1998 ANALYSIS CENTER WORKSHOP

PROCEEDINGS

DARMSTADT, FEBRUARY 9-11, 1998

ESA/ESOC
Darmstadt
Germany

Edited by
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T. Springer (AIUB)

International GPS Service

Association Internationale de Géodésie

Union Géodésique et Géophysique Internationale

International Association of Geodesy

International Union of Geodesy and Geophysics

The Federation of Astronomical and Geophysical Data Analysis Services

The research described in this publication was sponsored by many agencies who actively participate in the International GPS Service. The Proceedings of the Workshop were prepared and published by the European Space Centre of the European Space Agency.

FOREWORD

The 1998 Analysis Centre Workshop of the International GPS Service for Geodynamics (IGS) held in Darmstadt, Germany from 9 to 11 February 1998 followed a series of workshops dedicated to IGS Analysis Centre issues (1993 in Ottawa, 1994 in Pasadena, 1995 in Potsdam, 1996 in Silver Spring, 1997 in Pasadena; IGS workshops with a more general scope also took place in Bern in 1993 and Paris in 1994).

Discussions between representatives of the Analysis Centres present at IGS Governing Board meetings and Retreat held in San Francisco and Napa Valley in early December 1997 led to the identification of four major topics for the upcoming workshop, which were summarised as follows in the invitation to participate which was sent to some 70 persons from the IGS and user communities:

Topic 1: The IGS Analysis Products and Consistency of the Combination Solutions

The basic IGS analysis products (orbits, earth orientation parameters, clocks) are of very high quality, and should in general be more accurate and reliable than the solutions obtained by the individual analysis centres (ACs). This session will focus on the current combination process, reporting and feedback, along with possible enhancements in precision, consistency, robustness and results presentation. Furthermore, it should address a need (if any) for additional (global) products in order to meet current and future needs of IGS users.

Topic 2: Orbit Prediction and Rapid Products

The IGS is facing ever increasing demands for more precise and more rapid (real-time!) products. The computation of the rapid orbits and especially the orbit predictions, which are available in real-time, therefore are becoming more important and deserve special attention. This session will focus on ways of improving the quality of the rapid and predicted orbits. The current AC methods of generating the rapid products will be reviewed. The main objective will be the improvement of the (orbit) models and the reduction of turn-around time.

Topic 3: IGS Reference Frame Realization and Contributions to ITRF

The stability of the underlying reference frame defined by the global GPS network has been degrading due to the decrease in quality and availability of some stations of the previously selected group of 13 ITRF stations. More ITRF stations and a new approach to solving this problem is urgently required. The future IGS reference *frame realisation should be precise, robust and based on the GNAAC station combinations (G-SINEXes). Furthermore, the IGS reference frame realization should ensure a high product consistency in particular for orbits/EOP and the station coordinate (G-SINEX and P-SINEX) combinations. The new ITRF96 should be discussed in this session.*

Topic 4: IGS products for Troposphere and Ionosphere

Global tropospheric and ionospheric information can enhance precision and/or efficiency of various GPS and VLBI solutions (including LEO applications). Additionally it is also required for (global) calibration of ground and satellite based atmospheric (i.e. tropospheric/ionospheric) determination by GPS. A combined IGS solution for tropospheric zenith biases already shows *considerable promise. The IGS global ground network is also allowing progress to be made in development of regional and global ionospheric maps. Of particular interest is the assimilation of such maps into global models which may be based on atmospheric physics and/or on alternative sources of measurement data. The main objective will be to define an operational IGS ionospheric product (or products).*

Fifty-one active participants representing institutions in more than a dozen different countries (USA, Canada, Australia, France, UK, Switzerland, Italy, Spain, Norway, Denmark, Belgium, The Netherlands and Germany) contributed through presentation of papers, posters and intensive discussion to the workshop. The Proceedings which are documented in the present volume contain, in addition to introductory material (including the IGS Chairman's Report and the Summary Recommendations of the Workshop), a total of 25 full papers, 4 abstracts and 7 poster summary papers, covering in particular all workshop contributions relating to the 4 major topics.

I would like to thank all participants for their active involvement in the workshop, and to the speakers and poster presenters who, by the quality of their contributions during the workshop itself and rapid preparation of their manuscripts afterwards, once again demonstrated the amazing motivation of those involved in the IGS. The "Position Papers" relating to the key topics mentioned above were prepared in a short time and distributed to all participants in advance of the workshop. The authors (T. Springer, J. Zumberge, J. Kouba; T. Martin-Mur, T. Springer, Y. Bar-Sever; J. Kouba, J. Ray, M. Watkins; G. Gendt; J. Feltens, S. Schaer), working together by e-mail, made a fundamental contribution to the preparation and to the successful outcome of the workshop.

Thanks are due to the members of the Local Organizing Committee (Siegmar Pallaschke, Roberta Mugellesi Dow and Hiltrud Grunewald) for smooth organisation of the workshop logistics, the reception and visit to the satellite control facilities at ESOC, and the workshop dinner at Jagschloss Kranichstein.

The Scientific Programme Committee for the 1998 IGS Analysis Centre Workshop consisted of myself (as representative of the host institution), Jan Kouba (as IGS Analysis Centre Coordinator from 1994 to 1998) and Tim Springer (as future IGS AC Coordinator). Although we three also appear as editors, I would like to dedicate these proceedings to Jan Kouba with thanks for his massive contribution to the IGS analysis efforts since the beginning of the IGS, a contribution which will be difficult to match and will certainly not end with his retirement from Natural Resources Canada.

John M. Dow
ESA/ European Space Operations Centre
Darmstadt

April 1998

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Programme of Workshop

IGS ANALYSIS CENTRE WORKSHOP 1998

Sunday 8 February 1998

16:00 IGS Governing Board (GB) Business Meeting (separate invitation by Central Bureau)

Monday 9 February

08:15 Opening of Workshop registration desk
09:00 Welcome and introduction (J.M. Dow, C. Mazza, G. Beutler)
09:20 1. Mueller: Summary of conclusions of the GB Retreat

Topic 1: **The IGS Analysis Products and Consistency of the Combination Solutions**
(Session chair: J. Kouba, M. Rothacher)

09:40 Position paper by T. Springer, J. Zumberge, J. Kouba
10:00 J. Zumberge: Efficient estimation of precise high-rate GPS clocks
10:15 W. Soehne: Precise high-rate satellite clocks at GFZ
10:30 J. Ray: The IGS/BIPM time transfer project
10:45 Coffee break
11:00 Discussion
12:15 Lunch

Topic 2: **Orbit Prediction and Rapid Products**
(Session chair: T. Springer, J. Dow)

13:30 Position paper by T. Martin-Mur, T. Springer, Y. Bar-Sever
13:50 T. Springer, Y. Bar-Sever: Radiation pressure models for GPS
14:10 J. Zumberge: Identification of mismodelled satellites in the GPS predicted orbit
14:25 M. Romay-Merino: Real-time ephemeris corrections for EGNOS based on the computation of accurate orbit predictions
14:40 P. Silvestrin: The GRAS programme and projected requirements for orbit prediction and rapid products
14:55 Discussion
15:30 Coffee break
15:45 Analysis Centre Poster Session
18:00 Reception with buffet at ESOC

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Tuesday 10 February

Topic 3: **IGS Reference Frame Realization and Contributions to ITRF**
(Session chair: M. Watkins, G. Beutler)

09:00 Position paper by J. Kouba, J. Ray, M. Watkins

09:20 C. Boucher, Z. Altamimi, P. Sillard: ITRF96 and follow-on for 1998

09:35 Z. Altamimi: IGS reference stations classification based on ITFR96 residual analysis

09:50 M. Rothacher: Estimation ofnutation from GPS

10:05 G. Blewitt, R.S. Kawar, and P.B.H. Davies: Fiducial-Free Euler Vector Solutions from the GNAAC Polyhedron Time Series

10:20 Coffee break

10:40 Discussion

12:00 Lunch

Topic 4: **IGS Products for Troposphere and Ionosphere**
(Session chair: G. Gendt, M. Schenewerk)

13:30 Position paper (Troposphere) by G. Gendt

13:50 M. Becker, G. Weber: Troposphere model estimated from the data of the German permanent GPS net work GREF

14:05 Y. Bar-Sever: Tropospheric gradients - a new IGS product?

14:20 Discussion

15:00 Coffee break

15:20 Position paper (Ionosphere) by S. Schaer, J. Feltens

15:40 R. Warnant: The study of the TEC and its irregularities using a regional network of GPS stations

15:55 N. Jakowski, S. Schlueter, A. Jungstand: Monitoring the ionosphere over Europe and related ionospheric studies

16:10 J. Feltens: Routine production of ionospheric maps and Chapman profile approach for 3-D global TEC representation

16:25 R. Leitinger: The role of GPS data in ionospheric monitoring, mapping and nowcasting

16:40 S. Schaer: Mapping and predicting the ionosphere

16:55 Discussion

17:45 End of session

20:00 Dinner at Jagdschloss Kranichstein

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Wednesday 11 February

Contributed papers on other topics
(Session chair: Peng Fang)

09:00	Y. Bar-Sever: Low elevation tracking by TurboRogue receivers
09:10	Y. Bar-Sever, K. Hurst: Site specific antenna phase center calibrations
09:20	H. Habrich: Experiences of the Federal Office for Cartography and Geodesy (BKG) in processing GLONASS and combined GLONASS/GPS observations
09:35	M. Romay-Merino: Precise autonomous orbit determination for future navigation satellites without degradation during manoeuvres
09:50	T. Martin-Mur, C. Garcia-Martinez: ARP project - absolute and relative orbits using GPS
10:05	R. Neilan: Status of GPS modernisation effort in the US, including prospects for additional civilian frequencies
10:20	Free slot
10:30	Coffee break
10:50	Discussion on open AC issues (Facilitators by topic groups: J. Dow, J. Kouba, T. Springer)
13:00	End of workshop
14:30	Wrap-up Business Meeting (GB/CB members, session coordinators)

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Posters

1. CODE Analysis poster
2. EMR Analysis poster
3. ESA Analysis poster
4. GFZ Analysis poster
5. JPL Analysis poster
6. NGS Analysis poster
7. S10 Analysis poster
8. USNO Analysis Poster
9. Newcastle GNACC processing/ results
10. GFZ CHAMP poster and S/C model
11. SIRGAS (South America) RNAAC poster

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List of Participants

Zuheir Altamimi, Institut Geographique National, France
Poul Hoeg Andersen, TERMA (CRI), Denmark
Yoaz Bar-Sever, JPL, USA
Matthias Becker,BKG Frankfurt, Germany
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Geoff Blewitt, Univ. of Newcastle, UK
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Carine Bruyninx, Royal Observatory of Belgium
Stefano Casotto, Univ. of Padova, Italy
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Joachim Feltens, ESA/eds
Remi Ferland, Natural Resources Canada
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Jan Kouba, Natural Resources Canada
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Tomas Martin-Mur, ESA
Carlo Mazza, ESA
Ivan Mueller, Ohio State University, USA
Rolf Muench, ESA
Roberta Mugel lesi Dow, ESA
Ruth Neilan, JPL, USA
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Pierluigi Silvestrin, ESA
Wolfgang Soehne, GFZ Potsdam, Germany
Tim Springer, Univ. of Bern, Switzerland
Lambert Wanninger, TU Dresden, Germany
Rene Warnant, Royal Observatory of Belgium
Mike Watkins, JPL, USA
Georg Weber, BKG Frankfurt, Germany, Austria
Pascal Willis, Institut Geographique National, France
Jim Zumberge, JPL, USA

EXECUTIVE SUMMARY[1]

G. Beutler

The 1998 IGS Analysis Center Workshop took place 9-11 February 1998 in Darrnstadt. In addition, a business meeting of the IGS Governing Board was scheduled for Sunday, February 8, a wrap-up meeting of the Governing Board together with the convenors of the AC Workshop and the authors of the position papers concluded the Darmstadt IGS events. As usual I try to summarize the essential events of the Board meetings and of the workshop.

Governing Board Meetings (February 8 and 11)

IGEX-98

Pascal Willis, chair of the CSTG Subcommission on "Precise Satellite Microwave Systems", presented the draft call for participation for the "International GLONASS Experiment (IGEX)" to the IGS Governing Board. In essence it is proposed to organize a three months GLONASS test campaign by the end of 1998. The Experiment is organized by CSTG, it is sponsored by the IGS, the ION, and the IERS. The call for participation was prepared by the IGEX steering committee consisting of Pascal Willis (IGN, chair), Gerhard Beutler (AIUB), Werner Gurtner (AIUB), Guenther Hein (UFAF), Ruth Neilan (JPL), and Jim Slater (NIMA).

The draft call for participation consists of two parts, a description of the experiment and the actual call for participation. The IGS involvement is indeed essential: Major parts of the IGS infrastructure (network, data links, data centers) will be used. It is furthermore expected that some of the IGS Analysis Centers will answer the IGS Call for Participation.

The Steering Committee of the IGEX-98 is fostering participation in the 1998 International GLONASS Experiment IGEX-98 in the following areas:

- IGEX-98 Coordinating Center
- IGEX-98 Observing Sites
- IGEX-98 Data Centers
- IGEX-98 Analysis Centers
- IGEX-98 Evaluation Center(s)

All GLONASS satellites are equipped with arrays of LASER reflectors allowing the SLR community to range easily (!) to the GLONASS satellites. It was thus decided to closely coordinate the IGEX-98 with the SLR SubCommission of CSTG (Werner Gurtner from the IGEX-98 steering committee is the "liaison officer" to the SLR Subcommission). The participation of the SLR community is essential for validating the results and for the development of radiation pressure models for the GLONASS satellites.

The receiver situation is of concern to the IGS Board members. In principle one would like to use uniquely geodetic-type dual frequency combined GPS/GLONASS equipment (similarly as it was done for the 1992 IGS Test Campaign). In order to have access to a greater number of

[1] Reprint of IGS Mail No. 1806, 17 February 1998.

receivers the steering committee decided to be more flexible: In sequence of preference, the following receiver types may be used in IGEX-98:

- Combined dual-frequency GPS/GLONASS receivers
- Dual-frequency GLONASS receivers
- Combined single-frequency (Ll) GPS/GLONASS receivers
- Single-frequency GLONASS receivers

Receivers must be collocated with or tied to sites that have well-determined ITRF coordinates. IGS sites are preferable. The ITRF coordinates should have an accuracy of 1-5 cm.

Not only the receiver situation, but also the satellite situation has to be considered as a crucial issue. Today, there are only 14 operational GLONASS satellites available, Launches of GLONASS satellites have been announced, however. There is not much that the steering committee can do to improve satellite availability (!). Should the number of operational GLONASS satellites fall under a critical level, the IGEX-98 would of course have to be postponed.

The schedule for IGEX-98 is as follows:

February 1998	Distribution of IGEX-98 Call for Participation through mail e-mail services of the sponsoring agencies.
May	Proposals due
June	Evaluation of proposal by the Steering Committee Review/approval of the schedule Designation of the Oversight Committee (including Chair) Campaign Planning Meeting
September 20	Campaign begins
December 20	Campaign ends
early 1999	IGEX-98 Evaluation Workshop (possibly combined with the 1999 IGS Analysis Center Workshop)

The IGS Governing Board discussed the proposal in detail. It was finally decided that the Call for Participation should be sent out in February 1998 after a few modifications. The modifications underline the experimental (as opposed to operation oriented) character of IGEX-98. The chairman thanked Pascal Willis and the IGEX-98 steering committee for their planning work.

IGS Densification

At the eighth IGS Governing Board meeting in San Francisco (December 1998) it was decided to take the necessary steps to terminate the Pilot Phase of the Densification Project as soon as possible, but not before all discrepancies, errors, etc., in the understanding of station coordinates (and velocities) were removed (IGS Mail Message 1763). This condition could not yet be met. The IGS Central Bureau, together with the IGS Infrastructure Committee are still working on that issue. The basis is the list of discrepancies published regularly by the Analysis Coordinator.

It is the policy of the IGS Governing Board to come up with a unique IGS product of coordinates and station velocities. As all three GNAACS are willing to continue with their activities one has the problem that a unique series of coordinates has to be formed using the resulting SINEX files of the three SINEX files. Norman Beck, Chief of Active Control System, Natural Resources Canada (NRCan), kindly offered in a letter dated January 19, 1998 to produce the SINEX GNAAC combination, based on the three GNAAC solutions by University of Newcastle, JPL and MIT, The IGS Governing Board unanimously accepted this offer and asked the chairman to thank NRCan for providing this service to the IGS community. NRCan will start providing this combination as soon as possible (probably in March 1998).

As a side issue Norman Beck asked the chairman to explore the IGS Governing Boards views concerning an EUREF-like activity for North America. The discussion revealed that the Board and the GNAACS represented at the business meeting would in fact favour such a development. The EUREF solution, coordinated by Carine Bruyninx, is (amongst other) most useful to eliminate all station-related problems. Also, it makes sure that the solution is actually providing the reference frame for the continent, which is accepted and used by the European topography and geodetic services, The chairman was asked to write a letter to the existing and potential RNAACs in North America encouraging this level of cooperation.

"Densification of the ITRF using GPS" will be again on the agenda of the ninth IGS Governing Board Meeting, to be held end of May 1998 in Boston. I hope (and assume) that the Board will be in a position to decide about the operational phase of the densification issue.

1997 IGS Annual Report

Ruth Neilan and Jim Zumberge came up with a new format for the 1997 IGS Annual Report. They propose to produce the report in two parts (corresponding to 2 volumes). Part 1 would contain, so to speak, the top level information (CB report, IGS Analysis Center Coordinator report, report about current projects, etc.), Part 2 would contain the Analysis Center reports, the station reports, etc. Part 1 would be edited by the Central Bureau in a similar way as it was done with the 1996 Annual Report. Part 2 would be published based on “camera ready manuscripts”. In order to reduce the size of the Annual Report, page limits will be given to the authors. Both reports will be made available also in electronic form.

The proposal aims at reducing the costs of the Annual Reports and at having the Annual Report available much earlier.

After extensive discussions and after positive feedback from the Analysis Centers the Board accepted the proposal. The authors of the 1997 Annual Report will be notified concerning the expected contributions in the near future. The Annual report -- if possible both parts, but certainly Part 1 should be available in July 1998.

GPS Modernization Process and IGS Involvement

Ruth Neilan informed the Board that she was asked to chair a working group of the “US GPS Interagency Advisory Council (GIAC)" jointly setup by the U.S. Department of Defence (DoD) and the Department of Transportation (DoT). Ruth Neilan views this assignment as an important interface between the international scientific community represented in the IGS and operators of the GPS.

The IGS Governing Board in turn viewed this as a very positive development and encouraged the Central Bureau to play a very active role in this working group. The hope was expressed that views of the IGS community on issues like the "second civil frequency" or on the attempt to assign the frequency range 1559-1567 MHz to Mobile Satellite Services (MSS) (latest attempt made at the the WRC-97 in Geneva) could more easily be made known. The CB was in particular asked to coordinate efforts in such matters with other organizations like, e.g., the ION.

IGS Retreat, December 1998

At the seventh IGS Governing Board Meeting in Rio de Janeiro it was decided to organize an "IGS Retreat" in December 1997 with the IGS Governing Board Members and a very limited group of IGS Associates with the goal to come up with a plan for the future development of the IGS which then should be discussed by the entire IGS community and the Board (IGS Mail Message No 16S3).

About half of the time of the Sunday business meeting of the IGS Governing Board was devoted to the discussion of the "recommendations and action items" of the IGS Governing Board retreat in Napa Valley, December 12-14, 1997. The report was prepared by Ivan I. Mueller, who was also the program chair of the retreat. It was clear that the report could only be discussed at the business meeting; decisions on this matter will be taken at the next official IGS Governing Board Meeting (28 May 1998 in Boston). The complete report containing all recommendations and action items may be retrieved by ftp (see attachment). Let me point out that comments on the action items and recommendations are welcome!: no decisions have been taken so far, the process may still be influenced till the end of May.

The report contains fourteen recommendations and thirteen action items emerging from them. Let me comment a few of these recommendations and action items.

Recommendation 1 proposes to change the name "International GPS Service for Geodynamics" to "International GPS Service". The acronym "IGS" remains the same. The Board is in favour of this recommendation.

Recommendation 2 asks the "IGS to produce combined, internally consistent, global products". Product will include in future orbit parameters, station coordinates and velocities, earth rotation parameters, GPS clock corrections, IGS time scale, tropospheric zenith delays, and ionosphere models. Consistency of all products is the central issue, which was also discussed at the workshop (see below). The IGS/BIPM Project addresses the time-related issues.

Recommendation 5 asks that "the global IGS Network should be enhanced in the overall sense". An important (actually THE important) action item related to this recommendation is to appoint a Network Manager or Coordinator, within or outside the CB.

Recommendation 7 asks for a review of the definition of the terms "IGS Analysis Center", "Associate Analysis Center" at the Analysis Center Workshop in Darrnstadt.

Recommendation 8 recommends that Working Groups be appointed for "troposphere products", "ionosphere products", for "ITRF densification", and possibly for others. The working groups should have clear charters and structures.

Recommendations 9 to 12 are related to the IGS Central Bureau. It is in particular recommended that the tasks of the CB (as described in the Terms of Reference) are regularly reviewed, that future tasks are clearly defined. Moreover, requirements concerning the minimum number of persons working for the CB were stated.

Recommendation 14 asks the Governing Board to consider forming a committee, with external participation, with the task to prepare the IGS Long Range and Strategic Plan.

The above selection of recommendations and action items emerging from the IGS Retreat 1997 is of course a personal one. Everybody is encouraged to retrieve the complete report.

The Governing Board considers the "recommendations and action items" of the IGS Governing Board retreat in Napa Valley, December 12-14, 1997 as prepared by Ivan I. Mueller as an extremely useful document defining the development of the IGS at least till the end of the millenium (!). The Board thanked Ivan I. Mueller for his excellent work.

1998 IGS Analysis Center Workshop (9-11 February, 1998)

4 topics (see below) were dealt with in detail at the 1998 IGS Analysis Center Workshop. The first presentation within each topic was a position paper, topic 4 even was dealt with in two position papers. AU of the position papers were available over the internet prior to the workshop (ftp-address: see attachment). The final versions of the position papers will be available no later than March 15, 1998 under the same ftp-address. These remarks underline how well the workshop was prepared by the prograrnme committee, consisting of John Dow, Jan Kouba, and Tim Springer.

The workshop was formally opened on Monday, February 9 at 9 a.m. with a welcome address by Carlo Mazza, Head of Ground Systems Engineering Department of ESA, with an introduction by John Dow, and an overview of previous IGS workshops by Gerhard Beutler.

Topic 1: The IGS Analysis Products and Consistency of the Combination Solutions (Session Chair: Jan Kouba, Markus Rothacher)

The position paper entitled "the IGS Analysis Products and the Consistency of the Combined Solutions" written by T.A. Springer, J.F. Zumberge, and J. Kouba reviewed the quality, consistency, and reliability of current IGS analysis products (orbits, Earth orientation parameters, station coordinates, and clocks). The paper focused on current procedures to derive these products, on reporting and feedback. Seven recommendations were given at the end of the paper. All of them were accepted, some will ask for significant work by the IGS Analysis Centers in the near future, As the proceedings of the workshop (containing all position papers and resolutions) should be available rather soon, and as people interested in the resolutions may retrieve preliminary versions of the position papers under the ftp address mentioned, we may confine ourselves to highlight only a few of these resolutions.

First of all it is recommended that the IGS ACS include ephemerides for ALL operational satellites in the daily SP3-files, and that these ephemerides are characterized by MEANINGFUL accuracy codes. No format changes are necessary for this step, most of the analysis centers already provide such accuracy information. It was also discussed, however, that the user community of IGS products must be made aware of these accuracy codes, and that this community should be strongly encouraged to make use of these codes. This aspect might be more important in future, when more orbit information of "modest quality" will available (due to this resolution).

Precise single point positioning developed by Zumberge et al. is used extensively today. Consistency of orbit and clink information is crucial for this technique, The required consistency level (of millimeters) is much easier to achieve if the same software package is used to produce the global products (orbits and clocks) AND the coordinates using the single point positioning technique. It was/is most encouraging to see that already today, thanks to an essential upgrading of the combination technique, the consistency level for the combined IGS products is not far away from the best possible consistency level that may be reached (using one and the same software). It seems feasible that sub-centimeter point-positioning using IGS products should be possible in the very near future.

Other recommendations dealt with the “densification project”. It was recommended that deadlines in compliance with other deadlines in the IGS are used, that EOP information is included by all analysis centers in the GNAAC solutions, and that all discrepancies/errors in the RINEX files are removed.

Also, the minimal requirements (performance-wise) to become an IGS Analysis Center were reviewed (and probably clearly defined for the first time). As this recommendation was extensively discussed and modified at the workshop, it is advisable to wait for the final version of this position paper.

There were other interesting contributions in the first session. Jim Zumberge presented a technique at JPL to produce in an efficient way high-rate GPS clocks, Wolfgang Soehne from GFZ presented the GFZ procedures developed for the same purpose. Jim Ray gave a short status report of the IGS/BIPM project: the call for participation was issued in January, the next phase will consist of evaluating the proposals received in spring 1998.

Topic 2: Orbit Prediction and Rapid Products (Session Chair: Tim Springer, John Dow)

Tomas Martin Mur (ESA), Tim Springer (CODE) and Yoaz Bar Sever (JPL) reviewed the procedures for “Orbit Prediction and Rapid Products” in the position paper for topic 2. With the increasing demand for close to real-time products this issue becomes more and more important. It came out very clearly that data availability is THE critical issue. Global coverage is far more important than the number of stations (provided a minimum number of about 30 stations is available).

The paper also reviewed the prediction techniques used by individual IGS Analysis Centers and in the combination. Usually, IGS predictions are much better than broadcast orbits (the former, when compared to the IGS final orbits are of about 30-50 accuracy (extrapolation over 2 days), the latter are of 2-3 meter accuracy). There are exceptions, however, which are not always predictable. Two measures may improve the reliability of IGS predicted orbits: (a) reduction of the delay of data availability (see primary recommendation below), (b) reduction of the number of “unknown” parameters for prediction process.

New orbit models developed by Yoaz Bar-Sever at JPL and by Tim Springer at CODE are promising in area (b). Only improved data transmission may help in area (a): Therefore, the frost arid probably the primary recommendation of the position paper asks the operational and global data centers to give highest priority to the delivery of stations outside Europe and North America (!). This does not mean, of course, that data from Europe and North America are not important;

but due to the usually excellent infrastructure ftp retrieval guarantees quick availability of a sufficiently high number of stations (data outside these areas often have to be retrieved by the operational centers by telephone or other links).

All in all seven recommendations were given in the position paper for Topic 2. The first three addressed data availability (including more frequent than daily data download), the third recommends extensive tests of the two new radiation pressure models (which are made available by CODE and JPL) by all IGS ACS. The other three resolutions dealt with EOP series to be used with the predictions, studies to improve the accuracy codes for prediction, and the use of the NANU messages to reduce the number of blunders. An important issue, the change of the deadline for the IGS Analysis Centers to deliver the rapid orbits/cops to 4 p.m. U.T. by January 1, 1999 (from 9 p.m. U.T.), was extensively discussed at the workshop. A recommendation related to that topic will be contained in the final version of position paper 2.

The position paper was followed by technical papers related to topic 2: Tim Springer presented his "latest and greatest" radiation pressure model and compared it to the model developed by Bar-Sever. Jim Zumberge addressed the problem of identifying mismodeled satellites in GPS predicted orbits. A presentation by M. Romay-Merino dealt with considerations concerning real-time orbit computation for navigation using orbit predictions of the GPS, GLONASS, etc., in the context of GNSS. A contribution by P. Silvestrin described the GRAS (GPS/GLONASS) receiver being developed by ESA for support of atmospheric sounding and other applications.

Topic 3: IGS Reference Frame Realization and Contribution to ITRF (Session Chair: Mike Watkins, Gerhard Beutler)

The position paper by J. Kouba, J. Ray and M.M. Watkins addressed "IGS Reference Frame Realization" within/by the IGS. It was stated in particular that the current set of 13 ITRF94 stations and the current IGS approach to realize the ITRF are no longer appropriate. A new set of about fifty reference frame stations (based essentially on an IGS history of station coordinates AND the new ITRF96 as made available through the IERS) are about to replace the "old" set of 13 stations. It is expected that this measure will "dramatically" improve the IGS rapid EOPs. This in turn will improve the Bulletin A values of the IERS.

The paper also compares in detail the ITRF96 station positions and velocities with the purely IGS derived quantities for the selected fifty stations (and subsets of it). The agreement is excellent, indeed. It is therefore natural that recommendation 1 demands the IGS to adopt ITRF96 as early as March 1, 1998.

Other recommendations deal with technical aspects of producing the SINEX solutions, like, e.g., the inclusion of EOPs. Last but not least, it is recommended that a "super''combination of G-SINEXes for station coordinates, velocities and EOPS is researched and initiated on behalf of the IGS. The participants of the workshop were very much pleased to learn that NRCan would take on this new combination task (compare report about GB Meeting, topic "densification").

Very interesting and informative presentations concerning the establishment of ITRF96 followed the position paper. It became quite clear that the IGS is an important contributor to the ITRF. The histograms dealing with coordinate accuracies are interesting, as well. It might be worthwhile to look into the technique specific aspects: it seems in particular that the distribution of SLR-derived height errors supports the conclusion that, due to the unproblematic modeling of the troposphere in SLR, the SLR determined heights may significantly contribute to the height datum of the ITRF96.

Markus Rothacher et al. summarized their attempts to extract short-period nutation terms from CODE/IGS eop series. Apparently, for periods up to about 20 days, the results obtained by GPS are of equal or better quality than those obtained by VLBI. The work was motivated by the simple idea that "there is no reason NOT to solve for nutation drifts, if one is solving for led-values" ! It is expected that the results can be significantly improved, if a more appropriate orbit model (radiation pressure model) is adopted.

Geoff Blewitt et al. proposed to extract "fiducial-free Euler vectors" from the GNAAC Polyhedron time series. The method presented allows it very well to separate "normal" plate motion (represented through the Euler vectors, resp. their first derivatives) from "abnormal" (e.g., subsidence) or "apparent" (e.g., induced through antenna changes . ..) motion. It might be worthwhile to explore the interest within the IGS and the IERS community for such vectors as a regular IGS product.

Topic 4: IGS Products for Troposphere and Ionosphere (Session Chair: Gerd Gendt, Mark Schenewerk)

Troposphere

The position paper "IGS Combination of Tropospheric Estimates - Experiences from Pilot Project" was presented by Gerd Gendt from the GFZ Analysis Center, GFZ was gaining experience since more than one year of comparing and combining troposphere estimates for about 100 sites of the IGS Global Network stemming from individual IGS Analysis Centers.

Despite the fact that rather different processing options were used by the Analysis Centers (different levels of differencing, different binning, different cut-off angles) the consistency level reached is in general quite good. There was general agreement that the combined series of total zenith path delays for the entire IGS network are of interest for climatological studies. Gerd Gendt recommends furthermore that the troposphere combination product should become an official IGS product, that the weekly summary reports are made publicly available (in the IGS report series), and that the product distribution is performed using the ftp server of GFZ.

The IGS troposphere product would be of much greater value, if a significant number of permanent, accurate, reliable surface meteorology measurements series would be available. This is a station specific issue to be addressed by the Central Bureau, the Infrastructure Committee and the future Network Coordinator.

Gerd Gendt's recommendations were unanimously accepted, We are thus looking forward to see the announcement through IGS-mail that official IGS troposphere products are available.
Matthias Becker and Georg Weber from BKG Frankfurt (former IfAG) presented a study to use the German permanent GPS network (GREF) to extract regional troposphere information on a routine basis. The results are promising and should be seen as an attempt to make optimum use of a permanent network.

Yoaz Bar-Sever discussed troposphere gradient estimates performed at the JPL Analysis Center. He concludes that gradient estimates are significant and tend to improve station coordinate repeatability. The drawback has to be seen in the considerably increased number of parameters. Comparisons of monthly mean values for the JPL gradient parameters with those of the CODE Analysis Center show a good agreement. More work has to be done in this area.

Ionosphere

The position paper "IGS Products for the Ionosphere" was given by Joachim Feltens (ESA) and Stefan Schaer (CODE). They reviewed the ionosphere related activities within the IGS in previous years and they came up with a list of ten potential participating institutions in a future "IGS ionosphere service". Based on an e-mail inquiry they furthermore gave an overview of analysis methods and models used by the institutions mentioned. An important part of the presentation dealt with the definition of a future IGS ionosphere product. They recommend that all IGS ionosphere products

- must be based on the IONEX format,
- should refer to a two-dimensional grid in a (single layer) shell,
- should refer to the same shell height,
- should use identical reference epochs for subsequent ionosphere models,
- that one, maybe two, time resolutions have to be agreed on, and
- that naming conventions for ionosphere model files have to be defined.

The authors and the interested institutions are convinced that the development of an IGS ionosphere product makes sense and that a continuous series of IGS products should be produced at least over one full 11 years cycle of solar activity. It is of particular importance that the IGS models are covering the next period of maximum of solar activity (years 2001-2003). The key recommendation was to establish a pilot phase for such an IGS ionosphere service as soon as possible.

It was most encouraging that the experts in the field of ionosphere physics, in particular Drs. N. Jakowski (DLR Neustrelitz), R. Leitinger (TU Graz), and R. Warnant (Royal Observatory of Belgium, Brussels), and L. Wanninger (TU Dresden) were attending the workshop to give their input for the development of an IGS product. Their presentations showed that many activities in the ionosphere community are regional in nature -- and that there are good reasons for this. It became clear that the IGS (at least in a first phase) should stay out of regional ionosphere modeling, but should rather focus on global aspects. One had to conclude from the discussions that there is a great interest of the ionosphere community in a continuous series of global IGS ionosphere models.

That the modeling capabilities were significantly improved over the last few years emerged from two technical presentations given by Stefan Schaer and by Joachim Feltens. The former presentation showed (among other) that the parameters of the CODE models maybe successfully predicted, the latter presentation was also addressing mathematical aspects using a so-called "Chapman profile approach".

In the discussion portion of the session and in the wrap-up meeting at the end of the workshop the following procedure was proposed:

- Joachim Feltens and Stefan Schaer, in close cooperation with the existing "IGS ionosphere club", should come up with
- a proposal for global IGS ionosphere products (including the specification of parameters, formats, etc.)
- a clear proposal how to proceed (test phase, pilot phase, etc.)
- a proposal for the structure of the working group (what positions have to be created (e.g., IGS (Associate) Ionosphere Analysis Centers, Ionosphere Combination Center, Validation Center),
- a list of members for the future IGS Ionosphere Working Group.

- These specifications should be included in the final version of their position paper.

- John Dow and Gerhard Beutler should
  - draft a general “charter” for setting up Working Groups within the IGS and circulate this draft within the Governing Board,
  - develop in close cooperation with the “ionosphere club” the charter for the ionosphere working group and circulate this draft within the “ionosphere group” (which probably is the nucleus for the working group).
- Assuming that the structure of the ionosphere working group is acceptable to all parties interested in IGS ionosphere monitoring, the ionosphere working group should be established by the IGS Governing Board by the end of May 1998 in Boston.

This procedure was unanimously accepted by the IGS Governing Board and the session convenors at the wrap-up meeting on Wednesday, February 11. It should thus be possible to start an IGS pilot ionosphere service in the near future.

The workshop was concluded with a session addressing topics other than those treated in the previous four sessions. Let us mention in particular presentations by T. Martin-Mur and C. Garcia-Martinez (absolute and relative orbit determination using spaceborne GPS receiver), Y. Bar-Sever (low elevation tracking of TurboRogue receivers, site specific antenna phase center calibrations), H. Habrich (processing of GLONASS and combined GLONASS/GPS observations), and by Ruth Neilan (GPS modernization effort in the US).

Hospitality experienced in Darmstadt

As one may conclude from the above report, the Darmstadt IGS event really was a WORKshop. That the IGS Analysis Centers forma very dynamic group of enthusiasts became also clear at the reception on Monday evening and at the dinner at Jagdschloss Kranichstein. Despite its name there was no hunting before the dinner, one even had the option of a vegetarian menue (and this in a Jagdschloss -- “o tempera, o mores”!).

The Analysis Centers took the opportunity to thank Jan Kouba for his personal engagement and his great performance as IGS Analysis Coordinator. A Swiss railway clock presented to him will undoubtedly help him to understand the subtleties of the IGS/BIPM project. The clock is also complicated enough (it has at least two buttons and may be used in at least two different ways, e.g., as a pocket clock or as a clock on his desk) to represent a challenge for his technical skills. Jan will continue to serve as IGS Analysis Center Coordinator till the end of 1998. As the next IGS AC Workshop will take place only in 1999, the Darmstadt workshop was presumably the last workshop with Jan Kouba “in command” as AC coordinator.

The chairman also took the opportunity at the dinner to express the gratitude of all workshop participants to the local organizers from ESA, in particular John Dow, his wife Roberta, Siegmar Pallaschke, Rolf Muench, and Hiltrud Grunewald for their perfect organization of the 1998 IGS events in Darmstadt,

Gerhard Beutler
Chair, IGS Governing Board

SUMMARY RECOMMENDATIONS OF THE DARMSTADT WORKSHOP

Position Paper 1: The IGS Analysis Products and Consistency of the Combination Solutions

1. Inclusion of all satellites, which were used in the data analysis, with meaningful accuracy codes in the orbit products from all individual ACS. Use of these accuracy codes, or accuracy measures from the long-arc analysis, to identify and consequently downweight “bad” satellites in the orbit combination. In addition the IGS should increase the user awareness of the availability and importance of the accuracy codes in the SP3 files (see also Recommendation 4).

2. Enhancement of clock products. All ACS which submit clocks must also submit clock estimates from a, yet to be determined, subset of “core time stations”! All ACS are urged to submit clock estimates. Furthermore the ACS are encouraged to increase the sampling rate of the satellite clock products to 30 seconds. A format for station and satellite clocks, also suited for 30 seconds satellite clocks, will have to be defined.

3. Improved and automatic feedback to Data Centers (DC) and station managers in case there are discrepancies between RINEX files and station logs, data problems and unexpected problems (jumps) in the station coordinate solutions.

4. Create a central place (WWW) for feedback and information about the IGS products and their use.

5. Definition of minimal requirements for becoming an IGS AC. Any AC must produce all core products, i.e. orbits, EOPs, and SINEX, both on time and with sufficient (high) quality. The IGS terms of reference will be changed accordingly,

6. Additional accuracy digit for the IERS/IGS EOP file format. New format to be defined before June 28, 1998 by Jan Kouba in cooperation with Dennis McCarthy.

Position Paper 2: Orbit Prediction and Rapid Products

1, Ask the Operational, Regional and Global Data Centers to give the highest priority to the prompt retrieval and distribution of data from sites outside Europe and North America.

2. Ask the Operational, Regional and Global Data Centers to investigate and implement ways of reducing data retrieval and distribution delays.

3. Ask the Operational, Regional and Global Data Centers to study and implement more frequent down-loading of the data.

4. Ask those Analysis Centers that are evaluating more precise radiation pressure models to make them publicly available, and encourage all Analysis Centers to implement and use them when they have been validated.

5. Ask the IERS Rapid Service and the Analysis Centers to investigate and propose ways to obtain predicted cops (pole and UT1) for use in the calculation of IGS predicted orbits.

6. Ask the Analysis Centers and the AC Coordinator to study, monitor, and, if possible, improve the fitness of the accuracy codes for the predicted orbits.

7. Ask the Analysis Centers to investigate the ways and the consequences of reducing the turn-around time for rapid and predicted products.

8. Review data and rapid product delivery times at July 1 and October 1 in order to evaluate the change of the deadline for rapid products to no later than 16:00 UTC by January 31999.

Position Paper 3: IGS Reference Frame realisation and Contributions to ITRF

In order to increase the IGS product consistency and to prepare ground for adaptation of the new approach of ITRF realizations, the following recommendations were accepted by the workshop participants:

1. That IGS adopts ITRF96 as early as March 1, 1998 to replace the currently ailing and problematic IGS realization of ITRF94, which currently is based only on less than 13 ITRF stations.

2. As an interim measure and to facilitate an immediate ITRF realization improvement it is recommended that the selection of the new ITRF96 station positions and velocities for a large subset of the RF station is finalized at this workshop. This newly selected ITRF96 set of the 47 globally distributed IGS stations is to be used for ITRF96 realization in all IGS products beginning as early as March 1, 1998. IGS realization of ITRF is then accomplished by the above ITRF96 station coordinates/velocities together with the current official igs.snx, which contains antenna offset and height information in the SINEX format.

3. That all weekly submitted AC SINEX solutions (A-SINEXes) contain the EOP of the current week and that the submitted AC orbits/clocks (sp3) and EOP (erp) files are consistent with the above A-SINEX solutions. This is essential not only for the increased IGS product consistency but also for the future (improved) ITRF realization and IGS products. It is recommended that this is implemented and ensured by all ACS by June 28, 1998.

4. That the GNAAC combinations retain (and adjust) the submitted AC EOP information of the current week in their G- SINEX combined products, along with the usual station position solutions. It is recommended to be implemented by June 28, 1998.

5. The SINEX extensions as outlined in the Appendix IV, allowing the minimum datum and transformation parameter constraints to be coded in the SINEX format, are accepted and used by IGS on or before March 1, 1998. Furthermore, that IGS submits the SINEX extension for acceptance to Prof. Tom Herring of CSTG, who is currently responsible for the SINEX format. This will provide a means and encouragement to ACS and other IGS users to use (minimum) datum constraints, as well as it allow an efficient and safe monitoring of geocenter and scale changes (e.g. Ray, 1997). It is further recommended that only the AC Final products, which are based on minimum or no datum constraints, be accepted for the IGS Final orbit/clock/EOP/station combinations after June 28, 1998.

6. That a (super) combination of G-SINEXes for station coordinates and EOP is researched and initiated on behalf of IGS. This EOP (G-SINEX combination) cumulative solution would replace the current IGS EOP combination and it would lead to an official SINEX station solution product (both for global as well as the polyhedron stations). The polyhedron SINEX solutions could be produced by back substitution when P-SINEXes are made available to produce the IGS P-SINEX products (station positions/velocities only). The implementation goal should also be by June 28, with the official IGS SINEX (G and P) products on or before January 3, 1999 !

Position Paper 4a: IGS Products for the Troposphere

1. The pilot phase for the IGS Combined Tropospheric Estimates will be finished and the combined zenith path delay (ZPD) estimates will become an official product. The conversion into precipitable water vapor will be postponed until a sufficient number of surface met packages is available. At the moment it is to the customer to convert the ZPD by relying both on the existing RINEX met files as well as on interpolation within global or regional meteorological fields. The product will be archived at the global Data Centers.

2. All network operators will be encouraged to enforce the installation of met packages.

3. The Analysis Centers should strive to constrain the RF stations during the computation of the tropospheric estimates to reduce the biases in the ZPD estimates as much as possible.

4. All Analysis Centers provide TRO-SINEX files which are compatible to the weekly SINEX file, i.e. the daily station coordinates of the TRO-SINEX files should refer to the site description blocks given in the weekly SINEX file.

5. IGS will strive to get water vapor estimates from collocated water vapor radiometer and VLBI. During a calibration campaign all Analysis Centers will be asked to include those sites in their analysis for investigation of the biases in the ZPD estimates.

6. For each SINEX file the shortened version *.ssc without all matrices should be archieved too. The ssc-files should be formed at the Data Centers unless the ACS already submit both *.snx and *.ssc. This way also * .ssc versions for all the old SINEX files can be formed.

Paper 4b: IGS Products for the Ionosphere

1. Initially, the IGS should focus on two kinds of products:
   (a) TEC maps in grid form and
   (b) differential code biases (DCBs).

2. IGS TEC maps are global maps. Only global maps will be compared and perhaps combined, This policy may be reviewed after one year of pilot operations.

3. All TEC maps must be delivered to the IGS in the IONEX format [Schaer et al., 1998]. TEC maps delivered to the IGS thus are “snapshots” of the electron density referring to a particular epoch and to an earth-fixed reference frame.

4. Global TEC maps from each contributing Analysis Center are given the name cccGddd0.yyI,

where ccc is a 3-figure acronym for the AC (in uppercase), “G” says that this file contains global maps, ddd is the day of the year, “O” indicates a daily file, yy specifies the 2-digit year, and the last letter “I” stands for “ionosphere maps”. Example: CODGO41O.98I (or CODGO41O.98I.Z). These files are {compressed} and sent to the IGS Global Data Centers and are available to the interested user. Access Fortran routines are also made available.

5. The daily IONEX file, as produced by an IGS Analysis Center, should have a 2-hour resolution referring to the epochs 01, 03, ... 23 hours UT. RMS files corresponding to the 2-hourly TEC maps maybe included in the IONEX files. TEC/RMS maps refer to a two-dimensional grid in a single layer, The height of the single layer should be 450 km adopting a base radius of 6371 km. The latitude ranges from 87.5 to -87.5 degrees in steps of-2.5 degrees; the longitude ranges from -180 to 180 degrees in steps of 5 degrees. TEC/RMS values have to be given in units of 0.1 TECU.

6. Daily sets of differential code biases (DCBs) for the GPS satellites are recommended to be included in IONEX files. The exchange of satellite-specific DCBS is IONBX-supported, too. Note that the DCB reference maybe chosen arbitrarily and can be taken into account in the combination procedure.

Annex

IGS Fiducials for ITRF Reference Frame Control, ITRF96
47 stations, Darmstadt AC workshop, Topic 3, Rec. #2

id	City	Location	lon (E)	lat (N)	ht (m)	Agency
algo	Algonquin Park, Ontario	Canada	-78.0714	45.9558	201.9000	NRCan/GSD
areq	Arequipa	Peru	-71.4928	-16.4655	2489.9506	NASA/JPL
braz	Brasilia	Brazil	-47.8779	-15.9475	1107.0570	IBGE-JPL
brmu	Bermuda	Bermuda Islands	-64.6963	32.3704	-10.6158	NOAA
dav1	Davis	Antarctica	77.9726	-68.5773	45.4584	AUSLIG
drao	Penticton	Canada	-119.6250	49.3226	542.8755	NRCan/GSC
fair	Fairbanks, AK	USA	-147.4990	64.9780	320.0126	JPL-GSFC
fort	Fortaleza	Brazil	-38.4256	-3.8774	20.4850	NOAA
gode	Greenbelt, MD	USA	-76.8268	39.0217	15.5186	NASA/GSFC
gol2	Goldstone, CA	USA	-116.8890	35.4252	987.6665	NASA/JPL
graz	Graz	Austria	15.4935	47.0671	539.3059	ISR
guam	Dededo	Guam	144.8684	13.5893	202.9268	NASA/JPL
hark	Pretoria	South Africa	27.7077	-25.8871	1555.0000	CNES
hob2	Hobart, Tasmania	Australia	147.4387	-42.8047	42.0872	AUSLIG
irkt	Irkutsk	Russia	104.3162	52.2190	503.3754	DUT
kerg	Port aux Francais	Kerguelen Islands	70.2555	-49.3515	74.0583	CNES
kit3	Kitab	Uzbekistan	66.8854	39.1348	623.5264	GFZ
kokb	Kokee Park, HI	USA	-159.6650	22.1263	1168.3669	NASA/JPL
kosg	Kootwijk	The Netherlands	5.8096	52.1784	97.8582	DUT
kour	Kourou	French Guiana	-52.8060	5.2522	-24.7597	ESA
kwj1	Kwajalein Atoll	Kwajalein Atoll	167.7302	8.7222	39.2028	NASA/JPL
lhas	Lhasa	China	91.1040	29.6573	3625.6824	IfAG
mac1	MacQuarie Island	Australia	158.9358	-54.4995	-5.7467	AUSLIG
mad2	Robledo	Spain	-4.2497	40.4292	830.4708	NASA/JPL
mali	Malindi	Kenya	40.1944	-2.9959	-22.3241	ESA
masl	Maspalomas	Spain	-15.6333	27.7637	198.1606	ESA
mate	Matera	Italy	16.7045	40.6491	536.6528	ASI
mdo1	Fort Davis, TX	USA	-104.0150	30.6805	2005.4936	NASA/JPL
nlib	North Liberty, IA	USA	-91.5749	41.7716	208.0427	NASA/JPL
nyal	Ny Alesund	Norway	11.8651	78.9296	79.4598	NMA
ohig	O'Higgins	Antarctica	-57.9003	-63.3207	31.6952	IfAG
onsa	Onsala	Sweden	11.9255	57.3953	46.5782	OSO
pert	Perth	Australia	115.8852	-31.8020	13.7867	ESA
piel	Pie Town, NM	USA	-108.1190	34.3015	2348.7138	NASA/JPL
pots	Potsdam	Germany	13.0661	52.3793	145.4281	GFZ
sant	Santiago	Chile	-70.6686	-33.1503	724.0539	NASA/JPL
shao	Sheshan	China	121.2004	31.0996	23.0701	SAO-JPL
thul	Thule	Greenland	-68.7880	76.5373	56.0093	KMS-JPL
tid2	Tidbinbilla	Australia	148.9800	-35.3992	666.3630	NASA/JPL
trom	Tromsoe	Norway	18.9383	69.6627	133.4530	NMA
tskb	Tsukuba	Japan	140.0875	36.1057	68.2591	GSI
vill	Villafranca	Spain	-3.9520	40.4436	648.3720	ESA
wes2	Westford, MA	USA	-71.4933	42.6133	86.0138	NOAA
wtzr	Koetzting	Germany	12.8789	49.1442	667.0379	IfAG
yar1	Yaragadee	Australia	115.3470	-29.0466	242.3113	NASA/JPL
yell	Yellowknife, NW Terr.	Canada	-114.4810	62.4809	181.8642	NRCan/GSD
zwen	Zwenigorod	Russia	36.7586	55.6993	206.0122	GFZ

RECOMMENDATIONS AND ACTION ITEMS
IGS Governing Board Retreat
Napa Valley, December 12-14,1997

Ivan L Mueller

One of the conclusions of the Retreat has been that the IGS Terms of Reference (January 1996 version), with some "fine tuning", still reflects the current needs. For this reason and also to provide a framework for the Retreat's Recommendations (Rs) and Action Items (As) relevant portions of the terms are reproduced below, between dotted lines, with the Rs and As inserted at the appropriate locations.

In order to keep the Retreat as conducive for open discussion as possible formal Minutes were not kept. A Rshort handS/informal record suitable to jag the memories of the participants is available from the Central Bureau.

The Recommendations/Action Items and the explanatory text as presented below are based on the final summary discussion of the Retreat Coordinators on December 14, 1998, on correspondence and conversations after the Retreat.

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INTERNATIONAL GPS SERVICE FOR **GEODYNAMICS**
TERMS OF REFERENCE

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The term "Geodynamics" in the name of IGS, at its inception, was meant to indicate that the primary users of the service are scientists involved in geodynamics, specifically using GPS for determining and/or monitoring positions on the surface of the Earth with the highest accuracy. Since other types of users (especially from the atmospheric and oceanic science communities) are appearing on the horizon the suggestion was made to eliminate the term "Geodynamics" from the title of IGS.

- R 1: The name of the Service be the "International GPS Service".

- **Al:** Governing Board (GB) needs to consider R1 and vote.

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The primary objective of the IGS is to provide a service to support, through GPS data products, geodetic and geophysical research activities. Cognizant of the immense growth in GPS applications the secondary objective of the IGS is to support a broad spectrum of operational activities performed by governmental or selected commercial organizations. The Service also develops the necessary standards/specifications and encourages international adherence to its conventions.

IGS collects, archives and distributes GPS observation data sets of sufficient accuracy to satisfy the objectives of a wide range of applications and experimentation. These data sets are used by the IGS to generate the following data products:

- **high accuracy GPS satellite ephemerides**
- **earth rotation parameters**

- **coordinates and velocities of the IGS tracking stations**
- **GPS satellite and tracking station clock information**
- **ionospheric information**
- **tropospheric information.**

The accuracies of these products are sufficient to support current scientific objectives including:

- **realization of global accessibility to and the improvement of the International Terrestrial Reference Frame (ITRF)**
- **monitoring deformations of the solid earth**
- **monitoring earth rotation**
- **monitoring variations in the liquid earth (sea level, ice-sheets, etc.)**
- **scientific satellite orbit determinations**
- **ionosphere monitoring**
- **climatological research, eventually weather prediction.**

In the past the IGS combined products used primarily have been those related to the **IGS Reference Frames,** both terrestrial and inertial, recommended for GPS users. These are the station coordinates with their variations in time (defining the terrestrial frame) and the orbits of GPS satellites (defining the inertial frame), and the transformation parameters relating the two (the earth-rotation parameters). There have been some questions as to the internal consistencies of the above products.

Due to user requirements for using the GPS signals in various efficient modes and/or leading to more accurate results, it appears necessary for IGS to produce combined, timely and consistent additional products, specifically GPS clock corrections, possibly an IGS time scale, tropospheric zenith biases and global and possibly regional ionosphere models .These, together with the reference frames (all based on the IERS Conventions, 1996), constitute the **IGS Reference System** assuring consistency for all GPS users of positioning in all modes.

Although non-positioning GPS user requirements are not clear at this time, it appears that there is (or will be in the near future) an increasing demand for rapid (real-time) and more accurate GPS orbits as well as the satellites in the IGS framework (primarily the GLONASS and LEO satellites).

- R2: IGS is to produce combined, internally consistent, global products based on GPS observations as follows (several of these to a fair extent are already accomplished):
  a) station coordinates and velocities (incl.IGS SINEX products)
  b) orbital parameters
  c) earth rotation parameters
  d) GPS clock corrections
  e) IGS time scale
  f) tropospheric zenith delays
  g) ionosphere models

- **A2.1: The Analysis** Center Workshop in Darmstadt should address the issues a) - d) and f) and g) and make recommendations.
- A2.2 The recently established IGS-BIPM Pilot Project should address issue e) as already decided by the GB.

- R3: IGS should continue producing accurate orbits based on rapid and/or high rate data, investigate new requirements (e.g., for real timemeteorology forecasting a twenty-station network providing 30s data down loaded every 6-12 hours is suggested. For LEO see A4.2 below) and suggest and implement improvements in availability (IGR) and precision (IGP).

- A3: The Analysis Center Workshop in Darmstadt should address this issue and make recommendations.

- R4: IGS should support the tracking of GLONASS and LEO satellites.

- **A4.1**: The GB should support tracking of GLONASS satellites by actively promoting within IGS the International GLONASS Experiment (IGEX), currently scheduled Sep. -Dee., 1998, pending on the discussion on GLONASS at the GB business meeting in Darmstadt.
- A4.2: The LEO Working Group should continue its work (in collaboration with various groups involved in the use of LEOS for atmospheric science). Specific recommendations are to be made on the appropriate number of tracking stations and sampling rate (1 -5s?) and on the feasibility of IGS processing of occultation and/or other flight data.

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The IGS accomplishes its mission through the following components:
- **networks of tracking stations**
- **data centers**
- **Analysis and Associate Analysis Centers**
- **Analysis Coordinator**
- **Central Bureau**
- **Governing Board.**

NETWORKS OF TRACKING STATIONS

IGS Stations provide continuous tracking using high accuracy receivers and have data transmission facilities allowing for a rapid (at least daily) data transmission to the data centers (see below). The stations have to meet requirements which are specified in a separate document. The tracking data of IGS stations are regularly and continuously analyzed by at least one IGS Analysis Center or IGS Associate Analysis Center . . . .

IGS Stations which are analyzed by at least three IGS Analysis Centers for the purpose of orbit generation, where at least one of the Analysis Centers lies on a different continent than the station considered, are in addition called IGS Global Stations.

All IGS stations are qualified as reference stations for regional GPS analyses. The ensemble of the IGS stations forms the IGS network (polyhedron).
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The IGS global network needs an overall enhancement. The IGS Infrastructure Committee is involved considering issues related to the existing network e.g., instrumentation, monumentation, reporting, performance, data communication and flow, quality control, archiving, site and RINEX standards. Plans for a coordinated systematic effort to expand/densify the network to the proposed (about 200 stations) Polyhedron is still lacking, On the other hand, the regional densification efforts are progressing, and limits are to be set up as to the inclusion of the regional stations into the IGS Polyhedron (being pro-active at the same time). Use of the network for climatology would also require the installation of high stability accurate barometers.

- R5: The global IGS Network should be enhanced in the overall sense.

- **A5.1:** The IGS Infrastructure Committee is to continue its work and report to the GB at its next regular meeting in Boston.
- A5.2: The GB should consider appointing a Network Manager/ Coordinator, within or outside the CB, to coordinate a systematic effort to complete the IGS Polyhedron. The responsibility would include the formulation of network standards and checking performance.
- **A5.3**: The CB/GB should make a systematic and concerted effort to request stations to install high stability/accuracy barometers (the alternative of using routinely produced atmospheric pressure grids should be explored, although their availability in near real time might be a challenge).
- **A5.4**: The GB should consider organizing an IGS Network Workshop to have an open discussion on network/station issues and to develop a direct interaction between the GB and the stations, upon which rest all IGS activities.

DATA CENTERS

The data centers required fall into three categories: Operational, Regional, and Global Data Centers . . . .

The Global Data Centers are the main interfaces to the Analysis Centers and the outside user community. Their primary tasks include the following:

- **receive/retrieve, archive and provide on line access to tracking data received from the Operational/Regional Data Centers**
- **provide on-line access to ancillary information, such as site information, occupation histories, etc.,**
- **receive/retrieve, archive and provide on-line access to IGS products received from the Analysis Centers**
- **backup and secure IGS data and products.**

It was noted that, with the exception of CDDIS (which is doing an admirable job), not all Global Data Centers are producing regularly their Access Reports, In view of the importance of keeping track of the users of IGS products it is recommended that such reports be published on a regular basis.

- R6: It is recommended that all Global Data Centers publish Access Reports on a monthly basis.

- **A6:** The CB is to contact the relevant Global Data Centers and encourage them to comply with R6.

ANALYSIS CENTERS

The analysis centers fall into two categories: Analysis Centers and Associate Analysis Centers.

The Analysis Centers receive and process tracking data from one or more data centers for the purpose of producing IGS products. The Analysis Centers are committed to produce daily products, without interruption, and at a specified time lag to meet IGS requirements. The products are delivered to the Global Data Centers and to the IERS (as per bilateral agreements), and to other bodies, using designated standards.

The Analysis Centers provide as a minimum, ephemeris information and earth rotation parameters on a weekly basis, as well as other products, such as coordinates, on a quarterly basis. The Analysis Centers forward their products to the Global Data Centers.

Associate Analysis Centers are organizations that produce unique products, e.g., ionospheric information or Fiducial Station coordinates and velocities within a certain geographic region. Organizations with the desire of becoming Analysis Centers may also be designated as Associate Analysis Centers by the Governing Board until they are ready for full scale operation.

- R7: Depending on the outcome of the Analysis Center Workshop in Darmstadt the above descriptions of the Analysis and Associate Analysis Centers should be reviewed. The GB decisions in San Francisco/Napa Valley re. the GNAACs/RNAACs, may also have an effect.

- **A7: The** AC Coordinator together with the Chair of the Densification Project recommend the necessary changes to the Terms of Reference as per R7, if necessary.

ANALYSIS COORDINATOR

The Analysis Centers are assisted by the Analysis Coordinator.

The responsibility of the Analysis Coordinator is to monitor the Analysis Centers activities to ensure that the IGS objectives are carried out. Specific expectations include quality control, performance evaluation, and continued development of appropriate analysis standards. The Analysis Coordinator is also responsible for the appropriate combination of the Analysis Centers products into a single set of products. As a minimum a single IGS ephemeris for each GPS satellite is to be produced. In addition, IERS will produce ITRF station coordinates/velocities and earth rotation parameters to be used with the IGS orbits.

The Analysis Coordinator is to fully interact with the Central Bureau and the IERS. Generally the responsibilities for the Analysis Coordinator shall rotate between the Analysis Centers with appointments and terms specified by the Governing Board.

In view of R2 above, the present Analysis Coordinator's role will be significantly expanded and it is unlikely that a single person (ororganization) will be able to handle the responsibilities related to all the different combined global products now contemplated. There is also a question of coordinating the regional densification projects (connected to the Polyhedron) in some central way. One of the responsibilities here would also be the education of users on how to use IGS products.

- R8: It is recommended that Working Groups be appointed for **Tropospheric Products,** for **Ionospheric Products,** for **ITRF Densification** and possibly others (pending on the recommendations of the Analysis Center Workshop in Darmstadt). The Analysis Center Coordinator should bean ex-officio member of all Working Groups. The alternative of appointing individual “Coordinators” for each application (instead of the Working Groups) may also be considered.

- **A8.1:** Based on the recommendations of the Darmstadt Analysis Workshop, the GB should appoint new Working Groups or Coordinators as per R8 and clarify their relationship/interaction (reporting requirements, etc.) with the CB and the GB.
- **A8.2**: The concept of Working Groups or additional Coordinators, together with their responsibilities and reporting/interaction requirements should be incorporated in the Terms of Reference.

CENTRAL BUREAU

The Central Bureau (CB) is responsible for the general management of the IGS consistent with the directives and policies set by the Governing Board. The primary functions of the CB are to facilitate communications, coordinate IGS activities, establish and promote compliance to IGS network standards, monitor network operations and quality assurance of data, maintain documentation, and organize reports, meetings and workshops, and insure the compatibility of IGS and IERS by continuous interfacing with the IERS. To accomplish these tasks the CB fully interacts with the independent Analysis Coordinator described above.

Although the Chairperson of the Governing Board is the official representative of the IGS at external organizations, the CB, consonant with the directives established by the Governing Board, is responsible for the day-to-day liaison with such organizations . . . .

The CB coordinates and publishes all documents required for the satisfactory planning and operation of the Service, including standards/specifications regarding the performance, functionality and configuration requirements of all elements of the Service including user interface functions.

The CB operates the communication center for the IGS. It maintains a hierarchy of documents and reports, both hard copy and electronic, including network information, standards, newsletters, electronic bulletin board, directories, summaries of IGS performance and products, and an Annual Report,

In summary, the Central Bureau performs primarily a long term coordination and communication role to ensure that IGS participants contribute to the Service in a consistent and
continuous manner and adhere to IGS standards.

The Central Bureau has performed well, especially in the areas of coordinating the network and communication. However, partly due to the rapid expansion of IGS over the past several years, other CB tasks described in the Terms of Reference either had to be farmed out to persons(usually volunteers) outside the CB, contracted to other organizations (e.g., UNAVCO) or neglected.

In addition to the rapid expansion of IGS, the other major difficulty the CB is facing when trying to fulfill its responsibilities is primarily structural/ organizational in nature. Although it is difficult to assess the situation from the outside, it seems evident that partly due to the fact that probably no single person has full time responsibility within the CB, every one is "spread too thin" and fragmented. The Director of the CB has at least three jobs and it appears that only one person reports to her (the liaison to UNAVCO). The UNAVCO contract to help with the network involves one staff position spread out over six persons. Others working for the CB, instead of reporting to the Director, in fact report to one of JPLUS Group Supervisors, who inturn reports to certain Section/Division heads, not directly in charge of the Director of the CB. It appears that such a structure (although maybe efficient for other purposes), combined with the fragmentation of individual responsibilities, lead to difficulties in meeting JPLUS original commitment to IGS and in some cases even to conflicts of interests within JPL.

- R9: It is recommended that the tasks of the CB as described in the Terms of Reference be reviewed and the future tasks of the CB clearly defined, with the Rleft-overS responsibilities appropriately assigned to organizations or individuals outside the CB, which will closely interact with the CB.

- R1O: It is recommended that the host organization of the CB review and streamline the CB organization, with fragmentation reduced to a minimum and lines of reporting and responsibilities clearly defined.

- R 11: It is also recommended that at least two persons should be given full time responsibility within the CB. One of these should be the Director, the other may be the Network Coordinator (see A5.2 above).

- R 12: It is recommended that, provided that the recommendation for the additional Coordinators are adopted (see R8 above), their interaction with the CB be clearly defined.

- A9: The Director of the CB should discuss R9- 11 with the appropriate officials of the host organization and present a plan to eliminate the above difficulties to the GB and the progress at its next regular meeting in Boston.

- A lO: The GB should appoint a small sub-committee to work with the Director of the CB to accomplish R9 and R12.

- Al 1: The Central Bureau section of the Terms of Reference will have to be modified after the fact.

GOVERNING BOARD

The Governing Board (GB) consists of fifteen members. They are distributed as follows:
Elected by IGS Associates (see below):

Analysis Centers' representatives	**3**
Data centers' representative	1
Networks' representatives	**2**

Elected by the Governing Board upon recommendations from the Central Bureau, for the next term:

Representatives of Analysis, Data Centers or Networks	**2**
Members at large	**2**

Appointed members:

Director of the Central Bureau	**1**
Representative of the IERS	1
IGS representative to the IERS	**1**
IAG/FAGS representative	1
President of IAG Sect. II or Com.VIII (CSTG	**1**
Total	**15**

The appointed members are considered ex officio and are not subject to institutional restrictions. The other ten persons must be members of different organizations and are nominated for each position by the IGS components they represent as listed above (six persons) , or by the Central Bureau (four persons) for a staggered four year term renewable once. The GB membership should be properly balanced with regard to supporting organizations as well as to geography.

The election for each position is by the number of nominations received from the relevant IGS component, i.e., from the networks (for this purpose organizations operating two or more Global Stations are considered a network), from the Analysis Centers and from the Data Centers. In case of a tie, the election is by the members of the Governing Board and the IGS Associate Members (see below) by a simple majority of votes received. The election will be conducted by a nominating committee of three members, the chair of which will be appointed by the Chair of the IGS Governing Board...

The IAG / FAGS representative is appointed by the IAG Bureau (or by FAGS) for a maximum of two four-year terms...

The secretariat of the GB is provided by the Central Bureau...
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The experience of the past several years indicate that the nomination procedure for both groups of elected GB members, i.e., those nominated by the IGS Associates and those by the CB may be improved to assure wider participation in the nomination process. In addition, it has been suggested to include all (or most) Coordinators in the deliberations of the GB. The appointed representation of IAG and FAGS on the GB needs clarification as well.

- **Al 2:** The GB should appoint a sub-committee to review the current nomination/appointment procedures for GB membership and to recommend improvements by the end of 199S.

Additional Recommendations/Action Items:

- **A13:** Periodic performance review requirement for each IGS component be incorporated in the Terms of Reference. The GB is to set up procedures for such regular reviews (how often and how?) and for the follow up of the recommendations (whether positive or negative).

- R13: The GB should consider forming an Advisory Committee for Commercialization of IGS products. The Committee should include representatives of organizations experienced in such ventures, e.g., WMO, UCAR/NCAR, IRIS, ESA (its business arm).

- R14: The GB should consider forming a committee, with external participation, with the task to prepare the IGS Long Range and Strategic Plan. Reporting should be at the IAG General Assembly in 1999.

(January 31, 1998)

Topic 1: The IGS Analysis Products and Consistency of the Combination Solutions

The IGS Analysis Products and the Consistency of the Combined Solutions

T.A. Springer, J.F. Zumberge, J. Kouba

Abstract

The basic IGS analysis products (orbits, Earth orientation parameters, station coordinates, and clocks) are of very high quality, and should in general be more reliable and at least as accurate (if not more so) than the solutions obtained by the individual analysis centers (ACs). This position paper focuses on the current combination procedures, reporting and feedback. Possible enhancements in precision, consistency, robustness, presentation and feedback of the results are discussed. Furthermore, it addresses a need for additional products in order to meet the needs of IGS users.

Introduction

Many different combination activities are going on within the IGS. Ideally every AC would provide just one single file each day containing all estimated parameters, including orbit, Earth orientation parameters (EOPs), clocks, coordinates, and troposphere estimates together with their full covariance matrix. These solutions could than be rigorously combined in one single combination scheme! Of course this is not feasible for many reasons at this time; one obvious reason being the different models which are used. Another is that results from different ACS are not likely to be independent, since they are based on datasets which are largely common.

Therefore different combination activities were initiated by the IGS over the last years. The orbit combination, the first and most well known IGS combination, has played a major part in the improvement of the IGS products and has been the key to the overall success of the IGS. Based on its success other combinations have been initiated including the EOP, clock, and station coordinate combinations by the GNAACS (in the framework of the densification project), and the troposphere combinations by Gerd Gendt at GFZ. Currently others are planned like combination of station clock estimates, (in the framework of the time-transfer project), and ionosphere estimates.

Due to the diversity of the combination activities and consequently the different methods used, the consistency between **all** these IGS combined products is not (automatically) guaranteed. The complete decoupling of the orbit- and coordinate-combinations can lead to some problems. The resulting **IGS-coordinates,** which essentially represent the IGS reference frame, are not necessarily compatible with the **IGS-orbits** and **EOPs.** Furthermore the feedback to the AC's and other users of **IGS** products, coming from the different combinations, has very different levels of quality and usefulness. Some reports are very good and extensive whereas others give practically no information. The different combinations and resulting products also make it very difficult for "outsiders" to get and keep a good overview of the IGS activities and developments. It is even hard for those within the **IGS** to keep track of all activities and to find the necessary information!

In this position paper we critically review all different combination activities which are currently performed within the IGS. We review the:

- combination procedures which are currently used,
- consistency of the products within a combination (e.g. orbits, **EOPs,** and clocks),
- consistency of the products between different combinations (e.g. orbits, EOPS, clocks, and **Sinex),**
- feedback **from** the different combinations, and
- ways of improving any of the above.

One other aspect of the IGS which is discussed here will be the quality control of the data from all the IGS stations! Although the observational data in the **Rinex** format is one of the most important **IGS** products, if not **the** most important, the IGS has not been very successful in setting up and maintaining a standard for IGS stations.

IGS Combination Activities

Currently the following combination activities are performed within the IGS:

- Combinations by the IGS Analysis Center Coordinator for the Final, Rapid and Predicted results:
  - -- Orbit combination
  - -- EOP combination (polar motion, polar motion rates, UT, LOD)
  - -- Satellite Clock combination
- Station Coordinate combination

-- JPL, Michael **Heflin,**

-- MIT, Tom Herring,

-- NCL, Phil Davies, and

- Troposphere Combination at **GFZ,** Gerd Gendt.

As mentioned before ideally every AC would provide just one single product file each day containing all currently available products. Because this is not possible for obvious reasons we have the different IGS combinations listed above. This means that the resulting combined **IGS** products are not necessarily consistent at the required level of accuracy.

Another issue which we have to address is the extent to which the products of the individual ACS are internally consistent. For instance some ACS provide satellite clock estimates although they use double difference observations for their orbit estimates. We have to know and understand to what extend the orbits, EOPS and clocks of these ACS are consistent. Other possible inconsistencies exist, for instance high rotations sometimes observed in the orbit combinations indicate that for some ACS the orbit and pole estimates are inconsistent.

So besides the consistency of the IGS combined products we should also look for possible inconsistencies within the individual AC products. **All** inconsistencies, if any, should be detected and corrected, or reduced to an acceptable level, as soon as possible.

Review of ACC Combination

The **IGS** orbit combination was originally developed in 1993, [***Beutler** et al.*, 1995]. Since then many improvements and additions have been made by the Analysis Center Coordinator **(ACC)** and his colleagues at **NRCan,** [***Kouba***, 1995; ***Kouba** and **Mireault***, 1996]. However, the basic method of the combination, the L1 -norm, was not changed.

It is our impression that the **IGS** final orbits, EOPS and clocks are of very high quality and are in general more accurate and reliable than the solutions obtained by the individual ACS. Nevertheless, there are possibly a few improvements which can be made. First of all the consistency between the combined orbits and the combined clocks can, and should, be improved, especially with respect to those users who want to perform precise point positioning [***Zumberge et al., 1997a***]. A second improvement maybe found, as envisioned during the initial development in 1993, in the use of a priori weights for the individual satellites.

Consistency between the IGS orbits and clocks

The quality of the satellite clock estimates provided by the ACS has improved dramatically over the 1996--1997 timeframe. Thanks to the increased accuracy of the AC satellite clocks and the growing number of people interested in using precise point positioning (using precise orbits ***and*** satellite clocks) it became clear that the IGS orbits and clocks were inconsistent at the 200 mm level. To improve the consistency between the combined IGS orbits and the combined IGS clocks two changes were made recently to the clock combination algorithm.

The two new features are:

- an improved clock weighting scheme, using the clock estimates from one AC as reference instead of the satellites without Selective Availability (SA, only 1 remaining), and
- correcting the AC clocks, before the combination, based on the difference in the radial component between the AC orbit and the IGS combined orbit.

Different ACS use different reference clocks. Therefore the AC clocks have to be aligned before the combination to correct for the differences between the different reference clocks. For this purpose the satellites without SA were used, because their clocks can be accurately modeled fitting only an offset and a drift. At the same time the RMS of this fit was used for the clock weighting. Because only one satellite remains without SA the alignment has become unreliable. Therefore the alignment was changed by using one of the ACS as reference. The selected reference AC is aligned to GPS time, based on the broadcast clocks, using all satellites. All other centers are then to this reference AC.

Providing the orbits and the clocks of the individual ACS ax-e consistent then orbit differences between the ACS should show up in the clocks as well. In a first order approximation only the radial differences are important. Therefore an attempt to improve the consistency between the orbit and clocks, by correcting the AC clocks based on the radial AC orbit differences, was made **and** coded almost 3 years ago! It was only implemented recently due to other more urgent combination improvements/enhancements and because 3 years ago no improvement was found!

One way to evaluate the IGS clock/orbit product is to use it in precise point positioning [*Zumberge et al.,* 1997a] to analyze data from a single receiver. We have selected nine sites (Figure 1) and the 6-week period beginning November 16, 1997 to perform such an evaluation. The sites were selected to give reasonable global coverage. To ensure that the results using the JPL product wouldn't look artificially good, it was decided to exclude sites that were used by JPL for its IGS contribution during the test period.

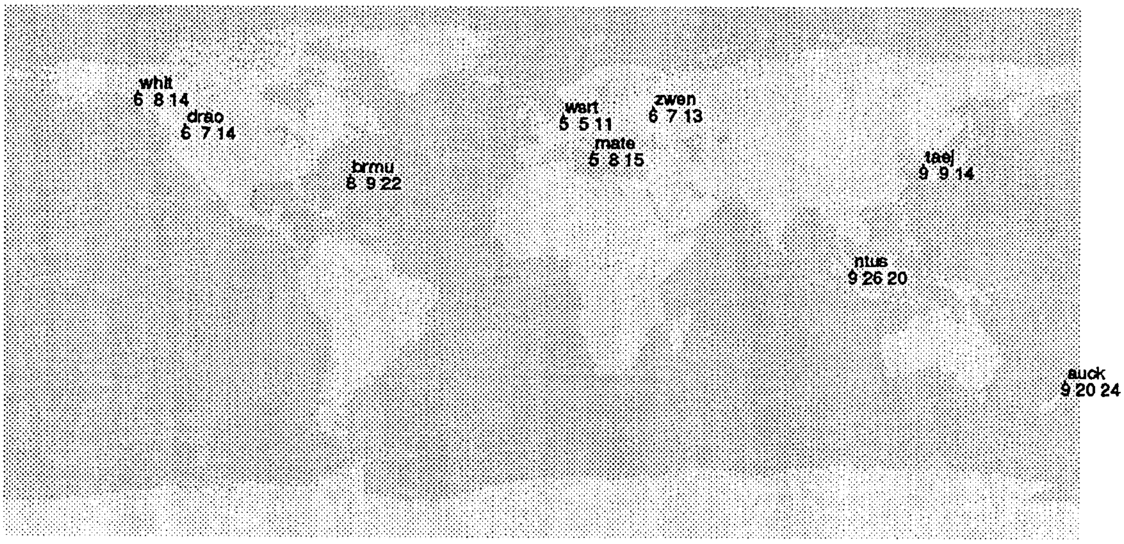

Figure 1. Sites used. The numbers indicate the observed daily repeatability for site coordinates in the North, East, and Vertical dimensions, using the latest clock combination technique, for the period December 7-- December 27, 1997.

The SP3 product contains both orbits and clock information for each satellite, once every 15 minutes. SA results in large and rapid fluctuations in the GPS clock correction. Thus only data that are on the even quarter hour in a daily Rinex file can be modeled to the sub-centimeter level for phase and half-meter for pseudorange, given a precise orbit/clock product. For each day and site, the data are used to estimate site coordinates, with satellite parameters -- orbits and clocks -- held fixed at their values in the SP3 file. For eclipsing satellites, the yaw angle was fixed at its value as estimated in JPL's contribution to the IGS. One could alternatively use the nominal yaw rates and obtain similar results. Gipsy/Oasis-II was used for all processing. On a given day, only satellites that are in both SP3 product files were kept. The JPL product contains only satellites which JPL considered usable, so this criterion attempts to exclude poorly modeled satellites.

Shown in Table 1 is the median of the daily repeatabilities of site coordinates as a function of orbit product and time window (the numbers indicate only fluctuations, and do not include any average offset). The product labelled ' 'IGSO" used the original clock combinations, For the product labelled ' 'IGS 1'' the improved weighting scheme was used and for the' 'NEW" product the radial corrections were applied in addition to the improved weighting scheme. For reference the results using the JPL orbits and clocks using the same timespan and sites are also given. Note that the solutions ' 'IGSO" and ' 'IGS 1'' are based on the official IGS products for those timeframes whereas the the "NEW" product represents the now operational (current state of the art) IGS clock combination (active since GPS-week 0938, day O for IGS and GPS-week 0940, day 1 for IGR).

With the latest implementations regarding the IGS satellite clock combination we find

Table 1. Median daily repeatabilities as a function of time and **orbit/clock** product. The table contains the median value of the nine sites. A change in the clock weighting scheme was implemented on Dec 7, and a proposed improvement using radial variations in contributed orbits was also evaluated ***(NEW)*.** The JPL results, using the same timeframes and sites, are shown for **comparison.**

Product	*period*	*'North **(mm)***	*East **(mm)***	*Vertical **(mm)***
IGS0	***Nov* 16--** Dec **06**	11	17	24
IGS1	Dec 07-- Dec 27	8	10	**16**
NEW	**Dec 07-- Dec 27**	**6**	**8**	**14**
JPL	Nov 16-- Dec 06	4	4	7
JPL	Dee 07-- Dee 27	4	6	8

typical daily **repeatabilities** of 10 mm horizontal and 14 mm vertical for stationary site coordinates. These are approximately a factor of two better than before these improvements were implemented and are approaching the individual AC consistency. This is quite an achievement in view of the very inhomogeneous input for the clock combination: not all ACS submit clocks, the quality of the clocks are very different and one AC provides clocks only every 30 minutes. However, the results using JPL's SP3 product indicate that there is still some additional room for improvement for the **IGS** product.

One feature of the results that is not well understood are significant variation among sites in the repeatabilities, which are indicated in Figure 1. An extreme case is Auckland, New **Zealand,** where the **repeatabilities** are approximately a factor of two larger than the median (this is not observed when the JPL product is used). Further enhancements maybe necessary to reduce these significant site-to-site variations.

One possibility to further improve the consistency of the combined **IGS** clocks may be found in the alignment of the AC clocks. Currently the alignment of the AC clocks is achieved by estimating one offset and drift per AC with respect to a chosen reference AC. In order to do proper clock alignment amongst ACS, i.e. to remove the effects of a single reference station, we need AC station clock solutions (e.g. also at 15 min sampling), or at least a subset of consistent AC station clock solutions. The station clock solutions are also essential to the time transfer pilot project *[Ray,* 1998]. Furthermore an important quality control could be realized by analyses of the stable hydrogen maser clock subnet of stations.

Note that there are some significant hurdles in the clock combination. The quality of the individual AC clock solutions are very different. Only three ACS (EMR, GFZ, and JPL) provide satellite clocks based on processing undifferenced phase (and code) data. Of these, GFZ has a sampling rate of only 30-minutes with respect to the nominal 15-minutes sampling. This may cause problems in the combination, something which will have to be studied. Note that for the rapid products the USNO AC also provides satellite clock estimates based on processing undifferenced phase (and code) data.

The clock estimates of two other ACS (CODE and ESA) are based on (phase-) smoothed code observations and may be noisier than the true “phase-clocks”. This may have some negative influence on the combined IGS clocks as well. It should also be investigated to what extent the clocks of these ACS are consistent with their other products, because for both ACS the primary products (orbit, EOP and coordinates) are based on double difference processing!

Clearly it would be very advantageous if all ACS would provide satellite and station clock estimates at least as frequently as every 15-minutes. Preferably the clocks should be of similar quality, comparable to the quality of the orbits.

Use of a priori satellite weights

One limiting factor in the orbit combination scheme is the fact that there is no (a priori) information about the quality of the individual satellites! Although the orbit exchange format (SP3) allows for the inclusion of (meaningful) accuracy codes for each individual satellite this option is not used by many ACS. In the combination scheme this information is only used, when available, a posteriori to compute the weighted RMS.

During the original development of the orbit combination software, using the L2-norm (least squares instead of the L1-norm) it was envisioned that at some stage a priori weights would be used for each satellite and possibly also for the ACS *[Springer and Beutler, 1993].* Because satellite specific weights were not readily available in 1993 it was decided to switch to the L1 -norm, a much more robust estimator than the L2-norm, to be less sensitive to bad satellites and therefore make the use of satellite specific weights obsolete.

However, looking at recent orbit combination reports several ACS exclude supposedly “bad” satellites from their orbit solutions. In many cases the bad satellites, however, were used in the actual data analysis and only removed from the final (SP3) product. The reason behind this is to ensure that users do not by mistake use these bad satellites. If all ACS would remove all, and the same, bad satellites there would be no problem except that we would lose (based on recent combinations) about 2 satellites each day! Because not all IGS users are interested in the highest precision this would be disadvantageous for several users. It is our conclusion that also “bad” satellites are to be considered IGS products, and therefore should be included in all AC submissions.

Another reason for this is that the omission of bad satellites in some, but not all, of the AC solutions could distort the combination. To avoid any distortions from missing satellites the combination, and its statistics, should be based on the common satellites only! The satellites submitted by only a few ACS can be combined a posterior using the estimated transformation parameters and weights.

Of course the inclusion of bad satellites in the combination could, despite the robustness of the L1 -norm, distort the combination. It would therefore be sensible to start using a priori satellite weights. The weights would, ideally, be based on the accuracy codes found in the SP3-header. However they could also be based on the 7-day arc fit which is performed in the orbit combination, In this way the bad satellites can easily be detected and downweighted in the combination. In any case the IGS should put more emphasis on the availability and the usefulness of the accuracy codes in the orbit files and request the ACS to submit solutions for **all** satellites, with the possible exception of satellite manoeuvres and exceptionally large modeling problems.

Review of GNAAC Combination

The combination methods of the three different GNAACs are described in detail in the IGS Annual Reports. The coordinate combination, based on the weekly SINEX files, has one very large advantage over the orbit combination. It has access to the full covariance matrix of the coordinate estimates. Therefore the combination method is both easier and more accurate than the orbit combination where we have no statistical information whatsoever.

It has been shown in several publications, ***[Davies and Blewitt, 1997]*** that the GNAAC combinations are better than most if not all AC solutions. We therefore conclude that the GNAAC combinations are in very good shape and can not significantly be improved. However, there are some persisting problems with site names, site ties, antenna types etc. etc. which have to be sorted out once and for **all soon.** Because these inconsistencies are a more generic IGS problem they are discussed in a later section.

The only "problem" with the GNAAC activities is that there is not yet an official IGS product! There is no official IGS combined solution and therefore no IGS reference frame. This is confusing for many of the IGS users and also quite illogical. Essentially we need onl y one GNAAC but redundancy may be useful. Therefore the easiest, and politically correct, decision would be that a combined IGS solution is based on a combination of the three GNAAC combinations, the "super" combination.

One planned addition to the Sinex submissions is the inclusion of the EOP parameters. This will facilitate and improve the IGS EOP combination. This improved combined IGS EOP can then be used in the orbit combination. In this way the IGS combined orbit will be consistent with the IGS reference frame, [***Kouba et al.,*** 1998]. However, this requires that the GNAAC combinations are done prior to the (final) orbit combination, e.g. before or on the second Wednesday (1 O days) after the end of the **GPS-week.**

Review of Troposphere Combination

For several months the tropospheric zenith delay estimates of most ACS, as provided in the (pseudo-)Sinex format, have been combined [*Gendt*, *1998]*. For this combination it is essential that the differences in the zenith delays, caused by differences in the station coordinates, are corrected prior to the combination. This is very similar to the correction of the satellite clocks based on the radial orbit differences. Clearly a consistent IGS coordinate (and velocity) set, the IGS reference frame, is helpful, if not essential, for the troposphere combination. The individual AC troposphere solutions can then be made consistent with this official IGS reference frame prior to their combination. In this way the troposphere estimates would be related to the "true" and constant reference frame.

One aspect that should be mentioned here is that in small networks there is a large advantage if a global station is included together with its estimated tropospheric delay. In a small network (few 100 km) it is difficult to estimated the absolute tropospheric delay. The inclusion of one "global" station with its previously determined tropospheric delay held fixed while adjusting the troposphere delays of all other stations solves this problem. This may be very important for future meteorological investigations. Here similar consistency problems, as encountered in the case of precise point positioning between the orbit and the clocks, may be encountered between the IGS combined tropospheric zenith delays and the IGS combined station coordinates.

One additional problem in the troposphere combination is the use of different mapping functions by the different ACS. The effect different mapping functions have on the zenith delay estimates should be studied. It should also be investigated how an IGS user can use the combined zenith delay, e.g. which mapping function he should use. Analogous to how the clocks are adjusted based on different reference clocks the zenith delay estimates should be corrected, calibrated, to account for the usage of different mapping functions. Other complicating factors are the estimation of tropospheric gradients and the antenna phase center variations.

Finally it is very likely that future troposphere estimates will include tropospheric gradients; at this time gradients are already routinely estimated at CODE and JPL. The current tropospheric Sinex format does not allow for the inclusion of tropospheric gradients.

Consistency between the Combinations

It is essential that **all** submitted AC products be either consistent, or sufficient info is included (e.g. EOP) that they can be made consistent before IGS combinations. This applies to all products, i.e. orbit, EOP, clock, Sinex, and troposphere.

Therefore the inclusion of the EOP parameters in the AC Sinex submissions and GNAAC combinations is absolutely essential in order to make the IGS orbits, EOPS and clocks consistent with the IGS reference frame [*Kouba et al., 1998].* All ACS therefore **must** included EOPS in their Sinex solutions **as soon as possible.** A nice benefit from this will be the (much) improved quality of the combined IGS EOP because it will be done using the full covariance matrix.

Review of feedback

In general all the results and combinations produced in the framework of the IGS are unique in the (scientific) world. However, there is always room for improvement! Therefore here it is tried to identify in what way all the information from the different IGS activities can be improved, enhanced, streamlined, and so on.

Because the troposphere combination is in its pilot phase it is not considered here. However, we would like to state that it already looks to be in good shape and the reports should soon become official and distributed using the IGSREPORT e-mail system.

In our opinion there is one central problem with respect to the feedback. The information is coming from very different sources and in very different formats. Therefore it is suggested that all interesting results are gathered and made available at a central place. The information should be made available both numerically and graphically, and automatically updated. The most like] y way of providing this kind of service is by using the World-Wide-Web (WWW). Essentially all kind of routinely produced information should be made available. Besides feedback and results from all different combinations the site should also provide documents describing the IGS, its products and how to access and use the different IGS products.

Some items which this WWW (feedback) site could contain are:

- time series of the transformation parameters coming from the orbit combination,
- time series of station positions,
- time series of network/station performance,
- access to the EOP plots and statistics as provided by USNO,
- documents describing different facets of the IGS,
- documents describing access to the IGS products,
- documents describing usage of IGS products,
- and many many more.

Some of these features are already available at the IGS Central Bureau (CB), and others have been proposed by CODE when it assumes the role of Analysis Center Coordinator (ACC). We expect cooperation and coordination between the CB and ACC to provide improved feedback.

ACC Final and Rapid Combination Feedback

The feedback as provided by the (final) IGS orbit combination is one of the most valuable within the IGS. It is clear that it provides excellent information. One point which can be improved is the navigation solution. Currently smoothed code observations are used which are not really capable of showing the quality of the orbits and clocks. Therefore it should be enhanced by using the carrier phase measurements. In this way it will automatically provide feedback about the consistency between the orbits and the clocks.

The feedback from the rapid orbit combination is also quite good, although the long arc test is not included here because, the rapid combination is done on a daily rather than a weekly basis. Therefore the feedback about the rapid orbits, of the individual ACS, maybe improved by performing a weekly comparison in the same way as is being done for the final orbits, In this weekly comparison the long arc test would then be included. One other positive effect of this is that it will give the rapid orbits more visibility and thus create some more awareness about the availability of these products.

The predicted orbit combination provides good feedback for all participants. However, if the combined IGS predicted orbit would be included in the proposed weekly rapid comparison, in the same way as the rapid orbit is included in the final combination, then the visibility and awareness of the prediction products and efforts is also guaranteed.

One upcoming problem for the rapid and predicted orbit is the change of time-zone which will take place when the ACC activities change from EMR to CODE (sometime in 1998). The deadline for the rapid products will have to be adjusted to allow the combination to be performed during "normal" office hours. Assuming that the rapid combination should be performed before 19:00 MET (e.g. 17:00 or 18:00 UTC depending on daylight saving time), this would mean a effective deadline around 16:00 hours UTC! In view of the increasing demands for real-time products (especially troposphere) this would be a (small) step in the right direction. It should be investigated if an earlier deadline is feasible (12:00 hours UTC?).

GNAAC Combination Feedback

The feedback of the individual GNAACS is very different. Thanks to the fact of having three different GNAACS the total feedback is sufficient. The recent addition, by the MIT

GNAAC, of providing station coordinates residual file is valued highly. Nevertheless there are some problems with the GNAAC combinations.

Most important y, and most disturbing, are the problems with station names, receiver and antenna types, and antenna heights and phase center variations. These are well known IGS problems which are not caused by the GNAACS. These station inconsistencies encountered in the GNAAC activities underline the bad situation of the IGS global network. Furthermore, the persistence of these problems, despite the GNAAC combinations, shows that the GNAACS are not very well embedded in the IGS structure. This situation should be ***much*** improved before any form of IGS reference frame realization can based on the GNAAC results. Hopefully the "super combination" will help to close the gap between the GNAACS, the ACS, the stations, and the data centers.

One other confusing part of the GNAAC feedback is the time at which the different GNAAC combinations are performed. The delay is usually much larger than that of the orbit combination an on several occasions a GNAAC center has provided several weeks at one time. For successful and timely realization of the IGS reference frame the GNAAC combinations will have to be performed both more regularly and more timely. The proposed implementation of the EOPS in Sinex and the use of the combined EOP in the orbit combination implies that the deadline for all GNAAC combinations will be 10 days after the end of the GPS-week. This will solve this problem.

Feedback to Data Centers and Station Managers

The IGS has not been very successful in controlling the quality of the stations, their data, their Rinex files and the resulting coordinate estimates despite several different checks which are being performed routinely, including:

- JPL network reports,
- CDDIS Rinex checking,
- IGSCB station log and Rinex checking.
- CODE Rinex checking,
- several GNAAC checks, and
- coordinate residuals from the MIT GNAAC.

Little action is taken based on all the available information. All different information pieces should be gathered at a central place (IGSCB, DCS, or ACC) and erroneous stations should be informed of their errors and their data files flagged by the IGS ***automatically.***

The (still unexplained !!) problems with the station of Madrid, throughout 1997, showed that the way station problems are currently handled within the IGS is completely insufficient, Many IGS customers used the station as fiducial for their local network which resulted in severe problems (due to the several cm apparent shift of the station). Also the list of discrepancies in antenna heights, antenna types between station logs and Rinex files, and consequently bet ween ACS and GNAACS, is (still) almost endless.

Despite all the checks being performed the situation has not really improved over the last two years. Therefore it is time to specify some (strict) guidelines on what the ***minimal*** requirements are to become and to remain an IGS station. In our opinion the absolute minimal requirement is the availability of a complete station log file at the IGSCB and Rinex files which contain information corresponding to the station log. The IGS should aim to provide ***only*** data from official IGS stations. This should take effect as soon as possible but no later than July 1998. Data from non-IGS sites may be made available but it should be clearly flagged by either putting the data in a separate directory at the DCs or by (re)naming the file.

The Rinex "file sequence number" maybe abused for flagging files in the following way:

- XXXXOO1 0.9802 -- normal name for an IGS station
- XXXX001 Z.98O_Z -- for an non-IGS station

Flagging non-IGS files in addition to improved and automatic feedback to the Data Centers (DC) and station managers is the only way to improve the current (bad) situation of the global network, It is the key to ensure and maintain a high quality global network! The details on how exactly to define a non-conforming station need to be worked out,

Future Products

It is very difficult to predict the future and especially the future of the IGS which is still developing rapidly. Nevertheless, we can reasonably anticipate some future demands and, consequently, products.

Combined troposphere and ionosphere estimates will possibly become official IGS products. A combined troposphere solution is already being generated routinely and may soon become official. For the ionosphere the situation is less clear but already an exchange format has been defined (IONEX) and at least one AC (CODE) already routine] y produces ionosphere "maps". So the generation of combined ionosphere solutions could be started very soon if enough participants are found. One "problem" with the ionosphere is that it is not a (by-)product of the normal processing algorithms, which use the ionosphere-free linear combination of the two carrier phase observations.

One large future “customer” of IGS products will be the Low Earth orbiter (LEO) missions. At the moment it seems that at a large amount, if not all, of the LEO data will be processed using precise point positioning. For most of the LEO missions it will be mandatory to have satellite clock estimates with a higher rate than the current 15 minutes. For the meteorological LEO missions (e.g. tomography) it will be mandatory to have access to satellite clock estimates with a 30 second sampling rate (assuming precise point positioning is used). If higher sampling rates are required than also a subset of the ground network stations will have to sample the observations at a higher rate. This poses no real problems because there is already a large number of sites with higher sampling rates. Only the data are not made available as official IGS data.

Finally, as discussed during the 1996 IGS AC workshop, there should be a “short” SINEX file format; a SINEX file without the covariance matrix. This would enable users to study time series of station coordinate solutions more easily. It might be wise to generate only a short SINEX file from the official IGS reference frame solution rather then generating short SINEX files for all available SINEX files, which could very easily confuse the IGS users!

Summarizing we foresee the following future IGS products:

- Troposphere and Ionosphere
- 30 sec satellite clocks
- 15 min station clocks
- Short Sinex file, only for the official IGS “super combination”

One other product might be estimates of the Earth’s Center of Mass, which could be included in the Sinex files. These estimates may also be useful for the orbit combination.

Furthermore the upcoming GLONASS test campaign (end of 1998) should be mentioned. Although not organized by the IGS, it may lead to some new products like, GLONASS orbits, the time difference between GLONASS and UTC and others.

Other, more distant, products may include:

- Earth’s center of mass estimates (included in Si nex)
- EOPS with a higher time resolution (hourly?) to verify and possibly improve sub-daily polar motion models.

- Estimation of **nutation** drifts. This has similar problems as the estimation of LOD (UTC drifts).
- Station coordinate solutions with a higher time resolution (hourly?) to verify and possibly improve Earth tide models.
- GLONASS products.
- \\\
- and probably many many more!

Generation of accurate high rate Satellite clocks

One drawback to the clock portion of the IGS combined **orbit/clock** product is that precise clock solutions are available only once every 15 minutes. Unlike the orbits, which vary smoothly with time, one cannot interpolate precise GPS clocks that are computed only four times an hour (due to SA). Thus only low rate data --4 measurements per hour -- can be analyzed with the precise point positioning technique. To apply this technique to upcoming missions with low-Earth-orbiting (LEO) satellites carrying GPS receivers, one will need nearly continuous knowledge of the GPS clocks. They must be determined frequently enough, therefore, that interpolation is feasible.

Zumberge et al. [1997b] describe a **computationally** efficient method for determining precise GPS clocks at the full rate of the ground **network;** the JPL AC computes such solutions operationally. The method exploits the globally distributed subset of the IGS network which has precise frequency references. The JPL high-rate solutions, and potential similar ones from other ACS, could be used to augment the existing IGS combined clock solution in a simple way.

Recommendations

Recommendation 1: Inclusion of **all** satellites, which were used in the data analysis, with meaningful accuracy codes in the orbit products from all individual ACS, Use of these accuracy codes, or accuracy measures from the long-arc analysis, to identify and consequent y downweight' 'bad" satellites in the orbit combination. In addition the IGS should increase the **user awareness** of the availability and importance of the accuracy codes in the SP3 files (see also Recommendation 4).

Recommendation 2: Enhancement of clock products. All ACS which submit clocks **must also** submit clock estimates from a, yet to be determined, subset of' 'core time stations" ! All ACS are **urged** to submit clock estimates. Furthermore the ACS are **encouraged** to increase the sampling rate of the satellite clock products to 30 seconds. A format for station and satellite clocks, also suited for 30 seconds satellite clocks, will have to be defined.

Recommendation 3: Improved and automatic feedback to Data Centers (DC) and station managers in case there are discrepancies between Rinex files and station logs, data problems and unexpected problems (jumps) in the station coordinate solutions.

Recommendation 4: Create a central place (WWW) for feedback and information about the IGS products and their use.

Recommendation 5: Definition of minimal requirements for becoming an IGS AC. Any AC must produce **all** core products, i.e. orbits, EOPS, and Sinex, both on time and with sufficient (high) quality. The IGS terms of reference will be changed accordingly.

Recommendation 6: Additional accuracy digit for the IERS/IGS EOP file format. New format to be defined before June 28, 1998 by Jan Kouba in cooperation with Dennis McCarthy.

add 1: To achieve the highest consistency of the orbit and clock combination it is mandatory that all ACS provide estimates for all satellites which were used in the analysis. Only manoeuvring satellites and very bad satellites (modelling problems larger than 1 meter) which ' 'darnage" the solution may be removed. Bad satellites should be flagged by inclusion of meaningful accuracy codes in the orbit files. This will allow a priori weighting of the satellites in the orbit combination which should improve the combination and its consistency. At the same time the users of the IGS products can, and should, use these accuracy codes to weight or remove bad satellites. The IGS should put some effort into increasing the user awareness of the availability and importance of the accuracy codes in the SP3 files. It should also be investigated if the commercial GPS softwares (can) use the SP3 accuracy codes. To avoid any distortions from missing satellites, in some of the AC solutions, the combination, and its statistics, should be based on the common satellites only!

add 2: "Core clock stations" are necessary to improve the AC clock alignment. Jan Kouba, Jim Ray will work out a list of clock stations by June 28, 1998. A higher clock sampling rate is necessary, or at least very advantageous, for several future missions but also for the precise point positioning users. Hopefully some of the ACS can provide 30 sec satellite clock and 15 min station clock estimates by June 28, 1998. Consequently a format for the clock products (TIMEX?) should be available by June 28 as well. The IGS GB will write a letter to all ACS requesting them to submit clock estimates.

add 3: Stations which are performing poorly or have incorrect/inconsistent documentation should be identified in a timely fashion. A file containing a list of such stations as a function of time, should be maintained and accessible by anonymous ftp from the Central Bureau, In addition the DCS should flag the Rinex data files. It is hoped the fiist step in the data “flagging” can be started by June 28, 1998. In the first step data from stations giving inconsistent information in the station logs and Rinex headers should be flagged. Ideally the flagged stations will not be used by the IGS ACS but at least they should not show up in the official IGS products. Further refinement and feedback will have to be controlled by the IGSCB and/or a future Network Coordinator. A necessary requirement here is a clear definition of on an ‘ ‘IGS-station”.

add 4: To enable a better overview of all IGS activities, products, combinations, and feedback a central WWW-site should be developed. This (feedback) site should contain descriptions of all the IGS activities. It should also contain documentation on how to use the IGS products, The information can either be at this site or provided using “links”. (This recommendation was part of the CODE ACC proposal)

add 5: At present there are no (clear) guidelines about what an IGS AC is required to do nor how to become one. Therefore a list with the **minimal requirements to be and to become an IGS** AC should be generated. The minimal requirements are the generation of Orbits, EOPS, Coordinates with sufficient accuracy. Estimation of satellite (and station) clocks and tropospheric estimates are highly recommended. Furthermore a long-term commitment is necessary.

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EFFICIENT ESTIMATION OF PRECISE HIGH-RATE GPS CLOCKS

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SUMMARY

Using carrier phase and pseudorange data from a small network of globally distributed GPS receivers with precise time references, we are able to estimate GPS clock parameters every 30 see, with sub-decimeter accuracy, in a computationally efficient manner. Over time and the Earth's surface, there are usually five or more satellites above 15 deg elevation angle with well determined clock solutions, although occasionally some isolated locations view fewer than four. The accuracy obtained is a factor of 100 to 1000 times better than that of clocks in the broadcast navigation message, and allows post-processing of high-rate single-receiver kinematic GPS data with few-cm-level precision when used in conjunction with precise GPS orbits. The clock estimates can be interpolated to arbitrary times, with an additional error due to Selective Availability (SA) clock dithering, of approximately 7 cm rms. The interpolation error could be reduced to about 2 cm if 15-sec data were analyzed instead of 30-sec data. The amplitude of the daily clock variability y is typically 24 m for satellites affected by SA. Temporal variations are well modeled by an auto correlation function p(d) = $\exp(-d^2/2\tau^2)$ with $\tau \approx$ 106 sec.

Acknowledgments The full paper "Characteristics and applications of precise GPS clock solutions every 30 seconds" has been accepted for publication in Navigation. The research described here was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

PRECISE HIGH-RATE SATELLITE CLOCKS AT GFZ

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INTRODUCTION

Within the routine IGS rapid and final analysis the raw GPS data is in general sampled to a lower data rate to reduce noticeable the amount of data and the computation time. At GFZ a sampling rate of 6 minutes was used up to now, since early 1998 it is changed to 5 minutes.

However for some applications like Precise Point Positioning or estimating the orbits of the so-called Low Earth Orbiters (Kang et al., 1995, Foeckersperger et al., 1997) it may be useful or necessary to determine the orbits and the clocks of the GPS satellites with the higher rate of the original data given in the RINEX files, i.e. 30 seconds. Whereas it is relatively easy to determine the satellites orbit position by means of interpolation within the orbit position file which is obtained by integration this method is not applicable to the satellite clock due to its non-smooth behaviour as a result of Selective Availability.

A straightforward way of estimation is the full treatment of the 30 second data within the IGS processing scheme instead of the computation with the sampled data. This procedure is not suitable due to the huge amount of computation time which would be necessary for processing 30 second data. So a more practical way was found by using the results of the IGS final computation as an input into the estimation process with the higher data rate.

FIXED AMBIGUITIES APPROACH

After the IGS final processing the GPS satellite orbits are available with a high accuracy of few cm (Gendt et al., 1997). Therefore they can be introduced as known parameters. The satellite positions are taken from the SP3 file and can be fixed during further adjustments. On the other hand all ambiguities within the sampled 6 minute data are found and estimated within the IGS adjustment as well as all bad data and outliers are identified and written into the so-called LOG files. With this information the raw high-rate RINEX data files are reduced to those parts for which the ambiguities are valid, New data before or after is neglected. As a result of such pre-processing new ambiguities may not be found within the high rate data. Beyond this the GPS data between the 6 minute epochs is separately inspected for bad records. Figure 1 shows the principle of this modified IGS-like analysis. For further reduction of the computation time the number of stations should be reduced to the minimum necessary to estimate the highest number of satellite clocks. On the other hand a good coverage must be maintained, especial] y on the southern hemisphere. In some cases it is better to include stations with worse clocks into consideration to avoid problems with gaps over problematic regions. These clocks are provided with very low weights during the analysis.

Because the number of stations used in the high-rate clock analysis in general will be smaller than the number of stations used in the IGS final analysis the starting time of the ambiguities is not identical to the starting time of the original scene. Therefore the ambiguities have to be shifted to the correct new epochs to avoid the problem that new ambiguities were automatically found by the program. With a number of about 20 stations which in general is sufficient for a good coverage the time of the estimation process including the time for the pre-processing part can sufficiently be reduced compared to the routine IGS analysis.

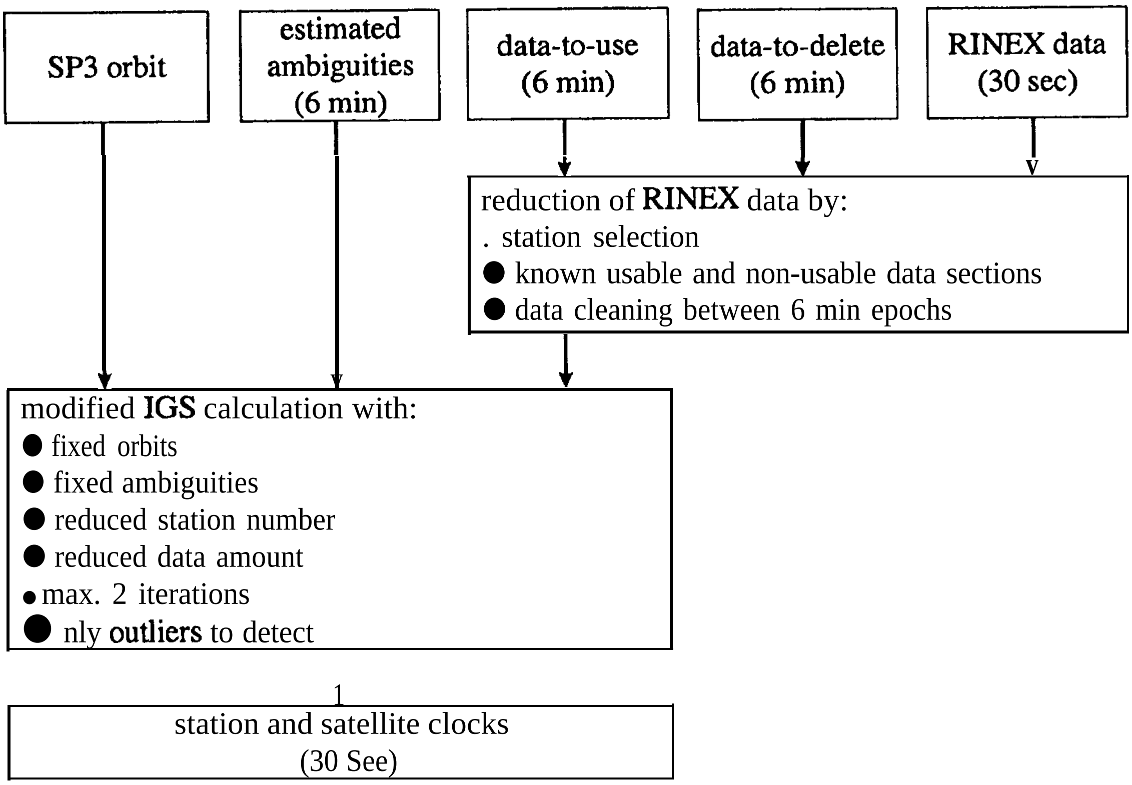

Fig. 1: Scheme of 30 second clock estimation with fixed ambiguities

FIXED STATION CLOCKS APPROACH

A second approach is based on the introduction of fixed station clocks besides the fixed orbits (Jefferson et al., 1997, Zumberge, 1998). Only stations with smooth and stable clocks are taken into account, This is tested by forming the differences to the mean of the nearest neighbors which have to be very small (few tenth of a nanosecond). After this selection the station clocks are interpolated to the necessary data rate of 30 seconds. This approach can be performed with a very small number of stations.

The advantage of the approach is the greatly reduced computation time due to the small number of stations and, of course, if only few iterations are necessary. The problem is that only few IGS stations with very stable clocks are available (~ 12-14) which, in addition, are not well distributed.

RESULTS

Results of differences between the various approaches are shown in Table 1. The first column of Table 1 shows the internal consistency of the two GFZ products, i.e. the IGS final clock solution against the 30 second solution with fixed ambiguities and fixed orbit. It can be seen that with the beginning of 1998 the fit became very small. This can be explained by a change within the IGS final computation which removed an inconsistency at the end of the final analysis.

The rms values concerning the solutions with fixed station clocks are slightly higher but mainly below 0.5 ns. One reason for the differences in the last column between the two 30 second clock solutions with fixed station clocks may be the different number of stations used: whereas JPL took 8 stations (Jefferson et al., 1997) the GFZ solution included all selected stations (11 - 12).

Tab. 1: rms values of differences between different satellite clock solutions, in nanoseconds

Day of year	GFZ-SP3 <-> GFZ with fixed ambiguities	GFZ-SP3 <-> GFZ with fixed station clocks	GFZ-SP3 <-> JPL with fixed station clocks	JPL with fixed station clocks <-> GFZ with fixed station clocks
97355	0.28	0.58	0.45	0.44
97356	0.26	0.83	0.46	0.65
97357	0.23	2.00	0.36	2.27
97358	0.27	0.49	0.45	0.35
98001	**0.04**	**0.40**	**0.42**	**0.46**
98002	**0.02**	0.45	0.46	0.39
98003	0.02	0.35	0.58	0.36

Besides the accuracy the number of the estimated 30 second satellite clocks is of particular interest, It clearly depends on the number of stations and on their distribution. For a routine IGS final estimation with about 50 stations usually 1-2 % of satellite clocks can not be estimated. If a number of about 20 equally distributed stations is used within the ambiguity fixed approach between 5 and 7 % of the clocks are not determinable. Within the fixed station clocks solution only 12-14 stations are usually available. In this case the number of lost satellite clocks is much higher: between 10 and 25 %. However these missing clocks are not equally distributed: usually great gaps are located over the South America and the pacific region whereas there are nearly no gaps over North America and Europe.

The Figures 2a and 2b show in detail the differences between the JPL and the GFZ satellite clocks for a single day. Figure 2a shows the full differences whereas Figure 2b is corrected for a linear trend. This trend can be explained as follows: Within the estimation process the satellite clocks are reduced to a specified reference clock. This clock is usually one of the very stable station clocks. But this connection leads to an offset and to a drift compared to GPS time because of the behaviour of the reference clock. Therefore beginning with GPS week 921 the clock solution at GFZ is corrected for these offset and trend. The offset correction is performed by calculating an average over all satellites. The drift correction is evaluated by an average over all stable station clocks; within this step possible resets or jumps of the reference clock are also detected and corrected, missing epochs of the reference clock are now bridged over by using other stable clocks.

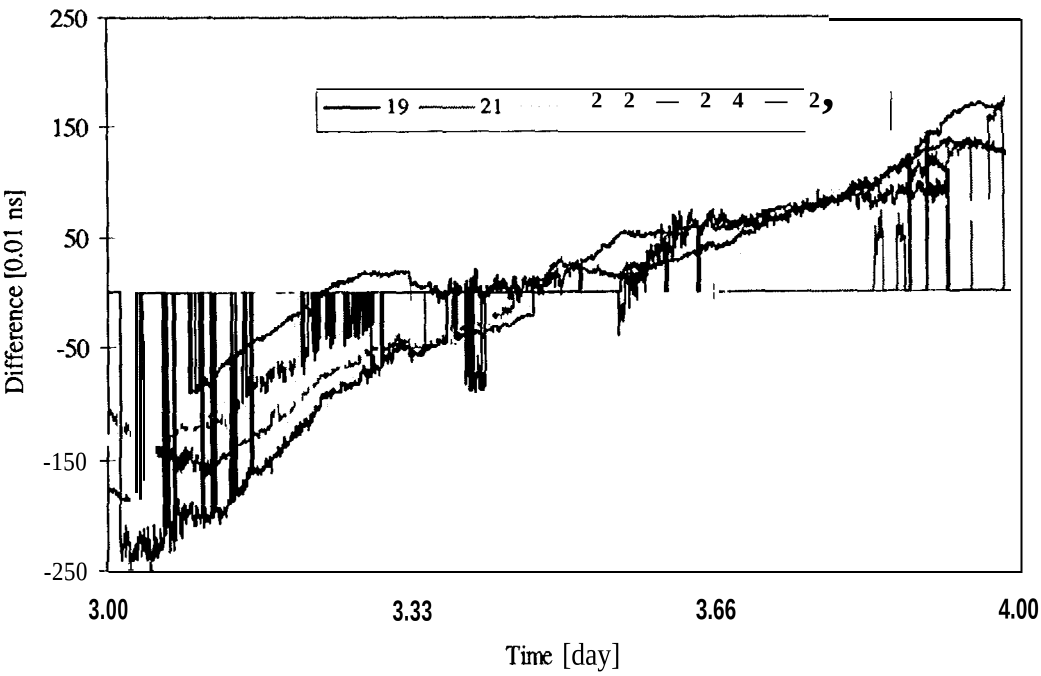

Fig. 2a: Differences between JPL and GFZ 30 second satellite clocks

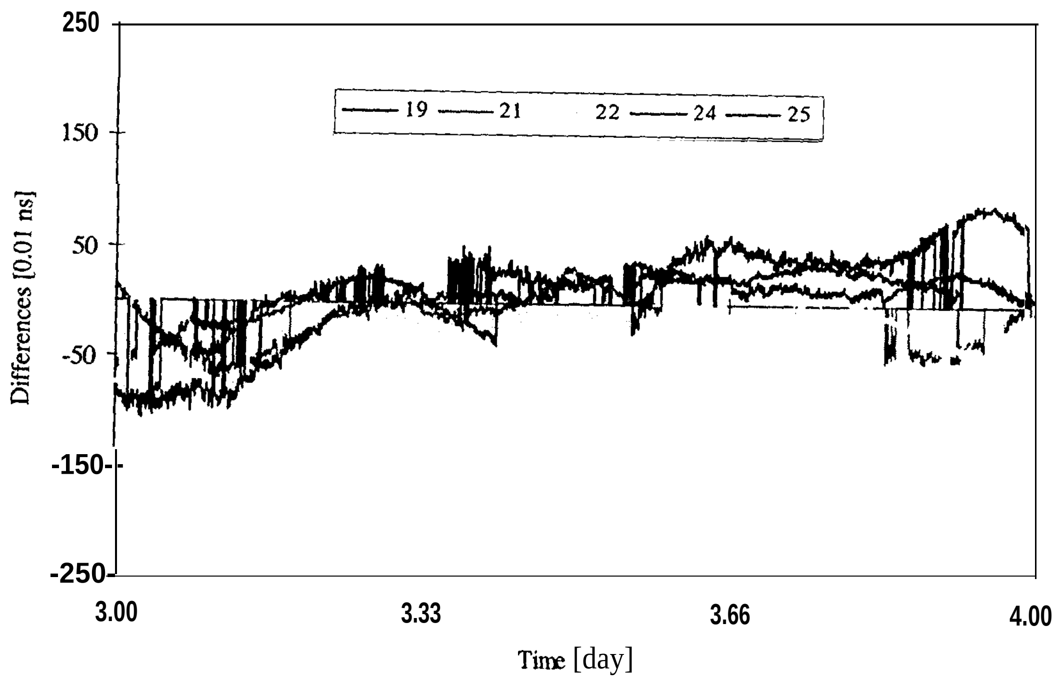

Fig. 2b: Differences between JPL and GFZ 30 second satellite clocks after trend correction

The Figures 3a and 3b show the improvement of the IGS final clocks of GFZ as a result of the changes starting with GPS week 921 for both offset and trend. Before week 921 the trend is nearly constant in the range of 90 nanoseconds per day whereas after the changes it is in the order of the accuracy of other Analysis Centers, e.g. CODE. In Figure 3a the gradual drift and the reset of the reference station clock before week 921 can clearly be seen in the GFZ offset.

The remaining differences in Figure 2b can be explained by the differences within the fixed orbits of the two variants. These differences mainly appear at the day boundaries where the GFZ orbit estimation still allows small jumps within the three day orbit combination process. A second explanation is the different handling of the ambiguities which are real values at GFZ whereas they were fixed to integer at JPL.

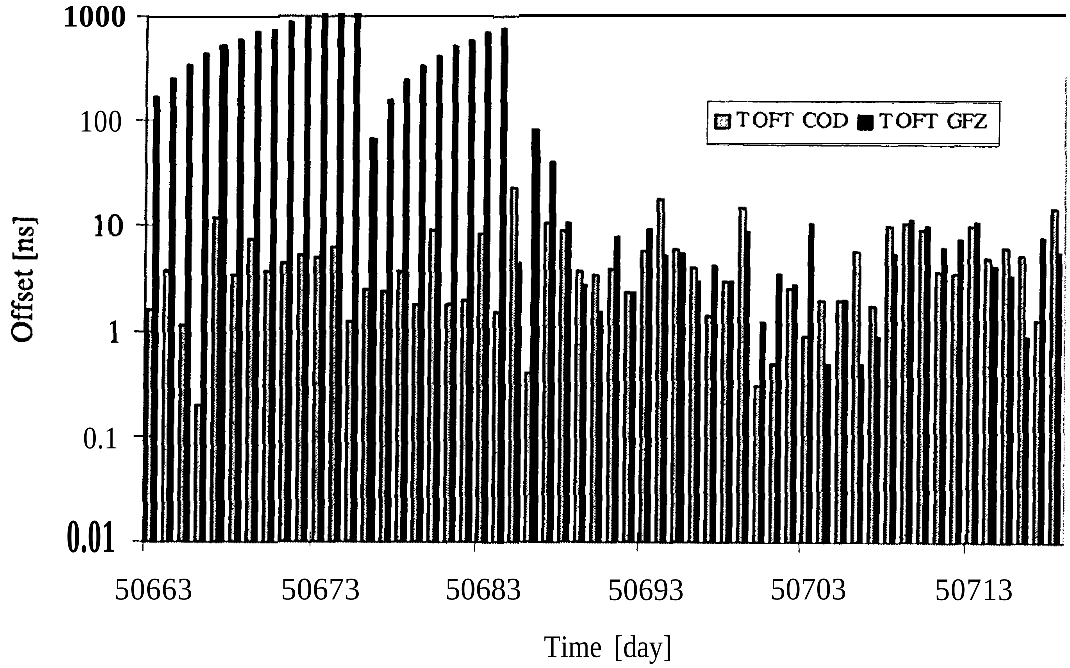

Fig. 3a: Offset of GFZ and COD IGS final clocks compared to GPS time, taken from IGS summary (logarithmic presentation)

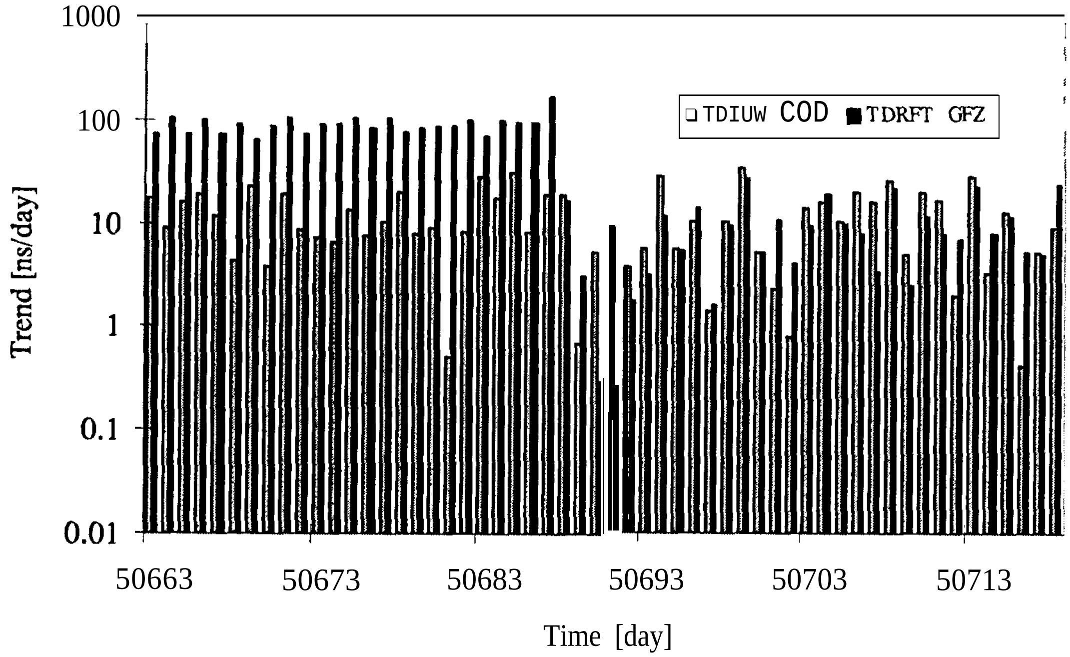

Fig. 3b: Drift of GFZ and COD IGS final clocks compared to GPS time, taken from IGS summary (logarithmic presentation)

HIGH-RATE STATION CLOCKS

One advantage of the fixed ambiguities approach is the simultaneous estimation of high-rate station clocks. Figure 4 shows the differences between the estimated 30 second station clocks and the interpolated clocks which are used as input in the fixed station clocks approach. The differences are exemplary shown for two stations, one of them (Onsala) with a very stable station clock.

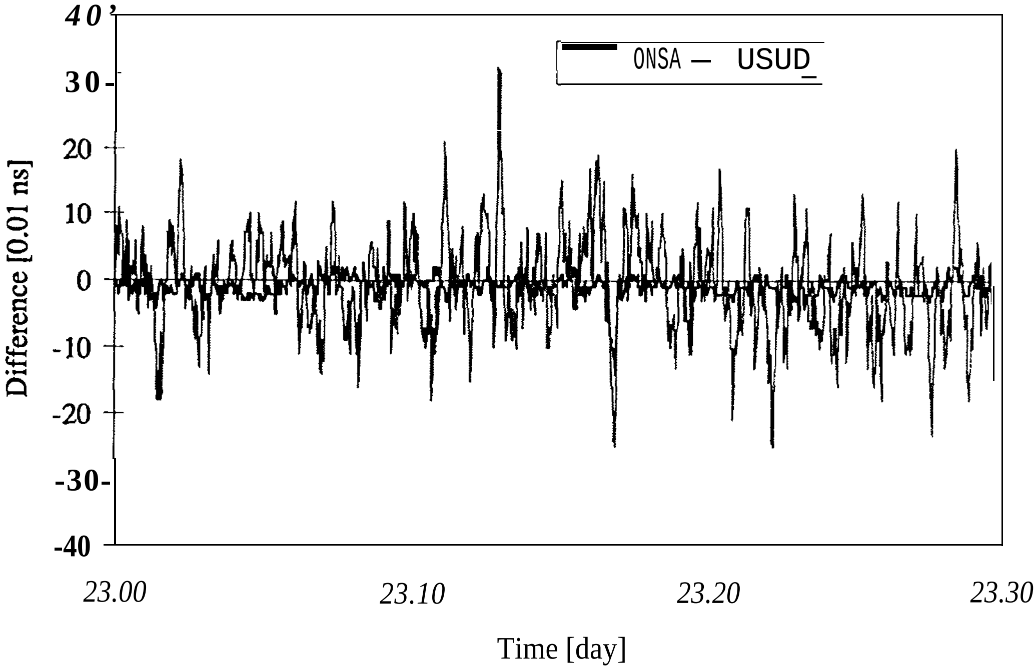

Fig. 4: Differences between adjusted an linear interpolated high-rate station clocks

It can be seen that for Onsala a linear interpolation is sufficient to keep well within a 0.1 nanosecond limit whereas for Usuda (which is only an example for some other stations with quite stable station clocks) a polynomial interpolation is necessary to use them as input in the fixed station clocks approach. On the other hand with the fixed ambiguities approach it is possible to estimate the high-rate station clocks with the same accuracy (clearly below 0.5 nanoseconds) as the satellite clocks.

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THE IGS/BIPM TIME TRANSFER PROJECT

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INTRODUCTION

The "IGS/BIPM Pilot Project to Study Accurate Time and Frequency Comparisons using GPS Phase and Code Measurements" was authorized in December 1997 jointly by the International GPS Service for Geodynamics (IGS) and the Bureau International des Poids et Mesures (B IPM). A general Call for Participation was issued shortly afterwards with responses requested by 15 March 1998. The respondents will form a working group co-chaired by C. Thomas, BIPM, and J. Ray, U.S. Naval Observatory (USNO).

A number of groups have been working for several years to develop the capability of using geodetic GPS techniques for accurate time transfer. A variety of convincing demonstrations has already been performed showing the potential for determining clock differences at the level of a few hundred picosecond. The current state of maturity of both the global tracking network and data analysis techniques now allows practical applications to be considered. The central goal of this Pilot Project is to investigate and develop operational strategies to exploit GPS measurements for improved availability of accurate time and frequency comparisons worldwide. This will become especially significant for maintaining the international UTC timescale as a new generation of frequency standards emerges with accuracies of 10^{-15} or better.

AREAS OF PARTICIPATION

It is expected that the Pilot Project will benefit from activities in a range of areas, including those listed below. Investigators have been invited to participate in one or more of these areas, or to indicate others.

Deployment of GPS receivers

In addition to the GPS receivers already installed as part of the IGS global tracking network, other receivers at laboratories having accurate time standards are sought. These should be high-quality geodetic receivers capable of recording and rapidly transmitting dual-frequency pseudorange and carrier phase observations. The station configuration and data distribution should conform to IGS standards and appropriate documentation must be filed with the IGS Central Bureau. General instructions for adding a new station to the IGS network are available at

http: //igscb.jpl.nasa.gov/igscb/resource/newstation.txt.

A log file should be completed and sent to the IGS Central Bureau for each IGS station. For this Project, due consideration should be given to electronic stability, environmental control, and other factors which might affect the timing results. Upgrading of existing tracking stations for better timing performance is also encouraged, Deployment of dual-frequency GLONASS receivers, especially collocated at IGS sites, would provide an additional data source of interest.

GPS data analysis

Strategies for analyzing GPS phase and pseudorange observations must be developed, consistent with other IGS products, to allow the routine, accurate characterization of time standards at a large number of independent GPS receiver sites and onboard the GPS satellites. This work will be done in close cooperation with the IGS Analysis Center Coordinator. It is expected that regular reports will be issued by participating analysis centers, analogous to those distributed by the IGS for other activities, and filed in the IGS Electronic Reports series.

The precise relationship between the analysis activities that are needed for this Pilot Project and those required for the official products of the IGS is not entirely clear at this point. Certainly, the Project should build and rely upon the existing IGS structure. There may, however, exist a need for clock analysis and related products beyond the charter of the IGS. Also, some changes in the current analysis procedures of the IGS may be advantageous for enhanced timing performance. For these reasons it is essential that the Analysis Coordinator be actively involved.

Analysis of instrumental delays

In order to relate clock estimates derived from GPS data analysis to external timing standards it is necessary to understand the instrumental electronic delays introduced by the associated hardware, Studies are sought to characterize the short-term and long-term sensitivities to environmental changes and to develop suitable calibration methods. Differences for the L1 and L2 frequencies must be considered. Studies of both GPS ground sites as well as the GPS satellites are sought.

Time transfer comparisons

Simultaneous, independent time and frequency comparison data are needed to compare with the GPS-derived estimates. Collaborations are sought with groups performing time transfer experiments using a variety of techniques. Close cooperation is expected with the Consultative Committee for Time and Frequency (CCTF) of the Comité International des Poids et Mesures (CIPM).

OBJECTIVES

To accomplish the overall goal of improved global accessibility to accurate time and frequency using GPS, several specific objectives can be set.

Accurate and consistent satellite clocks

Satellite clock estimates are among the "core" products of the IGS (Kouba *et al.*, 1998). The IGS combined solutions for satellite clocks are distributed together with the IGS combined orbits in the sp3 product files. It is essential that the clock information be as accurate as possible and also that it be fully consistent with the other IGS products. Kouba *et al.* (1998) describe the importance of global consistency to ensure that the point positioning technique (Zumberge *et al.*, 1997) can be applied without degradation.

A type of point positioning likely to become increasingly important is for tracking low Earth-orbiting satellites equipped with onboard GPS receivers, For this application the 15-minute tabulation interval of the sp3 orbit files is not adequate because the SA corruption of the broadcast clocks does not allow accurate interpolation over intervals longer than about 30 s (Zumberge *et al.*, 1998a). For this and other applications, the IGS ACS have been asked to provide satellite clock products with 30-s sampling rates and the IGS will probably begin producing a corresponding combined product (Springer *et al.*, 1998). Methods for efficiently computing high-rate satellite clocks have been presented by Zumberge *et al.* (1998b) and Soehne *et al.* (1998). A new exchange format will be needed to permit easy distribution of the new high-rate results.

Accurate and consistent station clocks

Presently, the IGS does not produce clock information for the GPS ground stations although doing so is mentioned in the IGS Terms of Reference. There is a clear interest in the user community for this information. Apart from time transfer uses, it could be used to characterize and monitor the performance of station frequency standards. Clock solutions from stations equipped with very stable frequency standards (especially H-masers) are needed to apply the method of Zumberge e? ***al. (1998a)*** to estimate high-rate satellite clocks. For this purpose, station clock determinations at intervals of about 5 minutes can be accurately interpolated to the 30-s intervals needed to solve for the satellite clocks provided that the ground stations are referenced to stable clocks.

For time transfer applications, such as envisioned for this Pilot Project, accurate anal ysis results for the station clocks are mandatory. As with high-rate satellite clocks, a suitable exchange format must be developed. Regular summary reports to describe the analysis results characterizing satellite and station clocks will be encouraged. These should be publicly distributed in the IGS Electronic Reports series. Some IGS ACS, particularly JPL and EMR, already include valuable clock information in the weekly analysis summary reports that accompany their Final product submissions.

From geodetic analyses of the GPS data, the effective “clock” of each station is determined for the ionosphere-corrected L3 phase center of the antenna displaced by the electronic delay to the point in the receiver where the time tags are assigned to the phase measurements. These clock determinations are relative measurements in the sense that usually a single station is chosen as a time reference and not adjusted. From the viewpoint of geodetic applications, the precise reference point of the analysis clocks is irrelevant. As a result, manufacturers of geodetic receivers have generally not taken care to provide easy or accurate access to the time reference points. However, for timing applications, such as time transfer comparisons with other techniques, the precise location of the clock reference and accurate access to it are essential. Consequently, the investigation of instrumental path delays and access points is critical to the success of the Pilot Project.

Even if one imagines a shift in the timing paradigm so that the GPS receivers are eventually regarded as a part of the outer “electronics package” of stable frequency standards, it is nonetheless vital to establish accurate access to the clock reference points. The effects of environmental influences will be even more important in that case and must be minimized. Doing so will require new approaches for isolating GPS receiver equipment, such as efforts by Ovemey *et al.* (1997).

Accurate and stable reference timescale

Ultimately, it is necessary that all clock information, for satellites and stations, be referenced to a common, consistent timescale. Individual sets of results from different ACS generally refer to different reference clocks. Thus, in the IGS combination process, the AC submissions must be realigned, This is currently done by choosing one submission as a reference solution, realigning its satellite clock estimates to GPS time based on the broadcast clocks for all the satellites (using only daily offset and rate terms), and then realigning all the other AC submissions to the reference solution (Springer *et al.*, 1998). Corrections are applied to each solution set to account for radial orbit differences compared to the IGS combined orbits. The IGS combined satellite clock estimates are then formed from the weighted average of the realigned, corrected submissions.

It has been suggested that the clock realignment and combination process would be improved if a common set of "fiducial" station clocks were used in all analyes and included in the IGS submissions (Springer *et al.*, 1998). Naturally, only stations equipped with very stable frequency standards (preferably geometrically well distributed) should be considered as candidate fiducials. Recommendations for this station set will likely be made during 1998.

Likewise, it is questionable whether GPS time is an appropriate choice for the underlying IGS timescale. The ideal choice should be accurate, accessible, and stable over all relevant time intervals (namely, 30s and longer). GPS time is readily accessible but not with an accuracy comparable to other IGS products due to SA effects. Nor is GPS time particularly stable. The clocks of the GPS constellation are monitored from US NO and this information is provided to GPS operations with the goal of maintaining GPS time within 28 ns (RMS) of UTC(USNO), allowing for accumulated leap second differences. In practice, the two timescales have been kept within about 6.5 ns (modulo 1 s) over the last two years (for 24-hour averages). However, the GPS time steering algorithm has a "bang-bang" character resulting in a saw-tooth variation with a typical cycle of about 25 days. This is equivalent to a frequency error greater than 10^{-1} over days to weeks, which changes periodically in an abrupt, nearly step-like fashion.

Almost certainly, an internal ensemble of the frequency standards used in the IGS network can be formed which would possess better stability than GPS time (Young *et al.*, 1996). There are currently about 27 IGS stations using H-masers, and about 40 with Cesium or Rubidium standards. Addition of new IGS sites located at primary timing laboratories would only improve this situation. A purely internal IGS timescale would probably not be stable against long-term drifts so some linkage to external laboratory timescales is required. Indeed, traceability to UTC(BIPM) is most desirable. In principle, this could be accomplished using the instrumental calibration data mentioned above, especially for the fiducial clock sites. It will be technically difficult, however, to achieve comparable accuracies for the calibration measurements to the few hundred picosecond level possible for the data analysis clocks. This will be one of the greatest challenges for this Pilot Project.

An alternative approach to provide external linkage that can be readily implemented uses monitor data for the GPS constellation that are collected and compared at the timing labs. USNO collects such data using pseudorange timing observations and makes the results publicly available. Using the observed offsets of GPS time relative to UTC(USNO), the corresponding IGS clock estimates can be related to UTC(USNO). Because of the effects of SA such comparisons would only be useful to remove long-tern differences. This is probably sufficient, at least for an initial realization. Other timing laboratories would be encouraged to provide similar monitor data for a more robust tie to UTC(BIPM). A potential problem with this approach is possible biases between the effective clocks transmitted by the satellites as measured from the pseudorange and carrier phase observable.

Challenges for an IGS timescale

Apart from the issues discussed above concerning calibration and external referencing for an IGS timescale, there are other practical questions that must be resolved. In particular, it may be difficult to form and maintain a timescale within the IGS product delivery schedule. This is likely to be especially true for the Rapid products even though that is probably also where the greatest user interest lies. Fundamentally, this does not seem overwhelming although it will require entirely new and highly automated IGS processes.

Other practical concerns are minimizing discontinuities at day boundaries, dealing with clock discontinuities and drop-outs in the ensembling process, and finding an appropriate robust ensembling algorithm. These subjects, together with those mentioned above, should be studied during this Pilot Project.

SCHEDULE

It is anticipated that the schedule of activities will be flexible, as dictated by technical progress. However, for planning purposes the following milestones are envisioned:

01 Jan. 1998	--	Call for Participation distributed
15 Mar. 1998	--	responses to Call for Participation due
01 Apr. 1998	--	establishment of Pilot Project Working Group
01 Jun. 1998	--	target for publication of first analysis report
Dec. 1998	--	interim report to the IGS Governing Board
Spring 1999	--	report to Consultative Committee for Time and Frequency
Dec. 1999	--	final report to the IGS Governing Board and BIPM

By the year ***2000,*** those aspects of this Pilot Project which are suitable for integration into the operational activities and official products of the IGS or BIPM should be underway. To the extent that some functions may not be suitable for the existing structure of the IGS, a new coordinator for this might be appropriate.

INFORMATION EXCHANGE

An e-mail exploder list has been assembled to allow a free exchange of ideas among Pilot Project participants. In addition, a Web site has been created at the URL

http://maia.usno.navy.mil/gpst.html

with information about IGS stations and frequency standards, a bibliography of background publications, a list of the participants, and an archive of e-mail.

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Topic 2: Orbit Prediction and Rapid Products

ORBIT PREDICTIONS AND RAPID PRODUCTS

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ABSTRACT

The IGS is facing ever increasing demands for more precise and more rapid (real-time!) products. The computation of the rapid orbits and especially the orbit predictions, which are available in real-time, therefore are becoming more important and deserve special attention, This position paper reviews the methods of generating the rapid and predicted products and proposes ways to improve the prediction accuracy and to reduce the turn-around time.

INTRODUCTION

The use of GPS techniques for near real time data processing requires fast availability of relatively precise GPS products. New fields of application require availability of GPS orbits with high precision and at short delay after the observations are taken. An example of this is the developing field of operational meteorology using GPS. The GPS derived precipitable water vapor (PWV) measurements have to be processed within hours after the observation so they can be used for weather forecast. In order to get the best observability of PWR precise predicted orbits have to be available.

The IGS have been producing orbits and cops with a 24 hour delay and predictions for the next day since 1996. These products are obtained as a combination of the results of a number of Analysis Centers and are currently available before 22:00 UTC (rapid products) and before 23:00 UTC (orbit prediction for the following day).

The factors that limit the accuracy of the rapid and predicted products are the availability of a sufficient set of tracking data and the accuracy of the orbit prediction models.

The IGS community has been working to speed the delivery of the measurement data, but we have not yet achieved a satisfactory status, because many stations are still late and this is normally the case for stations outside Europe and North America. Faster or more frequent delivery of the data could also allow for more frequent (sub-daily) delivery of precise and rapid products.

Progress has been made in the accuracy of orbit prediction models, with investigations on new radiation pressure models being presented in this session, but we still have problems for some satellites and some improvement is possible. It is also very important for users of predicted orbits to have a good estimate of their accuracy so they can de-weight or exclude those satellites that can not be well predicted.

DATA AVAILABILITY AND REDUCTION OF THE TURN-AROUND TIME

There are two aspects in the reduction of the turn-around time, measurement data and data processing. Data from a sufficient number of well distributed stations should be available before the rapid orbits can be computed. The current deadline for data to be used in rapid orbits is 05:00 UTC, but most ACS start computing their orbits later due to the lack data from stations in the southern hemisphere. In order to obtain a good rapid orbit the criticality is not only the number of stations but their distribution. We have studied the availability of data at CDDIS, as listed in the reports of CDDIS GPS tracking data holdings, and for the purpose of this study we have grouped the stations in six regions. The selection is of course arbitrary, the stations in the border between two regions could belong to one or the other region, but it is useful in order to analyze the arrival of the data. The regions that we have selected are:

- **AS:** Central and Eastern Asia
- EU: Europe, Asia Minor and the Canary Islands
- IN: Indian Ocean rim and islands
- NA: North America and Greenland
- PA: South Pacific, Micronesia and Polynesia
- **SA:** Caribbean and South America

These regions are shown in Figure 1.
We have checked the number of stations available at the following times:

- Within two hours of tracking. This is time enough for data retrieval at the operational data center, reformatting, and transmission to the global data center.
- Within five hours of tracking. This is the theoretical Rapid Orbit deadline.
- Within twelve hours of tracking. This represents a typical AC Rapid Orbit deadline.
- Within forty-eight hours of tracking. This is the theoretical Final Orbit deadline.

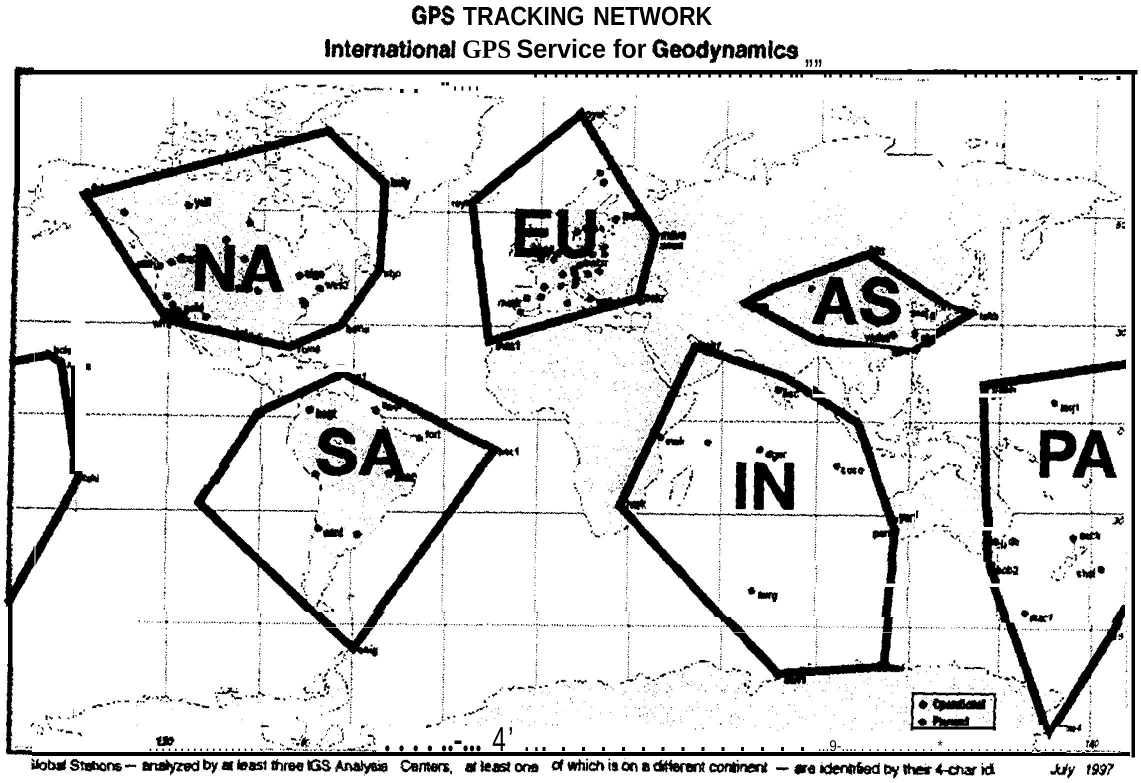

Fig. 1. Grouping of stations in order to study availability

The number of stations that were available at CDDIS for the period from Nov. 29th 1997 to Jan. 27th 1998 are **shown in Table 1. The two values that are shown are the minimum and maximum number of stations that were available at that time. Detailed plots for the studied** period are **in Figures 2 to 5.**

There are days for which no station is available at 12:00 UTC for some of the less covered regions (PA, SA). This means that the rapid orbits are calculated without taking in account any observations from a substantial part of the satellite orbits. This also affects the predicted orbits that will be obtained based on the rapid orbits. The ideal would be to have a minimum of 4 stations available from each of the regions at the time of the calculation of the rapid orbits. The maximum number of stations available at the different times also tells the capability of the system when everything goes well and for +5 hours a minimum of 6 stations are available from each of the regions when the data retrieval and transfer is at its best.

One of the ways to reduce the delay in the availability of data and to increase the probability of data being available would be to perform incremental downloads during the day. The data could be retrieved by the Operational Data Centers every 6 or 8 hours, processed and sent to the Global Data Centers where it would be available to the ACS. The current RINEX file naming convention can accommodate multiple files per day. It could be agreed that the ***statdoy0.yyo file*** **name would correspond to a a whole day and that** *statdoyi.yyo* with **i>1**

Table 1. Number of stations available at CDDIS for the last two months

Region	Delay after 00:00 UTC < 2 h	< 5 h	< 12 h	< 48 h
NA	**2-18**	**11-41**	20-50	25-54
EU	3-12	5-16	8-22	16-26
IN	o-3	2-9	4-11	5-12
AS	o-5	0-6	2-7	4-13
SA	o-3	0-8	1-11	3-13
PA	o-2	0-8	1-12	1-13
All	12-34	29-79	45-103	57-126

corresponds to a fraction of the day. Fractional files could be stored in a different directory accessible to the ACS and then combined in a whole day file for final archiving. Incremental delivery would insure that some data would be available for rapid orbits even if there were communication problems right after 00:00 UTC. It would also allow for more frequent computation of rapid and predicted orbits. Reduction of the turn-around time leads to improved predictions because the predicted orbit is less "old" and therefore better. At the moment we have a 24 hour delay of the predictions, but this could easily be reduced to 12 hours .

ORBIT MODELS

The most characteristic features of the orbit models that are used by the ACS for rapid and predicted orbits are listed in Table 2. Special emphasis is given to the description of radiation pressure models, stochastic accelerations and the handling of eclipsing satellites. One of the points that are handled differently by every center is the prediction of cops. To make the orbits more consistent the IGS could produce a set of predicted Earth orientation parameters, based on the rapid cops and that could be used for generating and using orbit predictions.

As can be seen in the Figure 6 the IGS rapid orbits are very close to the final orbits and it is believed that the best way to improve them would be through the increase in the amount of data that is available to the Analysis Centers, more data from remote regions and more recent data. Data from the same day could be used to improved the rapid orbits, if an incremental delivery system for the data from the IGS stations is implemented.

The situation for the predicted orbits is not so good, see Figure 7, even when the comparison wrrns with the rapid orbits sometimes goes down to under 50 cm, other times it is much worse. In Figures 8 to 11 it can also be seen the rms for individual satellites, both for the

Table 2. Rapid and predicted processing at the Analysis Centers

	CODE	EMR	ESA	GFZ	JPL	NGS	S10	USNO
RAPID ORBITS								
Started at (hours)	+8 to +12	+13	+14	+11	+8 to +11	+6.5	+15.5	+5
Duration (hours)	3.5	3.0	4.0	2.5	10.0	4.0	3.0	10.0
ROCK 4(2)T	yes	yes	yes	yes	yes	yes		yes
CODE orbit model	ye-s	-					yes	
stochastic DVs	along track per rev	-	3 comp. at eclipse exit	3 comp. at 12:00				
stochastic accel.					yes	-		X+Z
cycle per rev. ace.	-		radial (c+s)	-				
est. orb. par. per arc	6+5	6+3	6+2+2	6+2	6+2	6+2	6+9	6+2
est. orb. par. per rev.	1		(3)	3/2				
est. orb. par. per step					3			2
yaw rate estimated				yes	yes	-		yes
PREDICTIONS						N/A		N/A
IGR days fitted	-	4	4orl	3orl	4			
ACR days fitted	3		(1)	1	(1)		2	
cops	CODE	IGR/Bull.A	IGR	GFZ	JPL		S10	
ROCK 4 T			yes	yes	yes			
CODE orbit model	all	all	-	all	ax, ayc		all	
cycle per rev. ace.	-		all (c+s)	-	-			
est. orb. par.	6+9	6+9	6+2+6	6+9	6+2+4		6+9	
standard aat .	rms of fit	rms of fit	ae = 9	?	rms of fit		overlap	
bad fit sat.	rms of fit	rms of fit	ae= 13	100 cm	rms of fit		overlap	
eclipsing sat.	rms of fit	rms of fit	ae = 16	200 cm	rms of fit		overlap	
maneuvering sat.	-		excluded	-				

predicted orbits and for the broadcast orbits and for non-eclipsing and eclipsing satellites. It can be seen that there are problematic satellites (PRN#23) and that the rrns for eclipsing satellites is higher that for others. In general the predicted orbits are much better than the broadcast orbits but this is not always true.

Table 3. Effect of different perturbations on the GPS satellites over 24 hours

Perturbation	Magnitude (m)			
	Radial	Along	Cross	Total
Earth oblateness	**1335**	**12902**	**6101**	**14334**
Moon (gravitation)	**191**	**1317**	**361**	**1379**
Sun (gravitation)	**83**	**649**	**145**	**670**
C(2,2), 5(2,2)	**32**	**175**	**9**	**178**
Solar Radiation Pressure	**29**	**87**	**3**	**92**
C(n,m), S(n,m) (n,m=3..8)	**6**	**46**	**4**	**46**

Orbit models could be improved to improve the prediction accuracy for those satellites that are not problematic and especially to improve the prediction of eclipsing satellites.

The largest non gravitational effect on the GPS satellite orbits is the Solar radiation pressure (RPR). Table 3 shows the effect that different perturbations have on the GPS satellites. The values in Table 3 were computed by integrating a given set of osculating Keplerian elements over a time period of one day (24 hours) with the respective parameters turned on or off. Given is the RMS of the orbit differences over the full 24 hour arc-length over all satellites (using the full satellite constellation of 1-1- 1998).As can be seen the size of the perturbation caused by the Solar radiation pressure is only exceeded by the effects of the Earth oblateness, the gravitational effects from Sun and Moon and the lower harmonics (C(2,2) and S(2,2)) of the Earth gravity field. Clearly an accurate Solar radiation pressure model is as important as an accurate gravity model of the Earth.

The basis of the RPR-models currently used was furnished by Rockwell International, the spacecraft contractor for Blocks I and II [Fliegel et al., 1992]. The computer programs that embody this model became known for Block I as ROCK4, [Fliegel et al., 1985] and for Block II as ROCK42, [Fliegel and Gallini, 1989] although they are also known as the Porter models. The ROCK models are expressed in the satellite fixed coordinate system. This system has its origin in the center of mass of the satellite. Its Z-axis points in the direction to the center of mass of the Earth, and therefore along the satellite antennas. The X-axis is positive toward the half plane that contains the Sun and the Y-axis completes a right-handed system and points along one of the solar panel beams. For high precision geodetic work it is advised to estimate a scale term and a force in the Y-direction, the Y-bias, in addition to the ROCK model. The ROCK model therefore only serves as a-priori information. Both the scale term and the Y-bias are parameters which are supposed to vary slowly in time. Although the cause of the Y-bias is unknown its effect on the orbit is very significant. The claimed accuracy of the ROCK models is about 3%. Taking the nominal value of $1 \cdot 10^{-7} m/s$ for the solar radiation pressure and the claimed accuracy of 3% of the T20 model the expected error is approximately

$3 \cdot 10^{-9} m/s$. Furthermore the size of the Y-bias, which is not included in the ROCK models, is about $1 \cdot 10^{-9} m/s$. The effect of both error sources is about 3 meters (RMS over 24-hours). Of course we have to keep in mind here that the ROCK models were developed for orbit estimation using pseudo-range data! With pseudo ranges the orbit estimates have an accuracy of about 1 meter. For this type of accuracy the ROCK model is adequate to serve as a-priori model provided the scale term and the Y-bias are estimated,

Clearly for IGS type of accuracies, e.g. centimeter type orbit accuracies, the ROCK-models are inadequate, even when the scale and Y-bias are estimated. This is also obvious from the additional orbit parameters which most of the IGS ACS are estimating, be it deterministic and/or stochastic parameters. However, additional orbit parameters may weaken the GPS solutions significantly, especially the LOD estimates. Therefore it should be studied if an improved RPR-model can be found. Possibly it can be derived from the available IGS products and experiences. When developing a new RPR-model there are two questions which should be asked:

- How accurate/reliable can a new RPR-model be derived?
  - -which parameters should be estirnated/modeled
  - -how accurate can these parameters be estimated
    - . . . from real GPS data
    - . . . from precise orbits
  - -how accurate can we model these parameters (to what extend are the selected parameters correlated).
- What may be expected from a new (improved) RPR-model:

Improved (orbit) estimates. With a good RPR-model less orbit parameters will have to be estimated, or the estimated parameters may be (more) constrained, e.g. stochastic pulses. This may be especially useful for the rapid orbits.

More reliable orbit predictions. If less parameters are used for the orbit predictions they will become more reliable. This, however, depends on the type of parameters. Constant accelerations are much more "dangerous" than periodic (e.g. once per revolution) accelerations. Nevertheless good a-priori knowledge of the value of the RPR-pararneters will help in identifying "bad" predictions.

Better orbit predictions This will be difficult because, a better RPR-model will not directly lead to better predictions. For the predictions usually the precise orbits are used as pseudo observations. This means that the "observations" are 3-dimensional positions which are a very strong observation type; much stronger than the double difference phase observations normally used. This implies that a relatively large number of parameters can be estimated without too much problem. However, if the RPR-model improves the rapid orbits then also the predictions will become better. The quality of the orbit predictions depends quite strongly on the quality of the rapid orbits.

Table 4. Orbit fit (7-day) and orbit extrapolation (2-day) using different RPR models. Only scale (or Do) and Y-bias estimated

RPR MODEL	Fit RMS (cm)	Prediction Median (cm)	RMS (cm)
No Model	75	133	159
T20	76	134	161
T20 Scaled	72	119	151
JPL Scaled	10	45	58
CODE	6	17	31
CODE-9	5	17	22

The CODE and JPL IGS analysis centers have successfully developed new and improved RPR-models over the last years, [Bar-Sever 1997, Springer et al. 1997]. Table 4 list the results of a test using the different available RPR-models. It shows the RMS of fit using seven days of precise orbits. The orbit resulting from the 7-day fit was extrapolated for 48-hours. The last 24-hours of this extrapolation were compared with the “true” orbit. The CODE IGS Final products (orbit and EOPs) were used. In all cases only the scale term (or a constant acceleration in the direction sun-satellite) and the Y-bias were estimated. Only for the solution labelled CODE-9 more RPR-parameters (9) were estimated. This solution is given as reference to show the best obtainable predicted orbit for the selected test.

Table 4 shows that including the ROCK-model as a-priori RPR-model does hardly give any improvement, both in fit and in prediction. Although it was clear for a long time that the ROCK-models are not very accurate, this is a still surprise! Very clearly both the CODE and JPL RPR-models perform much better than the ROCK-model. The results also show that indeed it is very difficult to get better orbit predictions. However, the reduction of the number of parameters (from 9 to 2) without significant loss of accuracy should make the prediction more reliable. More important will be to study the effect on the orbit estimates. If the RPR-models help to improve the (rapid) orbit estimates then also the predictions will be improved.

QUALITY ASSURANCE

The inter-comparison of rapid orbits provides for an accurate assessment of the quality of the IGS rapid orbits. That is not the case for predicted orbits, where the different ACS are using basically the same information to generate the predictions. There are ways to decide which satellites are less predictable, like checking the fit rrns for the four days and considering whether they are in the eclipse season or a maneuver is going to be performed. This is a very important matter because users of the predicted orbits should use them in combination with the accuracy exponents that define the prediction error in order to get the best estimate of their derived products.

Lets assume that we have a parameter that we want to estimate based on the values of other variables and the estimation error for the parameter linearly depends on the error or the values of the variables. The estimates of the variables have an accuracy estimate attached and also a true accuracy. The accuracy estimate is used to weight the variables (that are used as observations) in the estimation of the parameter. For simplicity lets assume that the all variables provide the same observability for the parameter, and lets suppose that this is unity. The least-squares error for the parameter will be:

$$\varepsilon_x = \frac{\sum_i \frac{\varepsilon_i}{\hat{\sigma}_i^2}}{\sum_i \frac{1}{\hat{\sigma}_i^2}} \tag{1}$$

It can be observed that the error itself would be the same if all the accuracy estimates would be multiplied by a constant. That is not the case for the estimate of the accuracy of the paramete. Assuming that the values of the variables are not correlated:

$$\hat{\sigma}_x^2 = \frac{1}{\sum_i \frac{1}{\hat{\sigma}_i^2}} \tag{2}$$

We can also compute the actual accuracy of the parameter:

$$\sigma_x^2 = \frac{\sum_i \frac{\sigma_i^2}{\hat{\sigma}_i^4}}{\left(\sum_i \frac{1}{\hat{\sigma}_i^2}\right)^2} \tag{3}$$

The optimal set of weights (accuracy estimates of the variables) will be the one that would minimize the actual accuracy of the parameter. The values of the accuracy estimate that result are:

$$\hat{\sigma}_i = K \cdot \sigma_i \tag{4}$$

As an example the IGS predicted orbits for day 0942/0 produced the following values:

$$rms = 137.8cm$$
$$wrms = 49.0cm$$
$$wrms_{optimal} = 20.1cm$$

A more than twofold improvement in accuracy for the users of the orbits could have been achieved by setting the accuracy exponents to the (at the time of the combination unknown) optimal values!

It can be shown that the critical factor for the degradation of the accuracy is to set a low value for the accuracy exponent of a satellite that has not been predicted accurately. To mistakenly tag a good satellite as bad has a much smaller impact.

RECOMMENDATIONS

1, Ask the Operational, Regional and Global Data Centers to give the highest priority to the prompt retrieval and distribution of data from sites outside Europe and North America.

2. Ask the Operational, Regional and Global Data Centers to investigate and implement ways of reducing the data retrieval and distribution delays.

3. Ask the Operational, Regional and Global Data Centers to study and implement more frequent down-loading of the data.

4. Ask those Analysis Centers that are evaluating more precise radiation pressure models to make them publicly available, and encourage all Analysis Centers to implement and use them when they have been validated.

5. Ask the IERS Rapid Service and the Analysis Centers to investigate and propose ways to obtain predicted cops (pole and UT1) for use in the calculation of IGS predicted orbits.

6. Ask the Analysis Centers and the AC Coordinator to study, monitor, and, if possible, improve the fitness of the accuracy codes for the predicted orbits.

7. Ask the Analysis Centers to investigate the ways and the consequences of reducing the turn-around time for rapid and predicted products.

8. Review data and rapid product delivery times at July 1 and October 1 in order to evaluate the change of the deadline for rapid products to no later than 16:00 UTC by January 31998.

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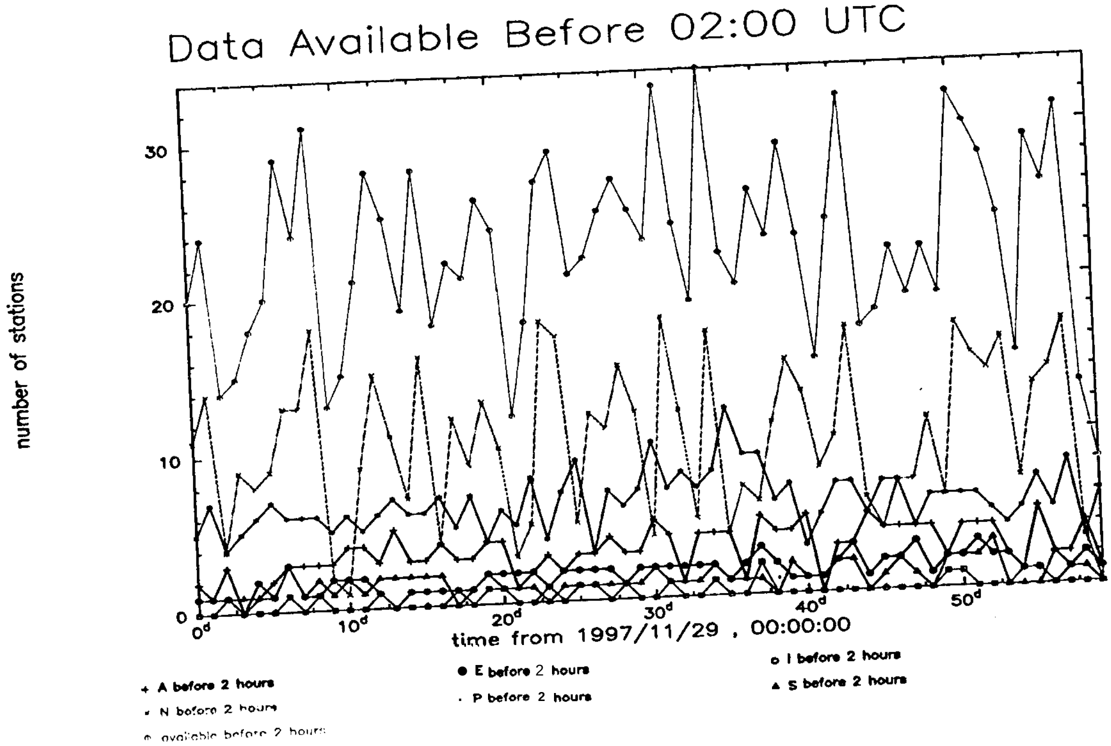

Fig. 2. **Data** available at **CDDIS** before **02:00 UTC**

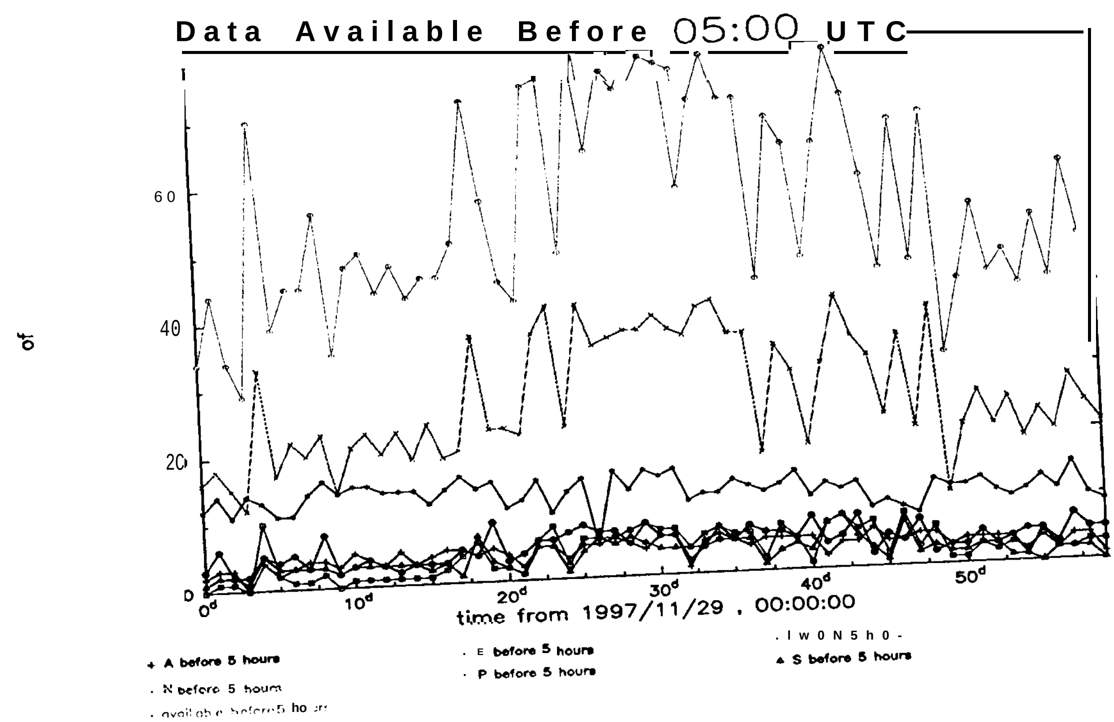

Fig. 3. Data available at **CDDIS** before **05:00 UTC**

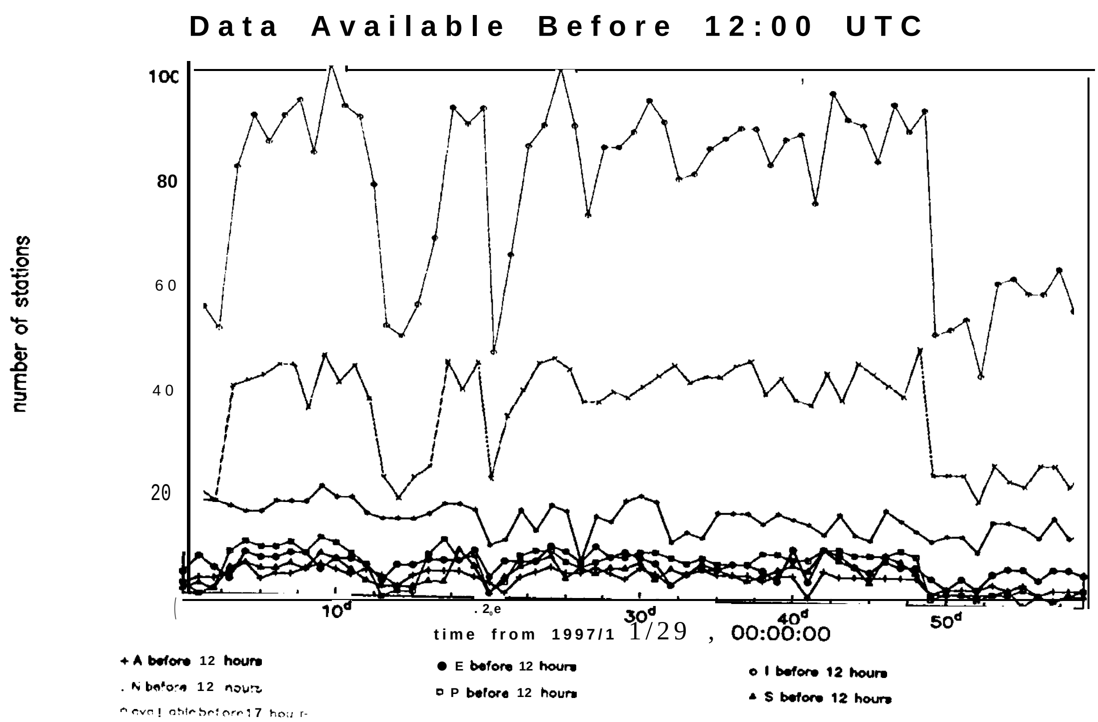

Fig. 4. Data available at CDDIS before 12:00 UTC

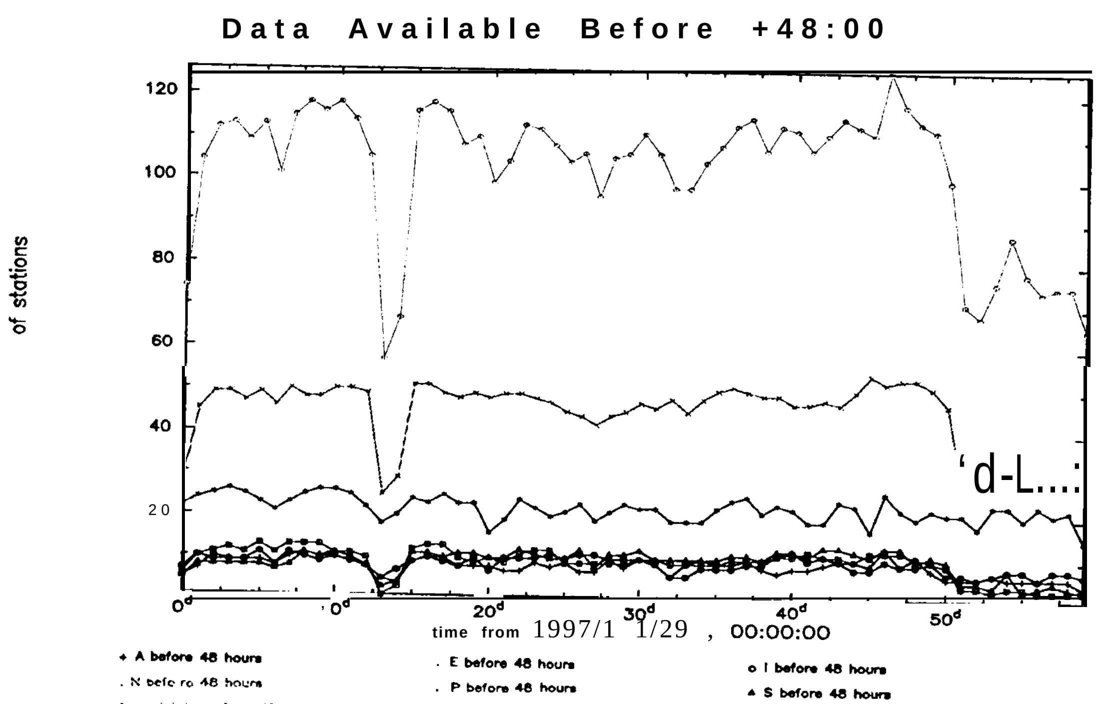

Fig. 5. Data available at CDDIS before 48 hours after collection

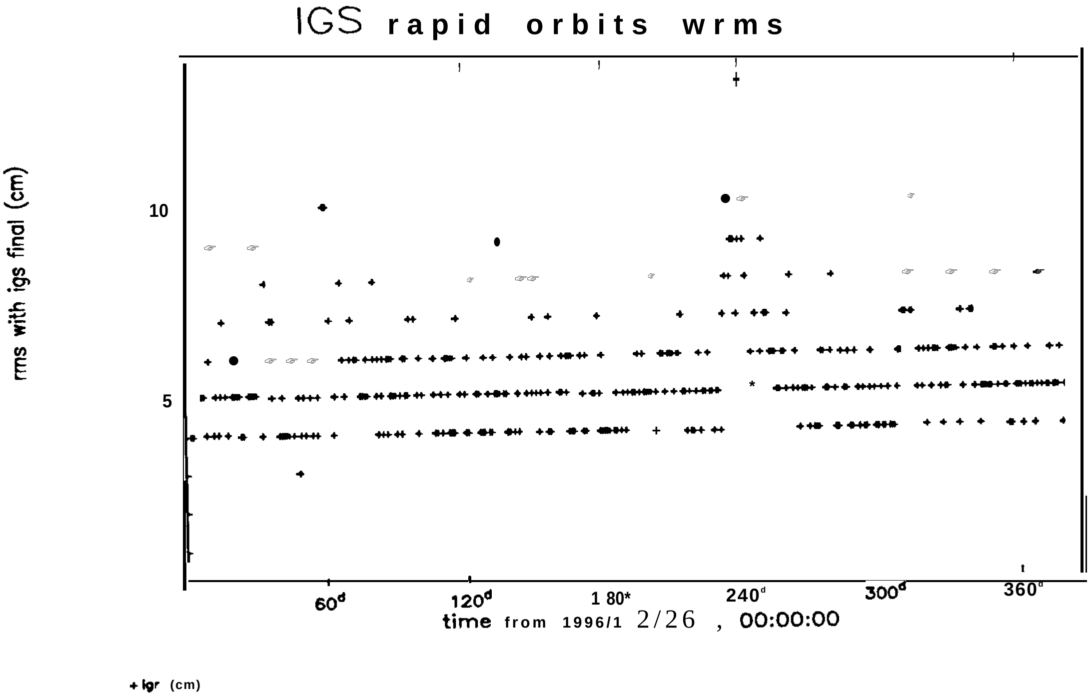

Fig. 6. Comparison weighted rms of rapid orbits with respect to final orbits

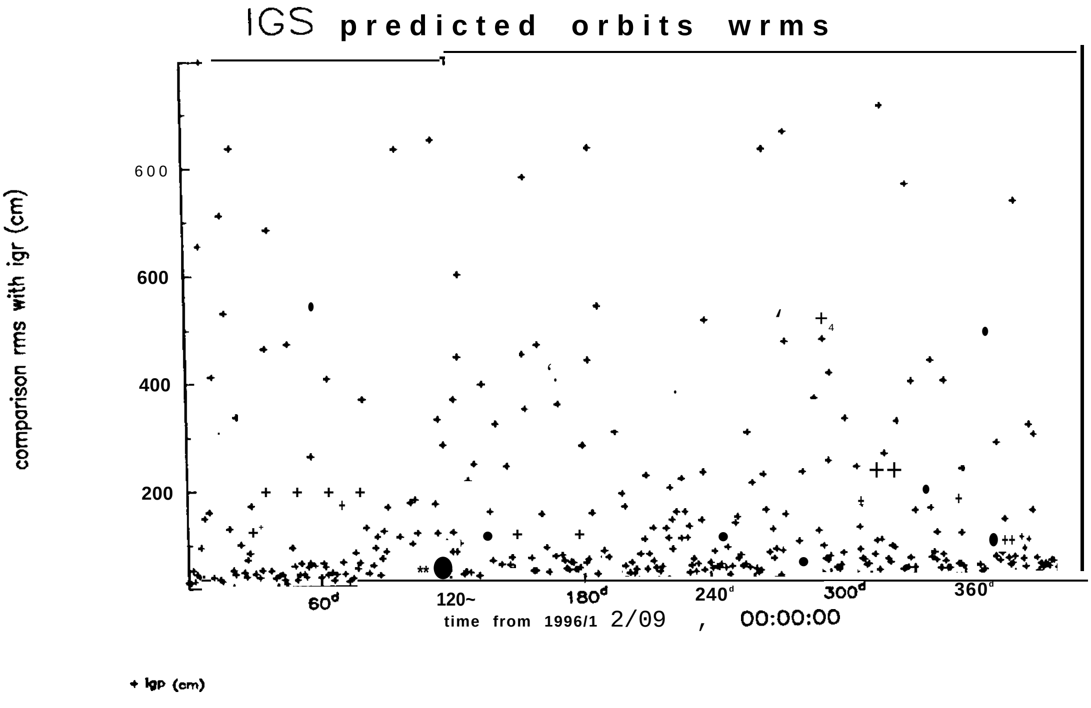

Fig. 7. Comparison weighted rms of predicted orbits with respect to rapid orbits

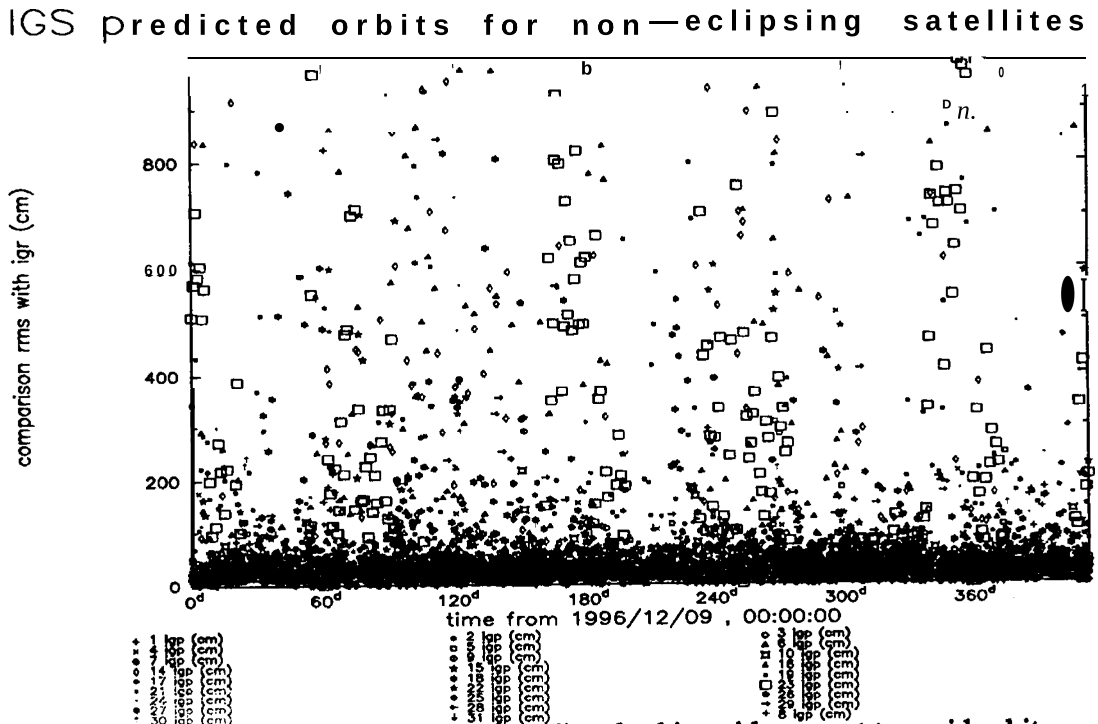

Fig. 8. Comparison rms of predicted orbits with respect to rapid orbits for non-eclipsing satellites

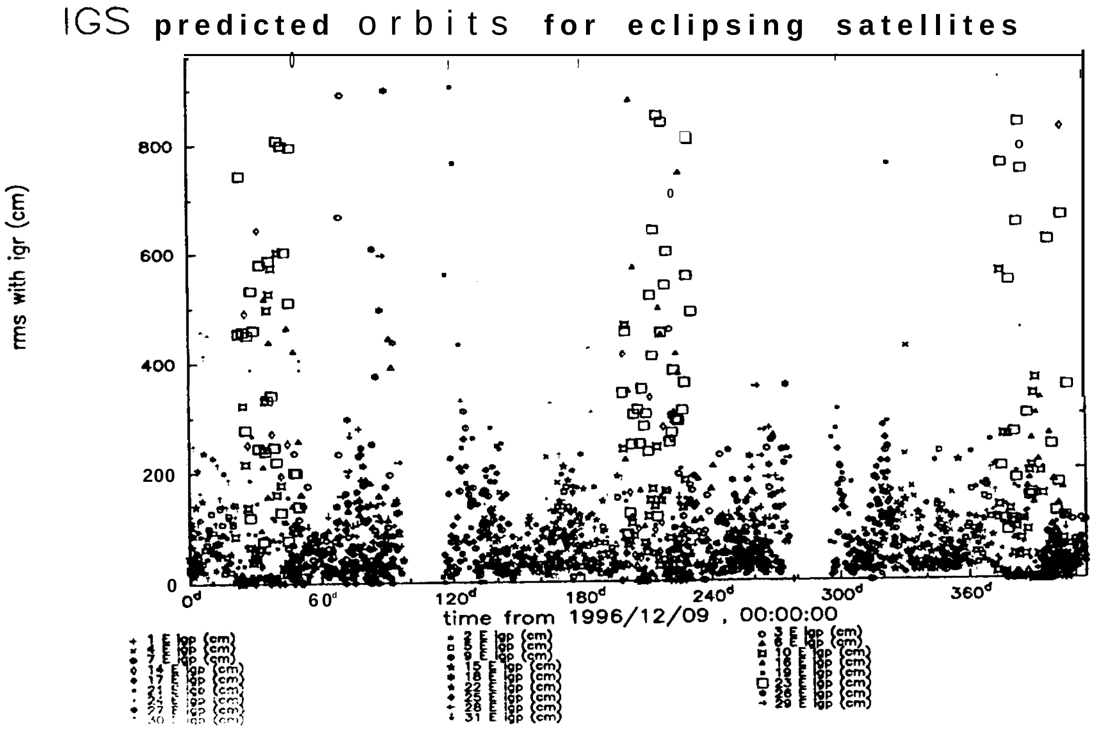

Fig. 9. Comparison rms of predicted orbits with respect to rapid orbits for eclipsing satellites

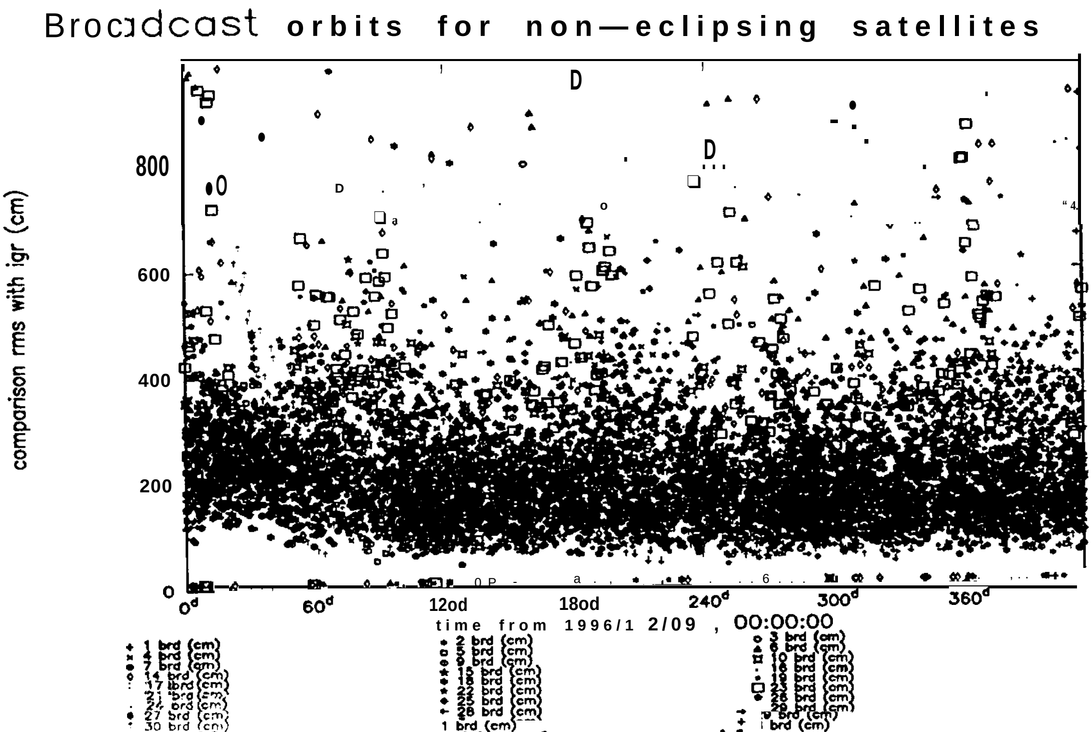

Fig. 10. Comparison& of broadcast orbits with respect to rapid orbits for non-eclipsing satellites

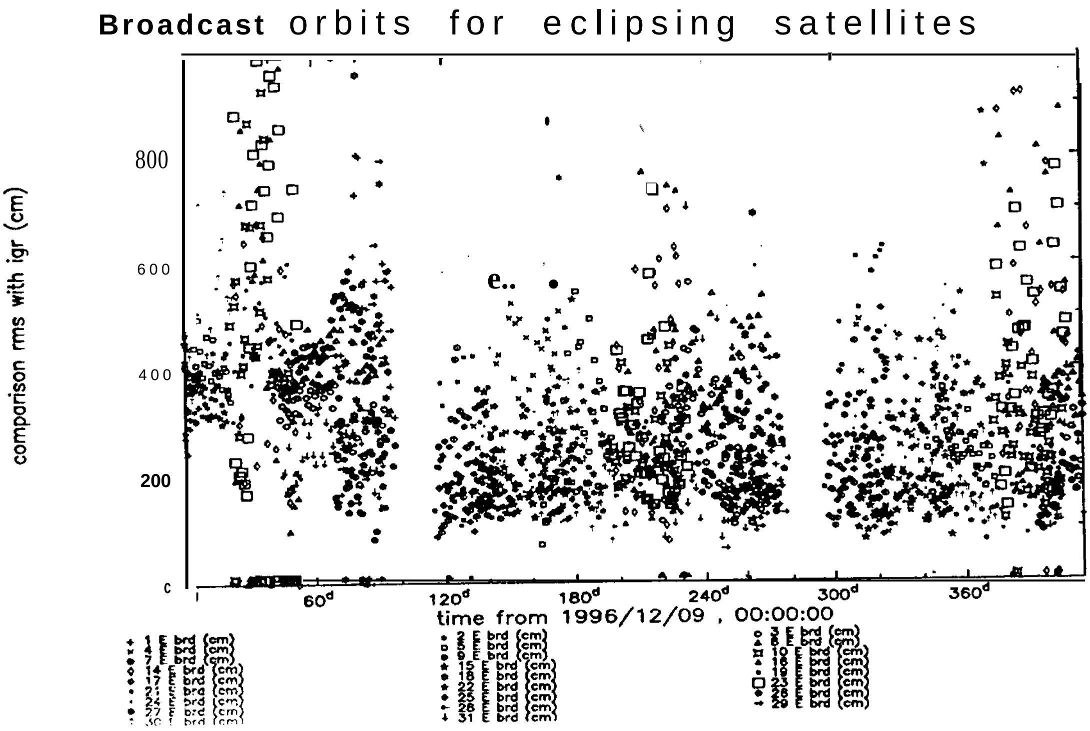

Fig. 11. Comparison rms of broadcast orbits with respect to rapid orbits for eclipsing satellites

A new Solar Radiation Pressure Model for the GPS Satellites

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Abstract

The largest error source in GPS orbit modeling is due to the effect of the solar radiation pressure. Over the last few years many improvements were made in modeling the orbits of GPS satellites within the IGS. However, most improvements were achieved by increasing the number of estimated orbit and/or solar radiation pressure parameters. This increase in the number of estimated satellite parameters weakens the solutions of all estimated parameters. Due to correlations the additional parameters may cause biases in other estimated quantities like, e.g., the length of day.

In this paper a recently developed solar radiation pressure model for the GPS satellites is presented. This model is based on experiences and results acquired at the Center of Orbit Determination in Europe (CODE) Analysis Center during its IGS activities since June 1992. The new model outperforms the existing ROCK models by almost an order of magnitude. It also allows a reduction of the number of orbit parameters that have to be estimated!

Introduction

The largest non-gravitational effect on the GPS satellite orbits is the solar radiation pressure (RPR). To underline this, Table 1 shows the effect of different perturbations on the GPS orbits. The results in Table 1 are based on integrating a given set of osculating Keplerian elements over a time period of one day (24 hours) with the respective perturbations turned on or off. Table 1 gives the RMS of the differences between the resulting two orbits, one with the perturbation turned on and one with the perturbation turned off. The RMS was computed using the full 24-hour arc length and all satellites (using the full satellite constellation of January 1, 1998). It can be seen that the size of the perturbation caused by the solar radiation pressure is only exceeded by the effects of the Earth oblateness, the gravitational attraction by Sun and Moon, and the lower harmonics (C(2,2) and S(2,2)) of the Earth's

Table 1. Effect of different Perturbations on the GPS satellites over 24 hours

Perturbation	Magnitude (m)			
	Radial	Along	Cross	Total
Earth oblateness	1335	12902	6101	14334
Moon (gravitation)	191	1317	361	1379
Sun (gravitation)	83	649	145	670
C(2,2), S(2,2)	32	175	9	178
Solar Radiation Pressure	29	87	3	92
C(n,m), S(n,m) (n,m=3..8)	6	4 6	4	4 6

gravity field. The results clearly show that an accurate solar radiation pressure model for the GPS satellites is as important as an accurate gravity model of the Earth.

The basis of the RPR models currently used was furnished by Rockwell International, the spacecraft contractor for the Block I, II and IIa satellites [*Fliegel et al.,* 1992]. **The** computer programs that embody this model became known as ROCK4 for Block I [*Fliegel et al.,* 1985], and ROCK42 for Block II and IIa satellites [***Fliegel and Gallini, 1989]. They are also known*** as "the Porter models". The ROCK models are expressed in the satellite-fixed coordinate system. This system has its origin in the center of mass of the satellite. Its Z-axis points in the direction of the center of mass of the Earth, and therefore along the satellite antennas. The X-axis is positive toward the half plane that contains the Sun and the Y-axis completes a right-handed system and points along one of the solar panel beams.

For high precision geodetic work it is necessary to estimate a scale term and a force in the Y-direction, the Y-bias, in addition to using the ROCK model. The ROCK model, therefore, only serves as a priori information. Both, the scale term and the Y-bias, are parameters which are supposed to vary slowly in time. Although the cause for the Y-bias is unknown, its effect on the orbit is significant. The claimed accuracy of the ROCK models is about 3%. Taking the nominal value of 1. $10^{-7} m/s^2$ for the solar radiation pressure acceleration of a GPS satellite and the claimed accuracy of 3% for the T20 model, the expected error in acceleration is approximately 3. $10^{-9} m/s^2$. Furthermore the size of the Y-bias, which is not included in the ROCK models, is about 1. $10^{-9} m/s^2$. The effect of both error sources is about 3 meters (RMS) over 24-hours! Of course, we have to keep in mind that the ROCK models were developed for orbit estimation using pseudo-range data. With pseudo-ranges, position estimates with an accuracy of about 1 meter may be obtained, For this type of accuracy the ROCK models are adequate to serve as (a priori) model, provided, the scale term and the Y-bias are estimated.

The ROCK models are inadequate for IGS-type accuracies, e.g., centimeter-type orbit accuracies, even if the scale and Y-bias are estimated. This is also obvious from the additional orbit and solar radiation pressure parameters which most of the IGS ACS are estimating, be they deterministic and/or stochastic in nature. However, additional orbit parameters may weaken the GPS solutions significantly, especially the the LOD (length of day) estimates, Therefore it would be advantageous if an improved RPR model could be developed. The experiences gained from our IGS analysis efforts in recent years have indicated that it will indeed be possible to derive an improved RPR model *[Springer **et** al.,* 1998].

Below we first present a summary of the most recent orbit results. Because these results are based on the extended CODE orbit model (ECOM) [***Beutler** et al.,* 1994], a short description of the ECOM is given as well. Secondly, results from orbit estimation using the GPS (IGS) precise orbits as pseudo-observations (orbit fit) are presented. Based on these results an "optimal" orbit pararneterization is proposed. Using this parameterization and all CODE final orbits and EOPS, as submitted to the IGS, a long time series for the selected (optimal) set of RPR parameters is generated. The last two years (1996 and 1997) of this time series are then used to generate our new solar radiation pressure model. The article concludes with an evaluation of the quality of our RPR model and a short summary.

The Extended CODE Orbit Model

In ***Beutler** et **al.** [1994]* our orbit model, ECOM, is presented and discussed in detail. We only summarize its basic characteristics. The considerations behind the ECOM are similar to those underlying the Colombo model [***Colombo, 1989]. The*** principal difference resides in the fact that the ECOM considers the Sun as the major' 'error source" for the orbits, whereas the gravity field of the Earth plays this role in the Colombo model. The Colombo model uses the radial, along-, and cross-track directions as the three orthogonal directions whereas, the D-, Y-, and B-directions are used by the ECOM. Notice that in earlier publication the B-axis was referred to as X-axis. To avoid confusion with the X-axis of the ROCK models, the B-axis is introduced hereto designate the third axis of the ECOM. ***Beutler et al. [1994]*** demonstrated that the performance of the ECOM is superior to that of the Colombo model, which is a clear indication that solar radiation pressure is indeed the major error source in the GPS satellite orbit model. In the ECOM the acceleration $\vec{a}_{rpr}$ due to the solar radiation pressure is written as:

$$\vec{a}_{rpr} = \vec{a}_{ROCK} + \vec{a}_D + \vec{a}_Y + \vec{a}_B \quad (1)$$

where $\vec{a}_{ROCK}$ is the acceleration due to the ROCK model, and

$$\begin{aligned} \vec{a}_D &= [a_{D0} + a_{DC} \cdot \cos u + a_{DS} \cdot \sin u] \cdot \vec{e}_D = D(u) \cdot \vec{e}_D \\ \vec{a}_Y &= [a_{Y0} + a_{YC} \cdot \cos u + a_{YS} \cdot \sin u] \cdot \vec{e}_Y = Y(u) \cdot \vec{e}_Y \\ \vec{a}_B &= [a_{B0} + a_{BC} \cdot \cos u + a_{BS} \cdot \sin u] \cdot \vec{e}_B = B(u) \cdot \vec{e}_B \end{aligned} \quad (2)$$

where $a_{D0}, a_{DC}, a_{DS}, a_{Y0}, a_{YC}, a_{YS}, a_{B0}, a_{BC}$, and a_{BS} are the nine parameters of the ECOM, and

$\vec{e}_D$ is the unit vector Sun-satellite,
$\vec{e}_Y$ is the unit vector along the spacecraft's solar-panel axis,
$\vec{e}_B = \vec{e}_Y \times \vec{e}_D$, and
u is the argument of latitude

The ECOM is a generalization of the standard orbit model which uses only two parameters to account for the solar radiation pressure, name] y a_{D0} and *aye*. Note that the Y-direction of the ECOM corresponds to the Y-direction of the body-fixed coordinate system. Although not really a solar radiation pressure model in the sense of the ROCK models, the ECOM does consider solar radiation pressure to be the major perturbing force acting on the GPS satellites. Therefore the ECOM provides an excellent tool to study the effects of the solar radiation pressure on the GPS satellites. It allows to detect in which direction the most significant unmodeled RPR forces act on the GPS satellites.

There are two methods to study the effects different parameters of the ECOM have on the orbit estimates. **The first, and most reliable method is to use the ECOM in real orbit estimation procedures using GPS observations, very much like the routine orbit estimation performed** at CODE as part of its IGS activities. **The second method** is to use the orbits as provided by CODE as "pseudo-observations" estimating an arc extending over several days which gives the best fit, in a least squares sense, to the observations. This second method is less correct but computationally much more efficient than the first. The generation of a 3-day arc using the "orbit fit" method typically takes 1 minute whereas the "orbit estimation" method will take several hours. Results from both methods, orbit estimation and orbit fit, will be discussed in the following sections.

Orbit estimation using GPS observations

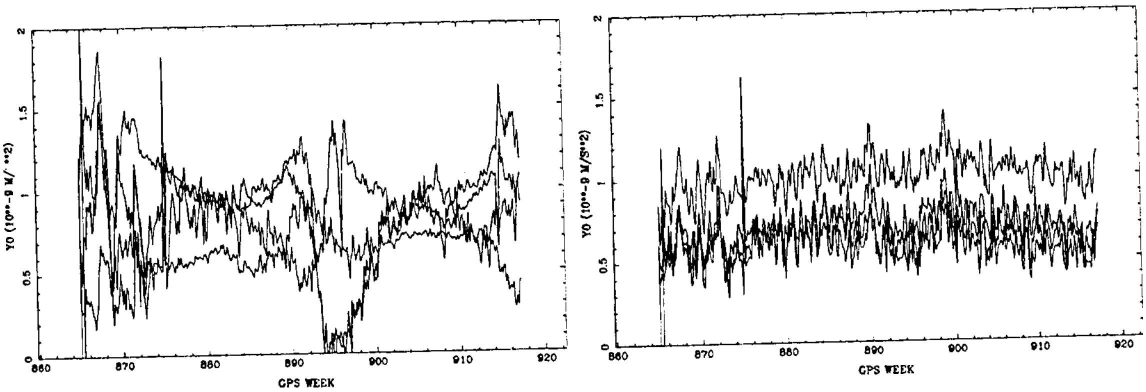
In 1996 the ECOM was fully implemented into the Bernese GPS Software. It was expected that not all nine parameters of the ECOM can (and should) be estimated when estimating 3-day arcs from real GPS data. Initial tests ***[Springer et al., 1996]*** indicated that it is best not to solve for "B-terms", but to estimate the constant and periodic terms in the D- and Y-directions plus small velocity changes (pseudo-stochastic pulses) in the radial and along-track directions. A careful analysis of this parameterization showed that it leads to a significant degradation of the quality of the LOD estimates. It was therefore decided to systematically test the different parameters of the ECOM in order to find the "optimal" pararneterization. In ***Springer et al. [1998]*** a detailed description of the results from two extensive tests using the ECOM is given. The difference between the two extensive test series is, that in the first test series pseudo-stochastic pulses [***Beutler et al.,*** 1996] were always estimated (stochastic test series) whereas in the second test series they were never estimated (deterministic test series), The stochastic test series showed that the estimation of the constant and periodic terms in the B-direction, in addition to the estimation of the constant terms in the D- and Y-direction, and the pseudo-stochastic pulses in the radial and along-track directions, significantly improves the quality of the orbit estimates. An improvement was seen in all estimated parameters: orbits, station coordinates, and EOPS. Only for the LOD estimates a small, but significant, degradation in quality was observed. The improvement of the orbit quality was estimated to be a factor of two to three, compared to the results without estimating the three terms in the B-direction! As a direct consequence of these tests the estimation of the B-terms was implemented for the generation of the CODE contributions to the IGS on September 29, 1996.

The second, deterministic, test series confirmed that the periodic terms in the B-direction most significantly reduce the orbit model deficiencies. Evidence was presented that the periodic signals in the Y-direction reduce the orbit model deficiencies as well. The periodic signals in the B-direction, however, were shown to be more important than those in the Y-direction. The deterministic test series further showed that a purely deterministic orbit parameterization, consisting of the constant terms in the D- and Y-directions plus periodic terms in the D- and B-directions, gives excellent orbit results. Because of a degradation of the LOD estimates this deterministic orbit model is currently not considered for the IGS activities at CODE.

The results based on one full year of routine orbit estimates using the standard (R3) and new (X3) orbit pararneterizations (3 B-terms) showed that the behaviour of the estimated stochastic and deterministic orbit parameters significantly improves with the new orbit pararneterization. This is true in particular for the Y-bias (see Figure 1), and the radial pseudo-stochastic pulses (see Figure 2). Tests without estimating the radial pseudo-stochastic pulses showed that with the new orbit pararneterization these pulses no longer have to be estimated. Considering the fact that pseudo-stochastic pulses are meant to absorb orbit model deficiencies it is clear that the modeling deficits are significantly reduced in the new orbit parameterization. Because the behaviour of all estimated RPR parameters in the X3 solutions is “predictable” it is expected that an improved RPR model may be developed.

Orbit estimation using satellite positions as pseudo-observations

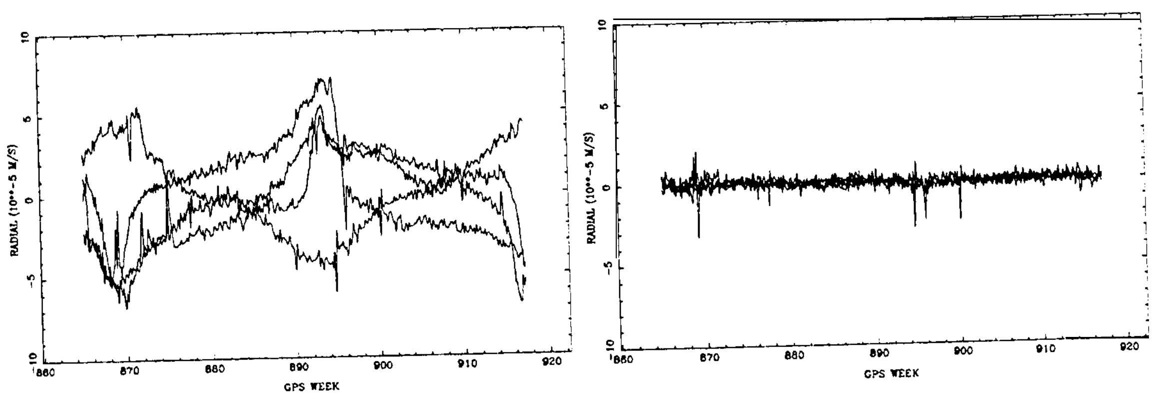
The essential difference between orbit estimation, using real (GPS) data, and orbit fit, using previously determined satellite positions as pseudo-observations, lays in the type of observations used. For the orbit estimation double-difference GPS carrier phase observations are used whereas for the orbit fit the observations are the position vectors of the satellites. The position vectors are very strong observations for orbit estimation whereas the double-difference carrier phases do not contain very much information about the satellite position. Only thanks to the dense global network it is possible to get accurate GPS orbit estimates based on carrier phase data. Due to this significant difference the



(a) Standard Orbit Parametrization

(b) New Orbit Parametrization

Figure 1. Estimated Y-bias (Y_o) using the two different CODE orbit **parameterizations.** Only **PRNs** 3,6,7, and 31 in orbital plane C are shown.



(a) Standard Orbit Parametrization

(b) New Orbit Parametrization

Figure 2. Estimated radial pseudo-stochastic pulses using the two different CODE orbit parameterizations. Only PRNs 3,6,7, and 31 in orbital plane C are shown.

results from orbit fit tests always have to be verified using real GPS data analysis.

The goal of the orbit fit tests was to find the optimal orbit parameterization. For this purpose a “standard test” was developed in order to be able to compare the results. The selected standard test consists out of a 7-day orbit fit using the CODE final products, e.g., precise orbits plus their respective Earth Orientation Parameters (EOP). The resulting 7-day arc is extrapolated, using orbit integration, for 48 hours. The last 24 hours of this orbit prediction are compared to the CODE final orbit for the same day. The period from March 13 to March 21 in 1997 was selected as test interval. The following quantities are considered as quality indicators for the orbit parameterization:

- the RMS of the residuals of the 7-day fit,
- the RMS of the residuals of the orbit prediction comparison, and
- the median of the residuals of the orbit prediction comparison.

First, we studied whether our standard orbit fittest gives similar results as the deterministic orbit estimation test discussed earlier. It was verified that the results were indeed very similar. Only one small anomaly was detected in the estimation of the periodic terms in the Y- and B-direction. In the orbit fit the effect of the periodic terms in these two directions are almost identical whereas in the orbit estimation test a significant difference was observed favoring the periodic terms in the B-direction,

As mentioned above the orbit fit method is based on a strong observation type making it possible to estimate a large number of orbit parameters. Therefore, our software was enhanced to estimated periodic terms up to six times per orbital revolution. Furthermore, modifications were made to allow for periodic terms in two other coordinate systems: the satellite-fixed reference frame **(Z, Y, X)** and the’ ‘classical” orbit system radial, along-, and cross-track (R, S, W). In addition, the argument for the periodic terms was slightly changed to account for the position of the Sun with respect to the ascending node. This change is a consequence of the assumption that the solar radiation pressure is the major’ ‘error source” in the GPS orbit modeling. It is therefore logical to relate the time argument of the periodic signals to the position of the Sun in the orbital plane. Thus, the argument of latitude is corrected for the latitude of the Sun in the orbital plane (u_o), ***[Rothacher et al., 1995].*** After extensive tests, using many different combinations of the available parameters, a small set of optimal orbit parameterizations was found, Table 2 lists these “best” parameterizations.

All candidate parameterizations were subsequently used in real orbit estimation using one full week of GPS data, This test confirmed that all 5 parameterizations perform very well apart from some correlation with the LOD. Because of the slightly better performance and its resemblance with the ROCK model, “model 5‘’ (Table 2) was selected as the’ ‘optimal” orbit parameterization. It consists of three constant terms in the D-, Y-, and B-directions

Table 2. Selected "optimal" orbit parameterizations.

Model	Constant Terms	Periodic Terms
1	D, Y, and B	B $\sin(u - u_0)$ and D $\sin(u - u_0)$
2	D, Y, and B	B $\sin(u - u_0)$ and B $\sin(2u - u_0)$
3	D, Y, and B	Z $\sin(u - u_0)$ and X $\sin(u - u_0)$
4	D, Y, and B	Z $\sin(u - u_0)$ and X $\sin(3u - u_0)$
5	D, Y, and B	Z $\sin(u - u_0)$, X $\sin(u - u_0)$, and X $\sin(3u - u_0)$

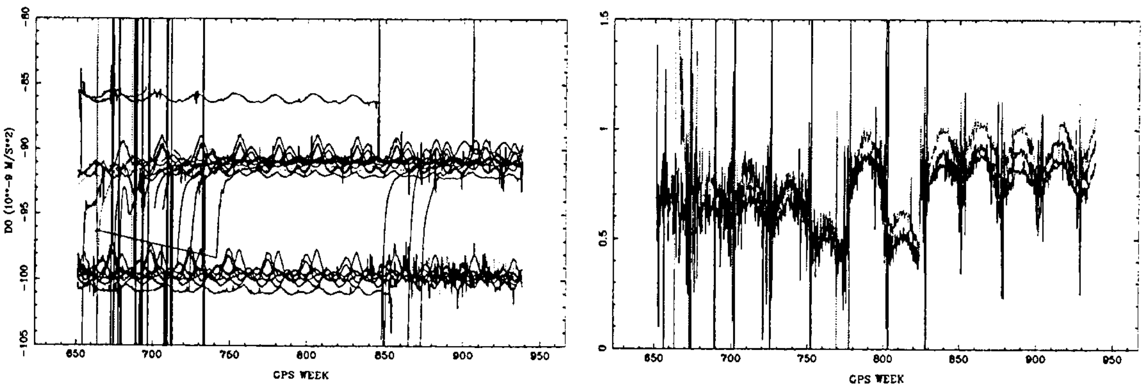
and three periodic sine terms: once-per-revolution terms in the Z-, and X-direction and one three-times per revolution term in the X-direction.

The New Solar Radiation Pressure Model

Using the "optimal" orbit parameterization (model 5 in Table 2) all final CODE orbits with their respective EOPs, as submitted to the IGS since June 1992, were used in an orbit fit. An arc length of 5 days was chosen and **no** a priori solar radiation pressure model was used. This resulted in a long time series, covering 5.5 years, of estimates for the selected (optimal) set of RPR parameters. It was hoped that, after careful analysis, this time series may be used to derive a new solar radiation pressure model. Figure 3 shows the estimated values for the direct solar radiation pressure (Do) and for the Y-bias (Y_o) accelerations as function of time over the full 5.5 years. Jumps are visible in the Y-bias time series. These jumps are related to the "bias" changes in the attitude system of the GPS satellites. These biases have been kept constant since approximately November 1995. Furthermore, the eclipse phases can clearly be seen in the Y-bias estimates: the estimates are somewhat anomalous during these phases.

A careful analysis of the estimated parameters as a function of time showed that the behaviour of satellites within one orbital plane is very similar. Clear annual and semiannual signals are present. Assuming that the Sun causes the observed signals it is logical to study the behaviour of the RPR parameters as function of the angle of the Sun above the orbital plane (angle β_0). **Note** that, if the absolute value of this angle is $\leq 14°$, the satellite is in eclipse. In Figure 4 the same two time series for the direct solar radiation pressure and Y-bias accelerations are shown but now as function of the angle of the Sun above the orbital plane. For the Y-bias a shorter time interval was selected to exclude the observed jumps, but more satellites are shown.

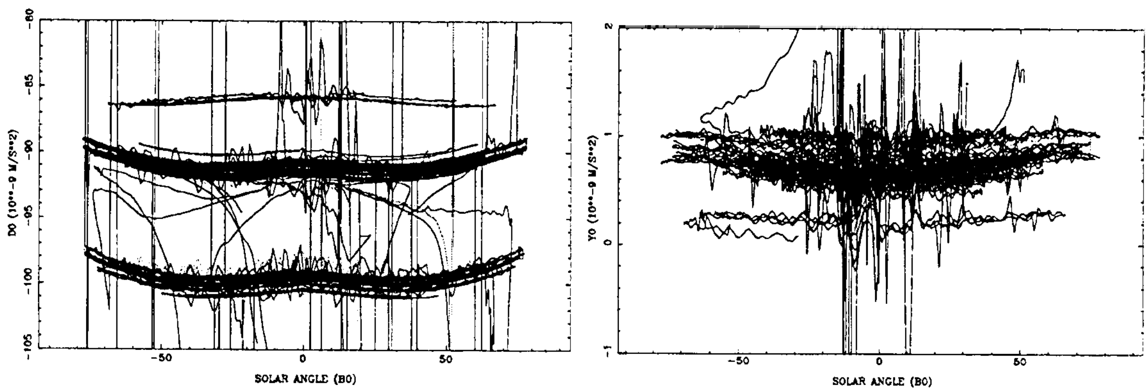
Clearly, the behaviour of the estimates of the direct solar radiation pressure acceleration and the Y-bias acceleration is very similar for all (Block II and IIa) satellites which indicates that a model can be easily derived for these parameters. The same is true for the constant term in the B-direction and for the once per revolution periodic term in the Z-direction. Both periodic signals in the X-direction do not show a very clear signal, nevertheless a model was estimated for these parameters as well. The Block I satellites, the uppermost



(a) Direct solar radiation pressure acceleration for the Block 1,11, and IIa satellites

(b) Y-bias acceleration for the satellites in orbital plane A (PRNs 9,25, 27)

Figure 3. Estimated direct solar radiation pressure acceleration (DO) and Y-bias (Y_0) acceleration as function of time over the interval from June 1992 to 1997



(a) Direct solar radiation pressure acceleration for the Block I, 11, and IIa satellites

(b) Y-bias acceleration for the Block II and IIa satellites

Figure 4. Estimated direct solar radiation pressure acceleration (DO) and Y-bias (Y_0) acceleration as function of the angle of the Sun above to the orbital plane. (for D_0 the complete interval from June 1992 to 1997 is shown whereas for Y. only the last two years (1996, 1997) are included)

lines in both plots showing the D_0 estimates, behave in a slightly different way. Although their behaviour is also predictable, no attempts were made to create a model for the Block I satellites. Due to the "jumps" in the estimates of the Y-bias, the model for this parameter had to be based on the estimates since 1996 only. It turned out that the performance of the complete model was better if all model parameters were uniquely based on the most resent results (since 1996). Apparently the (significant) modeling improvements made over the last few years are important when deriving a solar radiation pressure model.

Based on the careful analysis of the orbit fit results the following terms were included in the radiation pressure model:

$$
\begin{aligned}
a_D &= D_0 + D_{C2}\cos(2\beta_0) + D_{C4}\cos(4\beta_0) \\
a_Y &= Y_0 + Y_C\cos(2\beta_0) \\
a_B &= B_0 + B_C\cos(2\beta_0) \\
a_{Zp} &= \{Z_0 + Z_{C2}\cos(2\beta_0) + Z_{S2}\sin(2\beta_0) \\
&\quad + Z_{C4}\cos(4\beta_0) + Z_{S4}\sin(4\beta_0)\}\sin(u-u_0) \\
a_{Xp} &= \{X1_0 + X1_C\cos(2\beta_0) + X1_S\sin(2\beta_0)\}\sin(u-u_0) \\
&\quad + \{X3_0 + X3_C\cos(2\beta_0) + X3_S\sin(2\beta_0)\}\sin(3u-u_0)
\end{aligned}
\tag{3}
$$

Note that all three constants (D_0, Y_0, B_0) were chosen to be satellite-specific and that the Z_0-term was chosen to be Block type dependent. The values for all of the above parameters are given in the Appendix. Please note that the model is only valid for Block II and IIa satellites. Furthermore, the values given for PRN8 should be used with care because this satellite was launched late in 1997 and by the end of the year was still in its "outgassing" phase. Of course, satellite PRN23 should be used with care as well due to the problems with the orientation of its solar panels, The results indicate, however, that it should be possible to derive a tailored RPR model for PRN23.

Evaluation of the New Solar Radiation Pressure Model

Four different investigations were performed to evaluate the new solar radiation pressure model.

- The effect of the parameters of our RPR model on the satellite positions was determined to get an idea of the significance of the individual terms of the model.
- An error budget of the model was derived, based on the residuals of the RPR series, to get an idea of the remaining model errors.
- The model was compared, using our standard test, to other RPR models to check its performance.
- Finally, the model was tested in a real parameter estimation, using one full week of GPS observations.

The effects of the different parameters of the new RPR model on the orbit were estimated by integrating a given set of osculating Keplerian elements over a time period of one day (24 hours), once with the parameter turned on and once with the parameter turned off. The RMS of the difference between the two resulting orbits, over the full 24 hour period, was then computed to get an idea of the size of the effect. The results are given in Table 3.

Table 3. Effect of the individual parameters of the new RPR model on the GPS satellite orbits over 24 hours.

Parameter	Effect			
	Radial	Along	Cross	Total
DO (m)	29	87	3	92
Y_0 (cm)	49	350	8	354
B_0 (cm)	2	29	3	29
Z $\sin(u-u_0)$ (cm)	15	32	0	36
X $\sin(u-u_0)$ and X $\sin(3u-u_0)$ (cm)	2	11	0	11

As expected the *Do* (direct solar radiation term) and Y. (Y-bias) give the largest contributions. However, the contributions of the Be-term and the periodic term in the Z-direction (radial direction!) are not negligible! Note that the periodic Z-term has a signature very similar to the periodic terms in the B-direction, which CODE uses when computing its IGS orbit products. The periodic terms in the X-direction have an effect of only 11 cm. The typical RMS of the 5-day fits, used for the model development, is at the level of 5 cm. This means that the 11 cm effect is close to the noise level of the solutions. However, the IGS orbit combinations show an orbit consistency of about 4 cm between the orbits of different ACs. Thus, an 11 cm effect maybe significant.

The RPR model is based on the time series of parameter estimates computed by fitting 5-day arcs through the final products from CODE. The RMS of the residuals of the parameter estimates, after subtracting the estimated RPR model, is used to estimate the remaining errors in the model. For this purpose the RMS value was introduced as a "bias" in the corresponding RPR parameter and a 24-hour orbit integration was performed with this bias included. The difference between the biased orbit and the original orbit are a measure of the remaining orbit model errors. The results are given in Table 4. The total error budget was estimated by introducing the RMS value for all parameters as bias.

Table 4. Estimated model errors based n the parameter residuals

Error Source	Model Fit ($10^{-9} m/s^2$)	Magnitude (cm) Radial	Along	Cross	Total
D_0	0.0724	2	7	0	7
Y_0	0.0416	2	15	1	15
B_0	*0.2318*	1	15	2	15
$Z\ \sin(u-u_0)$	0.1187	2	4	0	4
X $\sin(u-u_0)$	0.1454	5	36	1	36
X $\sin(3u-u_0)$	1.5252	8	61	2	62
Total Error budget		11	79	4	79
RMS of 7-day fit (no par. est.)					52

Surprisingly enough the largest error source stems from the two periodic terms in the X-direction. This is remarkable in view of the very small effect these parameters have on the orbit. The estimated errors from the other parameters are all below the 20 cm level. The total error budget is estimated to be about 80 cm. To verify this, our standard test was used without estimating any parameters (except the 6 osculating Keplerian elements). The RMS of this 7-day fit may then be comparable to the estimated model error. The results are comparable but the error budget seems to be somewhat pessimistic. This may be caused by the relatively large error of the X-periodic terms. Also, the arc length of our standard test (7 days) is longer than the arc length used for the RPR parameter estimates (5 days). Therefore the remaining orbit model error is estimated to be of the order of 50 cm only!

Apart from CODE also the JPL analysis center has successfully developed a new RPR model ***[lJar-Sever,*** 1997]. To test the performance of different RPR models our standard test was used once more. Table 5 gives the results of the standard test using the different RPR models available: ROCK, JPL, and CODE. It shows the RMS of **fit** using 7 days of precise orbits and the RMS and median of the residuals of the prediction comparison. Again the CODE final products (orbit and **EOPs)** were used. In all cases only the scale term (or a constant acceleration in the direction sun-satellite *(Do))* and the Y-bias (Y_o) were estimated. Only for the solution **labelled** ' 'BEST" more RPR parameters (all 9 parameters of the **ECOM)** were estimated. This solution is given as a reference, Furthermore, the ROCK model was used in two different ways. First, it was used as a priori model and the accelerations *Do* and Y. were estimated on top of the model (solution: T20), which represents the way the ROCK model is normally used in the Bernese GPS Software. Secondly, it was used by estimating a scale factor for the complete ROCK model and the acceleration in the Y-direction (solution: T20 scaled), which represents the recommended usage of the ROCK model.

Table 5. Orbit Fit (7 days) and orbit extrapolation (2 days) using different RPR models. Only scale (or D_0) and Y-bias estimated.

RPR-MODEL	RMS of FIT (cm)	Prediction Median (cm)	RMS (cm)
No Model	75	133	159
T20	76	134	161
T20 Scaled	72	119	151
JPL Scaled	10	45	58
CODE	6	17	31
"BEST" (9 RPR par.)	5	17	22

Table 5 shows that including the ROCK model as a priori RPR model does hardly gives any improvement, both in the fit and in the prediction, compared to not including an a priori model. Although it was clear for a long time that the ROCK models are not very accurate, this is a surprise! Both the CODE and JPL RPR models perform much better than the ROCK model. The results of the CODE model are close to the "best possible" results. This means that the reduction of the number of estimated RPR parameters (from 9 to 2!), does not significantly degrade the accuracy of the results. This reduction of parameters should make the GPS orbit predictions more reliable! This is very important because it has become clear that the integrity of the predicted orbits is the most crucial factor for real time GPS data analysis [*Martin Mur et al.,* 1998].

Finally, the new RPR model was tested in a real GPS data processing experiment using one full week of data (7 days of 3-day solutions). Four different solutions were generated. For the first two solutions our standard (Do, Y_0) and new (Do, Yo, 130, B_p) orbit solutions were generated using the ROCK model as a priori model. For the second two solutions the same two orbit solutions were generated but now using the new CODE RPR model as a priori model. The results are given in Table 6.

Table 6. Results from real GPS data analysis using both the ROCK and CODE RPR models

	ROCK + Do Y_0	CODE+ Do Y_0	ROCK + Do Yo Bo B_p	CODE + Do Yo Bo B_p
Orbit Overlap (mm)	106	34	31	32
Orbit Comparison (mm)	66	54	50	51

A significant improvement can be seen for the standard solution (D_0, Ye). In fact, the standard solution using the CODE model has become almost as good as the two X3-type (D_0, Y_0, B_0, B_p) solutions. This is an important result because it means that three orbit parameters (the three B-terms) become obsolete! The slight difference in quality is most likely caused by the eclipsing satellites, which are not treated in any special way in the CODE model. The similarity in quality of both X3 (DO, Y_0, B_0, B_p) solutions shows once more that the periodic B-terms behave very similar as the periodic Z-terms.

Summary and Outlook

It has been shown that the new solar radiation pressure model as developed by CODE is superior to the ROCK model by almost one order of magnitude. The remaining model error was estimated to be about 50 cm, whereas for the ROCK model the error is about 300 cm. Although a significant improvement could be achieved with the new RPR model, it should be considered as a "first attempt" only. In the near future more time and effort will (have to) be spent on RPR models. Different models are required for the Block I and IIr satellites and also for PRN23. Furthermore, the behaviour of some of the parameters of the RPR model is significantly different, but not erratic, during the eclipse phases. Therefore, it is very likely that a special eclipse model maybe derived, One minor problem was discovered in the model. The so-called X3 orbit solutions, the official CODE solutions since September 1996, show a small scale difference with respect to the standard (R3) solutions and also with respect to the IGS combined orbit, Because the model was based mainly on our X3 orbits (only for the first few months of 1996 the R3 solutions were used) this scale effect has propagated into the RPR model. This means that all orbit estimates generated with this new RPR model will have a small scale difference of approximately 0.2 ppb (5 mm). Keep in mind that the "true scale" is not known,

The implementation of the CODE RPR model may improve the quality of the orbit estimates. In addition, the number or required (orbit) parameters maybe reduced. This will strengthen the GPS solutions significantly. Especially the generation of the so-called ' 'rapid" products may profit from this development. The predicted orbits may also improve; maybe not in accuracy, but certainly in integrity, thanks to the reduction of the required number of orbit parameters. Last but not least we hope that the model will enable us to generate GPS orbits based on SLR observations only. So far, the limited number of SLR observations and the large number of required orbit parameters made it almost impossible to generate accurate GPS orbits based on SLR data only. With our new RPR model we are are in a much better position because, it allows a 7-day fit at the 6 cm level solving for only two parameters.

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Appendix

This Appendix gives some statistics of the RPR model estimation and the values of the CODE solar radiation pressure model.

Table 7. Results from the CODE solar radiation pressure model estimation

Parameters	#Est.	RMs ($10^{-9} m/s^2$)
DO	15961	0.0724
Y_0	15815	0.0416
B_0	15406	0.2318
$Z \sin(u - u_0)$	15348	0.1187
X $\sin(u - u_0)$	15187	0,1454
X $\sin(3u - u_0)$	15760	1.5252

Table 8. The values of the CODE solar radiation pressure model

Parameters	Estimate (10-97 ?2/s2)	Formal Error ($10^{-11} m/s^2$)
D_{C2}	-0.813	0.176
D_{C4}	**0.517**	**0.124**
Y_C	-0.067	0.104
B_C	0.385	0.572
2_0 Block **II**	1.024	0.299
2_0 Block **IIa**	0.979	0.184
Z_{C2}	0.519	0.248
Z_{S2}	0.125	0.149
Z_{C4}	0.047	0.261
Z_{S4}	-0.045	0.164
$X1_0$	-0.015	0,157
$X1_C$	-0.018	0.297
$X1_S$	-0.033	0.168
$X3_0$	0.004	1.655
$X3_C$	-0.046	3.118
$X3_S$	-0.398	1.773

Table 9. The values for the CODE solar radiation pressure model. The values for PRN8 and **PRN13** should be used with care. PRN8 was launched by the end of 1997 end was still in its ‘ ‘outgassing” phase. PRN13 was also launched by the end of 1997 and is a completely new type of satellite (Block **IIr).** This new Block type most like will have a different solar radiation pressure model.

PRN	Block	*DO* ($10^{-9} m/s^2$)	Y_0 ($10^{-9} m/s^2$)	B_0 ($10^{-9} m/s^2$)
2	II	**-99.373**	0.6362	0.0480
14	11	**-99.290**	0.9064	-0.2510
15	II	**-98.985**	0.7048	-0.4749
16	II	**-99.108**	0.6496	-0.1170
17	**II**	**-99.010**	0.6604	-0.0770
18	II	**-99.359**	0.8683	-0.4783
19	II	**-99.850**	0.7057	-0.1449
20	11	**-100.396**	0.6642	-0,4997
21	II	**-99.477**	0.2592	0.0996
1	**IIa**	**-91.088**	0.7458	-0.4868
3	**IIa**	**-90.395**	0.5637	-0.3960
4	**IIa**	**-90.502**	0.7856	-0.2487
5	**IIa**	**-90.414**	0.7612	-0.2309
6	**IIa**	**-90.354**	0.7589	-0.3092
7	**IIa**	**-90.238**	1.0376	-0.2241
8	**IIa**	**-93.342**	1 .8394	-0.7143
9	**IIa**	**-90.317**	0.7955	-0.3569
10	**IIa**	**-89.546**	0.7819	-0.1772
22	**IIa**	**-90.944**	0.7319	-0.0179
23	**IIa**	**-78.592**	0.7440	-1,0843
24	**IIa**	**-91.436**	1.0537	-0,2214
25	**IIa**	**-90.785**	0.8556	-0.3851
26	**IIa**	**-90.377**	0.9750	-0.4144
27	**IIa**	**-90.291**	0.9482	-0.4224
28	**IIa**	**-90.951**	0.8210	-0.1303
29	**IIa**	**-91.015**	0.9078	-0.5188
30	**IIa**	**-90.455**	0.8285	-0.5409
31	**IIa**	**-90.370**	0.6269	-0.6173
13	**IIr**	**-99.599**	-0.2801	-1.6732