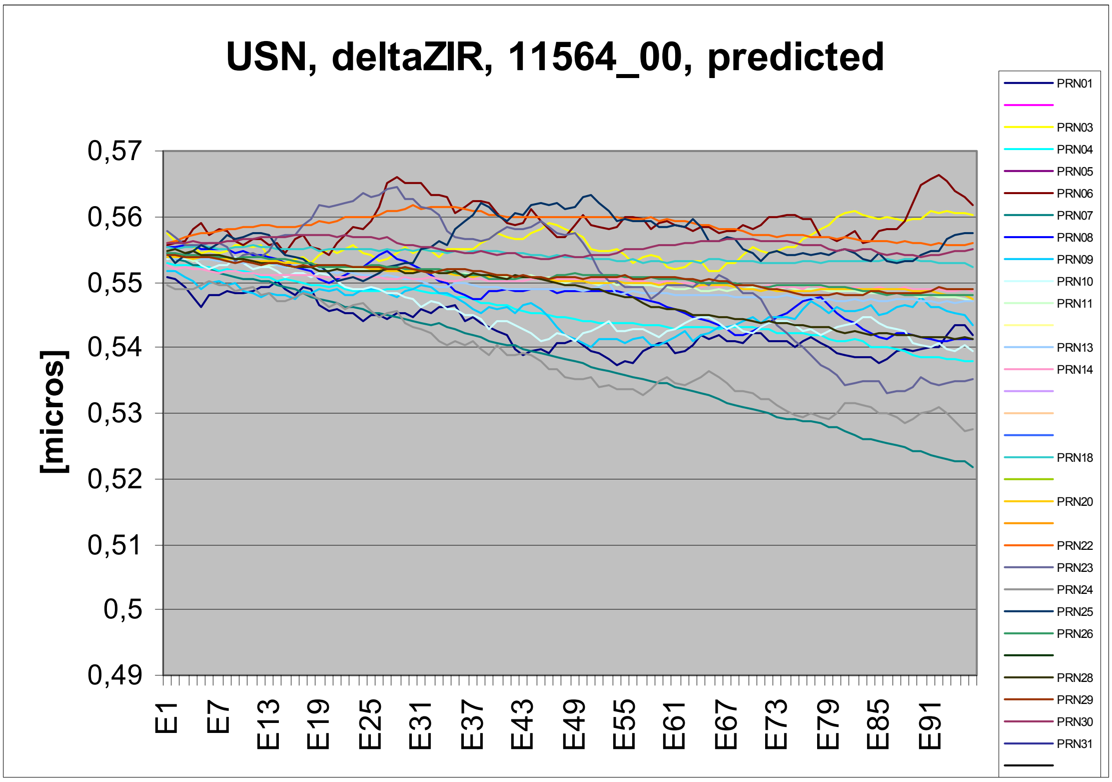


Figure 10d: raw clock difference, day 4 , 00 UTC

Example 3 is in principle related to the IGS Rapid Combination. The same software as described above has been used to show the raw clock differences per satellite between the IGS Rapid Combination (Wk 1159, day 3) and the accompanying JPL submission. This graph should demonstrate a number of missing clock epochs in the JPL clock RINEX file. While offset and drift of the solution w.r.t. the combination is unproblematic, these gaps pretend frequent reference clock jumps, which causes the combination software to reject the JPL- solution although the submitted clock values are in principle fine.

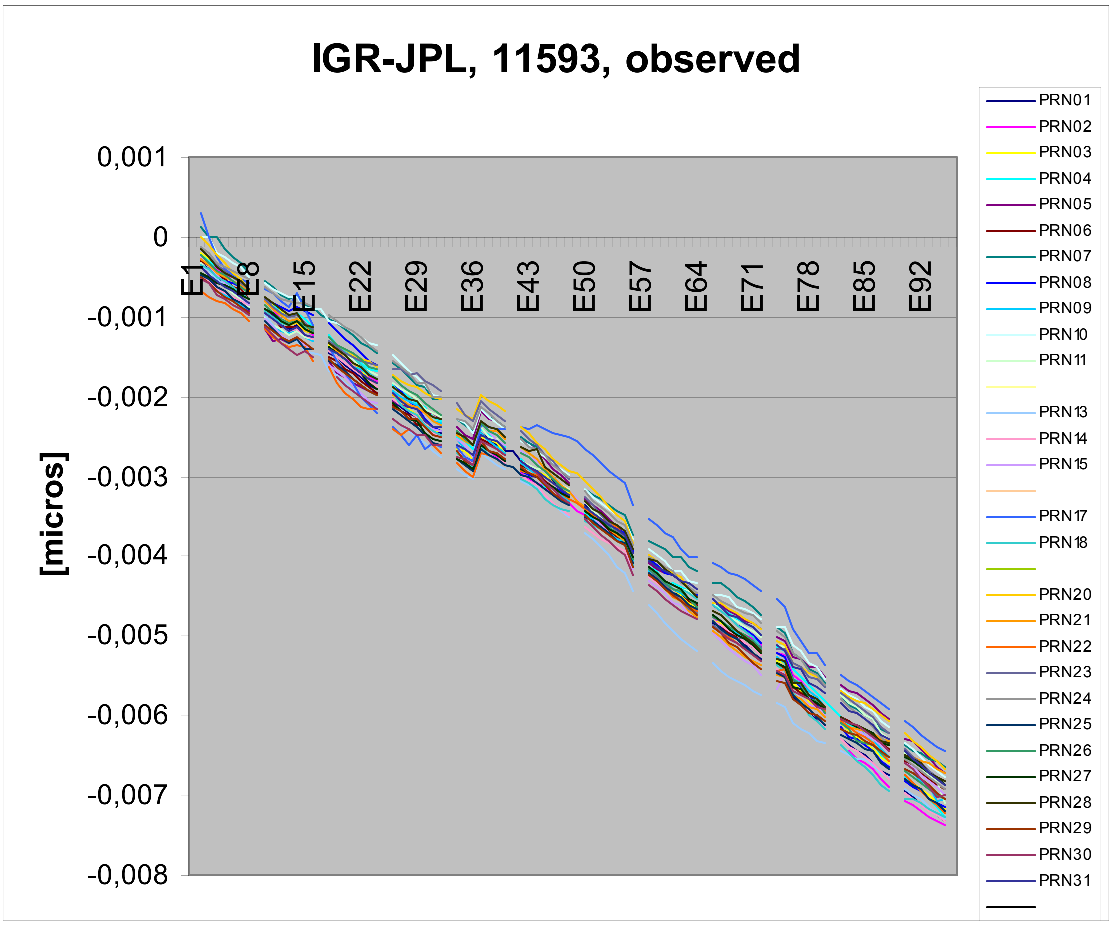


Figure 11: raw clock difference; IGS Rapid Combination-JPL

IGU / Percentage of Missing Satellites per AC

As mentioned above the Ultra-Rapid Orbit Combination usually suffers from a remarkable number of satellites missing in the AC-submissions (about 10-15%). The situation is illustrated in figures 12a and 12b. The figures are based on ultra-rapid comparison logs issued twice daily. Submitting 100% of the satellites would stand for all tracked satellites *times 2 (2 updates per day)*times 7 days *times the number of weeks. Missing full submissions as well as missing satellites within a submission reduce this score; satellites which are forwarded by less than 3 centers (and are therefore rejected from the combination) increase the score of the submitting AC.

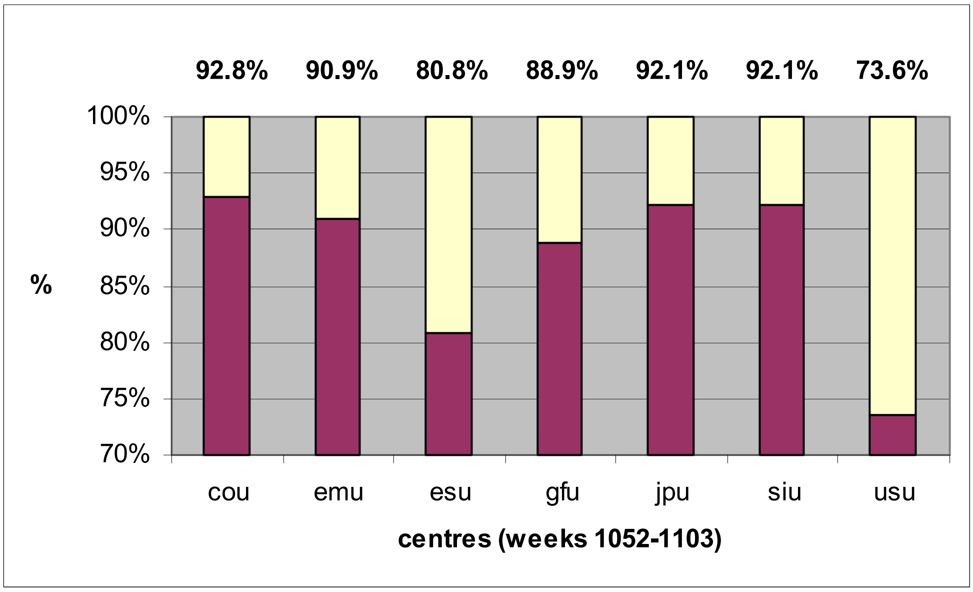


Figure 12a : since start of IGU experimental phase

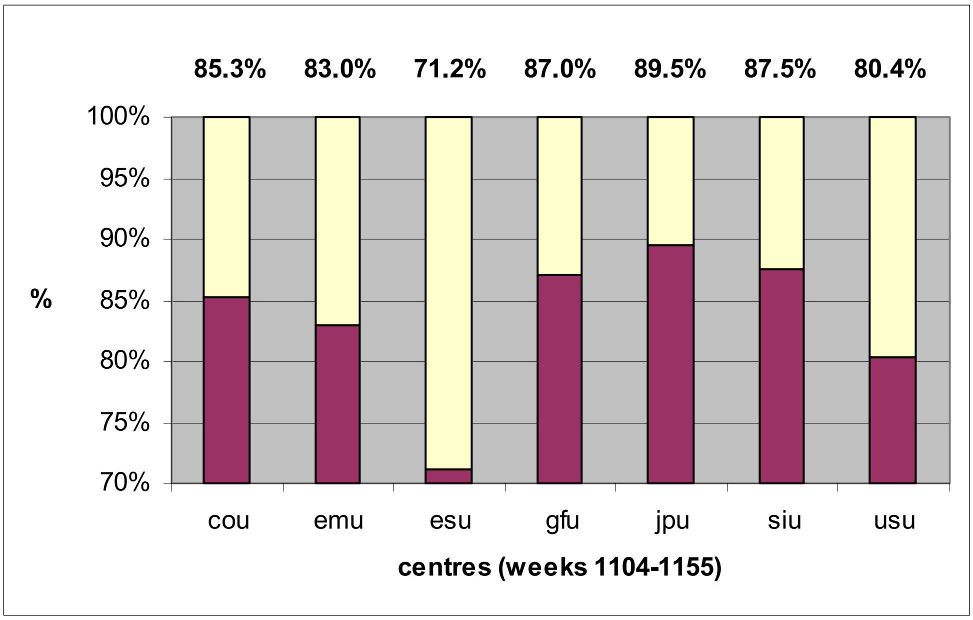


Figure 12b

The CODE submission (COU) has to be discussed explicitly. CODE provides full predictions (48 hours) instead of 24 hours orbit and clock estimates and 24 hours predictions. So, the CODE submission cannot be used for the combination process but will be included in the logfiles for comparisons. On the other hand the CODE column represents the true percentage of satellites passing successfully the combination process. In detail, within the period March 2000-Feb 2001 the IGU orbits covered about 93% of the satellites, while during the next year only about 85% passed the combination (about 4 missing satellites (out of 28) per IGU update). It has to stated that the accuracy of the submitted satellite orbits has been increased considerable over time. Nevertheless, the number of satellites included in the IGU orbits has to be enhanced again as soon as possible.

In this context figures 13a and 13b show the number of satellites with less than 3 AC-submissions (the combination software rejects that satellite from the IGU orbit file) over the past 1.4 years (in week 1087 the first official IGU products were issued). In case the COU solution (which is almost always available) would serve as the third missing solution this diagram shows, how often the COU prediction was better than 150 cm (quite better than broadcast) and how often worse than 150cm. The statement is quite clear: the predicted orbit cannot replace a regular orbit submission, based on 24 hours of observation. We urgently need all satellites in the AC submissions and we urgently need the COU orbit to be based on observations.

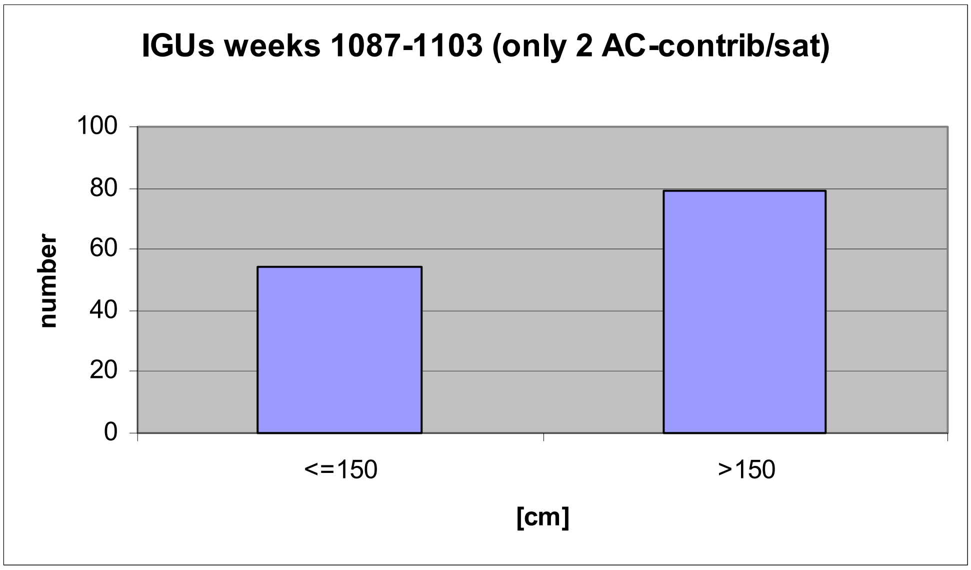


Figure 13a

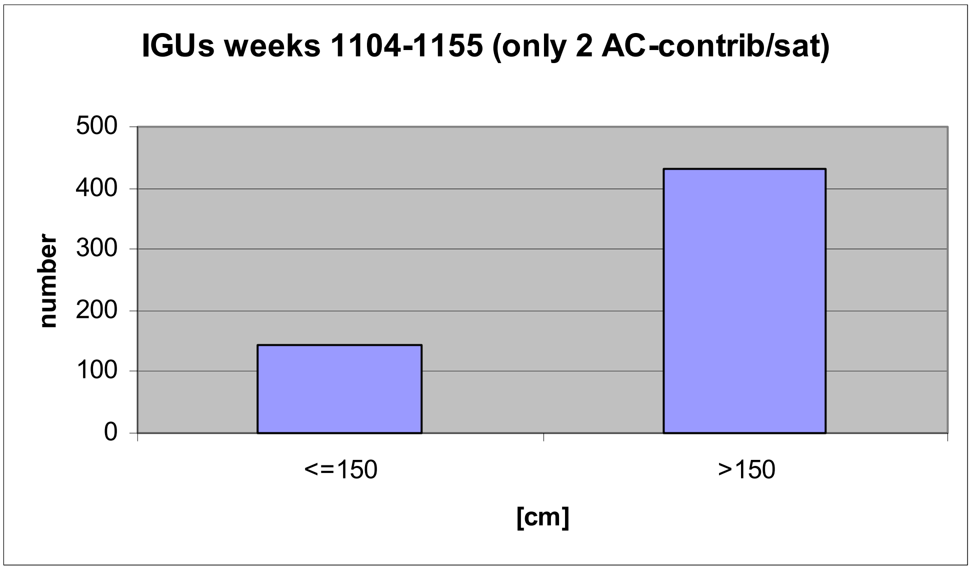


Figure 13b

Acknowledgements

The author wishes to thank Veronika Bröderbauer for the preparation of the Ultra-Rapid Comparison Plots and Elisabeth Fragner for her invaluable help in operating the IGS product combination software and for providing the GLONASS Orbit Combination Graphic.

References

IGS Workshop 2002 Recommendations
http://www2.geod.nrcan.gc.ca/~pierre/workshop_reco_website.htm

Review of IGS Analysis Products
R.Weber, J. Ray, J. Kouba
http://www2.geod.nrcan.gc.ca/~pierre/position_papers.htm

International GLONASS Pilot Project
J. Slater
Workshop Proceedings

Testing of the Proposed IERS 2000 Convention Sub-Daily Earth Rotation Parameter Model

J. Kouba
Natural Resources Canada, Geodetic Survey Division, 615 Booth Street, Ottawa, Canada
K1A 0E9
email: kouba@geod.nrcan.gc.ca

Abstract

The differences between the proposed International Earth Rotation Service (IERS) 2000 and the conventional IERS 1996 sub-daily Earth rotation parameters (ERP) models can reach 0.1 mas and 0.1 mas/day. The largest differences are seen for the beat periods of 14.2 and 360 days, which correspond to the diurnal tidal waves of *O1* and *(K1, P1)*, respectively. Precise independent polar motion (PM) rate solutions effectively doubles the sampling rate and allows for effective testing of sub-daily ERP models and other periodical effects at the diurnal and semi-diurnal frequency bands. The JPL independent daily PM rate solutions, which on November 12, 2000 have switched to the conventional IERS 1996 sub-daily ERP model from the older model of Herring and Dog (1994), now show no, or greatly reduced 14.2 day amplitude (*O1*) peaks. This has confirmed that the anomalistic amplitudes at the 14.2 day period, seen for JPL PM solutions prior November 12, 2000, was largely due to the use of the older sub-daily ERP model. The new IERS 2000 sub-daily ERP model is expected to perform equally well, or slightly better than the conventional IERS 1996 model, as indicated by the JPL PM rate solutions, corrected for the IERS 1996 and 2000 model differences (see Figure 1).

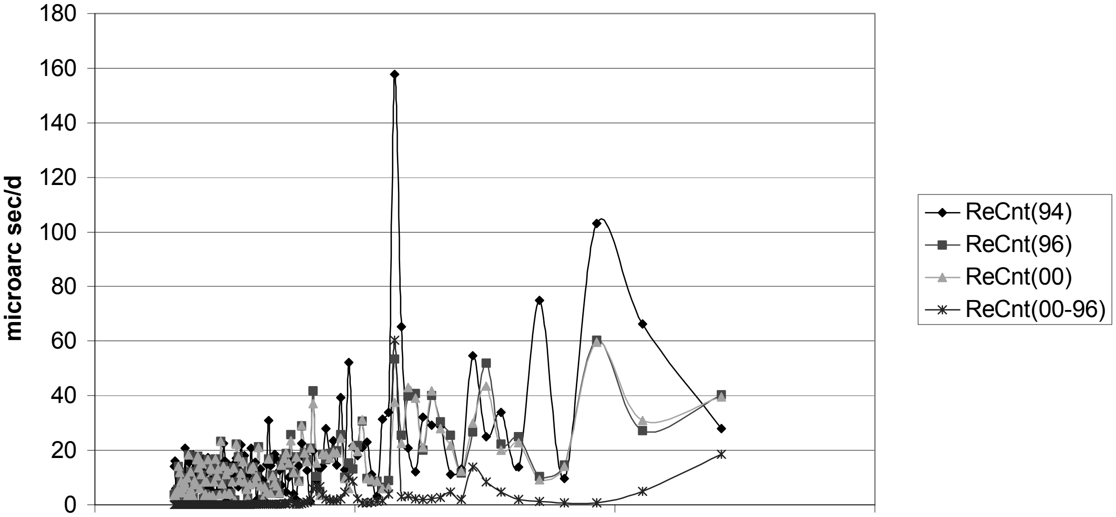


Figure 1: Spectra of JPL retrograde (negative) PM rate solution discontinuity tests (*ReCnt*) during February 2000 to July 2001. (Sub-daily ERP models: Herring and Dong 1994 (94) used prior November 12, 2000; IERS 1996 (96) and IERS 2000 (00) after November 12, 2000)

The analyses of noisier, but also independent EMR PM rate solution series did not produce any such indication. However, this continuity testing is not possible for the currently official IGS Final ERP series and the most of the AC ERP rate solutions, for which ERP rate continuities are enforced during each week. (For a complete report, refer to the electronic version of the workshop proceedings)

Reference:

Herring, T. A. and D. Dong, 1994, Measurement of diurnal and semidiurnal rotational variations and tidal parameters of Earth, *Jour. Geoph. Res., Vol. 99*, No. B9, September, pp. 18051-18071.

Long-Term Consistency of IGS Products

T. P. Yunck
Jet Propulsion Laboratory
California Institute of Technology
tpy@jpl.nasa.gov

The long-term consistency of IGS products is a pre-eminent concern for all of us. As the record of our products lenthens, our ability to tap that record for its potential science value depends critically on preserving strict consistency over the full history, despite inevitable changes in equipment and periodic updates of the ITRF. At present, to my knowledge, there are no uniformly accepted standards or procedures across the IGS for achieving such consistency, or any strict guidelines as to what constitutes long-term consistency. A number of strategies are now in use. When the ITRF is updated, some centers are able to reprocess their entire archive of data and redetermine all past solutions in the new frame. Other centers, owing to the computational burden of their processing approach, simply compute transformations to bring past solutions into the new frames. While the first approach is most desirable, it can present some serious challenges, particularly as the data record expands and expert analyst intervention remains a factor. Other intermediate options are also possible. Further discussion is provided in the position paper, “Review of IGS Analysis Products,” prepared by Ray and Weber for this workshop. We recommend that the IGS take up the general question of long-term consistency and seek a workable strategy for maintaining the internal consistency of official IGS products over the full archival history, despite differences in approaches at individual analysis centers. One goal should be to define a careful and rigorous transition procedure, with standards for each analysis center to follow and a certification process to assure compliance, when converting our products to each new ITRF release.

Extending the Standard Product 3 (SP3) Orbit Format

Steve Hilla
National Geodetic Survey, NOAA
1315 East-West Hwy, Silver Spring, Maryland 20910
email: steve.hilla@noaa.gov

Abstract

At the last IGS Analysis Center Workshop at USNO, it was suggested that a new SP4 orbit format be developed so that orbit files distributed by the IGS could include some type of clock accuracy information, and so that separate accuracy codes would be available for the observed versus predicted parts of the Ultra-rapid orbit files. Since modifications for adding these accuracy codes are relatively minor, they could be made in such a way as to be mostly backwards compatible; in which case the new format could be considered version C of the current SP3 format (SP3-c).

Previously, W. Gurtner and M. Rothacher have defined an SP3-b format for combined GPS/GLONASS orbits (see IGEX Mail 0042, 27-Oct-1998). This format is backwards compatible with the original Standard Product 3 format (SP3-a), with the exception of the satellite ID labels which were changed from an I3 field to a A1,I2 field to accommodate both GPS and GLONASS identifiers in a manner similar to RINEX files. Also, the orbit group at the National Imagery and Mapping Agency (NIMA) has added an "E" flag in column 75 of the SP3 Position and Clock Record, to denote a clock event (for instance, when a clock swap occurs on a satellite). The IGS can easily utilize both of these previous modifications for the new format. It has also been suggested to add "orbit event" flags as well: to denote when a satellite is in eclipse, when a portion of an orbit is predicted rather than observed, and/or when a satellite is undergoing some specific type of maneuver or change in status.

SESSION 2:
REAL-TIME APPLICATIONS AND PRODUCTS

Position Paper for the Real Time Applications and Products Session

Yoaz Bar-Sever, JPL, and John Dow, ESOC

Guided by the Charter of the IGS Real Time Working Group (RTWG) we seek to assess and address issues that pertain to the IGS developing real-time infrastructure and processes. As in any well-planned project the development of infrastructure, processes, and products must be governed by a set of clear, traceable, and realistic requirements. It is the primary goal of this session to explore the possible requirements for near real time GPS-based products, and analyze their implications. We do that by raising a number of key questions. We provide tentative answers to some questions, while others require more information before they can be answered. The questions and answers are meant to stimulate the discussion during our Session. We would like to hear the user-perspective on these questions, as well as the opinion of the analysis centers, and independent analysts.

First, we should be clear with our terminology. We think that the term “real-time” is too restrictive, and prefer the more flexible “near real time” (nrt) to describe latencies ranging from 0 to 6 hours. The boundary between rt and nrt may be drawn at the latency below which batch processing and data handling is no longer practical. The IGS is currently producing hourly Rinex files from a large sub-set of the network, which feed a number of batch-type processes, including the ultra-rapid orbit determination. We define, therefore, Real Time processes and application as those that require sub-hourly latency.

While we devote our attention to the real time processes, we should also examine their impact on the IGS’s nrt processes, some of which may be rendered obsolete, while others, may obviate the need for real time equivalent.

At the most fundamental level we would like to investigate the following question:

Q1) What are the nrt applications for GPS-based products, and what requirements they impose on these products (for example, in terms of latency, accuracy, reliability, availability)

A) The following table reflects our current understanding of the basic requirements by some of the well known applications for nrt GPS-based products. At our session, we would like to examine the entries in this table, change or refine them if necessary and, perhaps, add new entries.

Table 1. Applications for nrt GPS-based precuts and their basic requirements

Application	Latency	Accuracy (in terms of GPS orbits/clocks)	Reliability*	Spatial Scale
Weather Prediction	Hours	Medium (< 25 cm)	Low	Regional
Ionospheric Weather	Hours	Medium (< 25 cm)	Low	Global, Regional

Navigation: Satellites	Seconds	Low (< 50 cm)	Medium	Global
Navigation: Terrestrial	Seconds	Medium (< 25 cm)	High	Regional
Positioning:Earthquake and volcanics monitoring	Minutes	Medium (< 25 cm)	Low	Regional
Positioning: Structures	Seconds	High (<15 cm)	High	Local
Timing	Seconds	Low (<50 cm)	High	Global
Earth orientation	Hours	High (< 15 cm)	Low	Global

* The Reliability entries in Table 1 reflect our understanding of the ability of the user to absorb and/or identify occasional bad data without significant adverse effects

Table 1 omits one important component, namely, the nature of the desired nrt product. For example, weather prediction applications would normally ingest nrt estimates of tropospheric delay, but it may be that the potential user, say, the U.K. Met Office, would prefer to get the nrt GPS orbits and clocks, and derive the by-products of interest using in-house methods and resources. This leads us to the second fundamental question:

Q2) Should the IGS provide all the nrt GPS-based by-products or, perhaps, the IGS should stick to what it knows best – the estimations of GPS orbits and clocks.

A) The IGS should demonstrate the derivation and use of new GPS products, but should refrain from the long term production of products for which the IGS does not provide unique value. For example, the reliable and accurate estimation of tropospheric delays was demonstrated by the IGS, but the analysis can be (and is) carried out by individual organization. Also, this is a regional product by nature, where the IGS global network does not provide significant value. In general, the IGS should provide global-scale products: GPS orbits and clocks.

A related question is:

Q2b) Should the IGS provide solutions to all domains: civil, commercial, scientific, military, or should the IGS focus on just a select few.

A) The IGS should stay out of the military domain.

On a less fundamental, but practical level, we would like to probe the state of the art in nrt GPS processes. Here we will solicit contributions from the various IGS Analysis Center and from elsewhere, addressing the question:

Q3) What is the state of the art in nrt generation of GPS products

In particular, we would like to hear from the various contributors for the ultra rapid products, from the IGS coordinator about the combination of the ultra rapid products. We would like to hear about the JPL nrt orbit production. We would like to hear from analysts producing nrt tropospheric delay estimates, and from the coordinator of the nrt trop combination about the status of his experiment.

We would like the various contributors to our session to address in their talk the following question:

Q4) How should the IGS approach the combination, delivery, and quality control for the potential nrt products.

A) We think that it is premature at this point in time to analyze the possible combination strategies. That is because the combination strategy depends on such unknowns as the number and relative quality of the contributed products. Specifically, it is not clear at this point how many nrt GPS orbits are going to be available to the IGS, whether they are based on global or regional data sets, how are clocks treated, and what is their accuracy. We recommend a phased approach, beginning with a campaign for generating nrt products, to be followed by inter-comparisons and quality assessment. Only then combination and product delivery strategies can be analyzed fruitfully.

Finally, we would like to pose a set of practical questions:

Q5) Should the IGS continue the ultra rapid process

Q6) What will be the IGS nrt products

Q7)) Does it make sense to have a combination process for real time products, and if so, how

The Italian Near-Real Time GPS Fiducial Network for Meteorological Applications

R.Pacione(1), F.Vespe(2), R.Faccia(1), G.Colucci(1)
(1) Telespazio S.p.A. - Centro di Geodesia Spaziale Matera, Italy
(2) Agenzia Spaziale Italiana - Centro di Geodesia Spaziale Matera, Italy

Permanent networks of GPS receivers are presently established in many countries. They are primarily devoted to measure the motion of the Earth's tectonic plate, to study deformations associated with earthquakes and volcanoes, to monitor the post-glacial rebound and the global sea-level changes. Beside these applications they can provide, if properly equipped with surface meteorological sensors, continuous and well distributed measurements of Integrated Precipitable Water Vapor (IPWV) which are of great interest for numerical weather prediction and climate research.

The Italian Space Agency (ASI) manages a GPS network of 24 stations and further densification is in progress.The equipment generally consists of a Trimble 4000SSI or Trimble 4700 receiver with a choke ring antenna. The growing of GPS Real-Time and Near-Real-Time applications requires that the tracking network be switched from a daily to an hourly or sub-hourly data retrieval. Presently 16 Italian stations provide hourly data with a nominal latency ranging from 3 to of 10 minutes, Matera provides high rate data as well. GPS raw data collected at the remote stations are sent to Matera/Centro di Geodesia Spaziale (CGS) through INTERNET or ISDN line, are converted into RINEX format and are transferred to ASI web and ftp site GeoDAF (http://geodaf.mt.asi.it).

As far as the GPS atmospheric application is concerned, since January 1999 GPS Zenith Tropospheric Delay (ZTD) are routinely produced in post-processing mode and monitored for a network of 40 stations covering the Central Mediterranean area.(Pacione et al., 2001). Over Italy the network has an higher denser resolution since all the available Italian GPS permanent stations are included in the routine processing. In the middle of 2001 a Near-Real-Time data stream, relying on IGS Ultra Rapid products, has been set-up and it is running operatively providing GPS ZTD estimates for meteorological applications. It has been developed within the European program COST Action 716 (http://www.oso.chalmers.se/geo/cost716.html) dedicated to the "*Exploitation of Ground-based GPS for Climate and Numerical Weather Prediction Applications*".(Elgered, 2000) The GPS processing for the delivering of ZTD from a network of 30 stations, with a delay of 1h45', is performed using a 24 hours sliding window and a standard network approach. The IGU orbits, retrieved twice a day 03:00 and 15:00 UTC, are kept fixed but checked and possibly PRN excluded based on the analysis of the post fit phase observation residuals (Springer et al., 2000). The ZTD estimates of the last hour are taken out from the 24 hours batches and sent to the UK Met Office.

In order to be useful for assimilation into the Numerical Weather Prediction Model the requirements of timeliness and accuracy must be reached, that is 75% of observations must arrive within 1h45' to the met agencies and predicted GPS orbits must be used with minimum degradation of the ZTD products with respect to the Post-Processed ones. The performances of the system for the period June 2001-Febrary 2002 are discussed. We experience that 80% of the predicted solutions have been delivered; the statistic of the GPS hourly data availability per stations shows that 20% of them are available to the users too late to be processed in NRT mode or are lost. We notice that missing data and gaps cause problems in the analysis and instability in the ZTD estimates. To asses the accuracy of the NRT ZTD we compare 9 months of Post-Processed versus NRT estimates having a monthly station bias from -6mm to 10mm and a related standard deviation from 20mm to 5mm, this last decreasing in time due to processing tuning. Finally comparisons with other different NRT ZTD estimates on 1 month (February 2002) of solutions performed within the COST-716 Near-Real Time Demonstration Campaign (http://www.knmi.nl/samenw/cost716/index.html) show few mm bias and 5-7mm standard deviations.

REFERENCES

G. Elgered, An Overview of COST Action 716: Exploitation of Ground-Based GPS for Climate and Numerical Weather Prediction Analysis, *Proceedings COST-716/IGS Workshop, Oslo 2000*.

Pacione R., Sciaretta C., Vespe F., Faccani C., Ferretti R., Fionda E., Ferraro C., Nardi A., GPS Meteorology: validation and comparisons with ground-based microwave radiometer and mesoscale model for the Italian GPS permanent stations*, Physics and Chemistry of the Earth (A)*, vol.26, no.3, pp. 139-145 2001.

Springer T.A., Hugentobler U., IGS Ultra Rapid products for (near-) real-time applications,. *IGS Network Workshop 2000, Oslo.*

What About Using GPS for Weather Forecasting?

H. van der Marel, Delft University of Technology, Department of Geodesy, Thijsseweg 11, 2629
JA Delft, The Netherlands. E-mail: H.vanderMarel@geo.tudelft.nl

The use of ground-based GPS for estimating Integrated Water Vapor (IWV) has been investigated by many (inter)national studies and projects. Today, the operational potential of this technique is demonstrated by several projects. In this presentation we focus, as an example, on the European COST-716 project “Exploitation of Ground-Based GPS for Climate and Numerical Weather Prediction Applications for Europe”. In March 2001, COST-716 started a near real-time demonstration, which one-year later involved more than one hundred GPS stations for which Zenith Total Delay is computed within 1 hour 45 minutes.

The near real-time demonstration is organised around several near real-time networks. GPS data collection and processing is handled by six analysis centers: ASI, Matera, Italy; GOP, Czech Republic; GFZ, Potsdam; Germany, IEEC, Barcelona, Spain; Federal Office of Topography, Switzerland; Nordic Geodetic Commission. Each analysis center uses IGS and EPN data centers, completed with several local data centers, resulting in a dense network. The analysis centers are relatively “free” to organise the processing as they like, as long as they compute properly validated Zenith Total Delays (ZTD), with a well defined quality indicator, in an agreed format (COST v1.0 format), and deliver it to the UK Met Office (UKMO) - which acts as a gateway to other meteorological institutes - within 1h45m. An ftp-mirror at TUD/Delft holds the full archive. The ZTD is converted to IWV at KNMI using measured pressure and temperature at the GPS site or from nearby synoptic sites, and is compared routinely to Numerical Weather Prediction (NWP) models (http://www.knmi.nl/samenw/cost716.html).

COST-716 has shown it is possible to compute ZTD for NWP within 1h45m using existing GPS networks. The accuracy is sufficient for NWP and forecasting. The overall consistency between the solutions is about 5-6 mm for the Zenith Delay (1 kg/m^2 in Integrated Water Vapor), with biases of up to 3-4 mm. Comparisons with the post-processed EUREF solution are in the same range. The rms difference with Radiosondes is 11 mm + 0.1mm/km in ZTD, with some non-negligible biases. Assimilation trials show that the GPS data does not make the forecast worse, and in some cases give a slight improvement in the forecast of precipitation. A possible explanation for this modest impact could be that radiosondes and other data tend to dominate the models and the models are tuned for these observations. It is expected that (high resolution) 4D-VAR models would be better at utilizing GPS data, but it takes time to develop these models. On the other hand comparisons against NWP models were extremely useful, and often highlighted major discrepancies with the GPS observations, which would be useful for forecasting if available in time. Several nowcasting and forecasting applications emerged from the project. Ideally, these would require a data interval of 15 minutes (instead of 15-60 minutes), the timeliness of a real time service (latency < 1 hour), a spatial scale of the data that can be regarded as sub-regional and a horizontal spacing of better than 70-100 km. Accuracy and reliability should be more or less the same as NWP.

Operational weather prediction does not fall into a single category: some aspects are scientific, some civil, some military, and some commercial. This is more of a problem for operations than in the development phases, where the work can be treated as purely scientific. For operational work, ZTD computations for weather forecasting should be performed on computers managed by meteorological institutes in liaison with geodetic institutes, and would rely on IGS orbits and clocks. Orbit improvement, or the processing of a global network, should not be necessary for the ZTD processing. For some applications real-time orbits and clocks could be needed. It is not clear whether near real-time ZTD from IGS would be needed; it could be useful for comparison purposes or for constraining of stations common with IGS (this could apply to double difference processing in (sub-)regional networks).

Real-Time Delivery of the Canadian Spatial Reference System - Strategy and Applications

P. Héroux, Y. Mireault, F. Lahaye, P. Collins and K. MacLeod
Natural Resources Canada, Geodetic Survey Division,
615 Booth Street, Ottawa, Ontario, Canada, K1A 0E9

Since confederation, Canada has always relied on a consistent survey system as an integral part of the national infrastructure. In 1909, the Geodetic Survey of Canada was created by an order-in-council and given the mandate to provide control in support of all surveys and mapping within the country. Today, as part of Natural Resources Canada, the primary role of the Geodetic Survey Division (GSD) is to maintain, continuously improve, and facilitate efficient access to what is now known as the Canadian Spatial Reference System (CSRS). The CSRS serves as a reference for all positioning, mapping, charting, navigation, boundary demarcation, crustal deformation, and other georeferencing needs within Canada.

While continuing to serve ongoing requirements for survey control, the growing demands of Global Positioning System (GPS) users in particular have resulted in a new focus for the Division, a focus on supporting positioning from space. The Canadian Active Control System (CACS) was established during the 1990's to facilitate GPS user access to the CSRS. A real-time capability is expected to further expand access to the national reference frame and has been under development since the mid-1990's. A project for one mode of delivery of real-time GPS corrections using MSAT will be completed this year . This federal-provincial collaboration is known as the Canadian Differential GPS Service (CDGPS).

Through the perspective of efficiently delivering a national spatial reference frame in real-time, the requirements and components of CACS will be described, including the links to the International GPS Service (IGS) data and products. The current real-time data access and product distribution mechanisms and applications served will be described. Future applications will be considered along with anticipated system and user limitations.

SESSION 3:

REAL-TIME DATA/ PRODUCT EXCHANGE

Position Paper for the Session Real-time Data/Products Exchange

Mark Caissy, NRCan, and Ron Muellerschoen, JPL

INTRODUCTION:

The Ottawa workshop will provide an opportunity for us to share our knowledge and experiences in real-time data and product generation. The objective of this session is to lay down the foundation needed to facilitate a free flowing exchange of real-time data and products among IGS members. We will begin this process by developing recommendations for the design of a data and products exchange prototype and set a course for its implementation. The goal is to have in place a reliable, robust and manageable system of data and products exchange coming from a global network of multidisciplinary real-time tracking stations.

This document addresses the requirements for the design of a system that will allow the real-time exchange of GPS data and products within the IGS community, using the open Internet as a transport medium. The paper will focus on the main objectives in phase one of the IGS RTWG's Charter, namely the implementation of a prototype real-time data distribution system and the adoption of a real-time exchange format for GPS data on the open internet.

DISCUSSION

We have been asked to design and implement a data and products exchange prototype that will meet our above-stated goals. We must therefore attempt to see where we want to be several years from now and make every effort to ensure that our prototype design will fit into our vision for the future. We must also be inclusive, that is we must involve as many members of the IGS as possible through the sharing of real-time enabling technologies. By doing so, we will involve all interested members of the IGS community in real-time activities.

The remainder of this section will be for the discussion of the requirements considered necessary for the implementation of a data and products exchange prototype.

Requirements of a Data and Products Exchange Prototype

Routing

See note #1 at the end of the paper

Routing is the managed process of directing data packets from one node to another on a path to their final destination. At the lowest layer, dedicated hardware routers manage the routing of packets for all traffic on the Internet. It is recommended that at the application layer, the highest layer, special purpose applications be used to allow data to be forwarded from a data center to others via a connectionless UDP unicast. It will be the responsibility of these applications to respond to data requests from external users of the data. Initially, all requests for data will be serviced. Should this service prove to be over subscribed, so that the data centers cannot respond to all requests, or the centers bandwidth is being consumed due to excessive traffic, access control shall be implemented as described below.

See notes #2 & #3 at the end of the paper

Access Control, Confidentiality, and Data Integrity:

Due to the openness of the Internet, it is prudent to assess the prototype security requirements. Access control is considered important and it is recommended that access control be implemented as necessary accordingly to each facilities capabilities and concerns. Access control may be handled at the hardware level with dedicated firewalls, at the OS level using methods such as IP-chains, or higher up in the application layer.

Data confidentiality may be addressed through the use of encryption technology. However, we do not recommend encrypting the data at this time. The prototype is considered to be an open system and hence accessible to all. Encrypting the data creates an exclusive environment and is therefore not conducive to an open system.

Data integrity is considered a compulsory matter to address. Data integrity or authenticity can be provided through the use of a message authentication code (MAC) sometimes referred to as a cryptographic checksum. A MAC insures that data has not been altered along its transmission path, but moreover a MAC also enables one to verify that data came from the intended source. The MAC, represented as a bit-string, is a function of the data, and a secret key shared by the sender and the receiver. A MAC is typically attached to the end of a packet. MACs can vary in bit length depending on the required level of authentication assurance. A 16 byte MAC provides strong authentication of a received message and is recommended for the prototype.

Functionality / Logical Design

The data is to be distributed within a robust and reliable environment capable of real-time distribution of data and products on the Open Internet. The data from the real-time tracking stations will flow into the data centers. A mechanism shall be in place to inject the data being shared by the data center into the routing application. The routing application is required to listen for requests from users and based on the request take the required action. These actions will in the beginning be restricted to sending data or continuing to send data. Later actions may be required in dealing with a request to retransmit missed packets.

Since the recommended protocol (UDP unicast) is connectionless, the sender (server) will not know when the receiver (client) has shut down. The server shall stop sending data to the client after a reasonable timeout period (on the order of several minutes). In order to continue receiving data, the client must periodically make requests of the server. These requests shall also be unicast UDP packets.

Since there may be different data types (ie: GPS, meteorological, seismic etc) originating from a station, data requests may be required to be data type specific. Users should only receive data of the type they have requested from a centers accumulator (server). It may prove easier for data centers to distribute different data types on different ports, that is, set up parallel servers on separate channels for the different data types. This is the approach taken by JPL to distribute gps data, broadcast ephemeris, almanac information, ionosphere/timing information, and global differential corrections. It is recommended that different data types be made available on different port numbers.

Physical Network Topology

As a starting point for the prototype network, the raw data may be requested from the agency controlling the stations from which the data accumulates. This provides a very direct path for the data from the source to the end user. The data centers should strive to have redundant Internet services and servers providing access to identical data flows, (Figure 1 in prep). In this way all data accumulators/distributors can be viewed as being at the same level.

As the physical network grows in stations and users, distributed servers may be required to limit the demands placed on data centers supplying the real-time data. One possible scenario is the incorporation of global data centers in the role of global real-time data distribution centers (Figure 2 in prep). These distribution centers would be chosen because of their reliability/redundancy and Internet bandwidth. Careful consideration must be given to the design of such a hierarchical system, as there are drawbacks to this approach including single points of failure at any of the nodes of the hierarchy. Should one node fail, the higher nodes will not have access to the data being processed by the lower nodes. Another drawback is the management of this type of system. Should nodes accidentally feed back to lower nodes, packets will endlessly be circulated in a loop. It is not recommend that distributed servers be implemented at this time.

Performance and Scalability

It is envisioned that the network will begin small and grow to the required numbers over time. It is therefore important to not limit the prototype's potential performance or scalability. Bandwidth restrictions and Internet performance will play a factor here.

Reliability Requirements

The system must be designed carefully for reliability and high availability. The network software and hardware infrastructure should have the necessary redundancy to prevent disruption of the network because of failure of network or server components. Tracking station outages will make their data unavailable and makes geographical redundancy necessary. Data center outages will make all data routed through them unavailable. The concept of primary and secondary data centers will be important for the future growth of the system.

Network Management Monitoring and Maintenance

A critical requirement of the solution is to minimize the level of effort required to manage and troubleshoot the prototype and the future fully functional distribution system.

Data distribution centers are responsible for the maintenance and monitoring of connections with the outside world, as well as administering tracking stations or sub-networks under their umbrella.

It is recommended that a RT-network-coordinator monitor and report back to the data centers on: accessibility (is the data there), reliability (how often is the data not there), and integrity (is the data usable). The integrity of the data may be implemented by sampling the data at a configurable frequency and post-processing the results.

Formats

Due to the phased approached of constructing the prototype network, different data formats shall be accommodated. This is considered the quickest way in which to proceed to a prototype where real data is flowing. The format of the data will be known by information contained in a message wrapper. See "Design Requirements for Data Wrappers". Format translation functions will be required at the user end.

In later revisions, it may be possible to limit the data formats to a handful, if not down to one. Recommended format(s) shall be designed to minimize bandwidth consumption without compromising the resolution of the data to a point where products become negatively impacted. In the case of GPS data, dynamic range compression techniques may be employed for bandwidth minimization. For example, JPL's soc format makes certain assumptions of the data characteristics, such as reasonable magnitudes of multipath and exploits the ionospheric phase and group delay differences among the data types. See for example: http://gipsy.jpl.nasa.gov/igdg/papers/. Other examples of GPS data compression will be investigated.

Sharing of Expertise

It is recommended that centers with expertise in accessing data directly from receivers to putting the data on-line share their experiences and practices with others. It should be realized that some centers are restricted from open-sourcing code and from providing executable code. Additionally, it must be understood that centers have limited resources in providing expertise.

Design Requirements for Data Wrappers

We introduce the concept of a “data wrapper”. The "data wrapper" shall consist of minimally a header, and a MAC trailer.

See note #4 at the end of the paper

We highlight as an example, NRCan's message header

```
typedef struct _udpRelayMsgHdr_t {
   unsigned char        sync1;        /*  1 byte  */
   unsigned char        sync2;        /*  1 byte  */  Serial or Wireless requirement
   unsigned short       msgType;      /*  2 bytes */  Message Type
   unsigned short       cntrl;        /*  2 bytes */  Control Bits (Special Purpose)
   unsigned short       stationID;    /*  2 bytes */
   struct timeval       timestamp;    /*  8 bytes */ Network performance
   unsigned short       msgSeq;       /*  2 bytes */  Sequence Number
   unsigned short       msgSize;      /*  2 bytes */  Message Size including MAC
   unsigned short       dataSize;     /*  2 bytes */  DataSize
   unsigned short       reserved;     /*  2 bytes */
} udpRelayMsgHdr_t;                   /*----------*/
                                      /* 24 bytes */
```

The header information is followed by the data and the MAC is then appended.

The msgTypes include control packets and data packets and each data packet has an associated data format. Initially control packets shall be request packets to start or continue data service.

The stationID will indicate which station the request packet is requesting. A default stationID is recommended to indicate that all station data from the data center is being requested. These control packets shall originate from the clients requesting data. The station ID is unique to the controlling agency that is accumulating the data.

The msgSeq number is an incremental number attached to each data packet on a per station ID basis. Its period must be defined.

The "msgSize" indicates the total number of bytes in the message including the data and MAC, while the "dataSize" variable indicates how many bytes are in the data block.

The MAC is generated based on publicly available functions shared at both the send and receive ends. Generating and verifying a MAC has in NRCan's experience required very low (negligible) overhead.

Other control packets can be later defined to be requests for retransmission of missed packets. For these types of requests, the stationID and msgSeq number are meaningful.

The msgType for data packets shall contain information relating to the format of the data block. Data packets shall either be labeled original packets (default) or retransmitted data packets resulting from retransmission requests. This again is for later development.

In addition to this, in order to respond to station changes on the fly it may be necessary to transmit a station reference number. Should the station configuration change (like antenna heights or clock steering), the user needs to know this on the fly, and take the appropriate actions.

RECOMMENDATIONS

It is recommended that the IGS community and the RTWG in particular move forward on two fronts with the goal of completing phase 1 of the RTWG's charter as quickly as possible.

1) Involve the broadest membership as possible from within the IGS community.

   In order to achieve this we should: (beginning at the workshop)
   a. Identify interested agencies.
   b. Identify enabling technologies within the broad membership that can be shared.

2) Move forward on the development of the prototype.
   - By giving consideration to:

      i. The use of UDP unicast at the application level for directing data packets between data centers and users.

      ii. To the use of a MAC to ensure data integrity.

      iii. The use of different port numbers for different data types available at a data center.

    iv. The adoption of a wrapper for the data formats including a structure for request packets.

    v. Use the simplest physical network structure starting with data being available only from controlling data centers.

- Incorporating additional requirements identified during the workshop and deemed necessary for the prototype development.

Proposed Next Steps

In a short period of time, the RTWG shall:

i. Recommend a wrapper for the data formats, including a structure for request packets.
ii. Recommend port numbers in the range of the IANA Registered Ports (1024 to 49151) that have not already been registered by IANA (Internet Assigned Numbers Authority). See for example: http://www.iana.org/assignments/port-numbers

The RTWG shall make a request to IANA to register these port numbers. This step is generally done when trying to establish a new standard. It ensures that other legitimate Internet users will not ship packets on the same port number to your computer.

Centers will be asked to make a subset of their real-time data stream available with the interface defined by our initial prototype requirements. It is recommended that this data shall be made available within 3 months after the wrapper, request packets, and port numbers have been defined.

NOTES:

Note 1: As described we do not consider this to be an authoritative description of TCP/IP. It is limited to the authors' current knowledge and experiences. Please bring to the attention of the authors any errors in our understanding that you may encounter, both for our own edification and to incorporate into future revisions of this paper.

Note 2: TCP and UDP are the two predominant transport layer protocols. Both use IP as their network layer. TCP provides a reliable transport layer, whereas UDP sends and receives datagrams (hence its name User Datagram Protocol) on a best effort basis. UDP does not guarantee that the datagram ever gets to its final destination. UDP is considered connectionless, and is a many-to-one and one-to-many protocol. The many-to-one aspect can be used to easily build data accumulators. Multiple applications, lets call them clients, can send UDP packets to a central receiver, typically known as a server. Servers do not need to know of the existence of their clients a priori, but clients must know what servers exist on the network. On the outgoing side, the one-to-many aspect can be used to build data distributors. Here the data accumulator can respond to data requests, and forward copies of its data packets to multiple IP destinations. TCP on the other hand establishes a reliable connection between two IP addresses. It is a one-to-one protocol. It is possible but more difficult to build a many-to-one and one-to-many architecture using TCP. This generally requires either multiple socket instantiations, or forking dedicated processes for each connection. JPL's original data accumulators and data distributors were TCP based. These were abandoned in favor of UDP due to the high overhead required of TCP. TCP proved not to be an effective transport layer to many parts of the world where link layers were not well established.

Note 3: An alternative to UDP unicast is UDP multicast. NRCan's internal data distribution is based on UDP multicast. Although UDP multicast is ideally suited for our purposes, the Internet as a whole, specifially IPv4, does not currently support IP multicast across subnets. Version 6 of IP will fully support UDP multicast routing, but it is not known by the authors how and when the world's link layers will permit IPv6 packet routing If we could use multicast technology, all the operating real-time stations would send their data to a global multicast group, which is in essence a virtual IP address. A multicast client could subscribe to this multicast group and would automatically be forwarded the data. Internet routers using IGMP (Internet Group Management Protocol) would determine optimally how to route the data. In the case of multiple requests coming from almost similar clients, routes are constructed so that only one packet transverses a majority of the distance. At the last possible router, the packets are duplicated and sent off to separate destinations. It can be thought of as a branching architecture where branches grow out of other branches due to clients joining the multicast group. The drawback to this is an all-or-nothing data feed, in which case the "all" may overwhelm the client's bandwidth. The client is at the mercy of whatever has been placed in the multicast group and has no say as to what packets it would like to receive.

Note 4: The words "header", "wrapper", "upper-data layer" shall refer to some higher layer of the underlying data format.

NRCan's Internet Global Positioning System Data Relay (iGPSDR)

K. Macleod and M. Caissy - Geodetic Survey Division, natural Resources Canada
R. Fong - TesserNet Inc.
V. Forgues and T. Erskine - SourceWorks Consulting Inc.

Natural Resources Canada (NRCan), Geodetic Survey Division (GSD) has been operating the Canadian Real-Time Active Control System (CRTACS) since 1996. The CRTCACS comprises a Real-Time Master Active Control Station (RTMACS) and a network of continuously operating GPS data acquisition stations, called Real-Time Active Control Points (RTACPs).

The RTMACS receivers RTACP observation data every second and ephemeris data upon update. At designated intervals (every 2 seconds) the RTMACS computes wide area GPS corrections. The GPS correction product derived by the RTMACS is known as the Canadian GPS□C service.

The CRTACS is enabled by a managed frame relay wide are network (WAN). The managed frame relay network is very reliable and unfortunately the cost associated with the frame relay network is also very high. With a core network of frame relay stations NRCan decided to develop a less expensive data collection application to densify and extend the network. The WAN networking technology option that was chosen was the Internet.

The Internet provides economical real-time (less than 1.5 seconds) data collection capability. However, data transmitted over the open Internet is not secure and the quality of service is not predictable. To ensure that the data sent over the open Internet is secure a message authentication code (MAC) is used. The MAC insures that the messages are not altered in transit. To enhance security the data can also be encrypted so that unauthorized users cannot read the message content. The reliability and bandwidth of the Internet has improved significantly since its inception. In North America the backbone of the Internet is very reliable and has excess capacity. Until recently, connecting to the Internet has been problematic. However, with the availability of high speed Digital Subscriber Lines (DSL) Internet access is no longer as significant an issue. NRCan has a managed Asymmetric Digital Subscriber Line (ADSL) dedicated to real-time GPS data and correction collection and distribution. The dedicated ADSL will contribute to the overall quality of the Internet real-time data collection project.

NRCan built an Internet Global Positioning System Data Relay (iGPSDR) application to facilitate the routing of GPS data and corrections over the open Internet to a large number of National and International users. The iGPSDR securely routes data from source to relay, relay to relay, and relay to destination. Redundancy and quality of service features have been built into the iGPSDR. Since networks and data formats can change over time, the iGPSDR can be configured at run time thereby enabling uninterrupted service. If a network of iGPSDRs is built the bandwidth required to move data can be minimized and the reliability maximized.

IGS

SESSION 4:

NETWORK ISSUES

International GPS Service
Network, Data and Analysis Center Workshop 2002
Ottawa, Ont., Canada

Network Issues

Michael Schmidt, Natural Resources Canada, Sidney, BC, Canada
Angelyn Moore, Jet Propulsion Laboratory, Pasadena, CA, USA

Executive Summary

At the present crossroads in moving "Towards Real Time," the IGS finds itself (as always) in a position to learn from its past, address its present needs and anticipate future directions. In this paper we review the IGS network as it currently exists and its effectiveness in supporting the IGS suite of precise products. We note that modernized GPS / GNSS signals will affect all aspects of the IGS and that the IGS must begin to anticipate the necessary steps required to handle a modernized GPS signal as well as other (new) GNSS signals. The importance of careful archival of site meta data as well as GPS data for future usage, cannot be understated. Also addressed are the IGS' relationships to the industry which supplies equipment to the network, the reporting of IGS network performance, the evolution of data exchange formats and the (once fanciful) notion that there may be too many IGS sites in some areas of the world.

A number of recommendations are made, the principal ones being:

A) GPS / GNSS Modernization: The IGS must assess the implications of GPS modernization and new GNSS technologies on the delivery of IGS products; based on this, the IGS must consider the optimal means for ensuring a seamless transition to the modernized system(s).

B) Associate Regional Networks: The IGS should consider the concept of Associate Regional Networks (ARN) for those areas where agencies operate stations that meet the IGS criteria but where station density is greater than that required by the IGS. Data from ARN stations that are required globally would continue to be submitted to IGS data centers.

C) Instrumentation / Site Changes: In order to minimize jumps at Global Reference Stations, a set of best practices is encouraged including clear guidelines for equipment and site changes; any change in site coordinates whether due to instrument changes, seismic activity or other factors should be carefully noted and published.

D) Data Exchange Format and Industrial Relations: The IGS should establish a joint Task Force with GPS manufacturers to coordinate the evolution and international acceptance of the RINEX format, encourage standardization of meta-data nomenclature and coordinate any future data exchange formats.

E) Station Metrics: The IGS should examine the current station performance metrics and determine required changes; consider efficient methods of compiling and communicating station events or periods which may challenge present and future users' analysis; determine ways to improve any deficiencies in communicating station quality issues between AC's, the Coordinators (ACC, Ref. Fm. Coordinator, and NC), station operators, and outside users.

1.0 Background

As the IGS community moves towards the delivery of real time data and products we face not only the task of meeting the real time goals but also the challenges of a modernized GPS constellation, the renewed strength of the GLONASS system and the advent of the Galileo system. The integrity of the data and products provided by the IGS will be increasingly reliant on a robust infrastructure consisting of improved (real time) communication from tracking stations, upgrade of existing station instrumentation to handle the modernized satellite constellation(s) and provision of data and station quality control statistics in near-real time. The data exchange standards will have to be improved in order to meet the real time applications, specifically the requirements for real-time dissemination of meta-data and, perhaps more importantly, the flagging of site reconfigurations (instrumentation, antenna, height of antenna, etc.), with real time alacrity.

IGS stations presently provide continuous tracking of the GPS constellation employing geodetic quality, dual frequency receivers. IGS stations have to meet the requirements as set forth in: "Standards for IGS Stations and Operational Centers, Version 1.3 (9 February, 1999)", (http://igscb.jpl.nasa.gov/network/guide_igs.html). With GPS modernization starting as soon as 2003 it will be necessary to review this document and define the operating requirements for stations contributing data to the IGS. At the same time, it is essential to review the current network in terms of spatial distribution of sites, station / agency capability to provide data at various sampling rates and delivery latencies (real time, 1 hr, 24 hr, high rate, 30 sec, etc.) in order to determine the network requirements for the future. While we are moving toward real time delivery of data, we must continue to ensure that we do not compromise existing standards and products. Certainly in the near term there will be a continued requirement for the 24-hour data sets and 1-hour data sets. There may be justification to look at intermediate data delivery (e.g. 4-hr, 6-hr, 12-hr) as the GPS satellite constellation undergoes change and as new systems come on-line.

All IGS products are and will always be reliant on timely data delivery: the IGS Final Products are primarily reliant on the 24-hour data stream; the IGS Rapid and Ultra-Rapid Products are primarily reliant on the 1-hour data streams.

1.1 Summary of IGS Products

IGS Final Products	IGS Rapid Products	IGS Ultra Rapid Products
GPS Ephemeris	GPS Ephemeris	GPS Ephemeris
GLONASS Ephemeris		
Satellite & Station Clocks	Satellite & Station Clocks	Satellite Clocks
Station Coordinates		
Station Velocity		
Polar Motion	Polar Motion	
Polar Motion Rates	Polar Motion Rates	
Length-Of-Day	Length-Of-Day	
Zenith Troposphere		
Ionospheric TEC Grid		

Source: Weber et al 2002

The availability of these, and new products such as the ultra-rapid zenith troposphere delay currently under development, depends directly on the timeliness and quality of the raw satellite observables delivered to the analysis centers. Station changes, as recorded in IGS Site logs (and therefore in the IGS SINEX template), and in the meta-data fields of RINEX headers are critical to the analysis processes. The data and meta-data distribution system currently in place, while not perfect, meets most of the operational objectives of the IGS. The move to near-real time (hourly data) and the planned moved to high rate, real time data will force a re-evaluation of data delivery means.

2.0 GPS Modernization

The GPS constellation is about to undergo its first major upgrade since its inception, an upgrade that will require new instrumentation at reference stations around the world. Each agency which contributes data to the IGS will undoubtedly have to meet not only IGS requirements but also the agency's mandates and the demands of their immediate user groups.

The modernized Block IIR satellites (IIR-M) - 12 in total - will transmit a civil code on the L2 frequency (L2C) commencing as early as 2003. This is part of a broader plan to modernize the GPS signal structure to include Military code on L1 and L2 frequencies, add a new frequency in the Aeronautical Radio Navigation Service (ARNS) band, the L5 frequency (Block IIF satellites), in addition to the aforementioned new civil code L2C. Initially envisioned as a C/A code on L2, the new L2C code will in fact be an "improved" C/A code opening up the door for improved tracking and new applications. (For a full description of the L2C and Block IIR-M, Block IIF satellites see Fontana et al, (1) & (2)).

The first Block IIR-M satellite is scheduled to be launched in 2003 (Fontana, et al (1)). The projected schedule, to be confirmed, shows the first Block IIF launch date as 2005.

By 2011 the GPS constellation will have 28 satellites with full L2C capability of which 18 satellites will have L5.

The implication of these changes to the IGS will be far reaching. For the first time in the history of the IGS we will be forced to coordinate a systematic upgrade of the IGS infrastructure including IGS sites (receivers, antennas, etc.), downstream data handling and processing (data conversion, quality control and analysis) software. As the L5 is implemented new antennas will appear on the market, requiring calibration, and the downstream effect on apparent phase centers at longstanding reference frame stations and the IGS 'Global Stations' will have to be monitored.

2.1 Issues / questions to discuss wrt L2C and L5:

IGS Network Upgrades:

- Required Changes to IGS Network required for:
  - IGS 'Global Stations'
  - 24-hr sites
  - Near-real time sites (1-hr data)
  - Near-real time sites (15min files, 1 Hz data)
  - Real time sites
- Effect on IGS Products
  - Near term;
  - Long Term
- Effect on data handling / analysis systems:
  - RINEX standard / changes to converters
  - Data validation software (TEQC, GIMP, GPSPACE, ?.)
  - Analysis software (Bernese, GIPSY, GAMIT, ?.)
- Required Changes to Site Logs
- Coordination of upgrades, standardization for uniform data / product flow;

The mandates of individual agencies may in some instances drive the upgrades of IGS sites to equipment supporting modernization. The IGS must therefore prepare for the possibility of modernized data in the IGS stream as new satellites come online, and make recommendations for data handling.

It should be noted that the "natural" upgrading of stations to modernized equipment may not meet the core requirements necessary to ensure that the IGS continues to meet its goal of providing the highest quality GPS data and products. Once the GPS modernization impact has been assessed and the requirements for stations supporting modernization have been detailed in the "Standards for IGS Stations and Operational Centers" document, the IGS should consider issuing a non-binding call for letters of intent (LOI) to upgrade within a specific time period. Based on the response, the IGS could examine the anticipated global coverage and if necessary, target agencies working in deficient areas with letters of request to support the IGS' first phase of modernization support. Such letters may assist the agencies in approaching funding sources with requests related to modernizing stations.

This process of issuing requests for non-binding LOI’s could be utilized for station upgrades foreseen as necessary on a network-wide basis and would secure an initial set of upgraded stations, and thus help coordinate a phased upgrade.

3.0 IGS Station Distribution, Station Classification

As of March 2002 the IGS Network consists of 293 stations, representing some 200+ agencies around the world. Of the 293 stations, 117 are classified as IGS 'Global Stations'- *(see IGS Terms of Reference for definitions)*. These stations are, at a minimum, producing 30-sec., 24-hour RINEX files.

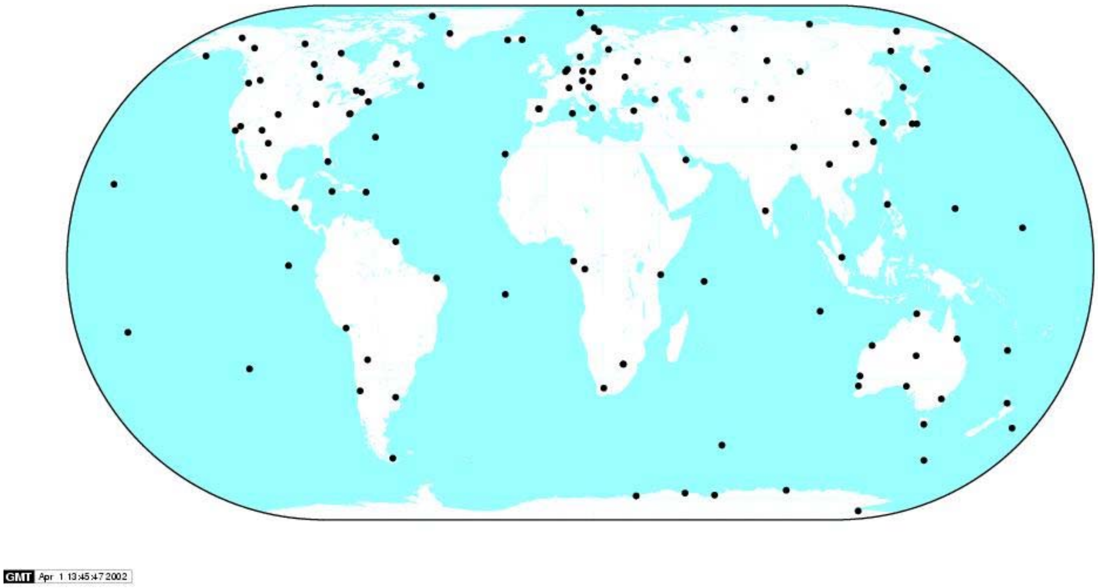


fig. 1 Distribution of IGS ‘Global Stations’

In the past 2 years the distribution of IGS ‘Global Stations’ has improved with new stations in Africa, Asia and S. America coming on line. However from fig. 1 it is evident that there are still some gaps in global coverage.

GMT Apr 1 17:46:01 2002

fig. 2 Distribution of 1-hr IGS Stations

Approximately 90 IGS stations are producing hourly 30-sec. RINEX files - It should be noted that (a) many, but not all, are IGS ‘Global Stations’ and (b) there are higher concentrations in North America and Europe. Given (a), there may be an insufficient number of IGS ‘Global Stations’ contributing to the rapid / ultra-rapid products, implying that there may be insufficient consistency between stations used by the AC’s for rapid / ultra-rapid products, as compared with stations used for the final products. It also follows from both (a) and (b) that the total number of stations contributing hourly data files is misleading in terms of worldwide coverage when compared to the scenario of an equally distributed network of 90 stations; see fig. 2 for the gaps and concentration(s) in coverage.

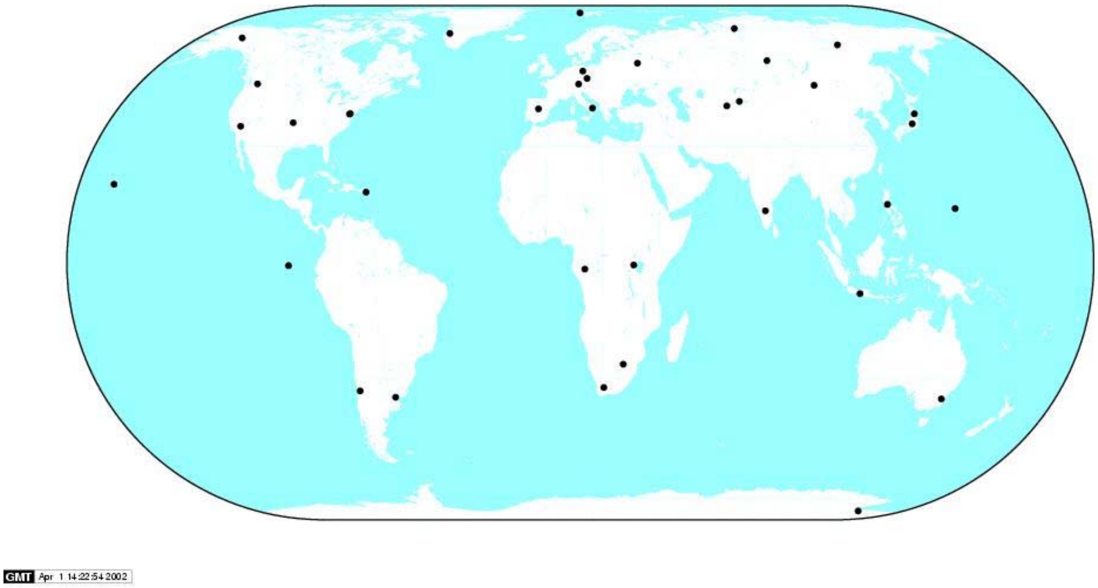


fig. 3 Distribution of IGS Stations providing 1Hz, 15 min files

There are approximately 35 stations providing data in near real-time, through the delivery of 15-minute, 1Hz data files. Agencies currently providing this data stream are GFZ, JPL, ASI (MATE), and GOPE. Approximately two-thirds of these are IGS 'Global Stations'. Other sites / agencies have demonstrated the capability to produce 1 Hz data, either in real-time or in near real-time.

3.1 Issues / questions to discuss wrt IGS Station Distribution, Station Classification:

- Is the current distribution of IGS stations (GPS and GLONASS) sufficient to meet final, rapid and ultra-rapid products?
- What is the minimal distribution of IGS stations required to meet real-time needs? How many of these have to be IGS 'Global Stations'?
- What is the optimal distribution of IGS stations required to meet real-time needs? How many of these have to be IGS 'Global Stations'?
- Of the stations / agencies currently providing, or with demonstrated capability to provide 1Hz data, which are willing / able to contribute to the IGS real-time delivery of data?
- What are the implications for the IGS Network in terms of the new GPS satellite signal commencing 2003?
  - Should the IGS set targets for the upgrade of current IGS stations to handle L2C and L5 wrt:
    - Timeframe;
    - Coverage (IGS 'Global Stations', 1 hour sites, real time sites);
- Is there a requirement for intermediate data delivery (4-hr, 6-hr, 12-hr)?

Once the IGS has determined the requirements for station distribution world-wide to meet the requirements to produce the varied IGS products and data streams, it will be necessary to address the issue of stations which are part of regional networks and / or are redundant to primary IGS objectives. The IGS as an organization values its inclusive and voluntary nature and, up to now, has accepted any proposed station meeting the technical requirements. In some instances, this benefits global geodesy if only by acknowledging the operation of a quality permanent station, which may lead to increased funding and participation of the host agency. However, today we find quite adequate coverage in many areas of the world. A certain amount of redundancy is desirable to guard against the impact of unforeseen downtime of any given station, but at some level, adding further stations may serve only to increase user confusion. The IGS must somehow balance the conflicting goals of inclusivity and providing a globally relevant data set of the highest precision.

It is proposed that the IGS consider the concept of Associate Regional Networks, networks which operate stations that meet the IGS criteria but at a density greater than that required by the IGS. These networks are recognized as being an integral part of the IGS but are linked at the Network level rather than at the station level. They would only submit data to IGS data centers from those stations that are required globally. Data and site logs from all their stations meet IGS standards and are made available and archived at the Associate Regional Network Data Center. Should a regional station later become globally significant, it would then be easy to absorb it into the main IGS data and meta-data distribution system. The principal IGS web sites (Central Bureau, CDDISA, IGN, EUREF, etc.) would provide links to Associate Regional Network web sites, ftp locations, contact information, etc. In this way, stations that meet all IGS requirements receive the recognition they deserve by means of the IGS Associate Regional Network label, without unnecessarily complicating the IGS Network and data distribution system.

A panel should be formed to consider the utility of proposed new stations in areas already hosting existing stations. This group should consider the need for redundancy in the region as well as the presence of desirable co-located equipment such as other space geodesy instruments, meteorological instrumentation, tide gauges, and so on. As quick action would be desired, this group should act by email and should ordinarily take a decision based on a minimum number of agreeing members and within one week to avoid stalling the process should a few members be unavailable for a period of time. The panel would need representation from at minimum, several ACs and several Working Groups and Pilot Projects.

IGS Associate Application Networks might also be considered to recognize specialized networks, supporting a given area of investigation rather than a particular region, if admitting all the member sites to the IGS Network would be undesirable.

4.0 Reference Frame Station Issues

Jumps in calculated IGS station positions, particularly those not removed by applying known factors such as antenna (and therefore phase center) changes, are of concern to the ability to support long-term, high-accuracy geodesy. This is of particular concern for Reference Frame (RefFm) sites. Figure 4 shows the vertical component of the combined solution at station HOFN, with a large offset coincident with a radome and antenna change in late 2001. Such behavior would be especially troublesome at a Reference Frame (RefFm) site.

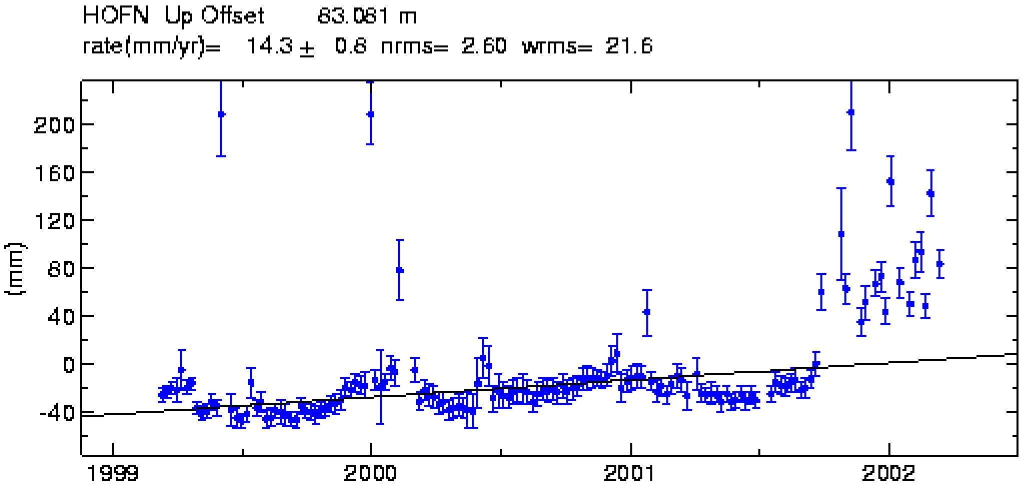


fig. 4 IGS SINEX combination data as graphed on MIT/GPSG's web page

We can imagine 4 classes of station position jumps remaining after all correct meta-data has been applied:

1. Those not concurrent with any known event
2. Those concurrent with natural, unavoidable events such as earthquakes
3. Those concurrent with, but whose magnitudes are not explained by, equipment changes
4. Those concurrent with related site events such as tree trimming

To serve long-term geodesy optimally, the IGS should strive to document all types thoroughly, and further, minimize the impact and occurrences of types 3 and 4, most especially at RefFm sites. They must continue to be documented in all cases, but we may consider formalizing the classification as a RefFm site in an attempt to minimize their frequency. A set of best practices crucial for RefFm sites should be drawn up, perhaps starting with:

- Equipment should be changed only when there is a clear necessity and benefit
- Planned equipment changes should have a period of at least 1 month overlap
- Site changes, e.g. construction of buildings in the vicinity of the RefFm monument, should be avoided as much as possible
- Equipment known to produce poorly understood behavior in calculated station positions, e.g. conical radomes, should be avoided

- Equipment not previously used in the IGS should be avoided until tested and well understood by IGS ACs

Once these are agreed upon, a letter to RefFm sites should acknowledge the special responsibility of maintaining a RefFm site and request the station operators' assistance in observing these recommendations to preserve the integrity of long-term time series.

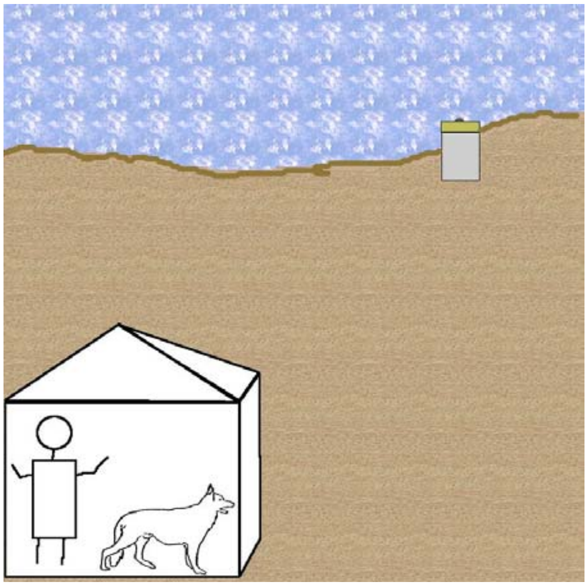


fig 5 - The IGS Reference Frame site of the future:
The equipment's job is to take the data.
The person's job is to feed the dog.
The dog's job is to bite the person if he tries to touch the equipment.

4.1 Issues / questions to discuss wrt Reference Frame Station Issues:

- How should jumps be recorded (to be examined jointly with RFWG)?
- What is to be done if a jump is inconsistently observed among the ACs?
- What if nonlinear motion is observed?
- What is the most efficient way to introduce new types / models of instrumentation to RefFm stations - (guidelines, overlaps, calibrations, etc.)?

5.0 Meta-Data Update in Real Time

Meta-data (receiver, firmware, antenna, antenna offsets, etc.) changes are presently announced via 'IGSMAIL' distribution with site logs updated at the Central Bureau; the SINEX template, (generated daily at the CB and used by the AC's as input parameters), consequently reflects the newly submitted information. In the real-time world this will not be sufficient as station changes could have a severe impact on real time analysis of data. The question becomes how best to update the user community of changes at real-time sites. The solution must support timely notification as a user acquires the stream; for example, if a station change has occurred while users were offline, they must become aware of the change before processing the data stream. Similarly, real-time analysis streams must be cognizant of, and take into account, station changes as they occur. Some options to consider:

- Real-Time data stream provides meta-data: The meta-data need not be sent at the same rate as the GPS data. Instead periodic updates, or "header" messages at a slow repeat rate is suggested (e.g. station meta-data update every 5, 15, (?), minutes). The advantage of this approach, as with the current RINEX standard, is that the meta-data is contained within the GPS data flow / files.
- Provide a pointer to the fact that new meta-data is available (from a defined location). A "station setup counter" can reference the equipment configuration. If the configuration (receiver/antenna/height/etc) is changed, the counter is incremented and users (programs) know to go seek the details (as previously defined). For instance, if the stream passed "3.3,4.4" as the "station setup counter", the AC would know the current setup is as in site log sections 3.3 (receiver) and 4.4 (antenna). If the string changed to "3.4,4.4" the AC would know the receiver has changed but the antenna has not and deal with it accordingly. This is only an example drawing on the current use of site logs to illustrate how the stream could provide meta-data information without providing the meta-data itself. The disadvantage(s) of this approach would be the reliance on external data sources, (i.e. site logs), which in the real world would occasionally be unreachable, e.g. due to a network outage other than at the site; in addition correlating the "station setup counter" with (for example) a specific site log or SINEX template format, places constraints on future development of these formats.
- Dispense a complete set of station configuration information to the user at the time of data stream acquisition. On station reconfiguration, dispense that information to all currently subscribed listeners.

5.1 Issues / questions to discuss wrt Meta-Data Update in Real Time:

Data / Meta-Data:

- Are current GPS / GLONASS data rates sufficient to meet present / new products?

- What is the target latency for:
    - Real time data?
    - Near-real time sites (15min files, 1 Hz data)
    - Near-real time data (1 hr files)?
    - 24-hr files?
- Is there need / justification to consider intermediate data delivery (e.g. 4-hr, 6-hr, 12-hr)?
- What guidelines do we need to institute for updating of IGS logs and meta-data fields in RINEX headers?
- How do we handle the update of meta-data in real time?

6.0 RINEX Format

The RINEX (Receiver Independent Exchange) format was developed as a means to exchange data between users irregardless of what brand of GPS receiver was used. The most recent version (version 2.10) of the RINEX standard was last updated Jan. 25, 2002. The format consists of six ASCII file types: Observation Data File, Navigation Message File, Meteorological Data File, GLONASS Navigation Message File, GEO Navigation Message File and Satellite and Receiver Clock Date File. The RINEX format has been adopted by most, if not all, manufacturers of GPS / GLONASS receivers / software. It is currently the standard for data exchange within the IGS using the Hatanaka and UNIX "compress" compression schemes. Having said that, not all RINEX generators / readers are necessarily compliant with all aspects of the current standard.

A draft of RINEX version 2.20 was presented at the IGS LEO meeting in Potsdam, in order to accommodate GPS data from LEO satellites. For proposed modifications see: ftp://ftp.unibe.ch/aiub/rinex/rnx_leo.txt .

It is not clear if these proposed changes are compatible with the needs of a modernized GPS system and whether they have to be re-visited. With the introduction of the Block IIR-M, with L2C code in 2003 and the Block IIF satellites with L5 in 2005, new observables will be added to the data stream. Changes to the RINEX standard require changes in existing computer programs that either generate and/or read RINEX files. Changes also have to be backwards compatible, so that new code can still read older files. It must also be recognized that the usage of the RINEX standard extends well beyond the scientific / IGS community. Commercial GPS software uses RINEX data format extensively, some even linking to IGS data centers automatically to retrieve data from the nearest IGS station.

In the short term the RINEX format will have to be changed to allow for the new observables. The IGS should also institute periodic reviews of its procedures to consider whether these are meeting and will continue to meet the IGS goals and objectives appropriately. It may be that another exchange format for the future should be considered, one which is sustainable and easy to extend as new observables and new satellite systems (e.g. Galileo) come on-line. Rather than comparing existing RINEX /

BINEX formats it is suggested that the requirements / specifications for an exchange format be defined and subsequent to that, a solution proposed.

The IGS could coordinate the modification of the RINEX format and the design of a new exchange format, consulting with the major stake holders, including the major manufacturers and software developers *(see also section 7.0 below)*.

6.1 Issues / questions to discuss wrt RINEX Format:

- Who within the IGS should be tasked to work on the next version of the RINEX standard? Is a 'working group' required?
- What is a realistic timeline for RINEX standard upgrade?
- How can we best address the need of a next generation exchange format?
- What is the best way to involve all major stake holders?

7.0 Manufacturer Relations

Information exchange between the IGS and manufacturers of geodetic GPS (and related) equipment is necessary for a number of reasons, including:

- Communication of requirements of IGS station instrumentation
- Communication of equipment capabilities
- Understanding of how proposed IGS changes affect manufacturer equipment and software
- Timely communication of information about equipment, such as appropriate model designations and descriptions, or observables tracked
- Calibration of antenna phase centers.

Immediate examples are (a) the proposed changes to the RINEX format and introduction of new formats, and (b) the continual need for agreed upon meta-data nomenclature prior to the deployment of GPS and ancillary instrumentation within the IGS. These issues are of mutual benefit to the IGS, to the manufacturers and to GPS users at large who are increasingly using more IGS products and data sets.

To achieve these goals, an "IGS Instrument Panel" should be formed. Vendors whose products are used in the IGS should appoint to the Panel a representative who is committed to swiftly and effectively providing needed information to the IGS. The Panel would also provide a link by which matters such as proposed format changes and future station needs may be discussed. A panel such as this could facilitate internationally agreed upon exchange formats and meta-data nomenclature standards (as for example found in the IGS Receiver / Antenna Table:
ftp://igscb.jpl.nasa.gov/igscb/station/general/rcvr_ant.tab).

8.0 IGS Metrics

IGS Station Performance metrics must answer many questions from different customers:

- Station operators:
    - How is my site doing?
    - How well does my site support the IGS?
    - Is there some way I might improve my site, even given local infrastructure constraints?
- Network Coordinator:
    - What sites need attention?
    - What areas need more sites, more sites with certain characteristics, or more sites for tolerance against occasional site failure?
- Users:
    - What site(s) should I use for my analysis?
    - Are there any known problems with site xxxx within this time period?

Answering all of these in a quick, easy-to-use manner may imply multiple reports or at least multiple sorts of data. Graphical and alphanumeric presentations each have their own strengths in communicating data and a combination of both should be considered.

Potential improvements to the existing IGSNet (ftp://igscb.jpl.nasa.gov/pub/mail/igsnet) reports have been discussed previously, but there has been no clear action defined. Here we examine pros and cons of the existing system as well as some of the alternatives.

IGSNET reports

The Quality score in the IGSNET reports uses engineering data from the JPL AC's IGS analysis:

- Number of valid clock solutions
- Number of phase breaks after editing
- Ratio of number of pseudorange measurements to number of phase measurements
- 3D formal error
- phase & pseudorange rms residuals

PRO: - plenty of actual data relevant to IGS analysis
CON: - Not all of the engineering data is typically available to the public.
- Dependence on the JPL AC
- No data for a given site if the JPL AC does not process it

SINEX combination residuals

PRO: - High relevance to the IGS
CON: - No data for a given site if it is not in the combination

TEQC summaries

PRO: - Easily generated for all sites

CON: - More of a quick look at the signals, rather than heavy-duty geodetic processing.

- Not able to verify a high correlation between high/low IGSNET Quality scores and any fields in the teqc summaries.

AG or similar mail-in point positioning runs

PRO: - Could get the same data as currently used in IGSNET Quality scores for any sites not processed by JPL AC

CON: - Dependence and burden on JPL (or other) AC

8.1 Issues / questions to discuss wrt IGS Metrics:

- What metrics are required by the Station Operators, Network Coordinator and users?
- What changes / improvements are required?
- What tools should be developed and / or adopted by the IGS? - for example are there software tools available that could be incorporated at the station operator level in addition to TEQC?
- Is there a requirement for a publicly available compilation of station "problem" periods? How would this be handled if there is a disagreement on the "problem"? (See also the station event reporting issues of Section 4.1).
- Are there deficiencies in communicating station quality issues between ACs, the Coordinators (ACC, Ref. Fm. Coordinator, and NC), station operators, and outside users?

9.0 Real Time Communication

The delivery of Real-Time GPS data from reference station to Regional Center (RC) and then on to the IGS and other user communities is broken into two components:

- Transfer of GPS data from Reference Station to Regional Network Center
- Transfer of GPS data and meta-data to the IGS and other users.

The transfer, in real time, of GPS data to Regional Centers can be independent of any IGS agreed upon delivery technology and/or standard. Options currently in use include frame relay, VSAT technology, dedicated phone lines, radio and the Internet or combinations thereof. Flexibility in "last mile" communications hardware and protocols between operating agencies and the stations increases the IGS' ability to bring together data from agencies operating stations under their own agencies' disparate missions and requirements. The advent of relatively inexpensive satellite Internet service is a possible solution to bring Internet access direct to the reference stations. It is possible to consider direct multicast of data from reference stations.

The delivery of the raw data and associated meta-data to the IGS community at large, whether from RC's or direct from station(s) does require an agreed upon delivery method. The current model of distributing data solely via discrete data centers may not be optimal for a real time environment. Instead a model whereby the data is distributed directly to the end users should be investigated. One such model could be the use of Internet Multicast. Using IP Multicast a server at an RC can multicast data to many users simultaneously thus permitting multiple analysis / data centers to share the same source simultaneously.

The possible drawbacks to the reliance on the Internet are centered on security and reliability. As the IGS evolves as an organization providing a number of products and services with an increasing and reliant user base, security to the service and reliability of the service will become critical. For these reasons the IGS must look at redundancy both in station distribution and in the distribution of all data (real time through 24-hr data sets) and products. The use of the public Internet, for example, may not be robust enough to ensure 100% data recovery at all recipient sites – (we have all experienced Internet "drop outs") …

In the near term it would be useful, if those operating real-time networks could provide detailed technical information, on-line, to help facilitate the delivery of real-time data from reference stations to Regional Centers. Further to this the IGS must engage in a discussion of how best to distribute data and products. It will be necessary to agree upon protocols for the delivery (broadcast) of real time data and develop non-proprietary, open source standards and tools to ensure robust data delivery.

9.1 Issues / questions to discuss wrt Real Time Communication:

- Dissemination / sharing of technical information for the retrieval of high rate (1Hz) data in real time from reference Station to Regional Data / Network Center;
- Delivery of high rate (1Hz) data in real time to the IGS community (method, protocols, etc.);

Acknowledgements

The authors would like to acknowledge the input from colleagues at their respective agencies, especially Herb Dragert (NRCan), Ruth Neilan (JPL) as well as the individuals who contributed to the session at the workshop: Ludwig Combrinck (HartRAO) Peizhan Zhang, (China Seismological Institute), Hanrong Sun, (China Seismological Institute), Peng Fang (SIO), Lou Estey (UNAVCO), Ruth Neilan (JPL), Werner Gurtner (AIUB). In addition we would like to acknowledge the participation of Robert Snow (Thales Navigation Inc.), Michel Bourdon (Leica Geosystems), Pat Fenton, Paul Stiles (NovAtel Inc.), Robert Ragsdale (Trimble Navigation - Canada), Neil Spriggs (Nanometrics Inc.), Morgan Smith (Topcon Positioning Systems).

A. Moore's portion of this work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Reference Material

(1)Fontana, Richard; Wai Cheung; Paul M. Novak; Thomas A. Stansell Jr.: The New L2 Signal; http://www.navcen.uscg.gov/gps/modernization/TheNewL2CivilSignal.pdf

(2)Fontana, Richard; Wai Cheung; Tom Stansell: The Modernized L2 Civil Signal, GPS World, September 2001;
http://www.navcen.uscg.gov/gps/modernization/ModernizedL2CivilSignal.pdf

Standards for IGS Stations and Operational Centers Version 1.3 (9 February, 1999) (prepared by IGS Infrastructure Committee and Central Bureau)
http://igscb.jpl.nasa.gov/network/guide_igs.html

IGS Terms of Reference, Revision, adopted December 1998,
http://igscb.jpl.nasa.gov/organization/bylaws.html#Network

RINEX:
ftp://ftp.unibe.ch/aiub/rinex/rinex210.txt
ftp://ftp.unibe.ch/aiub/rinex/rnx_leo.txt .

Weber, Robert; Jim Ray; Jan Kouba: Review of IGS analysis Products, IGS Network, Data and Analysis Workshop, April 2002

The IGS Network in Africa; an Update and Real-time Issues.

Ludwig Combrinck
Hartebeesthoek Radio Astronomy Observatory, South Africa

Abstract

The IGS network stations in Africa have increased slowly in number during the last five years, with the equatorial and southern part of Africa being the most densely populated at this time. HartRAO is targeting the 14 Southern African Development Community (SADC) countries as possible hosts for new stations. The aim is to develop the SADC GPS Network as an official SADC project. Internet connectivity has improved during the last five years, but for most African countries, Internet service providers (ISPs) are still only available in major cities.

Africa Internet Status

Poor distribution and irregular electricity networks in many African countries adversely affect the availability of Internet in rural areas. Most African capitals have more than one ISP; South Africa, Egypt, Morocco, Kenya, Nigeria, Tanzania and Togo have 10 or more. Countries with better developed infrastructures such as South Africa and the highly developed North African countries have more ISPs and they are also more widely distributed. Public telecom operators have established Internet services in 33 countries and although these usually provided the only international link, many now face competition with private sector international links via VSAT. Currently, lack of circuit capacity and high international tariffs suppresses access to sufficient international bandwidth that would be necessary for real-time GPS networks. There are currently a large number of information and communication development projects in Africa. Although real-time space geodesy is feasible from a limited number of countries at present, the future seems bright and the global geodetic community can expect Africa to participate.

SADC GPS Network

The SADC consists of 14 member states; Angola, Botswana, D.R.C., Lesotho, Malawi, Mauritius, Mozambique, Namibia, South Africa, Seychelles, Swaziland, Tanzania, Zambia and Zimbabwe. Of these, only South Africa, Seychelles and Zambia (very recently) have permanent GPS receivers. HartRAO is planning to install IGS stations in Namibia and Malawi in the near future. It is planned to equip all SADC member states with an IGS station within the next 2 years. The ultimate objective of SADC is to achieve an improvement in the living standards of the people of the Region. This can be achieved through development and economic growth, self-sustaining development and complementary national and regional programmes. Developing a SADC regional GPS network (Combrinck 1998) as a southern component of the African Reference Frame (Neilan and Wonnacott 2002), will aid in achieving this objective through providing modernization of local mapping agencies' national reference systems and surveying capabilities. A multitude of applications will benefit directly, amongst which are GIS, land distribution and management, mapping, civil engineering and scientific or research applications of GPS.

Conclusions

Africa has a bright future ahead, a future where information and communication technology will allow its participation in its own development and progress, as well as in scientific networks which will demand reliability, low latency and huge quantities of real-time data.

References

Combrinck, L. 1998. *A regional GPS network for southern Africa*. Unpublished talk delivered at the 23-26 March 1998 International Workshop: GPS Geodetic Investigations and Infrastructure in the Greater Middle East Region, New Castle Upon Tyne.
Neilan, R. and R Wonnacott. 2002. *Establishing a Continental Reference System in Africa, AFREF*. Unpublished proposal to International Council for Science, February 2002.

SESSION 5:

GROUND-BASED GPS IONOSPHERIC ESTIMATION

IONO_WG STATUS REPORT AND OUTLOOK
- POSITION PAPER -

J. Feltens
EDS Deutschland GmbH, based at
Navigation Research Office,
ESA, European Space Operations Centre,
Robert-Bosch-Str. 5, D-64293 Darmstadt, Germany

ABSTRACT

The IGS Ionosphere Working Group (Iono_WG) was established by the IGS Governing Board on 28 May 1998 and commenced working in June 1998. The working group's main activity is at the moment the routine provision of ionosphere Total Electron Content *(TEC)* maps with a 2-hours time resolution and of daily sets of GPS satellite (and receiver) hardware differential code bias (*DCB*) values. The computation of these *TEC* maps and *DCB* sets is based on the routine evaluation of GPS dual-frequency tracking data recorded with the global IGS tracking network. Currently final attempts are made to establish from the individual contributions a combined IGS Ionosphere Product and to commence with the routine delivery of that product. The implementation of near-real-time availability is then the next important task and, medium-termed, the development of more sophisticated ionosphere models. Also the inclusion of other than GPS-data might be an aspect. The final target is the establishment of an independent IGS ionosphere model.

Currently five IGS Ionosphere Associate Analysis Centers (IAACs) contribute with their ionosphere products to the Iono_WG activities. Once per week these ionosphere products are compared with a dedicated comparison algorithm. This comparison/combination algorithm was worked out and coded in 1998 from scratch. In the meantime the original comparison/combination algorithm was upgraded with new weights computed from the results of external self-consistency validations. The weekly comparisons are done with this new approach since August 2001. Furthermore, the IAACs *TEC* maps are routinely validated with TOPEX altimeter data since July 2001.

During the recent IGS/IAACs Ionosphere Workshop, ESOC, Darmstadt, Germany, January 17-18, 2002, a list of final actions was decided, which shall soon lead to the routine delivery of an official IGS Ionosphere Product. Based on the outcome of the Darmstadt Workshop and on the discussions at Ottawa, five recommendations were formulated in this Position Paper, which will be the basis for the Iono_WG members on how to progress - especially to come soon into a position to start with the routine delivery of an official IGS Ionosphere Product.

It is the intent of this Position Paper to give a short history and the current status of the Iono_WG activities. The recommendations stated at the end of this paper shall then be an orientation for the IAACs on how to progress, so that the Iono_WG can soon start with the routine delivery of a combined IGS Ionosphere Product to external users through the Crustal Dynamics Data Information System (CDDIS).

1 INTRODUCTION

This Position Paper will start with a project report providing an overview over the Iono_WG activities since its establishment in 1998.

The next aspect treated will be an overview about the routine comparisons, which are done until now at the designated Ionosphere Associate Combination Center (IACC) at ESOC. Key statistics of the routine TOPEX validations will be presented.

Based on the outcome of the IGS/IAACs Ionosphere Workshop in Darmstadt, 17-18 January, 2002, and on the discussions made at Ottawa, five recommendations are then formulated defining the way on how to progress by the Iono_WG.

Finally the Position Paper will conclude with a résumé of the achievements so far reached.

2 WG-ACTIVITIES SINCE ITS ESTABLISHMENT IN MAY'98

The Working Group started its routine activities in June 1998: Several so called Ionosphere Associate Analysis Centers (IAACs) provide per day twelve global TEC maps with a 2-hours time resolution and a daily set of GPS satellite $DCBs$ in the form of IONEX format files (Schaer et al., 1997). The routine provision of daily ground station $DCBs$ is under preparation. Currently five IAACs contribute with ionosphere products:

- CODE, Center for Orbit Determination in Europe, Astronomical Institute, University of Berne, Switzerland.

- ESOC, European Space Operations Centre of ESA, Darmstadt, Germany.

- JPL, Jet Propulsion Laboratory, Pasadena, California, U.S.A.

- NRCan, Natural Resources Canada, Ottawa, Ontario, Canada.

- UPC, Polytechnical University of Catalonia, Barcelona, Spain.

The mathematical approaches used by the distinct IAACs to establish their TEC maps are quite different. Details about the individual IAACs modeling can be found in e.g. (Schaer 1999; Feltens, 1998; Mannucci et al., 1998; Gao et al.; Hernandez-Pajares M. et al., 1999).

The IGS standards defining the form in which the ionosphere products must be delivered to the Crustal Dynamics Data Information System (CDDIS), are declared in the recommendations of the Darmstadt 1998 IGS Workshop Position Paper (Feltens and Schaer, 1998). In short summary the most important are: 1) TEC maps and GPS satellite $DCBs$ must be delivered in form of daily IONEX files (Schaer et al., 1997). 2) The TEC maps must have a time resolution of 2 hours, they must be arranged in a fixed global grid and refer to a shell height of 450 km. 3) Ionosphere products must be made available not later than the IGS Final Orbits, i.e. 11 days after the last observations.

Once per week the IACC performs the comparisons of the ionosphere products of all 7 days of the GPS week recently delivered to CDDIS. The comparison products and a weekly report are made available at ESOC's FTP account: ftp anonymous@nng.esoc.esa.de. A short summary is e-mailed through the IONO-WG list to the Iono_WG.

Apart from the routine activities the Iono_WG organized so far two dedicated high-rate tracking campaigns with the global IGS network during events which are of special relevance for the ionosphere:

1) The Solar Eclipse campaign on 11 August 1999: About 60 IGS sites, being located along the eclipse path from the east coast of North America over Europe and the Near - and Middle East, recorded on that day dual-frequency GPS-data with 1- and 3-second sampling rates. The high rate data are archived at the CDDIS and is open to research groups to study the ionosphere's reaction on the solar eclipse (*anonymous ftp* at *cddisa.gsfc.nasa.gov* in directory */gps/99eclipse*).
2) The HIRAC/SolarMax campaign from 23 - 29 April 2001: About 100 IGS sites, being located in the northern and southern polar regions and in the low latitudes including the crest regions at both sides of the geomagnetic equator, recorded over 7 days dual-frequency GPS-data with 1- and 3-second sampling rates. This IGS/Iono_WG activity was coordinated with other ionospheric observation programs or measurement campaigns using ionosondes, EISCAT, high resolution magnetometers, etc. to obtain a comprehensive view of the geomagnetic and ionospheric state. The high rate GPS and GLONASS data are archived at the CDDIS and is open to research groups to study the ionosphere's behavior under solar maximum conditions (*anonymous* ftp at *cddisa.gsfc.nasa.gov* in directory */gps/01solarmax*).

The Iono_WG is open to organize further campaigns of this type.

3 RECENT IMPROVEMENTS

3.1 Upgraded Comparison/Combination Approach

In short, the old comparison/combination approach (☞ see Appendix B attached) was based on unweighted and weighted mean TEC maps, which could be considered as something like "combined" TEC maps, and the individual IAACs TEC maps were compared with respect to the weighted mean TEC maps. The comparison of $DCBs$ was done basically in the same way. However, it was well known from the beginning, that the different IAACs models are based on very different mathematical approaches and the weights obtained with the old approach did obviously not represent the true quality of the input IAACs TEC maps.

The Iono_WG thus decided to upgrade the comparison/combination algorithm with a new weighting scheme, whereby the individual IAACs-weights are derived from external validations with self-consistency tests (☞ see Appendix A attached). The weekly comparisons are done with this new approach since August 2001. The external validations needed for this method are made routinely by the Ionosphere Associate Validation Centers (IAVCs) UPC and NRCan prior to the weekly comparisons at the IACC at ESOC.

Feltens (2002a) presents results obtained with the old and with the new comparison scheme: 1) The new comparison/combination approach favors the higher quality TEC maps more than the old approach did. 2) Currently discrete weights are assigned to defined geographic areas, which can cause “chessboard-like” patterns in the IGS TEC RMS maps and might in extreme cases also become visible in the IGS TEC maps. At Ottawa it was thus decided to compute from these regional weights corresponding global weights, which shall then be introduced into the comparisons/combinations. 3) The satellite $DCBs$ series provided by most of the IAACs are quite constant, oscillating between 0.2 and 0.4 $nanoseconds$ around their mean values.

3.2 *TOPEX Validations*

Since July 2001 JPL provides $VTEC$ data derived from TOPEX altimeter observables to the working group to enable validations. Due to its orbital geometry TOPEX scans every day only a limited band of the ionosphere. Additionally, the TOPEX data may be biased by +2-5 $TECU$. These two aspects must be kept in mind when interpreting the validations with TOPEX $VTEC$ data. The TOPEX validations are attached to the weekly comparisons.

Principally these TOPEX validations work as follows: JPL provides per day a so called TOPEX file containing $VTEC$ values derived from TOPEX altimeter data in dependency of time, latitude and longitude. In the different IAACs IONEX files $VTEC$ values for the same times/latitudes/longitudes are interpolated, and the corresponding TOPEX $VTEC$ values are then subtracted. The $VTEC$-differences thus obtained are used to establish different kind of statistics, like mean daily offsets & related RMS values for each IAAC.

3.2.1 Results

Figure 1 below condenses the basic statistics that were obtained from the TOPEX validations since 19 August 2001. The numbers plotted are:

- $mean$ ... mean IAAC $VTEC$ offset with respect to the TOPEX $VTEC$ values, i.e. the mean value over n differences $d = tecval(IAAC) - TOPEXtec$:
$$mean = \sum d/n \ ,$$
- $rms\text{-}diff$ ... RMS of differences:
$$rms_{diff} = \sqrt{\sum d^2/n} \ ,$$
- rms ... RMS of residuals with respect to the mean, set $v = tecval(IAAC) - mean$:
$$rms = \sqrt{\sum v^2/(n-1)} \ .$$

From GPS week 1158 on, the following two statistics parameters are included too (not in Figure 1):

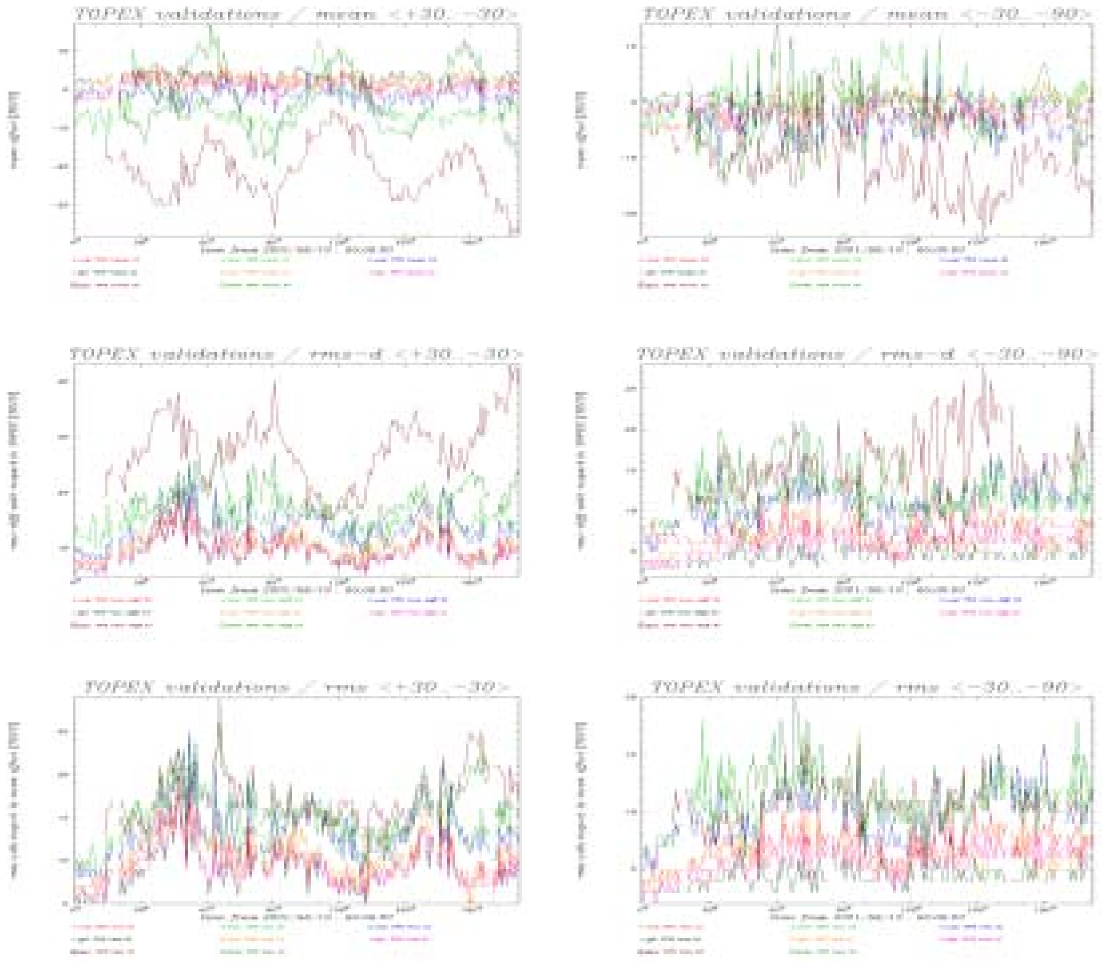
- sf/rms ... estimate of the scale factor of the RMS-values obtained from the TOPEX validation in relation to the corresponding IAAC RMS values, should be close to one for IAAC = IGS, i.e. for the combined TEC maps:
$$sf/rms = \sqrt{\sum \{d/tecrms(IAAC)\}^2/n} \ ,$$
- $wrms$ ... corresponds to a “mean” RMS and might be an indicator for a TEC map’s quality:
$$wrms = \sqrt{\sum \{d/tecrms(IAAC)\}^2/\sum \{1/tecrms(IAAC)\}^2} \ .$$

The TOPEX validations are done globally for all latitudes ("*+90..-90*") and separately also for medium and high northern latitudes ("*+90..+30*"), equatorial latitudes ("*+30..-30*") and medium and high southern latitudes ("*-30..-90*"). Beyond the IAACs *TEC* and the IGS *TEC*, also *TEC* computed with the GPS broadcast model ("*gps*") and *TEC* computed with CODE's Klobuchar-Style Ionosphere Model ("*ckm*") enter into the daily TOPEX validations. The latter two are provided by CODE.

When inspecting the curves in Figure 1 for the different latitude bands one recognizes immediately that the best agreement of the distinct ionosphere models with the TOPEX data is achieved at medium and high northern latitudes, while the worst agreement is in the equatorial region. The agreement in the southern medium and high latitudes is more worse than in the northern ones, but as far as not as worse as in the equatorial latitude band.

The other thing that can be seen from Figure 1 is that the IAACs *TEC* and the IGS *TEC* values, which are derived from GPS dual-frequency data, are considerably closer to the TOPEX *TEC* than the Klobuchar and especially the GPS broadcast model - and what is essential for the delivery of a combined IGS Ionosphere Product: The routine validations with TOPEX since July 2001 show an agreement of the "combined" IGS *TEC* maps with the TOPEX data on the same order as the best IAACs *TEC* maps.

Figure 1: The basic TOPEX validation statistics *mean*, *rms-diff* and *rms*.



cod: *red*, emr: *green*, esa: *blue*, jpl: *black*, upc: *orange*, igs: *pink*, gps: *dark red*, ckm: *dark green*.

Figure 1 (cont.): The basic TOPEX validation statistics *mean*, *rms-diff* and *rms*.

4 OUTCOME FROM THE WORKSHOPS IN DARMSTADT AND IN OTTAWA - RECOMMENDATIONS

On 17-18 January 2002 an IGS/IAACs Ionosphere Workshop was held at ESOC, Darmstadt, Germany. The major target of this workshop was (for the complete list see Feltens, 2002b): To talk about actions still needed to be undertaken before the routine delivery of a combined IGS Ionosphere Product can be started. Apart from that, discussions were made about new research activities to be considered by the Iono_WG, discussions of points which are of vital interest for the Iono_WG within the IGS, implementation of near-real-time availability of Iono_WG products, guarantee of reliability of Iono_WG products.

Based on the conclusions of the Darmstadt workshop (Feltens, 2002b) and on the discussions at Ottawa the following five recommendations were formulated, which shall serve as orientation for the Iono_WG on how to progress - as stated above, the major target is the start of the routine delivery of a combined IGS Ionosphere Product.

Recommendations:

(1) Start with the delivery of a combined IGS Ionosphere Product, as soon as the last required upgrades in the comparison/combination program are made in summer 2002.

(2) Combined IGS Total Electron Content (TEC) and RMS maps should be produced for the even hour numbers, i.e. 0^h, 2^h, 4^h, 6^h, ... , 24^h. In this way the 24^h maps of the previous day correspond to the 0^h maps of the current day.

(3) Global IGS Ionosphere Associate Analysis Centers (IAACs) TEC/RMS maps should cover all parts of the world.

(4) Explore the use of ENVISAT and JASON satellites for validation of IGS Ionosphere Products.

(5) In view of Near Real Time Monitoring of the Ionosphere the distribution of ground stations as well as the data flow (latency) has to be improved.

5 CONCLUSIONS AND OUTLOOK

The Iono_WG started working in June 1998 with the routine provision of daily IONEX files containing global TEC and RMS maps with a time resolution of 2 hours and a daily set of GPS satellite DCB values. Currently five IAACs contribute with their ionosphere products.

For the weekly comparison of IAACs ionosphere products a dedicated algorithm was worked out and coded from scratch at the IACC at ESOC. This “old” comparison algorithm was based on the concept of unweighted and weighted means and provided, so to say as by-product, also something like a “combination” of the IAACs individual ionosphere products. However, the IAACs use very different mathematical approaches and estimation schemes in their ionosphere processing, and this circumstance strongly reflected in the comparison results. The Iono_WG thus decided to upgrade this “old” comparison algorithm with a new weighting scheme using the results of external self-consistency test validations as input. The “new” comparison algorithm is now in operational use since August 2001. An analysis of the results obtained so far shows, that, apart from some minor weaknesses, the new approach seems to meet the demands for the computation of a combined IGS Ionosphere Product.

Additionally, since July 2001, routine validations of the IAACs TEC maps plus the “combined” IGS TEC maps with $VTEC$ values derived from TOPEX altimeter data are attached to the weekly comparisons. The results of these validations show an agreement of the "combined" IGS TEC maps with the TOPEX data on the same order as the best IAACs TEC maps.

Based on the conclusions made at the IGS/IAACs Ionosphere Workshop in Darmstadt, 17 - 18 January, 2002, and on the discussions at Ottawa, five recommendations were formulated on how to do away with remaining minor problems and to bring the Iono_WG soon into a position to start with the routine delivery of a combined IGS Ionosphere Product.

Beyond the realization of the combined IGS Ionosphere Product, goals and next steps are: enhancement of the IGS *TEC* maps time resolution, implementation of rapid products up to near-real-time availability, further validations, e.g. with ENVISAT altimeter data, and inclusion of higher order terms into ionospheric delay corrections modeling.

REFERENCES

Feltens, J., 1998, Chapman Profile Approach for 3-d Global TEC Representation, IGS Presentation, in *Proceedings of the 1998 IGS Analysis Centers Workshop*, ESOC, Darmstadt, Germany, February 9-11, 1998, pp 285-297.

Feltens, J. and S. Schaer, 1998, IGS Products for the Ionosphere, IGS Position Paper, in *Proceedings of the 1998 IGS Analysis Centers Workshop*, ESOC, Darmstadt, Germany, February 9-11, 1998, pp. 225-232.

Feltens, J., 2002a, Résumé of Three Years of Iono_WG Activities and Status of Comparisons & Validations, IGS/IAACs Presentation, in *Collection of Presentations of the 2002 IGS/IAACs Ionosphere Workshop*, ESOC, Darmstadt, Germany, January 17-18, 2002, in preparation.

Feltens, J., 2002b, IGS/Ionosphere Workshop, 17 and 18 January - Conclusions, *IGSMAIL-3711*, submitted on 25 January 2002, also in *Collection of Presentations of the 2002 IGS/IAACs Ionosphere Workshop*, ESOC, Darmstadt, Germany, January 17-18, 2002, in preparation.

Gao, Y., P. Heroux and J. Kouba, Estimation of GPS Receiver and Satellite L1/L2 Signal Delay Biases using Data from CACS, 10 pages.

Hernandez-Pajares M., J.M. Juan and J. Sanz (1999): ‘New approaches in global ionospheric determination using ground GPS data’, *Journal of Atmospheric and Solar Terrestrial Physics*, Vol 61, pp 1237-1247, 1999.

Mannucci, A. J., B. D. Wilson, D. N. Yuan, C. H. Ho, U. J. Lindqwister and T. F. Runge, 1998, A global mapping technique for GPS-derived ionospheric total electron content measurements, in *Radio Science*, Vol. 33, pp. 565-582, 1998.

Schaer, S., W. Gurtner and J. Feltens, 1997, IONEX: The IONosphere Map EXchange Format Version 1, February 25, 1998, in *Proceedings of the 1998 IGS Analysis Centers Workshop*, ESOC, Darmstadt, Germany, February 9-11, 1998, pp. 233-247.

Schaer, S. (1999): ‘Mapping and Predicting the Earth’s Ionosphere Using the Global Positioning System’, *Dissertation*, Astronomical Institute, University of Berne, Berne, Switzerland, 25 March 1999.

CURRENT STATUS OF ESOC IONOSPHERE MODELING AND PLANNED IMPROVEMENTS

J. Feltens
EDS Deutschland GmbH, based at
Navigation Research Office,
ESA, European Space Operations Centre,
Robert-Bosch-Str. 5, D-64293 Darmstadt, Germany

SUMMARY

The ESOC Ionosphere Monitoring Facility (IONMON) software is in operational use since the beginning of the year 1998 for routine IGS ionosphere processing. It employs a 3-dimensional ionosphere model, based on a Chapman Profile approach. However, three years of routine application show certain weaknesses and limitations of this algorithm:

- The ionosphere is a rapidly changing medium. ➔ *The current 24 hours time resolution must be enhanced with a sequential estimate processor: Establishment of normal equation systems with a certain time resolution, say 1 hour, and estimation of the ionosphere model parameters on one hand and of the Differential Code Biases ($DCBs$) on the other hand from this basic set of normal equations in different ways*
- The current mathematical model describes the vertical electron density distribution as only one layer. ➔ *The ionosphere must mathematically be described as superimposion of different layers.*
- From pure Total Electron Content (TEC) observables it is difficult to estimate profile shape parameters. ➔ *Electron density profiles derived from Champ occultation data will be introduced as additional observables to allow for a better spatial resolution.*

To improve performance, modifications are currently ongoing into the following directions:

- Enhancement of the time resolution for ionosphere fits.
- Modified $TEC/DCBs$ estimation scheme plus computation of $TEC\ RMS$ maps.
- Software tool to predict the ionosphere's state.
- Inclusion of other observation types than TEC data, namely Champ occultation profiles.
- Improvement of mathematical modeling into several directions (composition of several layers, alternative profile functions, α-layer handling, correction for the plasmasphere, height-dependent Scale Height).
- Availability of the improved ionosphere models through an upgraded external user interface.
- Inclusion of higher order terms (in the medium-term).

At the current stage of work the new algorithms are completely worked out, coded and compiled. In the next step they must be unit-tested and validated and then be implemented into the operational IONMON software. It is hoped that these different kinds of modification will lead to an improved routine ionosphere processing at ESOC.

Brief summary of UPC ionospheric activities

M. Hernández-Pajares, J.M. Juan, J. Sanz, M. García and R. Orús
gAGE/UPC, Barcelona, Spain (contact e-mail: manuel@mat.upc.es)

The authors report several ionospheric activities with GPS data, including those of IGS stations: the daily generation of global TEC maps, the development of new algorithms for real-time ionospheric corrections and for electron density retrieval. Let's describe them briefly:

The generation of **TEC Global Ionospheric Maps** (GIM's), from IGS data as an IGS Associate Analysis Center, are being done and delivered to the IGS community on a daily basis from June 1st 1998 (some details of the technique are described in *Hernández-Pajares M., J.M. Juan and J. Sanz, New approaches in global ionospheric determination using ground GPS data, Journal of Atmospheric and Solar-Terrestrial Physics, Vol 61, 1237-1247, 1999*). Moreover, since 2001, weights for the 5 different IAAC's involved in GIM's computation are being generated on a weekly basis as a function of the RMS for STEC predictions over a certain subset of IGS stations. This is done as one IGS Associate Validation Center (IAVC).

In order to improve the capability of computing **accurate ionospheric corrections in real-time**, we have developed a new technique combining a tomographic modeling of the Ionosphere with an accurate geodetic computation, which allows to improve the performance of both ionospheric and navigation software (*Hernández-Pajares M., J.M. Juan, J. Sanz, O.L. Colombo, Application of ionospheric tomography to real-time GPS carrier-phase ambiguities resolution at scales of 400-1000 km and with high geomagnetic activity, Geophysical Research Letters, Vol 27, No 13, 2009-2012, 2000*). The performance of this approach for fixed GPS sites separated several thousands of kilometers has been tested over four consecutive weeks in hard ionospheric conditions and over a wide range of latitudes crossing the equator (*Hernández-Pajares M., J.M. Juan, J. Sanz and O. Colombo, Improving the real-time ionospheric determination from GPS sites at Very Long Distances over the Equator, Journal of Geophysical Research - Space Physics, In Press , 2002*).

The last but not the least, in the context of the existing and incoming GPS receivers on board Low Earth Orbiters with antennas pointing to the Earth limb (CHAMP, SAC-C,...), the authors have developed **algorithms to improve the electron density estimations**. They are based on modeling the horizontal gradients of the electron content with a TEC model, that can be computed from IGS fixed sites. The new technique also takes into account the topside electron content, specially in very low satellites such as CHAMP (*Hernández-Pajares M., J.M. Juan, J. Sanz, Improving the Abel inversion by adding ground data LEO radio occultations in the ionospheric sounding. Geophysical Research Letters, 27, 2743-2746, 2000*). Moreover, we have applied new schemes combining complementary kind of data in the common framework of a tomographic voxel model, such as ground GPS and ionosonde which can provide a similar performance as the use of LEO GPS occultation data.

CODE Ionosphere Products

Stefan Schaer
Astronomical Institute, University of Berne, Switzerland
`stefan.schaer@aiub.unibe.ch`

Abstract

The list of ionosphere products as regularly generated at CODE includes final, rapid, as well as predicted products. The vertical total electron content (VTEC) is modeled in a solar-geomagnetic reference frame primarily using a spherical harmonics (SH) expansion up to degree and order 15. To convert line-of-sight TEC into vertical TEC, a modified single-layer model mapping function approximating the JPL extended slab model mapping function is adopted (to retrieve VTEC consistent to TOPEX-derived TEC). No external ionosphere model is used.

The global ionosphere map (GIM) information is made available generally in three different forms: (1) Bernese ionosphere files containing the originally estimated SH coefficients, (2) IONEX (IONosphere map EXchange) files containing VTEC grid maps at 2-hour intervals, and (3) content-reduced RINEX navigation data files containing daily Klobuchar-style ionospheric (alpha and beta) coefficients best fitting the (corresponding) IONEX information. In the CODE data archive, time series of all these products are accessible without any gaps back to 1995 (see `www.aiub.unibe.ch/ionosphere.html` for details). Solely the final product in IONEX format is delivered to the IGS. For comparison purposes, also our final Klobuchar-style model and the ionospheric model broadcast by the GPS system are supplied by CODE in form of IGS-compatible IONEX files. It is worth mentioning that, starting with GPS week 1158, our final ionosphere results are no longer results from a 24-hour analysis but results for the middle day of a 72-hour combination analysis done on the normal equation level. In this way, discontinuities at day boundaries can be minimized and a time-invariant quality level is achieved.

The new possibility to stack and manipulate GIM-related normal equations takes us a lot further towards producing a GPS/TOPEX-combined ionosphere product. The IGS policy with respect to "combined" products, specifically combinations with non-GPS/GLONASS data, has to be reviewed.

IGS IONEX files contain 12 VTEC maps for times 01:00, 03:00, 05:00, ..., 23:00 UT. This circumstance makes the interpolation between 23:00 and 01:00 UT difficult, especially for users interested in TEC information without discontinuities at day boundaries. Consequently, we propose to start to include 13 maps in IONEX files, referring to epochs 00:00, 02:00, 04:00, ..., 24:00 UT.

Instrumental biases, so-called differential P1–P2 code biases (DCB), for all GPS satellites and ground stations are an important by-product of the ionospheric analysis. They are estimated at CODE as constant values for each day, simultaneously with the parameters used to represent the global VTEC distribution. The DCB datum is defined by a zero-mean condition imposed on the satellite bias estimates. P1–C1 bias corrections are taken into account if needed. Latter corrections are routinely generated at CODE in the global satellite and station clock estimation procedure and newly as part of the final widelane ambiguity resolution step (on the basis of ambiguity-fixed double differences related to the Melbourne-Wübbena linear combination of code and phase measurements). Sliding 30-day averages of both P1–P2 and P1–C1 DCB retrievals are computed every day. At the end of each month, month-specific averages are produced and stored in our DCB data base. P1–C1 DCB files specific to the CC2NONCC utility program are offered.

For global ionosphere mapping in particular, a good GPS tracking station coverage is indispensable. Against this background, we could show that there is still much potential in improving the IGS data availability and latency, respectively. These problems actually concern final and principally rapid and ultra-rapid applications. Moreover, data from very remote stations (typically tide gauge stations) not yet meeting the few-day delay requirement might be utmost useful, not only for IGS ionosphere mapping but also for global orbit and clock determination.

IGS

SESSION 6:

LOW EARTH ORBITER

IGS LEO Position Paper for IGS Workshop Ottawa 2002-04-02

1 *Introduction*

The release of the CHAMP data in May last year has initiated the first concrete projects for the IGS LEO Pilot Project. Experience with CHAMP data processing shows that priorities have evolved since the initial call for participation for the Pilot Project. At the same time, the concrete objectives for the Pilot Project were never clearly formulated, which leads to some confusion among participating centres. To correct this and to set a clear set of objectives for the future, this position paper will summarise the development of IGS LEO until now, and then outline the planned development of IGS LEO activities.

The first part of the paper summarises the history and current status of the IGS LEO activities. The second part of the paper is formed by an IGS LEO charter, according to IGS Central Bureau policy. This charter should help to focus the activities of the Associate Analysis Centres around the principal objectives of the IGS LEO Working Group.

2 *Brief history of IGS LEO*

In order to provide the background to the current IGS LEO status, the most relevant steps in the development of the IGS LEO Pilot Project are indicated here below.

- March 1999 Potsdam workshop recommendations:
    1. **Ground station standards** for LEO stations sub-network
    2. IGS should develop **new rapid produc**t with < 3 hrs latency
    3. An efficient **1-hz ground data format** should be developed
    4. A **pilot project** for the use of flight receiver data should be initiated

These recommendations were accepted by the IGS GB in the La Jolla meeting (June 1999).

- January 2000 Call for participation (IGS MAIL 2669)
    1. For **GPS stations**, to provide global (sub-)hourly data and/or high-rate data
    2. For **Data centres**, to move towards (sub-)hourly POD and to provide high-rate and LEO flight receiver data
    3. For **LEO AAC**, to demonstrate LEO POD, to investigate potential improvements to classic IGS products
    4. For **Coordinator(s)**, to coordinate development, comparison, QA of new products, to assess requirements for LEO incorporation, to assess impact LEO on IGS products
    5. For **IGS analysis centres**, to develop capabilities for (sub-)hourly processing

- February 2000 Scheduled date for LEO standards outline

No formal standards have been published, essentially because practical experience with LEO data processing was not really available until after the launch of the first LEO satellites.

- April 2000 LEO proposals deadline

26 Proposals were sent in, roughly distributed as follows (note: some proposals relate to more than one of the addressed issues):

1. Ground stations	13
2. Data centres	3
3. LEO AAC	10
4. Coordinator	0
5. IGS AC	4

- February 2001 LEO Working Group Meeting, Potsdam
    1. Installation of IGS LEO mailing list
    2. Call for station plans
    3. Some suggestions on data formats (RINEX, SP3 extensions)

- May 2001 Release of CHAMP data

This effectively forms the moment at which concrete LEO GPS processing can start. Most earlier analysis was limited to incidental studies, using limited data sets with experimental status.

- May 2001 ESOC takes on role of IGS LEO AAC Coordinator

- June 2001 Inquiry after CHAMP POD processing status among AAC

Main conclusion : CHAMP POD is still very immature because of limited data availability so far. Many practical questions need to be answered regarding CHAMP data processing, only the mission centres (GFZ, CNES, JPL) have adequate LEO processing capability.

- July - Sep 2001 CHAMP POD implementations at the AAC

Installation of CHAMP web pages at ESOC in support of POD efforts.

- September 2001 Call for contributions to CHAMP POD campaign

- October 2001 CHAMP user meeting, Potsdam

This meeting aimed at solving various practical issues related to CHAMP processing at the AAC. It was well attended, a summary of conclusions is available through the ESOC LEO webpages

- Nov-Dec 2001 First results of the POD campaign

The Campaign results are published through the ESOC LEO webpages. The participating AACs are in a phase of continuous improvements in LEO POD, with precision levels gradually approaching 10 cm.

- January 2002 First CHAMP Science Meeting,

The IGS LEO session during this Meeting provided the following conclusions:

1. Different views exist on the future development of IGS LEO. A clear scope of the project and a set of objectives should be formulated.
2. LEO data availability and CHAMP POD are improving rapidly and no longer form the main blocking problem for progressing with LEO GPS analysis. JASON data is expected shortly.
3. Some form of continuation project for the CHAMP Orbit campaign should be organised

- Since January 2002 Ongoing improvements in analysis capability

A majority of the AACs contribute updates to their CHAMP campaign results. New gravity fields (EIGEN) and improved estimation methods are bringing CHAMP POD below the 10 cm level.

Inquiry among the AACs after combined LEO + GPS analysis capability suggests that a very small number of centres can already do this.

- April 2002 IGS Workshop Ottawa

First presentations on combined LEO + GPS analysis. Proposal of IGS LEO charter to focus activities. Proposal for concrete projects for spring / summer 2002

3 Current status of IGS LEO

GPS stations	• GFZ+JPL stations network provides 10-second data, but not at short latency (~ 1 week delay for public users) • IGS LEO proposals regarding ground stations have not been used so far • Need for high-rate data in relation to LEO is unclear Status: high-rate data (... 10 seconds) is available for analysis but not yet for short-latency operational use.
Data centres	• GFZ ISDC and JPL Genesis provide CHAMP FR data (~24 hr latency) • JPL Genesis also provides SAC-C data • LEO orbit repository established at CDDIS • JASON, GRACE expected shortly (...?)

	Status: available data is adequate for analysis purposes. For operational LEO processing, latency may have to be reduced to several hours. For (ultra) rapid LEO data processing, AC should have access to data immediately after LEO telemetry download, or via data relay satellites. For the current generation of LEO satellites this is probably unrealistic.
AAC for LEO project	• CHAMP POD has made substantial progress since data release, best available solutions are now around 6 - 8 cm • Capability for dynamic solutions in combined analysis with GPS: only at a small number of centres (GFZ, JPL, CSR, AIUB, TUM ?) • Combination analysis LEO + GPS is at the starting point
Coordinator	• AAC Coordinator is Henno Boomkamp at ESOC, since may 2001
IGS AC	• From the four centres with LEO+GPS capability, three are IGS AC • IGS Coordinator has suggested that 4 AC would be desirable in operational use. • ESOC, as a fourth AC, is in the process of implementing dynamic LEO+GPS combination solutions

4 IGS LEO charter

Here below follows the finalised version of the IGS LEO charter, which aims at providing a framework for the future activities of the IGS LEO Pilot Project. It includes a series of concrete projects on the basis of CHAMP, JASON and GRACE data.

The charter has been composed on the basis of the following inputs:

- The proceedings of LEO workshops in Potsdam since 1999, including the conclusions of the IGS LEO session during the CHAMP Science Meeting 2002.
- Various IGS mails related to the IGS LEO working group
- The call for participation in IGS LEO activities (IGS MAIL 2669)
- The proposals that were received in reply to the call for participation
- Practical experience with CHAMP processing, gained since release of the data in May 2001
- Personal communication

IGS LEO Pilot Project Charter

1 Goals

In general terms the objectives of the IGS LEO Pilot Project can be stated as follows:

1. To reach adequate understanding of the potential benefits of LEO flight receiver data for the enhancement of IGS products.

2. To develop the means that are necessary for reaching this understanding.

3. To identify the means that would be needed for making use of the benefits of LEO flight receiver data in eventual operational IGS processing.

The order in which these objectives are stated could suggest a natural order to proceed, but in practice these goals can not be strictly separated. Furthermore, the initial analysis may lead to the conclusion that further implementation of IGS LEO will not be relevant, or would require an effort that is not justified by the gain. This decision will be taken by the IGS Governing Board after presentation of the IGS LEO Pilot Project report.

In order to provide a basis for initiating concrete activities within the Pilot Project, the abstract objectives above will be reformulated in terms of more practical goals.

1.1 Assessment of the benefits of LEO data

All potential benefits of LEO data originate in the physical differences between GPS data received by an orbiting receiver and data received by a ground station. To arrive at a clear and complete assessment of potential benefits of LEO data to IGS, it will be helpful to be fully aware of these differences.

Goal 1	To establish and maintain a clear listing of all differences between LEO flight receiver data and terrestrial GPS data.

Any difference may bring an advantage or it may pose a problem; both aspects need to be taken into account. As a starting point a list of fundamental differences is provided in Annex A. This listing does not pretend to be complete, but provides a basis for the rest of this charter. The identified differences refer to tracking geometry, atmospheric delays, data flow and data processing. The first two affect the IGS output products, while the latter two affect the way in which these products are generated. This first Section will set the practical goals regarding the output products, the means of processing are discussed in Section 1.2.

Three of the classical IGS products can be expected to benefit from the properties of the LEO *tracking geometry*, namely GPS POD, GPS clocks, and EOP data. This sets a clear goal for the Pilot Project:

Goal 2	To compare GPS orbits, clocks and EOP parameters as generated by routine IGS operations for cases with and without the inclusion of LEO data in the analysis. The comparisons should be performed for a representative period of time, and should be done at the level of the IGS output products.

Before this comparative analysis can be performed several intermediate objectives have to be met. In particular, a representative number of Analysis Centres must be capable of including LEO data in their processing, and the quality of the LEO processing must be compatible with the precision levels of the IGS products. This leads to two further goals:

Goal 3	To develop the capability for combined LEO + GPS data processing at a representative number of Analysis Centres.

Goal 4	To improve the processing of LEO flight receiver data at points where available processing systems still prevent a positive impact of LEO data on IGS products.

These two goals will have been met, for any individual Analysis Centre, as soon as it is demonstrated that the inclusion of LEO data is beneficial at the level of the outputs from that particular Analysis Centre. Goal 4 will in particular relate to improvements in LEO POD, but may not be limited to that. A 'representative number of ACs' will be interpreted as four or more of the ACs.

The IGS troposphere product - and an eventual future ionosphere product - can benefit from the absence of *atmospheric delays* in LEO flight receiver data, or from the presence of other LEO tracking data in a combined solution with GPS. This leads to one further analysis goal:

Goal 5	To compare the IGS troposphere product for cases with and without LEO data, with the aim of analysing benefits that may be obtained 1. from LEO-based GPS observables, e.g. difference data for a LEO that passes through the line of sight between a ground station and a GPS satellites 2. from the inclusion of other LEO tracking data types, e.g. DORIS or SLR, in

	simultaneous processing of GPS and LEO satellites

1.2 Assessment of required means of processing

The other two fundamental differences in Annex A are the LEO data flow and the processing of LEO data at IGS centres. Both topics have an impact on the way in which IGS analysis centres operate. The relevant LEO processing capabilities can be separated in two categories:

1. The means that are required for doing analysis within the IGS LEO Pilot project itself.
2. The means that would be required for processing LEO data in an eventual operational scenario.

The differences between the two are mainly related to data latency and product latency: the Pilot Project analysis can be done with past data, while in nominal IGS operations the actual delays have to be taken into account.

Correcting the deficiencies in the first category must be part of the Pilot Project itself, otherwise the analysis can not be completed. The shortcomings in the IGS infrastructure for operational use of LEO do not have to be *corrected* during the Pilot Project, but they must be clearly *identified* as part of the Pilot Project. This, to ensure that the final decision on operational use of LEO data can be taken on the basis of adequate knowledge of the effort that will be required.

Goal 6	To establish and maintain a list of required analysis capabilities for using LEO data in IGS processing.

Goal 7	To monitor the existing processing capabilities, compare them with the required analysis capabilities, and take steps to correct deficiencies for as far as necessary for completion of the Pilot Project analysis.

Goal 8	To extrapolate the processing requirements that emerge during the Pilot Project into a set of conditions for operational implementation of LEO data in IGS processing.

2 IGS LEO Pilot Project structure

The following organisational elements are identified:

1. *IGS LEO Associate Analysis Centres*
   The Associate Analysis Centres are the research institutions that contribute to the Pilot Project analysis in any way. Initially, the IGS LEO AACs were the centres of which a proposal was accepted by the IGS Governing Board after the call for proposals. In the course of time, some aspects of the call for proposals have lost priority so that some centres have not (yet) contributed any results. At the same time some new centres have in fact contributed results and have become AACs at the discretion of the AAC Coordinator. This means that the list of active AACs is not in agreement with the list of accepted proposals. An overview of AACs is provided in Table 2.1, indicating which centres have contributed so far and are considered 'active' AACs.

2. *IGS LEO AAC Coordinator*
   The AAC Coordinator is the point of contact for the AACs during their participation in Pilot Project analysis. The Coordinator contacts the AACs with requests for concrete contributions, and combines these contributions into Pilot Project analysis results. These results form part of the conclusions that will be presented to the IGS Governing Board at the end of the Pilot Project.
   The AAC Coordinator since May 2001 has been Henno Boomkamp (ESOC).

Acronym	***Centre***	***ctr***	***igs***	***Proposal***			
				1	***2***	***3***	***4***
AIUB	Astronomical Institute, University of Bern	X	X	X			
ASI	Agenzia Spaziale Italiana, matera	X			X		
AUSLIG	Australian Surveying and Land Information Group						X
CDDIS	Goddard Space Flight Centre	X				X	
CISAS	Centre for Space Studies, University of Padua			X	X		
CNES	Centre National d'Etudes Spatiales, Toulouse	X		X	X		
CSR	Centre for Space Research, University of Texas	X		X			
DEOS	Delft institute for Earth Oriented Space Research	X					
ESOC	European Space Operation Centre	X	X	X			
GFZ	Geo Forschungs Zentrum, Potsdam	X	X	X	X	X	
GRGS	Groupe de Recherche de Geodesie Spatiale, Toulouse	X		X			
ICC	Cartographic Institute of Catalunya				X		
ISTRAC	Indian Space Research Organisation			X	X		
JCET	Joint Center for Earth Systems Technology, Maryland						X
JPL	Jet Propulsion Laboratory	X	X	X	X	X	
KAO	Korean Astronomy Observatory				X		
KMS	National Survey and Cadastre, Denmark				X		
NCL	Newcastle University	X					
NERC	UK Space Geodesy Facility				X		
NRCAN	Natural Resources of Canada		X		X		
OSU	Ohio State University			X	X		
RIG	Research Institute of Geodesy, Czech Republic				X		
SK	Norwegian mapping Authority						X
TUM	Technical University of Munich	X					
UCAR	University Consortium for Atmospheric Research	X					
UNB	University of New Brunswick	X		X			
USNO	US Naval Observatory		X		X		X

Table 2.1 : Associate Analysis centres of the IGS LEO Pilot Project.
Column ***ctr*** indicates those centres that have contributed analysis results, or participate in other ways.
Column ***igs*** indicates those centres that are also IGS Analysis Centres.
The proposal subjects are indicated as follows: 1 = LEO POD, 2 = high rate / short latency ground station data, 3 = data centre, 4 = other

3 *Working plan*

Regarding the objectives in Sections 1, the working plan of the IGS LEO Pilot Project consists in general terms of the following:

- To make sure that the necessary conditions for performing the Pilot Project Analysis are met. This is a continuous activity during the Pilot Project, and is the responsibility of the AAC Coordinator.
- To organise a series of projects that will step by step achieve the analysis goals from Section 1.1.
- To integrate the analysis results into a report to the IGS Governing Board, and in parallel derive the requirements for operational implementation of IGS LEO.

3.1 Succession of analysis projects:

1. With the arrival of LEO data for a new satellite, to organise a POD campaign to assess the POD status for this particular LEO, and to provide external reference orbits for AACs.
   External conditions:
   - Release of flight receiver data for the LEO to a substantial number of AACs.
   - POD capability at a substantial number of AACs.

   Start of project:
   - As soon as the external conditions are met.

   Duration of project:
   - First analysis results should be available within two months after the start of the campaign.
   - Incidental later contributions, for instance updates after modifications of the POD system at an AAC, will still be processed until the end of the Pilot Project.
   - The final report of the Pilot Project will contain the most recent POD contributions for all considered LEO satellites.

2. To organise analysis projects for combined LEO + GPS analysis at any AAC that has this capability (not necessarily limited to IGS Analysis Centres). These projects will concentrate on one of the technical issues at which benefits from LEO data are expected, and will demonstrate the impact of LEO data on the outputs of a single Analysis Centre. In parallel, these projects will help to consolidate the required analysis capabilities discussed in Section 1.2.
   External conditions:
   - Capability for combined POD analysis for GPS + LEO at a reasonable number of centres.

   Start of project:
   - Expected for spring - summer 2002

   Duration of projects
   - The projects should be completed towards the end of 2002.

3. To demonstrate that LEO data can have a beneficial impact on the individual outputs from at least four individual IGS Analysis Centres.
   External conditions:
   - Capability for combined LEO + GPS processing at precision levels that are relevant to IGS, at four or more IGS Analysis Centres.

   Start of project:
   - As soon as four Analysis Centres have reached the required capabilities. Expected around August / September 2002.

   Duration of project:
   - The Analysis Centre should produce its contributions to IGS for a representative period of time while including LEO data, in parallel to its normal IGS contributions which do not include the LEO data. The time required to generate these extra outputs may differ per AC, but a period of one month can be assumed to prepare LEO-based outputs for one week.

4. To demonstrate the impact of LEO data on the classical IGS products in combination solutions.
   External conditions:
   The demonstration 3 has been completed by four individual ACs
   Start of project:
   Autumn 2002

Duration of project:
The processing of the data will have to take place in parallel to normal IGS operations. Similar to these separate demonstrations, a period of one month can be assumed for covering a test period of one week.

5. Monitoring of the processing requirements is a permanent task of the AAC Coordinator. The required information is maintained on the basis of the analysis results that are provided within the other projects.

Anticipated duration of the Pilot Project

Progress within the IGS LEO Pilot Project is conditioned by many external factors, notably the availability of LEO data and the development of analysis capability at the AACs. However, it is reasonable to assume that the combination of the satellites CHAMP, JASON and GRACE A/B forms a representative basis for LEO availability to future IGS operational use. Adequate LEO + GPS analysis capability is expected to be available in the course of the year 2002. The planned Pilot Project activities can probably be concluded within 6 months after release of the flight receiver data for JASON and GRACE.

4 Initial ideas for an operational phase

The analysis that is foreseen to achieve the Pilot Project goals will be a reasonable reflection of the way in which operational IGS LEO analysis would take place. The main reason for this situation is that the number of centres that can be expected to do full LEO + GPS analysis is very limited, while the impact of LEO data on the combination solutions must be part of the demonstration. From the five centres that can be expected to have reached this capability during the course of the Pilot Project (JPL, GFZ, CSR, AIUB, ESOC), all but CSR are also IGS Analysis Centres. This means that by the time that the goals of the Pilot Project have been achieved the operational IGS LEO processing environment will have been implemented almost completely.

In the operational phase, the four (or more...) ACs that have LEO+GPS capability will routinely include the processing of LEO data in their IGS processing. Some additional monitoring activities will be needed to ensure stability of the LEO-based products. Furthermore, the processing should not become dependent on the availability of LEO data. In absence of the LEO data, for whatever reason, the IGS products must still be generated by the ACs that will have incorporated the LEO data.

5 Further comments

What is absent from the scope of the Pilot Project is the organisation of the LEO data flow under operational conditions. Furthermore, with respect to the initial call for proposals the concepts of high-rate station data and / or short latency station data have been excluded from this IGS LEO charter. These topics are considered to be related to IGS network operations rather than being particular to LEO missions in any way.

Most LEO flight receiver data will typically have a latency that is at least one orbital revolution larger than the latency of ground-based GPS data, due to the fact that the LEOs normally have only one data dump per orbit. At present the CHAMP data is available one week after real time, which would clearly exclude its use for the IGS rapid products. Nonetheless, the Pilot Project should not be limited by such considerations. If it can be shown, on the basis of past data, that short-latency LEO data brings substantial benefits, reasonable co-operation from the LEO mission management may be expected.

Annex A - Fundamental differences between LEO GPS data and ground based GPS data

1. The *tracking geometr*y between LEO flight receivers and the GPS constellation is different than for ground-based GPS receivers:
   - The LEO-GPS tracking geometry changes more rapidly with time, providing improved decorrelation between tracking observations over a given period in comparison to ground data.
   - The LEO data covers geographical areas where few ground-based stations are available, i.e. the oceans or central Africa. This can be beneficial in the construction of double difference combinations or in other analysis that involves common view geometry.
   - Baselines involving LEO receivers can be longer than between ground-based receivers. This improves the dilution of precision for the GPS tracking configuration and can therefore be beneficial to GPS POD.
   - The differences between LEO orbits and GPS orbits imply that in simultaneous dynamic POD solutions for LEO and GPS the typically high inclination of LEO orbits can improve the observability of EOP data.

2. The *troposphere and ionosphere* delays for the LEO are different than for ground stations:
   - For tracking data above a certain elevation, no troposphere and ionosphere delays occur on the line of sight between a LEO and a GPS satellite
   - Below a given elevation LEO occultation data is produced which may be useful for augmenting IGS troposphere and / or ionosphere products.

3. The *data flow* between receiver and analysis centres is different for a LEO or for a ground station.
   - LEO data is downloaded from the satellite to a telemetry ground station, from where it will typically enter a terrestrial data network like the data from any other IGS station. However, the data download takes place at discrete moments, when the LEO is in view of the involved telemetry ground station. This adds the duration of one or more orbital periods to the LEO flight receiver data latency.
   - The monopoly position of the telemetry ground stations implies that for LEO implementation in IGS the full co-operation of the LEO mission management will be a precondition, especially in near real-time applications.

4. The *processing* is different for LEO data and for terrestrial GPS data
   - For terrestrial GPS, a priori station positions are available with good precision and typically the station co-ordinates are not solved within the solution process. For the LEO, the orbital position needs to be solved within the IGS processing loop, or needs to be provided from LEO POD centres. The latter will add to the LEO data latency.

Impact of Different Data Combinations on the CHAMP Orbit Determination

S. Zhu, H. Neumayer, F.H. Massmann, C. Shi and Ch. Reigber

GeoForschungsZentrum Potsdam (GFZ) Telegrafenberg 14473 Potsdam, Germany
Div. 1: Kinematics and Dynamics of the Earth

Abstract

For the orbit determination of the CHAMP satellite three data sets are of major importance: GPS, satellite laser ranging and the accelerometer observations. The first two can be used independently for the orbit restitution, while the third one can only be used in combination with another data type(s). Different combinations of these data types (such as GPS only; SLR only; GPS plus accelerometer; GPS plus SLR, GPS plus SLR plus accelerometer; etc.) are tested for the POD. The aim is to investigate the usefulness and contribution of each data type and to study the advantages and weakness of various data combination procedures.

As far as the GPS-SST data is concerned, one can either fix the GPS orbits (and clocks) determined by using GPS data from ground stations, and restitute the CHAMP orbit alone (we call it two-step method), or combine ground and SST-GPS data together to determine the orbits of CHAMP and GPS satellites simultaneously (one-step). Following example shows a slight improvement of the CHAMP orbit by using the one-step method. (40 ground stations data are used, unit cm)

Method	GPS-SST data	Residual: code-phase	SLR residual
1-step	15441	91.1-0.82	5.6
2-step	15134	74.2-1.56	6.0

Theoretically, one-step method should give more consistent and homogeneous solutions for both CHAMP (LEO) and GPS satellites, since different type (e.g. altitude) satellites have their own strength and weakness. Combined solutions overcome in an optimal way the weakness of each. In ultra-rapid case, if only observations from about 20 ground stations are available, one does see perceptible quality improvement for both LEO and GPS orbits by adopting one-step method. In usual case the number of ground stations are much large, adding the data from one LEO satellites could not affect the GPS solution significantly. Our future plan is to see, whether apply one-step method for three LEO (CHAMP plus two GRACE) simultaneously could contribute to the GPS products more significantly.

LEO Processing Status at AIUB

Urs Hugentobler, Heike Bock, Gerhard Beutler

Astronomical Institute, University of Bern, Bern, Switzerland

In a first part the status of the determination of LEO orbits at the AIUB in the framework of the IGS LEO Pilot Project is illustrated followed by showing results from first simulations of a combined processing of GPS and LEO orbits in a second part.

Current approaches are based on zero-difference processing. An efficient procedure was developed for generating high rate (30-second) GPS satellite clock corrections based on phase differences. The phase clocks are constrained to the 5-min-clocks provided by CODE to the IGS.

A very efficient approach to reconstruct the trajectory of a LEO (or any moving receiver) is the use of epoch-wise differences of the phase eliminating the phase ambiguities. Code observations are used to get the absolute location of phase-connected orbit pieces. At epochs where no phase difference is available, e.g. due to a receiver reset, a jump in the trajectory may occur whose magnitude depends on the pseudorange accuracy. The neglected correlations between epochs reduce the obtained orbit accuracy compared to a solution based on zero- or double differences. Comparison of CHAMP kinematic orbits to the best available reduced-dynamic orbits show an RMS difference around 30 cm.

Kinematic positions estimated using code observations and position differences derived from phase epoch-differences may be used as pseudo-observations with their respective weight for the determination of a dynamic or reduced-dynamic orbit. Orbits obtained with this two-step approach show an RMS difference of about 15 cm with respect to the best CHAMP orbits.

One of the aims of the IGS LEO Pilot Project is the evaluation of a possible gain of a combined processing of GPS and LEO orbits for the classical IGS projects. An improvement could, e.g., be expected for the geocenter coordinates. The orbit of the LEO may gain from a fully consistent treatment of the high and low orbits. Results for TOPEX (Rim et al., 1995) show a minor improvement of the LEO orbit for a combined processing. Given todays precision of the IGS GPS orbits these results may, however, no longer be valid. (Visser et al., 2002) found indication for a degradation of the high orbits induced by modeling problems of the LEO. At this IGS Workshop S. Y. Zhu, on the other hand, showed results indicating a slight improvement of orbit results.

Using simulations we found a small decrease of the formal position accuracies for the GPS orbits by the introduction of a LEO into the double-difference processing in alongtrack and crosstrack direction. In parallel an improvement in the formal precision of the pole coordinates was found. Both results indicate a gain in the reference frame realization. Condition is that the dynamic orbit modeling for the LEO is good enough.

In view of the significant load added by the adding of LEOs to the IGS processing, in particular for double-differences, only a clear improvement of products can convince IGS Analysis Centers to introduce LEO satellites into their processing. More studies, therefore, are required.

Rim, H. J., B. E. Schutz, P. A. M. Abusali, B. D. Tapley (1995): 'Effect of GPS Orbit Accuracy on GPS-Determined TOPEX/POSEIDON Orbit', In Proceedings of ION GPS-95, 613-617, September 12-15, 1995.

Visser, P. N. A. M., . van den IJssel (2001): 'GPS-Based Precise Orbit Determination of the Very Low Earth-Orbiting Gravity Mission GOCE', Journal of Geodesy 74, 590-602.

LEO Activities at CSR - B. Schutz (CSR)

(Summary by Henno Boomkamp)

Even though CSR participation in IGS LEO may be mainly due to their involvement in the LEO missions, solid experience with GPS based POD is available at CSR and the presented results for CHAMP are clearly among the most precise solutions. The CSR POD method for CHAMP is typically a dynamic solution based on high-degree gravity field solution like TEG4. A strong parametrisation allows for absorbing remaining modelling errors. Solutions based on different GPS-based tracking observables were presented. Analysis methods at CSR include comparisons of SLR results between internal and external POD solutions, and separate analysis of high elevation SLR measurements to obtain insight in the radial orbit error. The correct observation was made that as soon as a certain level of orbit precision has been reached, it is no longer possible nor very relevant to conclude that one POD solution would be more precise than another. Current precision levels of 5-8 cm RMS should be considered adequate for starting further IGS LEO projects.

Comparison of Kinematic and Reduced Dynamic CHAMP Orbits Using Zero and Double Differences

M. Rothacher (TUM) - (Summary by Henno Boomkamp)

A variety of approaches to CHAMP POD have been studied at TUM. Differences are in modelling, from kinematic to reduced dynamic, and in the GPS observables that are involved in the solutions. Notable are in particular a method for fine ambiguity resolution from differences between epochs, leading to very clean phase observables, and the generic satellite-independent nature of the presented methods. From orbit comparisons with internal and external solutions, some typical behaviour of kinematic solutions could be confirmed. The most precise TUM results are obtained with a reduced dynamic, fine-ambiguity resolution method, but unfortunately this brings a very high computational load.

SESSION 7:

REFERENCE FRAME

REGIONAL NETWORKS DENSIFICATION

Ferland R., Altamimi Z., Bruyninx C., Craymer M., Habrich H., Kouba, J.

ABSTRACT

The core IGS products include a consistent set of station coordinates/velocities, earth rotation parameters (ERPs); GPS satellite orbits and station/satellite clock estimates. These products are generated from the weekly contributions of seven Analysis Centers (COD, EMR, ESA, GFZ, JPL, NGS and SIO). The final station coordinates, ERPs and precise satellite orbits are made available weekly with about two weeks delay after the GPS code and phase measurements are collected. The core products are currently aligned to the IGS realization of ITRS. The agencies generating solutions for regional networks have been using the IGS precise orbits and in some cases ERPs and clock estimates for their work. The reference frame realized by the precise orbits is implicitly used for regional network computations. The orbits, code/phase measurement noise level as well as the processing strategy, impose some limitations on the alignment of the regional networks densification to the ITRF. The resulting reference frame of the regional network, although close to the ITRF, requires some additional considerations. Several methods are available for the regional network densification. Some are presented here and proposed.

The case of the local networks is not specifically discussed here. It is assumed that the responsibility for local network lies either with regional or national agencies. However, the densification approaches discussed here for the regional networks are also likely applicable to local networks.

INTRODUCTION

There has been a need for geodetic network combination/densification/integration since the early days of traditional surveying. In fact, this was a primary incentive to the creation of the IGS itself. International Association of Geodesy (IAG) has also been interested in this subject for a long time, e.g. within Section I through Commission X on Global and Regional Geodetic Networks. Although the scope of Commission X is much broader than that of the RFWG, there are some common objectives when it comes to ITRF densification. Each Sub-commission of Commission X has a continental scope and their interest is not limited only to GPS, although it is undeniably the most widely used densification tool. Here, our interest is limited to networks of continuously operating GPS stations, which can be divided into global networks, i.e., the IGS polyhedron, and regional networks of continental size.

The objective here is limited to provide suggestions and guidelines to agencies with regional networks for the densification of their networks into ITRF, preferably with the use of the IGS products. It is here assumed that this regional network densification will be an ongoing weekly effort to add the most recent information to the continuously observing network.

From its terms of reference, the IGS primary mission is “to provide a service to support, mainly through GPS data products, geodetic and geophysical research activities”. This has been achieved with the generation of several official combination products: station coordinates/velocities, ERP’s, GPS satellite orbit, station/satellite clock corrections, tropospheric delays, and ionospheric TEC grids. These products are generated from the solutions provided by the IGS Analysis Centers (ACs). Within the IGS, the first four products are also known as the core products. The first two are combined products generated within the Reference Frame Working Group (RFWG). The RFWG charter states, “The group will generate the official IGS station coordinates and velocities, earth rotation parameters (ERP) and geocenter estimates…” The other two core products, i.e., satellite orbits and clock corrections, are generated separately by the AC Coordinator while maintaining full consistency with the station coordinate and ERP combined products from the RFWG. These last two products also instrumental in the densification of ITRF.

The RFWG terms of reference have also set a target of 200-250 stations for a “well distributed and high quality” global network, the so called the IGS polyhedron (Blewitt et al., 1994). This target number of

Polyhedron stations has been independently proposed by several individuals (Zumberge et al., 1994; Blewitt et al., 1994; Beutler et al., 1994). The underlying objective of the polyhedron is to support efficient densification of the ITRF for regional activities. More specifically, the well-distributed 200-250 station polyhedron network yields an average station separation of about 2000 km, which should facilitate precise relative positioning over baselines of 1000 km or shorter (Beutler et al., 1994). In areas where GPS is widely used (E.g.: Europe & North America) the target station separation has easily been met and even exceeded. The covariance information of the weekly and cumulative products is also required.

IGS GLOBAL/POLYHEDRON NETWORK

Originally, the IGS considered creating a global network (~100 stations) and a polyhedron densification network (~100-150 stations), for a total of 200 - 250 stations. The global network was to be generated from the global solutions submitted by ACs, while the densification network was to be assembled from a set of stations selected from the combined solutions of IGS Regional Network Associated Analysis Centers (RNAACs) (Blewitt et al. 1994; Davis, P. 1997). However, with a steady increase in the number of stations included in the AC global solutions, the goal of 200-250 well-distributed polyhedron stations in the cumulative solution has been achieved without the need for regional solutions. There are currently 218 stations available in the cumulative solution. The cumulative solution currently released, is a subset of a more comprehensive cumulative solution that includes over 300 stations. New stations are being added almost weekly. This is a significant development, considerably simplifying and speeding up the generation of the IGS polyhedron network and, in fact, eliminating the necessity for a distinction between the IGS global and polyhedron networks.

Within IGS, two Global network solutions are produced, namely, a weekly and a cumulative (multi-year) solution. The weekly solutions include station coordinates, apparent geocenter and daily ERP's. The seven ACs provide the essential building blocks, by generating weekly solutions and making them available using the "Software INdependent Exchange" (SINEX) format. Their combined weekly solutions currently contain station coordinates for up to 150-170 stations (+ implicit geocenter + daily ERP's). Their SINEX files also include full variance-covariance information for all the estimated parameters, the a priori constraints used in their solutions, as well as auxiliary information about the receivers and antennas. The weekly AC solutions are also routinely used by two IGS Global Network Associate Analysis Centers (GNAAC), namely, MIT and NCL. The MIT weekly combination includes station coordinates and daily ERP estimates while the NCL combination is limited to station coordinates. Currently, the GNAAC solutions are used to quality control for the official IGS weekly solution generated within the working Group. The cumulative solutions are updated weekly by rigorously accumulating the unconstrained station coordinates contained in the IGS weekly solutions as discussed above.

The IGS realization of ITRS is defined by a subset of stations from the IGS Global network. For the current IGS realization of ITRS (IGS00), 54 high quality station coordinates and velocities were selected (Ferland, 2001;Weber, 2001), and are generally referred to as the Reference Frame (RF) stations. There are generally between 45 and 50 RF stations in the IGS weekly combinations. The current IGS realization of ITRS was generated using a selected IGS cumulative solution (IGS01P37.snx), which was aligned to ITRF2000 by an unweighted 14-parameters (position/velocity) Helmert transformation using the selected 54 RF stations. The relatively large number of stations, their high quality and good global distribution ensure a stable and precise alignment to ITRF. The alignment of the IGS weekly combined SINEX products is done using all the available RF stations (subject to outliers detection/rejection). The excellent internal consistency between the IGS realization of ITRS and the weekly SINEX products enables their alignment to be precise and stable. In addition, the current IGS realization of ITRS includes data up to September 2001 while ITRF2000 includes IGS data only up to November 2000. Because the IGS realization of ITRS uses up to date data, it also benefits from a shorter extrapolation in time for generating current products, which reduces the effect of errors in the estimated coordinate velocities. This also contributes to the internal stability of the solutions. It is also feasible to update the IGS realization of ITRS only weeks before its implementation to ensure even greater consistency and stability. Weekly solutions with latency of no more than two weeks may also be used. The short latency also allows to quickly taking advantage of new stations.

The interaction between ITRF and IGS is two folds. On one hand, IGS, along with other techniques, provides cumulative solutions for an ITRF realization. This has generally occurred every 2-3 years. On the other hand, once a new ITRF solution is available, it is used every day without requiring "active" IERS intervention/support. This day-to-day interaction is very similar to the global/regional interaction that is discussed above.

As the process of quality improvement continues within the IGS, IVS, ILRS and IDS communities, a convergence of those techniques within the ITRF combinations is expected. The relatively important weight of all the GPS contribution and the weakness of the local ties have contributed to favor GPS stations within the ITRF combination. Each IGS contribution to ITRS is a cumulative solution, thus, determined from GPS measurements only. ITRF is however unique as it takes advantage of multiple techniques, each one having specific strength and weaknesses. IERS is considering adding station coordinates time series as a new ITRF product. Although, the details are not available yet, the weekly IGS solutions can already form the basis to participate to that eventual product. Regional networks will potentially be in a good position to take advantage of this product.

CONTINENTAL/REGIONAL NETWORKS

A continental-size regional network is here arbitrarily defined as having a station spacing of between 100 km and 1000 km and spanning only a limited portion of the globe. The IAG Commission X Sub-commissions should have their own definition of what makes a station "regional". The IGS global network provides up to date accessibility of the ITRF. Most agencies responsible for regional networks already benefit indirectly from the IGS realization of ITRS when using the IGS precise orbit products. Regional networks are generally installed and maintained because the station density of the global network is insufficient for the users applications. This is where regional networks do provide an increased station density and therefore an improved accessibility to the ITRF.

The following paragraphs describe the activities of some of these Sub-commissions and their regional GPS networks that are currently operational or being implemented. Most of these Sub-commissions are acting as official IGS RNAAC's. Two examples of RNAAC continental/regional networks and activities are described below.

EUREF

The EUREF GPS Permanent Network (EPN) currently holds about 120 stations in and around Europe. The observations are analyzed according to the distributed processing approach. Local Analysis Centers (LACs) process the observations of a subnet of EPN stations. The Network Coordinator specifies these subnets of stations, and ensures each station to be processed by at least three LACs. Similarly to the IGS, up to date auxiliary information (site logs) is available for all the EPN stations. The EPN Central Bureau checks the consistency between the site logs and the RINEX headers on a daily basis and requests corrections from the station managers. RINEX data from all the EPN stations are available at different Local Data Centres and one Regional Data Center. The EPN data flow is organised following the IGS example. All EPN stations in the SINEX files have valid 4-char IDs and associated DOMES numbers. The receiver and antenna names comply with the IGS standard names and the IGS phase eccentricity tables are applied. The antenna/receiver names and antenna heights used have been crosschecked with the site logs. This is the case for both, the LAC solutions and the combined solution.

The LACs generate a weekly solution of the station coordinates in the SINEX format and submit these files to the Analysis Coordinator (AC). These weekly solutions are generated using the IGS precise orbits. The SINEX files must include the a-priori constraints that had been introduced in the parameter estimation procedure. With it, the constraints could be removed before the combination. It is highly recommended to constrain these solutions to the current ITRF realization. This recommendation yields the best possible consistency of the station specific troposphere parameters, which are submitted by separate SINEX-Troposphere files. The AC combines the weekly subnet solutions of the LACs into the EUREF combined solution. A between LACs comparison of the station coordinates is used to detect and mark outliers by allowing a maximum difference of 5 mm and 10 mm for the horizontal and vertical components. A comparison of the combined solution of seven subsequent weeks is performed to detect outliers in the coordinate time series. A SINEX file of the weekly final combined solution is published at EUREF's Data Center at BKG as official product. The reference frame of this solution is defined by heavily constraining (0.01mm) the current ITRF coordinates of 13 carefully selected stations.

The 'Troposphere Parameter Estimation' special project requires the generation and submission of daily troposphere files in the SINEX Troposphere format. The combination of the troposphere solutions is under responsibility of the Troposphere Coordinator (TC). The 'Time Series Analysis' special project is responsible for the maintenance of the coordinate time series homogeneity of the EPN sites. This SP is keeping track of the station performance and corrects for jumps and outlier periods found in the time series. The information about the jumps and outlier period will be applied for the generation of multi-year EPN solutions; similar to the ones submitted the IERS for the ITRF97 and ITRF2000 realisations. The table of jumps and outlier period can be made available to the IGS in order to guarantee that multi-year IGS and EPN solutions are consistent.

Additionally to the official weekly SINEX file the AC generates two preliminary 'densification products': (1) A weekly solution of the EPN is generated starting week 1136, which is consistent to the weekly global IGS solution, by heavily constraining (0.01mm) the station coordinates of all overlapping stations of IGS and EPN. (2) A cumulative EPN solution is generated starting week 1149, which is consistent to the cumulative global IGS solution by heavily constraining the coordinates of all overlapping stations. These two solutions are no official EUREF products and not publicly available, but could anyway be submitted to IGS. The procedure to generate the regional densification could of course be modified depending of decisions of the IGS. Once the IGS has defined clear guidelines for regional densifications, such products are candidates to become official EUREF products.

NAREF

The North American Reference Frame (NAREF) densification network is a new initiative that operates under the auspices of the NAREF Working Group of the IAG Commission X Sub commission for North America. The objective is to densify the IGS global network in North America through the combination of various existing regional networks and the production of weekly coordinate solutions. Eventually, cumulative solutions with velocities estimates may also be provided. The results are presently available from the NAREF web site at <*www.naref.org*> and will soon be submitted to the IGS Global Data Center.

The selection of stations and solutions for NAREF combinations has involved the adoption of standards and guidelines for station monumentation, station operation, data processing, archiving and redundancy. Most of these standards and guidelines have been adopted from those proposed by the IGS and those used by EUREF. The selection of stations for NAREF has been limited to dual frequency receivers that collect continuous 24 hr data down to a 10 degrees elevation and at a 30 second data rate for a minimum of 5 days a week. They must also have reasonably stable, geodetic quality monumentation. These criteria have been determined primarily by the availability of CORS stations in the U.S. The selection of regional solutions for use in the NAREF combination has been limited to only those using state-of-the-art software and that follow, as much as possible, the processing strategies described in Rothacher et al. [1998]. In particular, fixed IGS precise orbits and Earth rotation parameters should be used for highest accuracy and reference frame consistency. The results must also be provided in the SINEX format. In order to provide some kind of quality check on the regional solutions, there should be significant overlap between the global and regional networks. Ideally, all stations should be included in more than one regional solution to allow for outlier detection. Unfortunately, this redundancy is not met everywhere. Unlike EUREF, most regional solutions are performed by independent organizations with limited budgets and objectives that are often different from those of NAREF. It has been difficult, if not impossible, to enforce such standards.

The entire NAREF network presently consists of 110 stations; 23 of which are IGS global stations and 87 represent the NAREF densification stations. Four regional solutions have been contributing to

NAREF since the beginning of 2001. Natural Resources Canada's (NRCan) Geodetic Survey Division (GSD) presently provides two independent Canada-wide solutions. One is based on the Bernese GPS Software with a total of 53 points, about half of which are in neighboring areas in the U.S. The other GSD regional network is based on the GIPSY-OASIS II software with 33 stations, all in Canada. Regional solutions are also obtained from the Scripps Institution of Oceanography for the Plate Boundary Observatory consisting of over 300 points along the West Coast of the U.S. and based on the GAMIT software. Only 53 stations in the northern part of the network are included in NAREF because of limitations in the combination software (this will be rectified in the near future). NRCan's Geological Survey of Canada, Pacific Division also submits a regional solution for their Western Canada Deformation Array (WCDA). This solution is based on the Bernese GPS Software and has 28 stations. Later this year, 4 new permanent GPS stations in the Canadian Arctic and approximately 21 new stations around the Great Lakes will be included in the GSD Bernese solutions. Obviously, this network only covers the northern part of North America. Coverage should improve significantly once solutions for the U.S. CORS network can be obtained from the U.S. National Geodetic Survey.

The weekly regional solutions are combined into a single weekly NAREF "combination" solution using a step-by-step procedure similar to that used to produce the IGS global network combination. All a priori datum constraints are removed from the regional solutions and each is aligned to the IGS weekly solution. During this alignment, the covariance matrix of the regional solution is scaled to make it compatible with that of the IGS solution and the residuals are examined for outliers. The aligned/scaled regional solutions are then combined together by a summation of normal equations and the combination aligned and scaled again with respect to the IGS weekly solution. After a final check for outliers, a minimum constraint is applied (currently, for station DRAO). In addition, a separate "integration" solution is provided where weighted constraints are applied to all common IGS stations based on the IGS global weekly solution (including covariance matrix).

The quality of the weekly NAREF combination solutions is estimated through comparisons with the IGS weekly solution and the residuals for each regional solution. Overall, the RMS of the residuals are less than about 2 mm horizontally (except for PBO which is rather noisy in the east component) and 4 mm vertically. It is important to realize that it is difficult to compare RMS values between different weeks and different regional solutions because different stations are used from week to week and in different regional solutions. Weeks or solutions with a poorly behaved station(s) will exhibit larger RMS values. The RMS of the fit between the NAREF minimum constraint combination and the IGS weekly solution varies from about 1-2 mm horizontally and 2-4 mm vertically. Realizing that the noise level of the IGS solutions is of the order of a few mm, the NAREF weekly combinations can be considered compatible with the IGS. Note that only the coordinates from the IGS global solutions are considered "official" for IGS stations.

DENSIFICATION METHODOLOGIES

Clearly, the IGS cannot assume the responsibility for all the weekly regional network combinations and analyses. However, following its charter, the IGS, should provide guidance for regional network processing and integration. Even though some initial strategies and guidelines were provided to the RNACCs by the IGS (see, e.g., Blewitt et al., 1994; Kouba et al., 1998), more detailed IGS guidelines and conventions are still missing for regional processing and, in particular, integration of regional solutions into the IGS realization of ITRS.

At least in one case, regional network processing has been, well organized at the Sub-commission level (e.g., EUREF). However, at the IGS level, there is a need for more coordination to achieve better consistency among the different regional solutions. For example, an agreed upon recommendation for common processing guidelines. Each regional network has some unique characteristics, some guidelines flexibility. There are two main components to the weekly regional effort. First, within each region, all contributors should follow the existing IGS guidelines for station logs and ID, equipment (receiver/antenna), monumentation, etc… (See "Standard for IGS Station and Operational Centers"). These guidelines are widely accepted and would maximize the consistency with the global IGS network. A copy of the standards (and more) can be found at the IGS web site <*igscb.jpl.nasa.gov*>. The EUREF provides an excellent example of such regional activity, and it should be used as a model. Their strategy is described above, and more details can be found at their website <*www.epncb.oma.be*>. The preference for EUREF has been to align directly to the ITRF, rather than its IGS realization. With the convergence of ITRF and its IGS realization, the distinction is expected to eventually become insignificant. Second, some analysis aspects of the densification issues are discussed below. Some characteristics of the global/regional analysis are reviewed along with their implications eventual densification methodologies.

The general objective of network densification is to provide a more convenient and accurate access to the reference frame. A desirable characteristic is to have the coordinates in the ITRF, since over the last few years it has become the global standard. Regional activities may prefer to use other reference frames for their own reasons (E.g. the North American Datum is currently fixed to the North American Plate). In those cases, transformation parameters are generally available for conversion.

Combining all the code and phase measurements available from all the stations in a rigorous adjustment would be the optimal approach in the least-squares sense, but is clearly not feasible. Also, it is not possible to rigorously subdivide this type of analysis into manageable subsets, leading to sub-optimal results. The general practice has been to break down the analysis spatially and temporally and to ignore the correlation between the subsets. Therefore, the analysis task is generally broken down spatially in sub-networks (several global and several regional); and temporally, in daily data sets. In the case of the station coordinate parameters, this potentially leads to multiple global and regional solutions for some stations, when ideally, a unique "optimal" set of station coordinates (velocity) is desired. The necessary overlap required to integrate the networks forces the reuse of the code and phase observations at selected common stations. For example, for GPS week 1152, the code and phase observations for station WTZR were used in the global analysis by six IGS ACs and within EUREF by four LACs.

The regional networks can be combined directly with the ITRF, or alternatively, with the IGS global network, in one adjustment by making use of all the available covariance information. If we assume the global/regional networks as uncorrelated, this alternative has the advantage of being optimal in the least-squares sense. The coordinates of all the stations are adjusted during the combination. The change in coordinates of the global stations during the adjustment can be alleviated by tightly constraining them. One side effect is to produce unrealistically small covariance information. However, even this approach may potentially become demanding, even prohibitive in some cases, specially considering (1) that the number of regional solutions may be increasing as well as (2) the number of stations within each regional solution is also very likely to gradually increase (3) that this effort may be required every week. There is a necessity to share the effort. Although, the processing load would potentially become demanding, most could probably be accommodated. However, the computational load is only one aspect of the total effort. From the IGS weekly experience, significant analysis/trouble shooting/reporting effort is also necessary especially in the early phase. The regional contributors have also a personal stake in the quality of the regional networks. The distributed effort also allows raising the level of expertise and interest within local/regional agencies. Each regional group also has some unique requirements, concerns and interests to address within the region, including the number of contributing agencies, resources limitations, number of stations network size, etc.

At the global level, there is generally significant overlap/redundancy between the global solutions being combined. This situation generally provides the necessary information for the detection/resolution of problems, and to also estimate statistics. The situation is quite different between the regional networks. There is little or even no overlap between the regional solutions. This lack of overlap significantly limits the ability to detect problems when comparing regional networks. The regional solutions can be compared/combined to the global solutions simultaneously or sequentially with limited effect on each other. This also suggests that a densification scheme could consider regional networks separately. This alternative is somewhat less rigorous, but can significantly simplify the whole integration process. This type of tradeoff has been proposed in the past within IGS … "IGS should provide the means to make the procedure as simple as possible without significantly compromising regional accuracy" (Blewitt, 1993). Additionally, this approach can easily be adapted to a decentralized densification effort.

There are several alternative approaches to integrate the regional (combined) solutions into ITRF. ITRF can be accessed directly or via the IGS realization of ITRS. If the IGS realization of ITRS is preferred, it can use the weekly or the cumulative solution. The use of the weekly solutions is suitable for series representations where non-linear station position departures are considered important. The use of the cumulative solutions, which assumes a linear station motion model, is the traditional realization.

When non-linear stations behavior is required, the series of IGS weekly combined solutions should be used to integration of regional solutions. The IGS weekly solution series do not have velocity estimates; but since an independent solution for each global station is generally available each week, it is only a matter of matching corresponding weekly solutions with the regional solutions of the same epoch. The IGS weekly and the regional station coordinates solutions should experience very similar non-linear temporal (real and apparent) behavior for the common stations. After estimating and applying a 7-parameters similarity transformation, the residual differences at the common stations should be small (2-3mm horizontally, 5-10mm vertically), which is a very desirable attribute to achieve maximum integration stability. Since the same code and phase measurements should be used, the residuals differences should be originating mainly from the differences in network geometry and processing strategy. Station with abnormal differences should be resolved or rejected. In fact, with this alternative, the integration instability to ITRF would be coming partly from (1) the number and the geometry of the overlapping stations between the two weekly solutions, and (2) the uncertainty in the alignment of the IGS weekly solution to ITRF. The first source of instability (Regional-IGS weekly) is very much networks/processing dependent and may be highly variable. As discussed above, the second source of instability (IGS weekly–ITRF) is minimized with a careful selection of reference stations. Recent tests have indicated that horizontally, the level of instability is sub-millimeter. The common stations in the global and regional networks should have their coordinates/covariances fixed to the global values (Blewitt, 1993) for the published solutions. This can be done with a back substitution. Inner constraints also known as datum constraints should also be applied to each transformed solution and properly reflected in the APRIORI SINEX block. These constraints can be applied as part of the transformation process (Altamimi, 2002) or separately as is currently done for the IGS weekly and cumulative solutions. The use of inner constraints avoids the distortion of the global and local solutions as well as their covariance information. Ideally, the covariances of the global and regional solutions also need to be made compatible by potentially rescaling one (preferably the regional) or both matrices. The use of heavy constraints on the global station coordinates or subset of, as is currently done within EUREF achieves similar results on the coordinates. However, it distorts the covariance information. Again, independent solutions could/should be maintained regionally. Comparisons with available GNAAC combinations could also be used to provide some independent quality assurance. These alternatives do not prevent the regional analysis centers from generating independent regional cumulative solutions. This type of parallel analysis is actually encouraged.

The use of the cumulative solutions may appear advantageous to combine regional networks directly to ITRF; but there are some disadvantages. Namely that (1) there is a significant lag between the time of the most recent observations are made and the time the solution is available (one to two years) (2) real or apparent temporal variations other than the linear station velocity and discontinuities are not modeled in ITRF. The first disadvantage can be mitigated with the high quality of the ITRF estimated velocities. The second disadvantage, i.e. non-linear station movements other than discontinuities, cannot be accounted for in the current ITRF. This problem is not unique to the ITRF solution; it is shared with all the cumulative solutions currently available. The IGS cumulative solution mitigates the extrapolation time problem, because it is updated every week and lags by at most two weeks. The non-linear temporal variations would not be accounted for, except for new stations with a very short history. A constraining/back substitution strategy similar to the one describe above can be applied here.

The “how” the regional solution should be integrated can take several forms. Before the combination, the common stations have two sets of coordinates/velocity with relatively small differences. The simplest way is to align the regional solution using 7/14 parameters (or a subset of) Helmert transformation using a selected set of stations coordinates and covariance. Alternatively, making use of their respective covariance information can combine the global and the regional solutions. Depending on the final objective, the weighting scheme can be altered to give preponderance to the coordinates of the global or regional solutions. Alternatively, a backward substitution can be used to fix one set of coordinates. To avoid confusion, the coordinates from the global station solutions, which should be more precise than the regional solutions, should be fixed in the integration. It is relatively simple to implement, making it possible for the regional agencies to do their own integration. Considering that the regional solutions have a continental scope, the number (>10) and distribution of stations should be sufficient for all continents. In the case of Africa, stations around the continent could also be included. A carefully selected subset of the common stations may also be used when many stations are common between the global and regional solutions.

Practical issues related to standard least squares such as variance factor estimation; outliers detection/rejection, numerical stability, etc…also need to be taken into account. Those are well documented in the geodesy literature. This short procedure provides the main steps that are/should be required to produce weekly regional products. It is concise version of the IGS weekly combination procedure described in (Ferland et al. 2000).

1) Validation:
    - Compliance with the SINEX format
    - Naming issues
    - Correct modeling inconsistencies

2) Unconstraining:
    - Remove inner and/or coordinates constraints
    - Check for numerical problems

3) Transformation (Helmert)/Combination:
    - Compute misclosures:
    - Check abnormalities (Investigate/Reject/Fix)
    - Compute partials/normals/estimated corrections/Residuals:
        - Check residuals (Investigate/Reject/Fix)
    - Iterate if necessary:

4) Prepare/distribute final statistics/reports.

A similar procedure is described in the NAREF section. Other alternatives may be provided by the Regional Networks Associate Analysis Centers (RNAAC) at MIT (Herring, 1996; Herring 1998) and NCL (Davis et al., 1996, Kawar et al, 1998ab) for example or by some effort by (U. of Colorado (Blewitt)).

CONCLUSION/RECOMMENDATIONS

1) The current IGS SINEX cumulative combination satisfies the IGS Polyhedron network (~200 stations). The originally planned use of the regional networks to complement the global network is no longer necessary. This allows for the densification of ITRF using the regional networks to be simplified.

2) Various regional networks densification alternatives have been proposed and discussed by the authors to integrate the regional solutions to the global IGS network. All the proposed solutions have strength and weaknesses. In an effort to keep the process simple and to provide internally consistent solutions, the weekly/cumulative regional SINEX solutions should be aligned using a Helmert transformation (7/14) to the appropriate weekly or cumulative IGS SINEX solution. For stations coordinates appearing in global and regional solutions, their differences should be within the noise level. This type of approach is currently being used to align the IGS weekly and cumulative solutions to its realization of ITRF. To avoid potential confusions, the common stations in the global and regional networks should also have their coordinates/covariances fixed to the global values.

3) Within each region, the IGS standards (monumentation/logs/naming/etc.) should be used <*igscb.jpl.nasa.gov*>.

4) The general strategy and structure used within EUREF <*www.epncb.oma.be*> should be followed and adapted as required by the other regions.

ACKNOLEDGEMENTS

Several very pertinent comments and suggestions were also provided by Dr. Claude Boucher. These contributions are gratefully acknowledged.

REFERENCES

Altamimi, Zuheir, (2002) How to Express a regional GPS Solution in the ITRF . Proceedings of the IGS Analysis Workshop. April 2002.

Beutler G., J. Kouba and Ruth E. Neilan (1994). Densification of the ITRF Through Regional GPS Networks: Organizational Aspects. In Proceedings of the IERS Terrestrial Reference Frame Through Regional GPS Networks Workshop, Pasadena, U.S.A, December 1994.

Blewitt, G. Y. Bock and G. Gendt (1993). Global GPS Network Densification: A distributed Processing Approach. Proceeding of the IGS Analysis Center Workshop. Jan Kouba ed. Ottawa Canada, October 1993.

Blewitt G., Y. Bock and J. Kouba (1994). Constructing the IGS Polyhedron by Distributed Processing. In Proceedings of the IERS Terrestrial Reference Frame Through Regional GPS Networks Workshop, Pasadena, U.S.A, December 1994.

Davis, P. B. H. (1996). Newcastle-upon-Tyne IGS Global Network Associate Analysis Center Report. IGS 1995 Annual Report, 1996.

Davis, P. B. H. (1997). Assembling the IGS Polyhedron, A densified weekly GPS terrestrial reference frame. Phd Thesis, University of Newcastle-upon-Tyne.

Ferland R. (2001). Activities of the International GPS Service (IGS) Reference Frame Working Group. Internatinal Association of geodesy Symposium, Budapest, September 2001.

Ferland, R., J. Kouba, D. Hutchison (2000). Analysis methodology and recent results of the IGS network combination. Earth Planets Space, 52, 953-957.

Herring T. A. (1996). MIT Global Network Associate Analysis Center Report. IGS 1995 Annual Report, 1996.

Herring T. A. (1998). MIT T2 Analysis Center Report. IGS 1997 Annual Report, 1998.

Kawar et al. (1998a). The Newcastle Global Network Associate Analysis Cenetr annual Report. IGS 1997 Annual Report, 1998.

Kawar et al. (1998b). The Newcasle Global Network Associate Analysis Center, 1998 AC Workshop held at ESOC Darmstadt, February 9-11.

Kouba J., J. Ray, and M.M. Watkins (1998). IGS Reference Frame Realization. In Proceedings of the IGS Analysis Center Workshop, European Space Agency, Darmstadt, Germany, February 1998.

Rothacher, M., T.A. Springer, S. Schaer, G. Beutler (1998). Processing Strategies for Regional GPS Networks. In F.K. Brunner (ed.), "Advances in Positioning and Reference Frames", IAG Scientific Assembly, Rio de Janeiro, Brazil, September 3-9, 1997. International Association of Geodesy Symposia, Vol. 118, Springer-Verlag, Berlin, pp. 93-100.

Weber, Robert (2001), Towards ITRF2000. IGS Electronic Mail, Message Number 3605, 20 Nov 2001.

Zumberge J.F., R. Liu (eds.). (1994). Densification of the IERS Terrestrial Reference Frame through regional GPS networks, IGS workshop proceedings, Pasadena, California, Nov. 30 – Dec. 2, 1994.

Satellite Antenna Phase Center Offsets and Scale Errors in GPS Solutions

S.Y. Zhu, F. -H. Massmann, Y. Yu and Ch. Reigber

GeoForschungsZentrum Potsdam, Division 1, Telegrafenberg A17, D-14473 Potsdam, Germany, phone: +49-8153-28-1586, fax: ..-1585, email: zhu@gfz-potsdam.de

Abstract

This paper studied two scale factors, which may affect GPS solutions: gravitational constant GM and satellite antenna phase center offset in z-direction. GM affects the scale of the orbits of satellites by 1/3 of dGM/GM. But its effect on the scale of a terrestrial frame realized by GPS technique is much small. The reason is, that the scale errors in the orbits are (largely) canceled in the double differences, or absorbed in the clock solutions. For example, we first fix a set of (IGS) GPS orbits and solve the station positions, afterwards we deliberately enlarge the orbit coordinates by a factor of (1+5.e-9), that is, to change the scale of orbits by 5 ppb, and solve the site position again by fixing the enlarged orbits. Comparing these two sets of station positions, one finds only less than 1 ppb scale variation. The conclusion is: **the scale of GPS orbits (just like the orbit of other satellites, such as LAGEOS) is sensitive to GM, but the scale of the GPS terrestrial frame is much less sensitive**! When one talks about the scale of GPS, one MUST distinguish clearly between the scale of the orbit and that of the terrestrial frame!

As far as the terrestrial frame is concerned**, the uncertainty in the satellite antenna phase center offset (z-direction) is almost equivalent to the scale error in the GPS orbits caused by the error in GM.** But **the uncertainty of the current available GM value is very small, while the errors in the z-off could be very large. This is the essential difference between these two factors.** Therefore although most of the z-off errors are canceled in the double differences, or absorbed in the clock solutions, the rest effect on the scale of the terrestrial frame is not ignorable small. Approximately, **delta scale = 7.8 dz**, where dz is the error of z-off in unit meter, while the scale change is in ppb. That is, 7 cm of dz in the BLOCK II and IIA satellites could produce 0.5 ppb scale variation. For BLOCK IIR dz could reach 1 m. The number of these satellites increases from year to year. ITRF2000 solutions (see Lareg, 2001) have shown that there are ppb level scale differences between GPS and other techniques, and between various GPS Analysis Centers (AC). The trends of the scale differences reach 0.2 ppb per year. Our study has shown that the uncertainty in the satellite antenna phase center offset **could be** one of the major reasons for these problems.

Densification of the ITRF: The NAREF Experience in North America

M. Craymer and M. Piraszewski
Geodetic Survey Division, Natural Resources Canada

In an effort to densify the ITRF, the IGS initiated a program of distributed regional processing to better manage the computational effort. In 2000, the North American Subcommission of the International Association of Geodesy's Commission X formed a North American Reference Frame (NAREF) Working Group to promote and coordinate such regional processing in North America. This coordination has involved the adoption of standards and guidelines for station selection, operation, data processing, archiving, redundancy, and the combination and integration of regional solutions within the ITRF and IGS global network. Most of these standards and guidelines have been adopted from those proposed by the IGS and those used by the European Reference Frame (EUREF) Technical Working Group.

In support of this densification initiative, the Geodetic Survey Division (GSD) of Natural Resources Canada has been contributing on two fronts: the provision of weekly regional solutions for Canada and the combination of regional solutions from other agencies across North America. Since the beginning of 2001, GSD has been computing two independent Canada-wide weekly solutions using GIPSY-OASIS II and the Bernese GPS Software. In addition to all IGS stations in the northern half of North America, the solutions also include all stations of the Canadian Active Control System (CACS), the Western Canada Deformation Array (WCDA), as well as a some selected stations of the US CORS network, the Alaska Deformation Array (AKDA), the Pacific Northwest Geodetic Array (PANGA), the Eastern Basin Range Yellowstone Array (EBRY). Also included until the end of 2001 were selected stations from the British Columbia Active Control System (BCACS) and the Quebec Permanent GPS Network. In additional to our own regional solutions, we have been receiving regional weekly solutions from the Geological Survey of Canada - Pacific Division for their WCDA and from the Scripps Institution of Oceanography for the Plate Boundary Observatory (PBO). We also expect to soon be receiving weekly solutions from the US National Geodetic Survey for their CORS network. This contribution will make NAREF truly North American in scope.

GSD has also been combining these regional solutions into weekly NAREF combinations. Overlap among these regional networks provide redundancy checks and allow for the determination of correct relative weighting of the different solutions relative to each other. The agreement among the regional solutions is generally less than a couple of mm horizontally and about 4 mm vertically. Agreement of the minimally constrained weekly NAREF combinations with the IGS weekly combinations is of the order of 1-3 mm horizontally and 3-6 mm vertically.

Different methods of integrating the combined NAREF solutions into the IGS global network were also investigated. It was decided to us a combination of Helmert transformation and a priori weighting of the IGS global stations. The later uses the full covariance matrix from the IGS solutions to propagate the global accuracies into the NAREF combination. Agreement of these integrated NAREF combinations with the IGS solutions is about 1 mm horizontally and 3 mm vertically. We presently have a time series of NAREF combinations from GPS week 1095 to present and soon hope to begin estimation cumulative solutions in an effort to determine velocities at the regional sites. More information can be obtained at www.naref.org.

How to Express a Regional GPS Solution in the ITRF ?

Zuheir ALTAMIMI

The usefulness of the densification of the International Terrestrial Reference Frame (ITRF) is to facilitate its access by users interested on small (regional or local) networks. Although a regional GPS solution is usually derived using IGS products (Orbits, Clocks,...), which are nominally expressed in the ITRF, its corresponding datum definition could be far from that of ITRF due mainly to the network configuration. The main question to be answered here is how to optimally express station positions of a regional network in the global frame of ITRF. This could be achieved by mainly (1) constraining coordinates of a subset of stations to their ITRF values or (2) aligning the regional solution to ITRF using a transformation formula. This paper will focus on the second method, based on minimum constraints approach yielding an optimal datum definition together with preserving the original characteristic of the regional solution.

The advantage of method (1) is that the regional solution is well expressed in the ITRF frame, while its disadvantage is that the selected stations will have their coordinates entirely determined by the ITRF selected values. Given the nature of a regional network and its effect on the estimation of the transformation parameters, its extremely important to be very careful when using method (2). In fact, the most efficient way to use is the transformation parameter alignment using minimum constraints approach as described hereafter.

The relation between a regional solution (X_R) and ITRF (X_I), over selected stations, could be written as:

$$X_I = X_R + A\theta \tag{1}$$

where A and θ are respectively the design matrix of partial derivatives and the vector of 7 transformation parameters:

$$A = \begin{pmatrix} . & . & . & . & . & . & . \\ 1 & 0 & 0 & x_a^i & 0 & z_a^i & -y_a^i \\ 0 & 1 & 0 & y_a^i & -z_a^i & 0 & x_a^i \\ 0 & 0 & 1 & z_a^i & y_a^i & -x_a^i & 0 \\ . & . & . & . & . & . & . \end{pmatrix}, \qquad \theta = \begin{pmatrix} T_x \\ T_y \\ T_z \\ D \\ R_x \\ R_y \\ R_z \end{pmatrix}$$

Un-weighted least squares adjustment yields a solution for θ as:

$$\theta = (A^T A)^{-1} A^T (X_I - X_R) \tag{2}$$

The approach of minimum constraints consists in using the matrix $B = (A^T A)^{-1} A^T$ in such a way that X_R will be expressed in the same frame as the ITRF solution X_I. Therefore to have X_R be expressed in the ITRF at Σ_θ level, a "datum definition" equation could be written as:

$$B(X_I - X_R) = 0 \qquad\qquad (\Sigma_\theta) \tag{3}$$

where Σ_θ is the variance matrix at which equation (3) is satisfied. Σ_θ is a diagonal matrix containing small variances (to be selected at the user level) for each one of the 14 transformation parameters.

In terms of normal equation, we then can write:

$$B^T \Sigma_\theta^{-1} B(X_I - X_R) = 0 \tag{4}$$

Using IGS product (orbits, clocks, etc.), the initial normal equation system of a regional solution before adding any kind of constraints could be written as:

$$N_{unc}(DX) = K \tag{5}$$

where $DX = X - X_{apr}$, N_{unc} is the unconstrained normal matrix and K is the right side vector.

The normal equation system (5) could be obtained also after removing classical constraints applied to a given regional solution.

Selecting ITRF subset of stations (X_I), the equation of minimum constraints (or datum definition) is:

$$B^T \Sigma_\theta^{-1} B(DX) = B^T \Sigma_\theta^{-1} B(X_I - X_{apr}) \tag{6}$$

Note that if the the ITRF values are used as a priori values, the right hand side of eq. (6) vanishes. Cumulating (5) and (6) yields:

$$(N_{unc} + B^T \Sigma_\theta^{-1} B)(DX) = K + B^T \Sigma_\theta^{-1} B(X_I - X_{apr}) \tag{7}$$

Solving for eq. (7) yields a regional TRF solution expressed in the ITRF at the Σ_θ level.

SESSION 8:

RECEIVER AND SATELLITE ANTENNA CALIBRATIONS

Receiver and Satellite Antenna Phase Center Offsets and Variations

Markus Rothacher, Forschungseinrichtung Satellitengeodäsie, TU Munich
Gerry Mader, US Department of Commerce, NOAA, Geoscience Research Division

Position Paper of the "Antenna Session"
IGS Workshop in Ottawa, April 8-11, 2002

Draft of April 5, 2002

1 Introduction

If highest precision is required, antenna phase center and multipath effects are crucial error sources in GPS site position determination. Especially the vertical component is heavily affected by erroneous antenna phase patterns and multipath. In many geodetic and geophysical applications (like, e.g., reference frame maintenance, global sea level change and post-glacial rebound) very high accuracy (site positions on the few millimeter level and site velocities at about 1 mm/year) is aimed at.

In order to achieve these aims, very accurate and consistent antenna phase center variations (PCVs) are needed for both, the receiver and satellite antennae and site-dependent effects (such as multipath) have to be reduced to the extent possible or determined from calibration measurements.

In Section 2 we consider the status of receiver antenna calibration results from various calibration methods (relative and absolute field calibrations and chamber measurements). The quality is limited by site-dependent effects (multipath, ...) that cannot easily be accounted for.

Section 3 summarizes the present knowledge on the satellite antennae and the methods to determine satellite antenna offsets and patterns and shows the relationship between receiver and antenna phase center variations.

After an overview of interesting new developments in the field (Section 4) the necessity of a new format for antenna information and clear responsibilities for the maintenance of antenna information are discussed in Section 5. The Appendix consists of the description of the new antenna information file format called ANTEX.

2 Receiver Antenna Calibrations

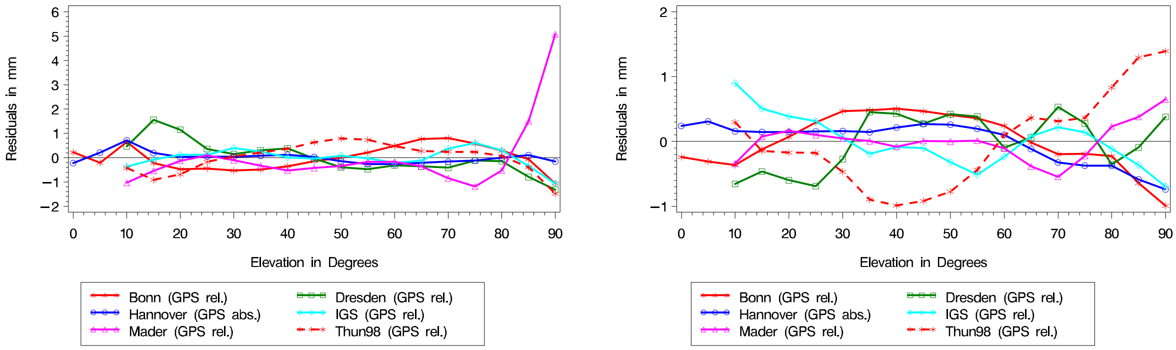
2.1 Relative Receiver Antenna Calibrations

This method for receiver antenna calibration has been used for a long time now (see, e.g., [*Mader*, 1999; *Rothacher et al.*, 1995, 1996]). Elevation-dependent (and azimuth-dependent) patterns are estimated from the GPS data collected on a very short baseline with accurately known endpoints. In order to be able to determine azimuth-dependent variations, the antenna to be calibrated has to be rotated between sessions (because of the north and south "hole" in the GPS satellite constellation). The official IGS antenna patterns stem from such relative field measurements and have a precision of about 1-2 mm (see also Figure 1 in Section 2.2).

For long baselines or if the antenna is tilted, however, absolute antenna phase patterns are needed to be able to correctly take into account elevation- and azimuth-dependent PCVs.

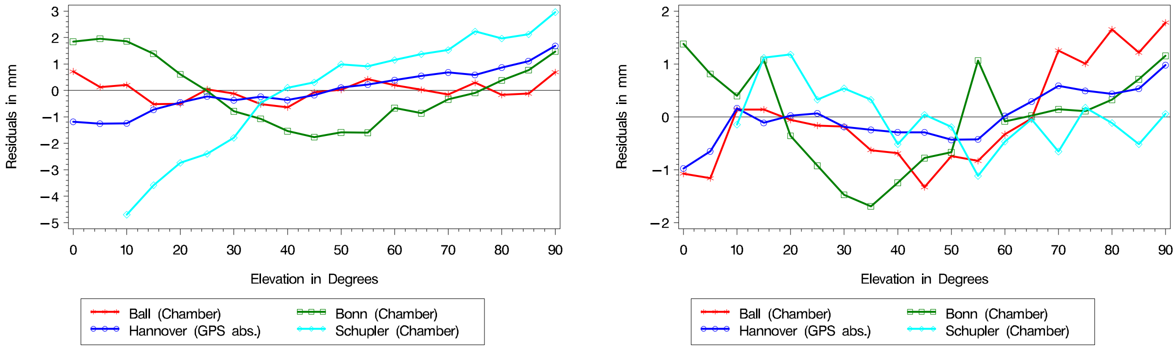
2.2 Absolute Receiver Antenna Calibrations

There exist two independent methods to obtain absolute receiver antenna PCVs nowadays: the measurements in an anechoic chamber (see, e.g., [*Schupler et al.*, 1995] or [*Rocken et al.*, 1996]) and the field measurements on a short baseline using a robot to tilt and rotate one of the antennae (see [*Wübbena et al.*, 2000]). The advantage of the robot measurements is, that real GPS signals are tracked with a real receiver and an antenna in the "usual" field environment.



(a) L_1 Frequency (b) L_2 Frequency

Figure 1: Differences between relative elevation-dependent antenna PCVs from different calibration sources. PCVs of the TRM14532.00 antenna relative to the AOAD/M_T antenna are shown.



(a) `AOAD/M_T`, L_1 Frequency (b) `AOAD/M_T`, L_2 Frequency

Figure 2: Differences between absolute elevation-dependent antenna PCVs from different calibration methods: chamber measurements from BALL, BONN, and SCHUPLER, and robot results of HANNOVER (IfE and Geo++).

In contrast to the relative antenna calibrations in the field, the robot measurements allow (1) the determination of patterns down to zero degree elevation or even below, (2) the elimination of multipath effects to a large extent, and (3) a dense and quite homogeneous coverage of the GPS antenna hemisphere.

The comparison of the different methods shows that GPS receiver antennae may be calibrated nowadays with a precision of about 1 mm nowadays, including the elevation as well as the azimuth dependence of the antenna phase center location. The absolute calibration results from the robot (a cooperation between the Institut für Erdmessung (IfE) and the company Geo++) are in very good agreement with the relative field calibration results on short baselines (see Figure 1 as an example, where the PCV differences with respect to a mean pattern are shown for a number of field calibrations; more details may be found in [*Rothacher*, 2001; *Mader*, 2001]). For some of the anechoic chamber patterns still unexplained differences compared to the absolute or relative field calibrations are seen. For the `AOAD/M_T` antenna different absolute calibration methods and measurement campaigns differ by about 1–4 mm (see Figure 2 and [*Rothacher*, 2001]). It is nice to see that especially the BALL chamber measurements and the Hannover values are in very good agreement (1–2 mm level).

2.3 Problematic Effects (Radoms, Snow, Multipath, ...)

Errors due to site-dependent effects (like, e.g., site-induced antenna phase center variations and multipath) are very difficult to reduce and may thus be considered as a major accuracy limiting factor (besides tropospheric refraction) for position determination with GPS in general and for heights in special.

When mixing different antenna types, you have no guarantee to obtain height estimates with sub-centimeter accuracy, even after correcting the observations for antenna specific phase center variations (as available at the IGS Central Bureau). For longer baselines you have the adverse circumstances that you have to make use of the ionosphere-free linear combination, which tends to amplify the phase center effects, and that you also have to estimate troposphere zenith delay parameters which are highly correlated with the antenna phase patterns. The conclusion is, that for precise site coordinate determination, whenever possible, the same antenna type should be used for all sites. This is especially true for the permanent stations of the IGS.

Without going into much detail, we would like to mention that multipath and the antenna environment have a crucial impact on the GPS results, too. Snow on the antenna, wet ground after rainfall, the height of the antenna above the ground, the monument design, the antenna ground plane, radoms, and any multipath producing or absorbing material around the antenna — to name just a few of the factors involved — may result in height changes of up to a few centimeters (see [*Jaldehag*, 1995; *Böder et al.*, 2001] and publications at UNAVCO `http://www.unavco.ucar.edu`). A recent example have been the changes in the height time series of about 5 cm of the IGS site Hoefn in Iceland, that were most probably caused by changes of the antenna type and setup. Unfortunately, it is extremely difficult to correct or model this type of antenna and environment effects and we will probably always have to live with some remaining effects from the antennae and from multipath that will adversely affect the GPS site coordinate estimates, especially the heights.

Out of these reasons it is very important, therefore, not to change the antenna equipment at an IGS site unless absolutely necessary. A change of the antenna characteristics is comparable in its consequences on coordinate and velocity estimates as moving the site to another location.

The work of the Hannover group and new developments at Haystack and at NGS(see Section 4) might give new insights into the possibilities to calibrate site-dependent effects.

3 Satellite Antenna Calibrations

In the last few years research groups started to realize that not only the receiver antennae, but also the satellite antennae show phase center variations. These variations are most certainly the reason for the scale factor that results in global GPS solutions, when absolute phase center patterns (from anechoic chamber or robot field measurements) are applied. Scale errors of the order of 15 ppb corresponding to an overall height change of about 10 cm are observed.

It is important to mention in this context that a very basic relationship exists between satellite and receiver antenna elevation-dependent PCVs. The nadir angle z' at the satellite (to the station) is related to the zenith angle z for the receiver at the ground (to the satellite) by

$$\sin z' = \frac{R}{r} \sin z \tag{1}$$

where R is the Earth's radius and r the geocentric distance of the satellite. Whereas the zenith angle z at the receiver ranges from 0 to 90 degrees, the corresponding nadir angle z', as seen from the satellite, only varies between 0 and approximately 14 degrees. An elevation-dependent phase center pattern $\Delta\phi(z)$ of the receiver antenna may thus be interpreted as a phase center pattern $\Delta\phi'(z')$ of the satellite antenna and vice versa with

$$\Delta\phi'(z') = \Delta\phi(z) \tag{2}$$

The consequence is, that errors in the satellite antenna patterns may be seen in the receiver patterns and vice versa.

3.1 Manufacturer Information on Satellite Antenna Offsets

The information available about the GPS satellite antennae and, especially, about the location of the antenna phase center is very sparse. Some details on the antenna characteristics may be found in *Aparicio et al.* [1996]. It is, however, not even known, whether the phase center offsets (from the center of mass of the satellite) from the manufacturers are offsets for L_1, L_2, or the ionosphere-free linear combination. From the estimation of satellite antenna offsets by various IGS analysis centers it also became clear that the satellite antenna offset information by manufacturer is not reliable (thinking, e.g., of the Block IIR satellites).

The offsets presently used by all IGS analysis centers are given in Table 1.

Due to these circumstances, people started to think about satellite antenna calibration methods to improve this situation. Due to the high correlation between receiver and satellite patterns, the global scale, absolute station heights, and troposphere zenith delays very accurate offsets and PCVs are extremely important. The possible approaches are discussed in the sections to come.

Table 1: Satellite antenna offsets used by the IGS.

Satellite Block	X (m)	Y (m)	Z (m)
I	0.210	0.000	0.854
II/IIA	0.279	0.000	1.023
IIR	0.000	0.000	0.000

3.2 Satellite Antenna Measurements on the Ground

Estimates of the L1, L2 and LC phase centers for the Block IIA GPS satellite antennae have been determined. These results indicate that the L1, L2, and LC phase centers have z-axis (toward the earth) offsets that differ significantly from the currently assumed offset values.

These calibrations used the Block IIA antenna as a receiving, rather than a transmitting antenna. The Block IIA antenna was pointed at the zenith from the roof of the Boeing facility in Seal Beach, CA, and was connected to a standard dual-frequency, geodetic-quality GPS receiver. By computing baseline vectors from a nearby reference antenna, first to a standard geodetic-quality GPS antenna, and then to the Block IIA antenna, the phase centers of the Block IIA antenna relative to the standard antenna could be determined. This calibration procedure is essentially identical to that used by NGS numerous times on previous antenna calibrations. The primary difference for this calibration was to limit the data used to satellites above 60^o elevation due to the highly directive antenna beam and to include only those periods when at least two satellites were in view.

Graphs of the phase residuals versus elevation from these solutions show greater azimuthal variations for L1 than for L2. These effects may be unique for these particular antennae and may depend on the tuning done to produce the desired amplitude response. These results mitigate much of the scale factor error introduced when absolute antenna calibrations are used for the global network of terrestrial antennae.

3.3 Estimation of Satellite Antenna Offsets and Patterns

The estimation of satellite antenna offsets from global GPS solutions has been performed by quite a few IGS analysis centers (see, e.g., [*Springer*, 1999]). It has been shown that it is difficult to get good absolute satellite antenna offsets, especially in the z-direction (towards the Earth), because of the bad separability between satellite clock estimates and satellite antenna offsets. The repeatability is of the order of a few decimeters. In contrast to this, relative offsets between different satellite blocks may be determined on a 1-5 cm level.

In view of the fact that the GPS satellite antennae consist of two large antenna rings, it has to be expected that not only antenna offsets but also antenna patterns have to be taken into account. An indication that this is indeed necessary is the fact that the absolute receiver antenna patterns lead to a scale of about 15 ppb, if the IGS satellite antenna offsets are used. The offset values determined by Gerry Mader, NGS (see Section 3.2) reduce this scale considerably, but not completely.

Therefore, at the TU in Munich, the necessary software modifications were done to allow for the estimation of satellite antenna patterns, i.e., variations of the phase center depending on the nadir angle z'. The results of such an estimation using the global IGS data is shown in Figure 3. We see that different patterns are obtained for Block II/IIA and Block IIR satellites. The patterns can be estimated with a precision of about 1-2 mm (repeatability from day to day). In order to be able to estimate these satellite PCVs the global scale has to be fixed (e.g. on the ITRF scale). More details will be given in a paper presently written by *Schmid and Rothacher* [2002].

Using these satellite antenna patterns, the problem of the global scale is “solved” and absolute receiver antenna patterns may be used at the ground. It would make sense for the IGS to adopt at one and the same time (1) a set of satellite antenna offsets (e.g., by NGS) together with a set of consistent satellite PCVs determined by TU Munich and (2) the absolute receiver PCVs from the robot measurements from Hannover. In this way, the most consistent set of both, receiver and satellite antenna PCVs available now could be applied.

4 New Developments

4.1 Antenna and Multipath Calibration System at Haystack

Despite the many efforts devoted by investigators to the calibration of site-specific errors, signal scattering and multipath remain an unsolved problem. Therefore, groups at the Harvard-Smithsonian Center for Astrophysics, MIT Haystack Observatory, and UNAVCO/UCAR (Kwan-Dong Park, James L. Davis, Per Jarlemark, Brian Corey, and many others) developed an Antenna and Multipath Calibration System (AMCS) for characterizing

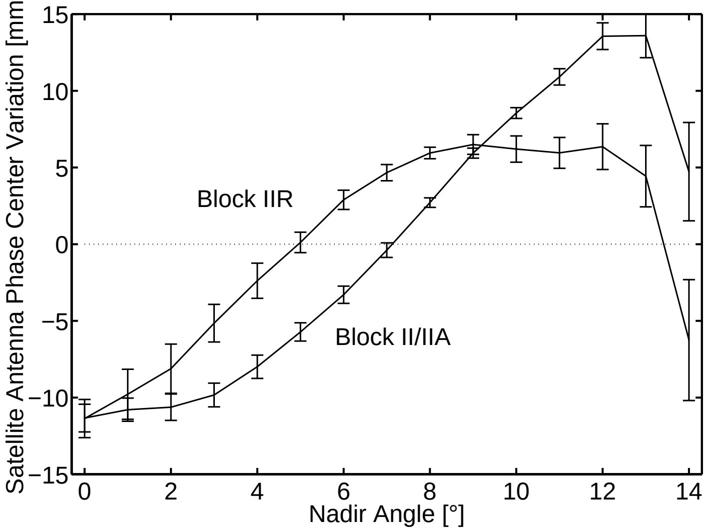


Figure 3: Antenna Phase Patterns (ionosphere-free LC) for Block II/IIA and Block IIR GPS Satellites Estimated from 8 Consecutive Global 1-Day Solutions (with standard deviation).

site-specific GPS phase measurement errors. The system consists of a high-gain, multipath-free, 3-m diameter parabolic antenna, two test antennae, and two Trimble GPS receivers. The parabolic antenna can track GPS satellites in the azimuth angle range of 7-357 degrees and the elevation angle range of 5-87 degrees with pointing precision of better than 0.5 degree.

There are two modes of operating the AMCS: Zero-baseline (ZBL) and AMCS modes. In ZBL-mode, the two receivers simultaneously record the signal from the test GPS antenna. In this operating mode, one can determine the receiver clock offsets and the phase biases for each satellite. Typical RMS accuracies of ZBL-mode phase residuals are sub-millimeter level, ranging from 0.4 to 0.7 mm. In the AMCS-mode, one GPS receiver records the signal received at the test antenna, and the other records the signal from the parabola. Thus, one can compare the phases from the two receivers, and determine the antenna and multipath calibration errors of the test antenna.

To assess the antenna and multipath calibration errors in AMCS-mode several experimental configurations have been tested. For example, the parabolic antenna can be parked pointing towards a fixed sky position (static-parabola) while a satellite drifts in and out of the antenna beam. The resulting RMS of the phase differences (or residuals) from these tests is usually two or three times larger than the RMS of the ZBL-mode. However, by modeling the azimuth and elevation angle dependence of the phase residuals, the RMS may be reduced to 1.2 mm. The system can also be programmed so that the parabolic antenna tracks a GPS satellite. The phase residuals obtained by tracking the same satellite over several days shows large amplitude variations over small elevation angle ranges with highly repeatable patterns. Modeling and subtracting the repeating patterns from the phase residuals results in an RMS of about 1.2 mm.

Recently, a second GPS antenna has been installed at a nearby location where the multipath effects are presumably less significant than at the location of the first GPS antenna. The second antenna is equipped with all-weather microwave absorber to further reduce multipath effects. The amplitude of the phase residuals obtained for the second antenna location are significantly smaller than for the first antenna, implying that the second antenna is less affected by multipath. These independent results also served to confirm that the origin of the phase patterns measured is multipath.

4.2 Phased Array Antenna/Receiver (NAVSYS)

NAVSYS Corporation has developed a 16 element digital beam-steering antenna array that is used with a high gain receiver to track the P(Y) code. Up to 12 GPS satellites on both L1 and L2 can be tracked. The beam steering array provides a nominal 10 dB increase in GPS signal strength compared to a conventional survey type antenna. The directivity of the digital beams created from the antenna array also reduces multipath errors, further improving the accuracy of the DGPS corrections generated by the GPS receiver and the navigation and timing solution computed. For C/N0 values above 52 dB-Hz, the P(Y) code receiver provides pseudo-range accuracies of 5 cm (1-sigma). The US Naval Observatory has purchased this type of receiver for evaluation in time transfer applications. Carrier phase outputs are also available for geodetic applications and NAVSYS is considering a semi-codeless version for the civil user.

A further enhancement of the beam steering receiver is to detect the multipath fields around the antenna array and to dynamically minimize these regions by applying nulls in the direction of the multipath signal sources detected for each satellite being tracked. NGS is planning an evaluation this spring of the NAVSYS digital beam steering receiver using the multipath nulling capability in a post-processing mode at the CORS site in Longmont, Colorado.

4.3 Possible VLBI Contribution

A working group of the IVS including members of the IGS and the ILRS was formed to study, whether the GPS satellite antenna phase centers might be determined using VLBI measurements of GPS satellites, or more precisely, using differential phase delay measurements between the GPS satellite and near-by quasars. A report of this working group is presently put together and will soon become available. According to this report the quality of a “map” of a GPS satellite antenna (similar to a radio source map) would only have a quality of the order of 40–50 cm and individual antenna elements could therefore not be distinguished.

It seems, however, that the position of a GPS satellite could probably be determined with an accuracy of about 3 cm. If this is true, a few VLBI observations to GPS satellites could be used to obtain the position of the satellites in the International Celestial Reference Frame (ICRF). The combined analysis of the GPS and VLBI data could then be used to directly get UT1 estimates that are in general not available from satellite data (only length of day (LOD)); but these ideas are outside the scope of this position paper.

4.4 GLONASS, Galileo, and GPS III

The satellite systems GLONASS and in future Galileo should also be considered here. At the moment, the same receiver antenna offsets and patterns are used for GLONASS and for GPS. This can be justified, since the frequencies are quite similar for the two satellite systems and no specific GLONASS calibration values are presently available to our knowledge. In the new antenna format proposed in the Appendix the generalization for GLONASS and Galileo antenna patterns has already been taken into account. The format is also ready to allow for a third GPS frequency.

5 New Format and Calibration Responsibilities

5.1 New Format

The format presently used by the IGS for PCVs (see file `igs_01.pcv` at the IGS Central Bureau Information System) is very simple and basic, but does not really serve the more general needs of various GPS communities. Because the IGS PCV values are generally accepted as the recommended phase center patterns and the format is used by most, if not all, commercial GPS software packages, the various institutions and communities involved in the antenna calibration issues would like to stick to a unique IGS PCV format, but more flexibility is required. The most important additions/modifications that should be included in a new PCV format are:

- Azimuth-dependent variations
- Antenna serial number to allow for individual patterns
- Flexible tabular interval
- Elevation cut-off information
- Information about the calibration source
- Generalization for GLONASS and Galileo
- Inclusion of satellite antenna offsets and patterns
- Formal errors of the phase center values

Further requirements are, that it should be possible to add new "blocks" of information to the format without causing problems. Especially the possibilities to allow for patterns of individual antennae and for azimuth dependent variations are very important for many commercial software packages. In Germany, e.g., each individual GPS antenna to be used in the official survey work of the federal states has to be calibrated and corrected for individual antenna phase patterns.

The old and new format should be maintained in parallel for a reasonably long overlap period to allow for a smooth transition to the new format.

The description and an example of the new format is given in the Appendix.

Table 2: Tasks in the Field of Receiver and Satellite Antenna Information

Topic	Institution(s)
Receiver and antenna names	IGS CB ?
Antenna reference point (ARP)	IGS CB ?
Antenna graphics or pictures	IGS CB ?
Antenna phase center patterns	Hannover ?
Satellite antenna offsets	NGS ?
Satellite antenna patterns	TU Munich ?

5.2 Responsibility for Antenna Information and Calibrations

At present, the IGS Central Bureau is updating the list of receiver and antenna names as well as the calibration results that are most often coming from Gerry Mader at NGS, but clear responsibilities have never really been defined. Because a lot of international and regional institutions rely on the IGS for the availability of consistent receiver antenna patterns, it makes sense to come up with a list of tasks that have to be performed to keep track of antenna and receiver names, antenna patterns etc. and to assign responsible institutions for these tasks. Table 2 contains a draft of such a list.

All information concerning satellite and receiver antennae should consistently be available at the IGS Central Bureau and it might make sense to have an official IGS antenna group to deal with the various issues in the field of antennae.

Ideally, results from at least two independent methods or groups should be compared/combined before an official IGS antenna "product" is released.

Whenever possible, the Hannover (IfE/Geo++) patterns should be used, because with their robot method the influence of multipath effects can be reduced considerably and patterns down to zero degree elevation can be produced. For antennae not calibrated in Hannover, relative patterns from relative field calibrations may be used after conversion to absolute patterns.

Maybe, in future, calibration results from the Haystack Antenna and Multipath Calibration System (AMCS) and the Phased Array Antenna/Receiver may also be used as a source of information.

6 Recommendations (Draft)

The sections above lead to the following recommendations for the "Antenna Session":

1) **Antenna Group:**
Should a group (working group ?) of antenna "experts" be established to take over the task to keep track of antenna issues in general and the transition to absolute phase center variations in special ? Is such a group needed ? Which members , which chair ?

2) **Same Antenna Type, no Antenna Changes:**
Whenever possible, the same antenna type (`AOAD/M_T`) should be installed on all IGS permanent sites.

The antenna setup (including antenna, radom, orientation, environment) should not be changed unless it is absolutely necessary.

3) **New PCV Format:**
Adoption of a new IGS PCV format for receiver and satellite antenna phase center corrections (offsets and patterns) with the additions/modifications according to Section 5.1.

May 31, 2002: New format available after review process.

January 1, 2003: New format as official format; the old format is still available, but no longer updated.

4) **New Receiver Antenna Offsets and Patterns:**
Adoption of absolute antenna PCVs for the receiver antennae. The absolute patterns and offsets (for the Dorne Margolin T antenna `AOAD/M_T`) are given by the robot calibrations obtained by the Hannover group (see Section 5.1).

May 31, 2002: New receiver offsets and patterns available for all major antenna types for tests by the IGS Analysis Centers.

September 30, 2002: Tests by the IGS Analysis Centers completed.

January 1, 2003: IGS Analysis Centers switch to absolute patterns.

5) **New Satellite Antenna Offsets and Patterns:**
Adoption of new satellite antenna offsets (NGS or Manufacturer) and corresponding, consistent patterns (TU Munich).

   May 31, 2002: Satellite antenna offsets and patterns are available for tests by the IGS Analysis Centers.

   September 30, 2002: Tests by the IGS Analysis Centers completed.

   January 1, 2003: IGS Analysis Centers switch to new satellite antenna offsets and patterns.

6) **Convention on Radoms to be Allowed for IGS Sites:**
Should there be some recommendations on what type of radoms may be used at IGS sites ???

It should be noted that recommendation 4) and 5) have to be implemented at the same time.

Appendix: New Antenna Phase Center Information Format

```
                                3 April 2002


                  ANTEX: The Antenna Exchange Format Version 1.0
                  **********************************************

                          M. Rothacher, R. Schmid
                     Forschungseinrichtung Satellitengeodaesie
                                TU Munich

ANTEX VERSION 1.0 FORMAT DEFINITIONS

 +--------------------+------------------------------------------+------------+
 |    HEADER LABEL    |               DESCRIPTION                |   FORMAT   |
 |  (Columns 61-80)   |                                          |            |
 +--------------------+------------------------------------------+------------+
 |ANTEX VERSION / SYST| - Format version (1.0)                   |  F8.1,12X, |
 |                    | - Satellite System: blank or 'G': GPS    |  A1,39X    |
 |                    |                     'R': GLONASS         |            |
 |                    |                     'E': Galileo         |            |
 |                    |                     'M': Mixed           |            |
 +--------------------+------------------------------------------+------------+
 |PCV TYPE / REFANT   | - Phase center variation type:           |  A1,19X,   |
 |                    |     'A': absolute values                 |            |
 |                    |     'R': relative values                 |            |
 |                    | - Reference antenna for relative values  |  A20,20X   |
 |                    |     (blank: AOAD/M_T)                    |            |
 +--------------------+------------------------------------------+------------+
*|COMMENT             | Comment line(s)                          |   A60      |*
 +--------------------+------------------------------------------+------------+
 |END OF HEADER       | Last record in the header section.       |   60X      |
 +--------------------+------------------------------------------+------------+
 |START OF ANTENNA    | Record indicating the start of an antenna|   60X      |
 |                    | section                                  |            |
 +--------------------+------------------------------------------+------------+
 |TYPE / SERIAL NO    | Receiver antenna:                        |            |
 |                    |  - Antenna type: strict IGS              |   A20,     |
 |                    |    rcvr_ant.tab antenna and radome codes |            |
 |                    |  - Serial number (blank: all representa- |  A20,20X   |
 |                    |    tives of the specified antenna type)  |            |
```

```
 |                    | Satellite antenna:                       |            |
 |                    |  - Antenna type: name of the satellite   |            |
 |                    |    block                                 |            |
 |                    |    Example: 'BLOCK IIR'                  |            |
 |                    |  - Serial number (blank: all satellites  |            |
 |                    |    of the specified block)               |            |
 |                    |    For the selection of a single         |            |
 |                    |    satellite the PRN together with the   |            |
 |                    |    satellite system flag (blank,'G','R', |            |
 |                    |    'E') has to be specified.             |            |
 |                    |    Example: 'G05'                        |            |
 +--------------------+------------------------------------------+------------+
 |METH / BY / # / DATE| - Calibration method:                    |     A20,   |
 |                    |     'CHAMBER','FIELD' or blank           |            |
 |                    | - Name of agency                         |     A20,   |
 |                    | - Number of single calibrations          |    I6,4X,  |
 |                    | - Date                                   |     A10    |
 +--------------------+------------------------------------------+------------+
 |DAZI                | Increment of the azimuth:                |  2X,F6.1,  |
 |                    |   0 to 360 with increment 'DAZI'         |     52X    |
 |                    |   (in degrees).                          |            |
 |                    |   360 degrees have to be divisible by    |            |
 |                    |   'DAZI'.                                |            |
 |                    |   Common value for 'DAZI': 5.0           |            |
 |                    | For non-azimuth-dependent phase center   |            |
 |                    | variations '0.0' has to be specified.    |            |
 +--------------------+------------------------------------------+------------+
 |ZEN1 / ZEN2 / DZEN  | Receiver antenna:                        |  2X,3F6.1, |
 |                    |   Definition of the grid in zenith:      |     40X    |
 |                    |   'ZEN1' to 'ZEN2' with increment 'DZEN' |            |
 |                    |   (in degrees).                          |            |
 |                    |   'ZEN1' and 'ZEN2' always have to be    |            |
 |                    |   multiples of 'DZEN'.                   |            |
 |                    |   'ZEN2' always has to be greater than   |            |
 |                    |   'ZEN1'.                                |            |
 |                    |   Common value for 'DZEN': 5.0           |            |
 |                    |   Example: '     0.0  90.0   5.0'        |            |
 |                    | Satellite antenna:                       |            |
 |                    |   Definition of the grid in nadir:       |            |
 |                    |   'ZEN1' to 'ZEN2' with increment 'DZEN' |            |
 |                    |   (in degrees).                          |            |
 |                    |   'ZEN1' and 'ZEN2' always have to be    |            |
 |                    |   multiples of 'DZEN'.                   |            |
 |                    |   'ZEN2' always has to be greater than   |            |
 |                    |   'ZEN1'.                                |            |
 |                    |   Common value for 'DZEN': 1.0           |            |
 |                    |   Example: '     0.0  14.0   1.0'        |            |
 +--------------------+------------------------------------------+------------+
 |# OF FREQUENCIES    | Number of frequencies, for which phase   |   I6,54X   |
 |                    | patterns are stored for the current      |            |
 |                    | antenna.                                 |            |
 +--------------------+------------------------------------------+------------+
*|COMMENT             | Comment line(s)                          |     A60    |*
 +--------------------+------------------------------------------+------------+
 |START OF FREQUENCY  | Record indicating the start of a new     |3X,A1,I2,54X|
 |                    | frequency section. The satellite system  |            |
 |                    | flag (blank,'G','R','E') has to be       |            |
 |                    | specified together with the number of the|            |
 |                    | frequency.                               |            |
```

```
 +--------------------+----------------------------------------+-----------+
 |NORTH /EAST / UP    | Receiver antenna:                      | 3F10.2,30X |
 |                    |  Eccentricities of the antenna phase   |            |
 |                    |  center relative to the antenna reference|          |
 |                    |  point (ARP). North, east and height   |            |
 |                    |  component (millimeters).              |            |
 |                    | Satellite antenna:                     |            |
 |                    |  Eccentricities of the antenna phase   |            |
 |                    |  center relative to the center of mass of|          |
 |                    |  the satellite in X-, Y- and Z-direction |          |
 |                    |  (millimeters).                        |            |
 +--------------------+----------------------------------------+-----------+
 |AZI/ZEN1/ZEN2/DZEN  | Record initializing a new phase pattern |  2X,4F6.1, |
 |                    | data block for azimuth 'AZI', from 'ZEN1'|   34X     |
 |                    | to 'ZEN2' (with increment 'DZEN').     |            |
 |                    | Neither other types of records nor     |            |
 |                    | comment lines are allowed after this   |            |
 |                    | record and within the subsequent data  |            |
 |                    | block!                                 |            |
 +--------------------+----------------------------------------+-----------+
 |(Pattern values)    | Phase pattern values in 0.01 mm.       |   mF8.2    |
 |                    | After 10 values (per azimuth) continue |            |
 |                    | values in next data record.            |            |
 +--------------------+----------------------------------------+-----------+
 |END OF FREQUENCY    | Record indicating the end of a frequency |3X,A1,I2,54X|
 |                    | section (see also 'START OF FREQUENCY'). |          |
 +--------------------+----------------------------------------+-----------+
*|START OF FREQ RMS   | Record indicating the start of an rms  |3X,A1,I2,54X|*
 |                    | value block related to the specified   |            |
 |                    | frequency.                             |            |
 +--------------------+----------------------------------------+-----------+
*|NORTH /EAST / UP    | Rms of the eccentricities (millimeters). | 3F10.2,30X |*
 +--------------------+----------------------------------------+-----------+
*|AZI/ZEN1/ZEN2/DZEN  | Record initializing a new phase pattern |  2X,4F6.1, |*
 |                    | rms data block for azimuth 'AZI', from |   34X      |
 |                    | 'ZEN1' to 'ZEN2' (with increment 'DZEN').|          |
 |                    | Neither other types of records nor     |            |
 |                    | comment lines are allowed after this   |            |
 |                    | record and within the subsequent data  |            |
 |                    | block!                                 |            |
 +--------------------+----------------------------------------+-----------+
*|(Pattern rms values)| Phase pattern rms values in 0.01 mm.   |   mF8.2    |*
 |                    | After 10 values (per azimuth) continue |            |
 |                    | values in next data record.            |            |
 +--------------------+----------------------------------------+-----------+
*|END OF FREQ RMS     | Record indicating the end of an rms value|3X,A1,I2,54X|*
 |                    | block (see also 'START OF FREQ RMS').  |            |
 +--------------------+----------------------------------------+-----------+
 |END OF ANTENNA      | Record indicating the end of an antenna |   60X      |
 |                    | section                                |            |
 +--------------------+----------------------------------------+-----------+
```

Example of an ANTEX file:

```
=============================================================================
     1.0            G                                   ANTEX VERSION / SYST
```

```
A                                                           PCV TYPE / REFANT
                                                            COMMENT
                                                            COMMENT
                                                            END OF HEADER
                                                            START OF ANTENNA
TRM33429-20+GP      1220226043                              TYPE / SERIAL NO
FIELD               FESG                     3    03-APR-02 METH / BY / # / DATE
     0.0                                                    DAZI
     0.0  90.0   5.0                                        ZEN1 / ZEN2 / DZEN
     2                                                      # OF FREQUENCIES
                                                            COMMENT
                                                            COMMENT
   G01                                                      START OF FREQUENCY
      0.20     -0.75     72.86                              NORTH / EAST / UP
     0.0   0.0  90.0   5.0                                  AZI/ZEN1/ZEN2/DZEN
   -6.19   -1.03    2.02    3.25    3.31    2.76    1.90    0.74   -0.80   -2.72
   -4.78   -6.55   -7.56   -7.48   -6.30   -4.35   -2.23   -0.61    0.00
   G01                                                      END OF FREQUENCY
   G02                                                      START OF FREQUENCY
     -0.19     -0.23     65.76                              NORTH / EAST / UP
     0.0   0.0  90.0   5.0                                  AZI/ZEN1/ZEN2/DZEN
   -6.75   -3.68   -1.52   -0.08    0.97    1.85    2.61    3.19    3.46    3.35
    2.89    2.20    1.45    0.80    0.34    0.09    0.00   -0.01    0.00
   G02                                                      END OF FREQUENCY
                                                            END OF ANTENNA
================================================================================
```

References

Aparicio, M., P. Brodie, L. Doyle, J. Rajan, and P. Torrione, GPS Satellite and Payload, in *Global Positioning System: Theory and Applications*, vol. 1, edited by B.W. Parkinson and J.J. Spilker, pp. 209–244, Progress in Astronautics and Aeronautics, Volume 163, 1996.

Böder, V., F. Menge, G. Seeber, G. Wübbena, and M. Schmitz, How to Deal With Station Dependent Errors - New Developments of the Absolute Calibration of PCV and Phase-Multipath With a Precise Robot, in *Proceedings of the ION GPS-01, Salt Lake City, Utah*, 2001.

Jaldehag, R.T.K., An Experimental and Theoretical Study of Antenna Related Error Sources, *Technical Report 276*, Chalmers University of Technology, Göteborg, Sweden, 1995.

Mader, G., GPS Antenna Calibration at the National Geodetic Survey, *GPS Solutions*, *3*(1), 50–58, 1999.

Mader, G., A Comparison of Absolute and Relative GPS Antenna Calibrations, *GPS Solutions*, *4*(4), 37–40, 2001.

Rocken, C., C. Meertens, B. Stephens, J. Braun, T. VanHove, S. Perry, O. Ruud, M. McCallum, and J. Richardson, Receiver and Antenna Test Report, UNAVCO Academic Research Infrastructure (ARI), 1996.

Rothacher, M., Comparison of Absolute and Relative Antenna Phase Center Variations, *GPS Solutions*, *4*(4), 55–60, 2001.

Rothacher, M., W. Gurtner, S. Schaer, R. Weber, W. Schlüter, and H. O. Hase, Azimuth- and Elevation-Dependent Phase Center Corrections for Geodetic GPS Antennas Estimated From GPS Calibration Campaigns, in *International Association of Geodesy Symposia, Symposium No. 115: GPS Trends in Precise Terrestrial, Airborne, and Spaceborne Applications*, edited by G. Beutler et al., Springer, Boulder, CO, USA, 1995.

Rothacher, M., W. Gurtner, S. Schaer, R. Weber, and H. O. Hase, Azimuth- and Elevation-Dependent Phase Center Corrections for Geodetic GPS Antennas Estimated from GPS Calibration Campaigns, in *IAG Symposium No. 115*, edited by W. Torge, pp. 335–339, Springer-Verlag, 1996.

Schmid, R., and M. Rothacher, Estimation of Elevation-Dependent Satellite Antenna Phase Center Variations of GPS Satellites, in preparation, 2002.

Schupler, B.R., T.A. Clark, and R.L. Allshouse, Characterizations of GPS User Antennas: Reanalysis and New Results, in *International Association of Geodesy Symposia, Symposium No. 115: GPS Trends in Precise Terrestrial, Airborne, and Spaceborne Applications*, edited by G. Beutler et al., Springer, Boulder, CO, USA, 1995.

Springer, T.A., *Modeling and Validating Orbits and Clocks Using the Global Positioning System*, Ph.D. dissertation, Astronomical Institute, University of Berne, Berne, Switzerland, 1999.

Wübbena, G., M. Schmitz, F. Menge, V. B öder, and G. Seeber, Automated Absolute Field Calibration of GPS Antennas in Real-Time, in *Proceedings of the ION Meeting 2000*, Salt Lake City, 2000.

Absolute Receiver Antenna Calibrations with a Robot

~~Martin Schmitz~~, Gerhard Wübbena, Gerald Boettcher

Geo++®
Gesellschaft für satellitengestützte geodätische und navigatorische Technologien mbH
D-30827 Garbsen, Germany
~~www.geopp.de~~

Günter Seeber, Volker Böder, Falko Menge

Institut für Erdmessung (*IfE*),
Universität Hannover
D-30167 Hannover, Germany
www.ife.uni-hannover.de

Phase variations (PCV) of GPS receiving antennas are a significant error component in precise GPS applications. A calibration procedure has been developed by Geo++® and IfE, which directly determines absolute PCV in a field procedure without any multipath influence. The precision and resolution of the procedure allows the determination of reliable elevation and azimuth dependent variations.

There exists several problems with existing relative field calibration procedures and with absolute chamber calibration results. However, PCV are urgently needed for mixed antenna type applications (e.g. RTK networks, engineering tasks). The goal of the developments is the separation of multipath and phase variations to get absolute PCV independent from a reference antenna and independent from site or location. Since 1995 the absolute PCV field calibration has been developed, which resulted into the Automated Absolute PCV Field Calibration in Realtime in the beginning of 2000.

The MP is eliminated through short-term differences, as MP is the same for subsequent epochs. The PCV information is reintroduced by orientation changes (rotations and tilts) of the antenna, which are performed by a robot. The robot itself is calibrated and gives a precise, fixed and stable rotation point for an antenna, fast orientation changes, a high level of automation and robot guidance in realtime.

The automated procedure serves for a homogeneous coverage of the antenna hemisphere by 6000 to 8000 different positions. Certain optimizations concerning satellite constellation, observation time, dynamic elevation mask are use in the operational calibration. The absolute field calibration has been verified intensively and has been compared to absolute chamber and relative calibration results. Also the major concern of the global scale associated with the use of absolute PCV has been experimentally proven to be due to the relative PCV. Over large baseline satellites are viewed under different elevations and hence different relative PCV.

The repeatability of the Absolute PCV Field Calibration is at the 1 mm level, which corresponds to the standard deviation in the 0.2 to 0.4 mm (1 sigma) range. A calibration gives absolute 3D offsets, absolute elevation and azimuth dependent PCV in a simultaneous adjustment of L1, L2 GPS and GLONASS signal within a few hours.

Two findings from the numerous calibrations already performed are the effect of dome construction on PCV and outliers in high quality geodetic antennas. The effect of domes may be small at the few millimeter level, but can also amount to PCV changes of 10 mm close to the zenith (~75 deg), or 12 mm at ~30 deg elevation for the ionospheric free linear combination L0. Within the “Dorne Margolin Type” choke ring antennas of two manufacturers outliers have been detected. Basically the offset was differing compared to a type mean, which transfers to 15 mm effects in L0 PCV.

Depending on the applications, PCV affects long term static GPS differently than real-time GPS. At the same time different antenna types are involved, which requires the knowledge of absolute PCV. The use of type means is appropriate for antennas not accesible, but uncertainties on the correctness remain. For precise applications an individual calibration is recommended. The PCV determination is also a first step to separate PCV and MP and to calibrate absolute station dependent carrier phase MP. Less investigations have been done on absolute PCV of rover antennas, which, however, becomes more important due to the mixed antenna situation in GPS reference networks and RTK networks.

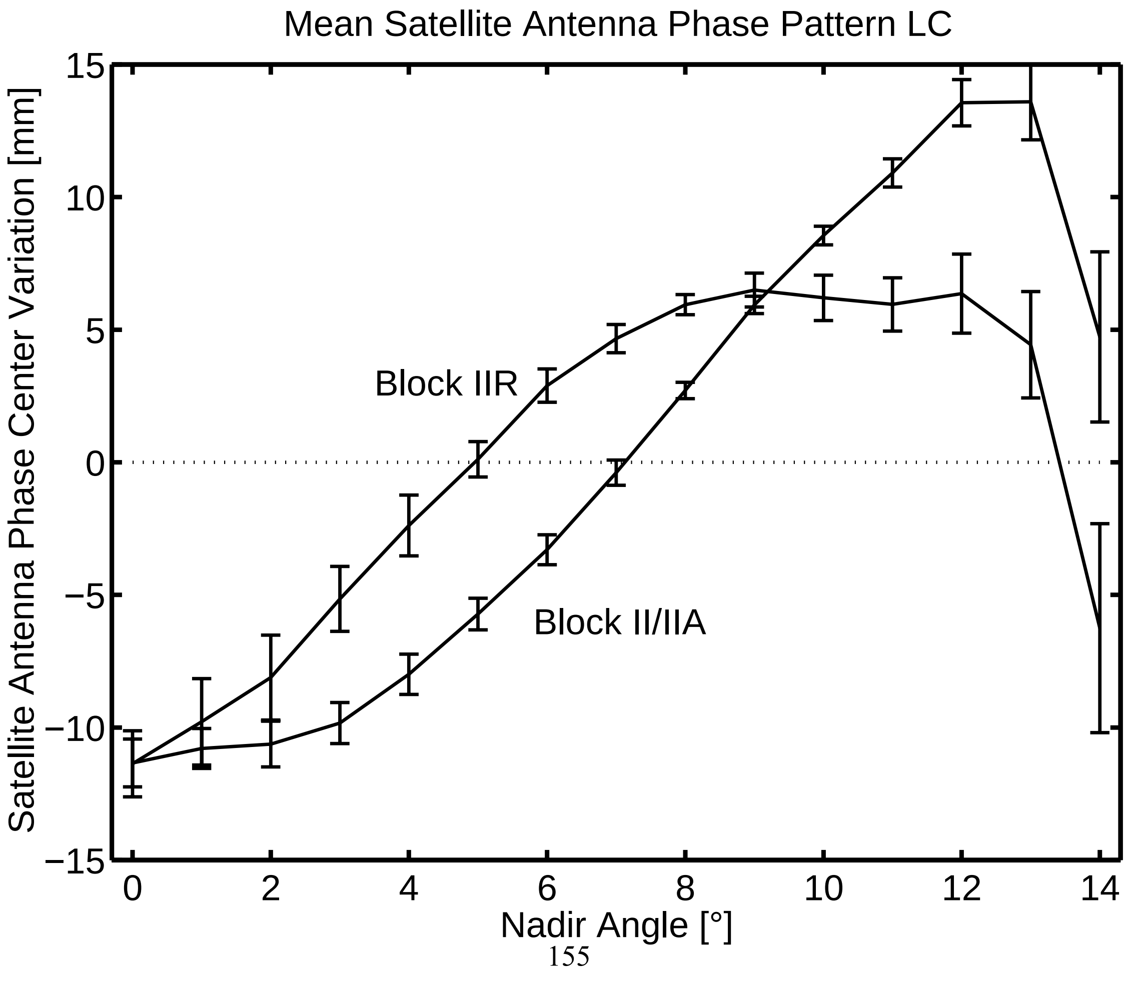
Estimation of Elevation-Dependent GPS Satellite Antenna Phase Center Variations

R. Schmid and M. Rothacher
Institut für Astronomische und Physikalische Geodäsie, TU München
schmid@bv.tum.de

At present absolute receiver antenna phase center patterns of reasonable quality are available (e.g. from robot measurements), but not in use, due to a large terrestrial scale of about 15 ppb that results in global GPS solutions. This effect is most probably caused by the GPS satellite antenna phase centers whose position varies with the emitting direction. Using relative receiver antenna phase center patterns these variations partially vanished in the past, because there is a one-to-one correspondence between receiver and satellite antenna patterns.

We implemented elevation- (resp. nadir-) dependent satellite antenna phase center variations into the Bernese GPS Software and estimated daily patterns for eight consecutive days with real GPS data from more than 100 permanent IGS stations. Thereby absolute receiver antenna pattern values from the group in Hannover (IfE/Geo++) were introduced and the global scale was fixed.

We could show that there are two different satellite antenna phase patterns, one for the Block II/IIA satellites and a different one for the Block IIR satellites (see fig.). The patterns could be estimated with a repeatability of 1-3 mm between different days and between individual satellites within one block. In several global parameters systematic effects showed up: e.g. the geocenter of the Block II/IIA orbits was shifted by about -2 cm in y-direction and the tropospheric delays increased by about 3 mm.



Multipath characteristics of GPS signals as determined from the Antenna and Multipath Calibration System (AMCS): Preliminary results

Park, Kwan-Dong, Pedro Elosegui, James Davis, James Normandeau
(Harvard-Smithsonian Center for Astrophysics)
Per Jarlemark (SP Swedish National Testing and Research Institute)
Brian Corey, Arthur Niell (MIT/Haystack Observatory)
Chuck Meertens, and Victoria Andreatta (UNAVCO/UCAR Facility)

ABSTRACT

Geophysical applications of the Global Positioning System (GPS) for studies such as global sea level change and glacial isostatic adjustment require very high accuracy (1 mm/year) determinations of site velocity, especially of its vertical component. Despite the many efforts devoted by investigators to the calibration of site-specific errors, signal scattering and multipath remain an unsolved problem. We have developed an Antenna and Multipath Calibration System (AMCS) for characterizing site-specific GPS phase measurement errors. The system consists of a high-gain, multipath-free, 3-m diameter parabolic antenna, two test antennas, and two Trimble GPS receivers. The parabolic antenna can track GPS satellites in the azimuth angle range of 7-357 degrees and the elevation angle range of 5-87 degrees with pointing precision of better than 0.5 degree.

There are two modes of operating the AMCS: Zero-baseline (ZBL) and AMCS modes. In ZBL-mode, the two receivers simultaneously record the signal from the test GPS antenna. In this operating mode, one can determine the receiver clock offsets and the phase biases for each satellite. Typical RMS accuracies of ZBL-mode phase residuals are sub-millimeter level, ranging from 0.4 to 0.7 millimeter. In the AMCS-mode, one GPS receiver records the signal received at the test antenna, and the other records the signal from the parabola. Thus, one can compare the phases from the two receivers, and determine the antenna and multipath calibration errors of the test antenna.

To assess the antenna and multipath calibration errors in AMCS-mode we have tested several experimental configurations. For example, we can park the parabolic antenna pointing towards a fixed sky position (static-parabola), and let a satellite drift in and out of the antenna beam. The resulting RMS of the phase differences (or residuals) from these tests is usually two or three times larger than the RMS of the ZBL-mode. However, we find that by modeling the azimuth and elevation angle dependence of the phase residuals the RMS reduces to 1.2 mm. We can also program the system so that the parabolic antenna tracks a GPS satellite. The phase residuals obtained by tracking the same satellite over several days shows large amplitude variations over small elevation angle ranges with highly repeatable patterns. Modeling and subtracting the

repeating patters from the phase residuals results in RMS of about 1.2 mm.

We have recently installed a second GPS antenna at a nearby location where the multipath effects are presumably less significant than at the location of the first GPS antenna. The second antenna is equipped with all-weather microwave absorber to further reduce multipath effects. The amplitude of the phase residuals obtained for the second antenna location are significantly smaller than for the first antenna, implying that the second antenna is less affected by multipath. These independent results also served to confirm that the origin of the phase patterns measured is multipath.

IGS

SESSION 9:

DATA CENTER ISSUES

Current Status of IGS Data Centers

Carey Noll
NASA GSFC, Greenbelt MD, USA

Abstract: The International GPS Service (IGS) has been operational for nearly ten years. This presentation will outline background information, current status, and recent developments at the IGS data centers. The overview will also include a review of data and product holdings at the various IGS data centers as well as statistics on data delivery. An introduction to the new IGS working group on data centers will be given.

Background

The International GPS Service (IGS) has been an operational service within the IAG since 1994. The IGS has established a hierarchy of data centers to distribute data from the network of tracking stations: operational, regional, and global data centers. This scheme provides an efficient access and storage of GPS data, thus reducing traffic on the Internet, as well as a level of redundancy allowing for security of the data holdings.

Recent Data Center Developments

The data and product types currently archived at the IGS Global Data centers are summarized in Table 1 below.

Table 1. IGS Global Data Center Holdings

Data Type	CDDIS	IGN	SIO
Data			
GPS daily (D format)*	X	X	X
GPS daily (O format)	X		X
GPS hourly (30-second)*	X	X	X
GPS hourly (high-rate)	X		
GLONASS daily (D)† format)†	X	X	
GLONASS daily (O)† format)	X		
Products			
Orbits, etc.*	X	X	X
SINEX*	X	X	X
Troposphere†	X	X	X
IONEX†	X	X	

Notes: * Official IGS data set/product
† Pilot project/working group data set/product

In 2001, approximately sixty percent of the daily GPS data files were available from the IGS global data centers within three hours; the same percentage of hourly, thirty-second files were available within fifteen minutes.

Real-Time Issues. Data center involvement in the archive and dissemination of real-time data will be dependent upon requirements developed by the IGS Real-Time Working Group and recommendations generated by this workshop. Early discussions imply that existing data centers would serve as a distribution or relay center, receiving real-time data from a network of stations and transmitting these data to interested analysis centers. Data center configuration information, such as storage capacity, network bandwidth, and redundant network connectivity needs to be determined for participating data centers. Redundancy of data flow paths is an obvious concern for the real-time activity.

IGS Data Center Working Group. At its last meeting in December, the IGS Governing Board recommend the formation of a working group to focus on data center issues. This working group will tackle many of the problems facing the IGS data centers as well as develop new ideas to aid users both internal and external to the IGS. The direction of the IGS has changed since its start in 1992 and many new working groups, projects, data sets, and products have been created and incorporated into the service since that time. Therefore, it is now an appropriate time to revisit the requirements of data centers within the IGS. The membership of this group will consist of contacts from the current IGS data centers as well as IGS colleagues with expertise in data archiving and data flow. Thus far, a draft charter has been developed and prospective members have been contacted; the charter will be presented at the IGS Governing Board meeting after this workshop for approval.

GPS Seamless Archive Centers (GSAC); Streamlining Data/Metadata Exchange in the GPS Community

Michael Scharber
Scripps Orbit and Permanent Array Center

Abstract

In an effort to help simplify and streamline both the discovery of, and access to, GPS-related data and metadata the GSAC, or GPS Seamless Archive Centers (a UNAVCO project) aims to build a cohesive, structured and replicated data/metadata exchange environment for all types of GPS users, data centers and researchers around the world. Through the formation of a structured set of cataloging mechanisms and participation of a network of GPS data providers, archive centers and top-level "brokers", called retailers, the GSAC offers users of GPS data the opportunity to span the entire GSAC-published data holdings of multiple physical data centers in a single "query" for information, or data collection session.

Providing a simplified and centralized point of access to the GSAC for users are the GSAC retailers - those agencies maintaining a GSAC database server (with a common GSAC relational schema) and providing an anonymously-available GSAC retailer "service" through a predefined http CGI protocol. The GSAC retailer service, in turn, provides a very simple API for client applications designed for data discovery, data collection, or both. The set of GSAC client applications, ultimately, offer various interfaces to the same superset of GPS-related data holdings and limited metadata contained in each and every GSAC retailer. From a single retailer client application a user can collect hundreds, even thousands, of files from dozens of archives, matching complex query parameters such as a window of time, a spatial bounding box, metadata constraints, or a combination of all three.

Also of use to data centers, the structured environment of the GSAC, combined with the various utilities available, provides convenient mechanisms for exchanging/mirroring data with other data centers, uncovering data corruption problems and metadata errors, and minimizing the time and network traffic required for these and similar operations.

Nearing the end of the "test" phase of the GSAC project several agencies are embarking on operational integration of GSAC utilities and services for the regular activities. In parallel, end user applications and web-based interfaces are being developed and tested for ease of use and functionality during this phase, after which users will have full access to the entire GSAC database of information.

With the anticipated participation of additional data centers the GPS community shall hopefully begin to reap the many benefits we hope the GSAC will provide. For more information please visit SOPAC's GSAC project page (http://gsac.ucsd.edu) for more information about the GSAC in general, SOPAC's participation in the GSAC and access to GSAC-related applications and contact information.

IGS Workshop 2002
Ottawa, Canada
Data Centers, Ideas and Issues

Loïc Daniel, IGN, France Edouard Gaulué, IGN, France

In this paper, I'll try to address some of the points that seem of importance to me, this will inevitably be biased by what we see from our position at IGN as a Global Data Center (GDC). I won't try to encompass all the aspects to be dealt with in this session or about data centers in general. This paper is intended mostly as a repository of present or potential problems that I have identified and an incentive to discuss and find ideas among the community.

1. Present situation

First I'll describe the raw characteristics of the data management at IGS data centers the way we do it presently, I'll try to summarize our activities and evaluate the impact in terms of computer and network loads.

Basic data management

These are the tasks that should be operated on the fly, with a minimal additional delay induced at each step. The data moving operations rely upon a layered structure of Data Centers. The goal is to propagate observations of the stations and products from analysis centers to final places where they are easily available to everyone. Most if not all of the files should end at the GDCs.

Two types of data flows may be considered:

1) file transfers between data or analysis centers as part of the general scheme defined by IGS in order to ensure the best performance in data availability to analysis centers and users. This is the "IGS data flow". It represents the main part of the day to day activities of the data centers. The objective is to put the data and product files at places where they can be downloaded by users. This is the part of the data flow that can be controlled, optimized and supervised because all actions are triggered by an identified component of the data network and following a predefined time table.

2) file transfers initiated by users of the service, this is the "users data flow". Users can be IGS analysis centers and any other kind of user of the IGS. This is much less controlled by data centers, the files are provided for download on an ftp server and users get them as they want without registering or making a special agreement whatsoever. In some cases, a user will issue a request for offline data and the data center will have to restore data and provide access but this tends to be the exception since most data centers (at least the global ones) strive for putting online all the files created since the beginning of the service.

SESSION 10:

WORKING GROUP REPORTS

International GLONASS Service – Pilot Project Status
March 31, 2002

James A. Slater, Chair
IGLOS Pilot Project Committee

1. GLONASS CONSTELLATION STATUS

Between January 1 and March 31, 2002, there were 6-7 healthy, operational GLONASS satellites. They are all in planes 1 and 3 of the constellation. The first new GLONASS-M satellite, GLONASS No. 711 in Plane 1/Slot 5, has not yet been designated as operational. It is not clear what if any problems may have been encountered after launch.

2. TRACKING NETWORK STATUS

A. GLONASS Receivers

The number of "permanent" tracking stations has grown slightly since December 2001. There are now 50 stations in the network, continuously tracking the GLONASS satellites and transmitting their data to the IGS Data Centers. Forty-five or more of these stations have been sending data to the data centers each week. Most of the receivers are Ashtech Z18 or JPS Legacy models. New stations that came on-line during the last three months include:

- Frankfurt, Germany (FFMJ)
- Kourou, French Guyana (KOU1)
- Zimmerwald, Switzerland (ZIMZ)

An updated list of participating stations is included at the end of this report.

B. SLR Tracking

The ILRS has agreed to continue to track three GLONASS satellites as part of their standard tracking protocol. In January 2002, the IGLOS Project Committee requested the ILRS to track two of the satellites in orbit plane 1 and one satellite in plane 3. Unfortunately, the new GLONASS-M satellite in Plane 1/Slot 5 has been set healthy since it was launched, although this does not prevent SLR stations from tracking it.

SLR Observations of GLONASS Satellites
(Jan. 1– Mar. 31, 2002)

Plane-Slot	GLONASS No. (SLR/Russia)	No. of Passes	No. of Normal Pts.	No. of Tracking Sites
1 - 7	80 (786)	417	2,056	22
1 - 6	86 (790)	71	387	14
1 - 3	87 (789)	204	950	20
1 - 5	88 (711)	9	69	3
3 - 24	84 (788)*			

*Although being tracked, the actual no. of passes, normal points and tracking sites for GLONASS 84 as of March 31, 2002 was not clearly defined when this table was produced.

3. ORBIT PROCESSING

BKG, ESA and the Russian Mission Control Center (MCC) continue to compute and make available GLONASS orbits on a routine basis. The MCC orbits are based on SLR data. A combination orbit is produced by Robert Weber, the Analysis Center Coordinator, from the orbits of these three centers.

4. USER INFORMATION

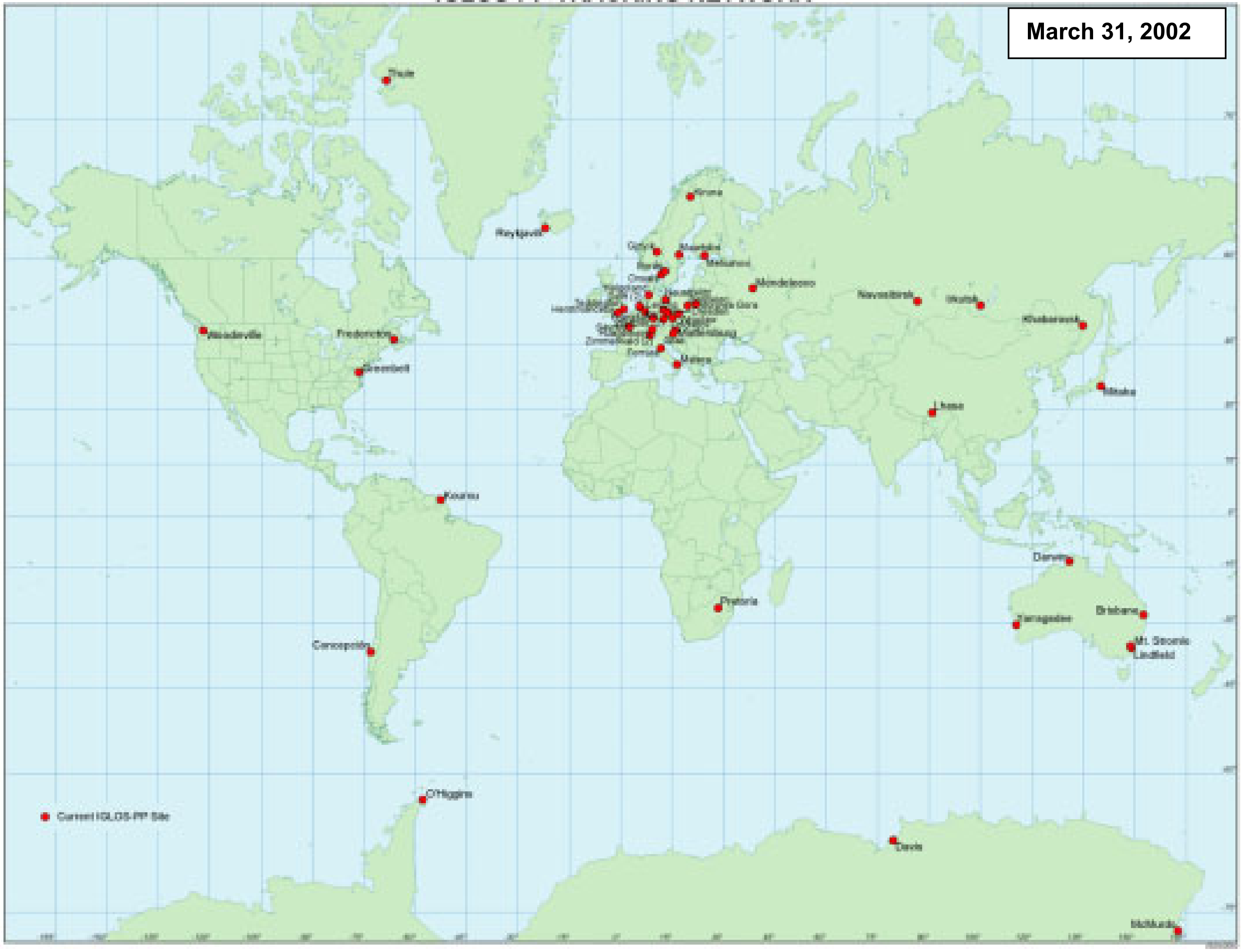
In order to identify any users of the IGLOS data products, both Ashtech and Topcon were contacted. According to Ashtech, they are selling few if any Ashtech Z18 receivers and not promoting the receiver any more. The number of receivers sold was so small that they thought it wasn't worth pursuing the owners, as many of them are already IGLOS participants. Attempts to contact Topcon have so far elicited no response, but we will continue to try to get Topcon's help in identifying a user community.

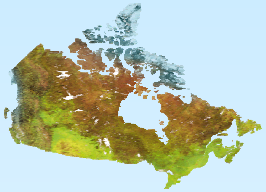
5. INTEGRATION OF IGLOS INTO IGS STANDARD OPERATIONS

In February, the IGS sent letters to all IGLOS participants officially inviting them to become part of the IGS. Procedural instructions were provided so that the IGLOS tracking stations could comply with IGS documentation requirements.

Incorporation of the IGLOS stations requires revised station log forms, some modifications to the Analysis Center processing software, and some adjustments at the global data centers to accommodate GLONASS data mixed in with GPS data. It appears that all is essentially ready to start combined GLONASS-GPS operations.

IGLOS-PP TRACKING NETWORK





IGS Reference Frame Working Group Report

Remi Ferland

02/04/10

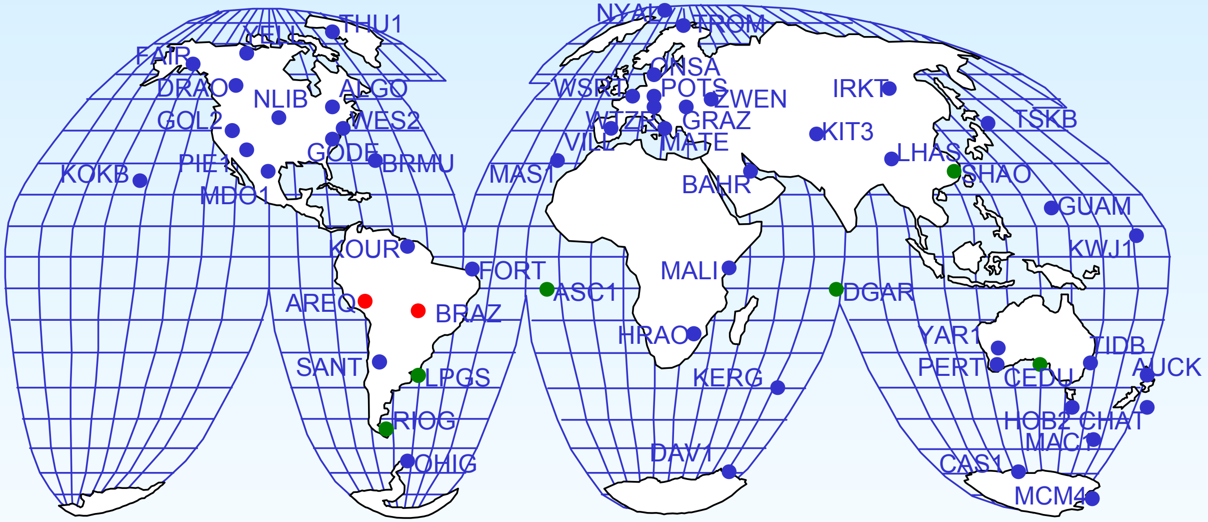
Natural Resources Canada Ressources naturelles Canada

Canada

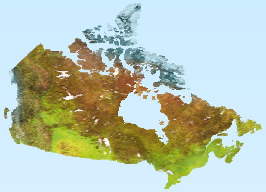
Summary

- Realisation of ITRF2000
  - Stations / Transformations (IGS97-IGS00)
- SINEX Combination
  - Stations / ERP’s / Geocenter
- Contribution to IERS Analysis Campaign
- SINEX V 2.0

IGS Realization of ITRS



- 🟥 Tracking Sites used for IGS97 but Removed for IGS00 (2)
- 🟩 Tracking Sites Added to IGS00 (5)
- 🟦 Tracking Sites used for IGS97 and IGS00 (49)

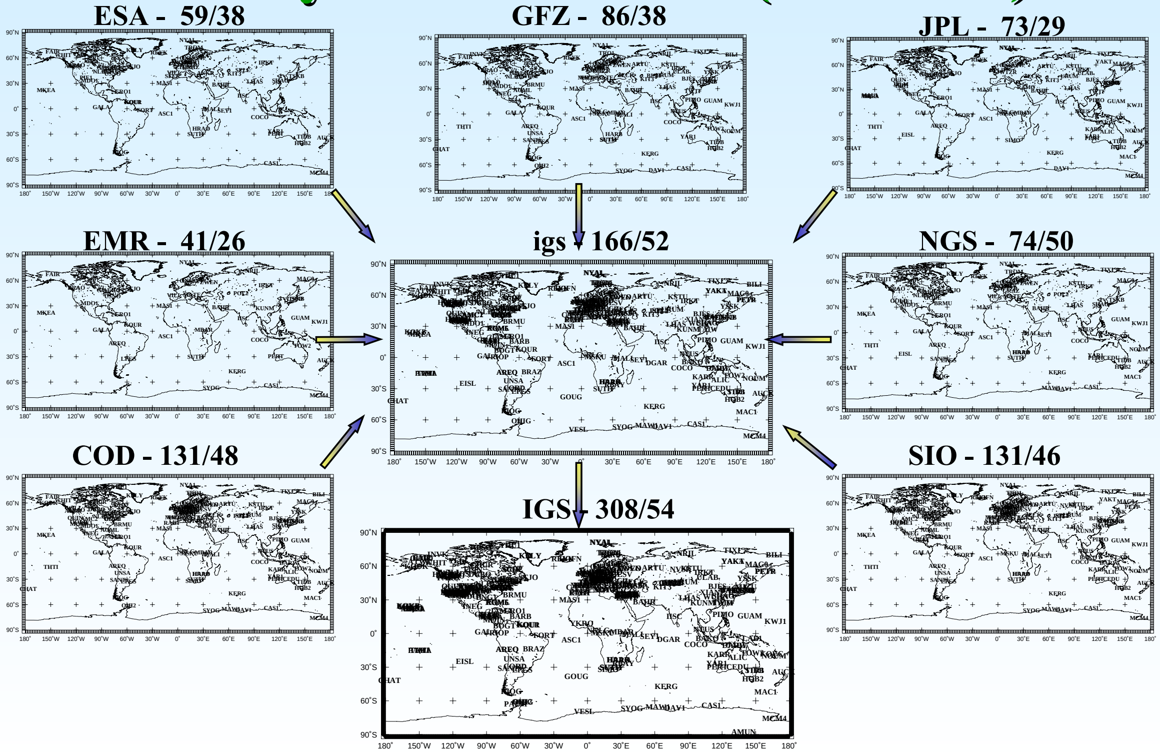


IGS00 highlights

- Stations (51 - 2 + 5 = 54)
- Implemented Wk 1143 (01/12/02)
- Transformation IGS00 to IGS97 (1998.0):

Parameter	Units	Estimate	Sigma	Estimate	Sigma
				(-/y)	(-/y)
R X	(mas)	0.04	0.05	0.00	0.04
R Y	(mas)	0.00	0.06	0.00	0.04
R Z	(mas)	0.04	0.04	0.03	0.03
T X	(m)	0.0060	0.0025	-0.0004	0.0017
T Y	(m)	0.0056	0.0033	-0.0008	0.0019
T Z	(m)	-0.0201	0.0051	-0.0015	0.0028
SCL	(ppb)	1.40	0.12	0.01	0.12

Weekly Combination (Wk1157)



ESA - 59/38

GFZ - 86/38

JPL - 73/29

EMR - 41/26

igs - 166/52

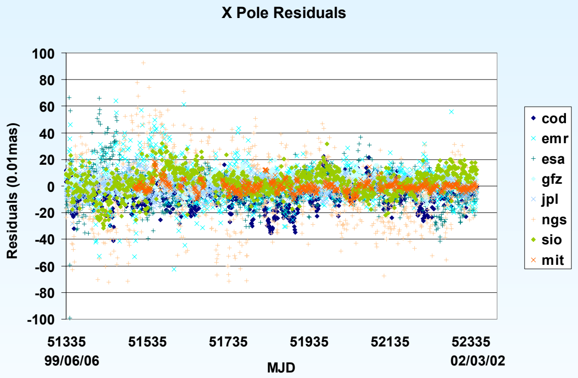
NGS - 74/50

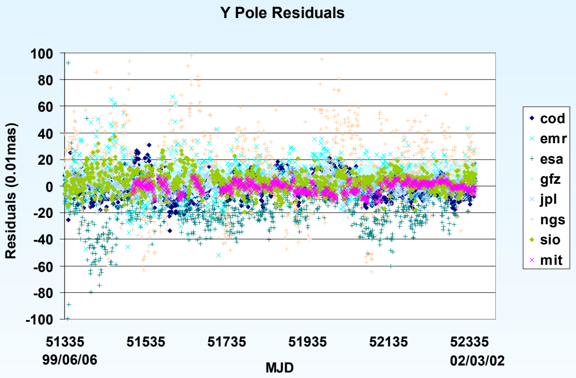
COD - 131/48

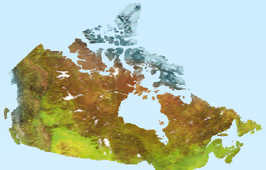
SIO - 131/46

IGS - 308/54

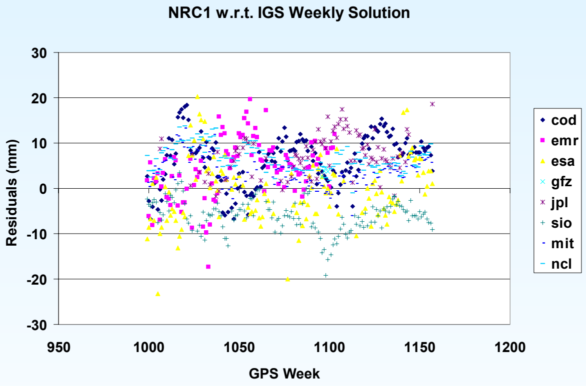
Daily AC & GNAAC X&Y Pole Residuals w.r.t. igs00P02


X Pole Residuals

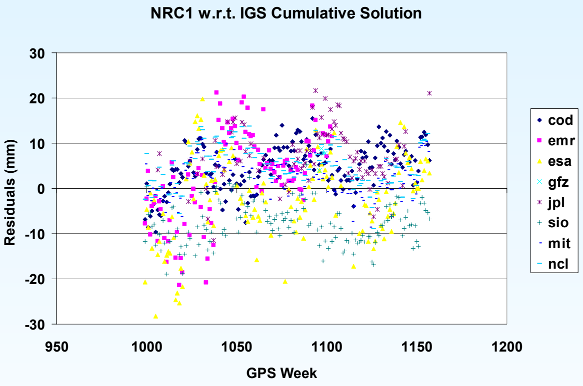

Y Pole Residuals



AC & GNAAC Height Residuals at NRC1 w.r.t. IGS Weekly & Cumulative



NRC1 w.r.t. IGS Weekly Solution

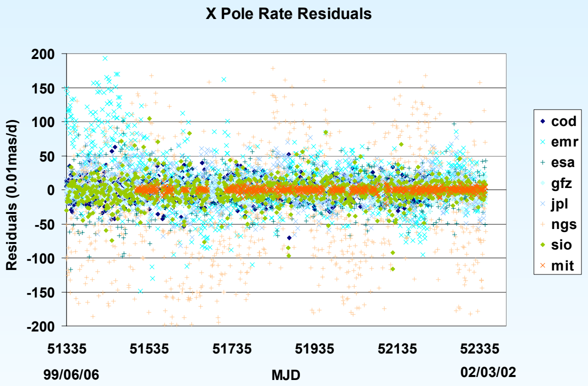


NRC1 w.r.t. IGS Cumulative Solution

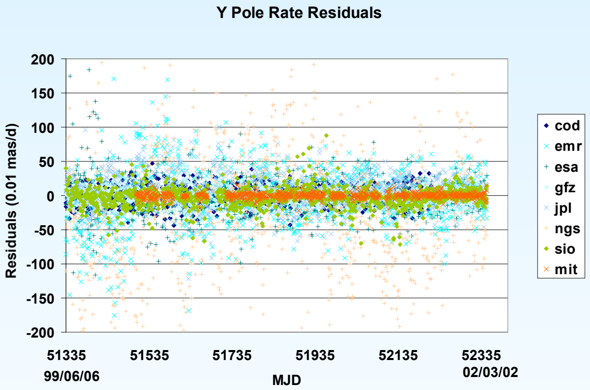
Tabular form of the time series residuals is available at:

ftp	macs.geod.nrcan.gc.ca
cd	/pub/requests/sinex/res

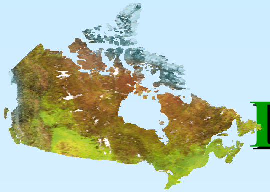
Daily AC & GNAAC
X&Y Pole Rate Residuals w.r.t. igs00P02



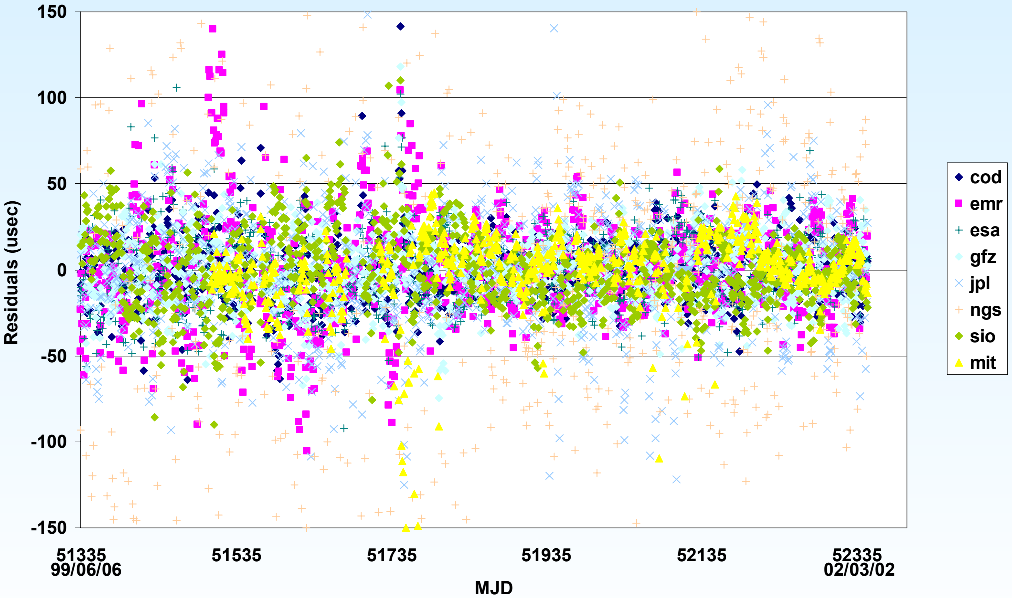
X Pole Rate Residuals



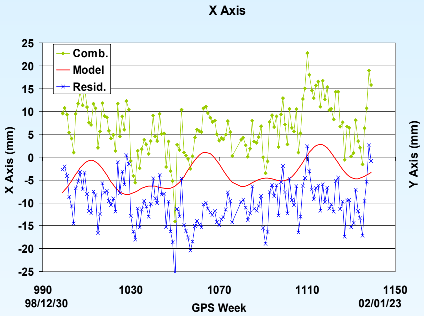
Y Pole Rate Residuals

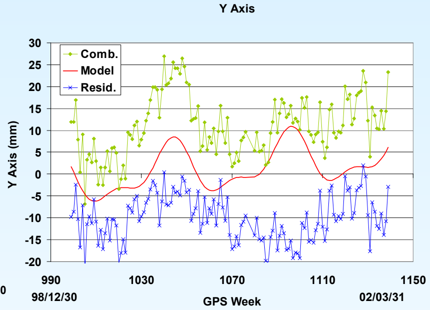


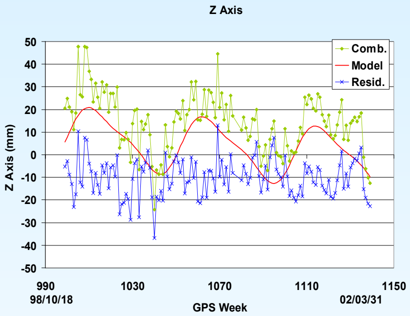
Daily AC & GNAAC LOD Residuals w.r.t. igs00P02



Apparent Geocenter (ITRF2000)







Comb shifted up 10mm

Resid shifted down 10mm

Linear:

Bias(99/02/28)	-6.2mm
Drift	1.7mm/y

Periods:

Annual	3.3mm
Semi-A	1.9mm

Linear:

Bias(99/02/28)	-1.6mm
Drift	2.4mm/y

Periods:

Annual	5.5mm
Semi-A	2.6mm

Linear:

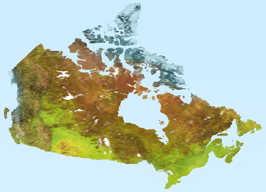
Bias(99/02/28)	8.8mm
Drift	-4.1mm/y

Periods:

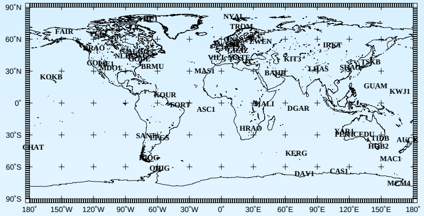
Annual	12.0mm
Semi-A	3.3mm

Contribution to IERS

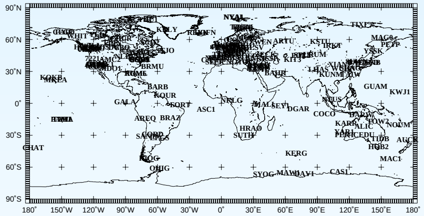
- Objectives:
  - – Understand/Resolve systematic bias
  - – EOP Accuracy Objective (0.1mas)
- Phase 1-Generate EOP's series with:
  - – Different network geometry
  - – Different weighting:
    - Minimal
    - Formal
    - Heavy (Formal * 0.01)



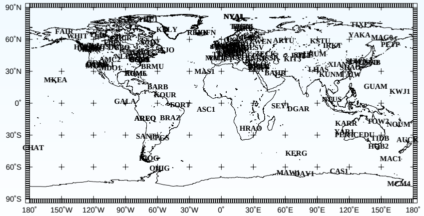
Contribution to IERS



54 Stations ITRF2000
54 Stations IGS00

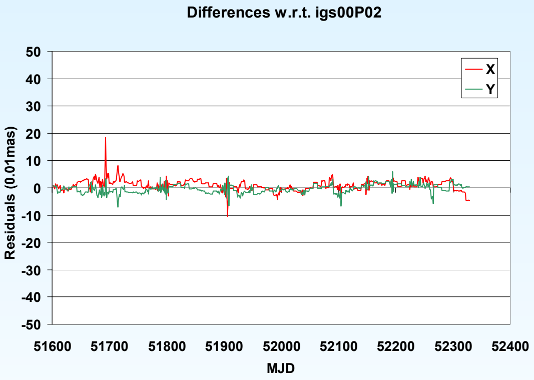


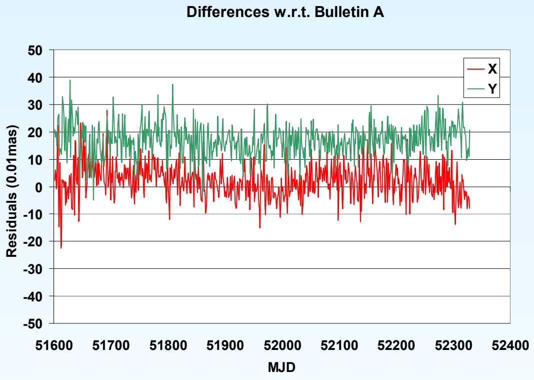
154 stations ITRF2000



132 stations IGS00

Typical X & Y Pole Differences w.r.t. igs00P02 & Bulletin A



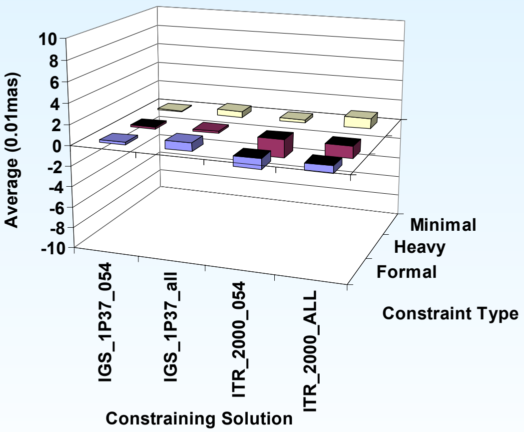


Constraining Solution : ITRF2000

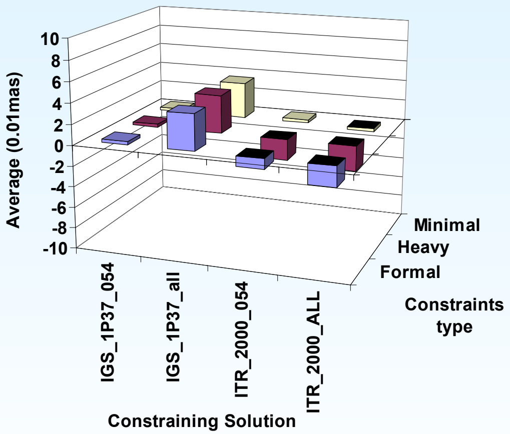
Number of Stations: 154

Constraints type: Minimal

Average X&Y Pole Differences w.r.t. igs00p02

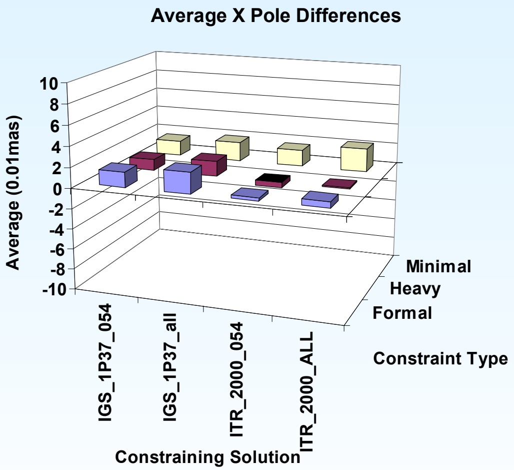


Average X Pole Differences

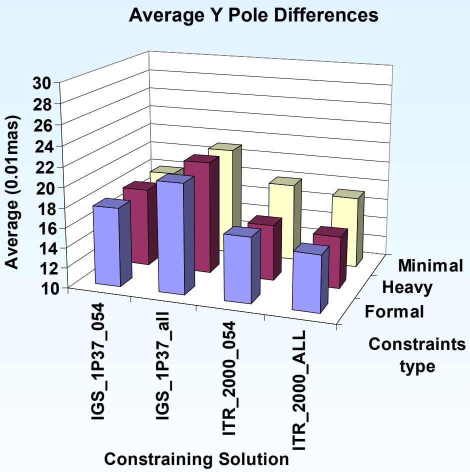


Average Y Pole Differences

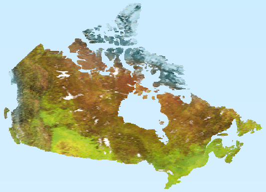
Average X&Y Pole Differences w.r.t. Bulletin A



Average X Pole Differences

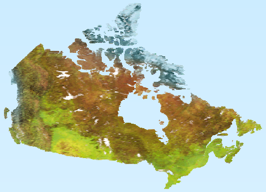


Average Y Pole Differences



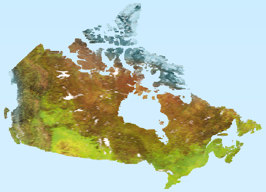
SINEX V 2.00

- Extensions proposed by IERS to Accommodate Multi-techniques
- New Parameters
- New Blocks (Normal eq. , Documentation)
- Solution Blocks Consistency
- Backward Compatibility



Summary

- Realization of ITRF2000
    - 54 Stations
- Combination
    - Stations(Weekly 160+ , Cumulative 200+)
    - ERP's (0.05-0.15mas, 0.15-0.50mas/d)
    - Geocenter (Annual & semi-annual periods)



Summary (Cont.)

- Contribution to IERS Analysis Campaign
  - Stability (+- 0.03 mas)
- SINEX V2.0
  - Backward Compatibility
- Some Constraints issues to resolve

Status of IGS/BIPM Time Transfer Project

J. Ray

- **Tracking Network**
  - nearly 300 stations in IGS network (March 2002)
  - stable clocks: ~40 H-masers, ~25 Cs, ~15 Rb
  - ~18 IGS stations located at timing labs
  - number of timing labs in IGS net growing steadily
  - Ashtech Z-12T receiver popular due to ability to calibrate
  - environmental stability issues remain important
  - multipath mitigation also important but poorly understood

- **Analysis Issues**
  - IGS combined clocks implemented officially on 5 Nov 2000
  - time scale stability limited by GPS time
  - internal IGS time scale developed by K. Senior
  - **how/when to implement new time scale officially ?** <<<
  - **how to ensure future time scale reliability ?** <<<
  - **future direct links to UTC ? (via BIPM & labs)** <<<

  - time transfer accuracy agrees approximately with formal error estimates (~115 ps), in the best cases
  - performance varies greatly among stations, apparently due to site-specific causes
  - limiting stability is $\sim 1.3 \times 10^{-15}$ at 1 d

  - **ACs: need to "densify" clock solutions ! (using PPP)** <<<
  - to include all stable clocks & timing labs

  - **maintenance of P1/C1 bias table ?** <<<
  - **eliminate cross-correlator receivers from IGS net ?** <<<

- **Calibration of Instrumental Timing Delays**
  - G. Petit *et al.* have developed absolute & differential calibration methods for Ashtech Z-12T
  - calibrated BIPM receiver now visiting timing labs
  - RINEX -> CGGTTS utility by P. Defraigne very useful for differential calibrations against common-view receivers

- **Intercomparisons with Other Techniques**
  - should now move from research to byproduct of BIPM's UTC/TAI combination/comparisons
  - will probably reveal longer-term instabilities in system calibrations & other similar effects

- **Future of Pilot Project**
  - pilot phase should end on 31 Dec 2002
  - **needs to transition to operational phase for IGS** <<<

  - will not be used operationally by BIPM yet
  - products need closer evaluation in quasi-operational mode & comparison with common-view/two-way satellite methods

  - **propose permanent liaison between IGS & BIPM** <<<
    starting in 2003 **<<<**

IGS/BIPM Pilot Project: GPS Carrier Phase for Time/Frequency Transfer and Time Scale Formation

J. Ray and K. Senior

Abstract. The development within the International GPS Service (IGS) of a suite of clock products, for both satellites and tracking stations, offers some experiences which mirror the operations of the Bureau International des Poids et Mesures (BIPM) in its formation of TAI/UTC but some aspects differ markedly. The IGS relies exclusively on the carrier phase-based geodetic technique whereas BIPM time/frequency transfers use only common-view and two-way satellite (TWSTFT) methods. The carrier phase approach has the potential of very high precision but suitable instrumental calibration procedures are only in the initial phases of deployment; the current BIPM techniques are more mature and widely used among timing labs, but are either less precise (common-view) or much more expensive (TWSTFT). In serving its geodetic users, the essential requirement for IGS clock products is that they be fully self-consistent in relative terms and also fully consistent with all other IGS products, especially the satellite orbits, in order to permit an isolated user to apply them with few-cm accuracy. While there is no other strong requirement for the IGS time scale except to be reasonably close to broadcast GPS time, it is nonetheless very desirable for the IGS clock products to possess additional properties, such as being highly stable and being accurately relatable to UTC. These qualities enhance the value of IGS clock products for applications other than pure geodesy, especially for timing operations. The jointly sponsored "IGS/BIPM Pilot Project to Study Accurate Time and Frequency Comparisons using GPS Phase and Code Measurements" is developing operational strategies to exploit geodetic GPS methods for improved global time/frequency comparisons to the mutual benefit of both organizations. While helping the IGS to refine its clock products and link them to UTC, this collaboration will also provide new time transfer results for the BIPM that may eventually improve the formation of TAI and allow meaningful comparisons of new cold atom clocks. Thus far, geodetic receivers have been installed at many timing labs, a new internally realized IGS time scale has been produced using a weighted ensemble algorithm, and instrumental calibration procedures developed. Formulating a robust frequency ensemble from a globally distributed network of clocks presents unique challenges compared with intra-laboratory time scales. We have used these products to make a detailed study of the observed time transfer performance for about 30 IGS stations equipped with H-maser frequency standards. The results reveal a large dispersion in quality which can often be related to differences in local station factors. The main elements of the Project's original plan are now largely completed or in progress. In major ways, the experiences of this joint effort can serve as a useful model for future distributed timing systems, for example Galileo and other GNSS operations.

.

.

IGS

SESSION 11:

POSTER ABSTRACTS

The IGS Global Data Center at the CDDIS – an Update

Carey Noll
NASA GSFC, Greenbelt MD, USA

Maurice Dube
Raytheon Information Technology and Scientific Services, Greenbelt MD, USA

Abstract

The Crustal Dynamics Data Information System (CDDIS) has served as a global data center for the International GPS Service (IGS) since its start in June 1992, providing on-line access to data from nearly 200 sites on a daily basis. This paper will present information about the GPS and GLONASS data and products archive at the CDDIS. General information about the system and its support of other international space geodesy services (the ILRS, IVS, and future IDS) will also be discussed.

The Crustal Dynamics Data Information System (CDDIS) is a dedicated data center supporting the international space geodesy community, providing easy and ready access to a variety of data sets, products, and information about these data. The data center was established in 1982 as a dedicated data bank to archive and distribute all Crustal Dynamics Project-acquired data and information about these data. Today, the CDDIS continues to serve as the NASA archive and distribution center for space geodesy data, particularly GPS, GLONASS, laser ranging, DORIS and VLBI data. The specialized nature of the CDDIS lends itself well to enhancement to accommodate diverse data sets and user requirements. The CDDIS is operational on a UNIX server with over 550 Gbytes of on-line disk storage. A majority of the archive is devoted to GPS data and products.

The CDDIS serves as one of the primary data centers for the following International Association of Geodesy (IAG) services: the International GPS Service (IGS), the International Laser Ranging Service (ILRS), the International VLBI Service for Geodesy and Astrometry (IVS), the International Earth Rotation Service (IERS), and the International DORIS Service (IDS).

The CDDIS has served as a global data center for the IGS since its start in June 1992, providing on-line access to GPS data from nearly 200 GPS and 50 GLONASS sites on a daily basis as well as the products derived by the IGS Analysis Centers from these data. The CDDIS supports a majority of the working groups and pilot projects within the IGS.

In May 2001, the CDDIS began supporting the IGS Low Earth Orbiter Pilot Project (LEO-PP) by archiving data from a network of approximately forty sites operating at a one-second sampling rate (typically). These data are available in files containing fifteen minutes of data stored in subdirectories by GPS day, hour, and data type. Starting in January 2002, the CDDIS LEO-PP archive expanded to include data from GPS receivers on-board the LEO satellites; currently data from SAC-C and CHAMP are stored in daily files, Hatanaka-compressed RINEX format, in subdirectories by satellite and day. In 2002, this satellite archive will be expanded to include data from ICESat and Jason. The CDDIS is also archiving CHAMP orbit products from associate analysis centers participating in a LEO-PP comparison project.

The CDDIS supported the Ionosphere Working Group's HIRAC/SolarMax campaign in April 2001. This weeklong activity was organized to study the effects of the solar maximum on the Earth's ionosphere using a dense, high-rate GPS tracking network. Data from 104 sites in thirty countries totaling thirteen Gbytes in size were collected and archived.

CODE – Current Issues Relevant to the IGS

U. Hugentobler, S. Schaer, M. Meindl, R. Dach, D. Ineichen, H. Bock C. Urschl, P. Fridez, G. Beutler

Astronomical Institute, University of Berne, Switzerland

The two posters presented at the IGS 2002 Workshop in Ottawa put a few flashlights on some new results from CODE and on several issues which require discussions within the IGS.

The first poster shows up-to-date results of global ionosphere mapping. The Earth's ionosphere is still very active as shown by the development of the mean vertical electron content over a period of more than seven years, a plot which is updated daily on http://www.aiub.unibe.ch/ionosphere.html. CODE IONEX maps are now resulting from the middle day of a 72-hour analysis to avoid discontinuities at the day boundaries. RMS maps give a clear indication of the station distribution, with high RMS patches in particular in regions in the southern hemisphere or over the oceans which are sparsely populated by IGS stations. The generation of a mixed ionosphere product containing observations from GPS as well as from TOPEX is planned and needs discussion concerning to the IGS policy.

Maps indicating the average availability of tracking data for the rapid and the final analysis at CODE show, in particular for the rapid analysis, that data from large regions on Earth do not arrive in time to be processed. This concerns especially interesting regions such as Siberia, Africa, and Southern America where the station density is low. The picture basically gives a map of the reliability of communication links. A number of stations at very remote locations and islands do not even provide data in time for the final analysis. Several of these sites are collocated with tide gauge stations. Data from such stations would significantly help to improve e.g. IGS ionosphere products.

At CODE, P1-P2 and P1-C1 code biases are determined routinely. The poster gives average values for the full satellite constellation as well as time series for selected satellites. CODE P1-C1 results are used as official IGS values. A method was developed to firmly determine the code tracking technology of a GPS receiver.

Finally it is shown in an impressive manner that the resolution of carrier phase ambiguities to integer numbers is essential also for the estimation of orbital parameters. At CODE, ambiguity resolution is now attempted for baselines up to 6000 km length.

The second poster is dominated by color coded time series of SP3-type accuracy codes for all satellites as well as corresponding statistical information and detailed time series for selected satellites. Time series of GPS satellite orbit accuracies as obtained from 3-day fits are given for the CODE final orbits and compared to corresponding series as extracted from the IGS final and ultra-rapid SP3 files. Apart from the significant improvement of the orbit quality over the years, it is striking to see that prominent patterns for some satellites do not show up in the IGS accuracy code time series indicating that effort should be put into the refinement of the estimation of accuracy information in the IGS orbit files.

In particular for the IGS ultra rapid orbits, many gaps can be observed in the time series stemming from satellites missing in the published orbit files. It should be the goal of the IGS to provide information for all satellites to the users accompanied with reliable accuracy information. In parallel, the users of IGS orbits should be urged to use this information.

Time series of geocenter coordinates extracted from weekly SINEX files from CODE and from GFZ match each other reasonably well. The reconstruction of geocenter information should be possible with any SINEX file. Technical problems related with SINEX have to be sorted out. Tests indicate that the fact that IGS orbits are referred to a coordinate frame which is displaced from the ITRF by the geocenter offset may have an effect on station repeatability in large GPS networks such as the EUREF.

With a plot of polar motion, the question of continuous representation of time variable parameters is addressed. As pole parameters, troposphere zenith delays parameters and coefficients of global ionosphere maps should be represented by piece-wise linear functions without discontinuities every n hours. Information should be provided to the users of these products on how to interpolate the tabular values provided by the IGS.

The IGS Ultra-Rapid Orbits in the COST–716 Campaign 2001

Jan Douša

Geodetic Observatory Pecný (Research Institute of Geodesy), Czech Rep.
Dept. of Advanced Geodesy (Czech Technical University), Czech Rep.

1 IGU orbits and COST–716 NRT campaign

The COST–716 (http://www.oso.chalmers.se/geo/cost716.html) is the European action for the exploitation of ground based GPS for climate and numerical weather prediction applications. The near real-time (NRT) demonstration campaign for the monitoring of the troposphere was started in February 2001 and the Geodetic observatory Pecný (GOP) has been operating as one of the GPS analysis centers. Our contribution in 2001 was based on the fixed IGS ultra-rapid (IGU) orbits. The monitoring of the IGU product during 2001 confirmed its high quality: 8/10 cm median/mean RMS for fitted and 18/50 for predicted portion, respectively. Only a single solution was missing during the whole period (doy 310) and other 2–4 were hardly usable for our application (doys: 059, 064, 079 and 112). All these cases were successfully handled by the prolonging of previous IGU orbits.

2 Results from the GOP tropospheric monitoring

We use the Bernese GPS software and the network approach for the NRT tropospheric estimation. Applying the subdaily IGU orbits, we could simplify our routine procedure for fixing the orbits. Nevertheless, we have implemented the satellite checking procedure based on the residual testing: a) very bad orbit cases resulted in the total PRN exclusion (already seldom during 2001 since they have been excluded usually during the IGS combination) and b) in other cases of the orbit unstability the PRN was excluded for every single baseline whenever disturbed the solution. The NRT solution was performed every hour, based on hourly pre-processing step and the last 12 normal equations stacking procedure. Hourly ZTD values were estimated keeping the coordinates fixed on the values solved for separately from the last 7 days. The network has consisted of the EPN sites located mostly in the central and eastern part of Europe. Additionally, the sites from UK Met Office and the sites from Belgium and Netherlands were included. The NRT ZTD product latency was usually 1 hour. Besides this solution, we provided also routine post-processed solution (PP, latency 1–2 days) based on a daily processing and IGS rapid orbits. The internal GPS consistency is presented in Fig. 1 by the ZTD comparison between the GOP NRT and PP solutions. The standard deviations are in most cases between 4-6 mm of ZTD (6-7.5 mm for a few sites on the margin of our network with baselines longer than 2000 km). The mean bias is bellow 1 mm. In addition, for the sites with nearby radiosondes available (< 80 km), we compared our ZTD NRT results (converted into the precipitable water vapor, PWV) with the values directly integrated from the radiosonde observations. The monthly (Fig. 2) and cumulated (Table 1) comparisons show the mean standard deviations between 1.2–2.1 mm in PWV and mean positive bias for GPS about 0.4 mm. The PWV comparison strongly depends on the quality of the reduced radiosonde profiles, as well as on the other missing information about the mutual GPS and radiosonde localizations, the radiosonde special problems, and many other factors.

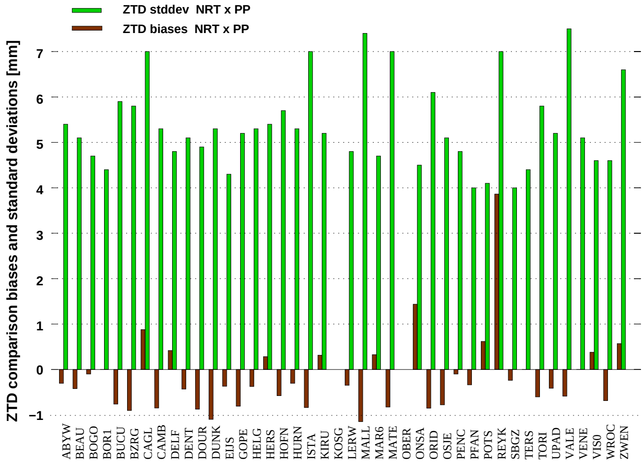


Fig. 1. ZTD comparison for NRT×PP GOP solution.

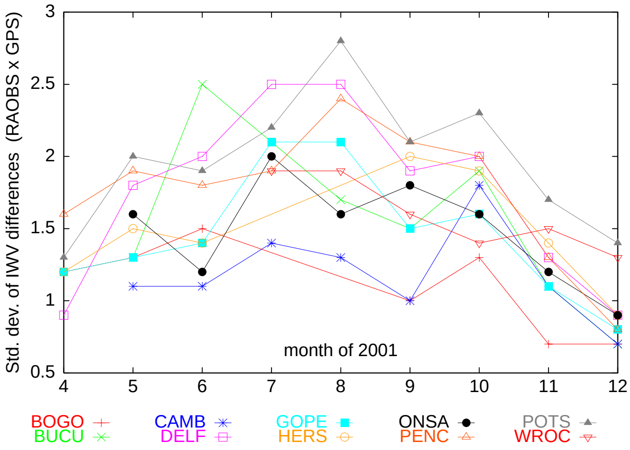


Fig. 2. Monthly GPS and radiosonde PWV comparisons.

Acknowledgements. The radiosondes data were provided by the British Atmospheric Data Center (BADC), the conversion of ZTD to PWV was done by Siebren de Haan (KNMI, the Netherlands) within the COST–716 monitoring activity. This work was supported by the Ministry of Education, Youth and Sports of the Czech Republic (OC 716.001) and Grant Agency of the Czech Republic (103/00/P028).

Table 1. PWV comparisons

site	bias [mm]	sdev [mm]	#	site	bias [mm]	sdev [mm]	#
BOGO	0.8	1.2	*228*	HERS	0.5	1.6	*257*
BUCU	0.6	1.8	*279*	ONSA	0.9	1.6	*277*
CAMB	0.9	1.3	*666*	PENC	-0.4	1.9	*350*
DELF	-0.1	2.0	*670*	POTS	-0.1	2.1	*847*
GOPE	0.5	1.6	*788*	WROC	0.7	1.6	*91*

Study of Different Analyzing Schemes for the Ultra-Rapid Orbit Determination Using the Bernese GPS Software

Jan Douša[1,2] and Urs Hugentobler[3]

[1] Geodetic Observatory Pecný, (Research Institute of Geodesy) Czech Rep.
[2] Dept. of Advanced Geodesy, (Czech Technical University) Czech Rep.
[3] Astronomical Institute, University of Berne, Switzerland

1 Description of variants

We have searched an optimal aproach for the Bernese GPS software between two extremes: a) a sliding window processing, b) a short-time data pre-processing with stacking the normal equations (NEQ). The period of 18 days was selected in the year 2001 (052-069), where 3 satellites (PRNs 6, 13, 18) were manoeuvered. These events were considered as unknown and were identified by the processing. Except for the unhealthy PRN 15 the orbits of all satellites were determined.

Table 1. Summarized setup for compared variants.

Ident	arcs	data	# NEQ	ambig par.	erp par.	stoch par.	# sites	arc split.
24H	72h	24h	3	no	no	no	51	diff
12H	72h	12h	6	no	no	no	51	diff
6H	72h	6h	12	no	no	no	51	diff
4H	72h	4h	18	no	no	no	51	diff
2H	72h	2h	36	no	no	no	51	diff
COD	72h	24h	3	yes	yes	yes	120	resd

Five variants have been set up for the estimation of ultra-rapid orbits, see Table 1. The common general strategy was designed as close as possible to the CODE rapid solution, but taking into account the aspects of the subdaily solutions with pre-processing windows ranging from 2 to 24 hours. Finally, the strategy was simplified in order to separate the following influences: fixing the ambiguities, introducing the stochastic orbit parameters and estimating the ERPs. An automatic arc splitting procedure is applied in the case of problems with the long-arc modeling (last column in the table). The 'resd' stands here for the residual checking after fitting the positions of two consecutive daily orbit arcs into a single one, while the 'diff' means checking the differences between the long-arc orbits (3 days) and the short-arc orbits (6×12 hours).

2 Comparisons and results

The comparison was based on two criteria: 1) an efficiency of the procedure expressed in processing time, 2) an accuracy of the fitted and predicted orbit arcs. The latter was derived from the residuals of Helmert transformation (3 rotations) between estimated satellite positions and the final IGS orbits. Daily arcs were compared in case of fitted portions, while predicted parts were divided into 4 intervals (0-6h, 6-12h, 12-18h, 18-24h). Although the subdaily solutions were updated several times per day, the comparisons were evaluated only for the last one of the day. No satellites were excluded from the comparison except those actually manoeuvered.

Figure 1A) indicates that variant 6H (6-hour pre-processing, 12 NEQ stacking) is a reasonable compromise among all others tested. The solutions based on the shorter NEQs (2H, 4H) are unstable due to a problem with ambiguity estimation, Fig. 1B. Consequently, some orbits were biased in the along-track component and an additional Z-rotation in the Helmert transformation decreased the comparison quality for all other satellites. The efficiency of both shortest variants was even not significantly higher since the number of parameters (tropospheric and ambiguities) was not much reduced. The solutions using a longer NEQs (12H, 24H) consumed 1,5-2,5× more processing time, achieving an accuracy equivalent to that of the 6H solution.

Finally, the new automatic procedure for long-arc splitting was successfully set up and tested. It does not require any a priori information and Fig. 1C) shows how the introducing a reasonable arc-splittings over the 3-day orbit solution is useful after 2-3 iterations. The procedure is efficient and general enough to accomplish the tasks for a subdaily orbit product with arbitrary update rate.

Acknowledgements. This project was supported by the Swiss National Science Foundation (20-57168.99) and by the Ministry of Education, Youth and Sports of the Czech Republic (OC 716.001, LN00A005).

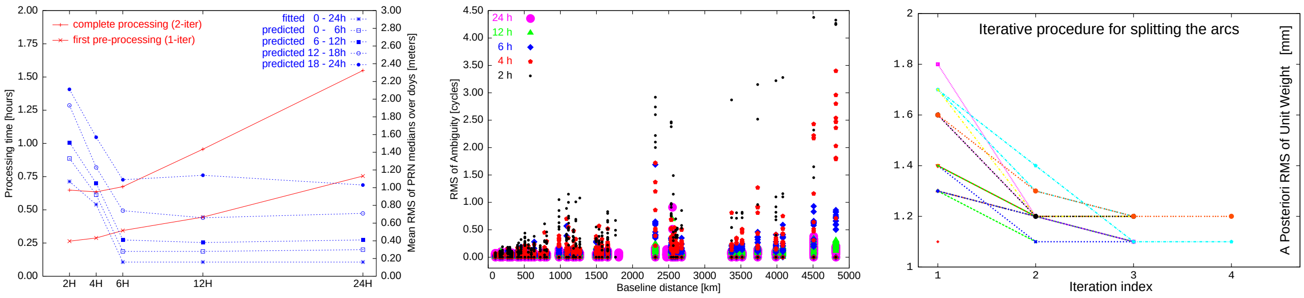


Fig. 1. A) The x-axis corresponds to the data NEQ lengths, y-axis shows the processing time, y2-axis gives the mean RMS of the comparison of the orbits with respect to the IGS final orbits. B) RMS values of baseline-wise estimated ambiguities for the strategies 2H, …, 24H as a function of baseline length. C) The improvement of the solution when iterative arc-splitting procedure for selected orbit has been applied.

Global NRT Solution from Geodetic Observatory Pecný AC

Jan Douša

Geodetic Observatory Pecný (Research Institute of Geodesy), Czech Rep.
Dept. of Advanced Geodesy (Czech Technical University), Czech Rep.

1 NRT GPS tropospheric monitoring, NRT orbits

Monitoring of the troposphere is the main topic at the Geodetic Observatory Pecný (GOP) in the field of near real-time (NRT) analyses. The quality of NRT orbits and the GPS geometry are the most crucial factors in this case. From March 2000, the IGS ultra-rapid orbits (IGU) are available beeing well suited for the operational GPS meteorology. It was proved in the GOP analysis for the COST–716 NRT demonstration campaign 2001 (see the independent contribution). Nevertheless, the improvements can be still expected because of two reasons:

1) from 2 to 6 satellites are generally missing in the current IGU product which weakens the GPS geometry,
2) applicable NRT IGU orbits are predictions for 3-15 hours causing the errors for some satellites up to the meters (exceptionally even tens of meters).

2 GOP processing system

Our aim is to share the effort in the precise NRT orbit determination. We tend to benefits from the use of the most reliable and stable combined IGS product prior to the individual orbit relaxation. Already at the end of 2000, the GOP tested the operational analysis of a global NRT network. Since October 2001, our analyses has been running continuously with a processing system based on early Bernese GPS software V5.0. The GOP global NRT solution is based on the effective procedure of stacking the normal equations (NEQs): after 6 hours iterative GPS data pre-analysis, the final 3 day orbits are determined with pure NEQ combination. The NRT analysis cycle is 3 hours and the orbit and tropospheric products are available 8× per day (2 hours after last observed GPS epoch). The final orbits are checked for the arc overlap consistencies and the orbits exceeding the criteria are automatically excluded. All the GPS observations (about 70 global sites) are downloaded through the GOP NRT data center.

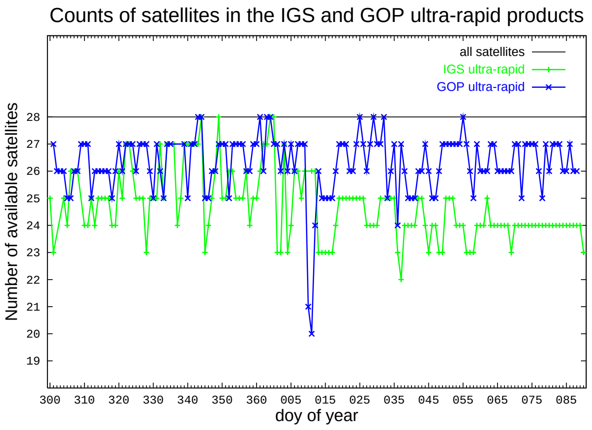


Fig. 1. The counts the satellites in the GOP and IGU products.

3 NRT products from GOP

During 5 months (November 2001 – March 2002), the performance of the GOP orbits shows the significant improvements from the start of 2001, and later on from the beginning of March (i.e. the last 30 days). The following changes have caused the improvements: the careful network reconfiguration, optimized station checking method, a new backup system for uninterrupted internet connection and some additional fine-tunings.

Only a few satellites are usually missing in our orbit product – generally less than by the IGU product, see Fig. 1. Together with checking the differences between the GOP NRT and IGS rapid orbits during the last 30 days (Fig. 2), we can demonstrate the potential improvements of the IGU combined product. The comparison of GOP orbits in last 5 months results in the mean median RMS of satellite positions of 13 cm and 24 cm for the fitted and 6-hour predicted portion, respectively. The same results give the comparison between the IGU and GOP orbits.

Additionally, the hourly tropospheric estimates are produced in the final steps of our NRT procedure using a final GOP orbits already fixed. The processing consists in the combination of last two 6-hour NEQs. Since February 2002 our tropospheric product has been regularly delivered to the NRT IGS trial combination. The simple cosistency ZTD checking with the combined product shows the mean standard deviation of 3.9 mm and mean absolute bias of 2.5 mm based on 350 pairs in average.

Acknowledgements. The author would like to thank for the possibility of sharing the experience with the Bernese GPS group, as well as the opportunity to take advantage of preparing Bernese software V5.0. Special thanks are given to Urs Hugentobler for the work on the NRT orbit determination and to Leoš Mervart for the hard work on the new version 5.0, for ADDNEQ2 combination program extensively used in our solution and for a new MENU support. This project was supported by the Grant Agency of the Czech Republic (103/00/P028) and by the Ministry of Education, Youth and Sports of the Czech Republic (LN00A005).

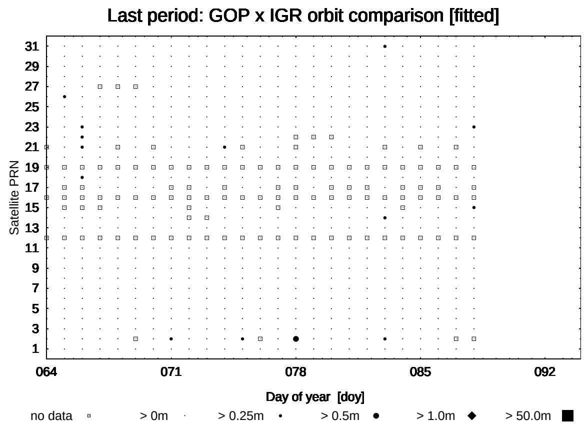


Fig. 2. The bullet-graph affirms the quality of the GOP fitted orbits.

This page intentionally left blank

Geoscience Australia Activities Related to the International GPS Service

J. Manning, R. Govind, J. Steed, B. Twilley, G. Luton, J. Dawson, P. Digney and G. Johnston

Geodesy Program, National Mapping Division (NMD), Geoscience Australia
Canberra, Australia

Abstract

The International GPS Service (IGS) and Geoscience Australia continue to have a strong relationship. Geoscience Australia (formerly the Australian Surveying and Land Information Group, AUSLIG) currently provides data from 15 permanently tracking GPS stations to the IGS, these stations are known as the Australian Regional GPS Network (ARGN). Future development of the ARGN will focus on the availability of near real time data and the augmentation of precise clocks and meteorological equipment at selected stations. Additionally Geoscience Australia has been an IGS Regional Network Associate Analysis Centre (RNAAC), contributing an Australian regional GPS solution, for almost six years. Apart from these contributions to the IGS, NMD is currently making use of IGS products, including precise GPS trajectories, Earth Orientation Parameters (EOP) and station coordinates and velocities in the delivery of an Internet based precise GPS processing service (AUSPOS) widely used by both the Australian and International GPS communities.

Developments in Absolute Field Calibration of GPS Antennas and Absolute Site Dependent Multipath

Gerhard Wübbena, Martin Schmitz

Geo++®
Gesellschaft für satellitengestützte geodätische und navigatorische Technologien mbH
D-30827 Garbsen, Germany
www.geopp.de

Günter Seeber, Volker Böder, Falko Menge

Institut für Erdmessung (IfE),
Universität Hannover
D-30167 Hannover, Germany
www.ife.uni-hannover.de

Antenna phase variations (PCV) and multipath (MP) are site dependent errors on GPS stations, which can have a magnitude of several centimeters. Neglecting these errors can cause severe problems in ambiguity resolution, but also for estimation of distance dependent errors (e.g. troposphere) and coordinates.

Geo++® and IfE have developed an operational procedure to determine the absolute PCV of an antenna in a field calibration completely independent from any multipath effects. Subsequently, it is now possible to separate between PCV and MP error components. The separation of the two error components is important as the error characteristics are different. PCV has a systematic antenna dependent impact on coordinate estimation as MP has a site dependent influence with a zero mean over an adequate time period. Currently, a procedure is under investigation, which gives absolute carrier phase multipath and can be used for absolute site multipath calibration.

The basic concepts of absolute carrier phase multipath calibration are the separation of PCV / MP and the separation of MP from a second station involved in differential GPS. Therefore, in a first step MP and PCV are separated while introducing absolute PCV for the used antennas. Secondly, the absolute MP for one single station is obtained through fast and pseudo-random movements of one antenna on a temporary reference station by a robot. The MP on the robot station is “randomized” or “noisified” through the movement and hence a decorrelation of MP between stations is possible. The systematic behavior of MP for the robot station is turned into noise. The single difference between a static station and the moving robot station contains the original MP of the static station and the decorrelated MP of the moving robot. Finally, a low-pass filtering gives the MP of the static station.

The initial testing of the absolut multipath calibration uses spherical harmonics for the multipath adjustment and a tabulated correction file, which utilizes the correction in the same way as PCV corrections. Both approaches are currently changed to achieve a better performance of the MP calibration. However, generally low MP frequencies are already reduced as high frequencies remain.

First results applying the MP corrections show a reduction of the noise level of L1 double differences (DD) in the order of ~20 % and of ~66 % for a 60 s moving average of the L1 DD. Comparisons of short-term coordinate estimations reveal similar improvements. L1 coordinate estimations of 60 s with the MP corrected observations give a reduction of ~50 % of the standard deviation in each coordinate component compared to a known reference position.

Hard- and software of the absolute MP calibration will be improved to enable faster and more effective measurements. Alternative models are investigated to substitute the spherical harmonics and to consider variation of multipath under changing environmental conditions (e.g. humidity on reflectors, SV orbit, snow). The absolute calibration of station dependent GPS error components will lead to improved global, regional and local reference station and RTK network services (e.g. IGS, SAPOS) as well as for precise GPS applications.

IGS Workshop "Towards Real-Time", Poster Session, April 8-11, 2002, Ottawa, Canada

Recent Results and Activies of the IGS Analysis Center at JPL

D. Jefferson, Y. Bar-Sever, M. Heflin, Y. Vigue-Rodi, F. Webb, J. Zumberge (JPL)
T. Martin-Mur (Raytheon/JPL), R. Meyer (Raytheon)

ABSTRACT

JPL has contributed regularly to the International GPS Service (IGS) as an Analysis Center since June, 1992. Over time, the IGS ground station network and GPS constellation has grown in size and quality and allowed us to achieve the best estimates of satellite orbits and other parameters to date. Concurrently, implementing new processing strategies and data models, as well as using late-model hardware, have augmented the realization of our most abundant and accurate GPS processing results ever, while keeping and surpassing product delivery deadline requirements. Presented in this workshop poster is an overview of what products we provide, a history of of strategy and processing improvements, and the current state of our operations and product accuracy.

Continental Plate Rotations Derived from International GPS Service Station Coordinates and Velocities, 1996-2002

D. Hutchison[1]
[1]Natural Resources Canada, 452-615 Booth St., Ottawa, Ontario K1A 0E9
Phone: 613-995-4379, Fax: 613-995-3215, Email: hutch@geod.nrcan.gc.ca

International GPS Service (IGS) Analysis Centres (ACs) currently compute daily precise station coordinates and Earth Rotation Parameters (ERPs). From these, weekly results are computed and forwarded to three Global Network Associate Analysis Centres (GNAACs) in an established ASCII format known as Solution Independent Exchange (**SINEX**). The GNAACs then combine these results on a weekly basis. On behalf of IGS, Natural Resources Canada (NRCan) combines all weekly SINEX files from the ACs to form a weekly and a cumulative solution and compares the results with those obtained by the GNAACs. Since GPS week 1143, all the solutions have been aligned to an IGS realization of **ITRF 2000**, the Year 2000 International Terrestrial Reference Frame (**IGS00**, 54 stations). The **weekly solution** contains estimates of station coordinates and ERPs pertaining to the GPS week, and the **cumulative solution** contains station coordinates and velocities at epoch Jan. 1, 1998. **IGS00** is a subset of the cumulative solution for GPS week 1131, itself aligned to **ITRF 2000**. Before GPS week 1143, NRCan's weekly and cumulative solutions were aligned to an IGS realization of **ITRF 2000**'s precursor, **ITRF97,** called **IGS97**. The latter is a 51-station subset of the cumulative solution for GPS week 1046 transformed to **ITRF97**.

Using the cumulative solution from any given week, we estimate rotation components (**Euler vectors**) of any continental plate represented and compare them statistically with results from published literature and two known plate motion models**:** **NNR NUVEL 1** and **NNR NUVEL 1A**. As of week 1162, some 215 stations and 19 plates are represented. Mean residual velocities are also computed with respect to each plate, thus providing net residual velocities over all stations with respect to both plate motion models.

Statistical tests from the cumulative solution for GPS week 1162 (labeled **IGS02P16** for the **16th** week of the year 20**02)** indicate that motions derived from IGS results for the Eurasian, Pacific and Australian Plates differ significantly from predictions of either model. (The Philippine, Cocos, Juan-de-Fuca, Scotia and Rivera Plates are not analyzed.) For Eastern and South-East Asia, some significant differences are shown to exist between station velocities observed from **IGS02P16** and those expected from the computed plate rotation for Eurasia (without China) derived from **IGS02P16**. The mean misfit between recorded horizontal velocities on plates with two or more stations and those predicted from appropriate Euler vectors for **IGS02P16** is approximately 1.5 mm/yr. Major plates such as North American, South American, Eurasian, Pacific, Australian and Caribbean show horizontal misfits of 1 mm/yr or less. Mean vertical misfit for **IGS02P16** is approximately 6 mm/yr.

NRCan Analysis Centre Contributions to the IGS

B.Donahue, P.Héroux, C.Huot, D.Hutchison, J.Kouba, Y.Mireault and P.Tétreault

Natural Resources Canada,
Geodetic Survey Division,
615 Booth Street,
Ottawa, Canada K1A 0E9

Abstract

As part of Natural Resources Canada (NRCan), the primary role of the Geodetic Survey Division (GSD) is to maintain, continuously improve, and facilitate efficient access to what is now known as the Canadian Spatial Reference System (CSRS). The CSRS serves as a reference for all positioning, mapping, charting, navigation, boundary demarcation, crustal deformation, and other georeferencing needs within Canada. While continuing to serve ongoing requirements for survey control, the growing demands of GPS users in particular have resulted in a new focus for the Division, a focus on supporting positioning from space. The Canadian Active Control System (CACS) was established during the 1990's to facilitate GPS user access to the CSRS. NRCan participation in IGS is an efficient way of providing for Canada a positioning and navigation infrastructure based on modern technologies and international standards. NRCan has been an IGS Analysis Center (EMR) since the 1992 initial IGS pilot phase. The poster lists some of NRCan current contributions to IGS and describes recent modifications, innovations as well as on-going and up-coming developments.

IGS97 to IGS00 Discontinuities in NRCan Rapid Products for GPS Week 1157

Solutions **DUT1**	**RX(mas) -Pmy**	**RY(mas) -PMx**	**RZ(mas)**	**Sc(ppb)**	**TX(cm)**	**TY(cm)**	**TZ(cm)**
NRCan Orbits	0.020	0.034	-0.141		-0.059	-0.003	0.848
Sigma	0.021	0.029	0.027		0.045	0.098	0.165
NRCan EOP	0.010	0.022	-0.202				
Sigma	0.021	0.028	0.054				
NRCan Stations	-0.023	-0.037	-0.173	-0.957	-0.286	-0.276	2.648
Sigma	0.019	0.019	0.039	0.113	0.050	0.065	0.101
IGS Realization	-0.024	-0.004	-0.159	-1.451	-0.45	-0.24	2.60
Sigma	0.092	0.099	0.076	0.270	0.41	0.50	0.75

NRCan Ultra-Rapid Orbit Products (EMU)

NRCan's Internet Global Positioning System Data Relay (iGPSDR)

S. Delahunt, K. MacLeod, M. Caissy, K. Lochhead

The poster session consists of two parts, one was a poster showing the Canadian Real Time Active Control Network (CRTACS) and a description of the Wide Area Network (WAN), the iGPSDR and the Canada-Wide Differential Global Positioning System (CDGPS) service. The second part was a real-time demonstration of the iGPSDR and CRTACS products.

The real-time demonstration used the iGPSDR to relay GPS observation data (Winnepeg) and GPS wide area corrections over the open Internet from NRCan's office in Ottawa to the conference hotel. The wide area corrections were localized for Winnipeg. The Winnipeg observation data, together with the localized GPS corrections were used to do real-time point positioning.

A COMPARISON OF GPS RADIATION FORCE MODELS

Victor J. Slabinski
Earth Orientation Dept.
U. S. Naval Observatory
Washington, DC 20392
U. S. A.
Email: slabiv@tos.usno.navy.mil

****

A poster paper presented at the
International GPS Service
"Toward Real Time Workshop"
2002 April 8-11
Ottawa, Ontario, Canada

Figures updated 2002 May 3 to include LM-IIR model predictions.

Abstract

The following models have been proposed to model the radiation force on GPS Block IIR satellites:

- The "CODE 1998" model reported by Springer(1998);
- JPL's GSPM_XYZ.1 model from Bar-Sever(1998a);
- The T30 model from Fliegel and Gallini(1996);
- The (Lockheed Martin Corp.) Block IIR model "LM-IIR" reported by Bar-Sever(1998b);
- CODE/VJS-01 model based on the author's recommended changes to some mathematical expressions in the CODE 1998 model.

We compare the secular perturbation rates predicted by the models, as a function of Sun angle from the orbit plane, with the observed values for a Block IIA and Block IIR spacecraft. The Block IIA comparison illustrates the accuracy of the CODE 1998 and the GSPM_XYZ.1 models in their intended application. The Block IIR comparison shows that the CODE/VJS-01 model gives the best accuracy of all models tested.

On-Line GPS Processing Using Bernese and IGS Products

Tomasz Liwosz and Jerzy Rogowski

Institute of Geodesy and Geodetic Astronomy,
Warsaw University of Technology, Poland
E-mail: tl@gik.pw.edu.pl

ABSTRACT

We would like to highlight a new project which has been started in our Institute. This is a service which enables users to process automatically their own GPS data through our Internet Web site. The user is requested to fill out the form and send RINEX file to our computer. Then our system begins to start. It downloads all necessary things to make processing, process data and afterwards sends results back to the user. System has been based on Bernese GPS Processing Software v.4.2. The poster presents brief description of the service as well as some first tests performed using it. However due to some technical problems it is not opened for users for now and it is still in testing mode.