INTERNATIONAL ASSOCIATION OF GEODESY

INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS

International GPS Service for **Geodynamics (IGS)**

Proceedings of the

IGS Analysis Center Workshop

October 12-14, 1993

Geodetic **Survey** Division
Surveys, Mapping and **Remote** Sensing Sector
NRCan
Ottawa, Canada

Edited by
J. **Kouba**

FOREWORD

In May 1993, at the Baltimore IGS oversight committee meeting, we were asked to host a small workshop of the IGS Analysis Centers. It was recognized that for such a workshop to serve its purpose and produce desirable results in time for the official start of the IGS on January 1,1994, it would have to be organized at the working level and include no more than 30 invited participants.

In the planning stage, three main topics were proposed for the workshop agenda. The first two topics identified clear goals to be achieved by the January 1, 1994 deadline: the improvement of analysis center products, formats, processing and reporting standards; and the research and selection of methods to generate official IGS ephemerides, which would be more reliable and more accurate than the individual center's orbital solutions. The third topic deals with future directions for IGS related research to facilitate rigorous integration of regional networks based on distributed data processing. Several participants were approached to prepare position papers to be distributed to the Analysis Centers at least one week prior to the workshop. Session facilitators were selected to focus the discussions and prepare written summaries. Finally, each of the seven Analysis Centers was asked to address in their presentation the above three topics and to highlight their unique processing approaches and future plans.

The technical program of the workshop was coordinated by Jan Kouba of EMR (NRCan) in consultation with J.F. Zumberge of the Central Bureau at JPL and members of the IGS Oversight Committee. Danielle Williams looked after administrative matters and logistics; the Surveys, Mapping and Remote Sensing Sector of the Department of Natural Resources provided additional financial support.

These proceedings contain the final workshop agenda, the list of the participants, revised versions of the three position papers, summary reports on discussions as prepared by the session facilitators and overall workshop conclusions and recommendations. Copies of the presentations by the IGS Analysis Centers and other were made available to the participants during the workshop and thus are not included here. Jan Kouba and R. Ferland have edited and arranged the material according to the workshop agenda to preserve it for the IGS records and for future reference. The Appendix provides IGS Resources Information prepared by the Central Bureau.

I would like to congratulate the IGS, the workshop organizers and all of the participants for a job well done. The technical expertise and collaborative spirit which prevailed during the workshop is reflected in its recommendations and this holds great promise for the future of the IGS. We are looking forward to similar participation in the implementation of the operational IGS starting in 1994.

J.D. Boal
Director and Dominion Geodesist
Geodetic Survey Division, SMRSS, NRCan.

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FINAL **AGENDA**

IGS Analysis Center Workshop

Ottawa, Canada October 12-14, 1993

Location:	The Citadel Inn Ottawa 101 Lyon St., Ottawa, Ont., ph. 613) 237-3600 1-800-567-3600
Registration:	$(Can) 100.00, cash exact amount would be appreciated (or $(US)80.00 also acceptable if preferred)

The workshop, in addition to a review of current approaches and possible improvements, will address the following issues:

1. IGS Processing Center standard report requirements and format,
2. Integration of results from Processing Centers into IGS (orbit) products,
3. Initiate research towards future integration of regional cluster stations and distributed processing.

AGENDA:

Tuesday, October 12

SESSION 1: IGS processing/reports/formats
(Chaudière boardroom, convention level (1 level above the lobby))

8:00	REGISTRATION (08:00-9:30)
8:30	WELCOME/INTRODUCTION J.D. Boal Prof. 1.1. Mueller
9:00	POSITION PAPER 1: IGS Processing Center standard report requirements and product formats (Goad/Zumberge)

Analysis Center presentations

9:30	CODE/AIUB
10:00	COFFEE
10:30	ESA
11:00	GFZ
11:30	JPL
12:00	LUNCH

13:30 NGS
14:00 S10
14:30 EMR
15:00 COFFEE

15:30 DISCUSSION (Facilitator: G. Mader)
Topics:
Standard IGS Processing Center reports product formats;
Core stations, selection and their affect on orbit/EOP accuracy;
Core station selection coordination between Processing Centers;
Solution and station information description, etc.

19:00 RECEPTION (Wine & Cheese), Penthouse Boardroom, 26th (PH) level

Wednesday, October 13

SESSION 2: IGS orbit products
(Chaudière boardroom, convention level (1 level above the lobby))
8:30 CSR Orbit determination experience (Schutz)
9:00 POSITION PAPER 2:
Combining the orbits of the IGS Processing Centers (Beutler/Kouba/Springer)
10:00 COFFEE

10:30 DISCUSSION (Facilitator: B. Schutz/J. Zumberge)
Topics:
Comparison and analysis of different orbits;
Method for orbit/clock combination;
Relative orbit/clock weighting, rejection of outliers;
EOP to be used;
Production cycle (daily, weekly), orbit submission deadlines statistical reporting and feed back to Processing Centers, etc.
12:00 LUNCH

SESSION 3: IGS processing standards
13:30 DISCUS S1ON: IGS processing standards (Facilitator: G. Blewitt/T.J. Martin-Mur)
Topics:
Review/updating the existing IGS/IERS standards;
Compatibility of orbit, clock, EOP, station site velocity and atmospheric modelling;
Specific recommendations for IGS implementation, etc.
15:00 COFFEE

SESSION 4: Integration of regional station clusters
(Chaudière boardroom, convention level (1 level above the lobby))

15:30 Position Paper 3: Regional clusters and distributed processing (Blewitt/Gendt)
16:30 DISCUSSION (Facilitators: Y. Bock/J. Kouba)
Topics:
Effective use of IGS products for regional/fiducial deformation monitoring;
towards distributed IGS processing (e.g. by Helmert blocking);
regional/fiducial data quality;
input and feedback from regional clusters to IGS. etc.
19:00 DINNER (Penthouse boardroom)

Thursday, **October 14**

SESSION 5: IGS applications/conclusions
(Chaudière boardroom, convention level (1 level above the lobby))
8:30 ADDITIONAL PRESENTATIONS AND DISCUSSION ON IGS PROCESSING AND APPLICATIONS (Facilitator: J. Popelar)
Long Term Behavior of Polar Motion Series Relative to the IERS/CB Series (M. Feissel)
ITRF Station Coordinates (C. Boucher, Z. Altamini, L. Daniel)
VLBI and GPS measurements of the Fennoscandian Uplift (J.M. Johansson et al.)
10:00 COFFEE

10:30 FINAL DISCUSSION/CONCLUSIONS (Facilitator: G. Beutler)

REMARKS

For each of the topics above an independent facilitator is assigned to be responsible for written conclusions and consensus (at least for the first two topics, i.e. IGS official orbit and official format/reports).
There will not be complete proceedings, though a written report containing position papers, facilitator's report/conclusions will be prepared by EMR for IGS distribution.
A registration fee of $100 will cover the cost of refreshments, reception and dinner.

LIST OF PARTICIPANTS:

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SESSION 1

(Processing standards, reports & formats)

IGS Position Paper, **IGS** Analysis Center Workshop
Ottawa, Canada, October 12-14,1993

IGS Processing Center standard report requirements and product formats

James F. Zumberge[1]*, Clyde C. Goad*[2]

1. Introduction

As the International GPS Service for Geodynamics develops into a bonafide service organization under the auspices of the International Association of Geodesy, it will become increasingly important to users of its products that contributions from IGS Analysis Centers (Table 1) adhere to common standards. Such standards include file formats, submission frequency, sites used in determination of precise ephemerides, and perhaps standards for analysis.

Of course, if enough standardization were to be imposed on Analysis Centers, the logical result would be no difference whatsoever among their products. Surely the **IGS** is too young an organization to impose rigid standards in any of these areas at this time. Rather than suggest such standards, perhaps it would be more fruitful at this time to:

- review what products are offered by each Analysis Center, with special emphasis on differences, strengths, and weaknesses;

- look at what stations are included in each Center's routine analysis;

- discuss what other products **IGS** Analysis Centers ought to be offering.

The paper will conclude with a list of questions that could form the basis for discussion at the Workshop.

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2. Department of Geodetic Science and Surveying, The Ohio State University, Columbus, Ohio 43210-1247 USA; e-mail: `cgoad@magnus.acs.ohio-state.edu`

Table 1. Current IGS Analysis Centers

COD	Center for Orbit Determination in Europe	Switzerland
EMR	Energy, Mines & Resources	Canada
ESA	European Space Agency	Germany
GFZ	GeoForschungsZentrum	Germany
JPL	Jet Propulsion Laboratory	USA
NGS	National Geodetic Survey	USA
S10	Scripps Institution of Oceanography	USA

2. Current Products

Table 2 summarizes products regularly produced by the Analysis Centers. The standard for filenames is

xxxwwwwd.ext

where xxx is a 3-character Analysis Center identifier (see Table l), wwww a 4-digit GPS week number, da l-digit day-of-week (O means Sunday, 6means Saturday, 7 means the entire week), and ext is a 3-character identifier to denote file ''type". Forexample, esa07137.erp indicates earth rotation parameters (.erp) by the European Space Agency for the entire GPS week 713. Other extensions include .eph, .sp1, and .sp3 for precise GPS ephemerides, and .sum for summaries. In Table 2, if a Center includes the product, the extension used in the file's name is indicated, otherwise a - is indicated.

Table 2. Products and Filename Extensions by Analysis Center

	COD	EMR	ESA	GFZ	JPL	NGS	S10
spl orbits				.eph	.sp1	-	.sp1
sp3 orbits	.eph	.eph	.eph	-	.sp3	.eph	.sp3
earth orientation	.erp	.erp	.erp	.erp	.erp	-	.erp
summary file	.sum	sum	.sum	sum	sum	sum	sum

Precise GPS Ephemerides

All Centers provide GPS satellite ephemerides, although there are some differences in filename extensions and formats. Five (COD, EMR, ESA, GFZ, and NGS) Centers use .eph as the filename extension. Of these, four provide files in the sp3 format and one (GFZ) provides the sp 1 format.

The other two Centers (JPL and S10) provide orbit files in both the sp 1 and sp3 formats, and use .sp 1 and .sp3, respectively, as filename extensions. (For a description of these formats, see NOAA Technical Report NOS 133 NGS 46, "Extending the National Geodetic Survey Standard GPS Orbit Formats", and "NGS Second Generation ASCII and Binary Orbit Formats and Associated Interpolation Studies", both by B. Remondi.)

One advantage of the sp3 format is that it allows a field for a clock estimate. Two Centers, COD and EMR, actually fill this field with satellite clock estimates, although their sign conventions are opposite.

(However, because of clock dithering implemented as part of Selective Availability, it is a mistake to think that clock solutions and precise ephemerides should necessarily be reported at the same frequency. Essentially, GPS orbits are smooth and can be reasonably interpolated given data spacing at intervals of 15 minutes, or even longer. GPS clock solutions, however, need to be supplied much more frequently (at least every 30 sec.) to derive accurate clock solutions at intermediate points by interpolation.)

The sp3 format differs from the sp 1 format also in that it (i) allows an "orbit accuracy exponent" for each satellite, (ii) has an extra digit of precision in its position fields (accurate to 1 mm.), and (iii) allows velocity information as an option (currently exercised by none of the Centers).

Given all this, there is little to recommend sp 1 over sp3, except perhaps that the sp 1 format has a much shorter and easier-to-understand header. The sp 1 format persists most likely because it was the first format to gain widespread use and some software was developed around it.

Before recommending sp3 as an "official" format, however, we ought to mention real disadvantages of both it and its sp 1 precursor. Neither allows for exclusion of certain satellites during certain times in the file. Thus a Center cannot submit weekly sp3 files if a certain prn was not used during one day of the week. Also, because of headers and other adornments, custom software must be used (and maintained!) to do what would otherwise be simple operations.

For example, it is tedious with these formats to (i) extract results from all Centers for a given prn at a certain time, or (ii) eliminate a certain prn from a file, or even (iii) concatenate files. While it is true that straightforward software can be written to perform these chores, a simpler "basic" format could be used which would rely solely on operating system commands (grep, cat, sort in Unix) for manipulations.

An example of a single record from such a format (and all records have the same fields) might be:

```
e jpl 03199308221215 .0000 -15667.935591 15329.100213 14845 .251566-0.3
```

The first field identifies the record as being an ephemeris record, the second field identifies the Analysis Center, and the third field identifies the pm. The next group constitutes a GPS time tag, followed by Cartesian earth-fixed coordinates. The record ends with some orbit accuracy field (we suggest the natural log of the 3drms error, in meters, which would give 10% resolution with one digit, and plenty of dynamic range). The fields in the above format are also pretty obvious, just by inspection,

With such a format, all of the file manipulation chores mentioned above are trivial using basic operating system tools. And orbit comparison is also simple (essentially a join operation to match up pm's and time tags between two files), Furthermore, the inclusion of a time-dependent orbit quality indicator could be very useful for maneuvering satellites. Better still for such satellites, the format allows for easy inclusion of high-frequency satellite coordinates during a maneuver (provided the maneuver is modeled).

While it is true that the size of the file would be larger (because of Center identifier and time-tag repetition), this seems fairly unimportant when the files are actually saved in some generic compressed format. As an example, a file in the above format was created for Saturday of GPS week 713. Its size is 187 Kilobyte, about 30% larger than jpl07 136.sp3. When compressed, however, it is 56 Kilobyte, compared to 49 Kilobyte for the compressed sp3 file. The 15% difference in the size of the new file arises because it actually contains more information than the .sp3 file, namely, orbit quality as a function of time.

Before moving on to earth orientation and summary files, some mention should be made of the current Center-to-Center orbit comparison procedure. Every day, each 2-Center subset of the 7-Center set is used in an orbit difference calculation. Denote by dx(t,i,j,p), dy(t,i,j,p), and dz(t,i,j,p), the Cartesian differences between Centers i and j of the location of satellite p at time t. The rms over times and pm's, common to both Centers, of sqrt(dx*2+dy*2+dz*2), is used as the orbit comparison metric.

One undesirable quality of the rms statistic is that it is extremely sensitive to the very poorest agreements. Consider the case where one prn is badly behaved on a given day. Centers that exclude such a pm tend to fare better in their orbit comparison values than those that include it. One solution would be to use the median of sqrt(dx^{A}2+dy^{A}2+dz^{A}2) as a statistic rather than the rms, since the median is not at all sensitive to either the best or worst agreements. Another solution would be to exclude the one or two pm's with the worst agreement (rms over time) in the grand rms calculation.

Earth Orientation

Except for NGS, all Centers submit .erp files with Earth Orientation Parameters. Table 3 identifies which of the fields, as originally defined in IGS Message 10, are included in .erp files, as a function of Center. A 15th field, not in IGS Message 10, is used by two Centers to indicate the time span of the observations.

The formats of the .erp files are rather dissimilar among Centers. For example, the EMR .erp file includes not only the table, but additional narrative which describes the solution. ESA includes field definitions in their .erp file.

Unlike the orbit files, the dissimilarity in the .erp files suggests that (i) there is currently little demand for the .erp product and (ii) whatever users do exist are unusually tolerant of format differences. Programs that read .erp files are not likely to work equally well on files from different Centers.

It is probably time to reconsider how to best summarize earth orientation results. When doing so it should be remembered that GPS measurements are sensitive to temporal changes in UT1 -UTC, and not UT1 -UTC itself. Additionally, because it may be useful to transform GPS ephemerides from the earth-fixed frame (as they exist in the .spx formats) to an inertial frame, the .erp file ought to have enough information to accurately invoke this transformation as a function of time. These concerns could be addressed by including time derivatives of the quantities as fields, and/or by including more than one record per day.

Table 3. **Earth Orientation Parameters (see IGS Message 10)**

key: o => included => excluded

	COD	EMR	ESA	GFZ	JPL	NGS	S10
MJD of the measurement	o	0	0	0	0	.	0
x of the pole	0	0	0	0	0	.	0
y of the pole	0	0	0	0	0		0
UT1-UTC **(s) (see note 1)**	o	o	o	o	o	.	o
uncertainty on x	0	0	0	0	0	.	0
uncertainty on y	0	0	0	0	0	.	0
uncertainty on UT	0	0			.	.	
rms residual	0			.			0
x, y correlation	0	.	.	.	0	.	0
x, **UT1 correlation**	0	.		.	.		0
y, **UT1 correlation**	0	.			.	.	
number of stations	0	.	0	0	0	.	0
number of satellites	0	.	0	0	0	.	0
number of passes	.		.	.			.
time span (see note 2)	0	.	0	.	.	.	.

notes:

1 ESA uses the UT1-UTC field to indicate d(UT1-TAI) /dt, and GFZ uses it for UT1-IAT.

2 Not included in original IGS Message 10 definition.

Summary Information

The third product offered by all Centers is the sum file. Shown in Table 4 is a summary of the kinds of information contained in this file, by Center. The categorization is subjective, of course.

Of the three product categories - precise orbits, earth orientation, and summary - the last shows the least uniformity among Centers, as the Table 4 clearly shows.

The following four categories are included by a majority of Centers in their sum files: product summary, remarks, and station summary and orbit quality. Of these, there is considerable variation in the orbit quality metric, which for the most part is a measure of orbit continuity from day to day.

Table 4. Information in . sum File, by Analysis Center
key: o => included => excluded

	COD	EMR	ESA	GFZ	JPL	NGS	S10	total
product summary	o	0	0	0	0	.	0	6
remarks	o	0	0	0	0	.	0	6
station summary	o	0	0	0	0	.	0	6
orbit quality	o	.	0	0	0		0	5
earth orientation	.		.	0	0	.	0	3
solution characteristics	.	0	0	0	.		.	3
solution statistics	o	.		0	.	0	.	3
length of day		.		0	0	.		2
station coordinates						o		1
baseline coordinates	.	.				.	0	1

3. Core Stations

Based on the sum files submitted for GPS week 713 (93 Sep 5-11), Table 5 indicates stations from which data are used as function of Center. Included stations are indicated by either a "*" or "o", depending on whether the station coordinates are fixed or estimated, respectively. Note that the meaning of "fixed" is not necessarily the same for all Centers, and can range from truly fixed (constrained absolutely to the apriori values) to an a priori constraint of 2 cm.

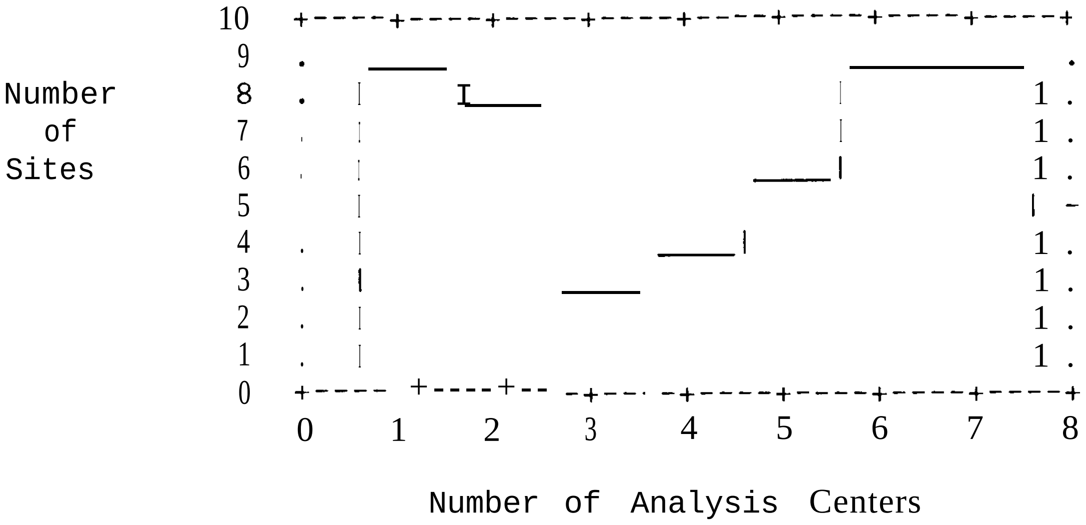
The distribution of the "total" column in Table 5 is shown in Figure 1. Thus nine of the sites are analyzed by only one Center, eight are analyzed by exactly two Centers, and so on, until we come to nine sites analyzed by all seven Analysis Centers.

Table 5. Sites Analyzed as Function of Analysis Center, GPS week 713
key: o => estimated * => fixed . => not used

		COD	EMR	ESA	GFZ	JPL	NGS	S10	total
Alberthead	Canada		o		.	o	.	.	2
Algonquin Park	Canada	*	*	*	*	*	*	*	7
Bermuda	Bermuda	.		.		o	o		2
Darwin	Australia		.			.		o	1
Penticton	Canada	0	0	.	o	0	0	*	6
Fairbanks	US	*	*	*	*	*	*	*	7
Fortaleza	Brazil					o	o		2
Goldstone	US	*	*	*	*	0		o	6
Graz	Austria	o	.	.		0		.	2
Hartebeesthoek	South Africa	0	*	*	*	*		0	6
Herstmonceux	UK	0	.			o	0	.	3
Hobart	Tasmania	0	.		o	0	0	0	5
Holberg	Canada	.	0		.		.		1
Jozefoslaw	Poland	0					.		1
JPL	US	.	.		0	0	0	0	4
Kiruna	Sweden			o	.	0	.		2
Kokee Park	US	*	*	*	*	*	*	*	7
Kootwijk	Netherlands	*	.		*	o	*	*	5
Kourou	French Guiana	o		o	o	0	o	o	6
Madrid	Spain	*	*	*	*	*		*	6
Maspalomas	Canary Islands	o	.	*	*	o	0	*	6
Matera	Italy	0		o	*	0	*		5
Lake Mathews	US	.		.		.		o	1
McMurdo	Antarctica	0	*	0	o	0	*	*	7
McDonald Obs	US		.			0			1
Metsahovi	Finland	0			0	0	*		4
North Liberty	US		.	.		0	.		1
Ny Alesund	Norway	0	.		.	0	.		2
Onsala	Sweden	*	.		0	0	*	*	5
Pamatai	Tahiti	o	0	.	0			*	4
Pietown	US	0	.		.	0	.	o	3
Pinyon Flat	US	.	.	.	.	0	.	0	2
Pales Verdes	US			.		.		0	1
Quincy	US	0	.			0		0	3
Richmond	US	0		0	*	0	0		5
Santiago	Chile	0	*	*	*	*	0	0	7
Scripps	US							0	1
St. John's	Canada	0	o	.	*	o	0	0	6
Tai Shai	Taiwan	0		.	*	0	*	0	5,
Tidbinbilla	Australia	*	*	*	*	0		*	6
Tromso	Norway	*	*	*	*	*	*	*	7
Usuda	Japan	o	.	o	o	o	o	o	6
Vandenberg	US		.			0		0	2
Westford	US	0		.	0	0	0	.	4
Wettzell	Germany	*	*	*	*	0	*	*	7
Yarragadee	Australia	*	*	*	*	*	*	*	7
Yellowknife	Canada	*	*	*	*	o	*	*	7
Zimmerwald	Switzerland	o	.		.		.		1
total		34	18	19	28	40	26	32	197

From Figure 1 we find that there are 28 sites, each of which is analyzed by a majority (4 or more) of Centers (not necessarily the same Centers, of course). One could consider these (or the 24 analyzed by 5 or more Centers, or the 18 analyzed by 6 or more Centers) as defining a sort of de-facto set of Core Stations. (It must be remembered, of course, that the indications in these tables represent a snapshot for one particular week. For example, JPL includes data from Pamatai whenever it can.)

Figure 1. Number of Sites (Y) Analyzed by Exactly x Centers



It is beyond the scope of this Paper to discuss details regarding a priori monument coordinates and station eccentricities, but this Workshop might be an appropriate time to agree on a common standard. It is suggested that station eccentricities, coordinates, and velocities be based on Tables 1 and 2 [SSC(IERS) 93 C 01 (epoch 1992.6)], respectively, from IGS Message 263.

From Table 5 we see that each of the following 13 sites is used as a fiducial by at least four Centers (again, not necessarily the same four Centers in each case): Algonquin Park, Fairbanks, Goldstone, Hartebeesthoek, Kokee Park, Kootwijk, Madrid, Santiago, Tromso, Tidbinbilla, Wettzell, Yarragadee and Yellowknife. All of these stations are contained in IGS Message 263, and all except Kootwijk are currently analyzed (whether estimated or fixed) by at least 6 of the 7 Centers. It is suggested that these be considered as candidates for standard fiducial sites.

4. Additional Products

The following excerpt from the IGS Terms of Reference identifies products to be supplied by IGS Analysis Centers:

These (GPS observation) 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,

The first two, precise GPS orbits and earth rotation parameters, have already been discussed.

Coordinates and Velocities of IGS Tracking Stations

Two Centers, NGS and S10, already include some station location information in their sum files (although the meaning of the numbers is not immediately obvious). Individual Analysis Centers have been working directly with the IERS for inclusion of GPS-determined station coordinates in the IERS annual report. This interaction between individual Centers and the IERS has been successful, and should continue.

There may be some value in producing daily station coordinate estimates, for quality control purposes if nothing else. For stations whose coordinates are fixed, difference among Centers in nominal values would be readily apparent. For estimated stations, daily repeatability of coordinates and baseline components could be used as additional measures of quality, like orbit repeatability. Finally, it might be of value to fixed-orbit users to include data from one or more core stations in the reduction of their network data set (a possibility discussed below in conjunction with clocks). It maybe advantageous in such a case to constrain the coordinates of such included stations to the values already obtained in the global solution.

GPS Satellite and Tracking Station Clock Information

As mentioned earlier, two Centers already include clock information for GPS satellites in their sp3-formatted orbit files. For reasons already discussed, it is not clear that it makes sense to include such information in the same file as the orbits.

Note that potential users of IGS precise orbits and clock solutions have two choices regarding how to define a reference clock in their local network. An approach that would always work, regardless of the network location, would be to fix GPS satellite clocks. As pointed out earlier, intentional SA dithering means that the fixed values need to be given frequently enough (at least every 30 seconds) for precise interpolation.

Another approach would be to include data from a nearby IGS station in the solution, and fix the value of its clock to that determined in an IGS global solution. Many of the stations have very stable clocks, and the dithering issue that plagues the GPS satellites is not an issue for station clocks.

A suggested format for satellite and station clock solutions follows the approach described earlier for a possible orbit format. Examples of satellite and station clock solutions from such a format is

```
c cod prn16 199309170215 0.0000 6.36451031615e-05 7.03e-08
c cod nyal 199309170215 0.0000 3.42833200249e-05 8.63e-08
```

Following fields that identify the record type ("c" for clock), the Analysis Center, the transmitter/receiver, and the GPS time tag, the clock solution and its uncertainty (both in sec.) follow. This simple format has all of the advantages discussed earlier for the proposed simplified orbit format. Furthermore, by judicious choice of time tags, it allows for discontinuities in clock solutions, which occur regularly when station clocks are adjusted to keep their biases small. There is no requirement in such a format that entries for a given transmitter or receiver be equally spaced in time, nor even that solutions for transmitters and receivers be supplied at the same interval.

Because of the record identifier field in the above format for clock solutions, and the format described earlier for orbits, record types could simultaneously exist in a single file, reducing the number of files with which to work.

(The idea of a record type identifier is not the only way to allow orbit and clocks to coexist in the same file. For example, orbits could appear first followed by some kind of terminator and then the clock solutions. The record-type-identifier approach has more potential, in that it allows for additional record types, including, say, ionosphere information, or a "new start" flag for orbits after a burn.)

Ionospheric information

All Centers use the ionosphere-free combination of phase and pseudorange, so that the electron density of the ionosphere does not need to be modeled. The linear combination L1 - L2 (or, with more noise, P1 - P2) is proportional to the columnar electron density along the transmitter-receiver line of sight.

Although it would be easy to construct an L1 - L2 product as a function of time and transmitter-receiver pair, it is not clear that there would be much of a demand for such a product.

More promising would be a model which considered physical causes of spatial and temporal variations in ionospheric electron density. By using data from the global network, parameters in such a model could be estimated. The result could be used to predict variations in ionospheric electron density at positions and times for which there are no measurements. (See for example, Mannucci et al., “A new method for monitoring the Earth’s ionospheric total electron content using the GPS global network”, presented at ION-GPS 93, 1993 Sep 22-24, Salt Lake City,, UT.) Such predictions could be used, for example, in the reduction of data from single-frequency receivers.

5. Summary

The following issues should be discussed at the workshop:

- Can we agree on a common orbit format?

- Should we modify the current format for presentation of earth rotation parameters?

- Can we agree on what information should be included in the summary file?

- Can we define a subset of the global network as constituting a “core”? Can we furthermore define a subset of that core as stations that should be fixed?

- Should we produce weekly files which contain station coordinates and clock solutions?

SUMMARY OF SESSION 1

The first session focused on IGS processing standards, reports and formats. A position paper authored by Jim Zumberge (JPL) and Clyde Goad (OSU) was presented by Jim Zumberge. This presentation was followed by reports from each of the seven Analysis Centers and a discussion on IGS product formats.

The principal products or reports that came under discussion were:

orbital solutions,
earth orientation solutions,
solution summaries.

There was considerable discussion regarding the inadequacies of the SP3 (and SP1) format for reporting satellite clock solutions and continuously estimating satellite position accuracies. There seems to be a user segment for frequent (i.e. every 30 sec. or less) satellite clock estimates. Less frequent reporting is of little use for point positioning and certain other applications given the effects of S/A. The use of a single estimate satellite position accuracy in the SP3 header was also criticized since this value may change significantly during the day. Several ideas for a new file format were suggested but in view of the proximity of the onset of the initial IGS service and the variety of opinions that were voiced the following recommendations were agreed to:

The orbit format will be SP3 beginning on 1/1/94 and work will begin on designing a new format.

The orbit files will contain satellite clock information, derived either from the broadcast message or a precise solution, and will be reported at the same 15 min. rate as the position information.

A separate file will be used for more frequent satellite clock reporting. The format of this file will be determined.

A metric describing the satellite position accuracy maybe added at the end of the position entries to describe changes in solution accuracies. Zumberge will coordinate an e-mail discussion regarding this format and definitions.

The Analysis Centers are using the IERS format for reporting the earth orientation results. There are some differences after the first six fields where some Centers are reporting additional information. Some Centers are also reporting EOP results more frequently, including more epochs in a file.

The solution summary files were quickly recognized as being highly variable in style and content and no discussions were held to try to establish a common format for this report.

The conclusion reached regarding the EOP and summary formats was that Zumberge would also coordinate preparation of EOP and summary file documentation based on the issues raised during the workshop.

The discussion also included the use of common core station data by the Analysis Centers. Since most of the Analysis Centers use the same station data (24 stations are used by at least 4 of the 7 Centers) and since a combined orbit product will be produced by IGS, the following issues were addressed.

Should the Analysis Centers:

- include the same core subset?
- constrain the same core subset?
- constrain at the same positions'?
- coordinate the velocity updates?

After discussion and a polling of the Analysis Centers it was recommended that the Analysis Centers will include in their solutions the following station data and that the positions of these stations will be tightly constrained or fixed to those values given in **IGS** mail 263.

Algonquin
Fairbanks
Goldstone
Hartebeesthoek
Kokee
Kootwijk
Madrid
Santiago
Tidbinbilla
Tromso
Wettzell
Yarragadee
Yellowknife

The Analysis Centers may use additional stations as desired but it was felt that constraining this subset of core stations would bring the orbit products to a common reference frame, thereby facilitating the task of combining the various orbits into a combined product.

SESSION 2

(IGS orbit products)

IGS **Position Paper, IGS Analysis Center Workshop**
Ottawa, Canada, October 12-14,1993

Combining the orbits of the IGS Processing Centers

Gerhard Beutler[1], Jan Kouba[2], Tim Springer[3]

Abstract

Currently seven IGS Processing Centers are producing daily precise orbit files (in the SP1 or SP3 formats) plus the corresponding Earth Orientation Parameters (EOP). These individual products are available at the IGS Data Centers (CDDIS, IGN, S10). Routine orbit comparisons performed by the IGS Analysis Center coordinator, Prof. Clyde C. Goad indicate that, after a seven parameter Helmert transformation, the orbit consistency approaches the 20 cm level (a coordinate RMS), but that outliers of 50 cm or more occasionally occur. These outliers usually can be attributed to individual satellites which were treated in different ways by different Processing Centers. However, the above orbit quality also indicates that some orbit combinations should be possible and feasible. The main advantage of a combined orbit is its reliability not its precision. Of course, the combined orbit should be as precise as the best individual orbit.

Two schemes of orbit combinations are considered here: (a) the first method consists of a weighted averaging process of the earth-fixed satellite positions as produced by the individual Centers; (b) the second method uses the individual IGS orbit files as pseudo-observations in an orbit determination process, where in addition to the initial conditions, different parameter sets maybe estimated. It is of course possible to use the orbits processed by method (a) in the method (b). This also allows to estimate the quality of both types of combined orbits. Both orbit combination methods have been tested on the January 1993 orbit data sets (GPS weeks 680 and 681) with an impressive agreement at the 5 cm level (coordinate RMS).

The quality of the combined orbits is checked by processing a set of test continental baselines in two different regions of the globe using different processing softwares. Both types of combined orbits gave similar baseline repeatability of a few ppb in both regions which compared favorably to the best regional orbits.

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1. introduction

The main objectives of the International GPS Service for Geodynamics (IGS) is to produce precise GPS orbits and to contribute GPS Earth Orientation Parameter (EOP) solutions to the International Earth Rotation Service (IERS). The IERS, in return is responsible for combining various EOP and station coordinate solutions, based on different and independent techniques, into a single EOP series and the corresponding station coordinate sets in the International Terrestrial Reference Frame (ITRF). Currently no 'official' product is issued by the IGS. The IGS could, however, provide a logical and an efficient extension of the ITRF through the definition of IGS orbits plus the timely approximation and resolution enhancements of the IERS EOP series (e.g. the IERS Rapid Service). It is clear that orbits, station positions and EOP must be made as compatible as possible. This is the main reason why there is such close cooperation with IERS both at the operational and management levels (observation and processing standards, governing boards, terms of references, etc.).

The IGS orbit should be more precise than most if not all the individual orbit solutions contributed to IGS, but more importantly it should also be more reliable and more consistent with IERS/ITRF. Besides, an 'official' IGS orbit makes an easier choice for uninitiated users, or for the users who seek officially sanctioned products, results or reference. The IGS orbits could only be available as fast as the slowest contributing Center, thus strict submission deadlines are required and have to be enforced by IGS. For this reason alone, or due to scientific, regional or political considerations individual IGS Center orbits may still be preferred by some users, and thus it is suggested that they will be archived and made available to the IGS users as well, in the same fashion as currently done by IERS for all the contributed EOP series.

Orbit combination by itself and as such would not be required if the processing standards, the modelling and the data sets used by different Centers were identical, and if the different software systems were consistent and compatible (different software systems under identical conditions should ideally give the same results). In this 'ideal' case a single (IGS) orbit could be produced by a single Center and the role of additional Centers would be that of providing back up, redundancy and security. Such IGS products may then be far from ideal, though, as they can be biased by the same amount due to e.g. inadequate 'standard' modelling. For this reason, as well as to give the IGS Centers some room for improvements and innovations, it is suggested that some latitude within reasonable processing guidelines and standards is desirable and allowed. It is hoped that all Centers may not be affected and/or failing in the same way at the same time. Then, some strategies and considerations for orbit combinations need to be considered as some small differences in orbits will exists even with the same software, data or similar estimation approaches. Another extreme case is a rigorous distributed processing, where data from different periods/regions are combined rigorously, e.g. at the normal matrix stage in a similar fashion as it was done for the NAD83 and other continental geodetic network adjustments. A rigorous combination of GPS processing is more complicated due to common satellite and station clock biases and requires some unique and complex strategies. As seen from the previous discussions, an IGS (orbit) product combination, strictly speaking, involves all the other topics of this workshop, namely the IGS formats, processing standards and distributed processing. It is also desirable that by January 1, 1994 when the IGS service becomes operational, some realistic and practically achievable orbit combination is established and results made available in a timely fashion.

In the first orbit combination approach all the submitted orbits are first transformed to a common reference frame consistent with IERS/ITRF and then combined by a weighted mean. This is the approach of Springer and **Beutler** (1993). Further studies, tests and enhancements can be found in Section 2. The advantage of this approach is its simplicity, and flexibility; as it can easily replace the current **IGS** orbit comparison and feedbacks. A similar algorithm can be adopted for a combinations of satellite clock solutions. Its disadvantages are daily orbit discontinuities and the fact that these combined **(IGS)** orbits may no longer satisfy the orbit dynamics. However, under certain conditions, the weighted average orbits also satisfy the orbit dynamics. Assuming that individual orbit solutions Xi(t) satisfy the well known differential equation of motion which relates the acceleration and the gradient of the Earth potential V, i.e:

$$\ddot{x}_i(t) = \frac{\partial}{\partial x} V(x) \Big|_{x_i},$$

and that the weighted average orbit is:

$$x_0(t) = \sum_{i=1}^{n} k_i x_i(t),$$

where k_i denotes the weight coefficients of the average and t is time. Differentiating $x_0(t)$ twice with respect to time, while assuming that the coefficients k_i are constant during the considered period, gives:

$$\ddot{x}_0(t) = \sum_{i=1}^{n} k_i \ddot{x}_i(t) = \sum_{i=1}^{n} \frac{\partial}{\partial x} V(x) \Big|_{x_i}.$$

Further considering that:

$$\frac{\partial}{\partial x} V(x) \Big|_{x_i} = \frac{\partial}{\partial x} V(x) \Big|_{x_0} + (x_i - x_0) \frac{\partial^2}{\partial x^2} (V(x)) \Bigg|_{x_0} + \ldots$$

and

$$\sum_{i=1}^{n} k_i = 1.$$

Neglecting higher order terms, one obtains:

$$\ddot{x}_0(t) = \frac{a}{\partial x} V(x) \Big|_{x_0} + \sum_{i=1}^{n} k_i (x_i(t) - x_0(t)) \frac{\partial^2}{\partial x^2} (V(x)) \Bigg|_{x_0},$$

where:

$$\sum_{i=1}^{n} k_i (x_i(t) - x_0(t)) = 0,$$

because of the above averaging. This confirms that:

$$x_0\ (t) = \sum_{i=1}^{n} k_i x_i () ,$$

also satisfies the equation of motion provided that the weights k_i are constant, $\sum k_i = 1$ and $(x_i\ (t) - x_0\ (t))$ *are* small.

The second and more elegant approach is to combine initial satellite state vectors and associated solar pressure parameters. Under certain conditions this approach is equivalent to the introduction of individual orbit series as pseudo-observations into an orbit improvement program. This is the approach proposed in Beutler et al. (1993) and further pursued in Section 3. The advantage of this orbit combination method is that orbital dynamics is maintained. Furthermore, arcs longer than 24 hours are possible (with less discontinuities), reliability is increased (even when all Centers are biased on the same day a correct solution, compatible with the neighboring days, is still possible) and this approach is directly compatible with a future rigorous/distributed processing. The disadvantages are the increased complexity and the requirement for a different algorithm for clock processing.

For both approaches it is essential that small systematic differences in coordinate and time reference frames are reconciled before any weighting is applied to ensure unbiased estimation in a consistent reference frame. This is a complex problem which requires a close cooperation with IERS and for the time with BIPM (Bureau International des Poids et Mesures). For orbit combinations it can approximately and implicitly be accomplished through a set of constrained tracking station positions, which are well determined and maintained by IERS to be compatible with IERS EOP. This is, in fact the practice already in effect. Additionally, the individual Center EOP solutions can be used here for removing further small differential rotations around X- and Y-coordinate axes, assuming that the corresponding orbits and EOP are consistent which may not be true for some Centers (Springer and Beutler, 1993). Small unexplained systematic differences can also be determined from previous and current orbit comparisons/ determinations along with long term statistics. These can be used for apriori parameters and weighting in an orbit combination adjustment. In this way, in an average sense, the proper reference frame would be maintained and used and no EOP parameters would be required. Another possibility is to use, for the apriori X and Y rotation parameters, the average pole offsets as determined by IERS for each Center. The time reference ideally should be compatible with UTC as determined by BIPM. In fact BIPM involvement in IGS would be mutually beneficial, as IGS could provide clock transfer and time system consistency better than one ns, which is almost an order of magnitude improvement with respect to the current state of the art time transfer capability and reference time maintenance. BIPM in return could provide precise time reference for IGS.

Operationally, a combination of the above two methods maybe desirable. The first approach can provide a quick look and feed back, it can also handle the reference frame transformation, appropriate weighting, blunder detection and rejections, etc. Then, the weighted average orbit can be introduced into the second approach, providing additional quality check and producing the final IGS orbit consistent with satellite dynamics. The quality of the proposed IGS combined orbits is tested in Section 4 by processing several continental baselines. Finally, in Section 5, a combination of satellite clock solutions is considered, which is similar to the orbit combination of Section 2.

2. ORBIT COMBINATION BY WEIGHTED AVERAGE

2.1 Method Description

The first attempt to combine orbits from different IGS Processing Centers was made at CODE at the beginning of 1993. For the description and principles of the method used see Springer and Beutler (1993). The combined orbits were obtained as weighted averages of the orbits computed by different IGS Processing Centers. However, before such orbit combination, small differences in reference frames had to be removed. This was accomplished in two stages. First, the differences between the corresponding EOP solution and the chosen reference pole were used to rotate the respective orbits around the X and Y axes. Second, to remove the remaining reference frame misalignment, a seven parameter Helmert transformation was then estimated for every IGS Center during the orbit combination.

For the weighted orbit combination, satellite and Center specific weights are also required. The Center specific weights can easily be obtained from previous combinations and/or orbit comparisons. For the satellite weights the previous experience may not be meaningful. In the first orbit combination attempt, the weights for both satellites and the Centers were determined in the first iteration and then applied in the second iteration. The Helmert transformation parameters were then estimated by the weighted least squares adjustment, also know as the L2-norm. For the current orbit combination an L1 - norm (Press et al., 1989), also known as a robust estimator, was adopted as proposed by Prof. C.C. Goad. The L1 -norm is less sensitive to outliers than the L2-norm, therefore 'bad' satellites do not disturb the estimated parameters, thus making the satellite specific weights unnecessary, provided that most satellites are of comparable quality. In the case when most satellites are 'bad' the L2 norm and satellite specific weighting are required. Using this technique, orbit combinations were performed for all the days up to September 4, 1993 and also for the orbits from the January 1993 Orbit Test. Both combinations are analyzed in the following two sections.

2.2 Results for the 1993 orbit combinations

Table 2.1 shows the number of orbits processed during GPS weeks 678-712, the mean and the corresponding standard deviations of the seven Helmert parameters for each of the current IGS Analysis Centers. These values are with respect to the combined orbits. In this table the average coordinate RMS is intentionally left out as it tends to get corrupted by 'bad' satellites. However, based on the results of the last few months the following average coordinate RMS values were observed for the currently contributing Centers: below 20cm for COD, EMR, GFZ, JPL, below 35 for ESA, S10 and below 50 cm for NGS. The RMS is normally well below this value as can be seen in Figure 2.1. Note that some large outliers have been removed from the plot and the remaining large RMS values are, in nearly all cases, due to either Anti-Spoofing (AS) or little or no data for a particular satellite.

Figure 2. : Orbit coordinate RMS with respect to combined (IGS) orbits for some IGS processing centers during 1993

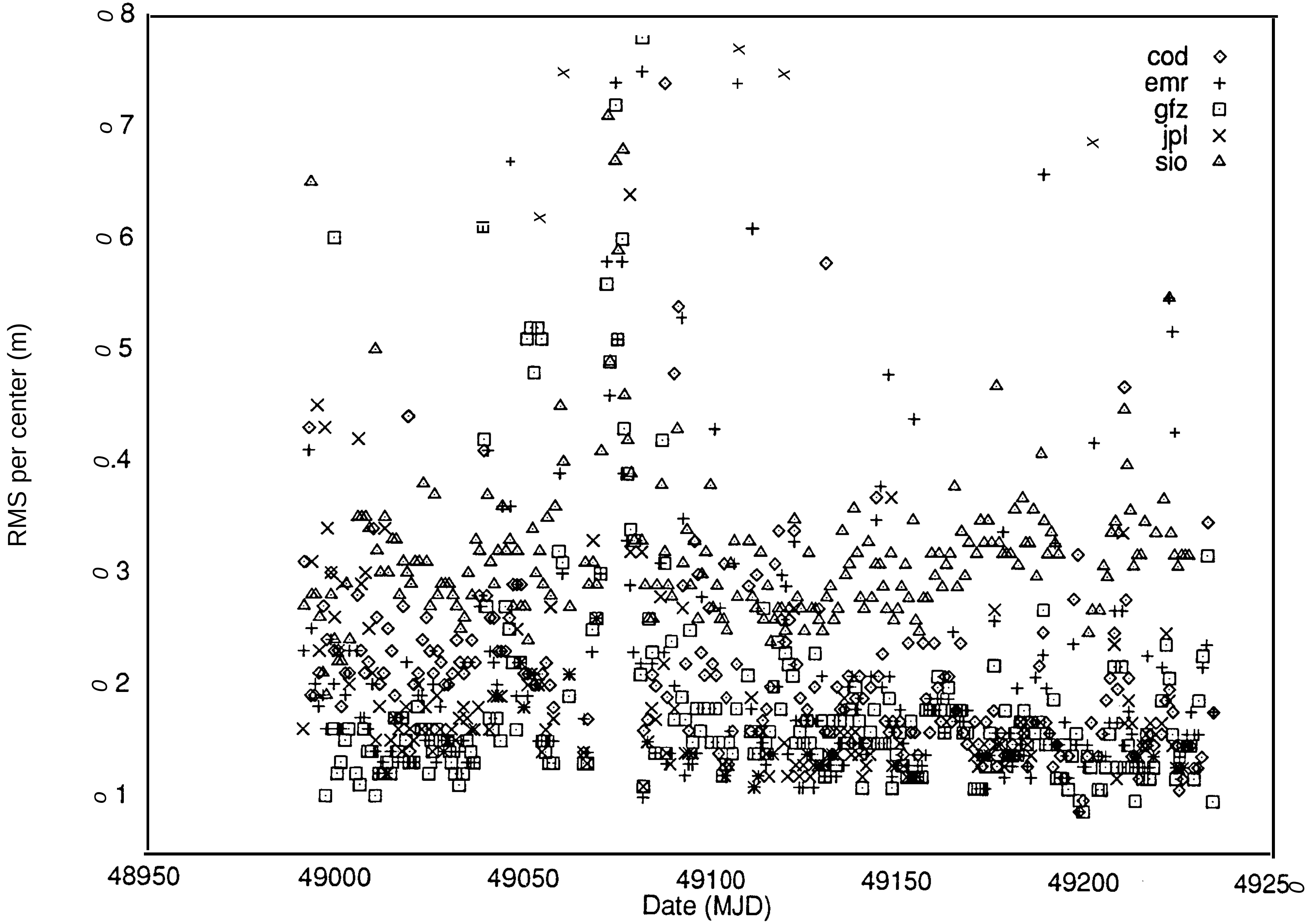


Table 2.1 Mean and R-MS of the Helmert Transformation Parameters during 1993

#ofOrb. RMS	DX (m)	DY (m)	DZ (m)	Rx (mas)	RY (mas)	Rz (mas)	Scale (ppb)	Center
244.0	-.014	.004	-.021	.15	.06	-.04	.1	COD
	.001	.001	.001	.02	.03	.06	.0	
244,0	-,007	.006	-.017	.02	-.34	.02	.5	EMR
	.001	.001	.002	.03	.05	.07	.0	
244.0	-.012	.003	-.027	.50	,24	.44	.2	ESA
	.002	.002	.003	.04	.04	.12	.0	
237.0	.026	.014	.002	.04	.24	-.04	-.9	GFZ
	.001	.001	.001	.03	.05	.18	.0	
223.0	.005	-.057	-.015	.59	.05	.00	.1	JPL
	.002	.003	.002	.03	.04	.08	.0	
230,0	-.013	.029	.052	-1.09	.47	-.02	-.7	SIO
	.001	.002	.002	.29	.08	,40	.0	
190.0	.013	.008	.073	-1.63	-1.15	-.34	2.5	NGS
	.003	.002	.003	.07	.17	.07	.0	

Thelargermeanrotations forSIOintheabove tablearemainlydue to thefactthatinthe beginning of 1993 theestimated EOP and orbit rotations did not show the usual high correlation for S10. However this correlation has improved considerably for S10 since the January orbit test. No EOP solutions were used for NGS, as they were not available from the IGS Data Centers, thus the mean rotations are much larger than for the other IGS Centers.

There are also some small scale differences between the orbits of the different Centers. Figure 2.2 shows the orbit scale parameters for COD, GFZ and NGS. The scale behavior for EMR and ESA are similar to that of COD although EMR has a small positive offset (.5ppb). The scale of S10 is close to that of GFZ (about -1 ppb). NGS has relatively large scale offset (2.5ppb) with respect to the other six Processing Centers. These scale differences may be related to satellite antenna offsets used by different Centers.

The best agreement is for the DX translation parameter, the largest mean difference is only 40mm! The DY translations show slightly larger scatter. Figure 2.3 shows the estimated DY translations during 1993 for COD, JPL and SIO.The larger variations around MJD 49100 are probably ’caused by Anti-Spoofing (AS). The DZ translation clearly shows the largest differences. This is not surprising as it is well known that the DZ component is the weakest in geocenter estimations by GPS. Figure 2.4 shows the estimated translations in the DZ direction during 1993 for ESA, GFZ

Figure 2.2: Orbit scale residuals with respect to combined (IGS) orbits for COD, GFZ and NGS during 1993

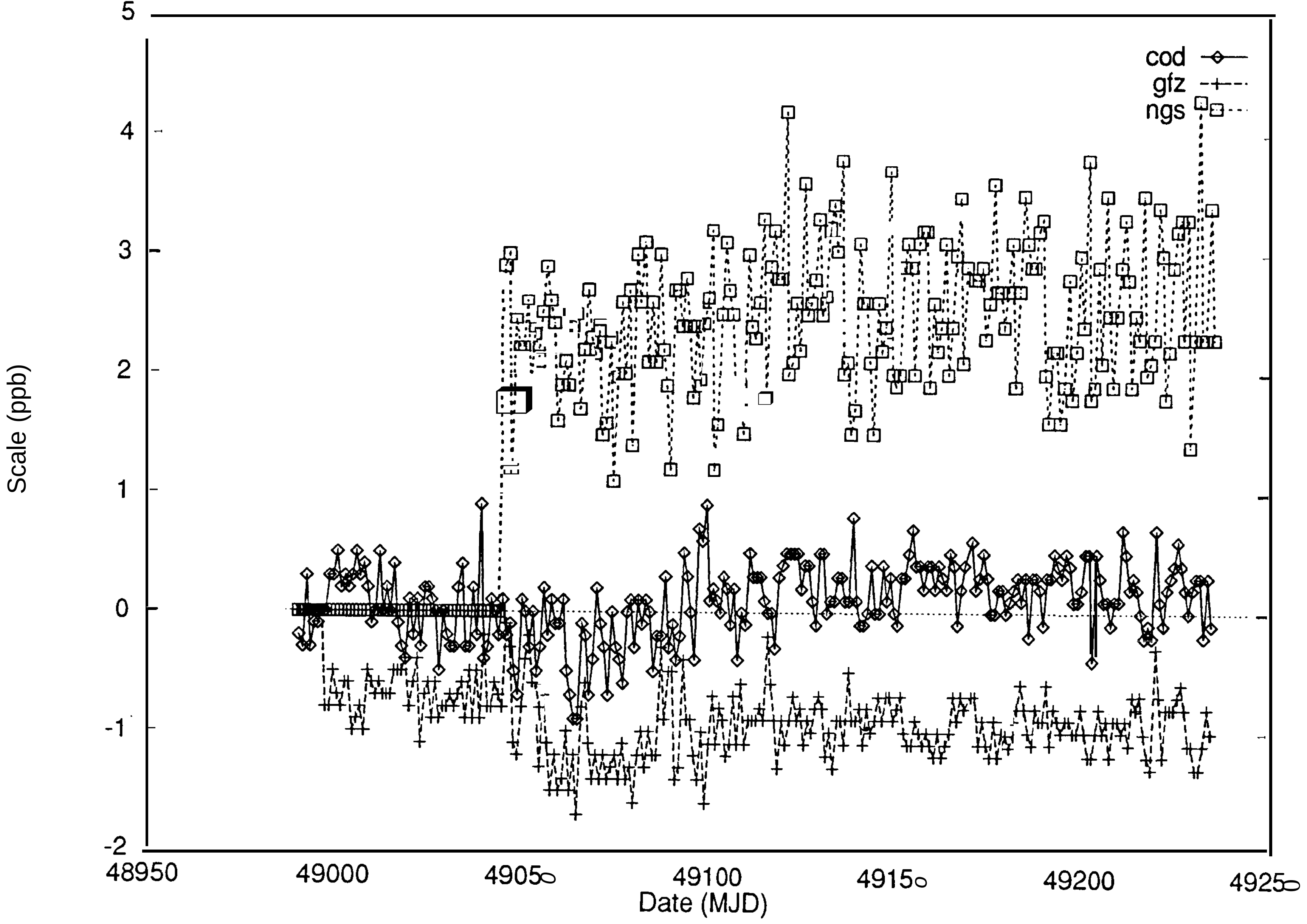


Figure 2.3: Orbit Y-translation residuals with respect to combined (IGS) orbits for COD, JPL and SIO during 1993

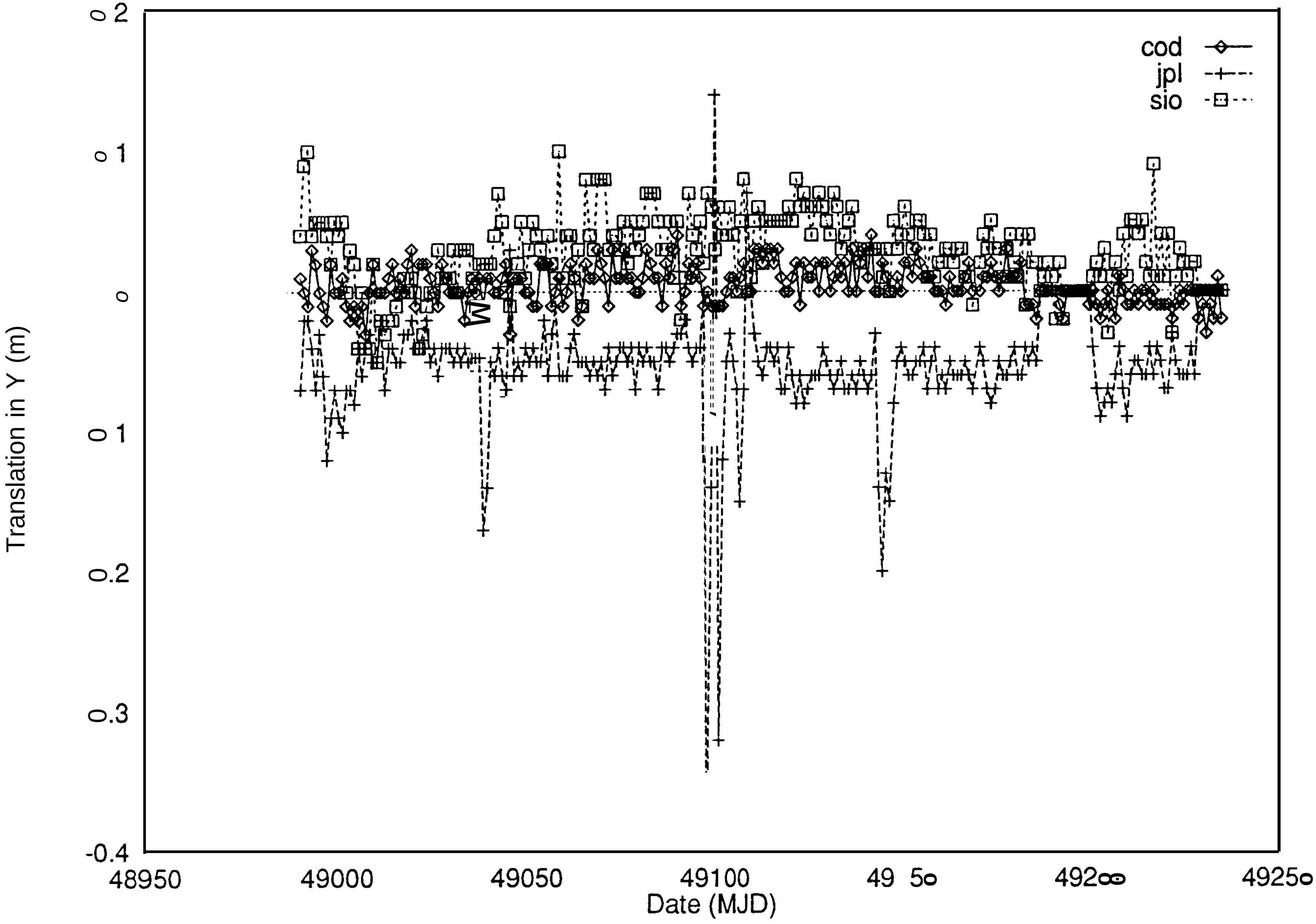
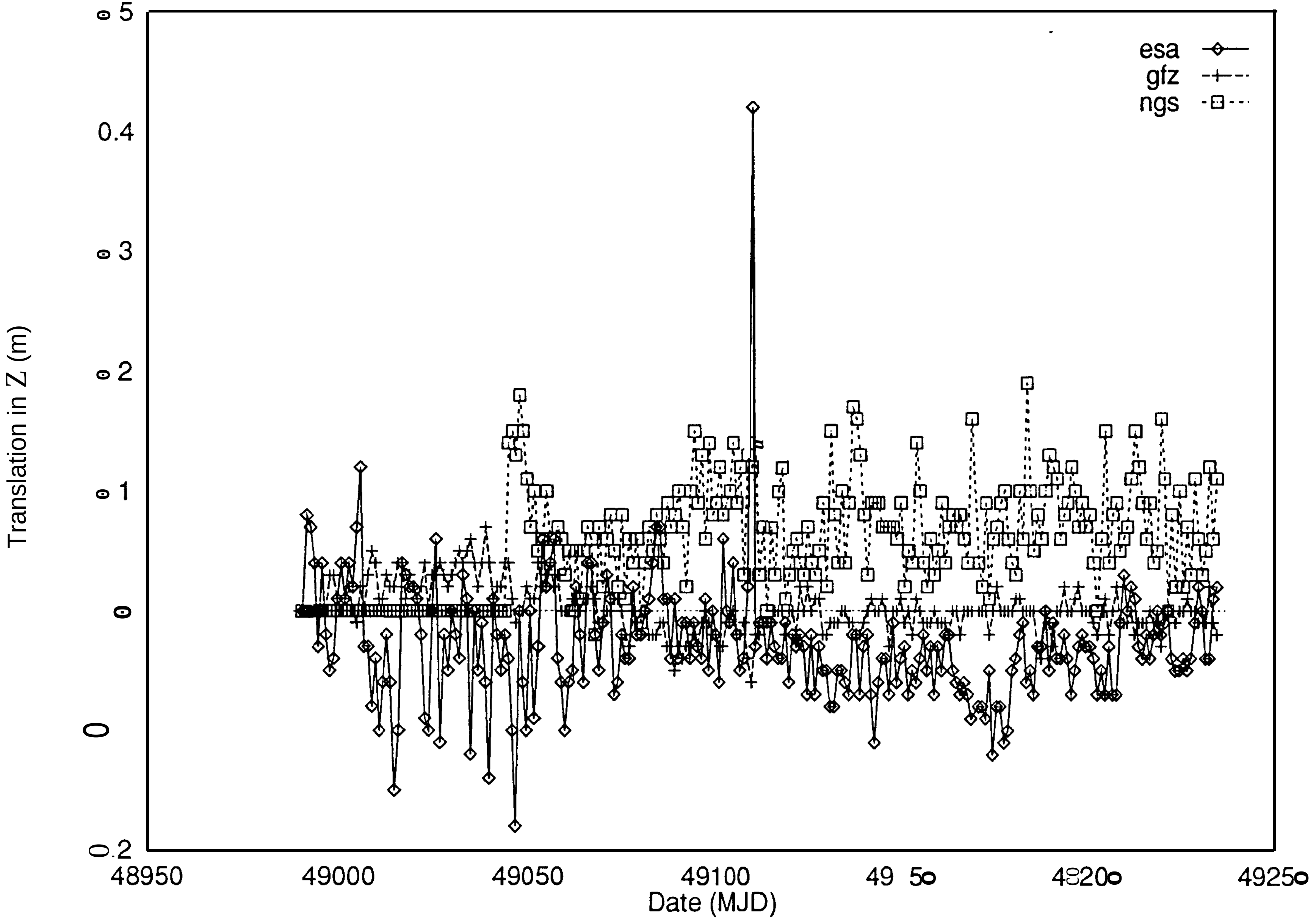


Figure 2.4: Orbit Z-translation residuals with respect to combined (IGS) orbits for ESA, GFZ and NGS during 1993



and NGS. Note that the day to day variations are not significantly larger than the variations of the other two components.

2.3 **Results from the January orbit tests.**

The main purpose of reprocessing the last two weeks of January 1993 was to study the differences between solutions from the different Processing Centers under controlled conditions such as using the same fixed station coordinates. Tables 2.2a and 2.2b summarize the mean and sigma values for the estimated Helmert parameters derived from the January orbit tests data (GPS weeks 680,681 or Jan. 17-30). The results are given for both the original (Table 2.2b) and the reprocessed orbits (Table 2.2a). Note that the first day of the first week has been left out due to problems with PRN 11 (a lack of data). Including this day would change the RMS considerably, making it unrealistic. Unfortunately not all the IGS reprocessed the data set or reprocessed the second week only. This is also reflected in the two tables below.

Table 2.2a Mean and RMS of the Helmert Transformation Parameters for 1993 January Orbit test.

#Orb. RMS	DX (m)	DY (m)	DZ (m)	Rx (mas)	RY (mas)	RZ (mas)	Scale (ppb)	RMS	Center
13.0	-.005	-.013	.003	.09	-.06	-.54	.0	.17	COD
	.002	.003	.004	.03	.03	.05	.0	.01	
13.0	-.011	-.003	.011	*.20*	.03	.00	.5	.15	EMR
	.003	*.003*	.003	*.03*	*.03*	.06	.1	.01	
8.0	-.035	-.010	.003	.20	.15	.59	.1	.36	ESA
	.006	.006	.017	.05	.04	.17	.1	.01	
13.0	.010	.002	-.016	.00	.22	.63	-.7	.15	GFZ
	.003	.002	.002	.04	.03	.11	.1	.01	
7.0	.001	-.017	.097	-1.93	-1.00	.08	.1	.34	SIO
	.010	.005	.007	.17	.09	.13	.3	.01	
13.0	.007	.019	-.008	.13	-.04	-.32	.4	.23	UTX
	.005	.004	.004	.13	.05	.11	.1	.02	

Table 2.2b Mean and RMS of the Helmert Transformation Parameters from the Original set.

#of Orb. RMs	DX (m)	DY (m)	DZ (m)	Rx (mas)	RY (mas)	Rz (mas)	Scale (ppb)	RMS (m)	Center
13.0	-.006	.000	-.011	-.26	-.04	.21	.2	.24	COD
	.004	.004	.007	.09	.07	.12	.1	.01	
13.0	-.013	.000	-.025	-.06	.00	-.05	.5	.16	EMR
	.004	.003	.005	.10	.08	.11	.1	.01	
13.0	-.038	-.009	-.036	.21	.01	2.48	.7	.64	ESA
	.013	.013	.020	.25	.12	.28	.3	.02	
13.0	.014	.028	.024	.50	-.26	1.06	-.7	.13	GFZ
	.002	.004	.004	.07	.10	.24	.0	.01	
13.0	.008	-.043	-.016	.11	-.34	-.07	.5	.22	JPL
	.004	.004	.005	.08	.07	.19	.1	.03	
13.0	.001	-.018	,035	-1.36	1.83	-3.65	-.3	.34	S10
	.006	.006	.006	.32	.26	1.24	.1	.01	

ESA has improved remarkably since the January, 1993 submission, this is visible for the 1993 results. Due to the problem with SIO orbits discussed above, those orbits were excluded from this combination. The most interesting difference between the two tables is the change in sigmas of the mean values. They are significantly lower for the January test results, for the rotations in particular, but also the mean rotation differences between Centers have become smaller. Figures 2.5a and 2.5b clearly show this. In the two figures only the estimated X-axis rotations are shown. The Figure 2.5a is for the January test and the Figure 2.5b is for the originally submitted results. Only the Centers available in both sets are shown here. Notice the much larger scale for Figure 2.5b.

From Tables 2,2a and 2.2b it can be seen that the reprocessing has primarily decreased the variation and differences of the rotations between the individual Centers. Consequently, due to the orbit-EOP correlation discussed above, it is expected that the EOP solutions have also improved accordingly for this test. The improvements seen here are mainly due to an improved coordinate set at the correct epoch (1993.06) and for some Centers also due to additional station data which was not used in the original processing (data submitted too late for routine IGS submissions of some Centers). Table 2.3 shows the estimated satellite sigmas in the orbit combination for the January test set. Note that for a sigma larger or equal to 99cm a sigma of 99 is specified. Here, one can clearly see the problem with PRN 11 on the first day of the tests (MJD 49004). On the last two days satellite 32 is missing. This is due to the fact at this time the PRN 32 was changed to PRN 1. It is also interesting to see that the problems with PRN 17 and 21 on the day 6 of the first week as

Figure 2.5a: Orbit X-rotation residuals with respect to combined (IGS) orbits for COD, EMR, ESA and GFZ for January test reprocessing

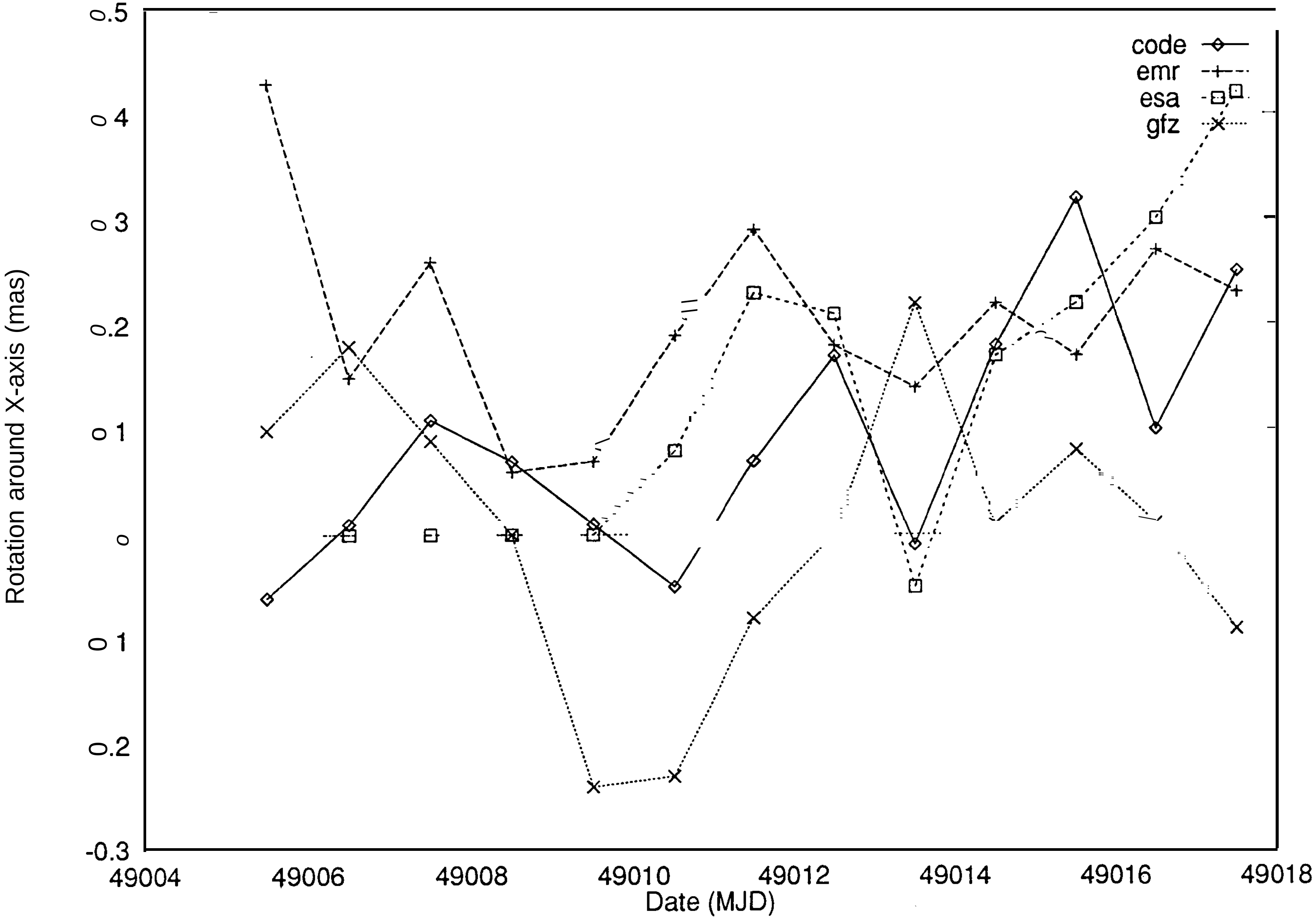
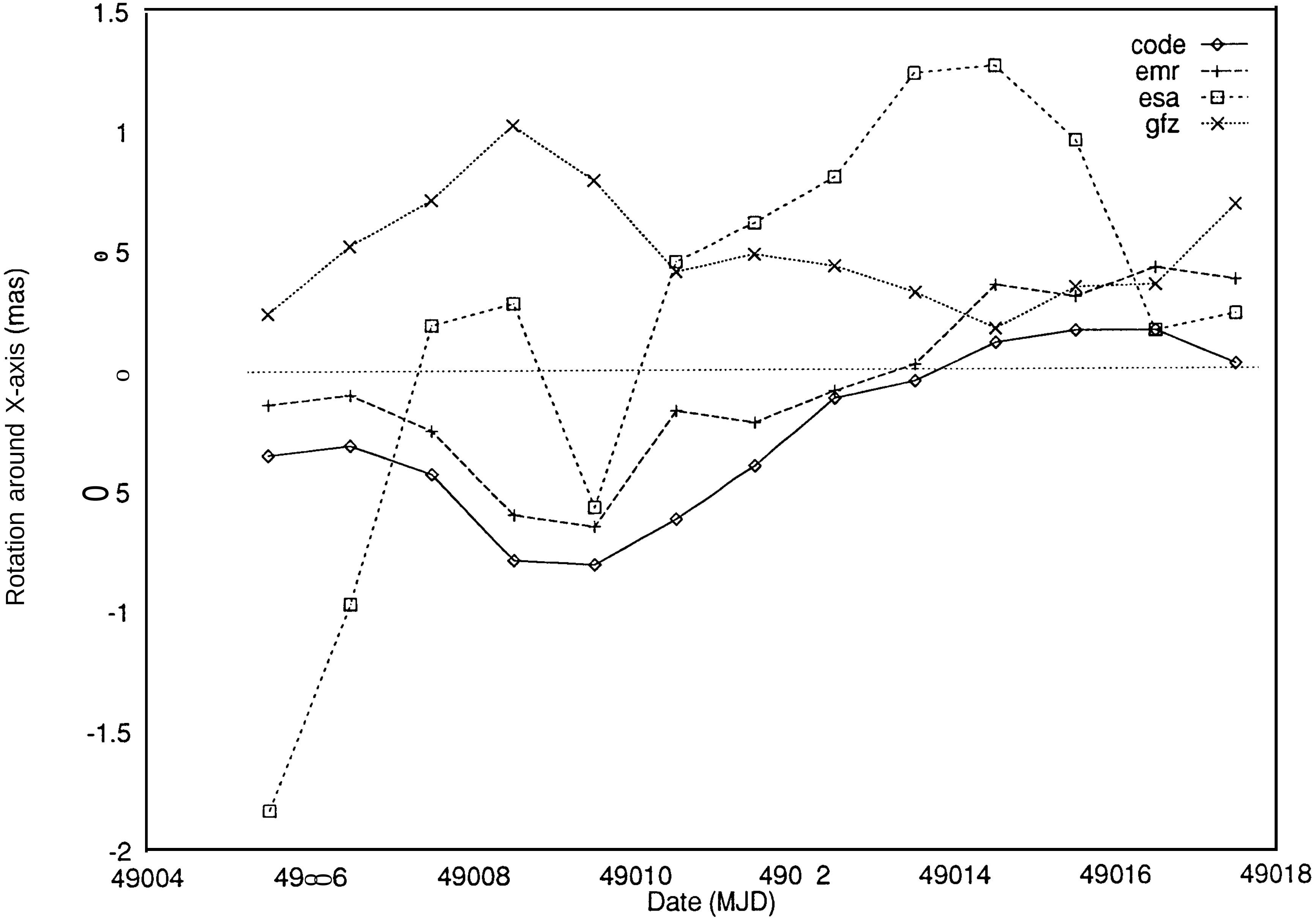


Figure 2.5b: Orbit X-rotation residuals with respect to combined (IGS) orbits for COD, EMR, ESA and GFZ for January test original submissions



discussed in Section 3 are here seen only for PRN21.

Table 2.3 Satellite Sigmas for the January Orbit Test.

MJD/PRN	0203 11 12 13 14 15 16 17 18 192021 2324252627282932
49004.0	24 1699 192821 1423 1524 16 10 19303326 19 13 15 13 15
49005.0	28 13 36 13 21 13 2227 19 19 1420 15 293935 24 17 15 17 28
49006,0	1608 19 16 15 15 182420 15 16 14 1621 31 4420 15 16 19 19
49007.0	17 12 17 1021 12 13 16 17 17 1022 1822362826 14 14 11 17
49008.0	14 12 13 17 19 15 10 16 18 13 10 13 192428 20 15 1420 1422
49009.0	17 19230920 18232825 12 12 11 562227 18 17 16 19 1629
49010.0	22 17 17 28 21 19222222 19 12 1931 2928 2223 13 18 23 17
49011.0	39 15 162321 26 18 16 17 18 11 24 19273023 19 19342628
49012.0	28 17 202227 242026 16 24 18 26 22 27 26 23 3021 2028 37
49013.0	26 1823 152421 2321 24 18 174023 192927 37 19202635
49014.0	36 19 17 2027 23 14232222 1621 20233227 28 18242634
49015.0	34 18232022 1621 29 1620 14 19 1628253238 18272537
49016.0	26 18 17203420 192826 18 1627 2030342629 182024
49017.0	23 17 2322 16 1621 21 21 222026 1843 26 31 25 21 2523

3. ORBITCOMBINATIONUSING ORBITDYNAMICS

3.1 Current IGS Orbit Comparison

Table 3.1 shows the routine orbit comparison performed by the IGS Analysis Center coordinator for the first two days ofweek680andthe thirddayofweek68 l. For the comparison method and the format description see the IGS mail (IGS Report Series, see(Goad,1993)). Onlytheorbitsfrom the COD, EMR, GFZ,andUTXCenters weresubmittedand comparedinthe first week and in the second week six submitted orbit series were compared (COD, EMR, ESA, GFZ, SIO, UTX). Table 3.1 also includes the combined orbits (labelled as IGS) described in the previous Section and treated as another Center.

Table 3.1 Orbit comparisons for Days 0, 1 of Week 680, 3 of Week 681
(DX, DY, DZ, RMS => m. ; RX, Ry, RZ => mas. Scale => ppb.)

ORBITCOMPARISON FORDAY1OFGPS WEEK 680 (day 1 is Sunday)

MODIFIED JULIAN DATE	DAY	MONTH	YEAR	Rotations - mas
49004	17	1	1993	Scale - ppb

DX	DY	DZ	RX	RY	RZ	SCALE	RMS	
-0.070	0.065	-0.003	0.8	-1.3	2.8	2.3	1.04	cod0680-->emr0680
0.548	-0.046	-0.108	0.8	5.2	3.4	12.8	4.09	cod0680-->utx0680
-0.094	-0.192	-0.096	-3.0	1.0	-5.7	-2.9	3.49	cod0680-->gfz0680
-0.081	0.105	-0.067	1.2	-1.6	2.0	2.5	1.01	cod0680-->igs0680
0.536	-0.017	-0.112	0.5	5.0	2.0	11.3	3.84	emr0680-->utx0680
-0.025	-0.258	-0.093	-3.8	2.3	-8.5	-5.1	4.43	emr0680-->gfz0680
-0.012	0.040	-0.063	0.4	-0.3	-0.8	0.2	0.41	emr0680-->igs0680
-0.340	0.112	-0.257	1.2	-3.4	-2.1	-11.0	3.07	utx0680-->gfz0680
-0.552	0.057	0.083	0.1	-5.3	-2.7	-12.0	4.03	utx0680-->igs0680
0.013	0.298	0.030	4.2	-2.5	7.8	5.4	4.28	gfz0680-->igs0680

ORBIT COMPARISON FOR DAY 2 OF GPS WEEK 680 (day 1 is Sunday)

MODIFIED JULIAN DATE	DAY	MONTH	YEAR	Rotations - mas
49005	18	1	1993	Scale - ppb

DX	DY	DZ	RX	RY	RZ	SCALE	RMS	
0.002	-0.013	-0.007	-0.4	-0.8	1.3	1.1	0.30	cod0680-->emr0680
0.037	-0.015	0.016	0.3	0.3	0.8	0.2	0.42	cod0680-->utx0680
0.173	0.002	0.111	1.9	0.7	1.0	1.7	0.94	cod0680-->gfz0680
0.025	-0.009	-0.008	1.0	0.6	0.7	0.0	0.16	cod0680-->igs0680
0.034	-0.001	0.023	0.7	1.1	-0.4	-0.9	0.48	emr0680-->utx0680
0.170	0.015	0.119	2.3	1.5	-0.3	0.7	1.01	emr0680-->gfz0680
0.022	0.005	-0.001	1.4	1.4	-0.6	-1.0	0.23	emr0680-->igs0680
0.139	0.016	0.094	1.5	0.4	0.1	1.5	0.93	utx0680-->gfz0680
-0.012	0.005	-0.026	0.7	0.3	-0.2	-0.2	0.34	utx0680-->igs0680
-0.147	-0.012	-0.118	-0.8	-0.1	-0.3	-1.7	0.92	gfz0680-->igs0680

```
-------------------------------------------------------------------------------------------------------
ORBIT COMPARISON FOR DAY 3OFGPSWEEK681 (day 1 is Sunday)
-------------------------------------------------------------    ------------------------------------------
MODIFIED JULIAN DATE DAY MONTH YEAR Rotations - mas
            49013            26    1          1993  Scale  -  ppb
-------------   -----------------------------------------------------------------------------------------
DX       DY       DZ       Rx       RY       RZ        SCALE RMS
-0.041   -0.008    0,034    0.5      1.3      0.4      -0.3     0.42     cod0681  -->esa0681
 0.003   -0.007   -0.006    0.6      0.0      0.4       0.3     0.22     cod0681  -->emr0681
 0.002    0.007   -0.014    0.3     -0.5     -0.4       0.2     0.27     cod0681  -->utx0681
 0.023    0.005    0.095   -1.5     -0.5      0.9       0.7     0.38     cod068l-->sioO681
 0.032   -0.045    0.029    0.6      0.2      2.2      -1.3     0.24     cod0681  -->gfz0681
 0.008    0.001    0.003    1,7      0.8      0,6      -0.3     0.14     cod0681  -->igs0681

 0.044    0.001   -0.040    0.1     -1.3      0.0       0.6     0.46     esa0681  -->emr0681
 0.043    0.015   -0.048   -0.1     -1.8     -0.8       0.5     0.50     esa0681  -->utx0681
 0.067    0.011    0.061   -1.9     -1.9      0.5       1.0     0.57     esa068l-->sioO681
 0.073   -0.037   -0.005    0.2     -1,2      1.8      -1.0     0.49     esa0681  -->gfz0681
 0.052    0.007   -0.031    1.3     -0.5      0.3       0.0     0.41     esa0681  -->igs0681

-0.001    0.013   -0.008   -0.3     -0.5     -0.8      -0.1     0.24     emr0681  -->utx0681
 0.021    0.013    0.101   ,-2.0    -0.5      0.5       0.5     0.37     ernr0681 -->sio0681
 0.029   -0.038    0.035    0.1      0.2      1.8      -1.5     0.23     emr0681  -->gfz0681
 0.007    0.010    0.010    1.2      0.8      0.3      -0.6     0.12     emr0681  -->igs0681

 0.016    0.000    0.098   -1.9     -0.1      1.2       0.7     0.44     utx0681  -->sio0681
 0.033   -0.049    0.044    0.3      0.6      2.6      -1.5     0.28     utx0681  -->gfz0681
 0.001   -0.004    0.013    1.4      1.2      1.0      -0,5     0.24     utx0681  -->igs0681

 0.015   -0.048   -0.066    2.1      0.8      1.2      -2.0     0.38     sio0681  -->gfz0681
-0.014   -0.004   -0.091    3.2      1.3     -0.3      -1.1     0.32     sio0681  -->igs0681

-0.029    0,044   -0.026    1.1      0.6     -1.5       0.9     0.19     gfz068l-->igsO681
-------------------------------------------------------------------------------------------------------
```

The remaining days not shown in the Table are similar to the third day of week 681. As seen from the above Table, the orbit RMS for all IGS Centers usually ranges between about 15 and 50 cm for each coordinate. For the first two days of week 680 the orbit quality is much worse, RMS values are approaching and sometimes exceeding 1 meter. Such comparisons do occur from time to time for all the IGS Centers and clearly this is not acceptable. One should find out the reason for such events. This also demonstrates two weak points of the routine IGS orbit comparison, namely:
(1) All satellites and one pair of Centers are used to perform the Helmert transformations thus making it more difficult to detect and exclude anomalous (erroneous) satellites/Centers.
(2) The algorithm does not make use of the physical laws, checks based on the positions of one

satellite given by one Center are not possible.

3.2 **The Proposed Method**

The proposed method consists of two steps: (1) data screening and (2) orbit combination. The goals of data screening are: detection and rejection of outliers (bad one-day satellite arcs); assignment of agency and satellite specific (orbit) observation weights. The screening is done separately for each agency and for each satellite, where the satellite positions are used as pseudo-observations in an orbit determination process. The residuals of the satellite positions may then be analyzed. To detect bad one-day arcs, not only the positions of the current day are required, but several neighboring days also have to be included. In this study one week of data (one week arc) was used for this stage which coincides with the IGS reporting and submission cycle and thus would not cause additional delays. However, ideally several days before and after the current day should be used. This procedure only makes sense if an orbit model is able to follow the actual satellite arc for at least one week with an accuracy comparable to or better than the accuracy of the satellite positions. Such an orbit model could be found (see: Beutler et al, 1993). With only 15 parameters; six for the initial state vectors and nine empirical parameters related to radiation pressure; the satellite positions of one agency during one week can usual] y be represented with an RMS of about 10 cm in each coordinate. The RMS rises dramatically if one or more faulty one-day arcs are included in the processing. Group RMS errors for the radial, along track and out of plane components for each day (file) are computed by this program, too. All this information can then be used in the following second stage of the proposed orbit combination method.

In the second, orbit combination step all the arcs of the current day (for all agencies) are used to produce the final set of orbits, The usual eight parameters are estimated: six parameters defining the initial state-vectors, the radiation pressure scale and Y-bias. The weights from the first screening stage can be used and the marked (rejected) orbits must be excluded.

Both the above stages can be efficiently accomplished by the program ORBIMP (Beutler et al., 1993).

3.3 **Results**

The screening step was applied to week 680 and week 681 separately. For most satellites this step did not cause any problem, usually the resulting RMS errors were at the 15-40 cm level. The Figure 3.1 shows a typical example (for GFZ, PRN 14, and week 680). However some problems were encountered during week 680. First, PRNs 17 and 21 appreciable y changed their mean motion on the sixth day of week 680. This signal was seen in the same way by all the Processing Centers, indicating a real orbital change (see Figures 3.2a and 3.2b, where the EMR results were used as examples). Therefore, in all the runs and results presented below, a set of three velocity changes were estimated for these two satellites at 12:OOUT on January 22, 1993 (MJD 49009). After this, the residuals of the satellites looked almost like those of a normal satellite. Such “sudden” impulse changes occur occasionally and can well be taken into account by the estimation of velocity changes. This is confirmed by an extensive experience with ORBIMP quality analyses of CODE orbits from weeks 670-715 at CODE.

In view of Table 3.1 it is not surprising that on the first day of week 680 PRN 11 showed a serious problem. The Figures 3.3a-3.3d, ordered in decreasing size of residuals, demonstrate that all Centers had difficulties modeling the orbit of this satellite on that day. This is mainly caused by the lack of the data (less than 30% of the usual amount) for this satellite observed by the IGS stations.

Figure 3 : Orbit residuals with respect to a week long arc for GFZ and PRN14

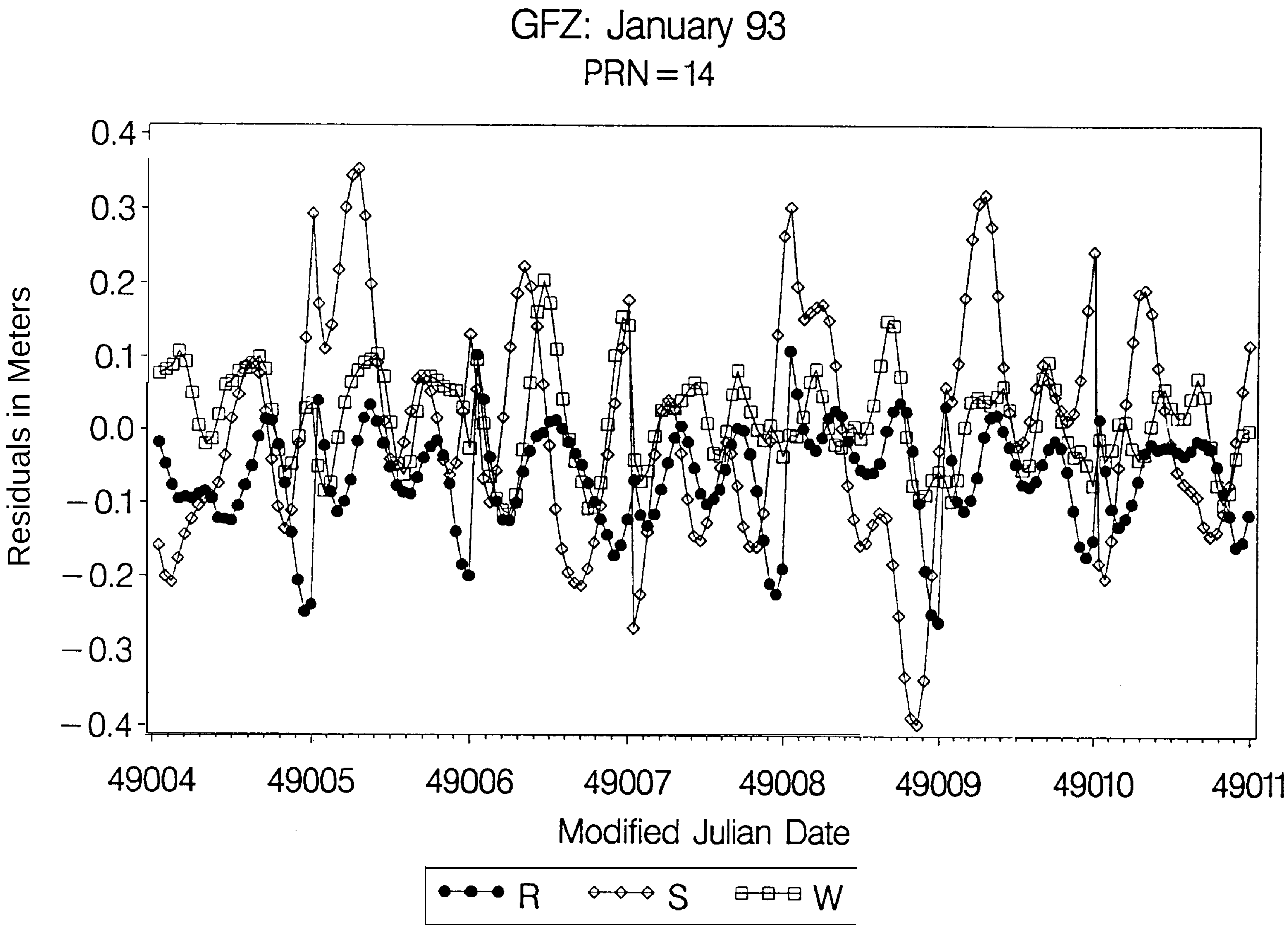


Figure 3.2a: Orbit residuals with respect to a week long arc for EMR and PRN17

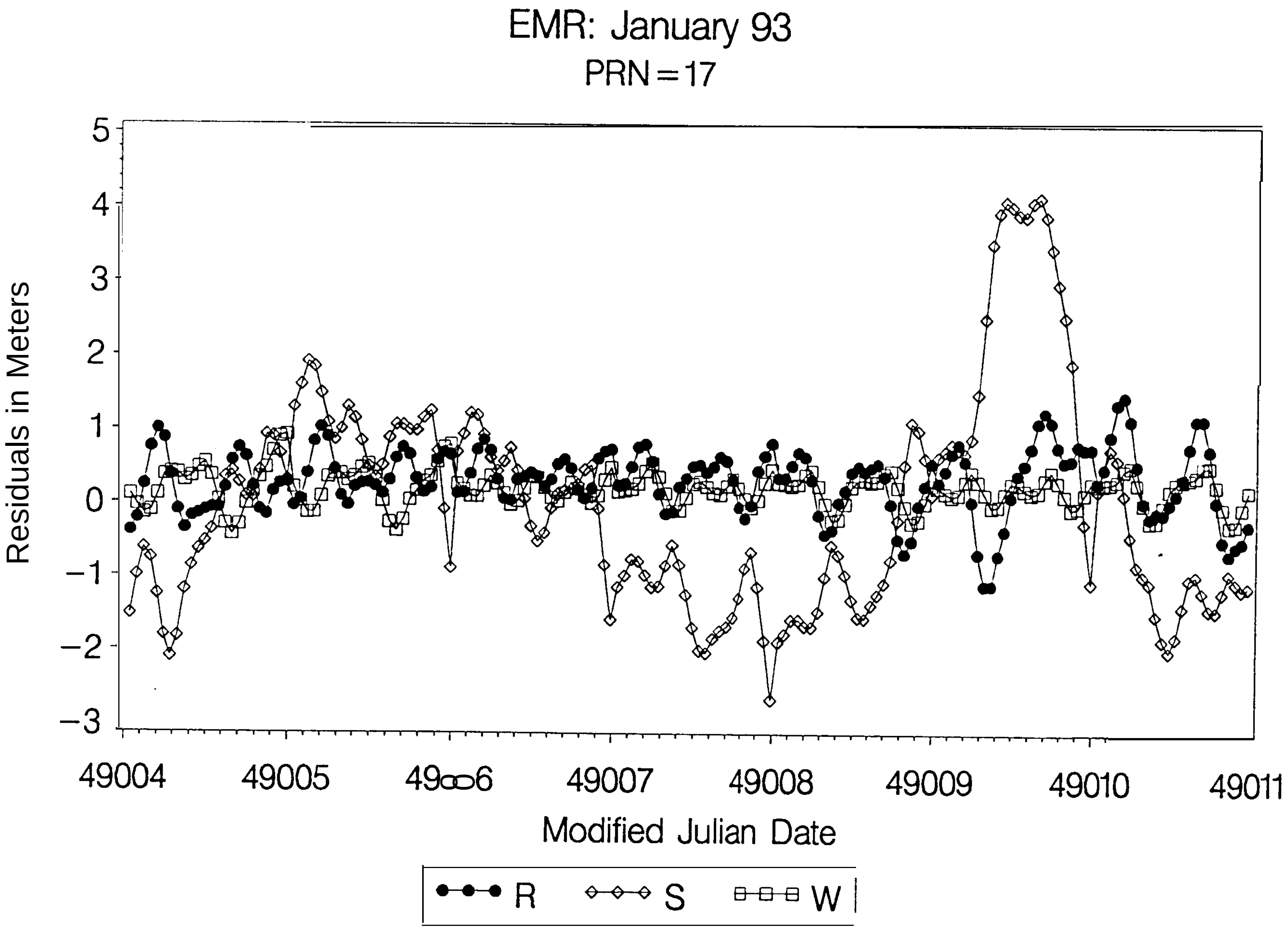


Figure 3.2b: Orbit residuals with respect to a week long arc for EMR and PRN21

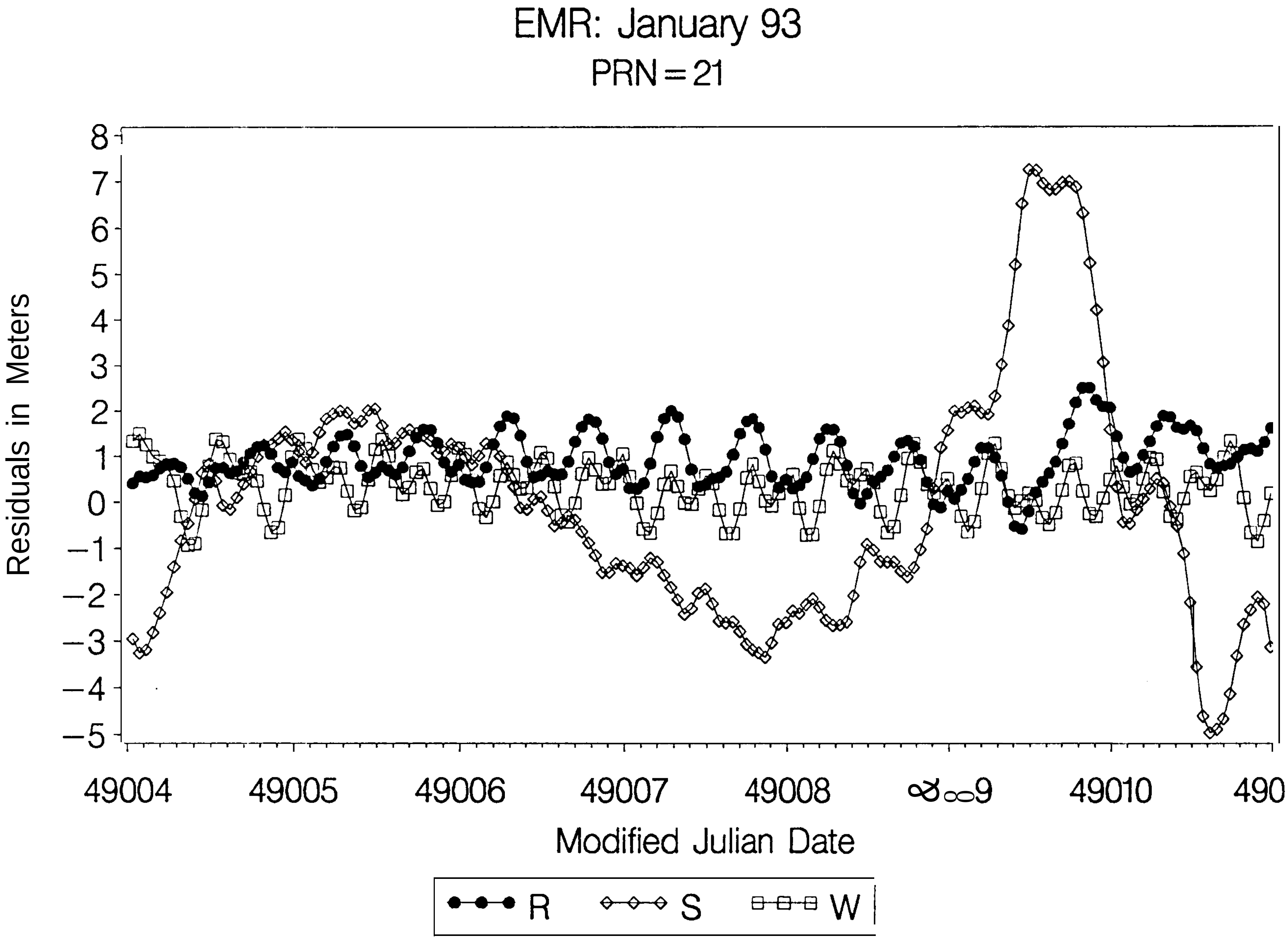


Figure 3.3a: Orbit residuals with respect to a week long arc for PC and PRN

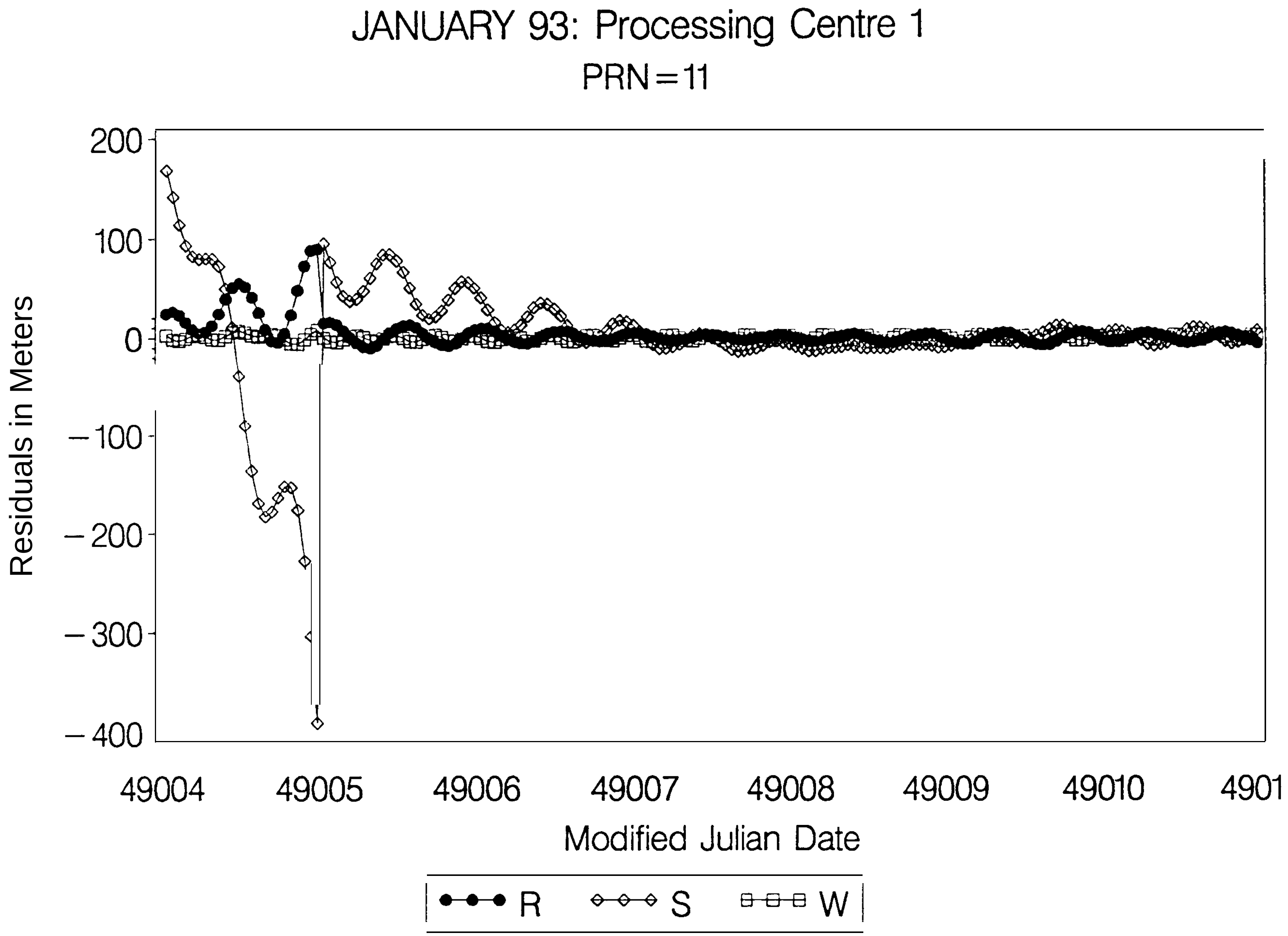


Figure 3.3b: Orbit residuals with respect to a week long arc for PC2 and PRN11

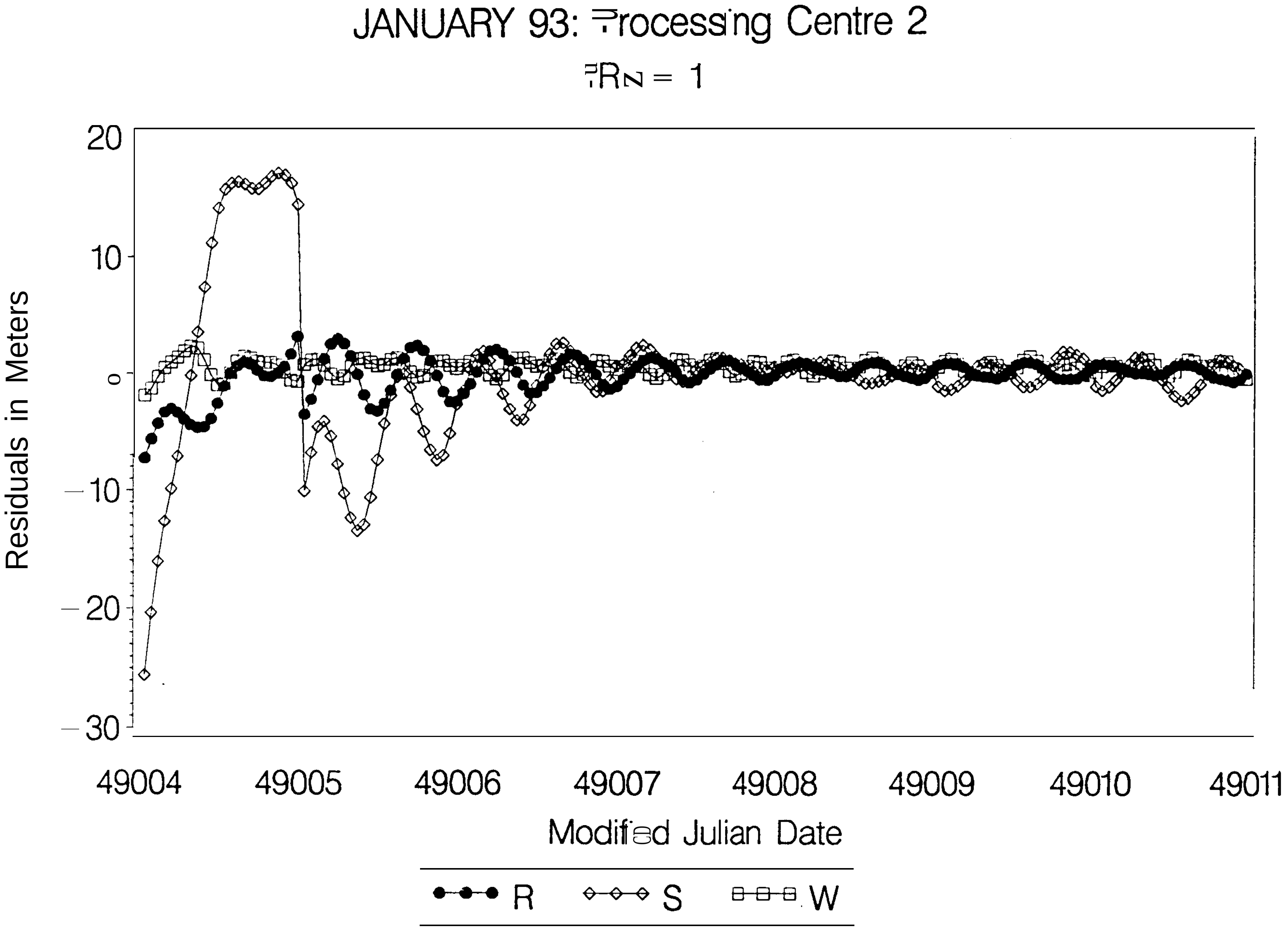


Figure 3.3c: Orbit residuals with respect to a week long arc for PC3 and PRN11

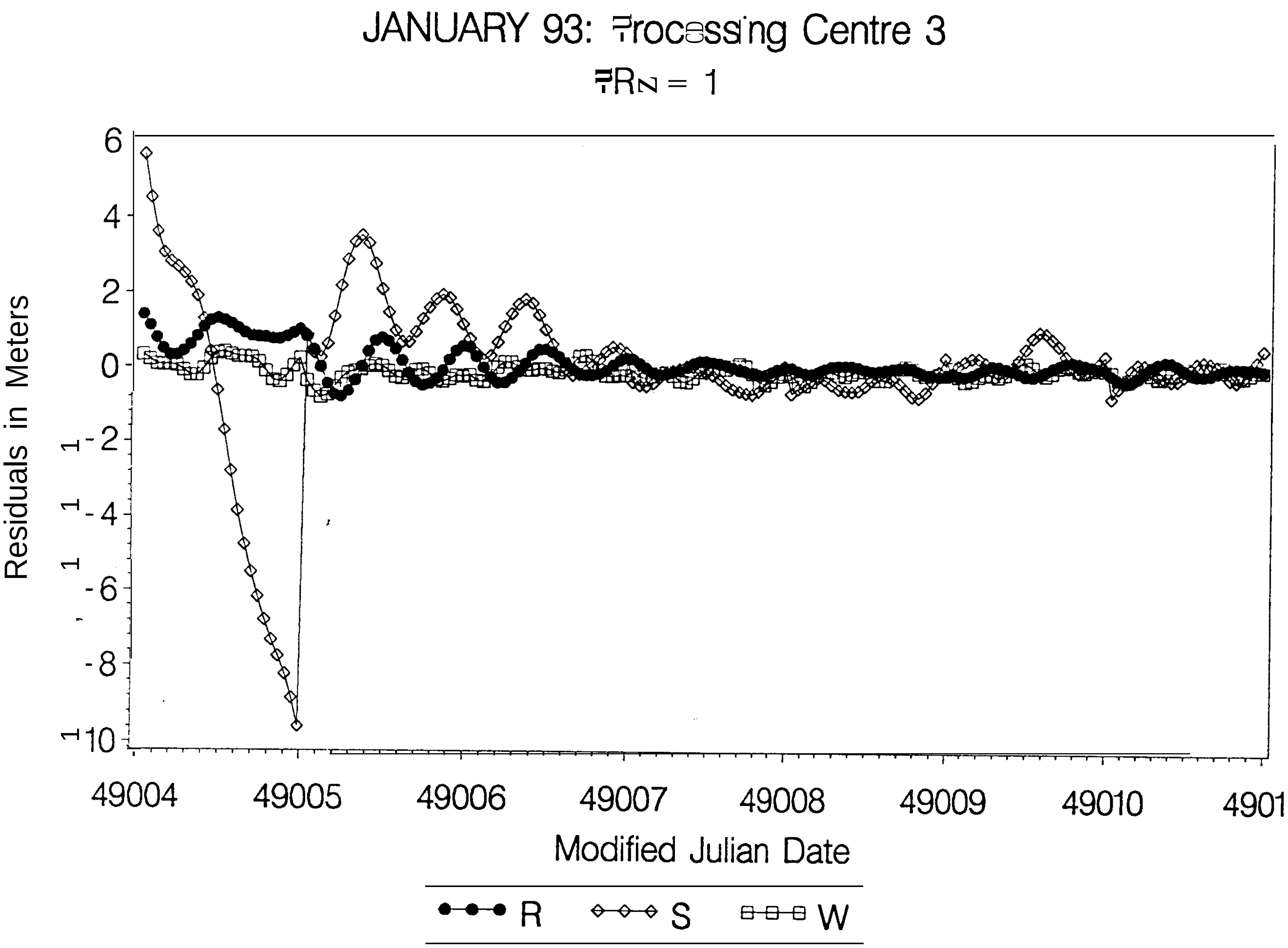
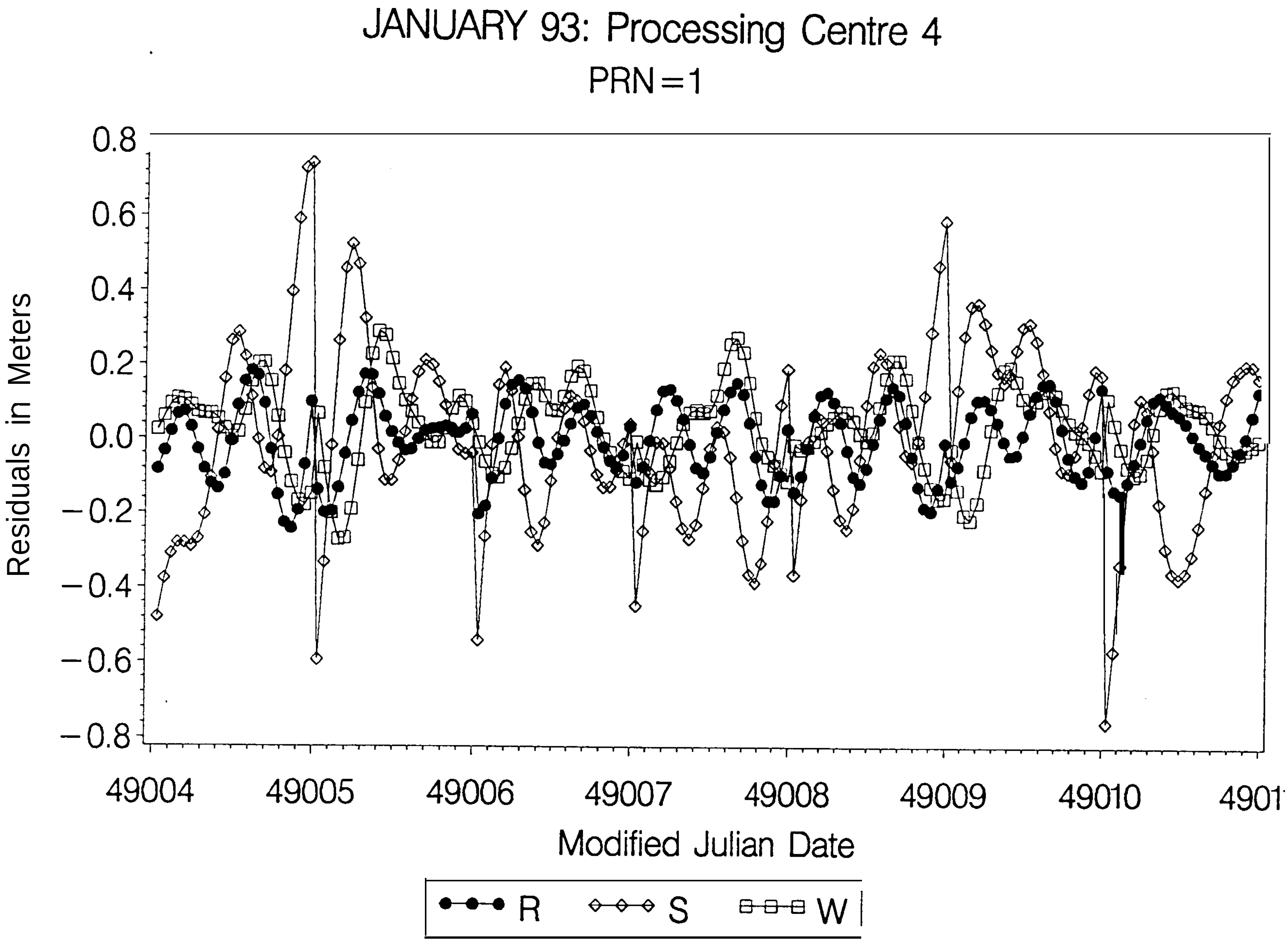


Figure 3.3d: Orbit residuals with respect to a week long arc for PC4 and PRN1



Such orbits must be qualified as outliers and removed for the orbit combination. After also removing the orbit of PRN32 in week 681 for one of the Centers (see Figure 3.4) the orbit data was considered clean.

Figures 3.5a and 3.5b characterize the first screening step for all the Centers involved, by showing the RMS errors (mean over radial, along-track and out of plane) for each satellite and each Processing Center. The combined orbits of Section 2 (labelled IGS) were also introduced here as another "ordinary" Processing Center. It is interesting to see that, after removing the outlier orbits, essentially all Centers encountered the same 'modeling difficulties', namely in week 680PRNs21 and 23 show high RMS values. Obviously the assumption of an isolated velocity change was not perfectly true for PRN21. PRN23 is usually difficult to model. The problems with PRNs 17 and 21 are isolated as can be seen from comparing Figures 3.5a and 3.5b. Satellite 23 remains a difficult 'customer'. The IGS orbits combined according to the previous Section by weighted averaging are of a remarkable quality.

The next step is to produce the new type of combined orbits. To have a homogeneous set over 14 days only the Centers which submitted orbit data for the entire span of the two weeks were used, namely COD, EMR, GFZ, and UTX. The Figures 3.5a and 3.5b indicate that, after rejecting the above anomalous orbits, the data are of comparable quality for all the four Centers. Therefore it was decided, for the present tests to use identical weights for all the Centers and all satellites. Single day arcs were determined with ORBIMP using each centre satellite positions. Due to the correlation between the orientation of the ITRF orbit and estimated pole coordinates x and y the pole positions as submitted by the Processing Centers were used for the transformation of their satellite positions into the inertial coordinate frame. The IERS standard model for the force field was used. A direct radiation pressure scale and the y-bias parameters were estimated along with the initial state vector for each satellite. The satellite parameters now refer to the inertial system J2000.0. For the back-transformation into the earth-fixed system one is free to select a new pole. Here, the pole positions produced by the IERS Rapid Service Sub-bureau (the final pole values as of September 17, 1993) were used. The same pole positions were also used in Section 2.

There are still some questions regarding the reference system definition, such as significant differences between various IGS pole solutions and the modelling of the sub-daily pole variations. To properly transform orbits into the inertial frame it is not sufficient to know the pole coordinates in the middle of the day (the only information available so far for each Center); one should know the pole positions actually used in the processing for each epoch during the day. With the pole models currently used it probably would be sufficient to have each pole coordinate characterized by an offset and a drift on each day. This information was only available and used for the CODE Center orbits.

To judge the quality of the combined solutions seven parameterHelmert transformations between our combined solution (labelled COM) and the individual orbit files (note, the combined orbits of Section 2 are labelled IGS) were computed. The RMS values after the transformations with respect to these COM files are shown in Figure 3.6. They are rather homogeneous for the four Processing Centers, which is to a certain degree due to the identity weighting used. What is really surprising is the consistency between the orbit combination based on orbital dynamics and that based on a refined averaging procedure (Section 2). The RMS error after the transformation between the two sets is about 5 cm with the exception of the first two days! The problem satellites for the days mentioned above were excluded. Also excluded were satellites 17 and 21 on the sixth day of week 680, the stochastic impulse in the COM-file but not in the IGS file introduces a significant difference. It is also important to note that not only there are very small RMS errors between the

Figure 3.4: Orbit residuals with respect to a week long arc for PCX and PRN32

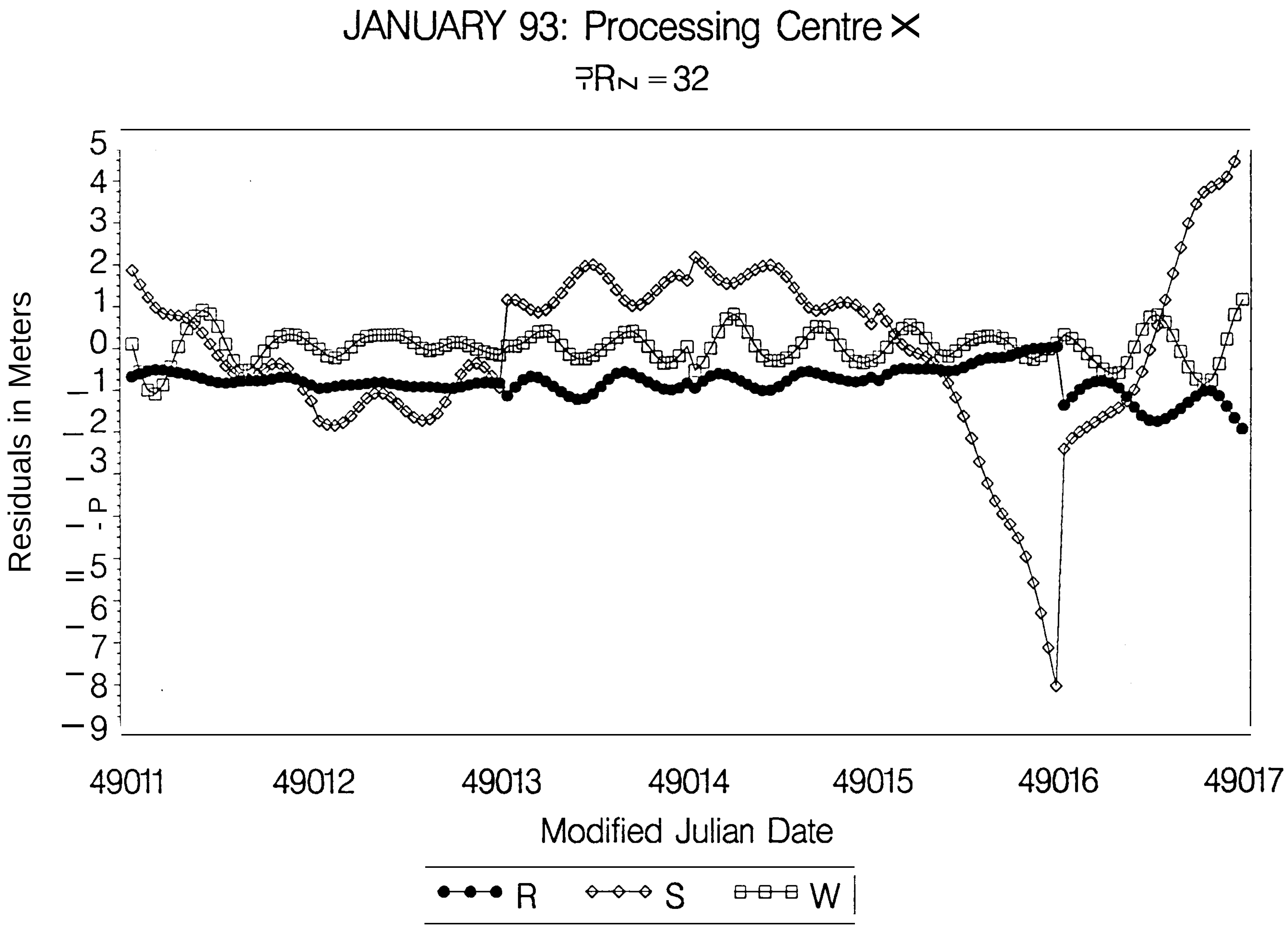


FIGURE 3.5A

QUALITY OF ORBIT FIT OF DIFFERENT CENTERS (ARC LENGTH = 1 WEEK)

Rms of orbit fits (mean per coordinate)

GPS WEEK = 680

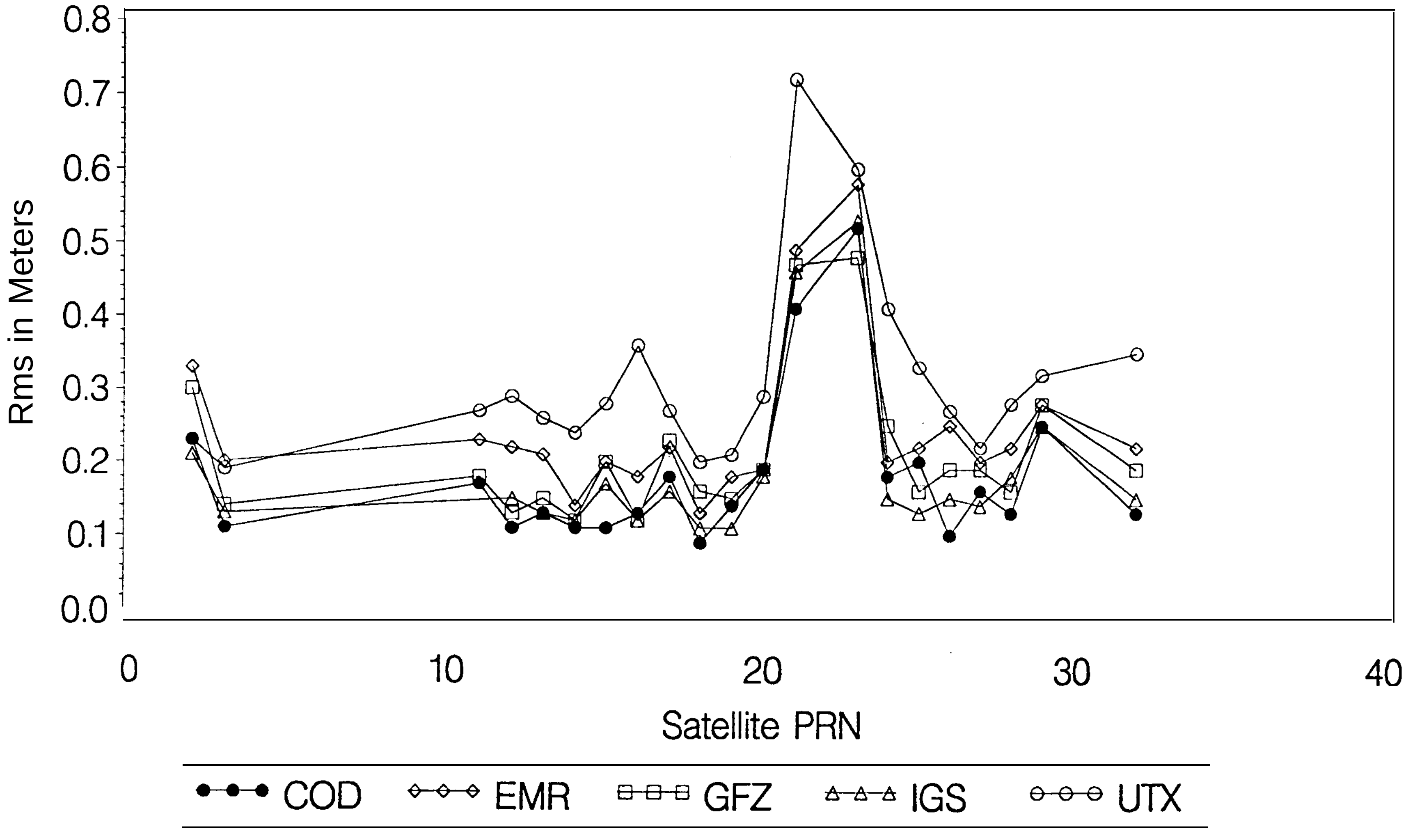


FIGURE 3.5

QUALITY OF ORBIT FIT OF DIFFERENT CENTERS (ARC LENGTH = 1 WEEK)

Rms of orbit fits (mean per coordinate)

GPS WEEK=681

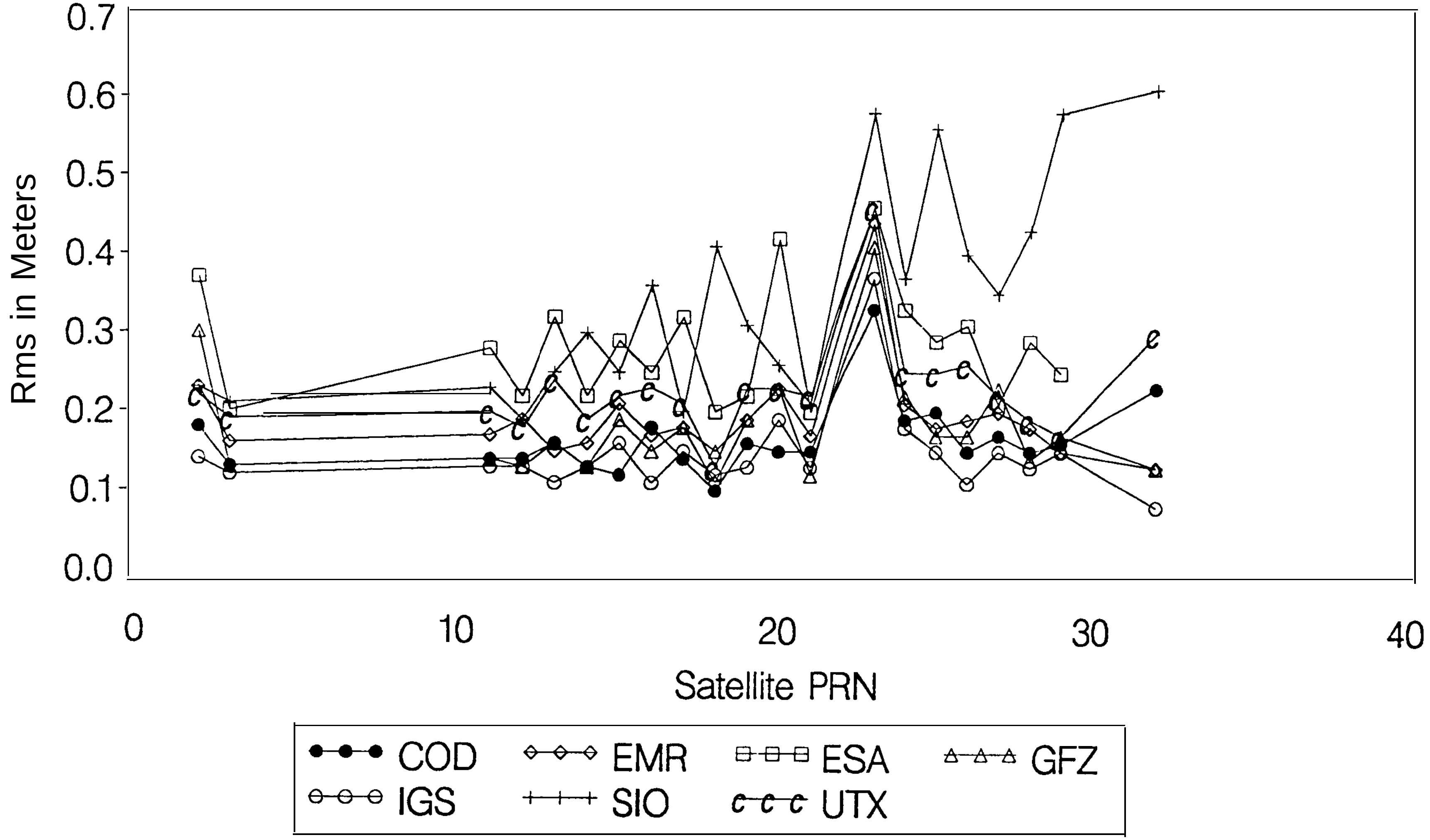
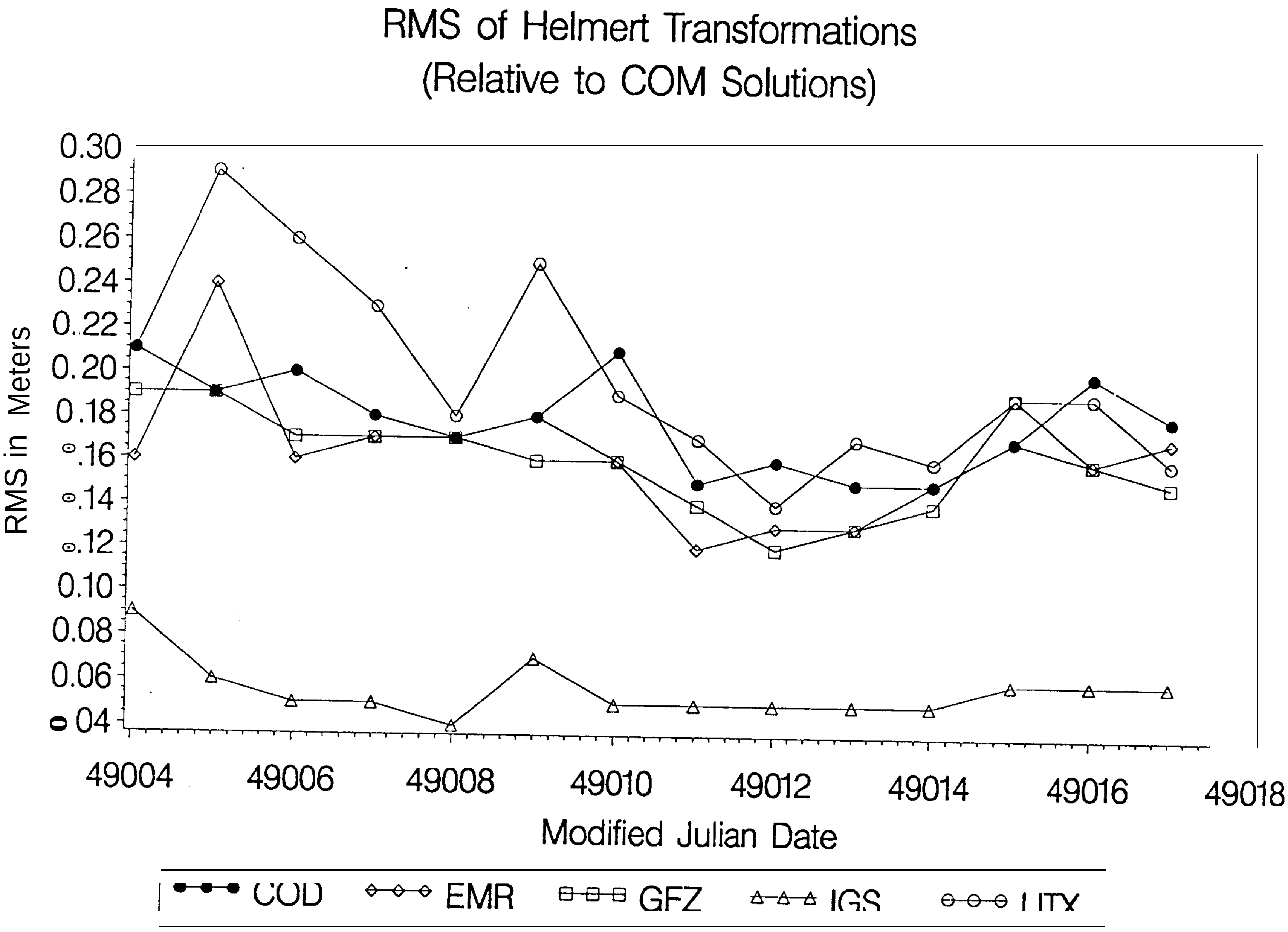


Figure 3.6: Orbit coordinate RMS with respect to combined (COM) orbits for some IGS processing centers during the January 1993 orbit test



IGS- and the COM-sets, but that the transformation parameters are very small, too (see Table 3.2).

Table 3.2 Transformation parameters between the COM and IGS Combined Orbits

MJD	DT days	DX (m)	DY (m)	DZ (m)	RX (mas)	RY (mas)	RZ (mas)	SCALE (ppb)	RMS (m)	
49004.0	1.0	-.003	.004	.015	-.1	-.2	.0	.1	.09	COM IGS
49005.0	1.0	.008	-.001	.007	.0	.0	.0	-.4	.06	COM IGS
49006.0	1.0	.006	-.003	.019	.0	.0	.1	-.4	.05	COM IGS
49007.0	1.0	-.003	-.010	.010	.0	.1	.1	-.5	.05	COM IGS
49008.0	1.0	.001	.001	.008	.0	.0	.2	-.5	.04	COM IGS
49009.0	1.0	.005	-.008	.015	.0	.1	.5	-.3	.07	COM IGS
49010.0	1.0	.005	-.010	.001	.0	.0	.2	-.3	.05	COM IGS
49011.0	1.0	-.003	-.011	.010	.0	.0	.6	-.4	.05	COM IGS
49012.0	1.0	.000	-.003	.002	.0	.1	.2	-.5	.05	COM IGS
49013.0	1.0	-.004	-.005	.013	.0	.0	.0	-.3	.05	COM IGS
49014.0	1,0	-.005	.000	.002	.0	.0	.0	-.3	.05	COM IGS
49015.0	1,0	.003	-.004	.016	.0	.2	-.1	-.2	.06	COM IGS
49016.0	1.0	.000	-.004	-.002	.0	.1	-.2	-.3	.06	COM IGS
49017.0	1.0	.004	-.009	-.003	.0	.2	-.2	-.3	.06	COM IGS
Mean	14.0	.001	-.005	.008	.0	.0	.1	-.3	.06	COM IGS
RMS of Mean		.001	.001	.002	.0	.0	.1	.0	.00	

4. BASELINE TESTS

4.1 North American baselines

The IGS and COM combined orbits along with the COD, EMR and GFZ orbits were used in GPS baseline processing tests. The first part of the test concentrates on the orbits above North America and involves four Canadian sites ALGO, DRAO, STJO and YELL. A double difference software was used for this test. The three baselines considered here are originating from station ALGO and are between 2000km and 3000km long. Each day was processed independently using phase observations only and solving for initial cycle ambiguities. In all cases the orbits were held fixed and identical data, options etc. were used for the five solutions each day. The only difference between the runs for a particular day was the orbit used. To check on both the orbit precision and the reference frame stability implied by the orbits, no Helmert transformation was used. In this way the orientation changes as well as regional orbital errors should be reflected in the latitude, longitude and height variations. The reference scale changes should also be seen in the baseline length variations. These variations can be effectively removed by Helmert transformations and inter orbit comparisons become difficult. In fact the reference frame stability as well as increased precision are two main reasons why precise orbits are used. In addition to the already mentioned problem satellites, DRAO, one of the most reliable station in the whole IGS network developed hardware problems, resulting in data loss on January 28,29 as well as shorter observation periods for January 24 and 27. For these reasons the DRAO data for Jan 24,28 and 29 was not used in the EMR orbit computation. All the available data sets (including the January 24 and 27 data at DRAO) were used in this baseline test. It should also be noted that two stations ALGO and YELL were held fixed in all the orbit computations along with additional 10 globally distributed stations. So the YELL-ALGO baseline results cannot be considered representative of achievable repeatability.

Baseline results are summarized in Table 4.1. As one can see the combined orbits compare quite well with the best individual orbits. It was not expected that the EMR orbits would perform better than the combined orbits, since the baseline software used is different and independent from the EMR orbit generation. This maybe due to the fact that the EMR orbits favor N.A. and Canada in particular by including data from six Canadian stations. The situation maybe completely different in other parts of the globe. The North baseline component is the most stable, the formal errors ranged from 1.5mm to 2mm, and thus is well suited to check orientation(EOP) errors at or below the 0.5mas (2.5ppb) level. From Table 4.1 it is apparent that the orientation for the combined orbits and EMR is at the 4-5mm level which corresponds to about 0.3mas at 3000km. The length repeatability is at the 3- 4ppb level for both combined and the best orbits. The formal length sigmas varied between 1 ppb for YELL-ALGO and about 2ppb for the remaining two baselines. As mentioned before, YELL-ALGO repeatability is not representative of achievable precision, but DRAO-ALGO and STJO-ALGO sigmas are meaningful. Removing the two most problematic days (January 17 and 27) results in significant scale improvements for the longest baseline (DRAO-ALGO), down to about 2ppb. Also listed in Table 4.1 are the height sigmas and they are also lower for the combined and regional orbits. Finally, the combined orbits of the first type (IGS) appears to be slightly better here, at least as viewed from North America. This may be due to problems on Jan. 22 mentioned in Section 3 and also due to the fact that IGS orbits employs the L1 norm which is supposed to be less affected by marginal and outlier orbits.

Table 4.1 N.A. Baseline Repeatability Sigmas (Jan 17-30, 1993)

	North (mm)	East (mm)	up (mm)	Length (ppb)	#
STJO-ALGO(1931km)					
IGS	5.0	9.6	11.2	4,7	14
COM	6.3	9.9	12.9	4.6	14
COD	5,3	11.6	12$8	5.8	14
EMR	3.9	7.6	9.8	3.7	14
GFZ	7.2	12.6	13.1	6.2	14
YELL-ALGO (2913km)					
IGS	6.7	10,7	21,4	2.5	14
COM	8.1	9.8	25.6	2.6	14
COD	8.1	10.5	23.2	3.0	14
EMR	6$6	8.4	13.3	1.9	14
GFZ	10.4	11.3	23.7	3.1	14
DRAO-ALGO (3075km)					
IGS	5.0	12.9	14.8	3.6	12
COM	4.3	16.7	18,0	4.5	12
COD	7.5	14.3	13.2	5.0	12
EMR	4.1	13.8	16.2	4.6	12
GFZ	6.7	21.3	24.1	5.7	12

4.2 European baselines

Thesecondpartof the test concentrates ontheorbitsabove Europeandinvolves thesitesMADR, KOSG, TROM and WETT. Stations MADR, TROM and WETT were held fixed in all orbit reprocessing, The same orbits as for the North American baseline test were used. The Bernese software version 3.4 was used and therefore the COD orbits might be favored due to using the same software which was used in creating the orbits. The same strategy as outlined above was used, i.e. the only differences between the solutions for a given day were the orbits used. On January 18, 1993 the TROM data was missing and could not be used in the KOSG-TROM baseline processing. Results of all the baseline processing are summarized in Table 4.2. Again the combined orbits compare quite well with the best orbits. However the COD orbit performs better than the combined orbits. This might be caused by the fact that COD orbits favor Europe.

Tables 4.1 and 4.2 show that viewed on a regional scale clear differences between the orbits of the individual Processing Centers exist. The combined orbits are performing well in both regions. Surprisingly the GFZ orbits which looked very good in the orbit combinations of Section 2 and 3 did not perform as well as one would'expect.

Table 4.2 European Baseline Repeatability sigmas (Jan 17-30, 1993)

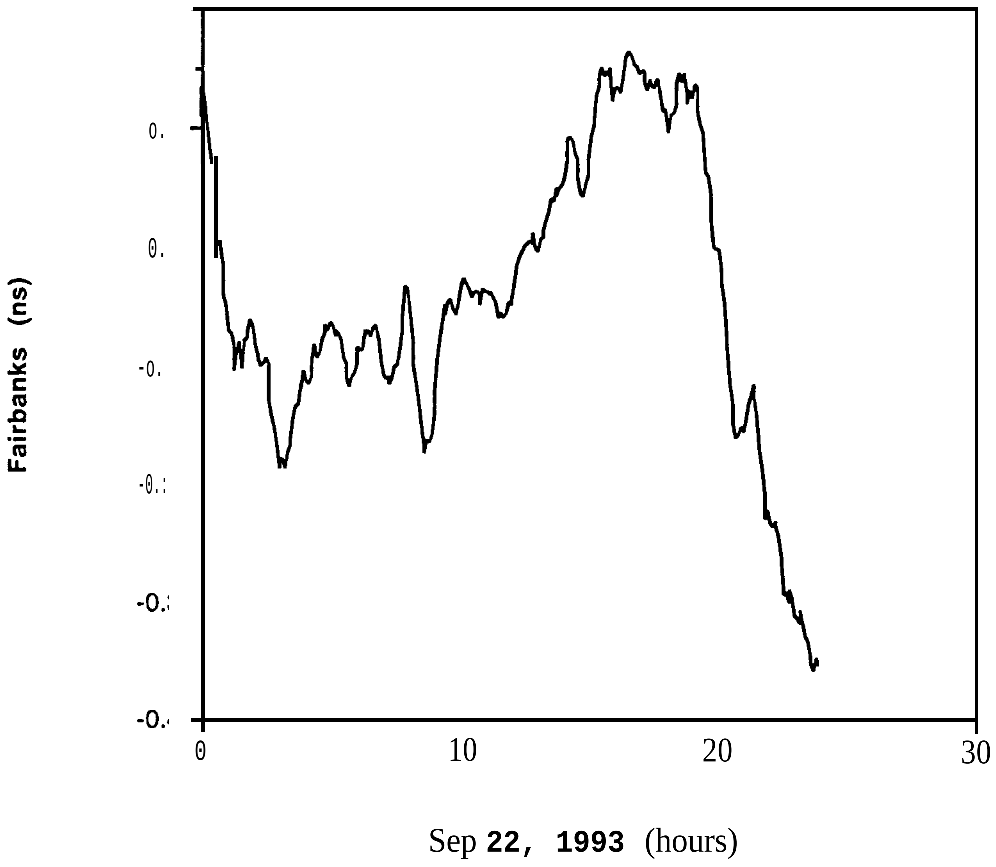
	North (mm)	East (mm)	up (mm)	Length (ppb)	#
KOSG-WETT (602km)					
IGS	5.8	4.3	17.0	5.3	14
COM	4.7	4.7	14.7	5.3	14
COD	4.6	3.6	15.2	5.9	14
EMR	7.1	5.7	20.8	6.1	14
GFZ	6.4	4.9	16.0	5.8	14
KOSG-MADR (1512km)					
IGS	6.6	8.7	12.9	3.0	14
COM	7.8	7.5	12.8	2.9	14
COD	4.7	6.3	12.6	3.1	14
EMR	8.9	9.3	20.3	3.3	14
GFZ	9.3	10.7	14,5	3.3	14
KOSG-TROM (2054km)					
IGS	9.9	19.1	21.1	3.6	13
COM	10.0	18.2	19.7	4.5	13
COD	8.4	13.2	18.0	3.0	13
EMR	13.7	26.7	25.1	5.1	13
GFZ	12.7	24.4	24.7	6.0	13

5. SATELLITE CLOCK COMBINATION CONSIDERATIONS

The satellite clock offsets along with satellite orbits are required for all positioning applications. Furthermore satellite orbit and clock errors are usually highly correlated so it makes sense to include them in the orbit products as well. Most geodetic applications do not require very precise satellite clocks, a precision of a few microseconds is sufficient to align orbits and observation data. Single station navigation and precise time transfers, on the other hand, need the utmost accuracy for the satellite clocks as the satellite clock and orbit errors map directly into the results.

Precise and optimal clock estimation from both pseudorange and phase data necessitates the undifferenced approach to the GPS data analysis. The usual double differencing data treatment nearly eliminates, by design, both station and satellite clock errors. Thus, for double differencing an additional step utilizing pseudoranges is required. Such clock estimation is suboptimal as phase data and other parameters (e.g. estimated tropospheric delays) are not available or used in this process. Nevertheless such clock solutions would still be useful in particular when precise pseudorange observations are available and used along with precise orbits. Currently only one IGS Center (EMR) estimates both satellite and station clocks and submits the satellite clock solutions

Figure 5.1: Clock solutions for FAIR Hydrogen Maser (HM) clock with respect to ALGO HM clock



to IGS in the sp3 orbit files.

In Figure 5.1 the station clock solutions for the two most precise Hydrogen Masers (HM) in the IGS network are compared, HM clocks have the highest precision and stability over periods of several hours. After removing an offset and drift they in effect provide a convenient ground truth at a cm (.03ns) level. The HM clock at ALGO served as a time reference and the FAIR HM clock was treated as unknown with a large, 1 second apriori sigma. As seen from the above figure the agreement between the two HM's is at the 0.1 ns (3cm) level which is also consistent with formal clock sigmas. The systematic variation of about 0.2ns seen is likely due to orbit errors and changes in observed satellite constellation rather than the instability of the HM clocks. Satellite clock solutions have formal errors comparable with the station clock solutions i.e. a few cm; but, the accuracy and consistency tests are not possible here since there is no HM satellite yet! The situation changes dramatically when clock estimation is based bn undifferenced phase data only (the current situation for AS satellites, since the problem with AS pseudorange observations has not been corrected at most IGS stations), then formal sigmas increase to about10ns (or 3m.).

For convenience and completeness clock solutions should be also combined and included in the IGS official orbit product. Problems with the combination of different satellite clock solutions are similar to the problems encountered with orbit combinations, i.e. first reconciling the reference time frame differences, then detection, rejection of outliers and weighting of the individual clock solutions. A clock combination can be based on the orbit combination approach of Section 2. Reference time frame problems are rather specific and depend on approaches to time reference definition within a particular solution, There are many possible approaches which can be used, ranging from a single station (fixed) reference to weighting some apriori clocks either for some stations or satellites or both. The ideal and most desirable case would be to introduce or connect some IGS stations to BIPM primary standards. This would not only enhance the IGS clock reference but also enhance BIPM's time transfer and maintenance. Currently it is not possible to combine the satellite clock information since only one Center contributes satellite clock solutions, however for the permanent service the contributing Centers should be encouraged to develop and submit satellite clock estimations.

6. CONCLUSIONS AND RECOMMENDATIONS

Two methods for orbit combinations were presented and tested here, the first is based on a weighted average and the second is a rigorous orbit determination with orbits introduced as pseudo-observations. Both methods gave nearly equivalent combined orbits, agreeing at 5cm (RMS) in position and below O. lmas in orientation. The baseline tests in North America and in Europe also indicated that both combined orbits are practically equivalent and comparable to or better than the best (regional) orbits. Both types of orbits implied precision and orientation stability at or below the 3 ppb and 0.5mas, respectively. Satellite clock solutions and combination at the 0.1 ns consistency level are also possible. Problems which require additional studies and attention include: the choice of reference pole (IERS or a GPS solution), sub-daily EOP representation, mitigation or elimination of orbit discontinuities, reporting orbit accuracy, processing standardization etc.

The following recommendations are offered:

1. The IGS combined orbits are based on both methods described and tested above, more

specifically the preanalysis can be based on the orbit dynamics method with longer arcs (Section3) and the combined orbits, at least in the beginning, are based on the weighting orbit method of Section 2.

2. Strict deadlines for orbit submission and the IGS orbit release are established and adhered to by all Centers and IGS (e.g. two weeks). After the deadline, late orbits will not be included into the combined IGS orbit.

3. Individual Center orbits will continue to be available from IGS.

4. The current orbit comparison will be enhanced and based on the adopted IGS orbit combination process.

5. Satellite clock solutions are combined by means of weighted averages and should be included in the IGS orbit product. The time reference for the clock solutions is consistent and based on the international time standards, i.e. a close cooperation between IGS and BIPM is established.

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SUMMARY OF SESSION 2

The second session concentrated on orbit combination and consisted of two presentations followed by a discussion. In the first presentation, entitled 'What can be learned from other satellites', Prof. Bob Schutz outlined the extensive experience with precise orbit determination at the Center for Space Research (CSR) of the University of Texas. The long arc precise orbit determinations (up to several years) for the LAGEOS and ETALON satellites were discussed. The ETALON satellites are particularly interesting as they have similar orbits to GPS. For both ETALON satellites, CSR was able to determine long arcs (600-800days) with some empirical orbit corrections every 30day with postfit range residuals of about 6cm. A possible problem identified and applicable to GPS is the error contribution of Earth gravity models due to the deep resonance of the GPS orbits. The GPS measurements on TOPEX/ POSEIDON as well as to a GLONASS laser reflector on PRN5 will improve GPS error modelling. CSR was able to fit external GPS orbits (from CODE and GFZ) to about 3cm RMS. In the second presentation Prof. G. Beutler presented the Position Paper II (see above) on some possible approaches to orbit combination. Two methods for combining orbits were proposed, the first one based on a refined weighted average and the second on orbit dynamics. The presentation was followed by extensive discussions on the subject.

The most controversial and lively discussions were on specific submission deadlines for orbit solutions. Finally, a two week (maximum) deadline was agreed upon at least for the initial stages, with the understanding that Centers will make an effort to submit their results as soon as they are available (daily or several times a week), hopefully well before this deadline. In any case, the maximum wait period will be two weeks from the date of data collection or until all Center results are submitted, whichever comes first. Another 'intensive' discussion related to benefits of fixing versus constraining some ITRF coordinates. It was felt that by not fixing the known ITRF coordinates the reference frame could be compromised (drifting orientation). However, it was pointed out that Centers which do not fix coordinates in fact show better frame stability than most Centers. By constraining the station coordinates, it is hoped that small unmodelled station movements and errors in the ITRF coordinates are mitigated. At the end it was agreed that both fixing and/or sufficient constraining are acceptable and consistent with IERS/IGS standards.

To reflect the nature of operation of both IGS and IERS two combined orbit products were proposed, the first 'Rapid orbit products' to be based on IERS Rapid service (Bull. A) and to be available as soon as all orbits are submitted or within two weeks. The second, 'Final orbit product' should be consistent with the final IERS EOP (Bull. B) and should be made available within a few months. This final IGS orbit could be potentially more accurate than the rapid orbit, e.g. due to using more accurate EOP or by including the late or resubmitted (corrected) orbits. In addition to creating both IGS products as above, the continuation of archiving and distribution of individual Center products was supported by all participants. As shown in the position paper some regional orbits may be approaching the precision of combined orbits for certain regions and also they will likely be available before the IGS orbit products are generated.

The relative advantages and disadvantages of both orbit combination methods proposed in the position paper were discussed. At the end the general feeling was that, at least for the time being, the weighted average method, based on the L1 norm should be adopted for the IGS orbit combination and the second approach based on orbital dynamics should be used for long arc orbit validation only. The L 1 norm estimation appears to be less sensitive to outlier orbits and thus safer for operational purposes. Besides it can also accommodate some unconventional orbit determinations (e.g. based on stochastic modeling for some orbit parameters). During the discussion, a question as to whether the weighted orbits satisfy the orbit dynamics was raised. The position paper was subsequently amended to answer the question. It is shown that indeed the weighted average orbits under some conditions also satisfy the orbit dynamics.

The differences between using one or two radiation scale parameters (in the X- and Z- directions) were raised and left to discretion of individual Centers. The net effect, as pointed out during discussions, is that the difference between one or two radiation scale orbits introduces significant RMS of about 10cm as compared to 3-5cm for comparable (one scale) orbit estimation. Since the current orbit disagreements are still larger and to foster some diversity (e.g. avoiding failures by all at the same time) both one or two radiation scale estimations were considered as acceptable. Note that orbit comparisons in Section 3 of the position paper favor the one scale orbit estimation.

Further discussion of the position paper related to significant improvements for reprocessed results as compared to originally computed and submitted ones. It was pointed out that there were only slight improvements for some Centers (e.g. CODE and EMR) mainly due to improved coordinates and additional data and some major improvements mainly due to significant improvements in orbit estimations (e.g. ESA and GFZ). Consequently one can also see (Figure 2.5b) that even L1 norm estimation fails when most orbits are of poor quality. Here the two precise orbits (CODE, EMR) are both biased on account of the large variation of the other two orbit series. Obviously the L2 norm estimation with appropriate weighting would have performed here better than the L 1 norm.

Finally it was felt that it would be desirable for the January orbit test reprocessing to be completed by all remaining Centers. For Centers which have already reprocessed the data set, this reprocessing only makes sense when new, improved estimation strategies are used.

SESS1ON 3

(IGS processing standards)

SUMMARY OF SESSION 3

This Session began with Geoff Blewitt's observation that, before Standards for Processing can be developed, we must first gather information on Analysis Center models, estimation strategies, nominal coordinates, and so on, so that commonality and differences can be seen and analyzed. He also spent some time putting together a preliminary list of what would constitute such "information". Geoff Blewitt volunteered to develop, in cooperation with the Central Bureau, a formal questionnaire to be filled out by Analysis Centers. The purpose of the questionnaire will be to systematically document differences and changes in the hope that these may be related to differences in solutions. A draft questionnaire will be made for review by Analysis Centers, and a final version will be distributed to each Center to fill out. Completed questionnaires will be made available to all Centers, IERS, and will be available on the IGS Information system being implemented at the Central Bureau.

All Centers agreed in principle to adopt the same set of fiducial coordinates for purposes of orbit/EOP products. The proposed list of stations is the same as in Session 1.

SESSION 4

(Integration of regional station clusters)

IGS POSITION PAPER, IGS ANALYSIS CENTER WORKSHOP
OTTAWA, CANADA, OCTOBER 12-14, 1993

Regional Clusters and Distributed Processing

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ABSTRACT

The primary role of the International GPS Service for Geodynamics (IGS) is to support worldwide high-precision surveys using the Global Positioning System (GPS) by providing timely products such as improved satellite ephemerides, earth orientation and terrestrial reference frame information, These products are generated by the IGS based on the analysis of data from an increasing number of worldwide GPS tracking stations and have been used already to support campaign-type GPS surveys of finite duration. In a parallel development continuously operating regional GPS clusters are being established to study crustal deformation at tectonic plate boundaries and to serve as active geodetic networks. These developments present challenges to the IGS. In practical terms, the increasing number of global tracking stations presents a computational and data handling burden on the analysis centers. Distributed processing of these data among these centers will allow the IGS to accommodate an expansion of the global network to the often-stated goal of about 200 stations. In programmatic terms, the IGS should consider playing a role in integrating the regional clusters within the framework provided by the global network, a task particularly important for geodynamics. In this position paper we outline and endorse a hierarchy and methodology for distributed processing and the integration of regional clusters. We present several scenarios and examples.

1. INTRODUCTION

1.1 Motivation

(a) Practical use of resources. It is clear that the steady expansion of the global GPS network is already creating computational challenges for the IGS analysis centers. For example, in a recent weeks (GPS Week 716) CDDIS Data Holdings Bulletin there are data from 50 stations from which we can distinguish regional clusters in Europe and California within the overall global framework. It is not inconceivable that the goal of 200 globally distributed GPS stations established several years ago for the NASA FLINN network [*Minster et al.*, 1991] will be met within 5-10 years, under the umbrella of the IGS, with a proliferation of regional clusters for various high precision geodetic applications. For example, there are plans to expand the 10-station Permanent GPS Geodetic Array (PGGA) in California by at least 5 stations per year so that by the end of the decade about 50 stations are expected to be in permanent and continuous

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operation. Likewise, Japanese government agencies are establishing a permanent, 60 station crustal deformation monitoring network in the Kanto plain and an active control network of over 100 stations across the entire Japanese archipelago. At the present time, the analysis centers use about 20 to 40 stations in their routine solutions. Data processing time is at best proportional to the square of the number of observing stations, so a 90 station network takes an order of magnitude more time to process than a 30 station network, Computer memory limitations present a similar problem. Fortunately, there is little reason to process a 90 station network simultaneously. There are a number of strategies that can reduce processing time by an order of magnitude without compromising regional positioning accuracy.

(b) Increased involvement. At present, there are seven analysis centers producing global solutions, with little need for more. As the number of stations increases around the world, new analysis centers can make a considerable contribution by focusing their attention on regional clusters, which they can monitor efficiently for problems. Single problematic stations might go unnoticed or ignored by those groups who are primarily interested in global parameters. A regional analysis center will have more of a vested interest in the performance of the regional cluster. It will also help ensure that the "polyhedron" does not remain that of -40 core sites used in the global processing, but that it include data consistently from, perhaps, hundreds of new permanent sites. The regional analysis center can also serve a dual function in providing assistance to users performing GPS surveys, and validating the resulting products. Needless to say, more involvement will also lead to a broader base of expertise and knowledge from which IGS can draw the best ideas and solutions to problems.

(c) Standardization and consistency. The recent trend to more stations is accelerating, with no reason to believe that it will slow down. The analysis of GPS data is computationally intensive so that it is not practical to reprocess all available data many times as is done with VLBI data, for example. Recognizing this, it is imperative that the routine data reduction of tomorrow's blossoming regional networks be done in a mutually consistent, acceptable, and archivable way. Without adequate preparation and organization, we may effectively lose a golden opportunity for unifying the world's GPS networks. It is assumed that there is no problem finding willing analysis centers (regional networks are not installed without some plan for analysis!). IGS can facilitate a consensus on a set of standards so that a required level of consistency and efficiency is realized. Given the benefits that regional network users will get in return (consistent reference frame, consistent orbits, expert information, etc.), it is likely that regional analysis groups will cooperate and abide by a reasonable set of standards.

(d) Enhancing the "Service" in IGS. Until now, IGS global analysis centers have been preoccupied with the technical details and practical aspects that are necessary to deliver the products. There now needs to be more focus on servicing our customers (of course, we the participants are customers too). The current status is that customers have little guidance on using the routine IGS global products for regional network geodesy, and there is no formal way to feedback, the regional solutions into the global reference frame. Any customers who want to get the highest levels of precision for their regional networks ought to be given explicit recommendations on how to proceed, and IGS should provide the means to make the procedure as simple as possible without significantly compromising regional accuracy. IGS should also specify the procedures by which the regional centers may submit their network solutions back to IGS (as emphasized above in point 1.2(c)).

(e) Defining the Role of IGS. At some point, increasing the number of stations in the global network will produce negligible improvement in the accuracy of estimated orbits and Earth orientation parameters (EOP). The question of exact] y how global parameter determination improves with the number of stations is subject to further research, and cannot be answered fully without using real data. Nevertheless, there appears to be a general consensus that the computation of GPS satellite ephemerides and earth orientation parameters can be accomplished adequately with the current distribution of global stations with some densification required in equatorial regions and in the southern hemisphere, for a total of about 30 to 40 well distributed stations. However, the IGS is a service for geodynamics which requires that the major tectonic plates (i.e., the global polyhedron) and plate boundaries be sampled adequately, With improvements in technology and lower equipment costs, it is very likely that permanent GPS arrays will become attractive alternatives to campaign-type (epoch) GPS surveys or even replace them altogether. In our opinion, we can anticipate within a decade a "core" global network (polyhedron) of about 200 stations with 10-20 regional clusters of 20-100 stations each, all tracking continuously. In fact, it is already difficult to distinguish between global and regional stations.

It is clear that there needs to be a mechanism to integrate densely sampled networks across plate boundaries into the global scheme. Regional arrays in plate boundary zones require (perhaps periodic) ties to the global reference frame through the coordinates and velocities of the global tracking stations in order to determine "absolute" displacements of these internally deforming regions (e.g., southern California). One could argue that the primary purpose of the global IGS network is to support the regional arrays. What is the IGS role in this scenario? Does it concentrate its efforts exclusively on the core network? Even in this scenario the computational burden on the analysis and data centers will be heavy. Can any one center manage 200 core stations? In our view the IGS has two main objectives. The first one is to support epoch and campaign type GPS surveys for geophysical/geodetic applications with global information such as orbits, earth orientation, terrestrial reference frame, etc. This is the most obvious and primary current focus of the IGS. The second, and as important, objective is to integrate (continuous and campaign-type) regional clusters with the global core network. With this motivation we outline below the purpose of this paper.

1.2 *Purpose*

(a) Assess the role of the IGS with regard to the data analysis of clusters of regional GPS networks, including recommended procedures, standards, feedback, quality assessment, customer services, the determination of network kinematics, and unified datum control for GPS surveys. (Network operations and data management are beyond the scope of this paper).

(b) Formulate a top level system design to carry out the above roles.

(c) Investigate technical options for combining regional and global solutions, both from the IGS point of view (maintenance of the polyhedron) and the user point of view (precise solutions in a consistent reference frame for an arbitrary epoch),

(d) Present several examples of the integration of a continuously operating regional array with the global IGS network and distributed processing.

(e) Converge on a consensus on the issues and come up with a series of recommendations.

(f) List those questions that require further discussion and/or research.

2. DESIGN

2.1 *Requirements, Guiding Principles, and Basic Design*

(a) The proposed interaction between the IGS and the regional networks can be represented by an analysis “system with two main components (Figure 1):

(i) a system that enables analysts of regional networks to successfully (as defined below) incorporate IGS global products into regional data processing for both the needs of the user and the needs of item (ii) that follows;

(ii) a system that enables analysts to incorporate regional network solutions into global IGS solutions in a consistent and standard way.

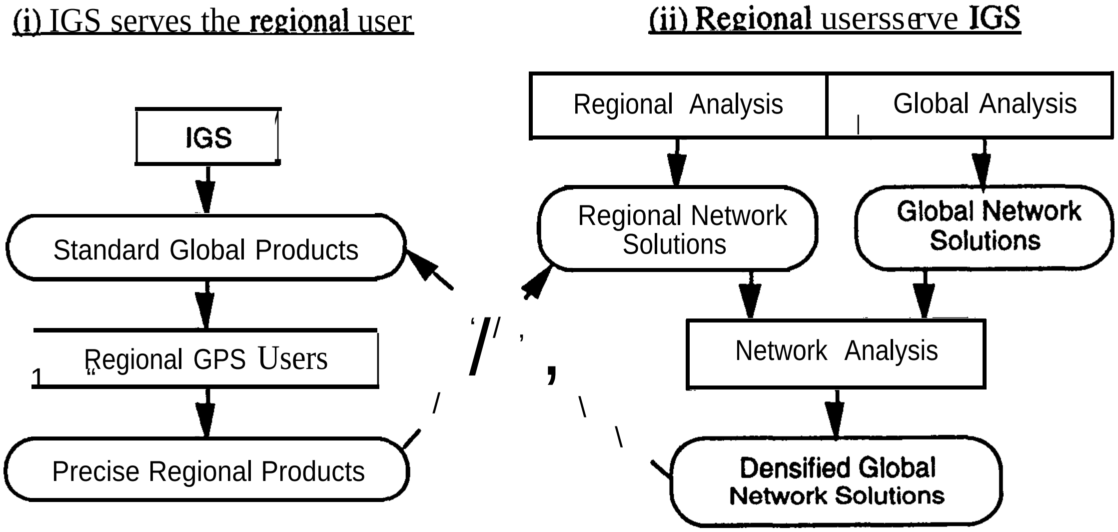

Figure 1: The two main components of the system. Rectangles denote actions, rounded boxes denote data, dashed arrows show how the two systems are **connected**.

(b) The system will have a distributed design involving 3 types of analysis centers. Figure 2 illustrates how the new system might be considered as a natural extension to the existing scheme for Global Analysis Centers **(GAC's)**, without significantly increasing the burden on existing operations, While a small centralized component is also necessary, the concept of distributed design should be pushed as far as possible without compromising issues of integrity and precision.

(i) Global Analysis Centers **(GAC's)** will operate much as today, routinely producing orbital and EOP parameters in a standard frame defined by the IGS Central Bureau, and annually producing a GPS global network solution. GAC's should be minimally disturbed by the extensions to the current system, but new activities would include the submission of **daily**[4] fiducial-free network solutions, and possibly other products to be **decided** (discussed later on).

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[4] In this context, “daily” means that there is a solution every day, but it does not mean that a 24-hour data arc is **required**. For example, **GFZ** currently uses a 32-hour data arc, JPL a 30-hour data arc, and S10 a **24**-hour data arc. A **GAC's** decision on length-of-arc is related to the precision of orbit and **ERP** products, and it would be unreasonable to ask that a GAC perform another, separate 24-hour data reduction for station

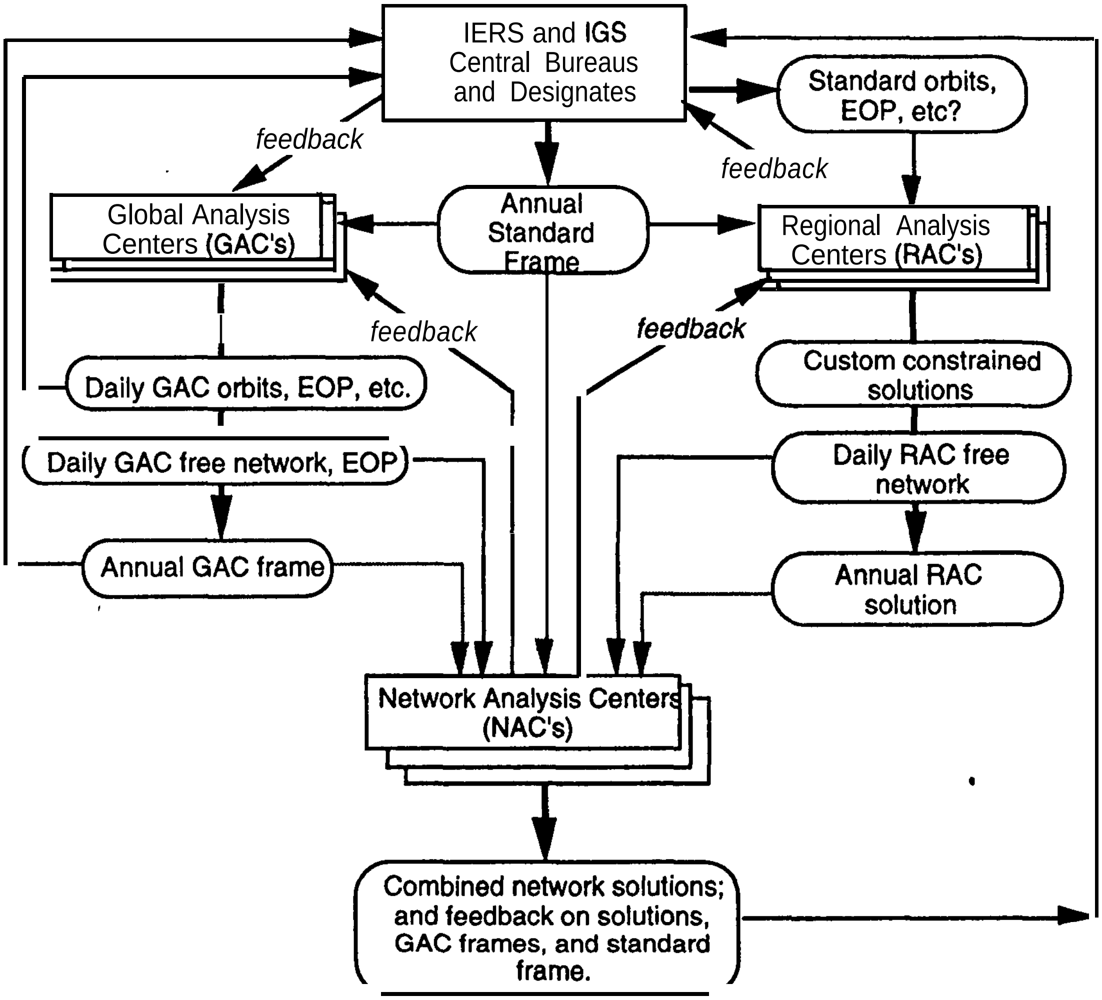

Figure 2. Distributed system design that builds on the existing system and embodies the basic ideas that were shown in Figure 1.

(ii) Regional Analysis Centers (**RAC's**) will analyze specific regional cluster(s) of stations following certain standards and flexible guidelines. RAC's will provide fiducial-free network solutions to IGS, but are of course free to impose any constraint they wish for their own research and internal purposes. **IGS** will provide the means for **RAC's** to impose meaningful constraints for this purpose (see below).

(iii) Network Analysis Centers (**NAC's**) will take RAC and GAC daily free-network solutions as input and produce combined solutions for reference frame investigations, quality assessment, feedback to **RAC's** and GAC'S, and to submit findings to the IGS Central Bureau who will then work with the NAC'S and the **IERS** Central Bureau to produce an annual update to the standard frame (to be then used by GAC'S for **orbit/EOP** production, and by RAC's and other customers for network constraints). A NAC has no obligation to look at all available solutions. Indeed, a NAC might routinely only combine one RAC solution with one GAC solution. This flexibility might encourage more NAC'S to get involved in the hope that it will result in more

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coordinates. Two (minor and acceptable) consequences are that the "daily" solutions will (1) be slightly smoothed to the degree that neighboring solutions use common data, and (2) have slightly different sensitivity to systematic errors.

quality assessment and feedback to RAC'S and GAC's, ultimately resulting in a better, more robust IGS. The problem of quality assessment for hundreds of stations per day is daunting, but can be realistically achieved with a distributed system.

Note that it expected that groups will serve in 2 or 3 of the above capacities,

(c) The system will accommodate those who have the most stringent accuracy requirements. It will also accommodate those who have less stringent requirements, but certain inputs to the system will have to at least meet certain accuracy standards. In design issues where there is a trade-off between achievable accuracy versus practical issues such as computational burden, accuracy will have the highest weight except for cases where either (i) productivity y would be reduced to an intolerable level, or (ii) it would be unreasonable to expect those affected to abide by the standard procedures. In any case, accuracy must meet a specified standard (given below). Not meeting accuracy standards should be regarded in the same way as a failure of a system component.

(d) The system will be designed so as not to limit regional baseline rrns accuracy to be worse than 5 mm + $10^{-8}L$ in the horizontal components (where L *is* baseline length) and 20 mm + $10^{-8}L$ in the vertical component. For absolute coordinate accuracy (in the global terrestrial frame), the system will be designed so as not to limit the rms positioning accuracy to be worse than of 10 mm horizontal and 25 mm vertical. These requirements are to be interpreted as "anywhere on the globe," and additional densification of the global network maybe necessary.

(e) The system will verify that the accuracy requirements are being met at several regions that are well-distributed around the globe, and provide sufficient feedback to analysis centers for them to take appropriate action as necessary.

(f) RAC's and other users of IGS global products will be given the means to produce regional results that meet agreed upon standards. These means should include (but not be limited to) sufficient information, recommendations, troubleshooting hints, feedback procedures, processing standards, possibly software tools and user guides, and a means of assistance in case of inquiries and analysis questions.

(g) There must be some standardized quantification of satellite orbit errors in IGS products, at least for those orbits that are degraded to the point that they will significantly affect regional baseline accuracy; and there needs to be explicit recommendations/instructions on how to use these indices for various user situations.

(h) IGS will develop and provide the means for analysis centers and other users to easily extract the standard coordinates of sites at an arbitrary epoch. This includes software tools, eccentricity information, phase center offsets, seismic displacements, and anything else that is pertinent.

(i) IGS will develop explicit instructions, analysis standards, formats, recommendations, etc., to RAC's and GAC's who wish to submit their network solutions to IGS for eventual incorporation into the global network solution. Along with their solutions, regional centers will provide IGS all pertinent information in some standard electronic form to be decided (e.g., assumed antenna heights, analysis strategy, etc.).

(j) IGS will develop instructions, analysis standards, formats, recommendations, etc., to NAC'S who will take ensembles of regional cluster solutions and routine global solutions to form full global solutions,

(k) The. system will have a centralized component (under the supervision of the Central Bureau) that screens and assesses contributed solutions from GAC's, RAC's, and NAC'S, and provides feedback to them. While any center can act to produce their own fully combined solution, IGS must also, in cooperation with the IERS, develop a standard solution for purposes expressed in item 2.1 (h).

(1) IGS will encourage participation of many RAC'S and NAC'S as part of its research and development strategy to incrementally improve products and-customer services by broadening its pool of active participants, IGS will draw up a plan regarding "membership" as a RAC or NAC. The most obvious mechanism is to accept RAC'S and NAC's as "Associate Analysis Centers" as defined in the IGS Terms of Reference,

(m) (i) GAC'S should use as many globally distributed stations in common (to all GAC's) as possible. More commonality will result in more robust network combinations and detection of errors. For purposes of this document, we call these "common stations". It is recommended that a list of common stations be discussed and agreed upon, keeping in mind the goals set forth in this document.

(ii) RAC'S should use at least 3 "common stations" in the reduction of the regional network data. Although strictly speaking, only 1 common station is necessary for a stable origin (the orientation being defined by fixing the GAC orbits), 3 are recommended for (i) more robust network combinations, and (ii) assessment of errors, by comparing RAC and GAC solutions for the common stations. Apart from quality control, the assessment of errors will allow for better weighting schemes to be developed for network combinations, and for detection and first-order correction of anomalous regional network rotations and distortion (possibly due to GAC orbit errors).

(iii) The list of common stations should be sufficiently globally distributed and dense such that any potential regional survey can be contained within a polygon of at least 3 common stations, with at least one common site within 2000 km of the regional network. If this is not possible with the current global network, then we recommend that IGS strive to ensure that future global sites be installed to meet this standard. For permanent regional arrays, this condition can be easily met by including at least one station from each of the regional arrays on the list of common stations. The map on the next page (Figure 3) shows the current status of the global network, where the solid line is the 2000 km contour.

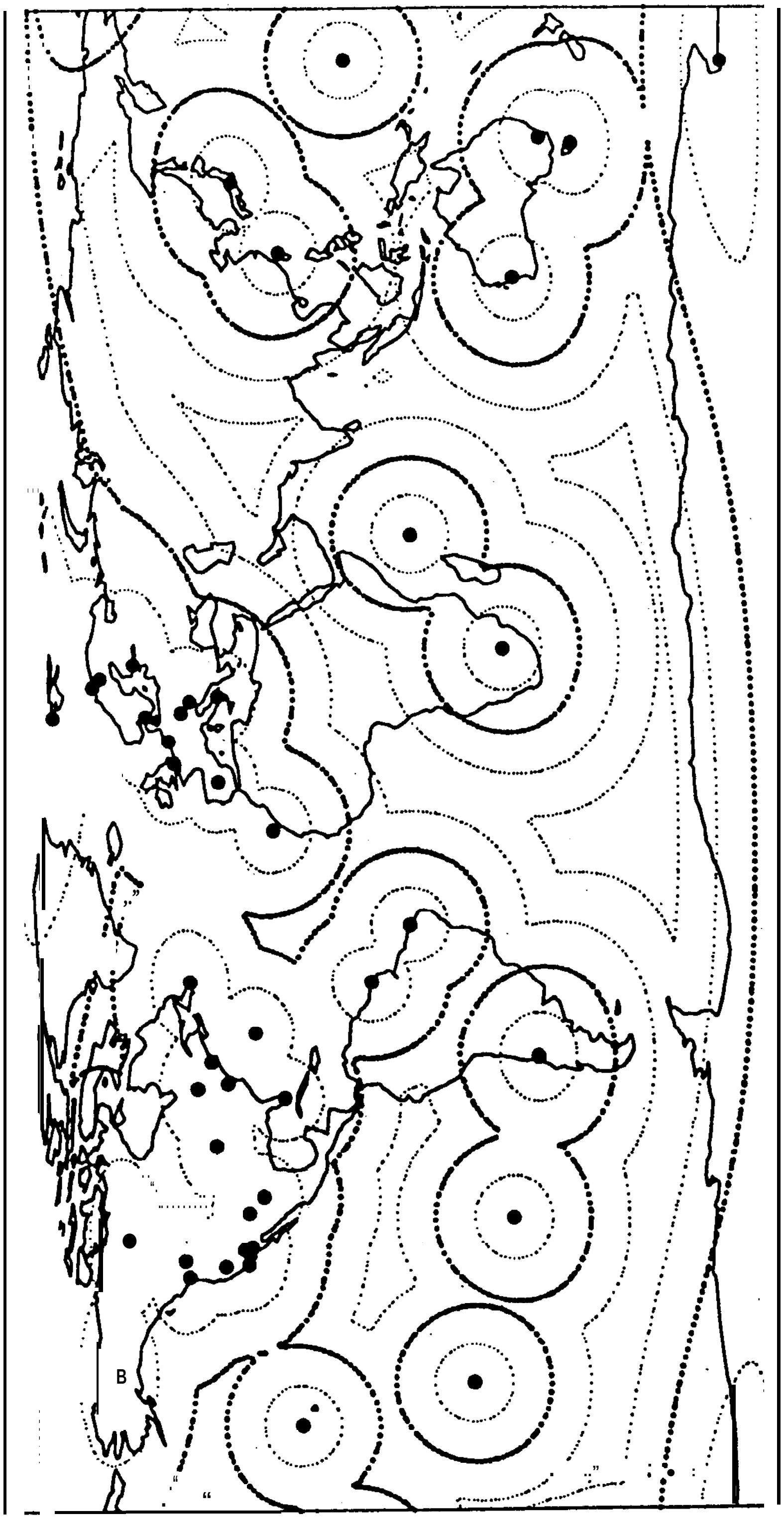

Figure 3. Station intervisibility contours for the current IGS network. The solid line is the 2000 km contour.

2.2 *Analysis Center System Design*

Figure 4 shows the activities of a GAC. Note that there is no direct link to RAC's or NAC's; communication of products takes place through the Data Centers.

Figure 5 shows the activities of a RAC. Feedback on problems with orbits or reference frame is sent to the data center, but it may also be sent directly to global analysis centers through an IGS electronic mail box. Regional data must be reduced with at least 3 stations that are also routinely analyzed in the global network for purposes of network combination and quality control (allowing a check on the level of agreement between the GAC and RAC solutions of common stations). Only fiducial-free network solutions are submitted to the data centers, with the exception of an annual regional reference frame submission which is sent for assessment (by NAC's) and for comparison with the ultimately adopted standard frame.

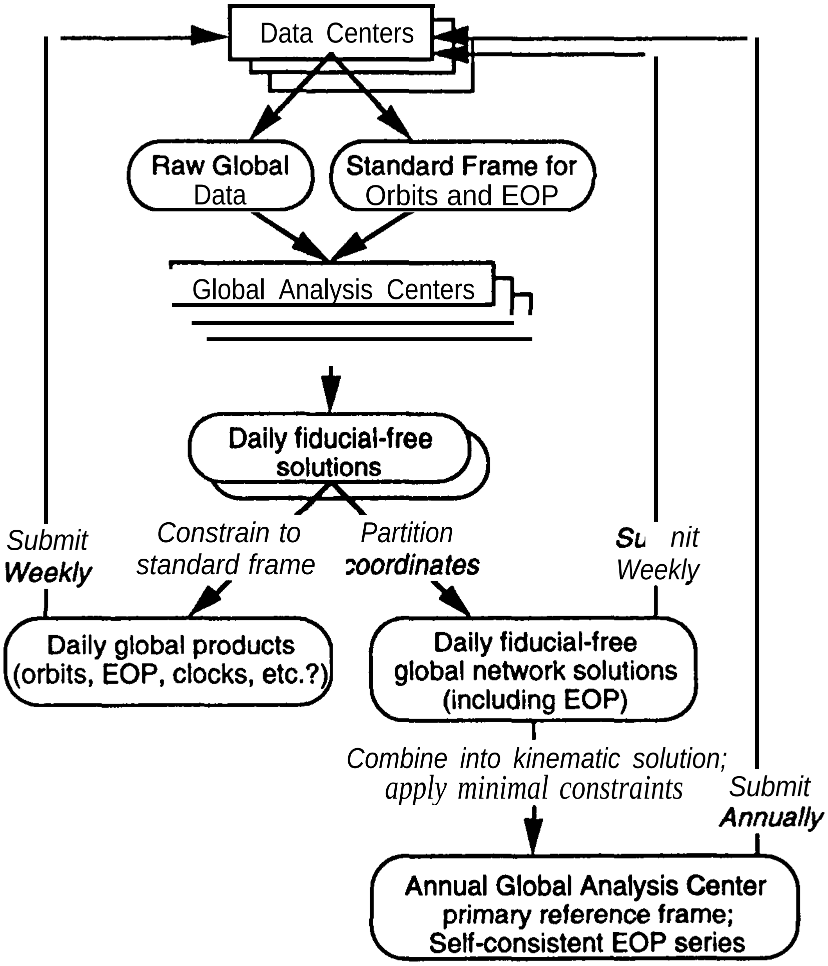

Figure 4. Global Analysis Center Flowchart

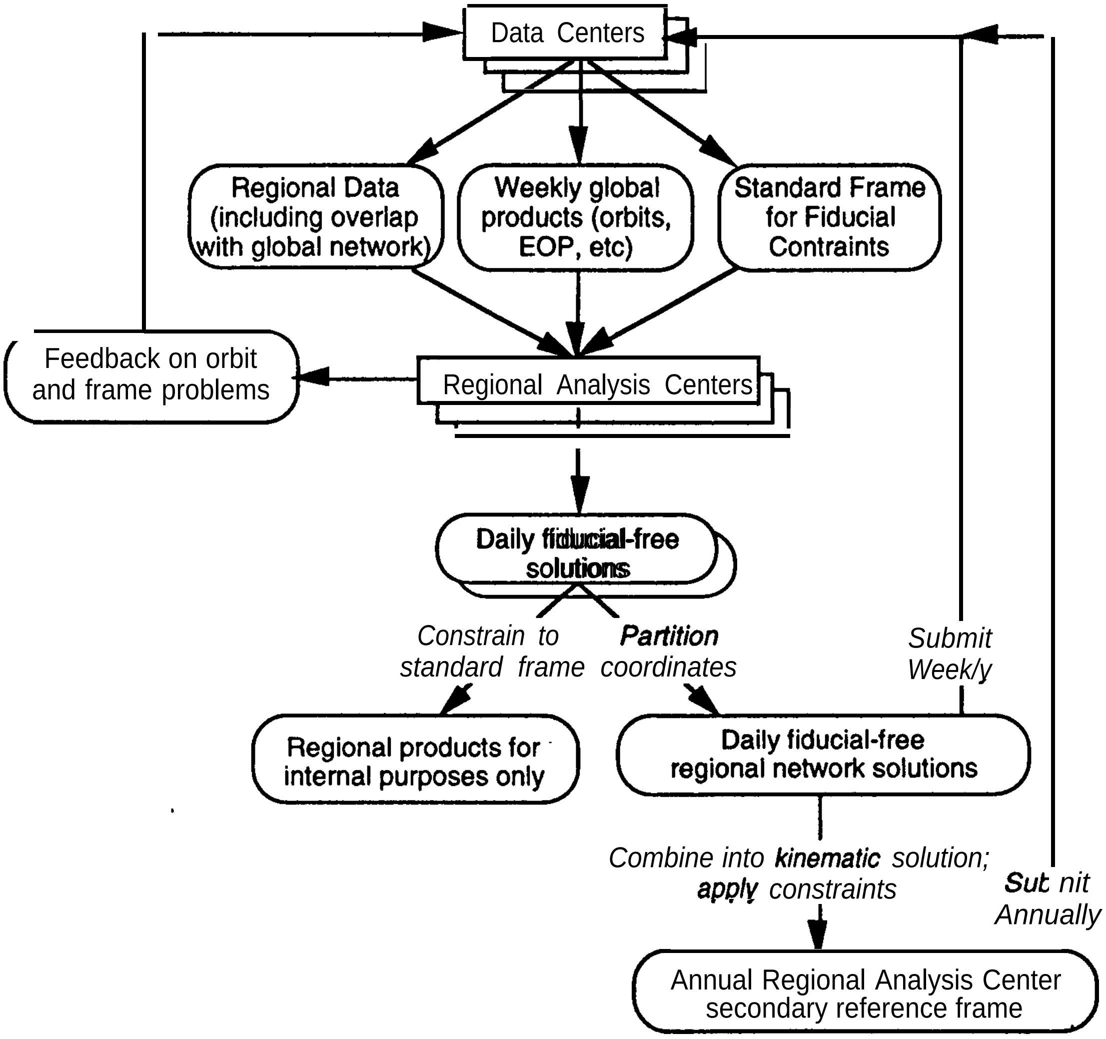

Figure 5. Regional Analysis Center Flowchart

Figure 6 shows the activities of a NAC. Feedback on problems with orbits or reference frame are sent to the data center, but it may also be sent directly to GAC's and RAC'S through an IGS electronic mail box. The combination frame solutions submitted by NAC'S, along with the primary and secondary frame solutions submitted by GAC'S and RAC'S, are ultimately submitted to the IGS and IERS Central Bureaus for incorporation into the ITRF and for producing an annual Standard Frame (which is to be consistent with ITRF, but is based entirely on IGS solutions).

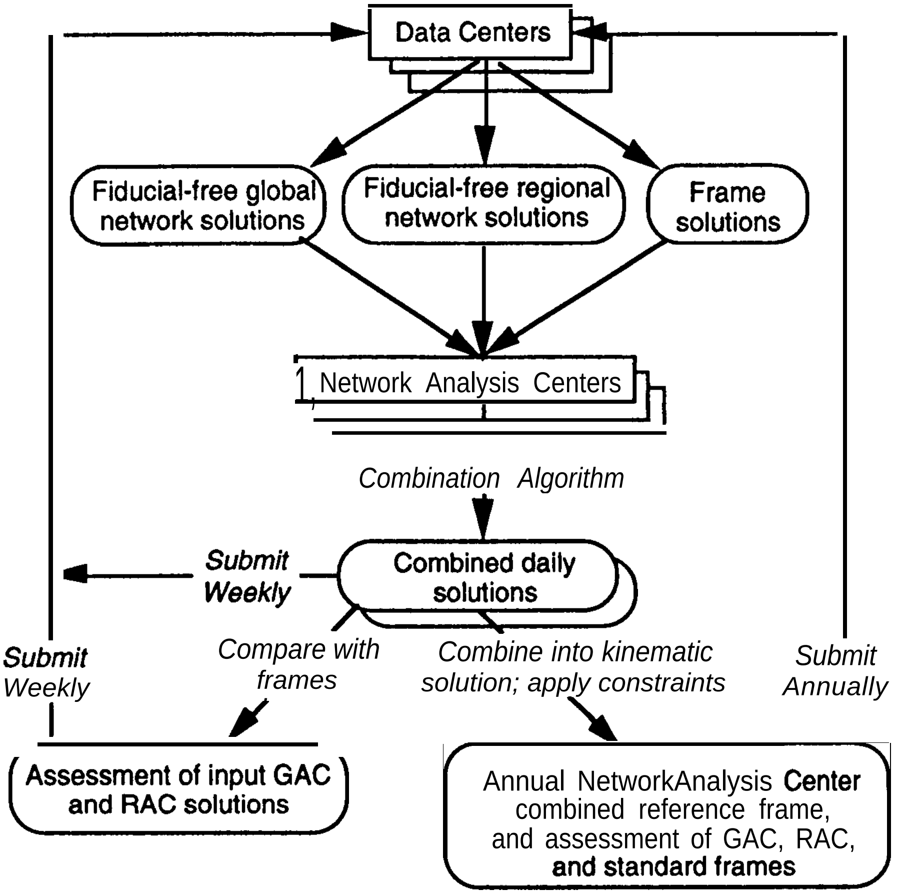

Figure 6. Network Analysis Center Flowchart

3. Technical Aspects

In this paper we have focused on the concepts rather than the technical details. Completing the details will take a considerable amount of further work; however, there are some technical aspects that we have felt important to clarify in this section.

3.1 *Fiducial-free approach and application of constraints*

Global Analysis The fiducial-free approach fixes no station coordinates when deriving the solution *[Herring et al., 1991; Heflin et al., 1992].* The scale is well defined by fixing the speed of light and GM to standard values, If both orbits and station coordinates are estimated simultaneously, the origin is by definition the Earth center of mass if the gravity field harmonics $C_{10}=C_{11}=S_{11}=0$. If, in addition to orbits and station locations, the pole position is estimated, then "loose" a priori constraints (to be defined below) should be applied to the solution in order to avoid possible numerical problems associated with a3-rank deficiency.[5] It is also important to keep the free network within a few meters of convention (ITRF) so that linear transformations can still be applied to the network solution. The rank deficiency is removed only after all solutions are combined into one, otherwise we would be faced with the difficult situation where solutions submitted by different agencies have different a priori constraints. For the routine production of orbits and EOP parameters, global analysis centers can save a lot of processing time if they first produce the loosely constrained solution to extract the “fiducial-free” network and EOP estimates; then fix a subset of stations to recommended coordinates, and extract the orbits and EOP in the standard frame.

Loose Constraints.[6] Loose constraints are applied in the form of a nominal value with an a priori standard deviation. “Loose” is defined such that the observable quantities that we care about (e.g., baseline lengths) are negligibly affected by the constraint. This raises two issues: (i) How good should the nominal values be? (ii) How “loose” should the a priori standard deviations be? In answer to the first question, only loosely constrain those station coordinates that are known to at least an order of magnitude better than the applied a priori standard deviation. In answer to the second question, what is relevant is the ratio of a priori variance to the variance computed in the absence of constraints. We note that the location of the network with respect to the geocenter (a net translation) can be particularly sensitive to indiscriminate application of a priori constraints, so we place a note of caution here. For example, if an *a priori* constraint of 10 cm is applied to all coordinates of a 25 station network, this effectively constrains the net translation to 10/~= 2 cm, which may be comparable to the formal standard deviation computed using the data alone (with no a priori constraints), thus significantly biasing the solution towards the nominal geocenter. We therefore simply recommend that (i) at least 3 stations (but < 100) be loosely constrained with a 10 meter a priori standard deviation, and that constraints should only be applied to stations whose nominal values are consistent with ITRF to better than a meter.

Regional Analysis. For regional network estimation where station coordinates are all estimated, the scale, orientation, and origin are defined by fixing the supplied orbits and polar motion. However, the network is not well tied to the origin for regional sized networks since a net translation is strongly correlated with the satellite clock parameters.’ One way to deal with this problem is to use the globally determined clock parameters, and not estimate the satellite clocks. However, this method is not likely to ever be as precise as including a station whose position is routinely estimated in global analyses (a “common” station). In addition, we recommend at least 3 common stations so that network orientation and scale can be monitored and corrected, and so that network distortions caused by remaining orbit errors can be corrected to first order.[8] In practice, a regional center can immediately produce a solution for it’s own purposes by constraining the coordinates of the 3 common stations to the ITRF. From the IGS point of view, it is important to receive the fiducial-free regional solutions because the common station coordinates themselves improve in time as more global solutions accumulate, and it is important to properly propagate those changes into the regional solutions. It is also important that the IGS

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[5] A 1-rank deficiency is caused by perfect correlation between station longitude and the ascending node Of the satellite orbits, and an additional 2-rank deficiency is caused by a perfect correlation between the X and Y pole parameters and a global rotation of station coordinates about the X and Y axes.

[6] Actually, no-constraints should be applied if solutions are represented by normal equations or SRIF matrices, as will be discussed in section 3.3.

[7] An equivalent point of view is that in the limit of short baselines, the direction to the satellites is the same for both stations, hence both stations can move together without significantly affecting single-differenced observations from the same satellite.

8$_9$common station coordinates give 3 origin parameters+ 1 scale + 3 orientation angles + 2-dim. strain.

receive the freely estimated locations of the 3 common stations, since they provide a tool to probe systematic orbit errors as they affect different geographical regions, Our recommendation to regional analysis centers is the same as for global analysis centers: the 3 (or more) common stations should be constrained with an a priori standard deviation of 10 meters, but the nominal values should be consistent with the ITRF at the level of 1 meter or better,

3.2 *Combination of regional and global coordinate solutions*

We have already outlined the fiducial-free approach and why it is important for the combination of regional and global coordinate solutions. The implicit assumption is that regional networks will add very little additional information to the determination of orbits or EOP. We should also note that it would be undesirable to adjust further the globally determined "common station coordinates" based on regional network solutions, because the same data would be used twice. Therefore, in combining regional with global solutions, we recommend that the global estimates for the common stations and their covariance matrix elements remain unperturbed by the regional solution, and that the solution be only augmented by those regional stations that are not common stations. Before augmentation, however, the common station estimates in the regional solution should be combined with the global solution in order to ensure reference frame consistency. Many of the details of the combination should probably be left to the NAC'S to develop, since it is not an entirely theoretical question and techniques will undoubtedly evolve as NAC's gain more experience with real data, Some of the issues that need to be addressed include relative weighting schemes, treatment of outliers or problematic solutions, minimal constraints, treatment of network distortion of common stations in regional solutions, etc. More complicated schemes will be able to derive, by backsubstitution, transformations, etc., a complete time-series of both global and regional station coordinates, and polar motion in a consistent reference frame.

What we do need to decide on is a parameterization and a format to submit fiducial-free solutions. This is a difficult problem due to differences in software packages.

3.3 *Parameterization of submitted solutions*

Parameterization should be flexible given that different software packages work in fundamentally different ways. Both the file name and file header will indicate what type of parameterization is used. The file name is important since it is useful for scripts to handle. The file header is important as a consistency check for the reading program.

(i) We should consider allowing both Cartesian (X, Y, Z) and spherical coordinates (spherical latitude, longitude, and radius). An alternative to this is to allow only Cartesian coordinates (as recommended by IERS), which would mean that centers such as GFZ who use spherical parameters would have to reformat their solutions. GFZ argues that spherical parameters have the advantage that they are more natural for imposing certain a priori constraints (e.g., orientation). Cartesian parameters have the advantage that they have homogeneous units, and are more natural for imposing certain a priori constraints (e.g., translation).

(ii) We should consider allowing three types of solution representation.

(a) The most basic representation has the parameter estimates x, and the variance-covariance matrix $M = (A^TCA)^{-1}$. The covariance matrix is more compactly written as the correlation matrix (because elements are from -1 to +1), augmented with the standard deviations. This is convenient for looking at an unfamiliar solution before deciding what to do with it (e.g., to perform some acceptance test). The disadvantage is that loose a priori constraints must be applied for every fiducial-free solution in order to remove the rank deficiency problem when computing the covariance matrix. Another disadvantage is that M must be inverted to form the weight matrix every time solutions are combined. This is not as serious a disadvantage as it might seem at first, because in practice, methods (b) and (c) below also require a matrix inversion if the solutions are to be checked prior to combination.

Examples of systems that currently use representation (a) include STAMRG (and some other GIPSY modules) [*JPL*, 1993], and GLOBK (MIT program for combining loosely constrained solutions from GPS and VLBI experiments [Herring, 1993; Dong, 1993; Feigl et al., 1993].

(b) A traditional representation in geodesy is the system of normal equations, including the coefficient matrix $N = A^TCA$ and the vector of normalized estimates $u = A^TCz$. This is more computationally efficient for combining solutions, since no inverses need to be calculated until the final solution is desired, Technically, no a priori constraints are necessary until the last step; however, as pointed out above, it is likely that, in routine operation, an inverse will be taken for purposes of acceptance testing.

An example of systems that currently use representation (b) is the GFZ software[*Zhu et al.,* 1993].

Going from system (b) to system (a): $M = N^{-1}$ and $x = N^{-1}u$
Going from system (a) to system (b): $N = M^{-1}$ and $u = M^{-1}x$

(c) A traditional representation in space navigation, closely related to (b), is the square root information formalism (SRIF) [*Bierman,* 1977], including information matrix $R = HA$, where H is a householder transformation designed to make R upper triangular, and the vector of normalized estimates $y = Hz$. This is the most numerically stable representation. When using normal equations, a computational precision is required that is equal to the square of that needed when using SRIF [*Vanicek and Krakiwsky, 1986*]. Like (b), no inversion is required until the last step, with the additional advantage that inversion can be very rapidly achieved using back substitution. Like (b), no a priori constraints need be imposed until the last step, but unlike (b), valid solutions can be computed for observable parameters even if rank deficiencies exist. Partial inversion for a subset of parameters is easy (by inverting only the lower right hand corner). It is less convenient than (a) for preliminary acceptance testing, but conversion to (a) is computationally quick (see below).

Examples of systems that currently use representation (c) include AMBIGON (and some other GIPSY modules) [*Blewitt,* 1989]. The SRIF method was used to combine global and regional GPS solutions by *Lindqwister et al. [1991].* Although the GIPSY module for network combination (STAMRG) currently exchanges files in representation (a), all internal computations are done after conversion to (c).[9]

Going from system (c) to system (a): $M = R^{-1}(R^{-1})^T$ and $x = R^{-1}y$
Going from system (c) to system (b): $N = R^TR$ and $u = R^Ty$

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[9] JPL uses Bierman's Estimation Subroutine Library ("ESL", public domain, FORTRAN) to perform the square-root factorization in going from system (a) to system (c), and the back substitution for R^{-1} [*Bierman, 1977*].

3.4 *Format of submitted solutions*

We acknowledge that there is work in progress by several individuals on working towards a universally acceptable solution format (J.T. Freymueller, T. Herring, R.W. King, and R. Noomen, private comm.). Rather than explicitly define a format, we prefer at this point to list the information content that we think the file ought to contain. For now, we discuss only GPS solutions, but it should be a relatively small step to allow, for example, VLBI, SLR, LLR, trilateration, and triangulation solutions. For all techniques, our previous comments on the importance of fiducial-free solutions are relevant (for example, no datum constraints in the case of traditional geodesy). The following guidelines have been written for representation (a) above, but can be easily adapted for representations (b) and (c). We recommend that:

(i) The format be ASCII, with up to 80 characters per line.

(ii) The covariance matrix be represented as an upper triangular correlation matrix where the diagonal elements are the standard deviations. The upper triangular array is written out column by column (write column *i* for all rows 1 to *i* before moving to column i+ 1) so that the position of the matrix element is independent of the number of parameters. Since parameters can be very correlated in free-network solutions, correlation coefficients should be quoted to 15 significant digits.

(iii) Each component of the estimate vector be the **full** estimate, meaning that it is the a priori plus the delta estimate. This approach is attractive since it is likely that different groups will use different a priori values, and we only need to know the full estimate when combining solutions. (assuming they are close enough for validity of linearity), and (e.g., when a new station comes on line). For the record, a priori values and their constraints (a priori standard deviations) should also be stored in the file. This might be useful, for example, if it is suspected that the basic assumption of linearity might be violated, or if a priori constraints might have had a significant and undesirable effect.

(iv) The estimate refer to the monument, except for those cases where the ARP (antenna reference point) is defined to be the monument.

(v) The basic unit be the meter for coordinates, radians for X and Y polar motion, and seconds for LODR.

(vi) Each file include for every station identifier the eccentricity vector from the monument to the ARP, and the assumed LC phase center offset, and the starting date for this information (to allow for changes in antennas). This information needs to be given explicitly because eccentricity vectors and phase center offsets may be in error, may be inconsistent between groups, or may get updated by new surveys or antenna measurements. In addition, a flag can be optionally set to indicate any removal of redundant information (as explained towards the end of item vii below).

(vii) Standard 6-character station identifiers be used in the station coordinate parameter names. Characters 1-4 should uniquely identify the monument. Characters 5-6 should be an "occupation number," used to force separate solutions for different epochs. In the context of permanent networks, the "occupation number" needs to be changed only if the station undergoes co-seismic displacement, or if the antenna is moved or changed. In the traditional context of field campaigns, this number might be used to identify experiment number. Note that every 6-character station identifier must have the information specified in item (vi) above. Note also, that if the antenna offset is changed in a known way, then this constraint can be applied as a last step. In the limit that the offset change is perfectly known, the two solutions will be adjusted to the same value (since they both refer to the same monument). In this case, it is acceptable to remove the redundant information so long as a flag is set to indicate this along with the information given in (vi) above. This flag indicates that more than one antenna height or type was used for that estimate, and therefore the eccentricity information given in this file is incomplete.

(viii) The header of the file include the epoch of the solution, start and stop time of input data, number of parameters, institutional identifier, date produced, a flag to indicate whether or not velocity parameters are included, a code number to indicate presence and types of constraint, a unique solution identifier, a quality control code, and optionally a descriptive character string. A solution "type" identifier will indicate whether representations (a), (b), or (c) are used (see Section 3.3), and whether Cartesian or spherical coordinates are estimated, An ambiguity resolution identifier will indicate whether the solution has been bias-fixed (integer carrier phase biases) or remains bias-free (real-valued carrier phase biases).

3.5 *Combination of orbital parameters and "sister solutions, "*

Fixing the regional orbits to that of the global solution leads to the problem that some satellites are better determined than others, and this information is no longer propagated into the regional solution. One consequence is that the regional covariance matrix will be artificially reduced. Another consequence is that the effects of badly modeled satellites will be amplified in the regional solution. The first problem can be partly mitigated by ad hoc resealing of the covariance matrix, or equivalently, by inflating the assumed data noise. The second problem might be partly mitigated by applying different weights to data from different satellites; however, the validity of this approach is questionable. On the other hand, it is clear that a very badly modeled orbit should be eliminated completely from the regional solution. Therefore, it is important that **GAC's** agree upon some method of indicating orbit quality.

Another approach is to combine not only station coordinate parameters, but also orbital parameters and EOP between regional and global solutions [***Lindqwister** et **al.**, 1991; **Dong,*** 1993; ***Feigl*** et *al.*, 1993]. This will formally propagate orbital errors into the regional network solution. This approach is not as convenient from the point of view of the user, who must now estimate all the orbital parameters. Moreover, it is not clear how to do this properly unless (i) the RAC is using exactly the same software as the GAC, (ii) the same nominal orbital parameterization is used at the same starting epoch (e.g., is solar radiation parameterized the same way?) , and (iii) the same nominal EOP series is used. The use of stochastic orbit parameters makes this scheme even more difficult. Nevertheless, IGS should be prepared to accommodate those RAC'S who might cooperate with GAC's in this way, because in principle such regional solutions are more rigorous, and it may be useful to assess the relative performance of such solutions versus those using fixed IGS products.

In the case that RAC'S and GAC'S cooperate to combine orbital parameters, we recommend that the RAC and GAC cooperate in forming a NAC, and prepare and submit the fully combined fiducial-free solutions themselves. In addition, the regional solution could be submitted separately from the global solution provided the file header contains information so that the necessity of pairing the two solutions is apparent. We recommend an identifier that states the name of its "sister solution(s)." It might be convenient to submit sister solutions for those users who are only interested in, say, the global portion.

A complication arises when the global free-network solution is computed and submitted first, followed by a later computation of a regional sister solution, The problem is that backsubstitution of the orbital parameters has not taken place for the global solution. Therefore, in order to ensure that the two free-network sister solutions have the same orientation, it is necessary to impose minimal rotational constraints on the global network covariance matrix (not the estimates!) prior to combining orbital parameters. This will ensure that the orbits will not rotate as a result of the combination. Perhaps this should be an option, and another flag could indicate whether or not reference frame orientation is consistent between the sister solutions. If not, the NAC's can still use the 3 common stations to ensure orientation consistency.

3.6 *Global calibrations for clocks and tropospheric delay*

Clock Calibration Clock solutions produced by GAC'S have several uses for RAC'S. (i) Some software packages initialize satellite clocks as the first step, and it would be preferable to use the most precise solutions available. (ii) Some packages (e.g., GIPSY) use a reference clock in order to realize coordinate time, and in this case it would be most useful if a good nominal clock solution were available for one of the "common stations" in the regional network. This will ensure consistency between coordinate time for the regional solution and the coordinate time for the global solution (i.e., the orbits will appear in the right place at the right time!). We therefore recommend that both satellite clocks and station clock solutions be available to RAC's, so that both philosophies of data processing can be easily accommodated. Minor modifications of the major software packages maybe necessary to read in these precise clock solutions and perform interpolation as necessary.

Tropospheric Calibration. It would also be beneficial for RAC's to calibrate tropospheric delay at one of the common stations, based on GAC solutions. This is especially important for smaller regional networks, where only a weak solution for absolute tropospheric delay can be obtained from the regional data alone. Two possible approaches to tropospheric calibration are given. (i) GAC's provide a line of sight tropospheric delay for every data point from a given station, These calibrations could be provided along with the data record in the RINEX file, or alternatively calibrated RINEX files could be provided; (ii) the zenith tropospheric delay is given (both wet and dry components) at fixed time intervals (say, every 30 rein) which can then be interpolated by the RAC, on the understanding that the RAC applies the appropriate wet and dry mapping functions.

We favor option (ii) since it becomes much easier to compare tropospheric calibrations between GAC'S. We note that tropospheric estimation is done very differently by different GAC'S, for example; some have a new constant zenith troposphere parameter over a fixed interval of hours, some estimate the zenith troposphere as a random walk process, and it is allowed to vary every data epoch. It is unlikely that differences in mapping functions will cause a problem for data above 15 degrees elevation. These differences should be much smaller than the ability of the regional GPS data themselves to resolve the absolute tropospheric delay.

3.7 *"Noise-Calibrated Pseudorange"*

The following discussion illustrates that much research can be done with regard to integrating regional and global solutions. We should acknowledge that the technical issues are quite complicated and techniques are likely to evolve and improve over the next few years, so IGS must be careful not to fix its mode of operation prematurely.

The concept of GAC'S producing "clean" data has been around for a while, but "clean" in this context has meant free of cycle slips and outliers. We can extend this concept by noting that post-fit residuals from GAC solutions are very good estimates of the actual data errors, and can therefore be used as calibrations to produce common station data that has substantially reduced noise.

Theoretically, if we calibrate data for the post-fit residuals and feed only a subset of that calibrated data back into the estimation process, it can be easily shown that we get exactly the same solution (provided there is sufficient data to prevent a rank deficiency). Therefore, we can think of this calibrated data set as simply a different representation of the GAC's solution. Note that there is no reason to use carrier phase any more: we can just as easily calibrate the pseudorange data provided the GAC has reduced the pseudorange and carrier phase data simultaneously in the filter. We therefore no longer have to estimate carrier phase ambiguity parameters when reusing this "noise-calibrated pseudorange."

When using such calibrated data for a common station in a regional network, it is important to heavily weight that data relative to the raw data from other stations. Theoretically, one might expect that the determination of a baseline from a regional station to a common noise-calibrated station will be improved by $\sqrt{2}$. In practice, we should recognize that the post-fit residuals we would have obtained were the regional station in the global solution, would have been correlated to some degree. These correlations can arise, for example, from orbit mismodeling or antenna phase center variations. Such correlated errors will be absorbed in part by the satellite clock parameters when computing the regional solution (or equivalently, will be difference away). But there is a potential problem when we calibrate the noise from only one station's data when that noise is correlated with a nearby station. The regional solution can no longer absorb this correlated component of error.

Hence the question of how much improvement can be expected depends upon the degree to which post-fit residuals are correlated, and can only be answered by tests with real data, which will be done shortly. It is potentially a powerful tool for reducing multipath effects at the common sites.

4. EXAMPLES

4.1 *Introduction*

An examination of the current list of operational IGS tracking stations (Figure 7) reveals that several distinct regional clusters are already in operation today, e.g., The "Western European cluster", the "Canadian cluster" the Western Canadian Geodetic Array (WCDA) [*Draggert et al., 1993]* in British Columbia, and the Permanent GPS Geodetic Array (PGGA) in southern California, The first two clusters serve primarily as active control networks while the latter two clusters have been designed to study the kinematics of plate boundary deformation and can be considered among the first IGS customers. In this section we present several scenarios and examples of distributed processing by referring to PGGA/IGS activities at Scripps Institution of Oceanography (S10). In the nomenclature of this paper, S10 plays the role of a GAC, NAC and RAC.

4.2 The *Permanent GPS Geodetic Array*

The Permanent GPS Geodetic Array (PGGA) is a network of continuously operating P-code receivers providing an uninterrupted record of crustal motion in near real time (Figure 7) [*Bock and Shimada, 1990; Bock, 1991; Lindqwister et aL, 1991],* Stations are spaced approximately 100 km apart to span the Pacific-North American plate boundary in southern California. The ability of the PGGA to monitor crustal deformation due to seismicity was demonstrated during the Landers earthquake sequence in June 1992, when small far-field coseismic displacements were accurately detected at all PGGA stations with respect to the

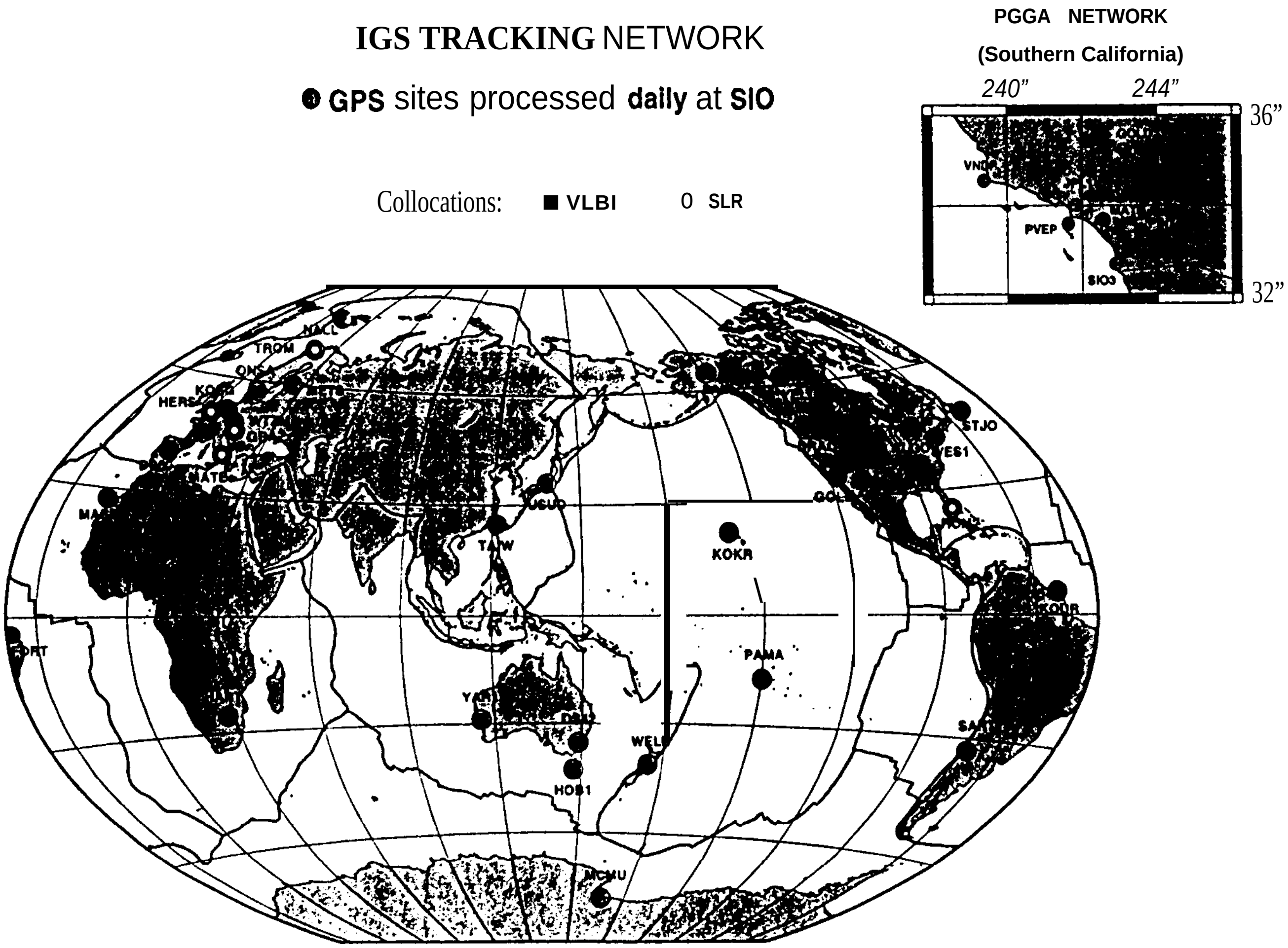

Figure 7. Permanent global tracking stations of the International GPS Service for Geodynamics (IGS) and the Permanent GPS Geodetic Array (PGGA) in southern California.

International Terrestrial Reference Frame realized by the coordinates and velocities of the IGS tracking stations [*Blewitt* et *al.*, 1993; *Bock et al.*, 1993]. Fortunately, the IGS began its test campaign several weeks before the Landers earthquake sequence so that the global tracking network was quite robust. The PGGA results were the first demonstration of sub-centimeter-level computation of coseismic displacements with respect to the ITRF and demonstrated the synergism between regional clusters and the IGS.

In August 1991, S10 began analyzing data from the PGGA on a daily basis. In order to compute precise satellite ephemerides, data from the available global tracking stations (pre-IGS) were analyzed simultaneously with the PGGA data, Initial solutions of PGGA and global data included a manageable number (15-20) of regional and global stations and 15 satellites so that the simultaneous analysis of all station data was straightforward. By the time of the Landers earthquake the total number of stations had increased to 25 with 18 satellites, still a manageable number for a simultaneous analysis. Today the IGS Global Data Centers archive data from over 50 stations and 25 active GPS satellites. S10 currently analyzes 32-35 stations in a simultaneous adjustment of 24-hour sessions, including both PGGA and global IGS data. With current processing schemes, top-of-the line scientific workstations and abundant disk space, the daily, simultaneous analysis of 35 stations is still manageable. However, as the number of stations increases above this number, the computation time and disk-space requirements are approaching a critical stage. Considering that we expect the number of PGGA stations to increase by at least five stations over the next few months and that several useful global stations will come on line, we have begun tests on distributed processing of PGGA and IGS data. Initial results from these tests are described below.

4.3 *Distributed Analysis: One Approach*

Analysis tools. The PGGA and IGS data are currently adjusted simultaneously at S10 in independent twenty-four hour (0-24^h UTC) segments using the GAMIT GPS software [*King and Bock*, 1993]. A weighted-least squares algorithm is used to produce a series of tightly-constrained and loosely-constrained solutions including the estimation of station coordinates, satellite initial conditions, tropospheric zenith-delays and phase ambiguity parameters [e.g., *Feigl et al*, 1993]. The adjustments and corresponding variance-covariance matrices for the station-coordinate parameters are output from the tightly-constrained adjustments in a format suitable for a standard weighted least squares network adjustment of station coordinates from both ambiguity-free or ambiguity-resolved(biases-fixed) solutions [e.g., *Bock et al., 1985; Dong, 1993].* In the loosely-constrained adjustments (also output for ambiguity-free and ambiguity-fixed solutions), the portion of the variance-covariance matrix for station and orbital parameters is recorded in an auxiliary file, henceforth referred to as a "solution file." In this representation, the underlying terrestrial reference frame is essentially undefined (a free network adjustment), although the physical models are implicit in the partial derivatives that were used to form the variance-covariance matrices (as is the case, of course, for the tightly constrained adjustments).

The solution files can then be manipulated to estimate any combination of station positions and velocities, orbital elements and earth orientation. This is done with the GLOBK software *[Herring,* 1993] which uses a Kalman filter formulation *[Herring et aL,* 1990] to combine the auxiliary files, with the ability to treat each type of parameter stochastically. This approach allows us the combination and, if necessary, the quick re-analysis of many daily IGS/PGGA solutions (we've generated at S10 almost 1000 of these daily solutions) using different terrestrial reference frames and with different station/orbital/earth orientation constraints. (Of course, if we would like to modify the underlying physical models then the individual, daily GAMIT solutions would need to be repeated, a formidable but not impossible task for 1000 days of data). Furthermore, this approach allows for the combination of data from many regional clusters, in combination with the global tracking stations (i.e., distributed processing).

The system developed at S10 for GAMIT/GLOBK users can be viewed as a prototype for one possible way in which IGS can support campaign-type surveys and regional clusters. S10 archives each day the following information:

(i) “clean” RINEX files for the PGGA and global tracking stations. Although GPS software packages provide “automatic” cycle-slip fixing algorithms, there are frequent anomalous conditions when human interaction is required. Providing access to clean RINEX data for a robust global (and California regional) network provides a considerable time savings for principal investigators, regardless of the software package, but particularly for packages that examine doubly -differenced phase measurements (e.g., Bernese, GAMIT).

(ii) Coordinates and velocities for the IGS and PGGA stations in the current standard global reference frame.

(iii) The GAMIT/GLOBK solution files. These files are an invaluable resource for the analysis of regional networks since they contain the complete geodetic content of the global tracking network, as described in this proposal. Once a standard software-independent exchange format is adopted for solution files this information will be readily available to all users and GPS data processing packages.

(iv) precise ephemerides in a short ASCII file that includes a set of 9 initial conditions (six state vector elements of position and velocity, and three radiation pressure parameters) for each satellite at the midpoint of each day (12:00 UTC). Since all GAMIT users use the same orbital integration program, it is a simple manner to generate a tabular ephemeris for a particular survey. This of course reduces the amount of orbital data that needs to be transmitted via electronic mail, compared to the transfer of many times larger NGS SP3 formatted files which are made available to the general user. An Earth orientation file based in the S10 analysis is also circulated,

4.4 *Distributed Analysis — Four Scenarios*

Scenario 1. This is a zeroth order example of distributed processing and the IGS concept, A surveyor goes to the field in southern California with one receiver knowing that the PGGA/IGS network is operating continuously, The current distribution of stations insures that any user in southern California will be within 100 km of a PGGA station. The surveyor occupies a set of stations in some GPS surveying mode (e.g., static, rapid-static) for a specified time depending on the application and accuracy requirements. At the end of the survey, the following information is copied electronically from the PGGA: RINEX data for the one or two closest PGGA sites, satellite ephemerides in NGS SP1 or SP3 format, time-tagged station coordinates (ITRF) for the reference PGGA site. Using this information and any of the scientific or commercial GPS software packages, the user computes station positions using the satellite orbits and PGGA station coordinates as fixed. This is a simple straightforward procedure in which PGGA/IGS plays strictly a service role. Depending on the length of time of a particular survey and assuming that standard field procedures have been followed, the station coordinate information can be used by geophysicists to study crustal deformation. This information could be retrieved in the form of solution files, in this case, strictly the solutions and variance-covariance matrices for station coordinates which could easily be integrated with the PGGA/IGS solution files.

Thus, there is the potential of feedback to the scientific community in return for the service role provided to the surveying community. With a sufficiently dense network in southern California, satellite clock information, tropospheric and possibly ionospheric corrections could also be made available.

As an example of this scenario, we choose the two newest stations in the PGGA, Lake Mathews in Riverside County and Pales Verdes in the Los Angeles Basin, about 90 km apart (Figure 7). We consider Lake Mathews the known site (base station) and Pales Verdes a new site to be surveyed. The surveyor requires the base (RINEX) data for Lake Mathews and Pales Verdes, the (time-tagged) coordinates of Lake Mathews and the IGS orbits for the period of the survey. Figure 8 demonstrates the precision that can be obtained in this scenario for the coordinates of the Pales Verdes site with a single 24-hour occupation. It shows the time history of 4 months of daily solutions using GAMIT, S10 orbits (generated independently of these two sites), and ITRF91 coordinates for Lake Mathews. The rms scatter of the baseline components from is 2,6 mm in north, 3,4 mm in east, and 13.9 mm in the vertical, which is more than an order of magnitude better than using the broadcast ephemerides [*Zhang*, 1993].

As another example, *Tsuji et al.* [1993] use the JPL precise ephemerides (as distributed by the IGS) as fixed parameters, and estimate the daily coordinates of a regional network of Minimac receivers in Japan for a period spanning June 1992 to August 1993. The global network site, Usuda, was also used as a single "common station" in the regional analysis. The resulting regional baseline was reported to be 1 to 2 parts in 10^8 in all three components over distances of 1000 km. The cpu time for the daily data reduction of the 5-station regional array was 10 minutes using the GIPSY/OASIS-II software on a HP9000/735 workstation, which is over an order of magnitude less time than it would have taken with a full global approach.

Scenario 2. A multi-year project measures crustal deformation by running several week long, epoch-type campaigns every 1-2 years. To analyze a campaign IGS (clean RINEX) data simultaneously visible from the surveyed region are retrieved, including station coordinates and velocities, satellite initial conditions for the days of the survey, and the solution files from the global IGS analysis. The survey data are analyzed simultaneously with the regional subset of the IGS data with orbit improvement to produce a second set of solution files, using the same physical models (software) and the epoch of the satellite initial conditions. The two sets of solution files can be combined easily to produce a set of coordinates for the survey stations with respect to the ITRF. Station velocities are computed by combining repeated measurements of the crustal deformation network.

As an example, we refer to an ongoing project to measure crustal deformation across the tectonically active Indonesian archipelago [*Puntodewo* et *al.*, 1993]. In 1991 and 1992a 6-station network was surveyed in Irian Jaya, the western part of the island of New Guinea, spanning the plate boundary between the Australian and Pacific Plates (Figure 9). In 1991, the data were analyzed in a simultaneous adjustment of global tracking and regional data since the total number of stations was manageable. In 1992, the analysis was divided into two steps. In the first step, the Irian Jaya data were analyzed (10 stations in 1992) with data from all IGS stations that had mutual visibility with those sites. Since the complete IGS data set analyzed at S10 was available in clean RINEX format, it was an easy exercise to clean the Irian Jaya data with the subset of the IGS data (incidentally, this ensured that the data could be processed later in any combination without any further editing). Initial conditions for the satellite state vectors were obtained from the IGS orbits and a simultaneous adjustment of the Irian Jaya and regional IGS data with orbit improvement was performed. Using three sets of solution files (the 1991 set, the 1992 total IGS set, and

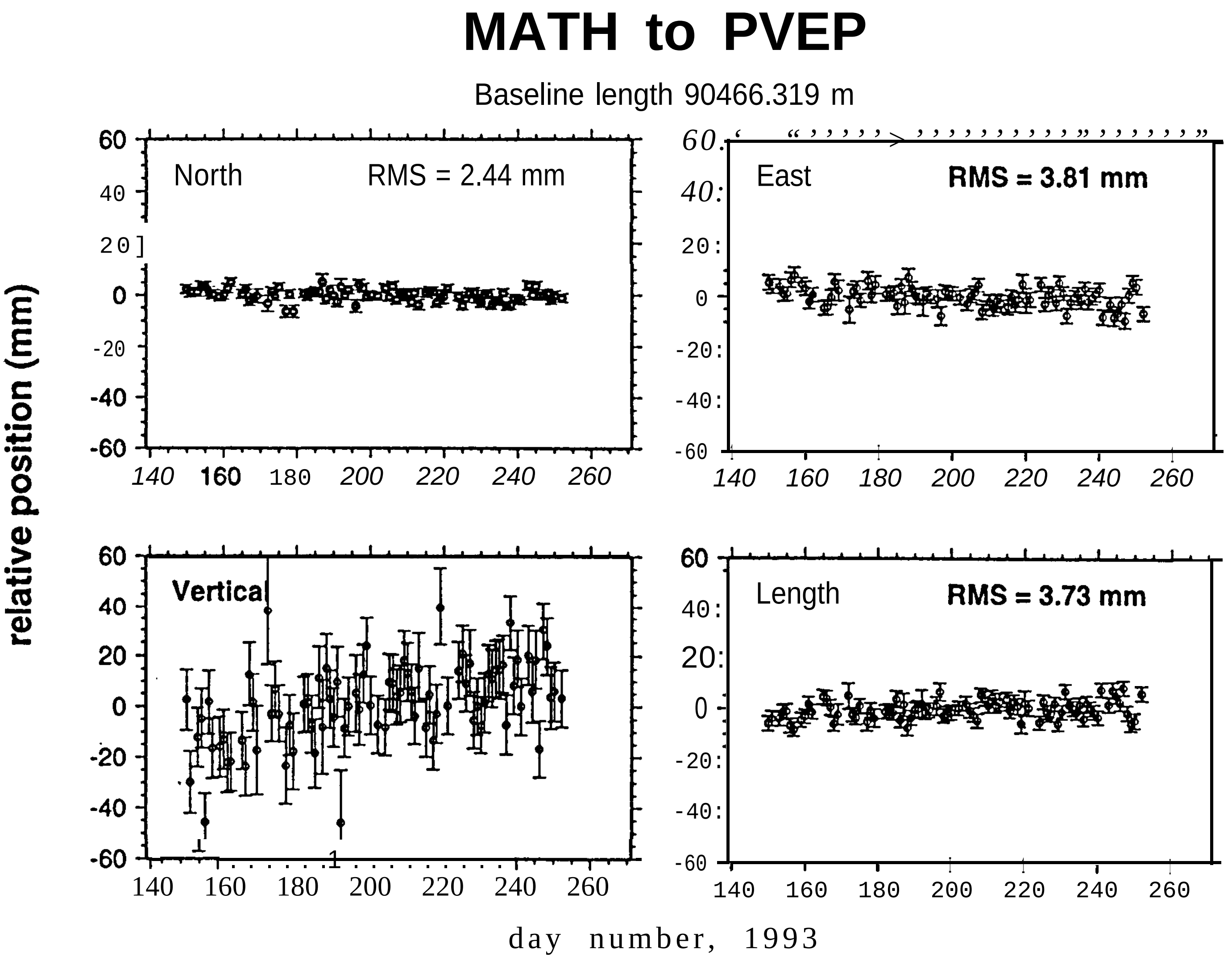

Figure 8. Time series for daily baseline determinations between the PGGA sites at Lake Mathews (MATH) and Pales Verdes (PVEP), in terms of north, east, and vertical components and length. Each point represents a solution based on 24 hours of data.

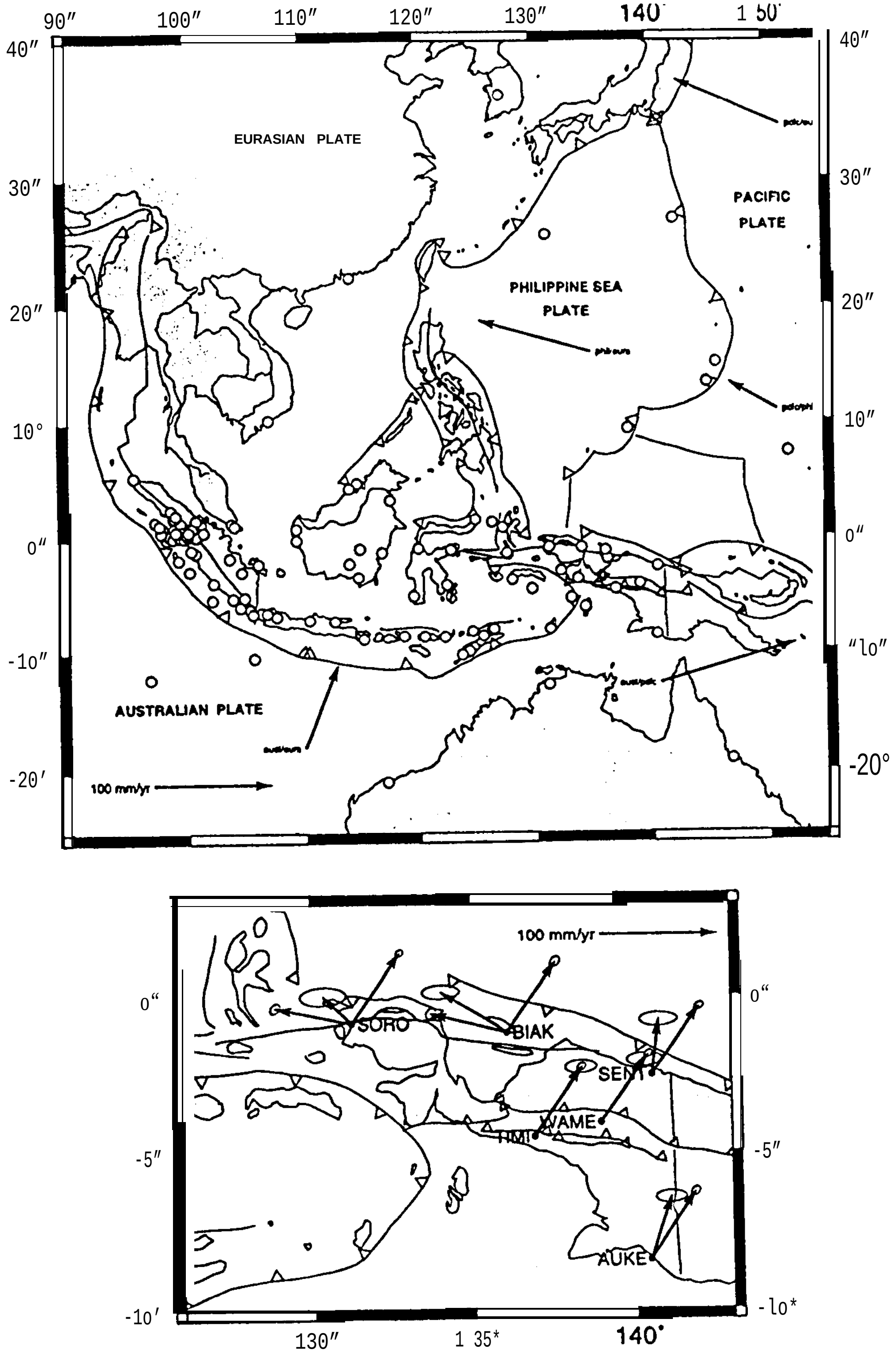

Figure 9.'(Top panel) Tectonic setting of Southeast Asia. Open circles indicate regional sites surveyed by GPS from 1989 to 1993. (Bottom panel) Irian Jaya, Indonesia and 6-station GPS network. GPS velocity vectors and one-sigma error ellipses are indicated for the 1992-1991 time period, in theITRF91 reference frame which adopts the no-net-rotation (NNR) NUVEL-1 plate motion model of Argus and Gordon (1991).

the 1992 regional IGS and Irian Jaya set) positions and velocities of the Irian Jaya stations were estimated with respect to ITRF91 and the NNR plate motion model *[Argus and Gordon;* 1990] (Figure 9). This approach allows us to integrate solution files from other experiments performed in Indonesia and surrounding areas in a similar straightforward matter [*Calais et al.,* 1993]. We have done this, for example, for a series of annual measurements across the Java Trench between Christmas Island and Java [*Tregoning et al., 1993]* and in the Flores Sea [*Genrich et al.*, 1993],

It is clear that with this approach diverse regional experiments taken at different time periods with a total of hundreds of stations can be combined in a uniform manner with respect to ITRF. Solution files can be exchanged between different analysis groups to develop a coherent picture of tectonic motion over a larger region than any one project provides. As long as the underlying physical models are not changed, the solution files can be analyzed many times as the ITRF improves with time. This is an example of distributed processing within the context of a single global IGS solution.

Scenario 3. There are two regional clusters in California for continuously monitoring crustal deformation, a southern California array and a northern California array, each of 20 stations. Each array does its own regional analysis. The southern California array acquires the clean RINEX data from the IGS analysis center which are analyzed simultaneously with two of the regional stations, producing expanded solution files. In a separate analysis the complete set of southern California stations are adjusted together with two stations of the northern California array. Thus the southern California analysis center produces two sets of solution files. The northern California analysis center analyzes all data from its own array including the overlapping stations analyzed by its southern California counterpart and produces another set of solution files. All three sets of solution files can then be input to a GLOBK-type program to produce a daily set of coordinate solutions for both southern and California arrays, with tight constraints applied to the global IGS stations.

To demonstrate this concept, we refer again to *Blewitt et al. [1993]* and *Bock et al. [* 1993]. Both analysis groups were able to determine “absolute” displacements of the PGGA stations using different software, processing algorithms and physical models, demonstrating that distributed processing is feasible. Both groups analyzed the PGGA and IGS data simultaneously. However, at some point the number of PGGA and IGS stations will grow to a point that it will not feasible or efficient to continue to do this. Therefore, we test whether we could have obtained the same results using a distributed processing approach. The Landers data were re-adjusted in two steps using the clean RINEX data from the original analysis in which both data sets were adjusted simultaneously [*Zhang*, 1993]. In the first step, the data set that included the entire IGS global data set was re-adjusted simultaneously with data from two PGGA stations (DS 10 and JPL1) generating a daily solution file for the five weeks before and after the earthquakes, In a second step, all the PGGA data (there were 5 stations operational at that time) were adjusted independently and simultaneously, generating a second set of solution files. Both sets of solution files were analyzed with the GLOBK software using the same station constraints for the global IGS stations as in *Bock et al. [1993].* The coseimic displacements estimated from this distributed approach were statistically equivalent as indicated in Figure 10.

In another test of distributed processing with the PGGA, *Lindqwister et al. [1991]* analyzed an unbiased selection of 23 daily sets of measurements spanning 8 months in 1990. A major concern was that the CIGNET tracking network at that time was instrumented with MiniMac 28 16AT receivers and antennas, and the PGGA with Rogue SNR-8 receivers. In an attempt to reduce the effect of different phase center variations between the two types of antennas, the data from each network were reduced separately, and then orbital elements were combined (3 epoch positions, 3 velocities, and 3 solar

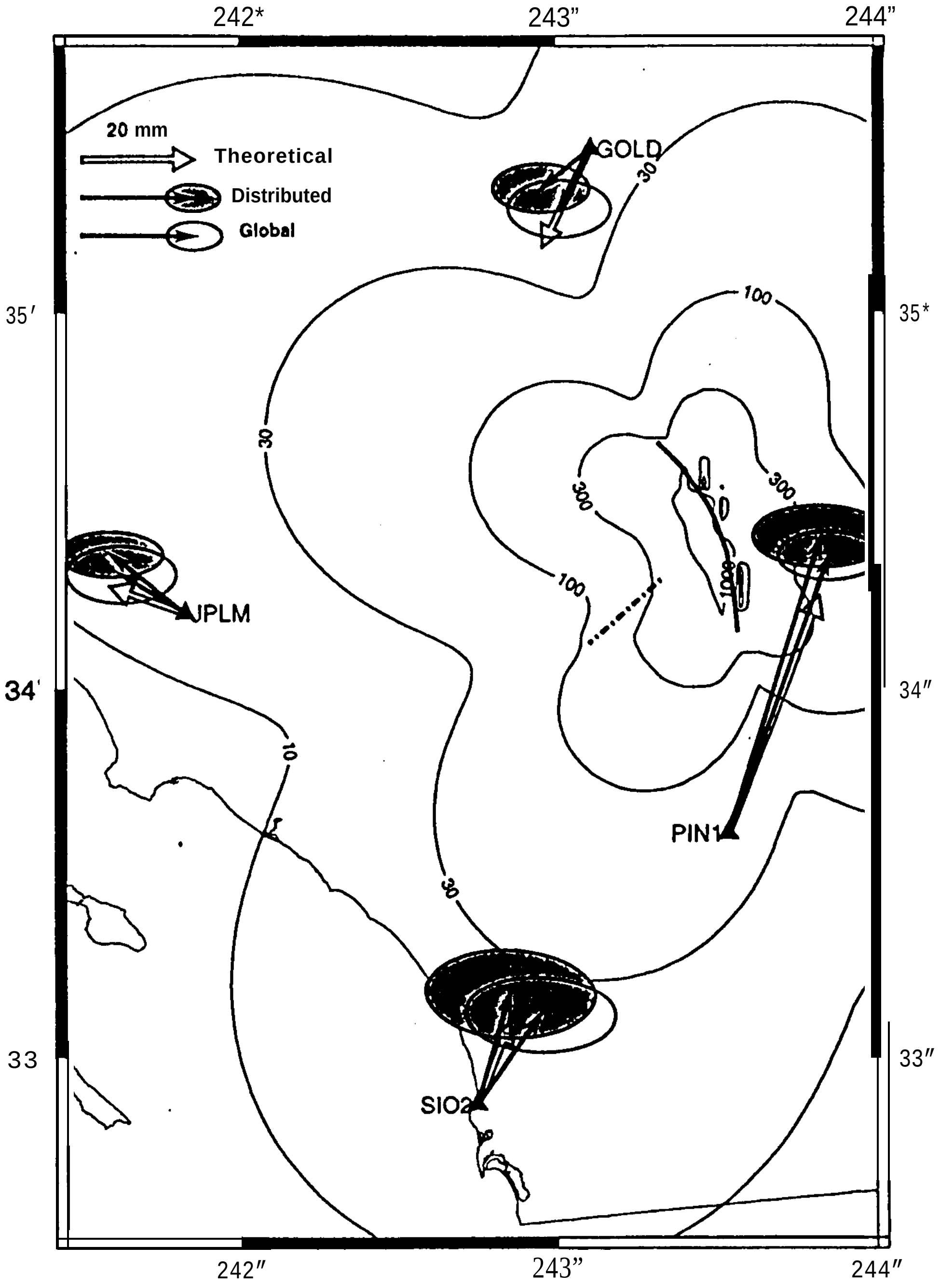

Figure 10. Observed (solid arrows) and modeled (blank arrows) displacements at four of the PGGA stations in southern California due to the Landers and Big Bear earthquakes of 28 June 1992. We show the displacements and 95% confidence ellipses computed processing the PGGA and IGS data in a simultaneous global solution (unshaded ellipses) and using the distributed processing approach explained in the text (shaded ellipses). The observed displacements are with respect to a global reference frame and, therefore, indicate absolute displacements of the California sites. The contours of displacement magnitude and the computed displacements are based on an elastic halfspace assumption for the behavior of the Earth's crust (all units mm). The surface trace of the Landers rupture is indicated by a heavy line and for the Big Bear earthquake by a dashed line.

radiation parameters for each satellite). They found that ambiguity resolution was not possible in the PGGA until after the combination of orbital elements, and that the resulting long-term repeatability of PGGA baseline coordinates was 3 mm in the north, 5 mm in the east, and 8 mm in the vertical. These number are actually representative of the level of precision obtained today with a full simultaneous regional/global network solution.

There are many combinations of adjustments that are possible in this scenario; we have presented one example. The only involvement of the IGS analysis center in this scenario is the passive role of making available (e.g., via anonymous ftp) the data and solutions to one of the regional analysis centers.

Scenario 4. The IGS has grown to 200 globally distributed stations. No analysis center is capable or willing to analyze all of these stations on a regular basis. The decision is made to distribute the processing load to several centers with overlapping stations. Each center produces a set of solution files which are adjusted at one analysis center to produce a single solution for all of the active stations, including one set of orbits, one set of earth orientation values and one set of station coordinates. The regional clusters are free to choose any combination of clean global tracking data and solution files from the analysis centers. Using the same approach as outlined in scenarios 3 and 4, the solution files from all analysis centers and regional clusters can be integrated at chosen intervals to produce a consistent set of coordinates (and velocities) for all stations with respect to the ITRF.

4.5 *Distributed Analysis: Complications*

In all of the above examples from S10 the same analysis software (GAMIT/GLOBK) was used so that the solution files were generated with the same physical models and using orbital arcs and earth orientation values consistent with the IGS analysis performed daily at S10. As long as the physical models (more specifically the partial derivatives in GAMIT used to form the normal equations) are not changed, the solution files from thousands of solutions and hundreds of stations can be re-analyzed with GLOBK in a very efficient manner. A change in the physical models (e.g., new parameterization of zenith delay parameters) requires that the solution files be re-generated with GAMIT. This is a fairly formidable task but can be done efficiently on state-of-the-art scientific workstations in a batch run, particularly if the individual solutions contain a manageable number of stations, which at the current state of the art is about 30-35. Since the clean RINEX files are available from earlier solutions there is no longer any data editing required.

As we have described in the earlier sections there are a number of complications in generalizing this approach and making it uniformly rigorous, for example: how to integrate the analyses of various regional and global analysis centers using different software packages, particularly when producing solution files with orbital parameters; how to avoid multiple use of data but preserve the connection to the global reference frame; how to properly weight solution files; how to check consistency of the solution files prior to combination.

5. **Broad Recommendations**

Specific recommendations for integrating the IGS global network and regional clusters have been presented in this paper. Here we summarize a series of broad recommendations.

(i) IGS adopt the concept of Regional Analysis Centers (RAC's) for the processing of regional clusters, and Network Analysis Centers (NAC's) for the combination of network solutions, and incorporates such centers into its structure. The details of "membership" need to be developed. It would be natural for RAC'S and NAC's to be, in official IGS terms, "Associate Analysis Centers."

(ii) GAC's produce and distribute, in addition to orbit and EOP solutions, "daily" fiducial-free network solutions, station and satellite clock solutions and tropospheric calibrations.

(iii) IGS encourage research into network combination, especially by the NAC'S which perform the routine work.

(iv) IGS develop and decide upon formats for the additional products described in this document.

(v) The type of activities sketched in this document begin as soon as possible, since the global network is very rapidly becoming unmanageable.

(vi) RAC's and NAC's send summary reports via IGSREPORTS e-mail, and send their products to the data centers.

(vii) IGS Central Bureau prepare itself for assessing contributions from GAC's, RAC'S and NAC'S, providing routine feedback, and providing general oversight to see that the new system evolves in a rational way. IGS Central Bureau (in consultation with IERS) is also responsible for overseeing the production of the standard frame.

(viii) IGS Central Bureau prepare itself for serving regional users (e.g., providing clear instructions, recommendations, help, etc.).

(ix) Data centers prepare themselves for the additional burden of making available the new products described in this document.

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SUMMARY OF SESSION 4

This session started with presentation of the third position paper which was also distributed to all Processing Centers the week preceding the workshop. The position paper, presented by Blewitt of JPL, was well prepared and addressed many relevant issues, including the research, organization and format requirements. The basic concept proposed is a nearly rigorous combination of regional clusters at the station level via reduced normal equations matrices ('fiducial free adjustments'). The second presentation, by Bock of S10 summarized the S10 approach to distributed processing and regional cluster integration. As pointed out by Bock, the simplest form of distributed processing is the utilization and fixing of the IGS (combined) orbits. In fact, such fixed orbit solutions can be viewed as a back substitution into a global (combined) solution, so the orbit combination discussed in Session 3 is the first and simplest step towards the distributed processing. Bock's presentation (not distributed before or during the workshop) which included some examples of distributed processing is to be integrated with Blewitt and Gendt's position paper for this workshop report.

During the discussions which followed, some concerns were voiced that undue work load increases for IGS Processing Centers may result from this undertaking. It is clear that the Analysis Centers cannot assume the responsibility for reducing and analyzing local (regional) network data. Most participants agreed that distributed processing, when properly designed and implemented, should only mean a minimal work load increase for current Processing Centers. Most additional work should be done regionally or at special Centers which were called 'Network Centers' in the position paper and which would be responsible for combining all regional station solutions. However, it was also pointed out during the discussion that there is no need to create a new IGS Center category as proposed in the paper, since all the pertinent functions are already included in the Associated Analysis Center category (see the terms of references). It was also recognized that IGS needs to foster and encourage regional analysis by stimulating research and providing guidelines. Furthermore, some representations at the governing board level which would specifically represent this effort would be greatly desirable.

The position paper suggests the combination at the station level, assuming that the effect of duplicate data and influence on global orbits is small and can be neglected. Another approach would be to do the combination at the orbit level. In this way only reduced normals from all global and regional orbits would be combined resulting in rigorous (global) combined solutions for orbits and EOP. The station solutions can then be obtained by back substitution, and this approach is in fact a rigorous orbit combination including the regional contribution as well. A combination of these two approaches is also possible. It is imperative, and it was agreed upon by all participants that all the Analysis Center should develop the capability of producing and distributing reduced normal ('fiducial free') solutions as soon as possible (some Centers have already developed this capability). For most Centers this will be the only additional effort resulting from the distributed processing.

It was also recognized that additional products, which may already be available at some Centers may be of considerable benefit to regional/distributed processing. More specifically, the tropospheric vertical delays, cycle slip corrected data, satellite and station clock solutions etc. Also some additional research is needed, e.g. the significance and mitigation of the overlap data (data used more than once) in distributed processing. The overlap data can be rigorously removed either at regional or global levels, but at significant computational cost increase. The requirements and desirability of a closer cooperation between IERS (ITRF) and IGS in particular with reference to the IGS distributed processing and ITRF reference frame maintenance were also discussed.

SESSION 5

(IGS applications)

INTERNATIONAL EARTH ROTATION SERVICE (IERS)
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8 October1993

Long term behaviour of polar motion series relative to the IERS/CB series

Table 1. The polar motion series analysed

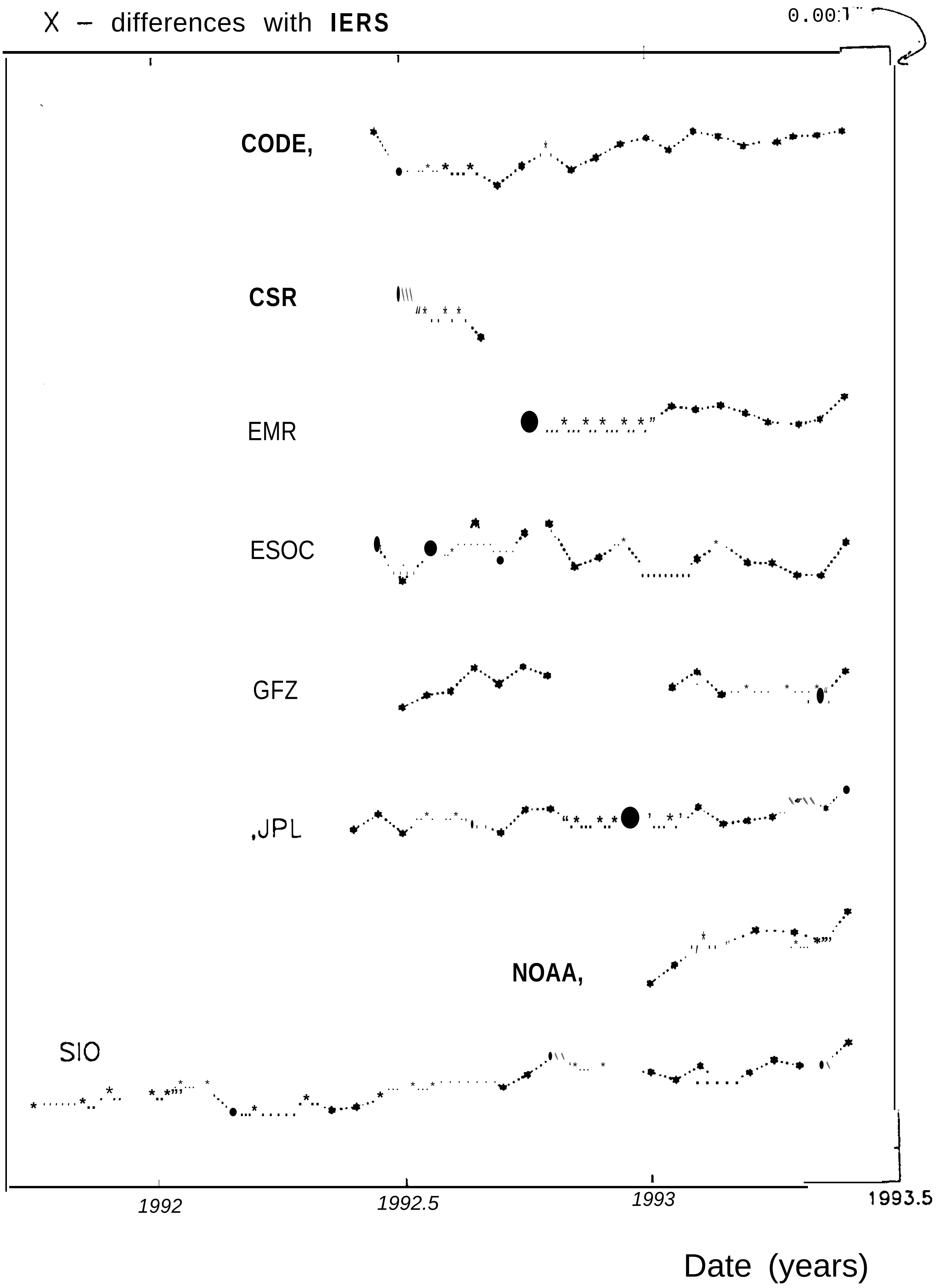
	Series	Data span (years)	Nb of dates	Status
VLBI	EOP (NOAA) 93 R 04	1992-93	155	Annual Report/Operational
	EOP (USNO) 93 R 09	1992-93	118	Annual Report/Operational
SLR	**EOP** (CSR) **93** L 02	1992-93	213	Operational solution
	EOP (DUT) **91** L 02	1992-93	120	Operational solution
GPS	EOP (CODE) *92* P 04	1992-93	461	**Annual Report** submission
	EOP (CSR) 92 P **02**	1992-92	76	Operational solution
	EOP (EMR) *92* **P** 04	1992-93	339	Operational solution
	EOP (ESOC) *92* P *02*	1992-93	259	Annual Report submission
	EOP (ESOC) 92 P 03	1992-93	375	Operational solution
	EOP (GFZ) 93 P 03	1992-92	131	Annual Report submission
	EOP (GFZ) **93 P** 01	1993-93	258	**Operational solution**
	EOP (JPL) *92* P 02	**1992-93**	**206**	Annual Report **submission**
	EOP (JPL) 92 P 03	**1992-93**	**307**	**Operational solution**
	EOP (NOAA) 93 P 01	**1993-93**	**253**	Operational solution
	EOP (SIO) 93 **P** 01	1992-93	600	Annual Report submission

Table 2 gives the observed linear drifts relative to the IERS solution. EOP(IERS) 90 C 04 corrected in drift to be consistent with the ITRF velocity field within ± 0.1 mas/year.

Table 2. Linear drifts relative to EOP(IERS) made consistent with the ITRF velocity field

	Series	Interval covered	dx/dt	dy/dt
			0.001"/year	
VLBI	EOP (NOAA) 93 R 04	1992,00 - 1993.70	0.2 ± 0.1	-0.3 ± 0.1
	EOP (USNO) 93 R 09	1992.00 - 1993.70	0.0 ± 0.1	-0.2 ± 0.1
SLR	EOP (CSR) 93 L 02	1992.00 - 1993.70	0.0 ± 0.1	-0.2 ± 0.1
	EOP (DUT) 91 L 02	1992.00 - 1993.70	1.0 ± 0.2	2.2 ± 0.2
GPS	EOP (CODE) 92 P 04	1992.45 - 1993.70	0.5 ± 0.1	1.1 ± 0.1
	EOP (CSR) 92 P 02	1992.45 - 1992.70	-5.2 ± 1.0	0.5 ± 1.1
	EOP (EMR) 92 0 04	1992.7S - 1993.70	0.5 ± 0.1	0.04 ± 0.1
	EGP (ESOC) 92 P 02	1992.45 - 1992.75	-1.0 ± 0.7	5.3 ± 1.1
	EOP (ESOC) 92 P 03	1992.75 - 1993.70	0.3 ± 0.2	-1.5 ± 0.2
	EOP (GFZ) 93 P 03	1992.4S - 1992.80	3.6 ± 0.7	-8.5 ± 0.7
	EOP (GFZ) 93 P 01	1993.05 - 1993.70	-0.3 ± 0.1	-0.1 ± 0.1
	EOP (JPL) 92 P 02	1992.40 - 1992.95	-0.2 ± 0.5	1.5 ± 0.6
	EOP (JPL) 92 P 03	1993, 00 - 1993.70	0.6 ± 0.1	0.4 ± 0.1
	EOP (NOAA) 93 P 01	1993.00 - 1993.70	-1.2 ± 0.3	-3.8 ± 0.3
	EOP (SIO) 93 P 01	1992.00 - 1993.70	0.7 ± 0.1	-0.9 ± 0.1

The two figures show the series of differences of the GPS series up to 1993.5, plotted at 0.05 year interval.

X – differences with IERS
0.001"
CODE,
CSR
EMR
ESOC
GFZ
,JPL
NOAA,
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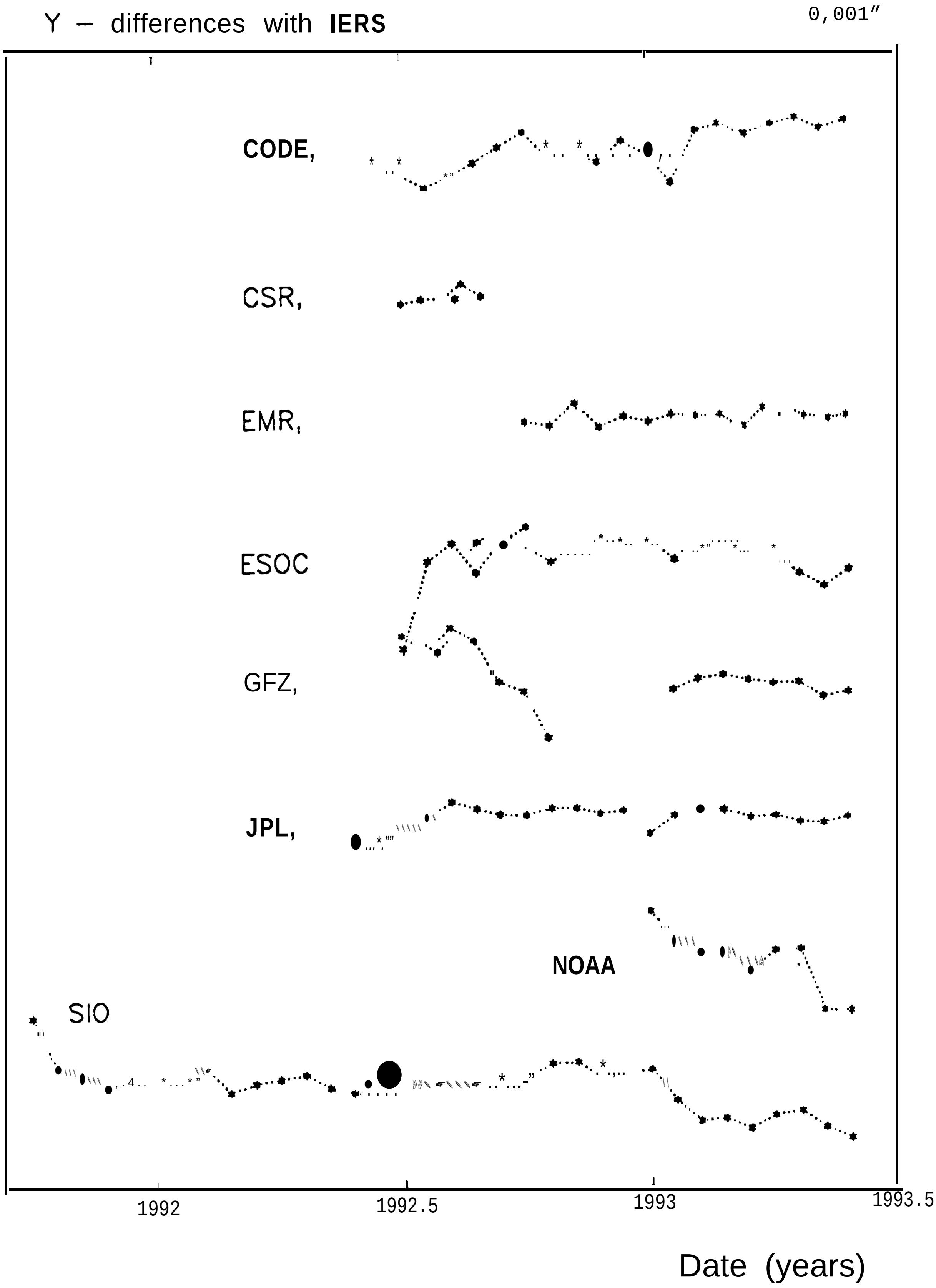
1992
1992.5
1993
1993.5
Date (years)



Y — differences with **IERS**

SUMMARY OF SESSION 5

In the last session, three additional presentations were given.

In the first presentation, Dr. Martine Feissel highlighted the IERS studies of the IGS pole solutions with particular emphases on the long term stability. It was noted that some GPS polar motion series exhibited drifts of several mas/year demonstrating the importance of VLBI. Also summarized were new developments and improvements in precession and nutation models supported by VLBI observations.

In the second presentation given by Dr. Feissel on behalf of Boucher and Altamimi, the latest ITRF solutions and coordinate sets were reviewed. The significance of the IERS/ITRF effort, which provides a common reference frame and connection to other space technique such as VLBI/SLR has been greatly appreciated and acknowledged by all participants. The plans to make the ITRF and EOP mutually consistent at the sub-mas level for the 1993 Annual Report were also highlighted. This will mean a small re-alignment of the ITRF reference frame to maintain the continuity of EOP.

In the last presentation, an interesting application of GPS with emphasis on the post-glacial uplift in Fennoscandia was presented. GPS data from the IGS core network, supplemented by an extensive regional network are being processed using a state of the art software (GIPSY II). This yielded a repeatability of a few ppb in distance for baselines of a few thousand km. Practically the same results were obtained with the best IGS orbits held fixed or with orbits determined from both regional and global (IGS) networks. Dr. Johansson expressed interest in using the future combined IGS orbits and also to become an IGS Associated Analysis Center.

CONCLUSIONS/RECOMMENDATIONS

1) **IGS** PROCESSING/REPORTS/FORMATS

SP3 will be the format of initial IGS orbit products; all Analysis Centers should comply NO LATER THAN January 1, 1994. Orbit files will contain SV clocks (either broadcast or precise) at same frequency as ephemeris.

The IGS Central Bureau (CB) is to coordinate the preparation of EOP and Summary formats based on issues raised during discussion. Time frame: end of November, mid- December. A separate format for higher-frequency precise SV clocks is required (format to be determined, and to be applicable to station clocks as well). Work to begin on the new format, with possibility that orbits and clocks can coexist in same file at different frequencies; CB is to coordinate e-mail discussion on the possible clock and orbit format.

Each of the following stations is currently used as a fiducial (coordinates are held fixed or tightly constrained) by a majority of Analysis Centers; data from sites denoted by * may be a concern in two ways: timeliness of data such as the DSN sites or discrepancies in the site tie information:

Algonquin Park
Fairbanks
Goldstone*
Hartebeesthoek*
Kokee Park
Kootwijk
Madrid*
Santiago
Tromso
Tidbinbilla*
Wettzell
Yarragadee
Yellowknife

Propose that coordinates of all of the above stations (with possible exception of the * sites) be fixed or tightly constrained by all Analysis Centers in their production of the orbit product and that all Centers use the same set of coordinates and velocities for the above sites

2) **IGS** ORBIT PRODUCTS

All Analysis Centers are encouraged to submit their products as soon as possible (daily) but not later than two weeks from the date of observation. When all Center orbits are received, or after the two week period whichever comes first, an IGS combined orbit product will be generated.

Two IGS orbit products will be generated based on principles developed in the position paper 2:
- ‘Rapid orbit product’ consistent with IERS Rapid Service (Bull. A), and available within two weeks.
- ‘Final (archive) orbit product’ consistent with the final IERS (Bull. B) pole values and available

within a few months

The IGS orbit products will be based, at least in the initial stages, *on* the weighted average combination method as outlined in the position paper and the second method, the orbital dynamics method, will be used for preanalysis and evaluation using multi-day arcs. Individual Center orbit series will continue to be archived and made available byIGS.

The Analysis Center coordinator responsible for generation of the IGS combined orbit is encouraged to provide useful and timely feedback to contributing Centers as well as to stimulate further research at other Centers to encourage future improvements.

3) IGS PROCESSING STANDARDS

First task is to gather information on Analysis Center models, estimation strategy, coordinates, etc. CB (Blewitt and Zumberge) will develop an electronic questionnaire to be filled out by Analysis Centers. Completed questionnaires will be made available to all Centers, IGN/IERS, and will be available on the IGS Information system being implemented at the Central Bureau. This way the differences and changes of estimation strategies and how this relates to solution differences will be systematically documented.

All Centers agreed in principle to adopt the same set of fiducial coordinates for purposes of orbit/ EOP products. The proposed list of stations is as above, in Session 1.

It is recommended that the January orbit test reprocessing (weeks 680 and 681) be completed by the Centers which have not done so yet, or which want to reprocess it again with improved (changed) orbit estimation strategies. For this reprocessing, theIGS Mail message 263 will be the standard for monument coordinates and antenna heights.

4) INTEGRATION OF REGIONAL STATION CLUSTERS

Using the IGS (combined) orbits is the simplest form of distributed processing thus should be implemented immediately to accommodate various regional processing.

Distributed processing should imply only minimal computational increase for the IGS ‘Analysis Center. Reduced normals (’fiducial-free’) contribution from IGS Analysis Centers will be necessary in the future distributed processing and all Centers are encouraged to develop this capability as soon as possible

Additional products, such as tropospheric calibration delays may also be useful for distributed processing also more research is needed for distributed processing strategies (e.g. the effect and mitigation of data overlaps (using data more than once)).

IGS should foster and encourage regional analysis e.g. through Associate Analysis Center membership, designating a Governing Board representation, recommendations and guidelines, research & publications, etc.

APPENDIX

(IGS resource information)

INTERNATIONAL GPS SERVICE FOR GEODYNAMICS

Resource Information

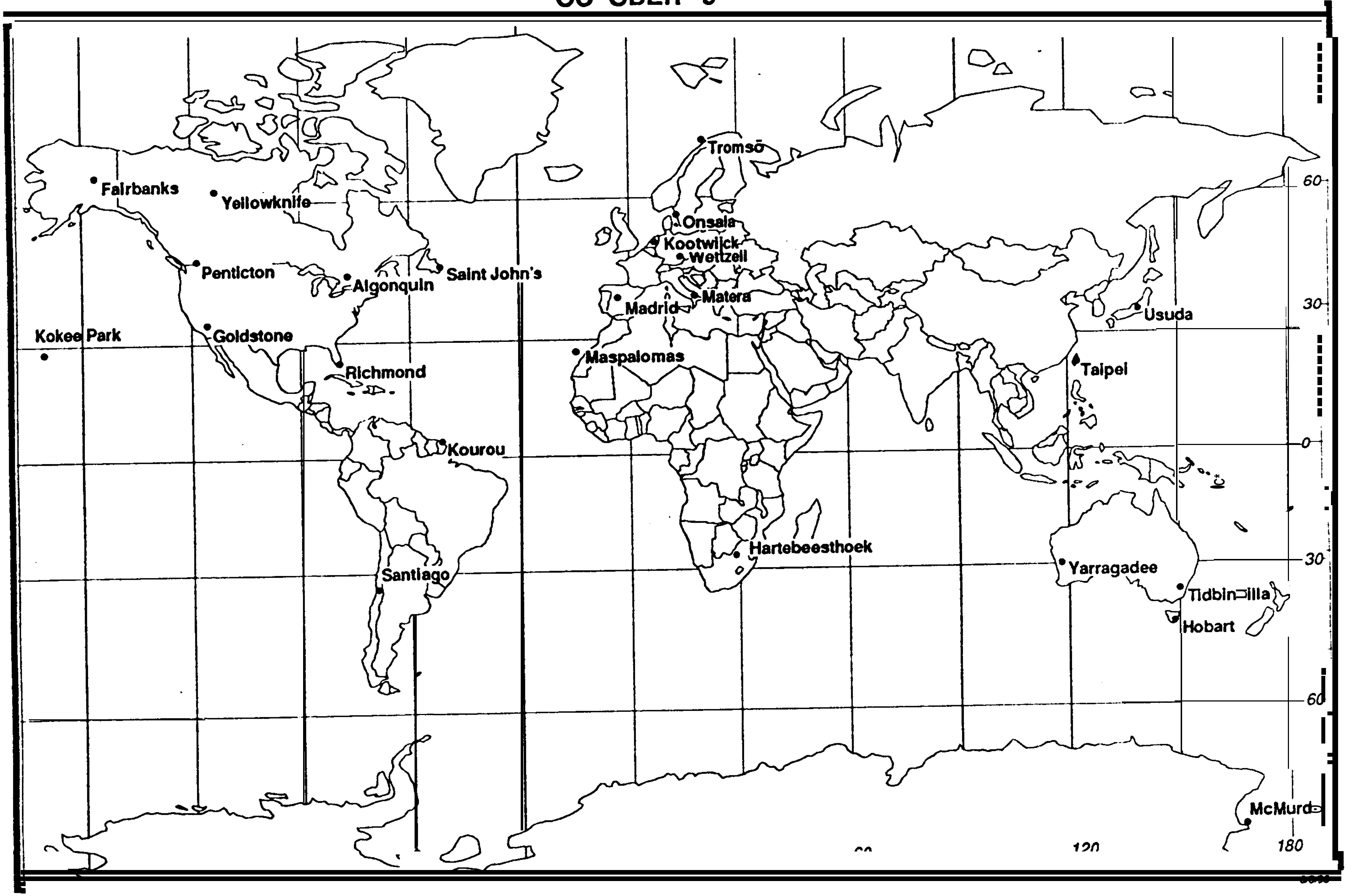
October, 1993

IGS Workshops for Analysis and Network Operations

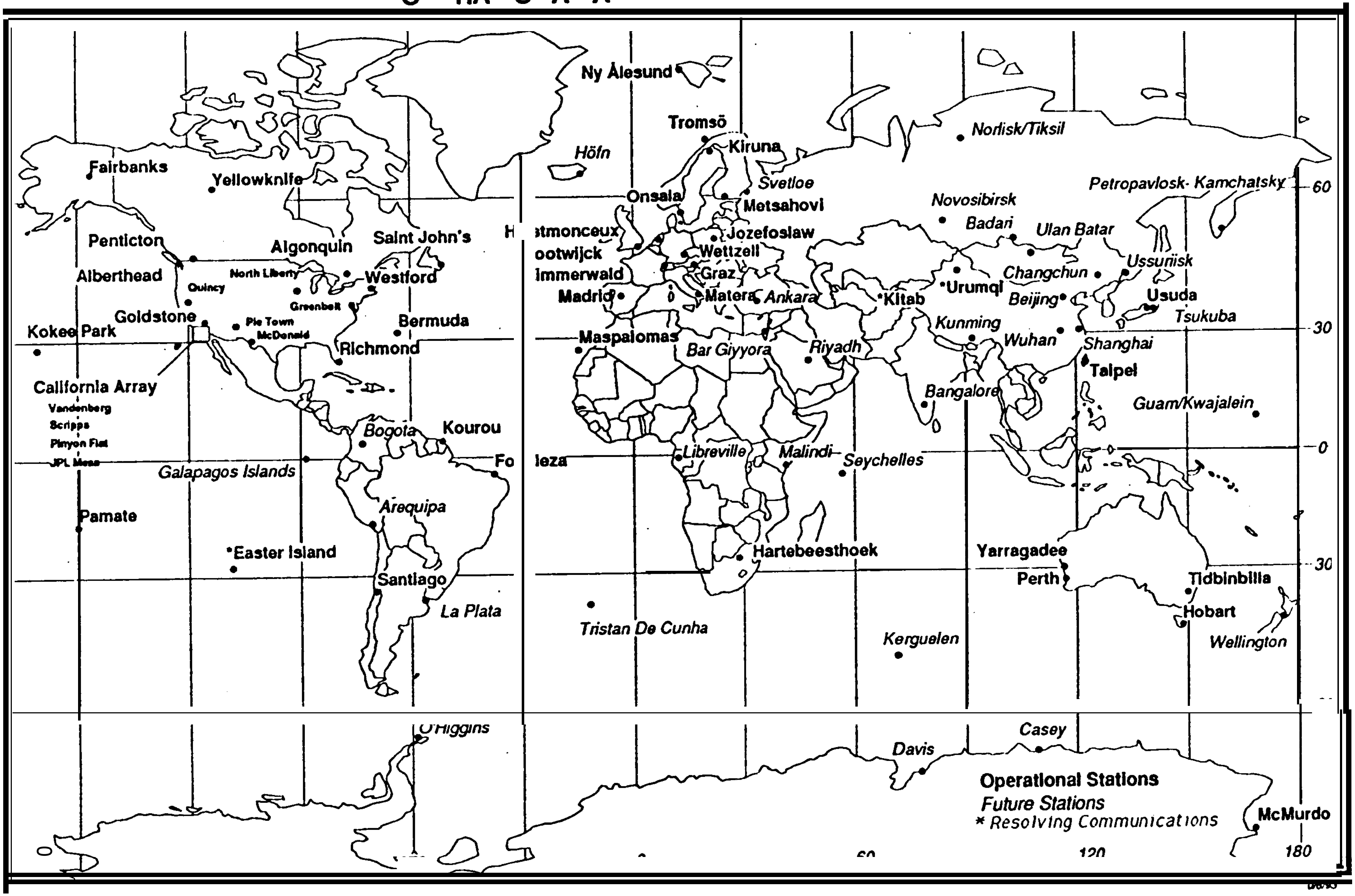
Association Internationale de Géodésie
Union Géodésique et Géophysique Internationale

International Association of Geodesy
International Union of Geodesy and Geophysics

OPERATIONAL STATIONS USED FOR GLOBAL ANALYSIS BY FIVE OR MORE IGS PROCESSING CENTERS
OCTOBER 1992



GPS TRACKING NETWORK OF THE INTERNATIONAL GPS SERVICE FOR GEODYNAMICS
OPERATIONAL AND PROPOSED STATIONS



Operational Stations

Future Stations

* Resolving Communications

IGS Network Stations
GPS Station Geographical Coordinates

	STATION	COUNTRY	LONGITUDE (E)	LATITUDE	AGENCY
1	Algonquin	Canada	-78.07	45.95	EMR/CGS
2	Alberthead	Canada	-123,48	48.38	EMR/GSC
3	Fairbanks	USA	-147.48	64.97	NASA/JPL
4	Fortaleza	Brazil	-38,58	-3.75	NOAA/NGS
5	Goldstone	USA	-116.78	35.23	NASA/JPL
6	Graz	Austria	15.48	47.07	ISRO
7	Greenbelt	USA	-76.82	39.02	NASA/JPL
8	Hartebeesthoek	South Africa	27.70	-25.88	CNES
9	Herstmonceux	United Kingdom	0 . 3 3	50,87	RGO
10	Hobart	Australia	147.43	-42.80	NOAA/NGS
11	JPL Mesa	USA	-118.17	34,20	NASA/JPL
12	Jozef oslaw	Poland	21.03	52.08	WUT
13	Kiruna	Sweden	20.25	67.88	ESOC
14	Kokee Park	USA	200.33	22.17	NASA/JPL
15	Kootwijk	Netherlands	5.80	52.17	DUT
16	Kourou	Fr. Guiana	-52.62	5.13	ESOC
17	Madrid	Spain	-4.25	40.42	NASA/JPL
18	Maspalomas	Canary Islands	-15.63	27.77	ESOC
19	Matera	Italy	16,70	40.63	ISA
20	McDonald	USA	-104.02	30.67	NASA/JPL
21	McMurdo	/Antarctica	166.67	-77.85	ARL/JPL
22	Metsahovi	Finland	24.38	60.22	FGI
23	North Liberty	USA	-91,50	41.80	NASA/JPL
24	Ny Alesund	Norway	11.85	78.92	SK
25	Onsala	Sweden	11.92	57.38	0 s 0
26	Pamate	Tahiti	-151.03	-16.73	CNES
27	Pent"don	Canada	-119.62	49.32	EMR/GSC
28	Perth	Australia	115.82	-31.97	ESOC
29	Pie Town	USA	-108.12	34.30	NASPJJPL
30	Pinyon Flat	USA	-116.45	33.60	SIO/JPL
31	Quincy	USA	.120.93	39,97	NASA/JPL
32	Richmond	USA	-80.38	25.60	NOAA/NGS
33	Saint John's	Canada	-52.68	47.60	EMR
34	Santiago	Chile	-70.67	-33.15	CEE/JPL
35	Scripps	USA	-117.25	32.87	SIO
36	Taipei	Taiwan	121.63	25.03	IESAS
37	Tidbinbilla	Australia	148.97	-35.38	NASA/JPL
38	Tromso	Norway	18.93	69.67	SK
39	Usuda	Japan	138.37	36.13	ISAS
40	Vandenberg	USA	-120.48	34.55	SIO
41	Westford	USA	-71,48	42.62	NOAA/NGS
42	Wettzell	Germany	12.87	49.13	IfAG
43	Yarragadee	Australia	115.33	-29.03	NASA/JPL
44	Yellowknife	Canada	-114.47	62.47	EMR/CGS
45	Zimmerwald	Switzerland	7.45	46.87	BfL

Status as *of: October* 8, 1993

IGS Network Stations
GPS Station Geographical Coordinates

	FUTURE SITES	**COUNTRY**	LONGITUDE (E)	LATITUDE	AGENCY
1	Ankara	**Turkey**	39.92	32.83	IfAG
2	**Arequlpa**	**Peru**	-71.48	-16.45	**NASA/JPL-GSFC**
3	**Badari**	**Russia**	102,23	51.77	**IAAS/JPL**
4	**Bangalore**	India	77.67	12.98	**GFZ**
5	Bar **Giyyora**	Israel	35.08	31.72	**NASA/JPL**
6	Beijing	China	39.92	116.38	**NBSM/GFZ**
7	“Bermuda	**U.K.**	-64.65	32.35	**NOAA/NGS**
a	Bogota	**Colombia**	-74,08	4.63	**NASA/JPL**
9	Casey	**Antarctica**	110.53	.66.27	**AUSLIG**
10	**Changchun**	**China**	125.42	43.92	SAO
11	Cocos **Island**	**Australia**	96.83	-12.20	**AUSLIG**
12	Darwin	**Australia**	131.13	-12.85	**AUSLIG**
13	Davis	**Antarctica**	77.97	-68.57	**AUSLIG**
14	**Darmstadt**	**Germany**	8.67	49.85	ESOC
15	● Easter Island	**Chile**	-109,38	-27.13	**NASA/JPL**
16	Galapagos Islands	Ecuador	-89,62	0.90	**NASA/JPL**
17	**Guam/Kwajalein**	Pacific Islands	167.47	9.38	**NASA/JPL**
18	**Hofn**	Iceland	-15.00	64.50	SK
19	**Kerguelen**	French Island	70.27	-49.35	**CNES/IGN**
20	● Kitab	Uzbekistan	66.88	39.13	GFZ
21	**Kunming**	**China**	102.83	25.17	SAO
22	La **Plate**	**Argentina**	-57.95	-34.90	GFZ
23	**Libreville**	**Gabon**	9.27	0,23	CNES
24	**Malindi**	Kenya	40.13	-3.23	**ESOC**
25	Novosibirsk	**Russia**	83.08	55.00	GFZ
26	**Norlisk/Tiksil**	Russia	88.03	69.35	
27	**O'Higgins**	Antarctica	-59.90	-63.32	**IfAG**
28	**Petropavlosk**	Russia	53.22	**54.53**	GFZ
29	**Riyadh**	**Saudi** Arabia	46.70	24.68	
30	Seychelles	**Islands**	55.60	-4,68	**NASA/JPL**
31	Shanghai	**China**	121.20	**31.10**	**SAO/NASA/JPL**
32	**Svetloe**	**Russia**	60.88	30.32	**IAA/JPL**
33	Tristan De **Cunha**	Island	-12.50	-35.50	**GFZ/JPL**
34	**Tsukuba**	**Japan**	140.08	36.10	GSI
35	**Ulan Batar**	**Mongolia**	106.87	47.90	GFZ
36	***Urumqi**	**China**	87.72	43.82	GFZ
37	**Ussuriisk**	**Russia**	132.57	44.07	**SDC/JPL**
38	**Villafranca**		2.67	42.25	ESOC
39	Wellington	New Zealand	174.78	-41.27	
40	**Wuhan**	China	114.25	30.50	**WTU/NGS**

•Resolving communications and data **retreival** paths.

Bold: To be Implemented by January 1994

All locations given in decimal degrees.

IGS Agency Acronyms:
Network Station Implementation and Operation

ACRONYM	AGENCY
IESAS	Academia **Sinica,** Institute of Earth Sciences, Taiwan
AUSLIG	Australian Survey **and** Land Information Group
BfL ‘	**Bundesamt** fur Landeslopographie (Federal Topography), Switzerland
CGS	Canadian Geodetic Survey, EMR, Canada
CNES	**Centre** National de Etudes, Toulouse, France
CEE	**Centro** de **Estudios Espaciales,** Chile
CDDIS	**Crustal** Dynamics Data Information System, USA
DMA	Defense Mapping Agency, USA
OUT	**Delft** University of Technology, Netherlands
DOSLI	Department of Survey and Land Information, Wellington, New Zealand
ERI	Earthquake Research Institute, University of Tokyo
EMR	Energy Mines and Resources, Canada
ESA	European Space Agency
ESOC	European Space Operations Center
FGI	Finnish Geodetic Institute, Finland
GFZ	**GeoforschungsZentrum** Institute, **Potsdam,** Germany
GSI	Geographical **Survey** Institute, **Tsukuba,** Japan
GSC	Geological Survey of Canada, EMR, Canada
GSFC	Goddard Space Flight Center, USA
IfAG	**Institut** fur Angewandte **Geodasie,** Frankfurl, Germany
IGN	**Institut Geographique** National, Paris, France
ISAS	Institute for Space and Astronautic Science, Sagamihara, Japan
ISRO	Institute for Space Research Observatory, **Graz,** Austria
IAA	Institute of Applied Astronomy, St. Petersburg , Russia
IBGE	**Instituto Brasileiro** de **Geografia** de **Estatistica,** Brazil
fNPE	**Instituto** National de **Pesquisas Espaciais,** Brazil
ISA	Italian Space Agency, Matera, Italy
JPL	Jet Propulsion Laboratory, USA
NASA	National Aeronautics and Space Administration, USA
NBSM	National Bureau of Surveying And Mapping, China
NGS	National Geodetic Survey, USA
NOAA	National Oceanic and Atmospheric Administration, USA
ROB	**Observatoire** Royal de Belgium, Brussels, Belgium
0s0	**Onsala** Space Observatory, Sweden
RGO	Royal Greenwich Observatory, UK
SIO .	Scripps Institution of Oceanography, San Diego, CA, USA '
SAO	Shanghai Astronomical **Observatory,** China
SDC	Space Device Corporation, Russia
SK	Statens **Kartverk,** Norwegian Mapping Authority, Norway
UFPR	University Federal de Parana, Brazil
WUT	Warsaw University of Technology, Poland
WTU	**Wuhan** Technical University, China

*Status: **October** 8, 1993*

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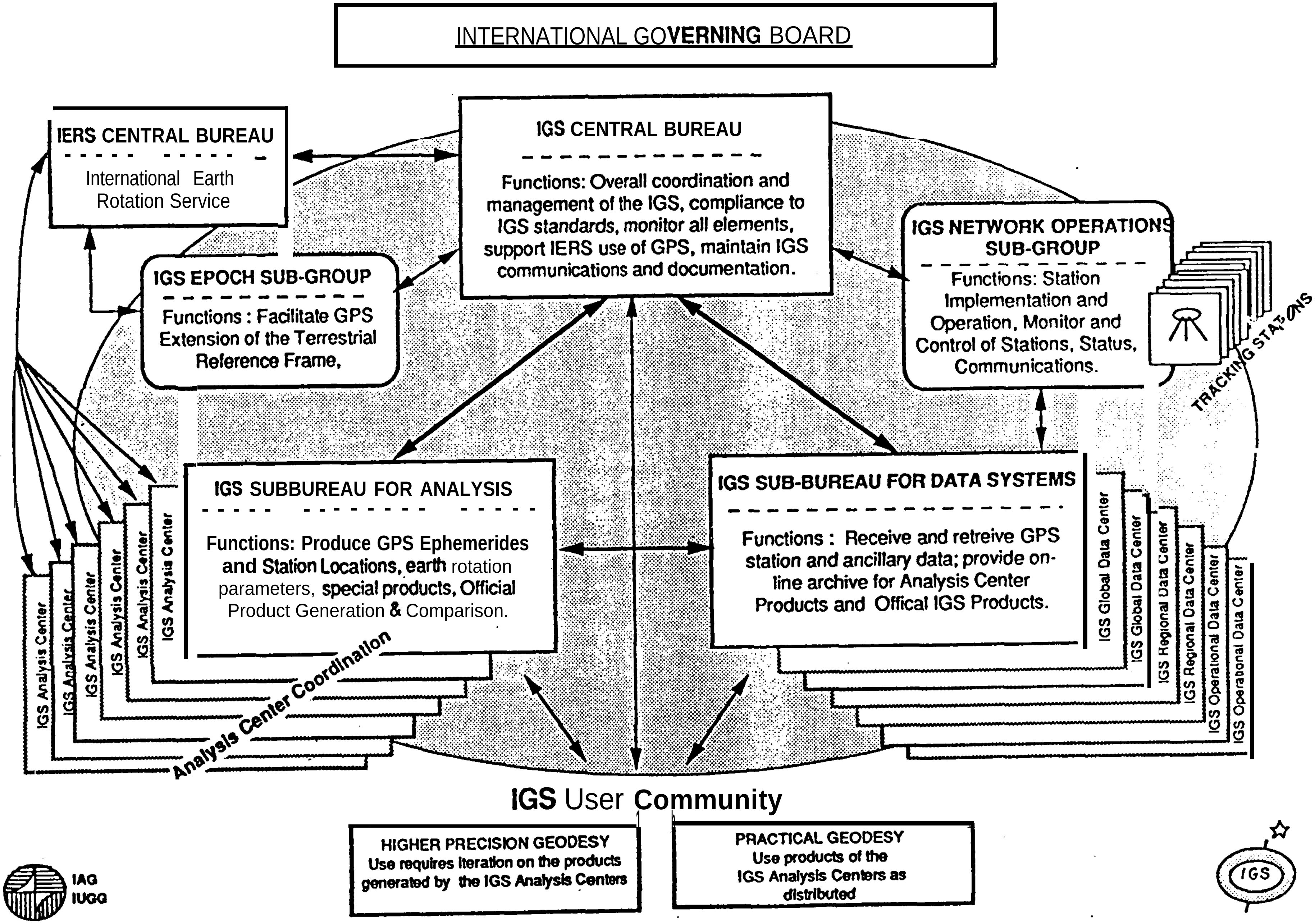
PROPOSED ORGANIZATION OF THE INTERNATIONAL GPS SERVICE FOR GEODYNAMICS IGS



INTERNATIONAL GOVERNING BOARD

IERS CENTRAL BUREAU

International Earth Rotation Service

IGS CENTRAL BUREAU

Functions: Overall coordination and management of the IGS, compliance to IGS standards, monitor all elements, support IERS use of GPS, maintain IGS communications and documentation.

IGS EPOCH SUB-GROUP

Functions : Facilitate GPS Extension of the Terrestrial Reference Frame,

IGS NETWORK OPERATIONS SUB-GROUP

Functions: Station Implementation and Operation, Monitor and Control of Stations, Status, Communications.

TRACKING STATIONS

IGS SUBBUREAU FOR ANALYSIS

Functions: Produce GPS Ephemerides and Station Locations, earth rotation parameters, special products, Official Product Generation & Comparison.

IGS Analysis Center
IGS Analysis Center
IGS Analysis Center
IGS Analysis Center
IGS Analysis Center
IGS Analysis Center

Analysis Center Coordination

IGS SUB-BUREAU FOR DATA SYSTEMS

Functions : Receive and retreive GPS station and ancillary data; provide on-line archive for Analysis Center Products and Offical IGS Products.

IGS Global Data Center
IGS Global Data Center
IGS Regional Data Center
IGS Regional Data Center
IGS Operational Data Center
IGS Operational Data Center

IGS User Community

HIGHER PRECISION GEODESY
Use requires iteration on the products generated by the IGS Analysis Centers

PRACTICAL GEODESY
Use products of the IGS Analysis Centers as distributed

IAG
IUGG

IGS

8/93