IGS

ANALYSIS CENTER (AC) WORKSHOP

Summary Recommendations of IGS Analysis Center Workshop

Dear IGS colleagues,

Below is a summary of the IGS analysis center workshop, which took place from 8-10 June 1999 at the Scripps Institution of Oceanography in La Jolla, California.

The appendix contains an e-mail with the AC and AAC action items which resulted from the workshop. This e-mail was distributed to the ACs and AACs on 16 June 1999 and is included for completeness.

We would like to remind all authors to provide a written contribution by 31 August 1999. Full length papers are preferred but an extended abstract summarizing your presentation is also acceptable. All submissions for publication in the workshop proceedings should be sent to the IGS Website at: http://igscb.jpl.nasa.gov/submissions/guide.html

The workshop at Scripps was most enjoyable and stimulating and on behalf of the IGS I would like to thank my co-convenor, Yehuda for his great effort and Myra Medina for the local organization which was quite excellent!

Summary of the 1999 IGS AC Workshop

The 1999 IGS analysis center workshop dealt with 2 major topics.

- Real- and near-real time products and applications
- Long-term stability and accuracy of GPS Reference Frame

The workshop was opened with a welcome address by John Orcutt, Director of IGPP, and an introduction by Yehuda Bock.

After the opening the status and challenges facing the IGS were addressed by Chris Reigber, Ruth Neilan, Carey Noll, Tim Springer, Angie Moore and Yehuda Bock.

Topic 1: Real- and near-real time products and applications

The position paper "Moving IGS products towards real-time" written by Gerd Gendt, Peng Fang, and Jim Zumberge, proposed the generation of both more rapid and frequent IGS products for (near-) real-time usage. The generation of these "ultra rapid" products should start on 3 October 1999 (GPS week 1030). The products, which will be delivered every 12 hours (2x per day), will contain a 48 hour orbit arc from which 24 hours are real orbit estimates and 24 hours are orbit predictions. The latency of this product will be only 3 hours. This position paper, which was available before the workshop, may be obtained from the IGSCB at the working location of: http://techinfo.jpl.nasa.gov/igs/files/
Note that once the proceedings of the workshop are complete, it will be moved to IGS Publications page at: http://igscb.jpl.nasa.gov/overview/pubs.html.

One of the "forces" moving the IGS towards real-time products is GPS meteorology. Applications of IGS products for ground and space based meteorology were presented by Seth Gutman, Mike Bevis, and Chris Rocken.

Another "force" moving the IGS towards real-time are the low Earth orbiter (LEOs) missions where again meteorology is of primary interest. Mike Watkins presented the status and recommendations of the IGS LEO working group. This working group, with support from other IGS components, will soon issue a call for participation for a "LEO pilot project" where the focus will be mainly on the data gathering issues (1 sec tracking data in hourly batches in near-real-time). Precise orbit determination (POD) of the LEO satellite (either OERSTED or SUNSAT, two satellite missions currently underway with GPS receivers) will also be of interest. This pilot project is planned for October 1999. Jim Zumberge and Angie Moore discussed two issues closely related to the LEO missions, i.e., the LEO ground network and suggestions for a new GPS binary data format.

Topic 2: Long-term stability and accuracy of GPS Reference Frame

The position paper "Achieving mm site positions and mm/yr site velocities for geodynamics" written by Tom Herring, Geoff Blewitt, and Remi Ferland was unfortunately not available before the workshop. However, the interesting presentation by Tom Herring, and also the presentation given by Mike Heflin, showed that there are significant geographically correlated variations in the GPS derived time series. Tom's prime conclusion was that if mm/yr velocities are expected we should "call him in 10 years". However, a presentation given by Hadley Johnson on site stability issues indicated that we might have to wait 20 years.

The geographically correlated effects may represent actual deformations although Tom Herring concluded that it is likely that they are caused by remaining deficiencies in IGS orbit modeling. These clearly are a cause of concern and require further attention. It also became clear (once again) that the feedback from the ACs to the station operators is still far from optimal. With respect to site stability calibration it would be helpful to have two receivers at a site. which was also recommended at the Network Workshop in Annapolis.

Zuheir Altamimi and Remi Ferland showed and discussed the quality of the ITRF-97. Clearly the ITRF-97 is again a major improvement w.r.t. its predecessor (ITRF-96). Remi Ferland showed results which indicate that the VLBI and GPS based polar motion estimates will be in much better agreement in the ITRF-97 than they are in the ITRF-96, where a 0.3 mas bias is observed. It was decided that the IGS will adopt the ITRF-97 reference frame starting with GPS week 1021, 1 August 1999.

Presentations by Jim Ray, Markus Rothacher, and Arthur Niell dealt with the problems of mixing different receivers and antennas in the global network. The antenna phase center offsets and variations, of both the receiver and transmit (satellite) antennas, represent one of the major remaining error sources in GPS data analysis. Jim Ray showed that the used of the different code observables (CA vs P1) causes problems for the IGS clock estimates and combination; for more details about this problem see IGSMAIL #2320.

Important in view of the long-term stability was the presentation by John Rush from NASA on the microwave spectrum issues and new GPS frequencies. Three important action items were suggested:

IGS Contact the International Telecommunication Union, and, each IGS member contact their local radio administration to encourage:

· The preservation of the radionavigation satellite service band 1559-1567 MHz for use by radionavigation satellite services, with no sharing of any portion of the band with MSS users. (WRC-00 Agenda Item 1.9)

· Addition of the radionavigation satellite service allocation to cover the band 1164-1188 MHz. (WRC-00 Agenda Item 1.15.1)

· The addition of an allocation for use in the space-to-space direction for radionavigation satellite services in the 1215-1260 MHz and 1559-1610 MHz bands. (WRC-00 Agenda Item 1.15.2)

The workshop concluded with an interesting tour along the posters of all the IGS analysis centers followed by presentations summarizing the status and activities of all the IGS working groups.

Workshop Recommendations

Besides the action items for the ACs and AACs (see appendix) and the three action items proposed by John Rush the following recommendations resulted from the workshop.

R1: The operational, regional and global data centers are asked to optimize the data transfer of the hourly RINEX-files in support of the ultra-rapid products

R2: The IGS LEO WG will issue a call for participation for a LEO pilot project which will start in October 1999.

R3: The IGSCB, in cooperation with the Infrastructure Committee, should enhance the newly developed receiver and antenna name list by adding the tracking techniques of each receiver. This is important in view of the available observables and their effect on the IGS clock estimates.

R4: The IGS ACs will have to decide and advertise whether the IGS clock estimates will be based on CA- or P1-code observations. The IGS will have to provide a table containing the CA-P1 code biases.

R5: Tom Herring will draft a letter for the IGS Governing Board to request VLBI tracking of the GPS satellites in order to determine the L1 and L2 phase center offsets of the GPS satellite antennas.

R6: Improve the feedback from the AC to the station operators in case of bad station performance. Better advertise the availability of feedback to the station operators. This is the responsibility of the Network Coordinator.

Kind Regards,
Tim Springer
Yehuda Bock

Appendix: E-mail send to ACs and AACs on 16 June 1999.

AC and AAC action items:

Date: As soon as possible

· ACs start submitting ERP files with their predicted orbits. These ERP files should include at least the PM offsets and their rates for the day of the predicted orbits. The inclusion of more values is allowed if this is convenient for the AC. Of course the ERP files should be consistent with the predicted orbits. The standard IGS ERP format should be used.

· ACs start submitting clock files with their final orbits and the clock files should contain the stations coordinates in the header (see new format description below).

· The IGS Analysis Center Coordinator (ACC) will contact the IERS, Duncan Agnew, and Hans-Georg Scherneck (et. al.) about setting up some kind of ocean loading service to provide the ACs, AACs, and other IGS customers with ocean loading corrections for the different IGS sites.

· The ACs are encouraged to (better) advertise the availability of accuracy codes in the orbit (SP3) files. The ACs developing and distributing their own GPS processing software are encouraged to add the capability to automatically use the orbit accuracy codes to their software.

Date: July 4, 1999. GPS week 1017

1. All ACs, AACs, RINEX files, site-logs, and IGS.SNX should contain the new receiver and antenna names! All IGS products from this week on should use the new receiver and antenna names. The "old but still valid" names become "invalid" for all IGS products after this date.

2. The 4-character id used for both the site-log and the RINEX file name becomes the official 4-character id for the respective site-receiver-antenna combination. This 4-character id should be used to label ALL results from this site-receiver-antenna combination, e.g., SINEX, clock files, etc. etc. New 4-character id's will be the responsibility of the IGSCB (of course stations may propose a 4-char id). The IGSCB will notify the IGS about changes in the 4-char id's by sending an IGSMAIL.

Date: August 1, 1999. GPS week 1021

1. All ACs, and AACs start using the ITRF'97 as terrestrial reference frame for their IGS products. Zuheir Altamimi will make available a special IGS SINEX file containing the ITRF'97 positions and velocities of the 51 reference stations (ITRF97_IGS_RS51.SNX and ITRF97_IGS_RS51.SSC). Remi Ferland will work together with Zuheir to ensure the correct list and naming (4-char) of the 51 sites. All ACs and AACs are encouraged to test the new reference frame and to study the changes between the ITRF'96 and ITRF'97 results. Please report your results to the Analysis Center Coordinator. The ACC will (try to) summarize the observed differences in the IGS products and document and distribute them using the IGSMAIL.

Date: October 03, 1999. GPS week 1030

1. The ACs are encouraged to start submitting "ultra-rapid" products two times per day according to the scheme as outlined in the position paper of the IGS workshop: title: Moving IGS products towards real-time authors: Gerd Gendt, Peng Fang, Jim Zumberge

To avoid naming conflict I would like to propose to use the following naming convention for the products. Use the first two characters of your AC and add a "u" as third character, e.g., cou, emu, esu, gfu... The combined products will be labeled "igu" as proposed in the position paper.

This completes my list of must urgent AC action items. Early next week I hope to distribute (after consulting with the organizers at SIO and the IGSCB) the complete list of recommendations and action items of the IGS workshop. Two important items on that list from an AC point of view are the upcoming call for participation in the LEO pilot project, and P1-CA code biases and its effect on the IGS clock estimates.

I hope to have informed/remembered you sufficiently.

Kind regards,
Tim Springer

Clock Format Change to Allow for Station Coordinates in Header
Jim Ray

Based on discussions at the IGS Analysis Center Workshop, held last week at Scripps Institution of Oceanography, Analysis Centers were asked to include station coordinates in their clock solution files. These coordinates should correspond to the values used in the clock analysis (whether fixed or adjusted). This will be a great convenience for users of these files.

This change can be accommodated in the existing "SOLN STA NAME / NUM" header record by using 35 previously blank spaces (for stations on or near the Earth's surface). Note that the geocentric coordinates should be given in millimeter units. The relevant portion of the changed format is:

```
+--------------------+----------------------------------------+------------+
|SOLN STA NAME / NUM | For each station/receiver included in  |            |
|                    | the clock data records, as well as the |            |
|                    | analysis reference clock even if it has|            |
|                    | zero values and is not included in the |            |
|                    | data records (number given in the      |            |
|                    | previous header record), include one   |            |
|                    | record with the following information: |            |
|                    | - 4-character station/receiver name    |   A4,1X,   |
|                    |   designator                           |            |
|                    | - Unique station/receiver identifier,  |    A20,    |
|                    |   preferably the DOMES number for      |            |
|                    |   fixed stations                       |            |
|                    | - Geocentric XYZ station coordinates   |   I11,X,   |
|                    |   corresponding to the analysis clock  |   I11,X,   |
|                    |   values reported (in millimeters!)    |    I11     |
|                    |                                        |            |
|                    | * REQUIRED for data types "Ax"         |            |
|                    |                                        |            |
+--------------------+----------------------------------------+------------+
```

An example of such a record would look like:

```
GOLD 40405S031            -1234567890 -1234567890 -1234567890SOLN STA NAME / NUM
----|---1|0---|---2|0---|---3|0---|---4|0---|---5|0---|---6|0---|---7|0---|---8|
```

Earlier this month, clarifications were added to deal with reporting analysis clock reference values when the time scale has been re-aligned.

All these changes are backwards compatible. The complete documentation is available at http://maia.usno.navy.mil/gpst/clock-format .

--Jim

IGS Analysis Center Workshop - Final Agenda

Theme: Real-Time Applications and Long-Term Accuracy
Dates: Tuesday, June 8 to Thursday, June 10
Place: Munk Conference Room, Cecil H. and Ida M. Green Institute of Geophysics and Planetary Physics (IGPP), Scripps Institution of Oceanography (SIO), La Jolla, California, USA

Conveners: Yehuda Bock (SIO; ybock@ucsd.edu) & Tim Springer (AIUB; springer@aiub.unibe.ch)
Local Organizer: Myra Medina, tel (619) 534-0229; fax (619) 534-9873; e-mail: mmedina@ucsd.edu. Please let Myra know if you plan to attend.

Registration fee: $85. The registration fee must be paid with a check, made out to UC Regents, or cash. No credit cards accepted. Yes, it is okay to pay by check on the first day. However, we would prefer that registration fees are sent to us before the meeting. Please mail check to:

IGS/IGPP Analysis Workshop
ATTN: Myra Medina
Scripps Institution of Oceanography
University of CA, San Diego
9500 Gilman Drive MC 0225
La Jolla, CA 92093-0225

Position Papers and Abstracts: As usual, position papers should be submitted and circulated before the workshop. We also encourage all other presenters to submit a 1-page abstract by Friday, May 28. The Central Bureau Information Service (CBIS) (http://igscb.jpl.nasa.gov/) will accept and distribute the position papers and abstracts for the workshop. Please also send a copy to ybock@ucsd.edu.

Proceedings: This will contain the position papers, abstracts, status reports of all working groups, and analysis center reports. All speakers should at least send a 1-page abstract of their talks before the workshop but are encouraged to send a full length paper for the proceedings. Working group/pilot project reports should cover the projects status, results, including charter, plans, schedule, members list, etc.

Poster Session: Posters will be up for the entire meeting. Size of poster boards is 180 x 120 cm.

Directions to meeting place and other information: These will be made available on the SOPAC Home Page (http://lox.ucsd.edu).

Final Agenda (as of May 30)

Tuesday, June 8

09:00 Welcome to SIO/IGPP (John Orcutt, Director IGPP)

Morning Session: IGS, Status and Challenges (Jan Kouba, Convener)

09:20 New developments and impact on IGS (Chris Reigber)

09:50 Central Bureau Perspective (Ruth Neilan)

10:10 Report on Network Workshop in Annapolis (Carey Noll/Ruth Neilan)

10:30 Break

11:00 Report on Core Products/Combinations (Tim Springer)

11:20 Report by Network Coordinator (Angelyn Moore)

11:40 Infrastructure Committee Report (Yehuda Bock)

12:00 Lunch

Afternoon Session: Real- and near-real time products and applications - 1
(Mike Watkins, Convener)

13:30 Position Paper: Moving IGS products towards real-time (Gerd Gendt, Peng Fang, Jim Zumberge)

14:30 Ground-Based GPS Meteorology (Seth Gutman/ Mike Bevis)

15:00 Space-Based GPS Meteorology (Chris Rocken)

15:30 Break

16:00 The IGS Low Earth Orbiters Working Group (LEOWG): Status and Recommendations from Potsdam Workshop, Influence of LEO's on GPS orbits and station coordinates - M. Watkins et al.

16:30 LEO Ground Network: Plans and Standards - J. Zumberge et al.

16:45 Status and Suggestions for the new GPS Binary Format - A. Moore et al.

17:30 Discussion

18:30 Dinner (Fish barbecue at Martin Johnson House, SIO)

Wednesday, June 9

Morning Session: Real- and near-real time products and applications - 2 (Gerd Gendt, Convener)

08:30 EOP Predictions and IERS Bulletin A (Jim Ray)

08:50 Station/Satellite Clock Combinations (Jan Kouba)

09:10 Ionosphere (Joachim Feltens)

09:40 Need for 1Hz global tracking (Jim Zumberge)

10:00 Error sources (multipath, tropospheric refraction) (Art Niell)

10:20 Break

10:50 Active control stations (Mark Caissy)

11:10 OWAG-B: A pilot project for operational water vapor estimation in a dense German GPS network (Galena Dick, Gerd Gendt, Chris Reigber)

11:25 Real-time data validation, compression and communication in the Dutch permanent GPS array AGRS.NL (Kees de Jong)

11:40 Discussion

Afternoon Session: Long-term stability and accuracy of GPS Reference Frame -1 (Yehuda Bock, Convener)

13:30 Position Paper: Achieving mm site positions and mm/yr site velocities for geodynamics (Tom Herring/**Geoff Blewitt/Remi Ferland)

14:30 ITRF97 and Quality Analysis of IGS Reference Stations (Zuheir Altamimi/Claude Boucher, Paul Sillard)

15:00 IGS Realization of ITRF (Remi Ferland): (moving to ITRF97; EOP comparisons)

15:30 Break

16:00 Efficient Densification and Long Term Accuracy (Mike Heflin et al.)

16:20 Analysis of IGS/AC EOP (wrt atmosphere & ocean) (Jan Kouba)

16:40 Unmodeled Effects (e.g., tides) (Duncan Agnew)

17:00 Experience with ocean loading (Herb Dragert)

17:20 Discussion

18:30 Free evening

Thursday, June 10

Morning Session: Long-term stability and accuracy of GPS Reference Frame -2 (Tim Springer, Convener)

08:30 GPS constellation errors (satellite phase center offsets) (Yoaz Bar-Sever)

08:50 Mixing of receivers in the global network (Jan Kouba/Jim Ray/Herb Dragert)

09:10 Antenna Phase Center Maps & Mixing Antennas (Markus Rothacher/Gerry Mader)

09:40 Monumentation & Site Stability Issues (Hadley Johnson, SIO)

10:00 In-situ site calibrations and procedures (Arthur Niell)

10:30 Break

11:00 Spectrum issues and new GPS frequencies (John Rush)

11:20 Discussion

12:00 Lunch

Afternoon Session: Working Groups, Results and Technical Issues
(Angie Moore, Convener)

13:00 Analysis Center Poster Viewing
CODE (Markus Rothacher and Stefan Schaer)
EMR (Caroline Huot)
ESA (Tomas J. Martin Mur)
GFZ (Gerd Gendt)
JPL (David Jefferson)
*NGS
SIO (Matthijs van Domselaar)
USN (Jim Rohde and Merri Sue Carter)

14:00 Site Densification (Remi Ferland)

14:20 Ionosphere (Joachim Feltens)

14:40 Troposphere (Gerd Gendt)

15:00 Time Transfer (Jim Ray)

15:20 IGEX (Robert Weber)

15:40 Break

16:10 Discussion and Wrap up

* Unconfirmed
** Contributing but not attending

Confirmed attendees (as of May 30):

1) Duncan Agnew
2) Zuheir Altamimi
3) Boudewijn Ambrosius
4) Per-Helge.Andersen
5) Yoaz Bar-Sever
6) Mike Bevis
7) Yehuda Bock
8) Claude Boucher
9) Mark Caissy
10) Jeff Dean
11) Kees de Jong
12) Herb Dragert
13) Lou Estey
14) Peng Fang
15) Joachim Feltens
16) Yanming Feng
17) Remi Ferland
18) Gerd Gendt
19) Javier Gonzalez
20) Seth Gutman
21) Mike Heflin
22) Tom Herring
23) Caroline Huot
24) Mike Jackson
25) Paul Jamason
26) David Jefferson
27) Hadley Johnson
28) Mikhail Kogan
29) Jan Kouba
30) Oddgeir Kristiansenn
31) Kristine Larson
32) Gerry Mader (June 9, 10)
33) Tomas J. Martin Mur
34) Myra Medina
35) Bill Melbourne
36) Angelyn Moore
37) Mark Murray
38) Ruth Neilan
39) Arthur Niell
40) Rosanne Nikolaidis
41) Carey Noll
42) Will Prescott
43) Jim Ray

44) Chris Reigber (June 8,9)
45) Chris Rocken
46) Erika Roegis
47) Jim Rohde
48) Markus Rothacher
49) John Rush (June 9,10)
50) Paul Sillard
51) Bill Schreiner
52) Victor Slabinski
53) Tim Springer
54) Grigory Steblov
55) James Stowell
56) Matthijs van Domselaar
57) Mike Watkins
58) Robert Weber
59) Katrin Weisse
60) Jim Zumberge

ITRF97 and Quality Analysis of IGS Reference Stations

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Abstract

A brief description of the 1997 International Terrestrial Reference Frame (ITRF97) is presented, underlying the most important results in terms of quality assessment. The quality of the 52 IGS Reference Stations is reviewed, based on the ITRF97 post fit position and velocity residuals. The noticeable improvement of ITRF97 with respect to ITRF96 leads to the recommendation of the use of ITRF97 instead of ITRF96. Moreover, the quality of the 5 ITRF96 rejected stations is significantly improved with ITRF97, and so all the 52 stations could be used by IGS as Reference Stations.

Although ITRF94, ITRF96 and ITRF97 are globally aligned in terms of datum definition, transformation parameters were estimated and commented, between the 3 IGS reference station sets (the 13 ITRF94, 47 ITRF96 and the 52 ITRF97).

ITRF97 Data Analysis

The ITRF97 solution was generated by combining station positions and velocities together with full variance-covariance matrices of 4 VLBI , 5 SLR , 6 GPS, 3 DORIS and one multi-technique (SLR + DORIS) solutions provided by IERS and IGS Analysis Centers in SINEX format. These solutions are summarized in Table 1 and illustrated in Figure1.

The ITRF97 solution is derived with the following properties (Boucher et al., 1999):

- All the individual matrices were orthogonaly projected to minimize the Reference System Effect;
- The projected solutions were then propagated to their Epochs of Minimal Position Variance;
- The reference frame definition (origin, scale, orientation and time evolution) is achieved in such a way that ITRF97 is in the same system as the ITRF96;
- Station velocities are constrained to be the same for all points within one and the same site;
- ITRF97 positions were estimated at epoch 1997.0;
- Transformation parameters from ITRF97 to individual solutions were also estimated at epoch 1997.0 for all solutions.

Table 1. Selected Solutions for the ITRF97 analysis

Solution	Data Span yy-yy	Station nb.	Ref. Epoch y:doy
VLBI			
SSC(GSFC) 98 R 01	79-98	129	97:001
SSC(GIUB) 98 R 01	85-97	49	93:001
SSC(USNO) 98 R 01	79-98	110	97:001
SSC(NOAA) 95 R 01	79-94	107	93:001
SLR			
SSC(CSR) 98 L 01	76-98	129	93:001
SSC(DUT) 98 L 01	83-97	72	93:001
SSC(GZ) 98 L 01	93-98	51	93:001
SSC(GSFC) 98 L 01	80-97	38	86:182
SSC(CGS) 98 L 01	86-98	76	93:001
GPS			
SSC(CODE) 98 P 01	93-98	139	95:314
SSC(EMR) 98 P 01	94-97	40	98:001
SSC(EUR) 98 P 01	96-98	67	97:074
SSC(GFZ) 98 P 01	93-97	76	97:001
SSC(JPL) 98 P 02	91-98	84	96:001
SSC(NRCAN)98 P 01	95-98	145	98:001
DORIS			
SSC(GRGS) 98 D 01	93-98	63	93:001
SSC(IGN) 98 D 04	90-97	69	94:001
SSC(CSR) 96 D 01	93-96	54	93:001
Multi-technique			
SSC(GRIM) 98 C 01	85-96	143	

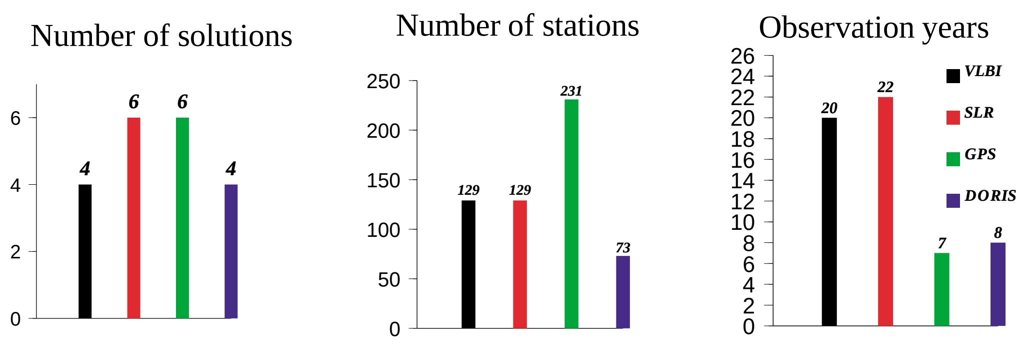

Fig. 1: Data used in the ITRF97 combination

ITRF97 Results

All the ITRF97 results are published in (Boucher et al., 1999) and available via Internet: http://lareg.ensg.ign.fr/ITRF/ITRF97.

In order to evaluate the ITRF97 quality, Figure 2 displays the position and velocity spherical errors, showing an improvement of the ITRF97 with respect to ITRF96. Moreover, Figures 3 summarizes the position and velocity Weighted RMS per solution.

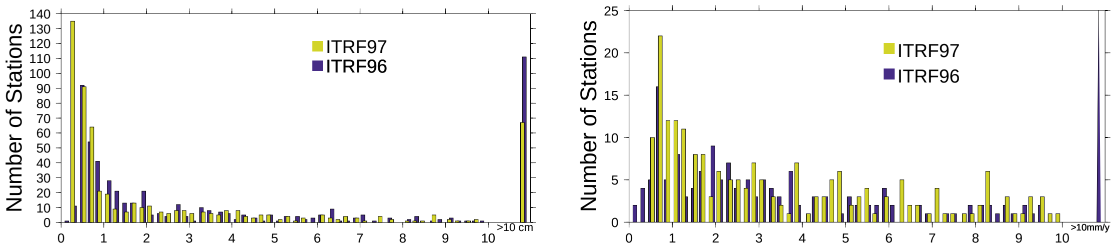

Fig. 2: Position (cm, at epoch 1997.0) and velocity (mm/y) spherical errors

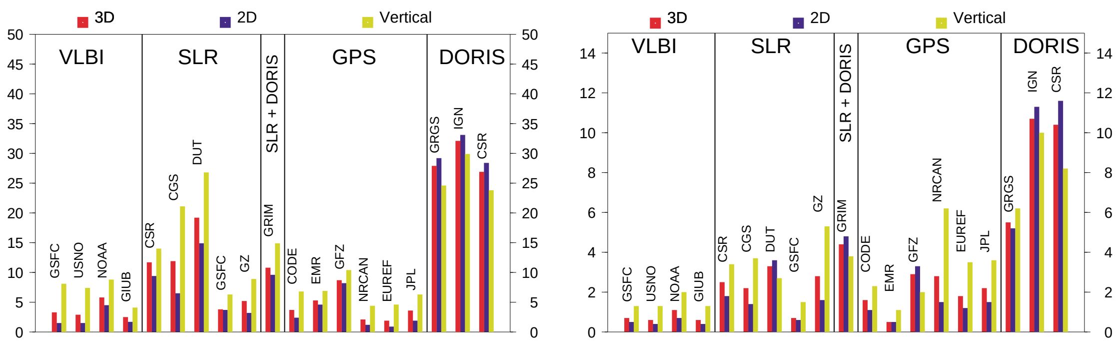

Fig. 3: ITRF97: Position and Velocity WRMS per Solution

Quality Analyis of IGS Reference Stations

52 ITRF GPS stations were selected by the IGS Analysis Centers in 1998 to be used as reference in IGS computations, replacing the old 13 ITRF94 stations (Kouba et al., 1998). The quality of these 52 stations, globally distributed, was analysed using ITRF96 residuals (Altamimi, 1998) and then reduced to 47, the 5 remaining stations were of poor quality. As continuation of this study, the quality of the 52 stations are again analysed in the light of the recent ITRF97 solution. 33 stations of the 52 are collocated with at least one of the 3 other IERS techniques (VLBI, SLR, DORIS). For the purpose of this analysis, position residuals of all the individual solutions included in the ITRF97 are computed at epoch 1997.0, taking into account velocity residuals. Based on 1997.0 position and velocity residuals, the 52 IGS Reference Stations were classified according to the 3 criteria in (Altamimi, 1998) that we repeat here:

1. Agreement GPS solutions for positions at epoch 1997.0
2. Agreement of solutions for positions at epoch 1997.0 in the collocation sites
3. Agreement of solutions for velocities

4. Classes were selected to qualify the 52 stations as described in Table 2.

Table 2. ITRF97 Classes for Station Positions at epoch 1997.0 and Velocities. ITRF97 post fit r esiduals *R* should be as indicated in the table, over the 3 components for at least 3 solutions (including local ties for collocation sites).
Unit: cm for positions, cm/y for velocities.

Class	A	B	C	D
Positions GPS-only sites	$R < 1$	$R < 2$	$R > 2$	
Positions Collocation sites	$R < 2$	$R < 3$	$3 < R < 5$	$R < 5$
Velocity	$R < 0.5$	$R < 1$	$R < 1.5$	$R > 1.5$

Table 3 summarizes the classification of the 52 GPSstations. For comparison, the ITRF96 classes are also listed in this table. A summary of the number of stations per class is given in Table 4, and illustrated on Figure 4. Figure 5 shows the coverage of the 52 sites.

Table 3. Classification of the IGS Reference Stations.

		ITRF96			ITRF97			Improv.		
CODE	DOMES nb.	Pos. GPS	Pos. Col.	Vel.	Pos. GPS	Pos. Col.	Vel.	Pos. GPS	Pos. Col.	Vel.
ALGO	40104M002	A	A	A	A	A	A			
AREQ	42202M005	A	A	B	A	A	A			+
AUCK	50209M001	C		C	A		A	+		+
BAHR	24901M002	C		D	B		B	+		+
BRAZ	41606M001	B		B	A		B	+		
BRMU	42501S004	A	m	A	A	m	A			
CAS1	66011M001	B		C	A		B	+		+
CHAT	50207M001	B		D	A		B	+		+
DAV1	66010M001	B		B	A		A	+		+
DRAO	40105M002	A	D	D	A	D	D			
FAIR	40408M001	A	A	A	A	A	A			
FORT	41602M001	A	A	A	A	A	A			

m : missing local tie

Table 3. Classification of the IGS Reference Stations (continued).

		ITRF96			ITRF97			Improv.		
		Pos.	Pos.	Vel.	Pos.	Pos.	Vel.	Pos.	Pos.	Vel.
CODE	DOMES nb.	GPS	Col.		GPS	Col.		GPS	Col.	
GODE	40451M123	A	B	A	A	A	A		+	
GOLD	40405S031	A	m	A	A	m	A			
GRAZ	11001M002	A	A	A	A	A	A			
GUAM	50501M002	A	A	B	A	A	B			
HART	30302M002	B	B	A	B	B	A			
HOB2	50116M004	A	m	A	A	A	A		+	
IRKT	12313M001	B		B	A		A	+		+
KERG	91201M002	B	D	C	B	D	C			
KIT3	12334M001	A	B	A	A	B	A			
KOKB	40424M004	A	A	A	A	A	A			
KOSG	13504M003	A	C	D	A	B	A		+	+
KOUR	97301M210	B	B	B	A	A	B	+	+	
KWJ1	50506M001	A		B	A		B			
LHAS	21613M001	A		B	A		A			+
MAC1	50135M001	A		B	A		A			+
MADR	13407S012	A	A	A	A	A	A			
MALI	33201M001	B		B	A		B	+		
MAS1	31303M002	A		A	A		A			
MATE	12734M008	A	A	A	A	A	A			
MCM4	66001M003	B		D	B		B			+
MDO1	40442M012	A	A	A	A	A	A			
NLIB	40465M001	A	A	A	A	A	A			
NYAL	10317M001	A	B	A	A	B	A			
OHIG	66008M001	B	B	B	A	C	B	+	-	
ONSA	10402M004	A	A	A	A	A	A			
PERT	50133M001	A		B	A		B			
PIE1	40456M001	B	B	A	B	B	A			
POTS	14106M003	A	C	B	A	A	A		+	+
SANT	41705M003	A	A	A	A	A	A			
SHAO	21605M002	A	A	A	A	B	A		-	
THU1	43001M001	A		B	A		B			
TIDB	50103M108	A	A	B	A	A	A			+
TROM	10302M003	A	D	C	A	C	B		+	+
TSKB	21730S005	A	A	B	A	B	A		-	+
VILL	13406M001	A		B	A		A			+
WES2	40440S020	A	B	A	A	B	A			
WTZR	14201M010	A	A	A	A	A	A			
YAR1	50107M004	A	B	A	A	A	A		+	
YELL	40127M003	A	A	A	A	A	A			
ZWEN	12330M001	A		B	A		A			+

Table 4. Number of stations per class.

	Class A	Class B	Class C	Class D
ITRF96				
GPS_only	38	12	2	
Colocation	18	9	2	3
Velocity	25	18	4	5
ITRF97				
GPS_only	47	5	0	
Colocation	21	8	2	2
Velocity	37	13	1	1

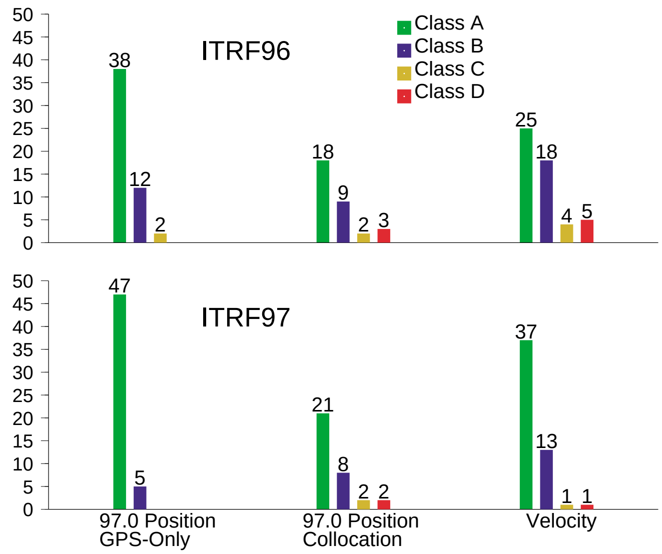

Fig. 4. Classification of the IGS reference stations.

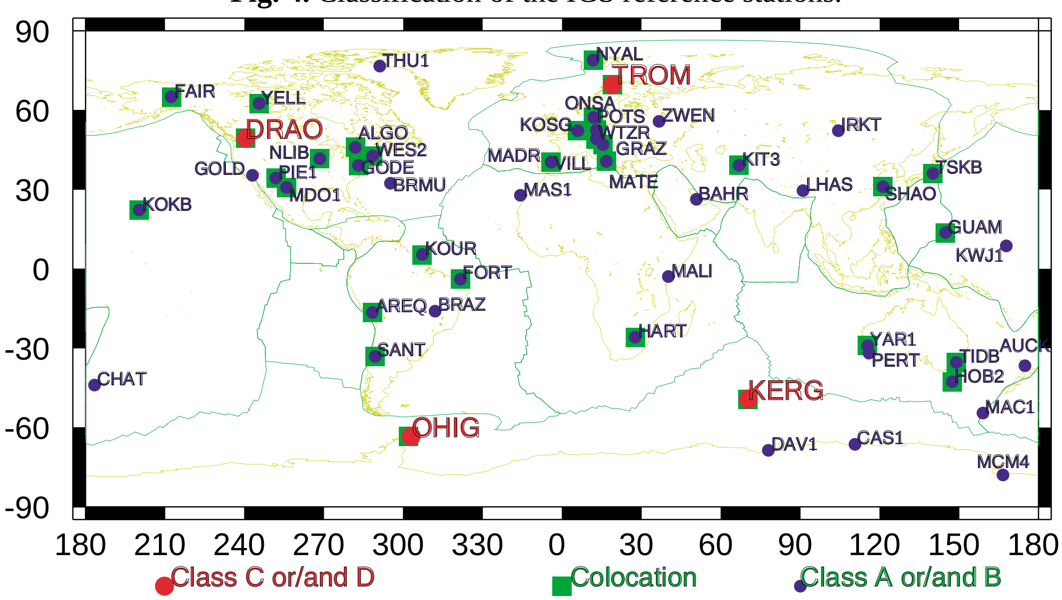

Fig. 5. Distribution of the IGS reference stations

Transformation Parameters Between IGS Reference Station Sets

Although ITRF94, ITRF96 and ITRF97 are based on the same datum definition (Boucher et al, 1998, 1999), non zero transformation parameters could occur between subsets of these ITRF solutions. This is due to the fact that the transformation parametres are very sensitive to particulary the network effect (the distribution of the stations over the globe) and the weighting used in the estimation of these parameters.

Table 5 summarizes the estimated transformation parameters at epoch 1999.0 and their rates between the 3 IGS reference stations sets. It should be noted that in order to minimize the Reference System Effect, the 3 covariance matrices of these sets were first orthogonally projected, (for more details on orthogonal projection, see for instance Boucher et al, 1999, and the ITRF97 WEB page : http://lareg.ensg.ign.fr/ITRF/ITRF97/).

Table 5. Transformation parameters and their rates between the 3 ITRF/IGS reference station sets.

$T1$ mm	$T2$ mm	$T3$ mm	D 10^{-9}	$R1$ 0.001"	$R2$ 0.001"	$R3$ 0.001"	Epoch
$\dot{T}1$ mm	$\dot{T}2$ mm	$\dot{T}3$ mm	$\dot{D}$ 10^{-9}	$\dot{R}1$ 0.001"	$\dot{R}2$ 0.001"	$\dot{R}3$ 0.001"	/ y
From ITRF96 to ITRF94 (nb. of common stations 13)							
-.1	.9	.3	.30	.137	-.079	.092	99:001
1.3	1.4	1.3	.25	.042	.040	.045	
-.2	.5	.1	-.03	-.016	-.030	-.028	
.3	.3	.3	.06	.011	.010	.012	
From ITRF97 to ITRF94 (nb. of common stations 13)							
-3.0	-2.0	14.8	-.96	-.037	.214	.231	99:001
1.1	1.1	1.1	.19	.032	.032	.034	
-.1	-.1	1.9	-.27	-.034	-.006	-.005	
.3	.3	.3	.05	.008	.008	.010	
From ITRF97 to ITRF96 (nb. of common stations 47)							
-1.6	-.2	13.5	-1.32	-.159	.248	.038	99:001
.6	.6	.6	.09	.020	.020	.020	
.3	.1	1.7	-.18	-.016	.011	-.011	
.3	.3	.3	.04	.009	.009	.009	

Conclusion

The ITRF97 results show a significant improvement with respect to ITRF96. We therefore recommend the use of ITRF97 instead of ITRF96. Moreover, the 5 ITRF96 rejected stations: (AUCK 50209M001), (BAHR 24901M002), (CAS1 66011M001), (CHAT 50207M001) and (MCM4 66001M003) are now, with ITRF97, of class A or B so that all the 52 stations could be used as reference stations for IGS purpose. Meanwhile, we have to note the following:

- 4 collocated sites appear to have velocity or/and local tie problems: (DRAO40105M002, class D), (KERG 91201M002, class D), (TROM 10302M003, class C) and (OHIG 66008M001, class C). But if based on GPS-only estimates, they could be maintained in the IGS Reference Stations list.
- 1 pure GPS station (AUCK 50209M001) appears in only two GPS solutions included in the ITRF97, which agree better than 1 cm in position and better than 5 mm/y in velocity.
- the peculiar case of the Westford site still need attention. Although the "best" position agreement (at 1997.0) between some GPS and VLBI solutions, plus local tie, is estimated to be about 11 mm, the "worst" agreement is about 43 mm.

Finally, in terms of transformation parameters between ITRF96 and ITRF97 IGS sets, it emerges from Table 3 that there are 4 "significant" transformation parameters at epoch 1999.0 of about: 14 mm translation along the Z-axis, 1.3 ppb scale difference, 0.16 and 0.25 mas in rotation around the X and Y axis, respectively.

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Real-Time Data Validation, Compression and Communication in the Dutch Permanent GPS Array AGRS.NL

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Abstract

In the Netherlands, research on establishing permanent GPS reference stations was initiated in 1993, resulting in a network of five stations together with a central processing facility. This network, the Active GPS Reference System for The Netherlands (AGRS.NL) is used for a wide variety of high-precision GPS applications. They include positioning, sea-level and subsidence monitoring and land-surveying, but also the determination in near real-time of the water vapor content of the atmosphere.

Already in 1993 it was recognized that real-time applications of permanent GPS arrays would become increasingly important in the near future. Therefore software was developed for the reference stations which should perform a number of tasks: communicate with the GPS receiver and meteorological sensors, validate the code and carrier observations in real-time, reformat the GPS and meteorological data in a compact, binary format and, finally, transmit this data to the central processing facility. Recently, the software was adapted to also incorporate the validation of Glonass observations. For the central facility, software was developed to receive the reference station data, store it and make it available to users in Rinex format for further processing.

Figure 1: Reference stations of the Dutch AGRS.NL

In this contribution, a description will be given of the implemented data validation (or integrity monitoring) functions, the dedicated compressed binary format and the data communication facilities of the AGRS.NL.

Introduction

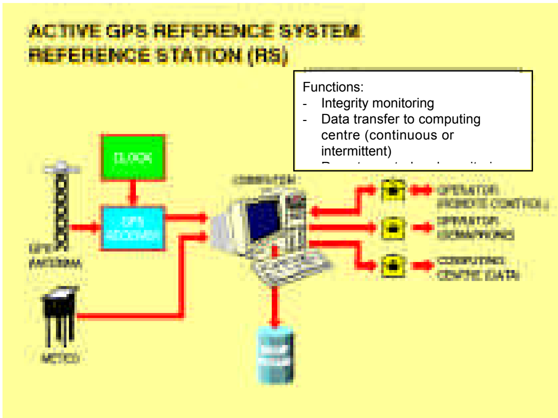


Figure 2: Reference station design of the Dutch AGRS.NL

Originally conceived in 1993 by Delft University of Technology (DUT), the Survey Department of the Ministry of Transport (MD) and the Triangulation Department of the Dutch Cadastre (RD), the Active GPS Reference System for The Netherlands (AGRS.NL) became operational in 1997. AGRS.NL is a permanent GPS array consisting of five stations, evenly distributed over The Netherlands, shown in Figure 1, and a central processing facility. The data of the AGRS.NL is used for a wide range of geodetic and non-geodetic applications. One of the original objectives of the AGRS.NL was to serve as a backbone for accurate GPS height determination within the context of the fifth primary levelling of The Netherlands. Other typically geodetic applications are the use of the AGRS.NL for sea-level monitoring along the Dutch coast and land-subsidence monitoring near the Groningen gasfield in the north of The Netherlands. But the AGRS.NL also serves as a reference for precise positioning and surveying in for instance aerial photogrammetry and dike profile determination. As for non-geodetic applications, DUT recently participated in a research project of the Royal Dutch Meteorological Office (KNMI) exploring the use of GPS for the determination of the integrated partial water vapor content of the atmosphere, [van der Hoeven et al, 1998]. Originally operated in a campaign-like fashion, IPWC estimates can now be made available in near-real time. For more information on these and other applications, the reader is referred to the internet site www.agrs.nl.

Each reference station of AGRS.NL is equipped with a geodetic quality dual-frequency GPS receiver, meteorological sensors, a PC with multiport serial controller, modems, telephone connections and an uninterruptable power supply, see also Figure 2.

The software running at the reference station, developed by DUT, performs the following tasks:

- Control receiver (e.g., set observation interval, minimum elevation, data format) and collect GPS data.
- Real-time integrity monitoring (or data validation) of dual-frequency GPS code and carrier data, see section 2.
- Control meteorological sensors (set data output interval) and collect temperature, pressure and relative humidity data.

- Log events (time the receiver started or stopped tracking a particular satellite, time a new navigation message was collected, time the integrity monitoring's filter was initialized, time an outlier or cycle slip was found in the GPS data).
- Temporarily store GPS data, quality control parameters and meteorological data on the reference station's local hard drive in a dedicated binary format, see section 3. The data will be automatically removed after a user-defined period.
- Transmit data, again in binary format, to the central processing facility, see section 4.
- Generate alarms, e.g., when the receiver did not track any satellites for more than twice the selected observation interval.

In parallel to this software, a commercially available package is running to remotely control the receiver.

Currently interfaces are available for the TurboRogue, Trimble SSE/SSi and JPS Legacy receivers. The JPS Legacy is a GPS/Glonass receiver. Data can also be processed off-line for these receivers. In addition, an interfsce was developed for the off-line processing of Rinex data.

At the central processing facility, the following tasks are performed:
- Collect GPS and meteorological data from all reference stations and store this data.
- Collect and store precise orbits and other data of interest from IGS.
- Process the data, i.e., compute a network solution to monitor the stability of the reference stations and compute atmospheric parameters, such as integrated partial water vapor.
- Distribute data to AGRS users through a WWW based service, [van der Marel, 1998].

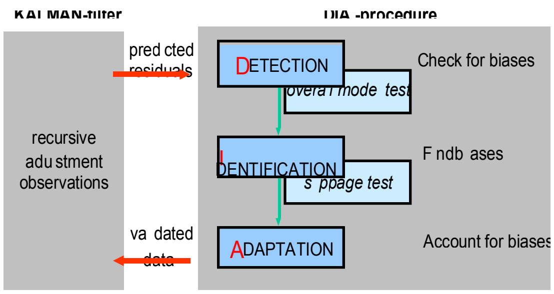
Data distributed to users may consist of the actual reference station data or data generated for a virtual reference station close to a user's survey location. The virtual reference station's data is generated using the real data from the actual reference stations, [van der Marel, 1998].

Integrity Monitoring of GPS Observations

In this section, the theoretical concepts on which the integrity monitoring software for GPS data is based, will briefly be explained. Although originally developed for GPS data, [de Jong, 1996], the approach has proven to work for Glonass data as well, [de Jong, 1998], [de Jong & Jonkman 1999].

Testing and Reliability

The integrity monitoring (or validation) of code and carrier observations is based on the recursive Detection, Identification and Adaptation (DIA-) procedure, [Teunissen, 1990], running in parallel to a Kalman filter, [Kalman, 1960], see Figure 3. The DIA-procedure aims to detect possible misspecifications in the observation model of the Kalman filter by means of statistical hypothesis testing.



The procedure consists of the following steps

1. *Detection:* An overall model test is carried out to diagnose whether unspecified model errors have occurred.
2. *Identification:* If a model error is detected, its potential source is identified by testing the original or nominal observation model against models extended with bias parameters.
3. *Adaptation:* After the identification of the most likely source for the model error, the observation model is adapted to eliminate the biases in the filters' state vector.

The nominal observation model is indicated as the observation model under the null-hypothesis; the models extended with bias parameters are indicated as models under alternative hypotheses. In the integrity monitoring software only one-dimensional alternative hypotheses, describing outliers or integer cycle slips in the observations are considered. These biases are assumed to be described by a known vector c_k and an unknown scalar , as c_k .

The test statistics associated with the DIA-procedure are based on the filter's predicted residuals or innovations sequence v_k, and its corresponding covariance matrix Q_{v_k}. The predicted residual is defined as the difference between actual and predicted observations. Under the null-hypothesis, the expectation of v_k is zero; under the alternative hypothesis the expectation equals c_k .

With these test statistics, the Detection and Identification step of the DIA-procedure can be described in the following manner. A model error is detected and the null-hypothesis is rejected in the Detection step, if the overall model test statistic exceeds a certain critical value. The critical value is set, based on the distribution of the overall model test statistic under the null-hypothesis. In the subsequent Identification step, the test statistics of the alternative hypotheses, indicated as the local slippage (LS) test statistics, are computed and the alternative hypothesis corresponding to the largest statistic is said to describe the most likely misspecification of the observation model. For this misspecification to be sufficiently likely however, the LS test statistic also has to exceed a critical value, which again is set based on the distribution of this statistic under the null hypothesis. If the largest slippage test statistic remains smaller than the critical value, then a misspecification other than the ones described by the alternative hypotheses is thought to be present.

The size of the model error that can be detected in the Identification step with a probability γ , the so-called power of the test, is referred to as the Minimal Detectable Bias (MDB), [Salzmann, 1991]. The MDBs can be computed once two reference probabilities have been specified: the probability of rejecting the null-hypothesis when it is actually true (α_0) and the probability of rejecting the null-hypothesis when an alternative hypothesis is true (γ_0). In addition they are a function of the a priori chosen standard deviations of the observations and the uncertainties in the Kalman filter's dynamic models. No actual data is required to compute MDBs. They provide an important diagnostic tool for inferring how well particular model errors, such as outliers and cycle slips, can be detected, see also subsection 2.3. The MDBs are said to describe internal reliability of a system.

Table 1: Receiver tracking scenarios. Cn (n=1,2,3,4,5) refers to code-correlation, X4 to cross-correlation tracking.

	Carrier			Code			
No. of obs.	L1	L2	C/A	P1	P2	P2-P1	Identifier
3	×	×	×	-	-	-	C3
4	×	×	-	×	×	-	C4
4	×	×	×	-	-	×	X4
5	×	×	×	×	×	-	C5

Measurement and Dynamic Models

The integrity monitoring functions were developed based on the philosophy that they should be applicable irrespective of the application(s) for which the data may originally have been collected. They should therefore not require any external information, like satellite and receiver positions, velocities and clock behavior or information on atmospheric effects. This can be accomplished by using the geometry-free observation model, [Euler & Goad, 1991], [Jonkman, 1998], as a basis for the measurement and dynamic models. In this model, observations are not parametrized in terms of the unknown station coordinates. Instead, the observations remain parametrized in terms of the original, unknown (pseudo-) ranges.

A total number of five basic observables are available from the GPS (and Glonass) satellites: two carrier observations (L1, L2) and three code observations (P1, P2, C/A). In addition, for GPS with Anti-Spoofing switched on, a technique known as cross-correlation may be deployed, resulting in a derived code observable, which consists of the difference between the encrypted P1 and P2 codes. The reconstructed P2 code observation is then obtained as the sum of the C/A and P2-P1 observations, resulting in (additional) correlation between the C/A and P2 code observation, [Teunissen et al, 1998]. The receiver tracking scenarios considered in the integrity monitoring software, running at the reference stations of AGRS.NL, are summarized in Table 1.

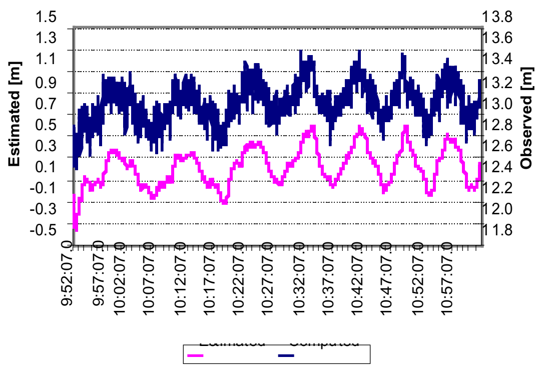


Figure 4: Estimated and computed P2 code biases.

Data processing is done on a single-channel basis. This means that data from each satellite is processed independently. There is consequently no minimum number of satellites required for the integrity monitoring to work. In addition, although it is possible to include a dynamic model for the distance between receiver and satellite, this will only work well if the observation interval is small and if the receiver clock behavior can be described by a low-order polynomial. Since both conditions are often not met, the distance and clock terms are eliminated, simply by subtracting one observation from the other ones. As a result, the only parameters that remain to be modeled are the biased (by carrier ambiguities and/or hardware delays) ionospheric effects and the offset between P1 and C/A code. Each of these parameters corresponds to one particular observation. Thus, if one or more observations are missing, the corresponding observations and parameters are simply omitted from the measurement model. For the ionospheric effect it is assumed that it can be modeled by a first order polynomial. The parameter describing the ionospheric rate of change is common to all observations in the measurement model. The corresponding dynamic or transition model for the ionospheric effect and its first order time derivative is assumed to consist of a zero-mean white noise process, characterized by its spectral density $q_I^{(2)}$.

In addition to the above mentioned parameters, it is also possible to include a dynamic model to describe biases in the code observations, [Jin, 1996], [de Jong, 1996]. These biases are mainly due to multipath, see also [de Jong, 1999] for more details on the influence of multipath on the parameters estimated by the integrity monitoring functions. Shown in Figure 4 are time series of the estimated and computed (using a linear combination of one code and two carrier observations, which is mainly a function of the noise in the code observations) code biases. As can be seen from this figure, these time

Table 2: Parameters used for the computation of MDBs

Standard deviations (m)		Spectral densities	
φ_1	0.003	$q_I^{(2)}$	10^{-8} m^2/s^3
φ_2	0.003		
C_1	0.3	Testing parameters	
C_2	0.3	α_0	0.001
$C_{C/A}$	0.3	β_0	0.80
C_{P2-P1}	0.4$^{(*)}$		

$^{(*)}$St. dev. σ computed as: $\sigma_{C_{P2-P1}} = \sqrt{\sigma^2_{C_1} + \sigma^2_{C_2}}$

series correspond very well. The integrity monitoring software is therefore an objective means to evaluate the susceptibility of a site's environment to multipath. It may therefore serve as a useful tool when selecting a point to become a reference station.

Design Computations

In this subsection the theoretical performance of the integrity monitoring software will be analyzed by means of the Minimal Detectable Bias (MDB)-measure introduced in the subsection on testing and reliability. MDBs will be given for the four receiver tracking scenarios of Table 1. Default parameters used for the computations are given in Table 2 and are based on the values given in [Jin, 1996] and [de Jong, 1996]. It appears that the code MDBs are roughly equal to four times the standard deviations of the code observations. The carrier MDBs are mainly a function of the observation interval, the spectral density of the ionospheric model and the standard deviations of the carrier observations, [de Jong, 1998]. Shown in Figure 5 are the carrier MDBs as a function of the observation interval. It can be concluded from this figure that even for observation intervals, or data gaps, as large as 60 seconds, the carrier MDBs are

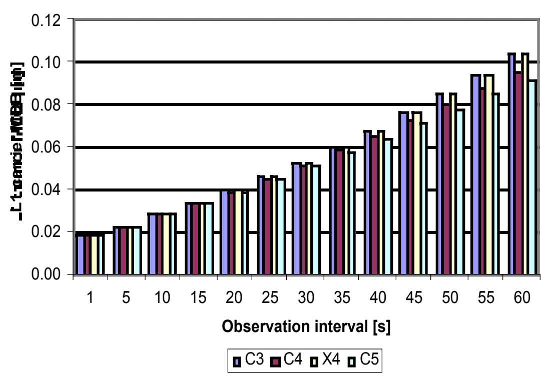


Figure 5: Carrier MDBs as function of the observation interval.

small enough to find even the smallest cycle slip, bearing in mind that a cycle corresponds to approximately 20 cm.

Error Detection

In order to appreciate the performance of the DIA-procedure, a cycle slip of one cycle was added to the L1 carrier observations of an arbitrarily selected GPS satellite. Data was processed using only a dynamic model for the ionospheric effects; code multipath was not accounted for. Observation interval was 30 seconds. Shown in Table 3 are the results of the three steps of the DIA procedure. A model error is clearly detected: the overall model test statistic is much larger than the critical value (71.5 vs. 3.4). Moreover, in the resulting identification step a cycle slip was correctly identified as the cause of the model error. From 6:07:00 onwards (the time the slip was added), the adaptation step of the DIA-procedure automatically corrected the L1 carrier observations by subtracting the estimated integer slip. The results of a similar test in which an outlier of 3 meter was added to the P1 code observation is also presented in Table 3.

Table 3: Example of performance of the dual-frequency integrity monitoring functions: in the first processing run, a slip of one cycle was added to the L1 carrier data of GPS satellite 9, in the second run, an outlier of three meters was added to the P1 code data.

Time		31/03/99 6:07:00-cont	31/03/99 6:07:00
Type of bias		L1 cycle slip of 1 cycle	P1 outlier of 3 m
Critical value overall test	3.4		
Critical value LS test	3.3		
Detection	Overall model test statistic	71.5	7.73
Identification	Alternative hypothesis	LS test statistic	LS test statistic
	L1 cycle slip	***16.9***	0.14
	L2 cycle slip	16.8	0.04
	P1 outlier	1.5	***5.53***
	P2 outlier	1.6	0.36
	C/A outlier	1.5	0.44
Adaptation	Estimated bias	1.02 cycle	2.80 m
	Cycle slip after rounding	1.00 cycle	-

Data Compression

For the efficient transfer and storage of GPS and related data, the receiver independent compressed binary (CBI) format has been developed, [van der Marel, 1996]. The current version of the CBI format contains records for:

- Station, receiver and antenna data.
- Dual-frequency GPS code and carrier observations.
- GPS navigation messages.
- Meteorological data.
- Events (see section 1).

In the near future, new records may be added, for example for Glonass observations and navigation messages.

Table 4: File size comparison (24 hour observation period, 30 s. observation interval).

	Unzipped	Zipped
CBI	600 KB	485 KB
Rinex w/o SNR	2300 KB	645 KB
Rinex with SNR	2970 KB	765 KB

The CBI format has been optimized with

Table 5: Example of bit assignments for a CBI record, containing dual-frequency code and carrier observations and related data, for a single satellite.

	Size (bits)	Range	Resolution	Units
Satellite	6	0…63	1	-
Channel QC	4	0…15	1	-
SNR (P1)	10	0…1023	1	volts/volt
Carrier (L1, frac.)	10	0…1	2^{-10}	L1 cycles
Carrier (L1, int.)	27	$\pm 2^{27}$	1	L1 cycles
Frequency QC (L1)	3	0…7	1	-
Code (L1)	32	$0 \ldots 2^{17}$	2^{-15}	C/A chips
Code (L1-L2)	28	$\pm 2^{12}$	2^{-15}	P chips
Frequency QC (L2)	3	0…7	1	-
Carrier (L1-L2)	21	±1024	2^{-10}	L1 cycles
SNR (P2)	10	0…1023	1	volts/volt
Spare	6	-	1	-
Total	160 (20 bytes)			

Signal to noise ratio (SNR) is stored in units of volts/volt and can be converted to C/No (dB*Hz) using the expression: C/No = 20log(SNR).

Channel QC can have the following values:

- 0 No problem (includes the case all biases could be identified).
- 1 Filter not initialized for this satellite.
- 2 Too many errors, filter will be re-initialized.
- 3 Model errors (biases were detected, but the likelihood of the alternative hypothesis with the largest local slippage test statistic was less than the critical value); filter will be re-initialized.
- 4 Carrier MDBs too large to find all cycle slips.

Frequency QC can have the following values:

- Bit 0 set Outlier identified in code observations.
- Bit 1 set Outlier identified in carrier observations.
- Bit 2 set Cycle slip identified in carrier observations.

respect to size for efficient transfer and storage. To this end, the data is packed in a unique binary format. CBI files are typically about four times smaller than corresponding Rinex files. The efficiency of the format is illustrated by the fact that well-known compression tools, like PKZIP, results in a file size reduction of only 20%, and unzipped CBI files are smaller than zipped Rinex files. In Table 4 this is illustrated for a 24 hour data file, collected with an observation interval of 30 seconds. It should also be noted, that when data is transmitted in small packages, e.g., continuously, from reference station to central processing facility, compression tools will actually result in an increased data block size, due to the included administration data.

Unlike compressed Rinex, [Hatanaka, 1996], the CBI format is a "stand-alone" format. This means that the contents of a record do not depend on the availability of other records to reconstruct for example the original observations. All required information is contained in a single record.

In Table 5 an example is given of the size of a single channel record, containing dual-frequency code and carrier observations and additional data, such as signal to noise ratios and quality control (QC) parameters. The size of this record is 20 bytes. From this table it follows that the resolution of a carrier observation is of the order of 0.02 cm, whereas for a code observation the resolution is 1 cm. A channel record is stored and transmitted as part of an epoch record, which contains record identifier, its size and the GPS time of observation; the size of this header data is eight bytes.

Data Transmission

Data in CBI format is transmitted to the central processing facility using modem and telephone lines. The software running at the reference station will dial a user-defined telephone number and transmit data. If no connection can be established or if data transmission is interrupted, the software will try to (re-)establish the connection. If after two attempts no connection can be established, the software will wait 15 minutes and repeat this procedure.

When a connection is established, the reference station and central facility negotiate about the first block of data to be transmitted. The receiving side stores the time, to which the last block it received, applies. The first block to be transmitted by the reference station is therefore the block immediately following this last block, stored at the central facility. This will guarantee a complete data transfer.

Before transmission, data may be decimated to a user-defined interval. For example, data may be collected at an interval of one second, but transmitted only once every 30 seconds. Data transmission can be done continuously or in bins. In the former case, the telephone line will be permanently open, which may be very expensive. Test have shown that it is no problem to transmit data, collected at one second intervals continuously, using a data rate of only 14400 bits per second. When data is transmitted in bins, the transmission interval is user-defined, for example once per hour or once per day. Transmitting data in this way takes only a very short time. Data received at the central facility is checked for transmission errors by comparing the transmitted checksum with the computed one. If these checksums do not match, the reference station is requested to re-transmit the last block of data.

Conclusions

In this contribution a description was given of the integrity monitoring functions, developed for the reference stations of the Dutch permanent GPS array AGRS.NL. The integrity monitoring is based on the recursive Kalman filter and the DIA (Detection, Identification and Adaptation) procedure, which is also recursive and parallels the Kalman filter. As a result, the developed procedures are well-suited for real-time implementation. Moreover, the integrity monitoring functions do not require any external information and are therefore independent of the application for which the data may have been collected.

An overview was given of the compressed binary (CBI) format, developed for temporary storage of GPS and meteorological data at a reference station and for transmission to the central processing facility of AGRS.NL. At the central facility, data is also stored in CBI format. It is made available to users, however, in Rinex format.

Finally, a brief description was given of the data communication between reference stations and central processing facility. Due to the efficient data compression, communication takes place using ordinary telephone lines, and allow for the real-time transmission of GPS data, collected with a high sample rate.

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Operational Water Vapor Estimation in a Dense German Network

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Introduction

Water vapor is a key element in the hydrological cycle and is an important greenhouse gas in the atmosphere. Its very inhomogeneous and highly variable distribution makes water vapor a crucial element in numerical weather predictions (NWP). In the past decades there was a great progress in remote sensing of the atmosphere, however, our knowledge about the water vapor distribution is still insufficient. Conventional observing systems such as radiosondes are not adequate for observing its high variability because of limited spatial distribution. A continuous, low cost monitoring of water vapor is offered by GPS.

Presently for the numerical weather prediction the derived water vapor must be available with a delay of only 2 to 3 hours. Therefore near real-time data retrieval and analysis are necessary. A significant impact on the quality of the NWP can only be expected if the network has a relatively high density. Both demands can be fulfilled best working on a national or regional basis.

Operational Water Vapor Monitoring in Germany

In the next three years a large strategic project named GPS Atmosphere Sounding Project (GASP) will be carried out by the four Research Centers GFZ, AWI, DLR and GKSS of the Helmholtz Society. GFZ leading this project will also cooperate with various national and international partners. It comprises space-based and ground-based GPS techniques and combines the expertise of GPS specialists and climate/weather modelers. The results from both parts will be assimilated into the NWP and climate models. Whereas the importance of the ground-based results is a continuous monitoring of the vertical integrated PWV, the space-based results yield vertical profiles laterally integrated over several hundred kilometers. Having a dense ground network those data can be used to validate the profile data.

The ground-based part of GASP will focus on an operational water vapor monitoring in a dense German ground network with the following goals:

- NRT data retrieval from German network

- Development of techniques and methods for quasi-operational determination of integrated water vapor
- Development of strategies for meteorological practice and research

On the basis of this project a cooperation with the German Weather Service (DWD) was initiated.

In Germany a great number of DGPS reference stations already exists. The most important network is the SAPOS network established by the Land Surveying Agencies in the 16 states of Germany. The final network will have more than 200 sites with a spacing of about 50 km all over Germany. At present 150 sites are already in place (Fig. 1). The infrastructure of ground-based GPS receivers, established for surveying and navigational purposes, could be used for the meteorological applications with a relatively small additional effort.

In order to gain experience with a NRT system and to assess the quality of tropospheric estimates obtained in a NRT analysis a small network was established. In December 1998 ten GPS receivers of GFZ were installed at synoptic sites of the DWD (Fig. 2). The GPS data and the meteorological surface data were transferred in hourly batches to GFZ. The analysis was performed in sliding 12-hour windows shifted by 2 hours.

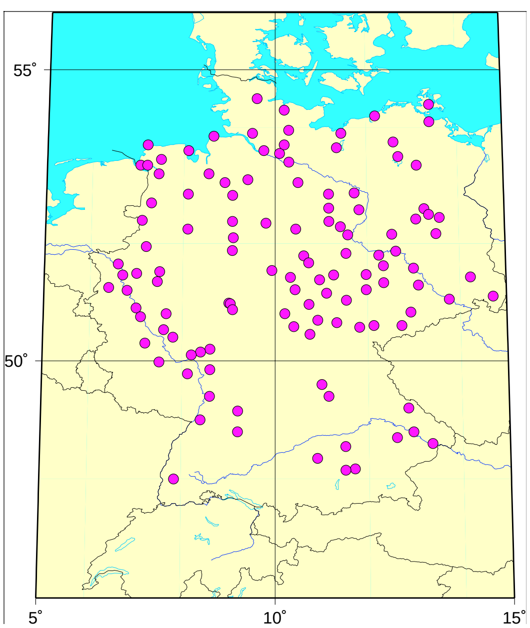

Fig. 1. German SAPOS Network of differential GFZ GPS stations (status 3/98)

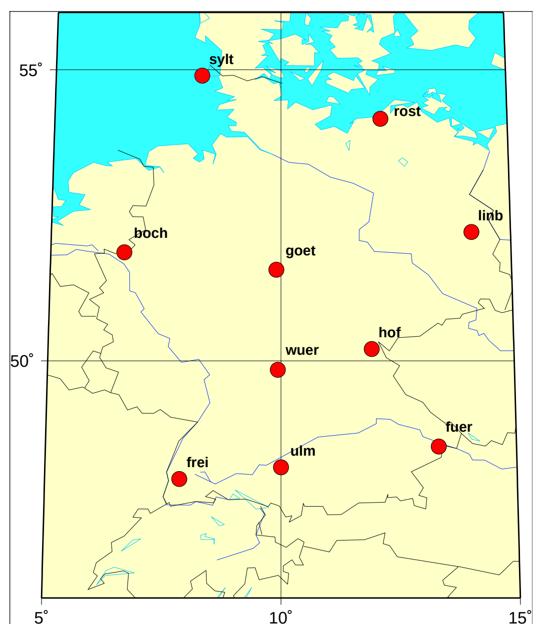

Fig. 2. Network of GPS stations of installed at synoptic sites of the German Weather Service

Among the estimated parameters are the satellite orbits (the predictions were used as initials), and the zenith path delays for hourly intervals. The station coordinates were fixed, once determined with sufficient accuracy.

An example for the monitoring of water vapor is given in Figure 3, where a frontal system is shown over Europe which develops within two days over Germany.

The results were validated using the post-processed estimates and co-located instruments like WVR and radiosondes. The consistency between NRT and post-processed estimates is very high (Fig. 4). There are no significant biases and the standard deviation in the difference is at the 1 mm level of precipitable water vapor (PWV). Both follow the high fluctuations in the same way.

An WVR operated by the DWD in Potsdam and radiosonde measurements in Lindenberg could be used for validation. At both sites the bias w.r.t. the GPS estimates was below the 0.5 mm level and the standard deviation was at ±1 mm, between WVR and post-processed GPS even ±0.6 mm (Fig. 5). The comparisons very nicely demonstrated that the bias between the different solutions does not depend on the total amount of water vapor (Fig. 6).

Occasionally, there are systematic effects in the differences between NRT and the post-processed estimates, which show repeated patterns from day to day, similar for all sites in the network (Fig. 7, top). The comparison with WVR data demonstrated that these effects are caused by errors in the NRT estimates (Fig. 7, middle). The sources for such errors are connected with the repeated satellite configuration and especially with problems in orbit predictions. The quality of the differential PWV in the network is much higher (bottom), but presently this information cannot be used in NWP models directly. However, if one calibration point exists in the network it can be used to correct for such effects in the whole network.

The various water vapor estimates were also compared with the solutions from the new, forthcoming prediction model of the German Weather Service called Local Model LM1 (Fig. 8). The agreement of GPS results and LM1 model results is very good. A small negative bias of about —1 to —1.7 mm can be stated for all instruments, the bias to the GPS solution is about —1.3mm and the scatter is within the range of 1.1 mm. To have a positive impact on the numerical weather prediction the GPS estimates should have an accuracy of better than 2 mm.

Outlook

The Project GASP is planning to provide in Germany the basis for an operational use of the GPS technique for atmospheric and ionospheric research and applications. The

Subproject 1 of GASP — use of ground-based GPS for water vapor monitoring — is carried out in close cooperation between GPS experts and specialists on weather forecast.

The GASP-1 results will become Germany's contribution to the COST Action 716 of the European Union named "Exploitation of ground-based GPS for climate and NWP applications" (1999-2003), which 14 European countries have already signed. In various European countries a great number of projects are initiated which will be coordinated within COST. So in near future the PWV will be monitored in Europe with a reasonably high spatial resolution, and the impact of these data on NWP will be studied. When combining all such efforts on the global scale (networks in USA and Japan, global activities of IGS), the GPS technology will provide a global data set of continuously recorded PWV which could complement existing measurements from other techniques.

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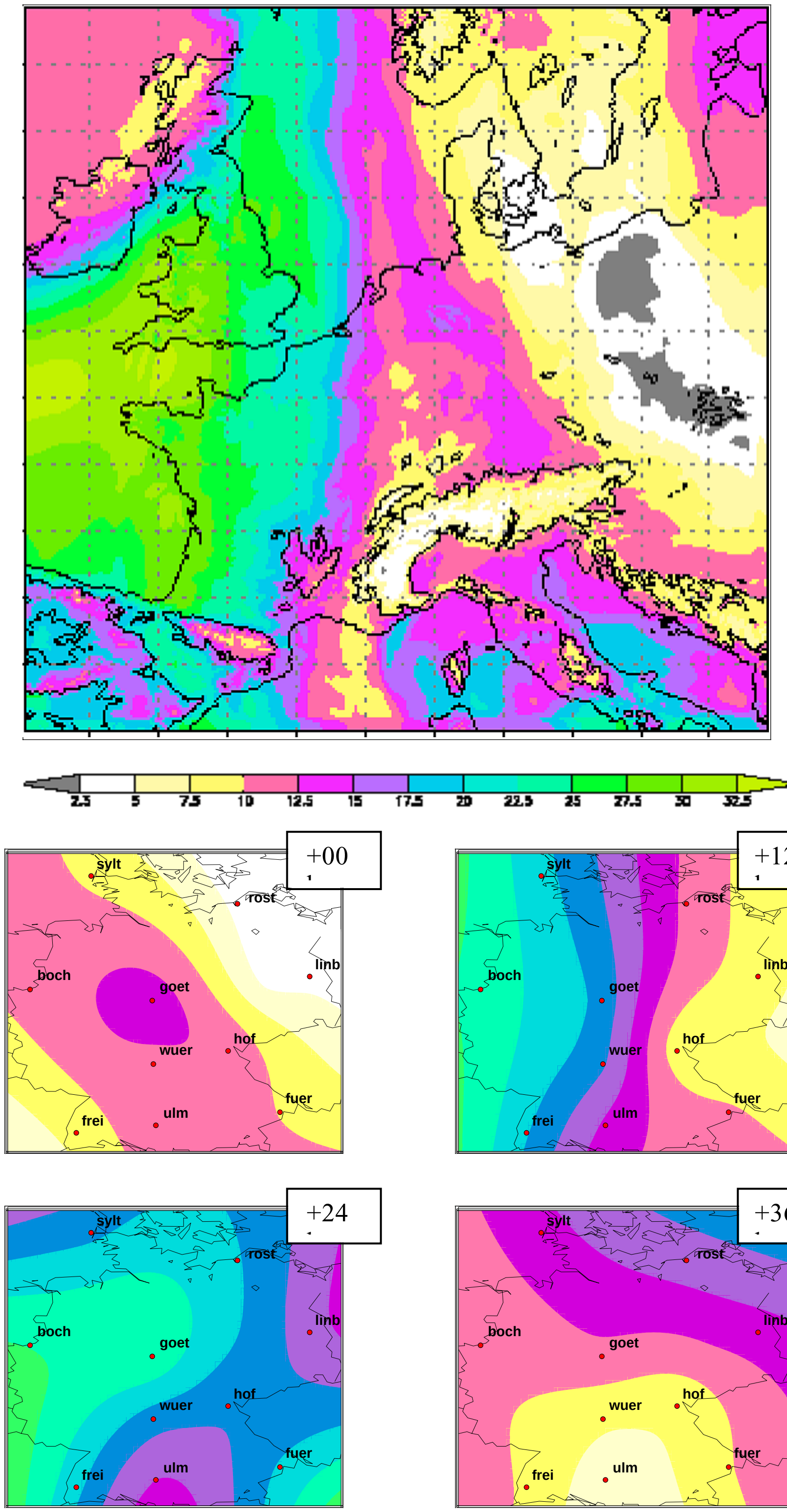

Fig. 3. Front at December 12-13, 1998. **Top**: Water vapor field over Europe from the Local Model of DWD at 12 December at 00:00 UT (Legende: PWV in mm). **Below**: GPS analysis results for Germany over the next 36 h

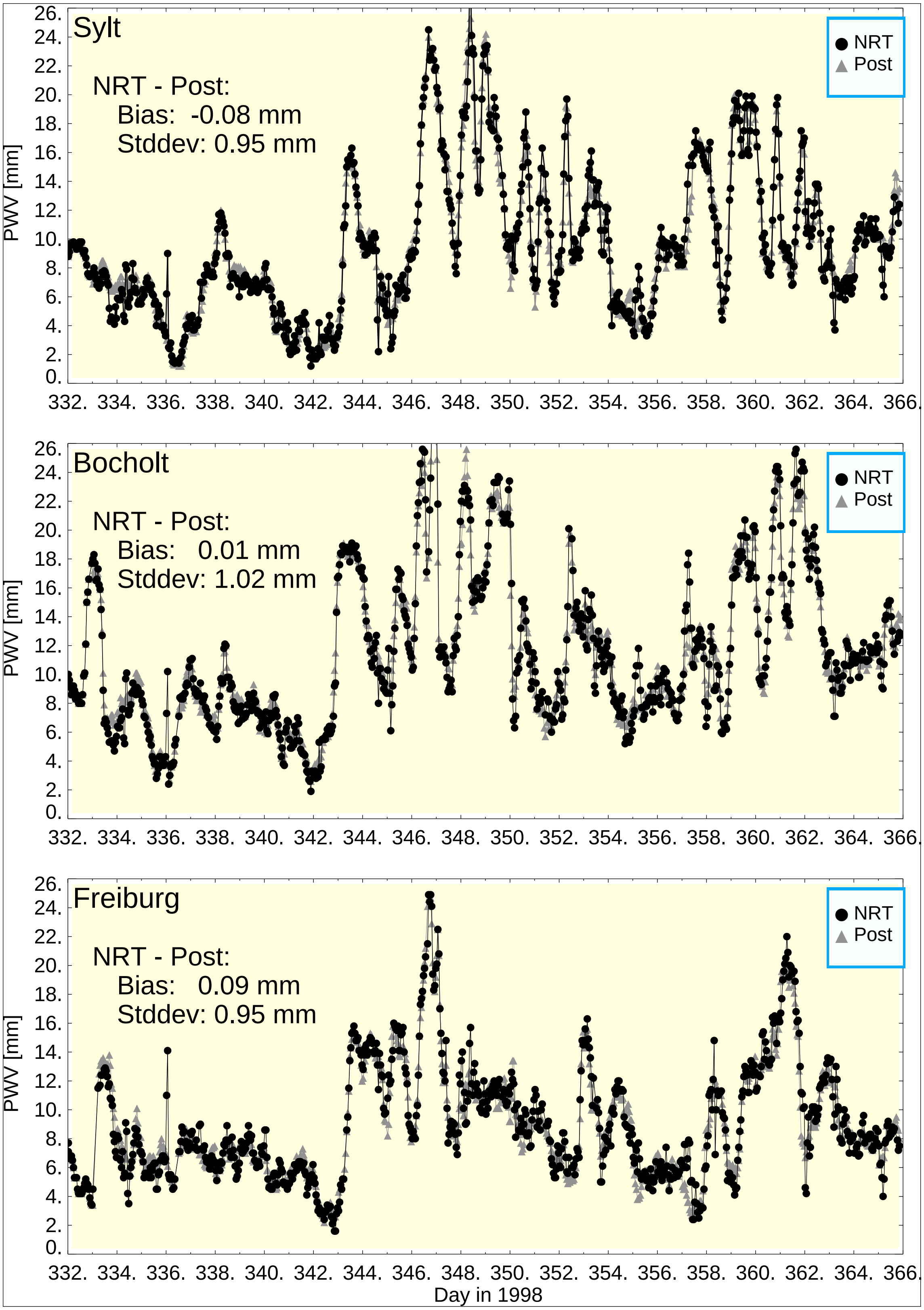

Fig. 4. Results from the near real-time monitoring experiment compared with post-processed estimates

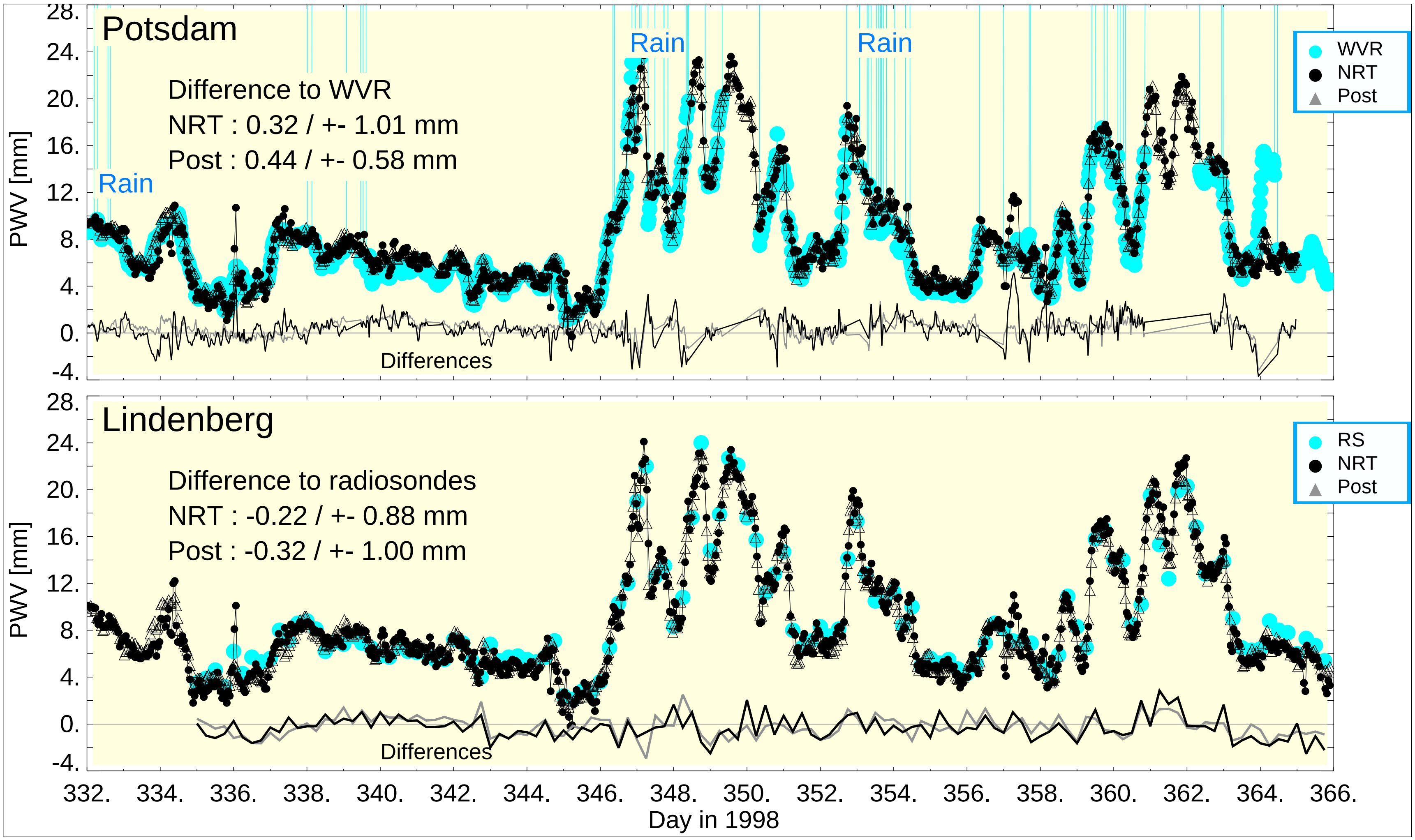

Fig. 5. Validation of GPS derived water vapor with water vapor radiometer in Potsdam and radiosondes data in Lindenberg (bias / standard deviation are given)

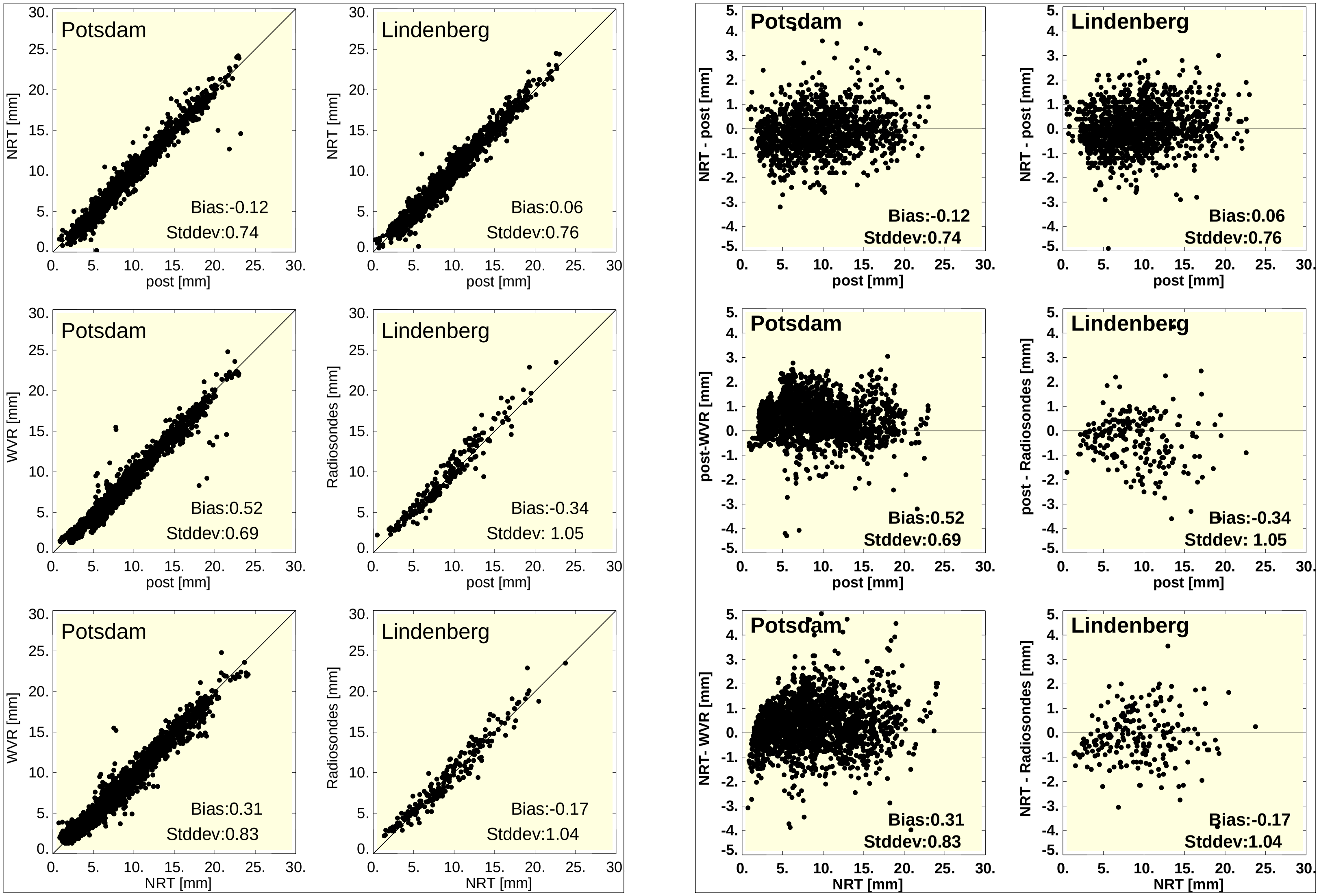

Fig. 6. Scatter-plot for Potsdam and Lindenberg comparing post-processing estimates, near real-time monitoring, water vapor radiometer measurements and radiosonde data

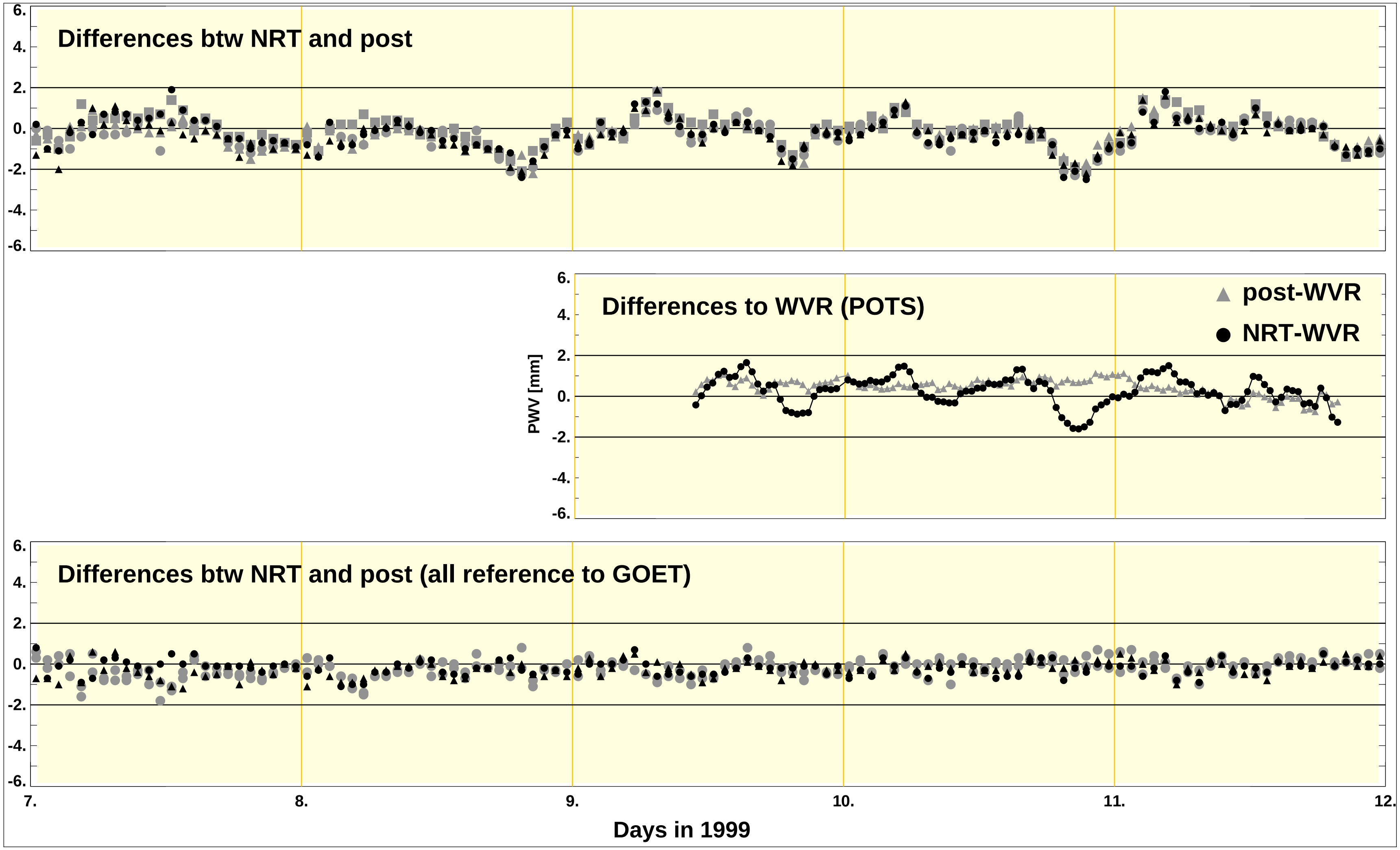

Fig. 7. Differences of precipitable water vapor between NRT and post-processed GPS estimates for five sites (LINB, POTS, ROST, SYLT, GOET) (top). Differences to WVR data at POTS (middle). Same differences as in the top, however referenced to GOET (GOET estimates subtracted from all NRT and post-processed estimates)

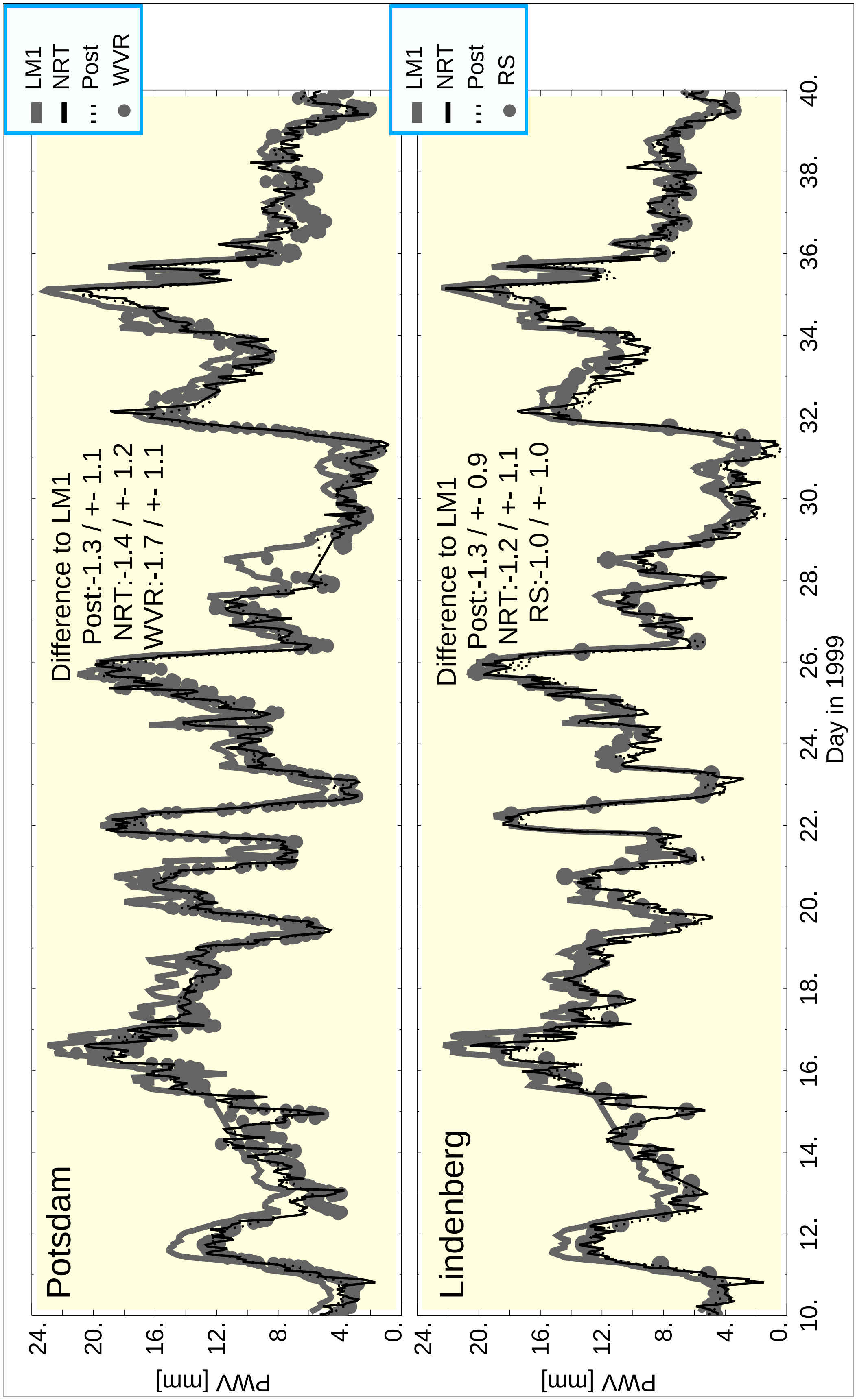

Fig. 8. Comparison of different water vapor estimates with the Local Model LM1 of the German Weather Service

Ocean Loading Corrections: Do We Need Them?
A Case Study at the WCDA Site Holberg

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Abstract

The coastal GPS stations of the Western Canada Deformation Array (WCDA) are subject to movements with tidal periods, due to the loading of the lithosphere by ocean tides. The predicted motions are often generated by various modelling programs, are sometimes applied in GPS analyses, but are rarely confirmed. Using a four-week continuous data set from the WCDA, and focusing on the site Holberg (HOLB), located on the northern tip of Vancouver Island, this study's objectives were to investigate the role of ocean loading corrections at coastal sites. Theoretical ocean loading displacements were obtained from the most recent version of LOADSDP by S. Pagiatakis (1999) which uses the Grenoble Global Model FES95.2 with 0.5 by 0.5 degree cells, modified by detailed regional modelling of nearby coastal ocean cells. GPS solutions were obtained using the Bernese software for 3-hr and 24-hr positional solutions with hourly tropospheric estimates in both cases. When no ocean loading corrections were applied, the resulting 3-hr vertical positions had peak-to-peak variations as large as 9 cm which were well correlated with the theoretical tidal predictions. With ocean loading corrections applied, the sigma for the repeatability of the 3-hr vertical positions was reduced from 22 to 15 mm. These results indicate that for sub-daily GPS solutions, it is prudent to apply ocean loading corrections to reduce the variability of the positional estimates. The repeatability of the 24-hr vertical positions was not significantly improved by the addition of ocean loading corrections. However, for the daily solutions without ocean loading corrections, almost all of the vertical tidal motion of the station is absorbed by the (1 hr) tropospheric delay estimates. Implications are that constraining station position, in our case to a daily average, causes tidal motions to be absorbed into the tropospheric delay estimates, thereby biasing estimates of precipitable water vapour (PWV).

IGS Realization of ITRF

R. Ferland
(NRCan)

The IGS station coordinates, Earth Rotation Parameters (ERP) and satellite orbit products are currently aligned to ITRF96. This is done with a set of 47 carefully selected stations, also known as the Reference Frame (RF) stations. Remarks on the RF stations performance are presented.

The ITRF97 realization is now available. Before using this new realization, we need to determine the magnitude of any discontinuity between ITRF96 and ITRF97 using the RF stations. The 14-transformation parameters between the two are determined using the original 47 RF stations. The results are given in Table 1. The sigmas are based on the propagation of the covariance information provided in ITRF96 and ITRF97. The formal sigmas for the rates are not included due to their small magnitude.

Table 1. ITRF96 to ITRF97 14-parameters transformation using the 47 RF stations.

	RX(mas)	RY(mas)	RZ(mas)	TX(mm)	TY(mm)	TZ(mm)	Scl(ppb)
At 1997.0	0.11	-0.21	-0.05	1.2	0.0	-11.0	0.82
Sigma	0.03	0.02	0.02	0.8	0.8	0.7	0.16
Rate	-0.011	-0.025	-0.028	-0.6	-0.1	-2.7	0.21

The performance of the Reference Frame RF stations between weeks 978 and 1008 was checked based on the station coordinates residuals. DAV1, FAIR, GODE, MAC1, MADR and WES2 were found to have an unusual number of rejections. In Table 2, the problem is briefly described for each station with recommended action proposed.

Table 2. Anomalous stations on the weekly combination between GPS weeks 0978 and 1008.

Station	Observed situation	Recommendation
DAV1	10mm bias in east and north wrt ITRF96	Keep, no significant bias wrt ITRF97
FAIR	Noisy height	Keep, Monitor closely
GODE	13mm east bias wrt ITRF96	Keep, no significant bias wrt ITRF97
MAC1	20mm east bias wrt ITRF96	Keep, no significant bias wrt ITRF97
MADR	Multiple biases wrt ITRF96	Remove from RF list
WES2	10mm east bias wrt cumulative solution	Keep, no significant bias wrt ITRF97

From the original list of RF stations proposed last year, five had to be removed due mainly to anomalous velocity, which were rendering the time propagation unreliable. Those same stations were verified again with ITRF97. The new estimated velocity was compared to the NUVEL-1A plate motion model. The comparison can be found in Table 3. The improvement is very significant. The only concern is with the height component at station CAS1. The five stations left out of the original RF station list last year should now be re-included.

Table3. ITRF96 and ITRF97 station velocity comparison to the NUVEL-1A plate motion model.

	ITRF96 — NUVEL-1A			ITRF97 — NUVEL-1A		
Station	N (mm/y)	E (mm/y)	H (mm/y)	N (mm/y)	E (mm/y)	H (mm/y)
AUCK	2.3	17.1	-0.6	-1.2	1	3.1
BAHR	-2.5	1.5	2	-6.2	2.5	2.2
CAS1	-7.3	2.2	13.9	-3.5	1.1	10.5
CHAT	2.5	25.3	-0.4	-0.5	1	1.2
MCM4	0.3	9.5	27.4	-0.1	5	-6.9

The weekly combinations between GPS weeks 978 and 1008 were originally aligned to ITRF96. They were recombined and realigned to ITRF97 using the same RF stations. The differences in PM-x and PM-y pole resulted in shifts of -0.27 mas and 0.17 mas. The polar motion shift was also verified by reprocessing GPS week 1006 with GIPSY using ITRF97. The difference with solutions obtained using ITRF96 showed a polar motion shift of PM-x= -0.25 and PM-y=0.20 mas. Those results are consistent with the previous results within 0.03 mas. Also, by propagating the rotations in Table 1 to the epoch GPS 1006, we get PM-x (RY)= -0.26 PM-y (RX) = 0.086. The results are almost identical for the X pole and within 0.1 mas for the Y pole.

Site Densification

R. Ferland and D. Hutchison (NRCan)
Reference Frame Working Group

One objective of the Reference Frame Working Group is to generate IGS station coordinates and velocities, Earth Rotation Parameters (ERP) and geocenter estimates along with the appropriate covariance information. A cumulative solution, which contains at least a set of estimated coordinates and velocities at a reference epoch for each station is updated weekly. The weekly preliminary submissions started with GPS week 999. Work is continuing to improve on the quality and timeliness of the submissions. The cumulative solution includes GNAACs solutions since GPS week 837. Starting with GPS week 978 the ACs were included in the combination while the GNAACs were included to control the quality of the combination. Although the combination was only made available starting with GPS week 999, the procedure was tested on weekly solutions dating back to GPS week 978.

To meet the objective a semi-automated procedure was put in place. The procedure does: 1) validate the format; 2) check (and correct) site names and parameters; 3) as required, rescale, condition and unconstrain the matrices; 4) align to ITRF; 5) compare to ITRF, to other solutions, to the previous and current weekly solution and to the cumulative solution; 6) reject outliers; 7) combine the weekly and cumulative solutions; 8) iterate if needed; 9) correct inconsistencies with igs.snx; 9) prepare summary report.

Corrections such as pole tide, LODR to LOD are also applied when appropriate. The AC LOD bias with respect to IERS Bulletin A; similar to what is done in the AC coordinator's LOD combination, is also applied. The ERPs are always referred to the origin. Occasional problems with the unconstraining or inversion of matrices are usually resolved by rescaling the estimate diagonal matrix and/or the apriori diagonal matrix. All the weekly matrices are also rescaled by a variance factor (chi**2/dof) determined by a comparison with the combined cumulative solution. The outlier detection threshold is currently set at 5 sigmas. Some solutions contain multiple estimates for a given point at a site. Those are usually recombined to produce a unique solution per point per site.

The alignment of all weekly solutions is done with a 7-parameter similarity transformation. MADR is currently not used in the similarity transformation estimation. All the other common points between each weekly solution and ITRF96 47 Reference Frame stations are used to estimate the transformation. Unit weight on the coordinates is assumed.

There are 7 product files generated each week. They are available from cddisa.gsfc.nasa.gov. There are three residual files (igsyyPwwww.itr, igsyyPwwww.res, IGSyyPww.res), two SINEX files (igsyyPwwww.snx, IGSyyPww.snx), one ERP file (igsyyPwwwww.erp) and one summary file (igsyyPwwwww.sum); where yy is the last two digits of the year, ww is the week of the year and wwww is the GPS week. The three residual files (igsyyPwwwww.itr, igsyyPwwwww.res, IGSyyPww.res) list the station residuals with respect to 1) the ITRF Reference Frame stations at the current epoch, 2) the weekly combination and 3) the cumulative combination at the current epoch. In the case of the weekly combined solution, the residuals are also given for the ERPs and the geocenter. The weekly and the cumulative combinations are aligned to ITRF96 using respectively a 7-parameter transformation at the current epoch and a 14-parameters transformation at the reference epoch. Inner constraints are also applied to the solutions to remove singularities.

The report is divided in 5 sections: 1) Contacts, 2) Products, 3) Combination Strategy, 4) Remarks and 5) Results.

The last section presents a summary of the results. It is divided in 7 sub-sections: 1) the variance factor, 2) the stations residuals weighted average and RMS; 3) the 7-parameter transformation to the reference frame; 4) the geocenter; 5) the ERP residuals weighted average and RMS; 6) the outliers; 7) the conflicts.

The solution is presently computed on average within 2 days after the last GNAAC combination is available.

Moving IGS Products Towards Real-Time

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Introduction

The number of real-time and near real-time (NRT) applications of GPS is steadily growing. At present the most important application the scientific community has to be prepared for is the atmospheric and ionospheric monitoring from both ground-based and space-based receivers. In preparing the near real-time monitoring the global tracking network is just in the phase switching from a daily data retrieval to an hourly one. And it is foreseeable that in a few years even real-time (1-sec direct) data transfer with global distributed sites will be feasible. For the near future the generation of global products within IGS will be based on hourly data retrieval. This will allow for much faster IGS products which should be named "ultra-rapid".

There could arise a fundamental problem in the maintenance of an international coordination and standardization if for NRT applications individual institutions and organizations generate their own global products (like GPS orbits, terrestrial reference frame, Earth orientation parameters) and have their own user community. Therefore IGS should try to play an important role also in this field, even though IGS will not be directly involved in the NRT monitoring, at least for the near future. IGS should use its infrastructure (H/W and S/W) and its experience to support the upcoming activities to most possible extent in the following topics:

- NRT global network and data archives
- rapid products for GPS orbits, EOP and satellite clocks
- predictions for orbits and EOP

In trying to force IGS moving towards real-time one should stay on the principles which has given IGS the great power it has demonstrated in the past, namely:

- a global network and archiving system which is operated in a unique manner with clearly stated rules (e.g. data formats, station log-files)
- products based on combination of the individual contributions from various Analysis Centers (AC)

The combination yields not only more accurate (this may be sometimes marginal), but most of all more reliable results. An intrinsic part of each combination is a quality control of the results and a feed-back to the ACs. This principle has had an inestimable impact on the improvements gained during history of IGS.

Having this in mind we should try to find ways to have the combination for the ultra-rapid IGS products too.

The demands on the delay of the products resulting from atmospheric monitoring are very stringent, a delay of less than 2-3 hours is acceptable. This can only be fulfilled by the individual groups, focused on special projects, if all components are performing optimal. Therefore the IGS cannot be expected to be faster than those groups and to have a rapid product ready before those groups start their analysis. That means the relevant IGS products have to be predicted ones.
The list of items to be discussed in this context includes

1. NRT data (GPS and meteorological)
2. ultra-rapid orbits and EOPs
3. predicted orbits and EOPs
4. ultra-rapid clocks
   (clock predictions not possible or only for a few seconds ahead)
5. ultra-rapid zenith neutral delays (ZND)

This paper will focus on the first three items.

Remarks on Clocks

Ultra-rapid clocks should be postponed until IGS has solved its clock combination problem for its usual products. At the moment only the clocks contained in the sp3-file and sampled for 15-minutes are available, which is a too large sampling rate to be used in any precise analysis. An outlook on short range clock predictions is given the section entitled “Predictions of Satellite Clocks.”

Remarks on ZND

During the computation of the ultra-rapid product the IGS ACs will get ZND estimates in the global network. In addition, the regional ACs will stabilize their regional ZND estimates by adding global IGS stations, and so automatically ZND estimates will be obtained for those sites. All these solutions may in principle be a first step into a global NRT monitoring. Presently, it will be not meaningful to start with such a product for various reasons: (i) the network is not dense enough yet, (ii) the met sensor network is insufficient, and (iii) the meteorologists are not ready to use this product. Nevertheless, ultra rapid ZND estimates from the IGS sites may be used for calibration and quality check in regional application. Activities in this direction may start if the quality of such an IGS product has been assessed.

Near Real-Time Data

The number of stations with an hourly download of data has already a global distribution and is steadily growing. In Fig. 1 are shown the sites available at CDDIS and BKG (former IfAG), and the planned CHAMP network. The number of global sites at CDDIS is about 50. An additional 20 European sites are available at BKG. The present distribution will not allow the derivation of products with the usual IGS level of accuracy, but is sufficient to start with experiments. Large gaps are in Asia and Africa. The upcoming high-rate CHAMP network will also provide the usual 30-sec data and will stabilize the network performance. The distribution will be significantly improved, but will not close the gaps in large parts of Asia and in Africa. The station operating agencies having sites in this region are asked to install the hourly download with these sites with the highest priority.

Investigating the data availability for the hourly RINEX files in the global network at CDDIS and in the European network at BKG delays from 2 minutes up to 50 minutes can be found. Many sites are available at CDDIS within 12 to 25 minutes, while others only within 40-50 minutes. At BKG most sites are already available within 10 minutes (fastest sites within 2 minutes). Unfortunately, there is an additional delay of about 30 minutes before the BKG sites are available from CDDIS. Such additional delays have to be avoided in future. The full data flow, from downloading the data at the receiver to the availability at the global Data Centers, has to be organized with minimal (no unnecessary) delay; each additional minute between the various steps may sum up to several minutes which cannot accepted.

Met Data

The demands for hourly met data have to be clarified. There are tendencies in the meteorological community (Danish Meteorological Institute - DMI, United Kingdom Meteorological Office - UKMO) to use ZND values directly in the numerical weather prediction models, postulating that they contain more information than the separated integrated water vapor alone. If this proves to be the way to follow hourly met data retrieval will not be needed.

For the climate studies and atmospheric investigations the usual daily met files can be used without problems.

Earth Orientation Parameters and Predictions

Currently, the quality of the earth orientation parameters (EOP) derived from the IGS rapid products is very high, at 0.13 mas for polar motion, 0.096 ms for UT, and 0.026 ms for LOD while comparing with IERS Bulletins A and B (C04 series) (Figure 2).

Ultra-Rapid Estimates

The new ultra-rapid EOP (constant and trend) may no longer estimated at UT noon time. They will be generated at the middle of a session, typically the time of orbit initial condition, that moves forward in time with a specified time interval, for example, two hours. Hence, there will be multiple EOPs given per day. This type of estimates will not only provide necessary support for the endusers of ultra-rapid orbital products in their critical applications, but can be used for EOP prediction as well.

Having estimates for sliding windows the study of higher frequency features of EOP (periods of a few days, or sub-daily) may benefit. This will of course depend on the length of the data session. Using shorter sessions (e.g. 12 hours) shorter periods will show up, however, the orbit predictions will be more problematic in this case. To have a higher stability, especially for the orbit solutions and predictions, daily sessions are proposed at present, which to high degree will smooth the shorter periods.

Predictions

In order to assure that the EOP contributed (rotational) error of predicted orbits during earth-fixed orbit generation is not greater than 6 cm, the errors of predicted EOP have to be at or better than 0.5 mas in polar motion and 0.03 ms in LOD. Currently, all ACs either use predicted portion of Bulletin A or make their own predictions for generating their predicated orbits in earth-fixed positions (sp3 format). The accuracies of predicted EOP in Bulletin A are about 0.75 mas for pole position and 0.16 ms for UT in a RMS sense over 24 hour period (J. Ray, 1999). Ocassionally, poor prediction may occur that partly contribute to large orbits errors in terms of rotation. In the case of ultra-rapid products, predicting EOP at higher accuracy will be feasible for two reasons, assuming the prediction method remains the same, (1) the time to future epoch to be predicted will be shorter, (2) denser estimates will be available.

Predictions for UT1 are more problematic. However, for the rapid orbit product in the earth-fixed system (sp3 product) the UT1 error cancel. Significant is only the change of UT1 for the prediction interval, namely the predicted LOD.

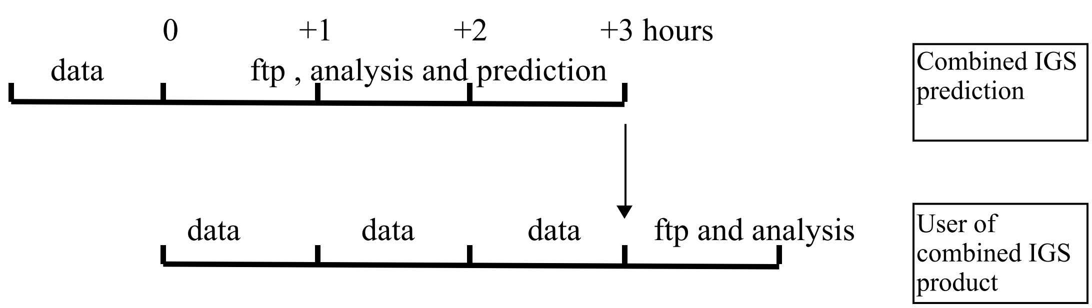
If predictions for a very short interval (<24 hours) are needed, rather simple predictions techniques will yield sufficient accuracies. Tests on the EOP predictability, using linear extrapolation of polar motion and using the last LODR also for the next day (having table entries at noon this is effectively a prediction for 12 hours), have shown that it is achievable to obtain predicted polar motion at 0.3 mas and LOD at 0.06 ms.

For the combination of the orbit predictions it will be important to start taking into account the EOP predictions used by the individual ACs. Therefore all ACs are required to submit their EOP predictions together with their other products. For the alignment of the orbit predictions the EOP predictions from the Bulletin A should be used.

Ultra-Rapid Orbits and Predictions

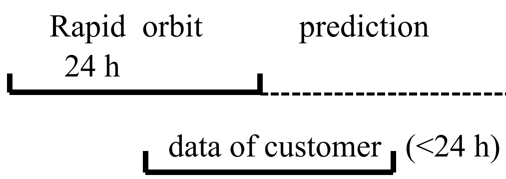
At the moment the combined rapid orbits for the previous day (D) are ready at 17 UT (day D+1), and the predictions for the next day shortly before midnight, having a prediction interval from 24 to 48 hours (day D+2). Some ACs deliver their rapid product already around 8 UT in the morning together with the predictions for the rest of the day which is up to now an AC specific product used by special users. It is clear that the predictions quality depends on the length of the prediction interval and therefore the predictions for the first 24 hours are of much higher quality. To get some numbers on the prediction accuracy with time the available short-range predictions from CODE and GFZ were used. Three arbitrary days were selected. In Fig. 3 are compared the predictions for the first and the second day (intervals from 0 to 24 hours and 24 to 48 hours). The predictions for the first day are significantly better and besides a few problematic satellites most of them are below the 20 cm level often better than 10 cm. The medians for the prediction variants divided into 6-hour bins are given in Fig. 4. Whereas for the second day the prediction error typically grows for 15 to 40 cm, the error for the first day is growing from 8 to 15 cm. For prediction length up to 12 or 18 hours the median is at the level of 10 cm. The median was chosen as a measure because it is not affected by outliers. The number of satellites which can be predicted within a given accuracy range can be seen from the histogram in Fig. 5. The number of satellites to be considered as outliers is much smaller for the first day. Whereas for the second day typically 5 satellites are in each of the ranges 30 to 60 cm and >60 cm, respectively, their number for the first day is only 1 or 2.

With the availability of hourly GPS data an ultra-rapid product can be generated much faster and several times each day. To have a better understanding of the problem in NRT analysis the following time line should be discussed:



Supposing the time schedule above is valid for IGS and supposing that the user has the same schedule and the predictions must be available at the time the user starts his ftp for the data, then IGS has to predict the orbits for at least 3 hours. Even if in future the IGS analysis may be ready earlier as assumed above predictions will be needed. In the following we suppose that the ultra-rapid orbits are computed using a sliding 24-hour window shifted by n hours. The IGS product will be the orbit for this window plus a prediction for a time interval to be defined (see below). The product should be named ‘igu’.

Up to now the IGS rapid products and predictions are provided in separate files containing information for exactly one day each. For the igu-product this principle will not be appropriate any longer because the customer usually is going to use the rapid and the predicted part at the same time.

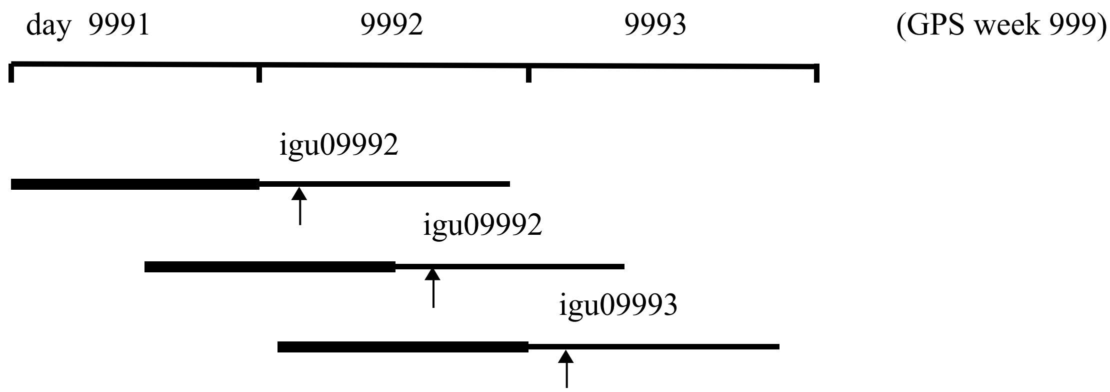


That’s why the igu sp3-file should contain both parts, having no jumps in-between them. This principle simplifies all applications and also the product delivery especially near the day boundaries (having in mind problems with naming of files, identifying corresponding files, etc.). The product file will be named with the day, the prediction starts. Each day only one igu-file exists which will be regularly updated (no version numbers). It is ensured that this product can be used for all applications having data up to 24 hours backwards.

The ACs should submit their ultra-rapid orbits/predictions also in this way, together with the EOP results and the EOP values used for the predictions. The combination center will make a combination of both parts ensuring the continuity in between them.

The continuity between the estimated and the predicted part is a critical point. The easiest way to get a continuous orbit is to simply integrate the orbit beyond the used data interval. The quality of such an prediction will depend on the length of the data base used and the length of prediction interval. For a short data basis (about 1 day) the prediction will be good for a short interval only (no numbers available; have to be investigated). The best prediction quality can be gained using more than one day. This can be achieved e.g. by stacking of normal equations or fitting a longer orbit through orbit products for several previous days. This may lead to two different products, (1) an estimated orbit plus its prediction , (2) a fitted orbit plus its prediction. In the latter case the estimated part will be replaced by the fitted orbit which may reduce the accuracy for this part to some degree. The ACs will come up with different approaches, which should be evaluated during a Pilot Experiment. The selection of the appropriate procedure will also depend on the length of the prediction interval, and may be changed in future.

A Pilot Experiment for generation of igu-products is proposed to start at the end of August 1999, (GPS week 1025). In a first step the ACs should produce ultra-rapid products twice a day using the hourly RINEX-data and submit their products shortly before 3 UT and 15 UT, so that the combined product will be available at 3 UT and 15 UT. By this scheme the first ultra-rapid product each day will have the same data interval as the usual rapid product, but is available 14 hours earlier. A new product is added 12 hours later. To illustrate the procedure and the naming convention (a detailed schedule is given in the Appendix):



Legend: ↑igu product generation time, combined product ready

Denoting the product generation time with G and the delay of the product with D this will give:

Estimated orbit : from G-D-24h to G-D (D= 3 h)
Predicted orbit : from G-D to G-D+24h (G= 3 or 15 UT)

The estimated orbit and the prediction should both have an interval of 24 hours (at least 15 hours are needed for the proposed schedule). The igu-file will contain an orbit for 48 hours, and a comment-line should be inserted informing where the prediction starts. It is for the ACs to decide how to optimize their procedure (see comments above) to achieve the best estimates and predictions ensuring the continuity (at least having no significant jumps) in-between both orbit parts.

Starting with the proposed schedule the IGS should gather experience and can test

- the use of hourly RINEX-data
- the timeliness of computation and combination of ultra-rapid products
- the use of sp3-files not cut at the day boundaries
- the quality of the predictions with time to define an optimal repetition interval
- the influence of EOP prediction strategies

This scheme above will have a much longer prediction interval than 3 hours (the minimal length discussed earlier) but will be a drastic shortening to the existing product (from 24-48 h [mean 36 h] to 3-15 h [mean 9h]). It can be expected that these predictions are already of such a quality sufficient for the NRT applications, otherwise the scheme will have to be revised as a result of the Pilot Experiment.

It should be pointed out that the present rapid product should not be replaced by the new ultra-rapid one. As long as for the new product the station distribution is not optimal the present product will have a superior quality and should be provided further on. The present predictions for the second day however could be stopped as soon as the ultra-rapid product has proved its reliability.

Having a smaller repetition interval for the products than one day and having customers which rely on the timeliness of each product to get the shortest and best predictions it may be more critical if the combination is not ready in time. Therefore the Analysis Center Coordinator should propose ways to ensure the timeliness of the combined ultra-rapid product also in case of hardware problems (computer, internet).

Predictions of Satellite Clocks

Although somewhat beyond the scope of the present position paper, it is appropriate to discuss briefly the issue of clock extrapolation. It may not be too long before a significant number of IGS sites are configured so that their data are continuously streaming from the receiver over some communication channel to a central processing facility. If the total latency in such a system is on the order of seconds, then decimeter-level real-time kinematic positioning is possible.

Assuming that the temporal variations in GPS clock solutions are represented by an autocorrelation function

$$\rho(d) = \exp(-d^2/2\tau^2)$$

for delay d with $\tau \approx 105$ sec, we show in Figure 6 the clock error as a function of extrapolation time, based on a simulation. The magnitude of the variations is assumed to be 24 m.

The lower curve assumes that, using data up to and including time t, the analysis system produces noiseless estimates of clocks at times $t - 2$ sec, $t - 1$ sec, and t. Quadratic extrapolation of these can predict the clock in the future to better than 1 cm, provided that the extrapolation time e is less than 10 sec. By the time e reaches 100 sec, however, the extrapolation error exceeds 10 m. This error arises solely because of the stochastic nature of clock variations under selective availability.

A more realistic assumption is that clock estimates have some noise, say, 1 cm each. To reduce the rate at which this error grows with extrapolation time, one strategy is to use estimates at times $t - 2e$, $t - e$, and t to predict the clock at time $t + e$. The noise propagation from quadratic extrapolation is approximately 4 cm, independent of e. This component of the error dominates until e ≈ 10 sec, at which point the stochastic nature of the clock variations begins to be more important. This scenario is shown in the upper curve of the figure.

These rough calculations are intended to suggest that, for real-time applications, latencies of 10 sec or less will be required to ensure that the clock error from extrapolation will not be the dominant error source.

Proposed Time Schedule for the Experiment:

Day	Time	Action
D-1	20:00 UT	retrieve global network data from day D-1, 19:00-19:59;
…		
D-1	23:00 UT	retrieve global network data from day D-1, 22:00-22:59;
D	00:00 UT	retrieve global network data from day D-1, 23:00-23:59;
		BEGIN orbit computation using data from D-1 23:59 backwards;
D	01:00 UT	retrieve global network data from day D, 00:00-00:59
D	02:00 UT	retrieve global network data from day D, 01:00-01:59;
D	02:45 UT	**DELIVER ORBIT** covering t1 to t3 (t1= D-1 00:00 t3= D 24:00) (rapid orbit for t1 to t2 and predictions for t2 to t3; t2=D 00:00)
D	03:00 UT	**DELIVER COMBINATION** of orbits and predictions from t1 to t3
….		
D	12:00 UT	retrieve global network data from day D, 11:00-11:59;
		BEGIN orbit computation using data from D 11:59 backwards;
D	13:00 UT	retrieve global network data from day D, 12:00-12:59;
D	14:00 UT	retrieve global network data from day D, 13:00-13:59
D	14:45 UT	**DELIVER ORBIT** covering t1 to t3 (t1= D-1 12:00 t3= D+1 12:00) (rapid orbit for t1 to t2 and predictions for t2 to t3; t2=D 12:00)
D	15:00 UT	**DELIVER COMBINATION** of orbits and predictions from t1 to t3

The submitted and combined igu-files have to be named with the day, the prediction starts (e.g. cou<wwwwd>.sp3, emu<wwwwd>.sp3,..., igu<wwwwd>.sp3).
The sp3-file should contain a COMMENT with the start time for the predictions:
* PREDICTION 1999 12 31 24 59 <any further comment >

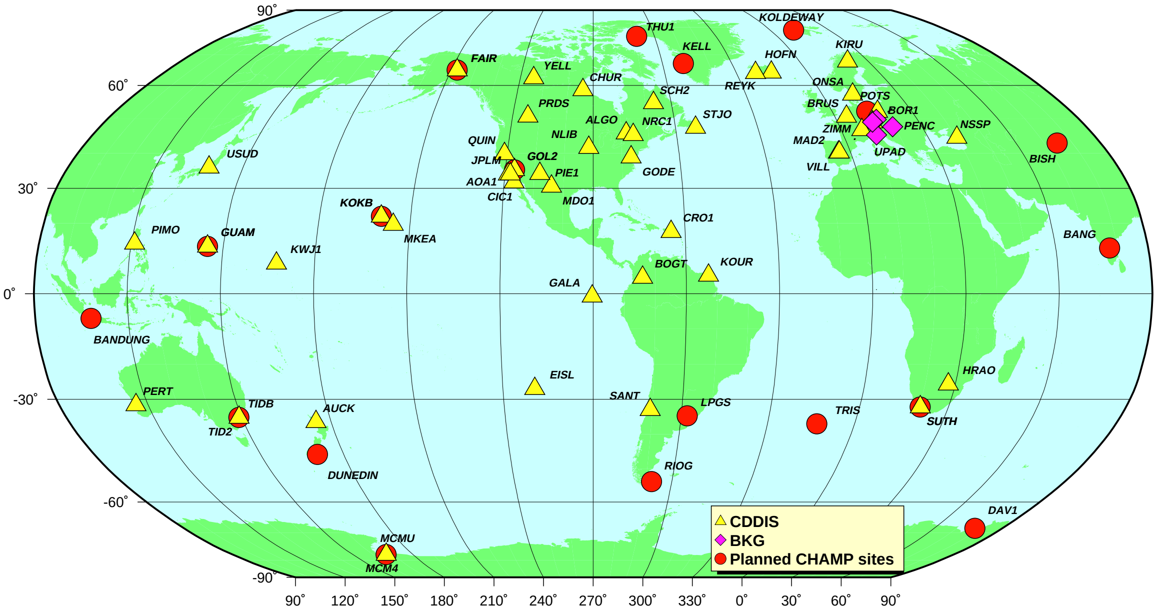


Fig. 1. Network of sites with hourly data download

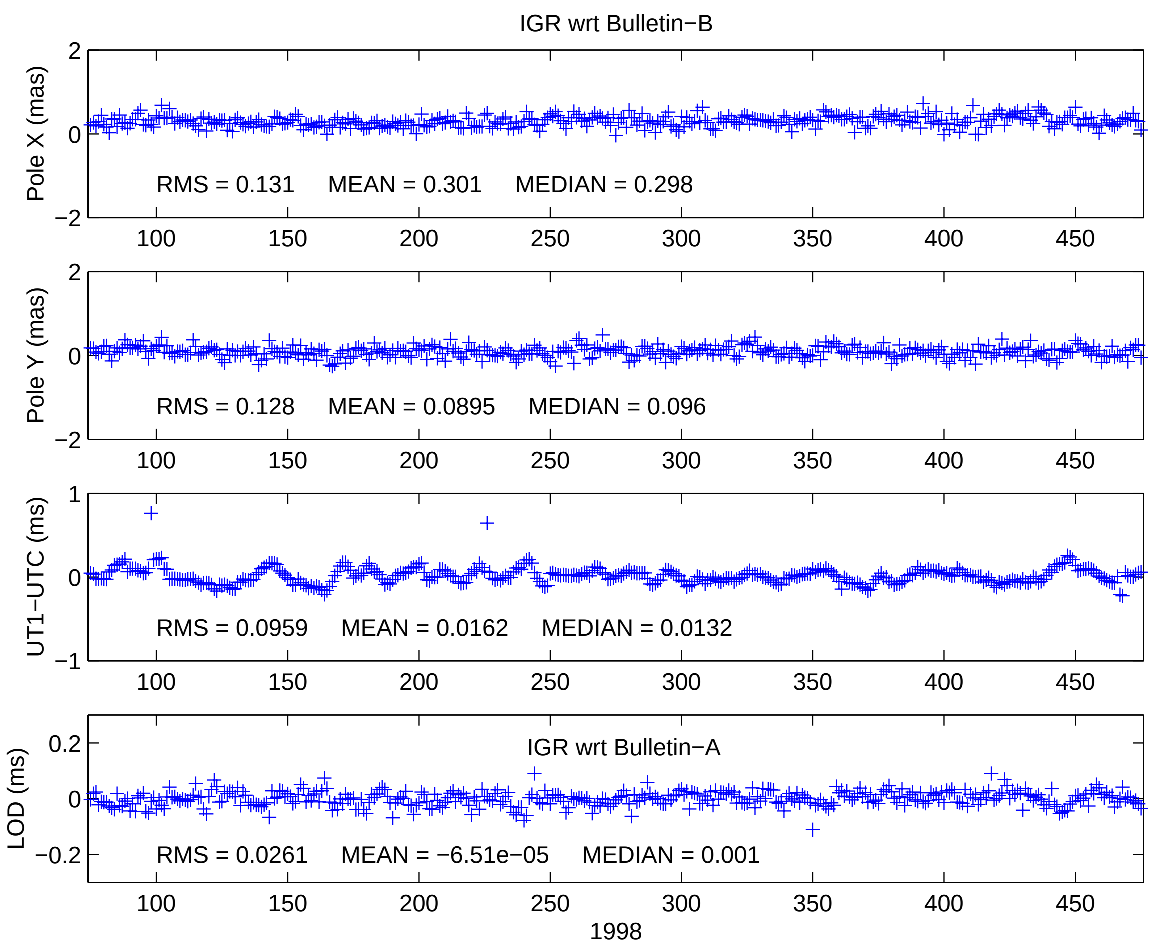


Fig. 2. Comparisons of EOP from IGR with IERS Bulletins A and B (C04 series)

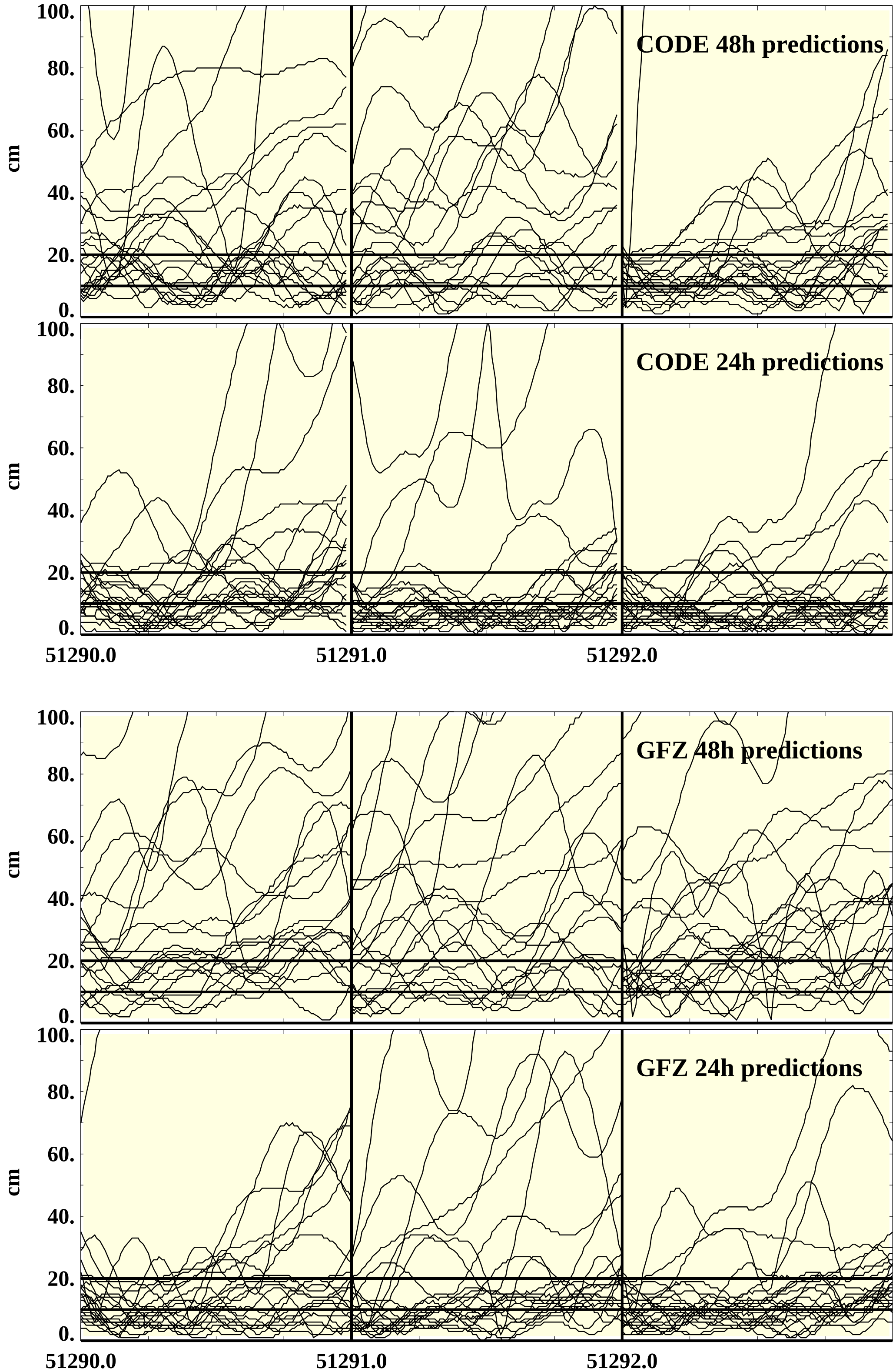


Fig.3. Accuracy of predicted satellite orbits for 3 selected days from CODE and GFZ (days 1999/112 to 114). Predictions for all satellites for 0-24 h and 24-48 hours

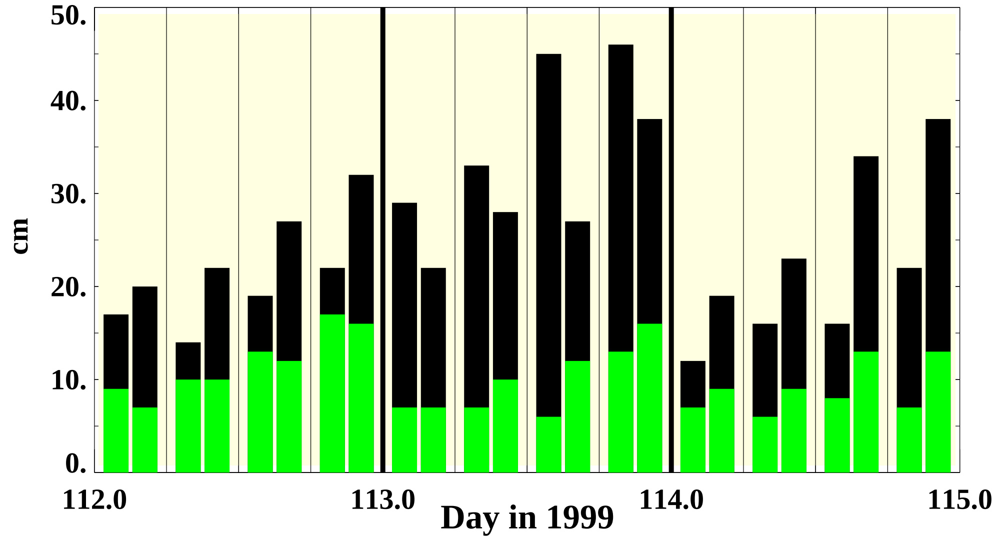


Fig. 4. Accuracy of predicted satellite orbits (median) divided into 6-hour intervals for 3 selected days in 1999. In each column the accuracies for the predictions from 0-24h and 24-48 h, respectively, are given. (left: CODE, right: GFZ)

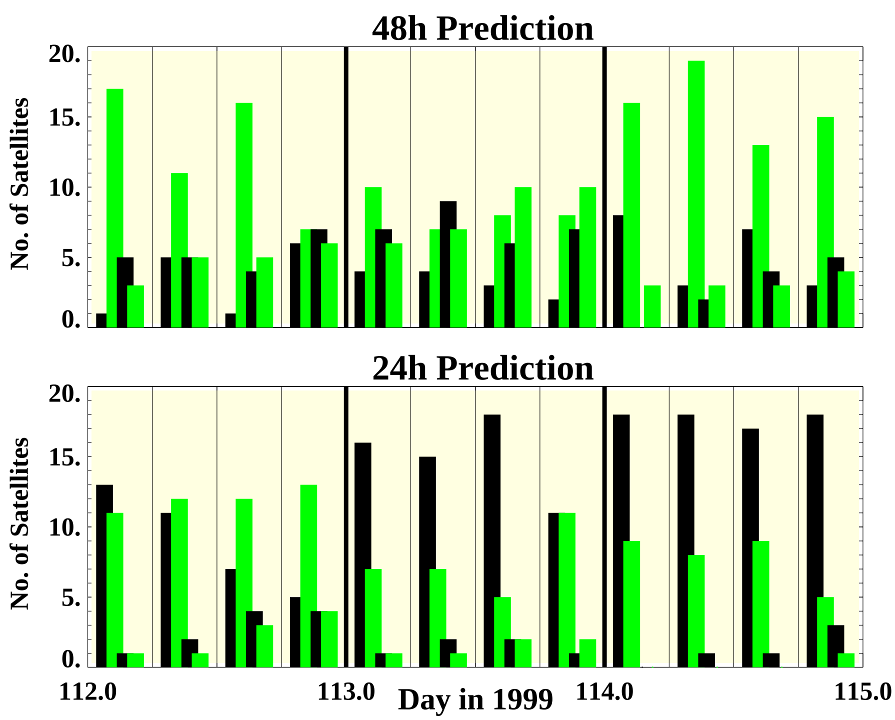


Fig. 5. Histogram for orbit prediction accuracy in 6-hour intervals for 3 selected days in 1999. Predictions from 0 to 24 hours (bottom) and 24 to 48 hours (top). The bars represent the prediction accuracies from 0-10 cm, 10-30 cm, 30-60 cm and >60 cm (from left to right) in each 6-hour bin.

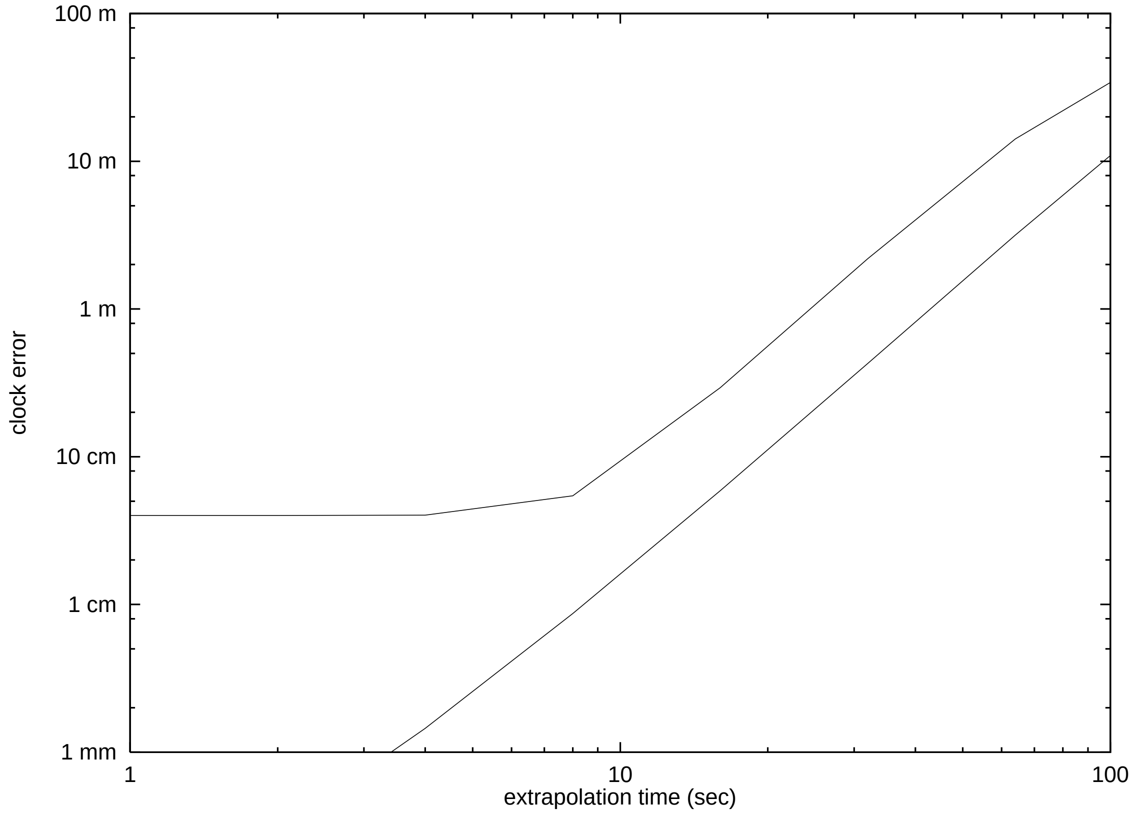


Fig. 6. Accuracy of short-range satellite clock predictions

Recommendations

1. The operational, regional and global data centers are asked to optimize the data transfer of the hourly RINEX-files.
2. The ACs start to submit ultra-rapid products twice a day (2:45 UT, 14:45 UT, starting GPS week 1025) for orbits and EOP including predictions. Based on sliding window approach the new products will cross day boundaries. In one and the same file the rapid orbits and the predictions are offered having no jumps in-between.

The ultra-rapid products are combined by the AC Coordinator.

Status Report of Tropospheric Working Group

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At the 10th IGS Governing Board Meeting, 6th December 1998, the "IGS Troposphere Working Group" was established. The charter, the list of members and the working plan is presented below. This short report should summarize the present status of the IGS tropospheric product.

Present Status

Since 1997 the IGS regularly generates a combined tropospheric product on a weekly basis. It is based on the submission of the individual IGS Analysis Centers (AC), which compute their tropospheric estimates during or after the generation of the IGS final products. The product is the weighted mean of the total zenith path delay of the neutral atmosphere (zenith neutral delay - ZND). The individual AC biases are calibrated on a weekly basis (Gendt 1996). The product delay is 2 to 4 weeks. Since SIO has joined this activities in February 1998 all IGS ACs contribute to the combination. Some analysis characteristics important for the troposphere product are summarized in Table 1. The standards for the analysis are converging, so five ACs have implemented the Niell mapping function, and their is the tendency to use an elevation cut-off angle of 15 degrees.

For more than 150 sites the product is available now (Fig. 1). Nearly 90 sites are used by three or more ACs, which allows to derive reasonable quality measures. The other sites are mostly located in the dense parts of the network, where typically all sites have nearly the same quality in the ZND estimates, and therefore their quality may be deduced from the neighboring sites. The quality of the product (internal consistency between ACs) is at the level of 4 to 6 mm in the ZND, which corresponds to ≤ 1 mm in the water vapor (Fig. 2). The biases are even smaller, however, changes in the analysis parameters of the ACs can be seen in most cases in the series.

The histograms in Figure 3 reveals that for most sites the standard deviation is below the 4 mm level. Especially CODE and SIO have pronounced peak at 2 – 3 mm, caused by the fact that both centers use many sites in the denser parts of the network where the quality is significantly better than for the sparser parts. Systematic effects in the biases can clearly be seen for CODE and SIO. The primary reason may be the different cutoff angles applied by both centers. The 7 ^{o} of SIO is smaller than the usual 15 ^{o}, and the weighted 10 ^{o} degrees of CODE seems to correspond to an effective angle of about 20^{o}.

Table 1. Solution characteristics (changes are indicated with its effective GPS week)

Analysis Center	Cutoff angle[deg]		Mapping function	
CODE	20 (Wk 925),	10	Saast. (Wk 925),	Niell
EMR		15		Lanyi
ESA		20		Saastamoinen
GFZ	20 (Wk 943),	15	Saast. (Wk 928),	Niell
JPL		15	Lanyi (Wk 919),	Niell
NGS		15		Niell
SIO		7		Niell

(SIO submitted since week 944, 1998/039)

Table 2. Differences in the precipitable water vapor between GPS estimates and WVR measurements in Potsdam.

Analysis Center	Bias [mm]	Std. Dev. [mm]	Cutoff angle [degree]
CODE	-1.23	0.91	10
ESA	-0.72	1.07	20
GFZ	-0.94	0.89	15
NGS	-1.50	0.98	15
SIO	-1.29	0.90	
IGS Combination	-1.09	0.83	-

Comparisons with co-located techniques were performed for Potsdam only. Here a water vapor radiometer (WVR) operated by the German Weather Service is available. Five ACs had contributed with GPS estimates since February 1998, before that time only CODE and GFZ. The derived ZND was converted into precipitable water vapor (PWV) and compared to the WVR. All GPS solutions monitor the fluctuations in the water vapor with high accuracy (Fig. 4). Statistics on the difference for 1998 are given in Table 2. The scattering is in the level of ±1 mm, the best value is for the combined series. All ACs have a negative bias of about –1 mm. In this case, different from the overall picture (Fig. 3), CODE and SIO agree best, which implies that the bias behavior will vary from site to site. Separate daily statistics are plotted in Figure 5. The fluctuations in the biases are rather large over the time period. Some larger deviations can be seen at the beginning and in the middle of the interval, which may be caused by problems in the WVR data. All GPS solutions give nearly the same picture in the difference to the WVR, and they show also the same fluctuation in the bias. The daily scattering (daily biases applied) is approaching a level of half a mm.

The number and quality of the meteorological sensors is slowly improving. Up to now only 30 sites have reported meteorological data, typically about 25. Presently there are tendencies by some meteorological institutions (UKMO, DMI) to assimilate the ZND directly into the numerical weather prediction (NWP) models. If this proves to be a good solution then it may have an impact on the installation of meteorological sensors for the regional applications devoted to NWP. However, for sites used in climate studies, which is the case for the global IGS network, meteorological sensors are important. Therefore IGS should strive to complete the installation of sensors in its global network. For climate studies the usual daily RINEX-met files are sufficient.

The accuracy of the pressure sensors is most important and critical. No direct feed-back from the analysis can be gained. The only possibility to check the sensors is by a regular (e.g. yearly) 'calibration' which is in fact a comparison with a high-precision reference instrument. As long as only systematic errors will be found they can be corrected, otherwise the sensor have to be checked by the manufacturer. In instruments having not the most precise sensors their temperature dependence is corrected. If such instruments are running for many years without any calibration quality problems may occur (cmp. Fig. 6). To reduce the temperature dependent effects and to have a more representative calibration it should be recommended to have the pressure sensor located within a building. All parallel registrations with a reference instrument can normally not calibrate a wide temperature range, and chamber calibrations are typically done at a specific temperature.

Presently only a few geodetic users retrieve the IGS tropospheric products (looking into servers at CDDIS, IGN and GFZ). Hopefully, the interest of meteorologist into the product may grow in parallel with the acceptance of GPS products for NWP models.

The near real-time (NRT) monitoring of water vapor is more suited to individual countries or organizations. Such applications will be supported by IGS in providing global data, NRT orbits and its predictions (Gendt et al., 1999). For IGS sites contributing to the NRT orbit production also NRT tropospheric estimates will be available. These estimates may be offered to the regional groups for their quality control. Such control may be performed using the ZND directly, there is no need to have meteorological surface data for that purpose. In a first step the quality of those NRT products should be assessed , afterwards a decision how to proceed (e.g. with or without a combination) should be discussed.

Working Group Charter

Recognizing the important contributions that GPS can make to meteorology, climatology and other environmental disciplines, due to the ability to estimate tropospheric quantities that affect the GPS signal, the IGS has sanctioned the creation of a Troposphere Working Group.

The IGS Troposphere Working Group will promote, coordinate, facilitate, guide, and enhance the generation of useful tropospheric products based on data from the IGS ground network of GPS receivers. The primary tropospheric product that is currently generated from ground-based GPS data is the estimate of total zenith path delay. Ancillary measurements of surface pressure and temperature allow the extraction of precipitable water vapor from the total zenith path delay estimates.

Water vapor is a key element in the hydrological cycle and is an important greenhouse gas in the atmosphere. Monitoring of long-term changes of its content and distribution is essential for estimating changes in climate. The very inhomogeneous and highly variable distribution of the atmospheric water vapor makes it to a crucial element in weather forecasting. Conventional observing systems such as radiosondes and remote sensing, are insufficient for observing its high variability. Water vapor can also be estimated from space-born GPS receivers using ray tracing techniques. The ground-based and the space-based technique complement each other. The ground-based GPS provide continuous, high temporal resolved, vertical integrated water vapor at a site having a global coverage which is good over the continents and limited over the oceans. The space-based GPS provide high vertical resolution (lateral integrated over few hundred kilometers) with good global coverage, but discontinuous in time and geographical location. Both techniques are dependent on ground-based data as well as on precise GPS orbits and its predictions.

The Troposphere Working Group will:

- Promote improvements in estimation techniques and data handling procedures through on-going collaboration and communication between the group members; and enhance the implementation of standards and technologies which will minimize the systematic differences in the estimates of the analysis groups.
- Support the IGS Associate Analysis Center for tropospheric solution combination (currently GFZ) in refining and assessing the combination algorithm, and in quality control assessment of the derived products.
- Advertise and promote the utilization of the IGS tropospheric products by the widest possible user group. Provide feedback to the IGS from users of the tropospheric products.
- Devise and evaluate the generation of new IGS tropospheric products n consultation with the potential user community.
- Generate and maintain a prioritized list of sites that are candidate for deployment of meteorology sensors and/or GPS receivers based on their potential impact on atmospheric and environmental studies.
- Gather, analyze and disseminate information to support the proper selection, installation and maintenance of instruments that affect the tropospheric products.

- Organize and coordinate periodic campaigns for the calibration and assessment of the performance of instruments and products. Disseminate the results of these campaigns together with relevant recommendations for action.
- Support a regular quality assessment of the derived products using permanently running collocated techniques.
- Promote synergy between space-based and ground-based GPS techniques through interaction with active researchers in both fields.

List of Members

Y. Bar-Sever	(AC JPL)
M. Bevis	(GB Member)
P. Fang	(AC SIO)
C. Garcia-Martinez	(AC ESA)
G. Gendt (Chair)	(AC GFZ)
C. Huot	(AC EMR)
W. Kass	(AC NGS)
M. Rothacher	(AC CODE)

Members ex officio:
Director of CB (R. Neilan)
AC Coordinator (T. Springer)

Working Plan

Promote improvements in the installation of meteorological packages (number of sites and reliability of met data) by generating a list of candidate new sites and assessing the quality of the existing met data (continuous efforts, first resume at the end of 1999)

Quality assessment for derived tropospheric estimates on a more regular basis using collocated VLBI, WVR etc. (End of 1999)

For the reduction of systematic errors strategies should be developed which improve the consistency in the station height estimation (the main error source for many sites) by the Analysis Centers (End of 1999)

References

Gendt, G (1996): Comparisons of IGS tropospheric estimates. Proceedings IGS Analysis Center Workshop, 19-21 March 1996 Silver Spring, Maryland USA, Eds. R E Neilan, P A Van Scoy, J F Zumberge, pp.151-164

Gendt, G, P Fang, J F Zumberge. (1999): Moving IGS towards real-time. This volume.

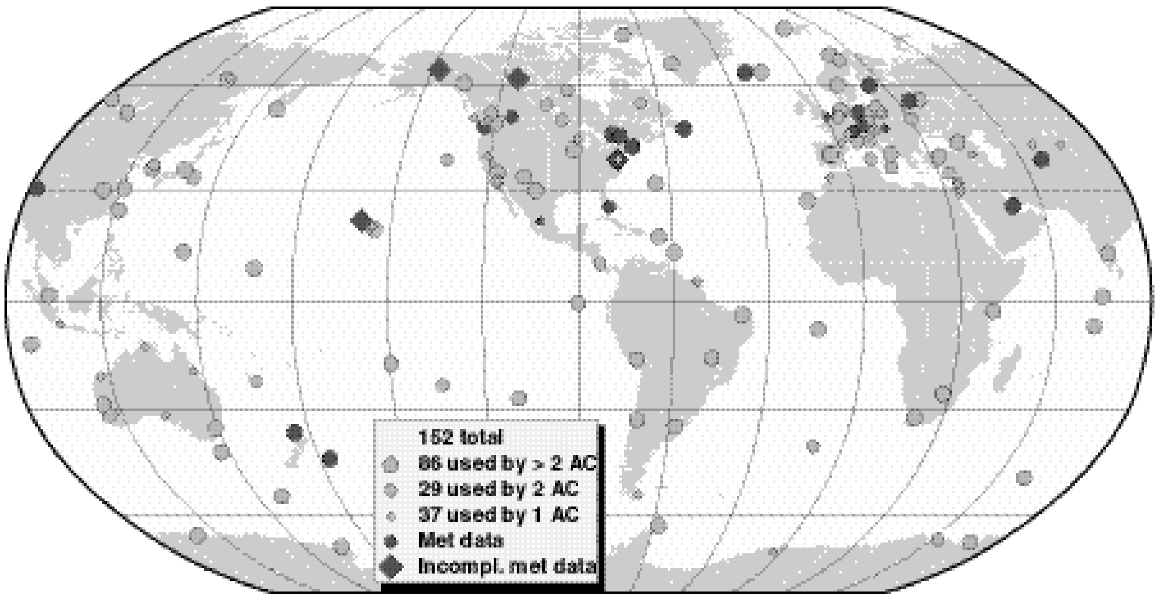

Fig. 1. IGS stations with tropospheric estimates. The existing meteorological packages are given.

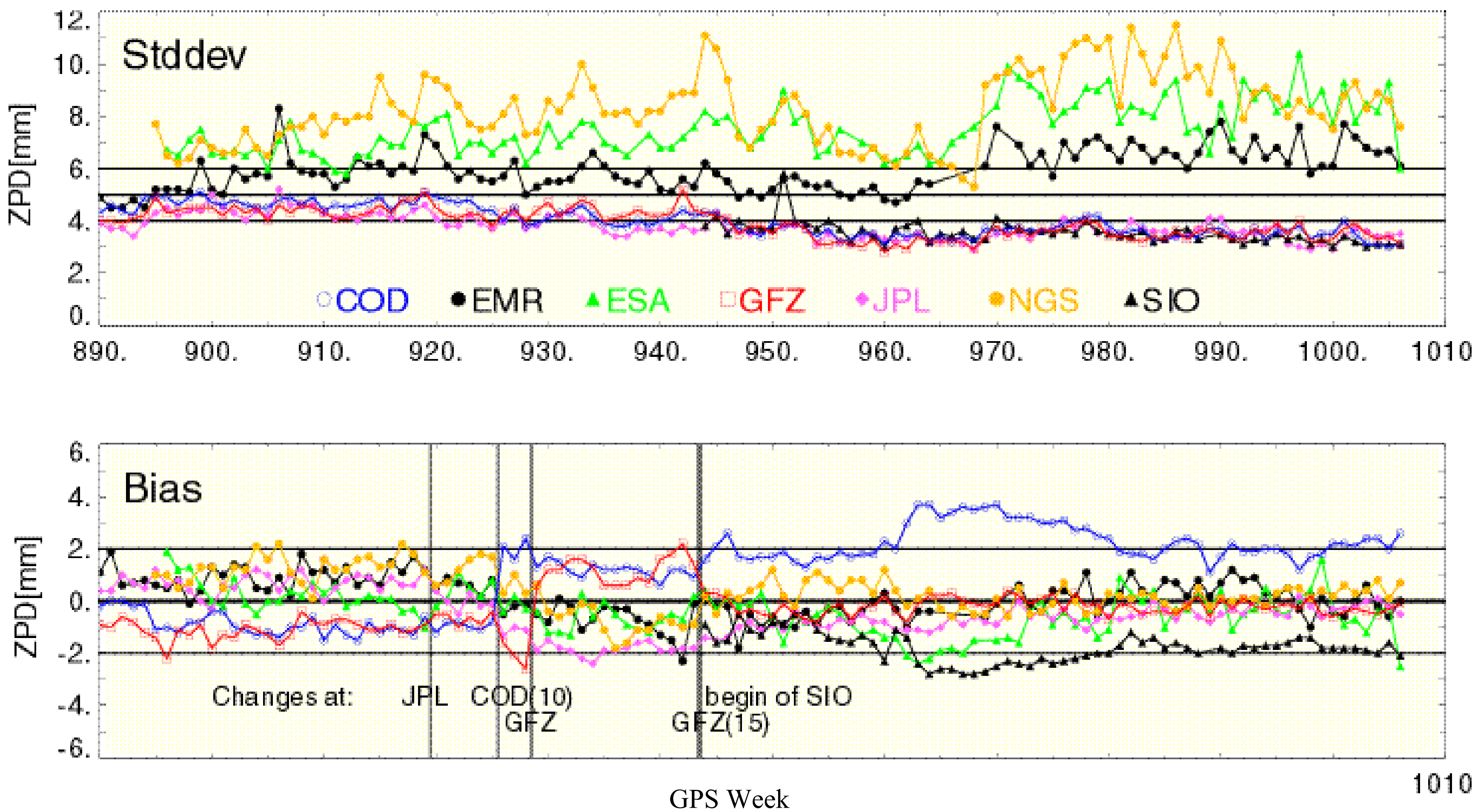

Fig. 2. Difference in the zenith neutral delay between the individual GPS estimates and the IGS Combined Product. Mean values (over all sites) per week and Analysis Center

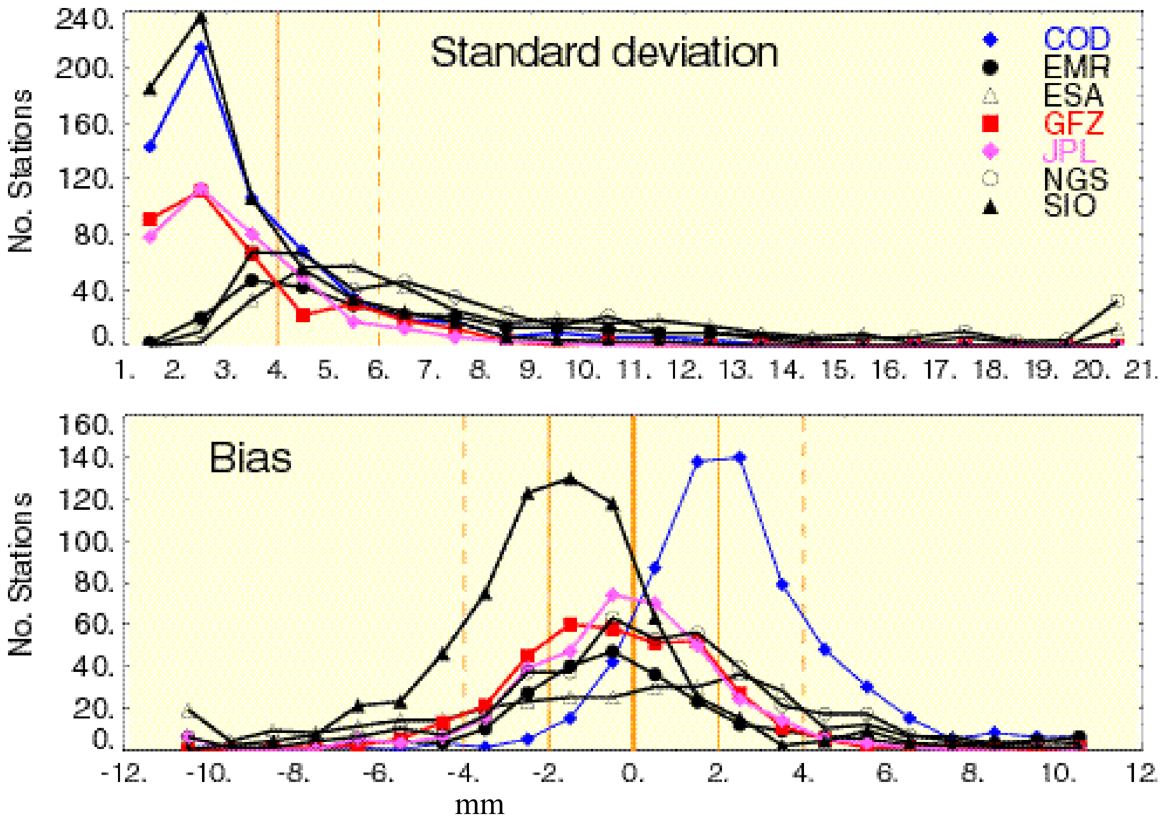

Fig. 3. Differences in the zenith neutral delay between the individual GPS estimates and the IGS Combined Product. Histograms of standard deviation and bias for the GPS weeks 999 to 1004

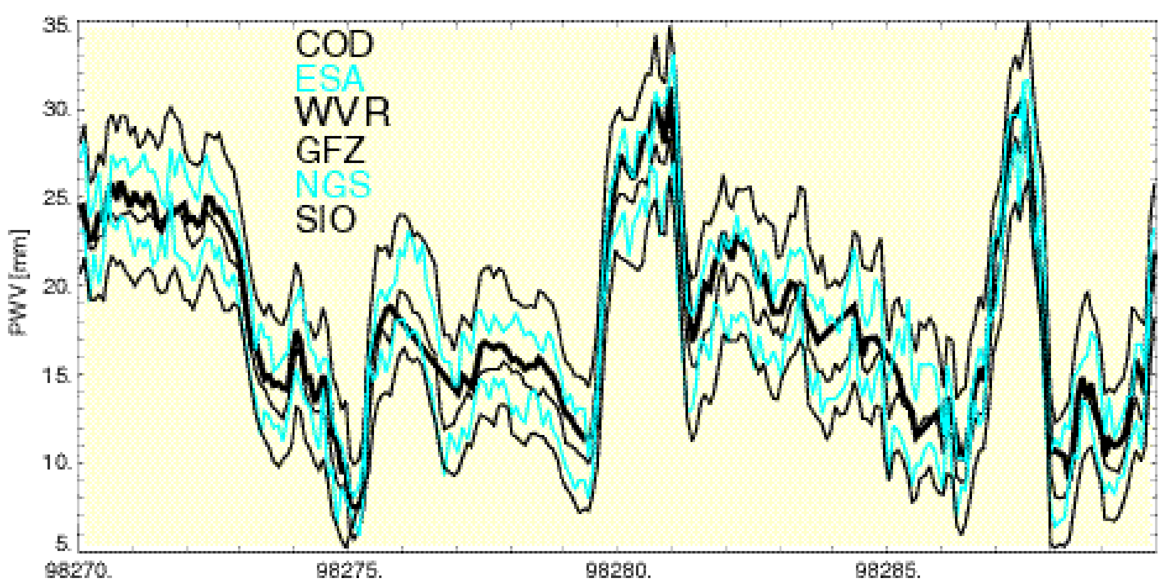

Fig. 4. Comparisons of precipitable water vapor between GPS estimates and a Water Vapor Radiometer data of the German Weather Service at Potsdam (20 days in 1998; the GPS estimates are shifted for better visibility).

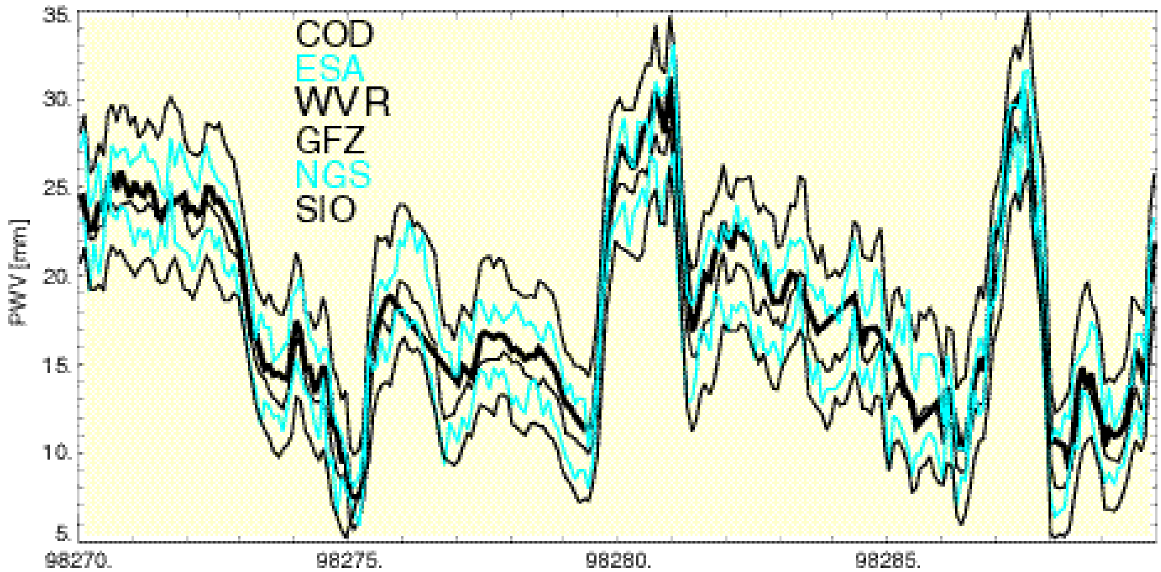

Fig. 5. Comparisons of precipitable water vapor between GPS estimates and a Water Vapor Radiometer data of the German Weather Service at Potsdam. Daily standard deviation (top) and daily biases (bottom) of the differences for all individual ACs for the year 1998.

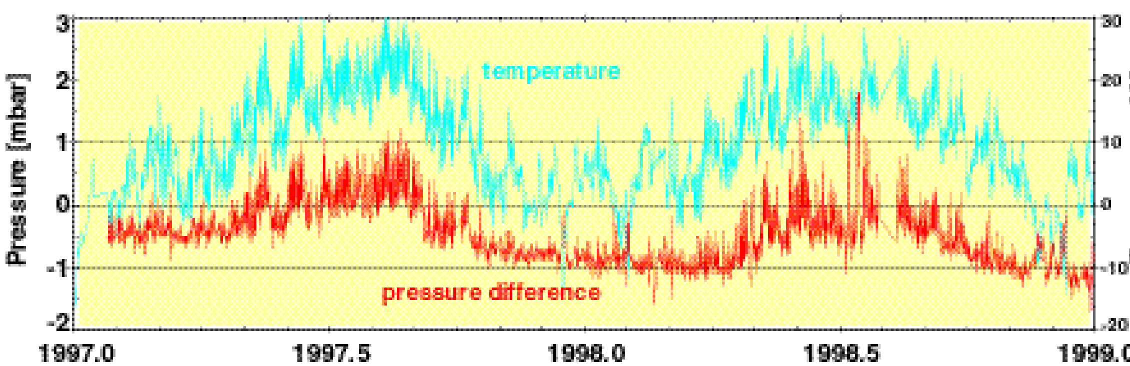

Fig. 6. Pressure sensor at GPS station Potsdam with a nominal precision of 0.5 mbar. Difference to co-located high precision reference sensor.

Real and Near-Real-Time Products and Applications: Ground-Based GPS Meteorology

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One of the immediate applications of real-time GPS orbits is in ground-based GPS meteorology for use in weather forecasting. The accuracy and availability requirements for integrated (total column) precipitable water vapor (IPW) calculated from GPS tropospheric (neutral atmospheric) signal delays are defined by modern numerical weather prediction (NWP) models. IPW calculated from NWP models without GPS is accurate to about 10% on average, or about 2 mm IPW during the winter months and 4 mm IPW during the summer months. During active weather events, NWP errors between 30% and 50% are not uncommon. Errors in NWP accuracy are largely attributable to poorly defined initial conditions. Poor initial conditions, especially in the moisture field, come from the fact that atmospheric water vapor in under-observed in both time and space. Ground-based GPS-MET provides us with a way of making accurate water vapor observations at low cost, under all weather conditions, with high temporal frequency. The goal of the NOAA/FSL GPS-IPW Demonstration Network is determine the circumstances under which improvements in the description of the 3-dimensional moisture field, with consequent improvements in short-term weather forecast accuracy, can be achieved by assimilating 1-dimensional GPS signal delays (or retrieved IPW) into NWP models. The trend in numerical weather prediction is toward higher vertical and horizontal resolution models and shorter data assimilation cycles. Indeed, some operational NWP models such as the improved Rapid Update Cycle (RUC-2) running at the National Center for Environmental Prediction are already assimilating data at 1-h intervals. To be part of the next-generation upper-air observing system for NOAA, ground-based GPS-MET will require real-time orbits with at least the same level of accuracy achieved by rapid orbits in 1996 (~25 cm). We anticipate that this will necessitate an improved level of quality control over what is presently available. Orbits must be available at the completion of the data acquisition cycle: 1-h is mandatory, 0.5-h is preferable to stay ahead of shortening data assimilation cycle in the next few years.

Efficient Densification and Long Term Accuracy

Michael Heflin, David Jefferson,
Yoaz Bar-Sever, Frank Webb, and James Zumberge

IGS Workshop, June 9, 1999

Efficient Densification

Use of precise GPS orbits and clocks allows densification which is both accurate and computationally efficient. Each station-day of data can be processed independently in about 2 CPU minutes with current workstations. There are several benefits to this approach including: consistent modeling for all sites, use of a single global reference frame defined by precise global orbits, clocks, and a 7-parameter Helmert transformation, counting data from each site only once, long term accuracy as demonstrated by comparisons with VLBI, SLR, and NNR-NUVEL1A, and reduced cost. The productivity of GPS processing has increased dramatically with the number of sites processed each day increasing by more than an order of magnitude from 21 in 1991 to more than 300 in 1999. This growth in the number of sites is still increasing, with densification efforts underway in plate boundary zones such as California.

Daily Precision

Time series from 200 global GPS sites with data spanning more than one year indicate median daily coordinate precision of 4 mm N, 6 mm E, and 11 mm V. Baseline precision scales with length and reaches coordinate scatter for the longest global baselines. Spectral indices were also computed for all 200 sites. White noise, flicker noise, and random walk noise, would yield indices of 0, -1, and –2, respectively. The median spectral index was observed to be –0.4, consistent with white noise, some and annual and semi-annual terms, and possible smaller contributions from other noise types.

Long Term Accuracy

Comparisons of GPS velocities with those from independent techniques such as VLBI and SLR are used to estimate accuracy. Table 1 shows the level of agreement between recent solutions. The agreement between GPS and VLBI is now comparable to the level of agreement between VLBI and SLR. Three dependent data sets, based partially or completely on the same data which went into the GPS solutions, were also compared in Table 1. ITRF96 and ITRF97 are dependent in the sense that they are based partially on GPS velocity estimates. SCIGN solutions from JPL and SIO are compared in the last column. Overall, GPS velocities appear to be accurate at the level of 1 mm/yr N, 1 mm/yr E, and 3 mm/yr V based on about 5 years of GPS data.

IGS Comparison Results

Seven IGS analysis centers compute estimates for many parameters based on data from the global network. Comparison of these dependent solutions provides a measure of relative GPS precision. Differences in data handling, modeling, and analysis strategies all contribute to the comparison results shown in Table 2. These results are based on daily estimates except for coordinates which were compared weekly and velocities which were based on roughly five years of GPS data. The level of agreement has improved dramatically since 1991 with some parameters improving by more than an order of magnitude.

Table 1: Velocity Comparisons

Independent Data Sets

	GPS-VLBI	GPS-SLR	SLR-VLBI	
N	1.3	1.6	1.1	mm/yr
E	1.0	2.1	1.4	mm/yr
V	2.7	2.8	2.2	mm/yr
#	33	17	9	common sites
T	5.5	4.7	-	GPS years

Dependent Data Sets

	GPS-ITRF96	GPS-ITRF97	SCIGN JPL-SIO	
N	1.2	1.3	0.9	mm/yr
E	1.7	1.2	1.4	mm/yr
V	2.8	2.6	3.0	mm/yr
#	44	44	31	common sites
T	5.0	5.1	3.9	GPS years

Table 2: Best IGS Comparison Results

Orbits:	3 cm
Clocks:	0.2 nsec
Polar Motion:	0.1 mas
Length of Day:	0.02 msec/day
Tropospheric Delay:	4 mm
Coordinates:	2 mm N, 2 mm E, 5 mm V
Velocities:	1 mm/yr N, 1 mm/yr E, 3 mm/yr V
Geocenter:	1 cm X, 1 cm Y, 2 cm Z
Scale:	1 ppb

Comparisons of IGS and AC ERP/ERP Rate Solutions with Atmospheric and Oceanic Angular Momentum

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Since June 30, 1996, all AC and IGS ERP solutions are fairly consistent and refer, at least nominally, to the same ITRF datum. Furthermore, they account for the IERS sub-daily ERP model and include separate ERP rate solutions. Thus the period of June 30 1996 to Dec. 1998 was chosen for detail comparisons of AC ERP and ERP rate solutions with the IGS Final ERP as well as both IERS ERP series (C04 and the Bulletin A). During this period the best AC and the IERS ERP solutions compared to the IGS series at the 0.1 mas level, though some AC and IERS series show anomalistic signals at 7 and/or 14 day periods. The AC ERP rate solutions, submitted to the IGS combinations, were also compared to the IGS Final ERP rates as well as the ERP rates computed from atmospheric angular momentum (AAM) series which is available through IERS. The comparisons for each AC and IGS Rapid (IGR) ERP rates are summarized in the Table 1 for PM x (Xrt) , PM y (Yrt) rates and LODR, both for the inverted barometer (ib) and no inverted barometer (nib) AAM models.

Table : RMS of AC ERP rate differences with respect to AAM ERP rates during June 30, 1996 and Dec. 1998 with (ib) and without (nib) the inverted barometer corrections.

			mas/d		ms/d	
AC	Xrt(nib)	Xrt(ib)	Yrt(nib)	Yrt(ib)	LODR(nib)	LODR(ib)
COD	0.486	0.355	0.627	0.308	68.7	71.1
EMR	0.755	0.684	0.854	0.648	76.4	80.6
ESA	0.722	0.586	0.834	0.555	75.4	79.0
GFZ	0.505	0.395	0.637	0.374	67.3	71.6
IGR	0.542	0.447	0.693	0.421	69.5	72.8
JPL	0.515	0.368	0.640	0.368	69.2	71.6
NGS	0.925	0.866	1.232	0.961	100.3	106.9
SIO	0.494	0.347	0.628	0.310	69.1	71.9
IGS	0.492	0.353	0.631	0.314	66.6	69.8

The best AC and IGS ERP rate solution differences with respect to the AAM derived ERP rates had RMS of about 0.3 mas/d and 70 micro s for PM rates and LODR. Correspondingly, the best ACs and IGS gave ERP rate/AAM correlation of better than 0.8, 0.6 and 0.9 for PM x, PM y rates and LODR, respectively. The spectra of ERP rate-AAM differences, apart from the annual and semiannual periods, also show several peaks in the 20 to 85 day period bands. Since the ocean angular moment (OAM) series of Ponte et al., (Nature/Vol. 931(29), Jan. 1998) was available only up to April 1996, the overlapping IGS combined PM series of January 1995 to April 1996 was used in this AAM/OAM study. The Table 2 summarizes differences of ERP rates (computed from the IGS ERP) with respect to both AAM and AAM+OAM derived ERP rates. As seen from the Table 2, the inclusion of OAM improves significantly both PM x and y rate RMS, down to about 0.2-0.3 mas/d level.

Table 2. IGS combined PM X and Y rate differences (mas/d) with respect to the AAM and combined OAM and AAM (AAM+OAM) PM rates based on no inverted barometer (nib) and inverted barometer (ib) correction models during Jan. 1995 and April 1996.

	Xrt(nib)		Xrt(ib)		Yrt(nib)		Yrt(ib)	
	mean	rms	mean	rms	mean	rms	mean	rms
AAM	-0.040	0.583	-0.018	0.464	0.019	0.553	-0.020	0.312
AAM+OAM	-0.064	0.508	-0.042	0.332	-0.023	0.556	-0.061	0.232

Accounting of OAM also improved PM/(AAM+OAM) correlation. Significant correlation already started from the 6 day periods and an overall correlation was about 0.8 for both PM rate components. Furthermore it virtually eliminated the semiannual signals in the IGS PM rates.

New IGS Station and Satellite Clock Combination

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In order to take the full advantage of the IGS clock solutions and to conform to the international conventions (UTC), it is essential that both satellite and station AC clock solutions are combined in a consistent manner, while maintaining consistency with the IGS orbit and station combinations.

Following the principles set forth in the Position Paper #3 of the 1998 Darmstadt AC workshop on the new IGS ITRF realization, a stand alone clock combination program was developed, utilizing a number of existing combination subroutines to ease the incorporation into the IGS automated combination process. The program allows for the input of both sp3 as well as the latest version of the new clock format. For each input AC clock solution, it solves and corrects for reference clock errors/instabilities as well as satellite/station biases, geocenter and station/satellite orbit errors. External station clock calibration and/or constraints, such as those resulting from the IGS/BIPM timing pilot project, could then be easily introduced via a subset of the fiducial timing stations, in order to facilitate a precise and consistent IGS UTC realization for both station and satellite combined clock solutions. Furthermore, the new clock combination process enforces strict conformity and consistency with the current and future IGS standards such as: DOMES # = NO station clock solutions, the new IGS ITRF realization (through the new IGS combined SINEX station product) and the IGS.SNX template. The new clock combination, though currently set up for a 15 min sampling, should also be readily adaptable for a 30 sec clock combination by simply increasing the appropriate dimensions.

Currently only GFZ and EMR submit the station/satellite solutions in the new clock format, so the USNO rapid clock solutions, in the new clock format, was kindly provided for the GPS week 0995 and it was used for testing. All the corresponding orbit and station (SINEX) solutions, along with the IGS Final orbits and a recent preliminary IGS SINEX combination (Ferland, priv. comm. 1999) were also utilized for the testing. Station clock solutions were found to be much more prone to outliers than the already established sp3 satellite clock submissions, so that a simple outlier testing/ detection (unlike in the existing IGS satellite clock combination) had to implemented as well. The table below summarizes the station/clock test combination RMS for the week 0995.

Table: RMS of the new station/satellite clock combination, consistent with the IGS/AC orbit and SINEX solutions for the week 0995, for 27 satellites and up to 68 stations (in ns).

Day/0995	EMR		GFZ		USNO	
	sta	sat	sta	sat	sta	sat
Day 0	.17	.23	.19	.13	.17	.14
Day 1	.08	.22	.16	.11	.14	.11
Day 2	.09	.19	.11	.14	.08	.15
Day 3	.22	.26	.22	.10	.14	.15
Day 4	.22	.26	.22	.09	.14	.18
Day 5	.39	.26	.23	.13	.10	.10
Day 6	.17	.31	.34	.11	.11	.11

Additionally, for the week 0995, the existing sp3 clock files of the five ACs (COD, EMR, ESA, GFZ, JPL) that provide satellite clock solutions in their sp3 orbit files were also combined with the new clock combination system. Then, the official IGS orbits, augmented with the newly combined satellite clock solutions, were subjected to the standard evaluation by precise GIPSY navigation at the IGS stations WILL, BRUS and USUD, as done every week within the IGS combination process. The IGS orbits with the new combined satellite clocks performed equally well, or marginally better than the standard IGS orbit/clocks.

The Effects of Site Specific and Troposphere Errors on Sub-daily Results

Arthur Niell
MIT Haystack Observatory

Elevation- (and azimuth-) dependent errors that are intrinsic to the data, or that are introduced in the analysis, generally produce systematic errors in the estimated parameters, e.g. position or zenith wet delay. While site-specific errors, such as elevation-dependent phase error due to multipath and scattering, might not vary over weeks or longer, parameters estimated sub-daily might have errors due to the variation during the day of the satellite constellation. On the other hand, conditions that do change on a sub-daily scale may require corresponding updates to the analysis for the highest accuracy. An example is the change in the atmospheric mapping function because of variations in the temperature and humidity profiles in the troposphere.

Suggestions for improvements in each of these areas will be offered.

In-Situ Site Calibration and Procedures

Arthur Niell
MIT Haystack Observatory

Site-to-site differences of the antenna phase response must be considered one of the primary sources of loss of accuracy in GPS measurements. Since the phase response of each antenna is affected by the total electromagnetic environment, it is virtually impossible to calculate any correction. Instead, the error must be either estimated from the data or calibrated by measurements at the site.

Site specific phase corrections (SSPC) determined from the post-fit phase residuals can reduce the systematic variation of position due to changes in sky coverage, but such corrections do not reduce biases in the position or ZWD that are inherent to the data. A proposal will be described for calibration of the SSPC.

An alternative approach is to measure the phase error by comparison with an antenna having significantly better phase characteristics. I will describe the Antenna and Multipath Calibration System (AMCS) being developed by Davis, Corey, Jarlemark et al, which is based on a steerable parabolic antenna as the reference.

Equipment does not stay calibrated forever, or components may fail and must be replaced with uncalibrated components, or firmware may be changed to “improve” the results. Equally insidious is the change of external environment, usually not under the control of our community. In order to maintain the highest accuracy, the quality of the raw data must be monitored to catch such problems as early as possible. A few simple, automated procedures may provide the type of surveillance needed.

IGS/BIPM Pilot Project to Study Time and Frequency Comparisons Using GPS Phase and Code Measurements

Interim Report
14th Meeting of the Consultative Committee for Time and Frequency (CCTF)
20-22 April 1999

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Introduction

The "IGS/BIPM Pilot Project to Study Accurate Time and Frequency Comparisons using GPS Phase and Code Measurements" was authorized in December 1997 jointly by the International GPS Service (IGS) and the Bureau International des Poids et Mesures (BIPM). A Call for Participation was issued shortly afterwards with responses received from about 35 groups. The respondents have formed a working group which was formally initiated on 18 March 1998. Co-chairing the Project on behalf of the IGS is Jim Ray (U.S. Naval Observatory, USNO) and for BIPM originally Claudine Thomas (BIPM), succeeded by Gérard Petit (BIPM) in late 1998.

A number of groups have been working for several years to develop the capability of using established geodetic GPS techniques for accurate time and frequency transfer. A variety of convincing demonstrations has already been performed showing the potential for determining clock differences at the level of about 200 ps or better. The current state of maturity of both the global GPS tracking network, precise orbits, and data analysis techniques now allows practical applications to be considered. The central goal of this Pilot Project is to investigate and develop operational strategies to exploit GPS measurements for improved availability of accurate time and frequency comparisons worldwide. This will become especially significant for maintaining the international UTC timescale, calculated by the BIPM, as a new generation of frequency standards emerges with accuracies of 10^{-15} or better.

The respective roles of the IGS and BIPM organizations are complementary and mutually beneficial. The IGS and its collaborating participants bring a global GPS tracking network, standards for continuously operating geodetic-quality, dual-frequency GPS receivers, an efficient data delivery system, and state-of-the-art data analysis groups, methods, and products. The BIPM and its timing laboratory partners contribute expertise in high-accuracy metrological standards and measurements, timing calibration methods, algorithms for maintaining stable timescales, and formation and dissemination of UTC.

The Project was originally planned to run until January 2000. By that time, the prospects for integration of suitable aspects into the operational activities and official products of the IGS or BIPM could be assessed and the future need for the Project re-evaluated. The progress of the Project and other related information, including a list of participants, are documented at the Web site http://maia.usno.navy.mil/gpst.html.

Working Group Meetings

BIPM, 22-23 June 1998

The 1st meeting of the Pilot Project working group was held at the BIPM (Sèvres, France) on 22-23 June 1998 with representatives from about nine timing labs, BIPM, several IGS Analysis Centers, the IGS Analysis Coordinator, and the IGS Central Bureau. It was a relatively intimate, informal gathering in the rather elegant setting of the BIPM, with superb facilities and support. The forum provided a good opportunity to initiate this collaborative project. The presentations were accompanied by ample discussion which allowed the concerns and goals of the various participants to be fully voiced.

The timing community expressed their strong need for a frequency transfer method capable of comparing the new ultra-stable oscillators now under development, such as the cesium fountain and ion trap standards with stabilities of 10^{-15} over one day or better. GPS geodetic techniques should be suitable and the timing groups hope to gain from the IGS expertise in this area, particularly with data analysis.

The IGS would prefer to link its clock products to the international UTC timescale rather than GPS broadcast time for improved stability and accuracy. In order to do this, accurately calibrated links are necessary at IGS stations located at timing labs.

There were considerable and fruitful discussions of a range of technical issues related to GPS receivers, antennas, cables, etc. Proposals for calibration approaches and independent comparison activities were considered.

PTTI, 30 November 1998

The 2nd meeting of the working group was held on 30 November 1998 associated with the 30th Precise Time and Time Interval (PTTI) meeting (Reston, Virginia, USA), which began the following day. Representatives of 10 participating groups gave brief summaries of their recent activities or plans, including a report from the CCTF working group on two-way satellite time transfer (TWSTT). Afterwards, a general discussion of instrumental calibration issues ensued. While it was generally conceded that calibration is the central issue that must be resolved for time transfer applications, it was felt that the effects on instrumental stability are sufficiently well understood that GPS carrier phase can already be usefully applied for frequency transfer, at least for systems maintained under strict metrological conditions.

During the main PTTI meeting, a special session, organized by Kristine Larson (University of Colorado, USA), featured nine papers on "Applying GPS Carrier Phase to Time and Frequency Transfer."

Next meeting

A workshop has been proposed for 10-11 December 1999 in the Los Angeles area immediately following the 31st PTTI meeting in Dana Point, California, USA. The first day of the meeting would be held jointly with members of the TWSTT working group. A decision on this proposal will be forthcoming shortly.

Areas of Participation

Deployment of GPS receivers

In addition to the GPS receivers already installed as part of the IGS global tracking network, other receivers at laboratories having accurate time standards are sought. These should be high-quality geodetic receivers capable of continuously recording and rapidly transmitting dual-frequency pseudorange and carrier phase observations. The station configuration and data distribution should conform to IGS standards and appropriate documentation must be filed with the IGS Central Bureau. A log file should be completed and sent to the IGS Central Bureau for each IGS station. For this Project, due consideration should be given to electronic stability, environmental control, and other factors which might affect the timing results. Upgrading of existing tracking stations for better timing performance is also encouraged. Deployment of dual-frequency GLONASS receivers, especially collocated at IGS sites, would provide an additional data source of interest, although this is primarily within the scope of the International GLONASS Experiment (IGEX-98); see Willis (1998).

GPS data analysis

Since its inception, the IGS has produced and distributed satellite clock products based on combinations of clock solutions submitted by its Analysis Centers using GPS phase and pseudorange observations. Strategies must be developed, consistent with other IGS products, to expand the clock products to include the GPS receivers at a large number of independent, global sites. A robust subset of these sites should be equipped with high-quality frequency standards with the goal being to routinely and accurately characterize and compare them. This work is being done primarily within the established IGS analysis framework in close cooperation with the IGS Analysis Center Coordinator. The extent to which operational analysis activities may be needed beyond those required for the expanded IGS products is not entirely clear at this point. However, research into refined analysis techniques and close inspection and validation of analysis results is clearly necessary.

Analysis of instrumental delays and calibration

In order to relate estimates for internal GPS receiver clocks derived from data analyses to external timing standards it is essential to understand the electronic delays introduced by the associated hardware. Studies are needed to characterize and control the short-term and long-term sensitivities to environmental changes, which affect frequency comparisons, and to develop suitable calibration methods for time comparisons. Differential biases between the L1 and L2 frequencies must be considered. Studies of both GPS ground sites as well as the GPS satellites
are sought.

Time transfer comparisons

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

Objectives

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

Accurate and consistent satellite clocks

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

In the PPP method, data from a single, isolated GPS receiver (pseudorange and phase at both frequencies) are reduced using IGS orbits and satellite clock values instead of broadcast GPS constellation information. This is completely analogous to the way a conventional stand-alone navigation receiver operates except that by using phase data and precise IGS information the instantaneous receiver position can be determined at the ~5 cm level with respect to the IGS reference system. Similarly, a precise determination of the local receiver clock can be made, relative to the underlying timescale of the IGS satellite clocks. This approach can be readily exploited for simple, global dissemination of sub-ns time and frequency information. Just as the IGS has adopted (and contributes very significantly to) the ITRF as the realization of its terrestrial reference system, the timescale for its clock products should be traceable to UTC.

A type of precise point positioning likely to become increasingly important is for tracking low Earth-orbiting satellites equipped with onboard GPS receivers. For this application the 15-minute tabulation interval of the sp3 orbit files is not adequate because the SA corruption of the broadcast clocks does not allow accurate interpolation over intervals longer than about 30-s (Zumberge et al., 1998a). For this and other applications, the IGS Analysis Centers have been asked to consider providing satellite clock products with 30-s sampling rates and the IGS may begin producing a corresponding combined product (Springer et al., 1998), which would require a new exchange format and mechanism for convenient distribution. Methods for efficiently computing high-rate satellite clocks have been presented by Zumberge et al. (1998b) and Soehne (1998). On the other hand, U.S. government policy now mandates discontinuing SA no later than the year 2006 and possibly as soon as 2000.

Accurate and consistent station clocks

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

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

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

Doing so requires new approaches for isolating GPS receiver equipment, such as efforts by Overney et al. (1997).

Accurate and stable reference timescale

Ultimately, it is necessary that all clock information, for satellites and stations, be referenced to a common, consistent timescale. Individual sets of results from different IGS Analysis Centers generally refer to different reference clocks. Thus, in the IGS combination process, the solution submissions must be realigned. This is currently done by choosing one submission as a reference solution, realigning its satellite clock estimates to GPS time based on the broadcast clocks for all the satellites (using only daily offset and rate terms), and then realigning all the other AC submissions to the reference solution (Springer et al., 1998). Corrections are applied to each solution set to account for radial orbit differences compared to the IGS combined orbits. The IGS combined satellite clock estimates are then formed from the weighted average of the realigned, corrected submissions. The internal precision of these combined clock products is currently in the 200 to 300 ps range.

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

Likewise, it is questionable whether GPS time is an appropriate choice for the underlying IGS timescale. The ideal choice should be accurate, accessible, and stable over all relevant time intervals (namely, 30 s and longer). GPS time is readily accessible but not with an accuracy comparable to other IGS products due to SA effects. Nor is GPS time particularly stable. The clocks of the GPS constellation are monitored from USNO and this information is provided to GPS operations with the goal of maintaining GPS time within 28 ns (RMS) of UTC(USNO), allowing for accumulated leap second differences. In practice, the two timescales have been kept within about 6.5 ns (RMS, modulo 1 s) over the last two years (for 24-hour averages). However, the GPS time steering algorithm

has a “bang-bang” character resulting in a saw-tooth variation with a typical cycle of about 25 days. This is equivalent to a frequency error greater than 10^{-15} over days to weeks, which changes periodically in a nearly square-wave fashion.
Almost certainly, an internal ensemble of the frequency standards used in the IGS network can be formed which would possess better stability than GPS time (Young et al., 1996). There are currently about 30 IGS stations using H-masers, and about 40 with cesium or rubidium standards.

Addition of new IGS sites located at primary timing laboratories would only improve this situation. A purely internal IGS timescale would not be stable against long-term drifts so some linkage to external laboratory timescales is required. Indeed, tracability to UTC is most desirable. In principle, this could be accomplished using the instrumental calibration data mentioned above for the fiducial clock sites. It will be technically difficult, however, to achieve comparable accuracies for the calibration measurements to the ~200 ps level possible for the data analysis clocks. This is the foremost challenge facing the Pilot Project.

An alternative approach to provide external timescale linkage that may be implemented more readily uses monitor data for the GPS constellation that are collected and compared at the timing laboratories. Using the observed offsets of GPS time relative to UTC(k), the corresponding IGS satellite clock estimates can be related to UTC(k) for a set of timing labs k. Because of the effects of SA such comparisons must be made at exactly the same epochs, otherwise the monitor data would only be useful to remove long-term differences (e.g., daily offsets and rates). Even this is probably sufficient, though, at least for an initial realization. If enough timing laboratories provide such monitor data, a moderately robust tie to UTC might be achievable. A difficulty with this method is that potentially significant biases between the observables of geodetic and timing receivers must be accurately determined and removed.

Apart from the issues discussed above concerning calibration and external referencing for an IGS timescale, there are other practical questions that must be resolved. In particular, it may be difficult to form and maintain a timescale within the IGS product delivery schedule. This is likely to be especially true for the Rapid products (available by 17:00 UTC after each data day) even though that is probably also where the greatest user interest lies. Fundamentally, this does not seem overwhelming although it will require new and highly automated IGS processes. Other practical concerns are minimizing discontinuities at day boundaries, dealing with receiver clock discontinuities and drop-outs in any ensembling process, and finding an appropriate robust ensembling algorithm. These subjects, together with those mentioned above, should be studied during this Pilot Project.

Status Of Activities

Communications

To facilitate the exchange of information among Pilot Project participants, a Web site was created. In addition, an e-mail exploder was set up to distribute messages to all participants with ~120 recipients, including ~50 "observers." The Web site is continuously updated with information about meetings, a list of participants and observers, procedures for establishing new IGS stations, data formats, the configuration of GPS receiver and clock equipment at stations, and so forth. All e-mail messages are archived, publication lists are maintained, and links are provided for other related sites.

GPS receiver network

The IGS tracking network currently consists of ~200 permanent, continuously operating, geodetic stations globally distributed. Of these, ~70 are equipped with external frequency standards, the remainder using internal crystal oscillators. The external standards in use are: ~30 with H-masers, ~20 with cesiums, and ~20 with rubidiums. The 11 IGS stations listed in Table 1 are located at timing laboratories (as of April 1999).

Table 1. IGS stations located at BIPM timing laboratories

IGS Site	Time Lab	GPS Receiver	Freq. Std.	City
AMC2	AMC *	AOA TR with ACT	H-maser	Colorado Springs, CO, USA
BOR1	AOS	AOA TurboRogue	cesium	Borowiec, Poland
BRUS	ORB	AOA TurboRogue	H-maser	Brussels, Belgium
GRAZ	TUG *	AOA TurboRogue	cesium	Graz, Austria
MDVO	IMVP	Trimble 4000SSE	H-maser	Mendeleevo, Russia
NRC1	NRC *	AOA TurboRogue	H-maser	Ottawa, Canada
PENC	SGO	Trimble 4000SSE	rubidium	Penc, Hungary
SFER	ROA	Trimble 4000SSI	cesium	San Fernando, Spain
TOUL	TA(F)	AOA TurboRogue	cesium	Toulouse, France
USNO	USNO*	AOA TurboRogue	H-maser	Washington, DC, USA
WTZR	IFAG	AOA TurboRogue	H-maser	Wettzell, Germany

* participates in TWSTT operations

Additional timing laboratories have expressed an interest in installing geodetic GPS receiver systems and some expect to do so in the near future. Advice has been provided to some of them concerning IGS procedures, hardware options, and other considerations. In addition, a number of laboratories are equipped with 3S Navigation dual GPS/GLONASS receivers but do not participate in the IGS because the receivers track L1 only for GPS; some of them do contribute to the IGEX-98 campaign.

Some of the existing IGS stations have been contacted in an effort to improve their timing performance, where reasonable and mutually beneficial. HRAO (Hartebeesthoek Radio Astronomical Observatory, South Africa) agreed to supply a 5 MHz external signal from an H-maser already at the site for VLBI observations. The KOKB (Kokee Park, Hawaii) external reference was switched from an old style NR H-maser to a Sigma Tau unit and its frequency offset, relative to UTC(USNO), was adjusted to be close to zero. Similarly, the existing Sigma Tau H-maser at FORT (Fortaleza, Brazil) was also frequency adjusted. Reconnection of the existing H-maser at HOB2 (Hobart, Tasmania, Australia) was encouraged after more than a year of using an internal crystal. In January 1999, an IGS Mail message (#2136) was sent to advise the IGS community of plans for developing new combined station clock products, which depends on a subset of receivers equipped with stable frequency standards. The Analysis Centers were asked to use as many of these 35 "fiducial clock" sites as possible to ensure a sufficient number of solution clocks in common so that precise reference realignment can be performed in the combination process. The operators of the "fiducial clock" sites were requested to report any changes that could affect the timing performance of their stations. A list of the "fiducial clock" stations (as of April 1999) is given in Table 2.

Significant changes in the IGS network configuration are expected during the next year. The many factors contributing to this were considered at the IGS Network Systems Workshop held in Annapolis, Maryland, USA, on 02-05 November 1998. Among other things, the GPS Week rollover on 21 August 1999 and the year 2000 rollover both require upgrades (at least new firmware) for most receivers. More serious is the declining performance of the older AOA TurboRogue receivers, which, for historical reasons, form the core of the IGS network. The upturn of solar cycle 23 ,with its associated increase in ionospheric activity, has caused tracking to suffer, especially at lower elevation angles and for the weaker L2 frequency. The effect is so severe in equatorial regions that many of the TurboRogue stations in those areas report no useful data during daylight hours when the ionosphere is most active. These difficulties are much less apparent for the new generation of Y-codeless, dual-frequency geodetic receivers (e.g., Ashtech Z-XII, AOA Benchmark, Javad Legacy, etc.), which are gradually becoming more common in the IGS network. During this period of transition, however, the mix of different receiver types, which report distinctive data types, may create other problems if care is not taken. In particular, the codeless pseudorange observables are biased (up to ~2 ns) compared to TurboRogue cross-correlated pseudoranges and the biases are satellite-dependent. If mixed, estimates for GPS satellite clocks will be degraded, as will precise point positioning using them. Suitable data handling and analysis procedures are being developed within the IGS to avoid this problem.

Table 2. IGS ™fiducial clock⌡ stations (as of April 1999)

IGS Site	Time Lab	GPS Receiver	Freq. Std.	City
Primary set (21):				
ALGO	---	AOA TurboRogue	H-maser	Algonquin, Ontario, Canada
BRUS	ORB	AOA TurboRogue	H-maser	Brussels, Belgium
DRAO	---	AOA TurboRogue	H-maser	Penticton, BC, Canada
FAIR	---	AOA TurboRogue	H-maser	Fairbanks, AK, USA
FORT	---	AOA TurboRogue	H-maser	Fortaleza, Brazil
GODE	---	AOA TurboRogue	H-maser	Greenbelt, MD, USA
GOL2	---	AOA TurboRogue	H-maser	Goldstone, CA, USA
HOB2	---	AOA TurboRogue	H-maser	Hobart, Tasmania, Australia
IRKT	---	AOA TurboRogue	H-maser	Irkutsk, Russia
KOKB	---	AOA TurboRogue	H-maser	Kokee Park, HI, USA
MATE	---	AOA TurboRogue	H-maser	Matera, Italy
NLIB	---	AOA TurboRogue	H-maser	North Liberty, IA, USA
NRC1	NRC	AOA TurboRogue	H-maser	Ottawa, Ontario, Canada
NYAL	---	AOA TurboRogue	H-maser	Ny-Alesund, Norway
ONSA	---	Ashtech Z-XII	H-maser	Onsala, Sweden
PIE1	---	AOA TurboRogue	H-maser	Pie Town, NM, USA
TID2	---	AOA TurboRogue	H-maser	Tidbinbilla, Australia
USNO	USNO	AOA TurboRogue	H-maser	Washington, DC, USA
WES2	---	AOA TurboRogue	H-maser	Westford, MA, USA
WTZR	IFAG	AOA TurboRogue	H-maser	Wettzell, Germany
YELL	---	AOA TurboRogue	H-maser	Yellowknife, NWT, Canada
Secondary set (14):				
GRAZ	TUG	AOA TurboRogue	cesium	Graz, Austria
HRAO	---	AOA TurboRogue	H-maser	Krugersdorp, South Africa
KOUR	---	AOA TurboRogue	cesium	Kourou, French Guyana
MAS1	---	AOA TurboRogue	cesium	Maspalomas, Gran Canaria, Spain
MDO1	---	AOA TurboRogue	cesium	Ft. Davis, TX, USA
MDVO	IMVP	Trimble 4000SSE	H-maser	Mendeleevo, Russia
MEDI	---	AOA TurboRogue	H-maser	Bologna, Italy
METS	---	AOA TurboRogue	H-maser	Metsahovi, Finland
MKEA	---	AOA TurboRogue	H-maser	Mauna Kea, HI, USA
NOTO	---	Trimble 4000SSI	H-maser	Noto, Sicily, Italy
PERT	---	AOA TurboRogue	cesium	Perth, Australia
SANT	---	AOA TurboRogue	cesium	Santiago, Chile
TSKB	---	AOA TurboRogue	cesium	Tsukuba, Japan
VILL	---	AOA TurboRogue	cesium	Villafranca, Spain

With the arrival of new GPS receiver models and new vendors, new opportunities for timing applications may arise, particularly if the needs of the timing community are clearly voiced. The announcement by Ashtech of their “Metronome” timing option is an encouraging indicator of such possibilities.

GPS data analysis

For most geodetic applications, receiver and satellite clocks can be treated as true nuisance effects. Any GPS signal delay common to all observations at a given epoch, whether due to a genuine clock-related timing variation or to some other non-clock bias, will be interpreted in the data analysis as a clock-like effect. But, by the same token, because such effects are common to all simultaneous observations and are geodetic nuisances, they can be removed altogether by forming observation differences (usually, double differences between pairs of receivers to a single satellite to eliminate satellite clocks and between pairs of satellites involving a single receiver to eliminate receiver clocks). With undifferenced data, combining pseudorange and carrier phase observations allows the clock-like effects (including the true clock together with other similar biases) to be determined directly. However, only differential clock variations can be estimated. That is, a single receiver clock is normally chosen as a fixed reference and all others are determined relative to that reference. Dual-frequency pseudorange data are required. Otherwise, the carrier phase ambiguity bias parameters cannot be separated from clock biases. The precision of estimated clock variations does depend on the phase data, but the "absolute" value of the clocks depends on the time-averaged pseudorange data. Consequently, long spans of continuous phase data without cycle slips or resets in the phase ambiguity biases favor better clock determinations by providing longer intervals of pseudorange averaging. This is particularly important when one considers the much greater susceptibility of pseudorange observations to multipath errors. The formal uncertainty of clock estimates is typically around 130 ps for a data rate of 5 minutes.

Table 3. Operational clock products available from IGS Analysis Centers

IGS AC	Clock Products * Rapid	Final	Institution, City
CODE	GPS	yes	Univ. Bern, Bern, Switzerland
EMR	yes	yes	NRCanada, Ottawa, Canada
ESA	yes	yes	ESOC, Darmstadt, Germany
GFZ	yes	yes	GeoForschungsZentrum, Potsdam, Germany
JPL	yes	yes	Jet Propulsion Laboratory, Pasadena, CA, USA
NGS	GPS	GPS	NOAA, Silver Spring, MD, USA
SIO	no	no	Univ. California, San Diego, CA, USA
USN	yes	N/A	USNO, Washington, DC, USA

* ™GPS∫ refers to broadcast GPS time; USN does not contribute to Final products

Of the seven IGS Analysis Centers (eight for the Rapid products), five currently provide satellite clock estimates; see Table 3. The IGS is committed to expand its operational product set during 1999 to include combined clocks for the tracking receivers as well as the GPS satellites. A detailed plan for doing this was developed among the Analysis Centers and considerable progress has already been made. The first step was devising an exchange format for clock-like data. This was done using as a model the RINEX standards for exchanging GPS receiver observations. The initial format version was released in August 1998 and was designed to handle receiver calibration data, receiver discontinuity observations, data analysis results, or monitor data from the observations of satellite clocks at timing laboratories. The complete specifications are available at http://maia.usno.navy.mil/gpst/clock-format. It was also necessary for the IGS Analysis Centers to agree on a common set of vector offsets for the separation between the phase centers of the GPS satellite transmit antenna arrays and the satellite centers of mass. These vectors are not accurately known a priori and any differences in the assumed values for the radial components will manifest themselves as biases in the estimated values for the satellite clocks. To ensure that satellite clock determinations from the various

Analysis Centers can be compared and combined consistently, the IGS adopted a common set of vector offsets on 29 November 1998. In the usual spacecraft-fixed coordinate system (where the z-axis is directed from the satellite center of mass towards the Earth center), the IGS offset values are:

Block II & IIA:	dx = 0.279 m;	dy = 0.000 m;	dz = 1.023 m
Block IIR:	dx = 0.000 m;	dy = 0.000 m;	dz = 0.000 m

To permit improved realignment and weighting of the clock solutions from the Analysis Centers to the same timescale, the subset of clock estimates common to all solutions must be sufficiently large, preferably including all the GPS satellites and as many stations with stable frequency standards as feasible. If too few stations are common to all, then the IGS combined results will not be improved over the current method using only the satellite clocks. Thus, a set of 35 “fiducial clock” sites was identified (see previous section) and the Analysis Centers were encouraged to include as many of these as possible in their solutions. All but eight of the “fiducial clocks” sites are equipped with H-maser frequency standards, the others having cesiums; six are located at timing laboratories.

Two IGS Analysis Centers already deposit their satellite and receiver clock solutions (in clock RINEX format), together their other weekly Final solution products, at the IGS Global Data Centers: EMR (Natural Resources Canada, Ottawa, Canada) and GFZ (GeoForschungsZentrum, Potsdam, Germany). The USN (USNO) Center posts plots of their Rapid clock solutions at a Web site together with plots and clock files for solutions made using the IGS Final orbits. It is expected that operational clock solutions from other Analysis Centers will soon become available.

For the time being, IGS combined clock products (satellites only presently) are aligned to broadcast GPS time using a linear fit over 24 hours for each satellite. The quality of the timescale realization is limited by the effects of SA modulation, independent of the underlying stability of GPS time. Until direct and accurate access to UTC realizations are available, this procedure will be continued.

The possible need for additional operational clock analyses beyond the official products of the IGS (once combined receiver clocks are in place) is unclear at the moment. Since the Analysis Centers use data from variable subsets of IGS sites and not all IGS sites are included, it is likely that some procedure will be desirable to “densify” the official clock products. This would be analogous to the IGS Regional Network Associate Analysis Centers, which analyze and combine data from regional GPS networks consistently with the IGS core network, to provide densification of the terrestrial reference frame. A similar method could be established to provide consistent receiver clocks estimates for stations which are not included in the IGS core products.

Another area deserving greater attention is the careful examination of clock analysis results for anomalies and other problems which could limit their usefulness in timekeeping operations. For example, day-boundary discontinuities are an inevitable consequence of the usual strategy of processing data in 24-hour batches. Even if the discontinuities are consistent with the standard errors of the clock estimates, roughly 200 ps, methods must be developed to minimize their effects in time and frequency comparisons. Evidence exists, however, for some discontinuities much larger than expected, at about the ns level (Ray et al., 1999b). These have been attributed to pseudorange multipath effects at specific sites but a quantitative demonstration is lacking. There is a considerable body of geodetic literature concerning the effects of multipath and other phenomena in the local antenna environment which can corrupt position determinations (especially heights) and tropospheric path delay estimates. A host of factors can be important, including antenna mounts, antenna design, radomes, nearby ground cover variations such as due to snow, local structures and other reflective surfaces, etc. Potentially any error source which varies with elevation angle is a concern and can correlate with height and troposphere parameters. However, the constant bias part of such effects, which corrupts clock estimates, has not been adequately considered because of the negligible impact on geodetic measurements. New studies are needed to expand the scope of prior geodetic investigations in order to understand how best to site antennas for timing applications.

Calibration studies

There are, as yet, no geodetic receiver systems for which the timing calibration bias is known which would allow their internal clocks to be accurately related to external time standards. This circumstance is a fundamental obstacle to exploitation of GPS geodetic techniques for time transfer and is a central concern of this Pilot Project. Two types of instrumental calibration approaches are being pursued by various groups. One method characterizes the delay through individual components of the receiver system (antenna, antenna preamplifier, RF cables, receiver modules, etc). Results for a number of component types have been reported by several groups. A second method attempts the end-to-end calibration of a complete (or near complete) system by injecting simulated GPS signals. Ron Beard reported at the working group meeting at BIPM (June 1998) on work at the Naval Research Laboratory (Washington, DC, USA) to develop a calibrator of this type, within a controlled anechoic chamber. Both methods involve significant technological challenges. Generally, the first method is more accessible, at least for certain components, and has the advantage of permitting the most sensitive system elements to be identified. An overall accurate system calibration determination, which is required for time transfer applications, is difficult to obtain, however. The end-to-end method is clearly desirable for practical uses but it currently requires unique, expensive test equipment which may not be suitable for routine operational settings. A variant calibration scheme, using front-end signal injection, has been proposed by Tom Clark (NASA, Greenbelt, MD, USA; private communication) specifically for field operation. The idea is analogous to the phase calibration tones injected into geodetic VLBI receiver systems but is complicated by the need to synthesize stable coded signals that will be tracked by the receiver together with the actual satellite signals.

In contrast to direct instrumental calibration approaches, it should be feasible and probably simpler to calibrate a geodetic receiver system relative to a previously calibrated timing receiver by collocated common viewing of satellite clocks (Ray, 1999a). The two receiver systems must be situated in close proximity and all cable delays must be accurately known. If care is taken to apply equivalent analysis methods to both data sets, it should be possible to determine the end-to-end calibration delay through the geodetic system to the 1-ns level or better, relative to the timing receiver.

Some geodetic receivers, in particular the AOA TurboRogue, have a well known tendency to reset their internal clocks occasionally, even when driven from a very stable external frequency standard. This causes a discontinuity in the observed clock variation. Fortunately, the TurboRogue was specifically designed to allow such resets to be quantitatively measured by monitoring the 1 pps output signal, which faithfully tracks the internal clock state (Larry Young, JPL, Pasadena, CA, USA; private communication). Data from the IGS TurboRogue station at USNO, which is equipped with a high-quality 1 pps monitoring system, confirm this within the ~0.1 ns precision of the geodetic results (Ray, 1998a). With a very stable 1 pps measurement system and sufficient integration, such clock resets, while nonetheless annoying, can probably be calibrated and corrected at the few ps level.

The level of understanding and control of environment factors that affect frequency comparisons is much more advanced than time calibration (Petit and Thomas, 1996). Standards of metrological control are well known in the timing community and have been implemented to varying extent at several IGS stations. Studies of the temperature sensitivity of specific system components are emerging, e.g., Overney et al. (1997). To overcome variations within the antenna, 3S Navigation offers their TSA-100 temperature-stablized unit, designed to limit group delay changes to less than 2 ns over the range from -20°C to +50°C. The TSA-100 is intended for use with GPS or GLONASS receivers and so spans the relatively broad frequency range encompassing both sets of transmissions. For GPS-only observations, the requirements are less stringent. Thermal cycling effects for RF cables are widely recognized but not always well controlled because of the insignificance for geodesy. Common RF cable types can have sensitivities of ~1 ps/°C/m, but much better cable types are available with sensitivities of ~0.03 ps/°C/m. Additional benefit can be gained by shielding and/or burying them to reduce outside exposure. The significance of such measures was shown by Ray (1998b) for the IGS site at USNO, where the cable type and path were changed on 12 August 1998. Pronounced diurnal clock variations (~400 ps) seen prior to the changes were reduced to the noise level, around 100 ps (Ray, 1998b; see also Larson et al., 1998). Large thermal sensitivities in GPS receivers, as much as 100 ps/°C, prompted Overney et al. (1998) to design an environmentally controlled enclosure for their receiver system, known as the Geodetic Time Transfer (GeTT) terminal (see also Taris et al., 1998).

Frequency comparisons at the level of 10^{-15} over one day, or better, appear entirely feasible already, provided that reasonable care is taken to minimize environmentally induced variations. Indeed, Bruyninx et al. (1998) found the GPS instrumental limitations to be below 10^{-15} if temperature stabilization is enforced. Petit et al. (1998) and Thomas (1998) showed that when using temperature-stabilized antennas, cables with low temperature coefficients, and receiver units in a temperature-controlled laboratory, frequency comparison of the same clock by two different systems in the same laboratory may be performed with a stability below 1×10^{-16} over one day. For the less than ideal situation using the USNO station with strong diurnal signals, Larson et al. (1998) reported an observed frequency stability of 2.5×10^{-15} in one day over a 2360-km baseline.

Comparison experiments

Only a few controlled experiments have been conducted so far to compare geodetic timing results with other techniques. Larson et al. (1998) show geodetic time variations that agree within 1 ns with TWSTT results over a 167-day period comparing USNO to the AMCT station in Colorado Springs, CO, USA. Other long-baseline tests are underway.

Proposed Recommendation

Time and frequency comparisons using GPS phase and code measurements

The CCTF, considering

- that the IGS has established an infrastructure of global GPS observing network, data distribution system, robust analysis methodology, and high-quality products,
- that a joint IGS/BIPM Pilot Project has been established to study time and frequency comparisons using GPS phase and code measurements,
- that calibration methods are still lacking to fully exploit the capabilities of these techniques for time comparisons,

fully supports the joint IGS/BIPM Pilot Project, and recommends

- that timing laboratories participate in the IGS by installing appropriate GPS receivers and following the IGS standards and procedures to the greatest extent possible,
- that appropriate methods be developed to calibrate the instrumental delays relating the receiver internal reference to the external clock,
- that the IGS reference for clock products be aligned as much as possible to UTC,

· that the timing laboratories and the BIPM take the necessary steps to allow the IGS to realize this goal.

Reports and Presentations

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19 April 1999, 4th General Meeting of CCTF Working Group on TAI, at BIPM, Sèvres, France; J. Ray, IGS/BIPM pilot project status report, presentation.

20-22 April 1999, 14th Meeting of the Consultative Committee for Time and Frequency, at BIPM, Sèvres, France; J. Ray and G. Petit, IGS/BIPM pilot project interim report, presentation and this report.

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Recommendations for Handling Non-Rogue Data

*J. Ray, H. Dragert, and J. Kouba**[1]

Summary

The transition of the IGS network from a core of Rogue/TurboRogue (TR) receivers to newer codeless tracking architectures is natural and beneficial. However, the new receivers provide pseudorange observables which can be biased compared with TRs. This is of no significance for data analysts who process only carrier phase observables. For analysts who use the pseudorange observations, their estimates for satellite clocks can depend on the receiver model and the RINEX translation process. To avoid mixing data with different satellite biases, which will degrade the IGS satellite clock products (and precise point positioning using them), we recommend RINEXing and analysis procedures to maintain compatibility with the heritage TR tracking network until a sufficient fraction of stations is upgraded. At a future date to be decided, a uniform switch of the IGS to the new observables can be made.

Rogue/TurboRogue Observables (CC type)

The AOA Rogue and TurboRogue (TR) receivers produce the following 4 observables:

C1	= C/A code at L1 freq.
L1(C1)	= C/A-based phase at L1 freq.
P2'	= codeless pseudorange at L2 freq.
L2'	= cross-correlated phase at L2 freq.

The P2' pseudorange-type observable and the L2' phase are actually formed by a process which tracks the cross-correlated (P2-P1) pseudorange and the (L2-L1) phase differences:

P2'	= C1 + (P2-P1)
L2'	= L1(C1) + (L2(P2)-L1(P1))

Analysis software then has available two pseudorange (C1, P2') and two phase (L1(C1), L2') observables which can be linearly combined to form an ionosphere-free pseudorange and phase observation for each receiver-satellite observation epoch. We denote these as CC (for cross-correlated)receiver and observable types.

* Various individuals have contributed to the development of this proposal, including J. Kouba, H. Dragert, J. Zumberge, R. Muellerschoen, L. Estey, and W. Gurtner, although they do not necessarily endorse it. The text has primarily been written by J. Ray, H. Dragert, and J. Kouba, who are responsible for the contents.

Modern Codeless Observables (non-CC type)

Newer receiver models (e.g., Ashtech Z-XII, AOA Benchmark, AOA TurboRogues upgraded with ACT, etc.) provide direct measurements of P1 and P2 without the use of the Y-codes, with 6 (or more) observables available:

C1	= C/A code at L1 freq.
L1(C1)	= C/A-based phase at L1 freq.
P1	= Y1-codeless pseudorange at L1 freq.
L1(P1)	= Y1-codeless-based phase at L1 freq.
P2	= Y2-codeless pseudorange at L2 freq.
L2(P2)	= Y2-codeless-based phase at L2 freq.

The first 2 observables (C1, L1(C1)) correspond to the same quantities measured by the TurboRogues, but the others are not quite the same. Because it would be confusing to report two different L1 phase values (L1(C1), L1(P1)) in RINEX observation files, the one based on the higher SNR C/A-code is usually preferred. It should be noted however that the current default offload in Conan Binary, Conan ASCII, or RINEX format from the AOA BenchMark receiver provides L1(P1) instead of L1(C1), and does not provide C1.

We denote these as non-CC receiver and observable types.

Since phase is inherently ambiguous and according to specifications (L1(C1)-L1(P1)) is a constant fraction of a carrier wavelength, the distinction between L2' in TurboRogues and L2(P2) in these receivers is not significant. However, the difference between the CC pseudorange pair (C1, P2') and the non-CC pseudorange pair (P1, P2) can be important for some applications, since the (C1-P1) pseudorange difference varies between satellites and can reach up to 2 ns (0.6 m).

Biased Pseudoranges and Their Consequences

The (C1-P1) pseudoranges from non-CC receivers are not zero-mean, but are biased up to ~ 2ns (see Appendix). The biases vary from satellite to satellite but tend to be relatively stable in time. These effects can be readily seen in data from modern receivers that output both L1 pseudorange observables. (Note that most CC type receivers also output both L1 observables under non-AS conditions.) Using the non-CC (P1, P2) pseudorange pair is not consistent and will be biased with respect to the CC pair (C1, P2') by (C1-P1) at both frequencies. Hence, the ionosphere-free pseudoranges will also be biased by (C1-P1), which will go directly into clock estimates. Note that since the biases change from satelite to satellite (unlike for phase observables) they will not be eliminated by double differencing.

If CC and standard non-CC pseudorange data are mixed, then estimates for the satellite clocks will be corrupted in a way that depends on the mix of receiver types and their geometric distribution. Considering that the IGS clock products have a precision at about 0.2 ns, this is highly undesirable. Point positioning using non-CC data and IGS/AS products that are based on CC-type data will also be correspondingly degraded.

On the other hand, data analyses which use only carrier phase observables, and therefore have no sensitivity to the absolute values of the satellite clocks, are not affected by these pseudorange biases. Pseudorange ionospheric estimates, which are based on the (P2-P1) difference for CC and non-CC receivers, are also unaffected.

Recommendations for Station Operators

For the time being, we strongly recommend RINEX translation procedures for non-CC receivers that provide sufficient pseudorange observables in order to allow CC-type pseudorange observables to be synthesized by the user. This will permit consistency within the IGS network to be preserved until the heritage core of TR receivers is largely replaced.

Specifically, station operators using modern non-CC receivers are asked to ensure that the C1 observable, if available, is reported in their RINEX files together with the P1 and P2 observables. This will allow RINEX users to form the synthetic observable

P2' = C1 + (P2-P1)

UNAVCO has kindly provided modifications to their `teqc' toolkit to support this need for certain receiver types; for further information please refer to http://www.unavco.ucar.edu/software/teqc/. Options for using teqc for particular non-CC receivers are given below.

AOA Benchmark & Upgraded TR

Data must be downloaded from the receiver in TurboBinary format. An offload of data in Conan Binary format from the BenchMark receiver will contain only the 4 observables P1, L1(P1), P2, L2(P2). The offload in TurboBinary however provides all six non-CC observables described above. (Note that the Turbo Binary files will be almost three times larger in size than the commensurate Conan Binary files.) Then the appropriate teqc option is

teqc -aoa tbY - O.obs L1L2C1P2P1S1S2

where S1 and S2 are recommended to provide full-precision SNR values as additional observables; other suitable teqc options should also be included, normally in a configuration file. The output RINEX files should then contain the C1, P1, L1, P2, and L2 observables, as well as the SNR values. For the "-aoa" options, teqc already adds the appropriate comments to the RINEX header to indicate which observables have been formed.

[actions needed for other receiver types ... still needs to be done]

Ashtech Z-12

The ASHTORIN translator provides all the necessary pseudorange data. Of possible interest is the use of teqc to extract the L1(C1) phase from either the Ashtech B-file (as also Werner Gurtner's ASRINEXO translator does) or from an Ashtech MBEN/PBEN real-time data stream. The teqc option to set is "+Ashtech_CA_L1". By default, teqc extracts the L1(P1) phase as its RINEX "L1" value.

Leica

does not output C1 observable ...

Recommendations for IGS Central Bureau

Because the RINEX format contains no specific indicator of the precise nature of the pseudorange observables reported (whether the CC-style P2' or the non-CC P2 observables are used), data users must rely on the "REC # / TYPE / VERS" RINEX header recorder together with knowledge of the generic types of the various receivers available. This fact underscores the vital importance of reliable RINEX headers, which the IGS Central Bureau is asked to rigorously enforce.

In addition, it is necessary for the IGS Central Bureau, working with receiver experts, to compile information characterizing all receiver types as either CC or non-CC style. This information should be readily available and specifically linked with the various "official" receiver names used by the IGS.

A preliminary partial list of receiver types follows: [needs work here to verify and complete!!!]

Cross-Correlation (CC) Style Receivers

ROGUE SNR-8*
ROGUE SNR-12*
TRIMBLE 4000*
TRIMBLE 4*00 ????????????
TRIMBLE 7*00 ????????????

Non-Cross-Correlation (non-CC) Style Receivers

AOA SNR-12 ACT
AOA BENCHMARK ACT
ASHTECH Z-XII
LEICA ???? (does not output C1 pseudorange)
JPS *

Recommendations for Data Analysts

The IGS Analysis Center Coordinator should ensure that IGS products are as consistent as possible with either CC or non-CC observables. This information should be readily available to all IGS data and product users.

For the time being, it is recommended that the IGS adopt CC-style observables as a standard. Observables, biases, and analysis products should be handled to ensure maximum consistency with this standard. Specifically, those Analysis Centers which process pseudorange data are strongly encouraged to: 1) Check their network mix and verify that the data RINEX from non-CC receivers being used are consistent with the recommendations above. 2) Use the (C1, P2') pseudorange pair, or the equivalent, rather than the (P1, P2) pair in their analyses. The 2nd recommendation can be accomplished in two possible ways:

a) Synthesize CC Style Observables

Use a utility to convert raw RINEX files to CC-style RINEX files by synthesizing the P2' = C1 + (P2-P1) observable and using the C1 pseudorange rather than P1. Obviously, this is only possible if the raw RINEX files hold all the necessary information.

A RINEX utility converter is available for ACs wishing to use this option (ftp://maia.usno.navy.mil/pub/noncc2cc.f).

b) Apply Satellite-based Bias Correction

Alternatively, corrections for the satellite-based biases can be applied based on empirical tabulations (such as have been compiled by the JPL group; see Appendix). In this case, the (P1, P2) pseudorange pair would be replaced by [P1 + f(i), P2 + f(i)], where f(i) is an empirically-determined function that represents the average value of (C1 - P1) as a function of GPS satellite PRNi. The Appendix describes results from Ron Muellerschoen at JPL.

A disadvantage of the synthesis approach (a) is that additional noise is introduced in forming the (C1, P2') pair that is not in the directly observed (P1, P2) pair. If temporal variations in the f(i) biases are small compared to the noise in the 30-s measurements of (C1 - P1), then using f(i) would introduce less error (approach b). On the other hand, if temporal variations in the f(i) biases are significant, then approach (a) yields smaller errors.

Future Changes

As the IGS network continues to evolve these recommendations will be reviewed and modified. In particular, the IGS Analysis Center Coordinator may propose to end the CC-style standard and change to non-CC observables when that seems appropriate.

Appendix

Date: Wed, 14 Apr 1999 21:46:04 +0000
From: "Ronald J. Muellerschoen" <rjm@cobra.jpl.nasa.gov>
Subject: Re: handling TR and non-TR data

<edited by J. Ray to add table headers>

I've been periodically computing global solutions for CA-P code bias since Oct of 97 with a network of 14 to 15 Ashtech Z-12 receivers. The variation over this period (in general) has been about 4-5 cm. The biggest change was prn 7 when the bias changed from 20 cm sometime between 12/22/97 and 4/12/98. I hadn't looked at these biases until almost a year later when I turned the process back on 3/18/99. The biggest change at this time was 8 cm for prn13, 7 cm for prn31, 6 cm for prn29 and prn 18, 5 cm for prns 15, 30,17 while all others were less than 4 cm.

The below table are the results of hourly solutions of the CA-P code bias for the last three weeks. Note in all this I am assuming that the CA-P code bias at a particular station I have chosen is not changing. (To compute the solution I fix the CA-P code bias at this station to a particular value. A
closer look at the values of CA-P code bias for the different prns all have a similar signature, which would indicate that the CA-P code bias at my reference station is not entirely stable.

Average (P1-C1) Biases over 3 weeks for 15 Ashtech Z-12 Receivers
(units are meters)

prn #	average	hi value	low value	spread	var. of ave.	numb.
prn 1	ave: -0.134	hi: -0.07	lw: -0.23	sp: 0.16	sigma: 0.030	n: 505
prn 2	ave: -0.378	hi: -0.31	lw: -0.45	sp: 0.14	sigma: 0.027	n: 505
prn 3	ave: -0.017	hi: 0.06	lw: -0.08	sp: 0.15	sigma: 0.029	n: 505
prn 4	ave: 0.358	hi: 0.43	lw: 0.29	sp: 0.14	sigma: 0.030	n: 505
prn 5	ave: -0.253	hi: -0.18	lw: -0.35	sp: 0.17	sigma: 0.030	n: 505
prn 6	ave: 0.099	hi: 0.17	lw: 0.03	sp: 0.14	sigma: 0.029	n: 505
prn 7	ave: -0.410	hi: -0.15	lw: -0.50	sp: 0.35	sigma: 0.060	n: 505
prn 8	ave: -0.324	hi: -0.23	lw: -0.40	sp: 0.16	sigma: 0.031	n: 505
prn 9	ave: 0.047	hi: 0.14	lw: -0.04	sp: 0.18	sigma: 0.035	n: 505
prn 10	ave: -0.588	hi: -0.52	lw: -0.65	sp: 0.13	sigma: 0.026	n: 505
prn 13	ave: 0.459	hi: 0.53	lw: 0.40	sp: 0.14	sigma: 0.029	n: 505
prn 14	ave: 0.057	hi: 0.14	lw: -0.03	sp: 0.17	sigma: 0.030	n: 505
prn 15	ave: -0.407	hi: -0.33	lw: -0.48	sp: 0.14	sigma: 0.028	n: 505
prn 16	ave: -0.290	hi: -0.22	lw: -0.36	sp: 0.14	sigma: 0.029	n: 505
prn 17	ave: -0.372	hi: -0.27	lw: -0.45	sp: 0.18	sigma: 0.037	n: 505
prn 18	ave: -0.038	hi: 0.03	lw: -0.12	sp: 0.15	sigma: 0.032	n: 505
prn 19	ave: 0.051	hi: 0.13	lw: -0.02	sp: 0.15	sigma: 0.032	n: 505
prn 21	ave: -0.171	hi: -0.10	lw: -0.24	sp: 0.14	sigma: 0.028	n: 505
prn 22	ave: -0.510	hi: -0.44	lw: -0.58	sp: 0.14	sigma: 0.029	n: 505
prn 23	ave: -0.206	hi: -0.14	lw: -0.27	sp: 0.13	sigma: 0.030	n: 505
prn #	average	hi value	low value	spread	var. of ave.	numb.
prn 24	ave: 0.034	hi: 0.11	lw: -0.04	sp: 0.15	sigma: 0.029	n: 505
prn 25	ave: 0.176	hi: 0.28	lw: 0.09	sp: 0.19	sigma: 0.038	n: 505
prn 26	ave: 0.342	hi: 0.42	lw: 0.28	sp: 0.14	sigma: 0.027	n: 505
prn 27	ave: -0.067	hi: 0.02	lw: -0.16	sp: 0.17	sigma: 0.036	n: 505
prn 29	ave: 0.227	hi: 0.30	lw: 0.17	sp: 0.13	sigma: 0.029	n: 505
prn 30	ave: 0.470	hi: 0.53	lw: 0.40	sp: 0.14	sigma: 0.028	n: 505
prn 31	ave: -0.255	hi: -0.18	lw: -0.32	sp: 0.14	sigma: 0.029	n: 505

The "sp:" column (spread) is the hi value - low value, or the max variation of the estimates over the 3 week time span. The "sigma:" column is the variation of the estimates, n is the number of hourly solutions. Note prn 7 is again anomalous with the largest variation.

My convention is, to convert P code data to CA code data, subtract the above "ave:" value from range and phase. To convert back, (CA to P code) add the above "ave:" value. The widelane observable of course remains unchanged.

Optimal Geometry of IGS Stations in Eurasia

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We processed by GAMIT/GLOBK all data from permanent GPS stations of IGS since 1992 through March 1999 including the data from stations in eastern Europe and Siberia that we operate since 1996. Some of our stations are in the part of Siberia that belongs to North American plate. We determined poles of rotation of both plates with respect to ITRF-NNR and the relative pole of rotation Eurasia / North America from a set of stations in cratonic interiors of both continents. This pole lies at lat=74.2N ±0.5, lon=115.2E ±1.8, with a rate of rotation ω=0.236 ±0.003. It is about 1000 km to the north of the NUVEL-1A pole, such that the rate of shortening between two plates in east Asia is twice larger than the NUVEL-1A prediction. Residual station velocities with respect to plate prediction, are remarkably similar for both continent: RMS value is about 1.2 mm/year. To check the numerical stability, we investigated the variance-covariance matrix of this Euler vector assuming a uniform standard deviation of ±1 mm/year for N and E components of station velocities. Three geometries of station polyhedron were assumed: uniform coverage of stable Eurasia, stations in Western Europe only, and stations in eastern Europe and stable Asia only. Addition even of 2-3 stations in Asia to the dense western cluster improves the constraint on the Euler pole dramatically, by a factor of 2-3.

We also tested the Euler pole position by using a geometry of stations employed in Larson et al. (1997). We found for that geometry: lat=78.4N ±0.8, lon=111.2E ±5.5, with a rate of rotation ω=0.256 ±0.006. This is reasonably close to our determination for the optimal geometry which was unavailable in 1997. Yet the difference with values published in Larson et al. (1997) is large (lat=68.1N, lon=126.6E). We attribute such deviations to the rapid improvement in the GPS station velocities within the last two years.

Four more permanent stations planned in stable Eurasia for installation in 1999 will significantly improve our understanding of the motion of Eurasian plate because of improved stations geometry. This is clearly demonstrated by covariance matrix.

Report on the Status of the International GLONASS Experiment (IGEX)

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Introduction

In February 1998 the Call for Participation for an international field campaign of GLONASS observations was distributed by the IGEX steering committee (Chair: P.Willis). The 'International GLONASS Experiment' has been proposed as a joint project of :

- the CSTG (International Coordination of Space Techniques for Geodesy and Geodynamics),
- the IGS (International GPS Service),
- the ION (Institute of Navigation) and
- the IERS (International Earth Rotation Service).

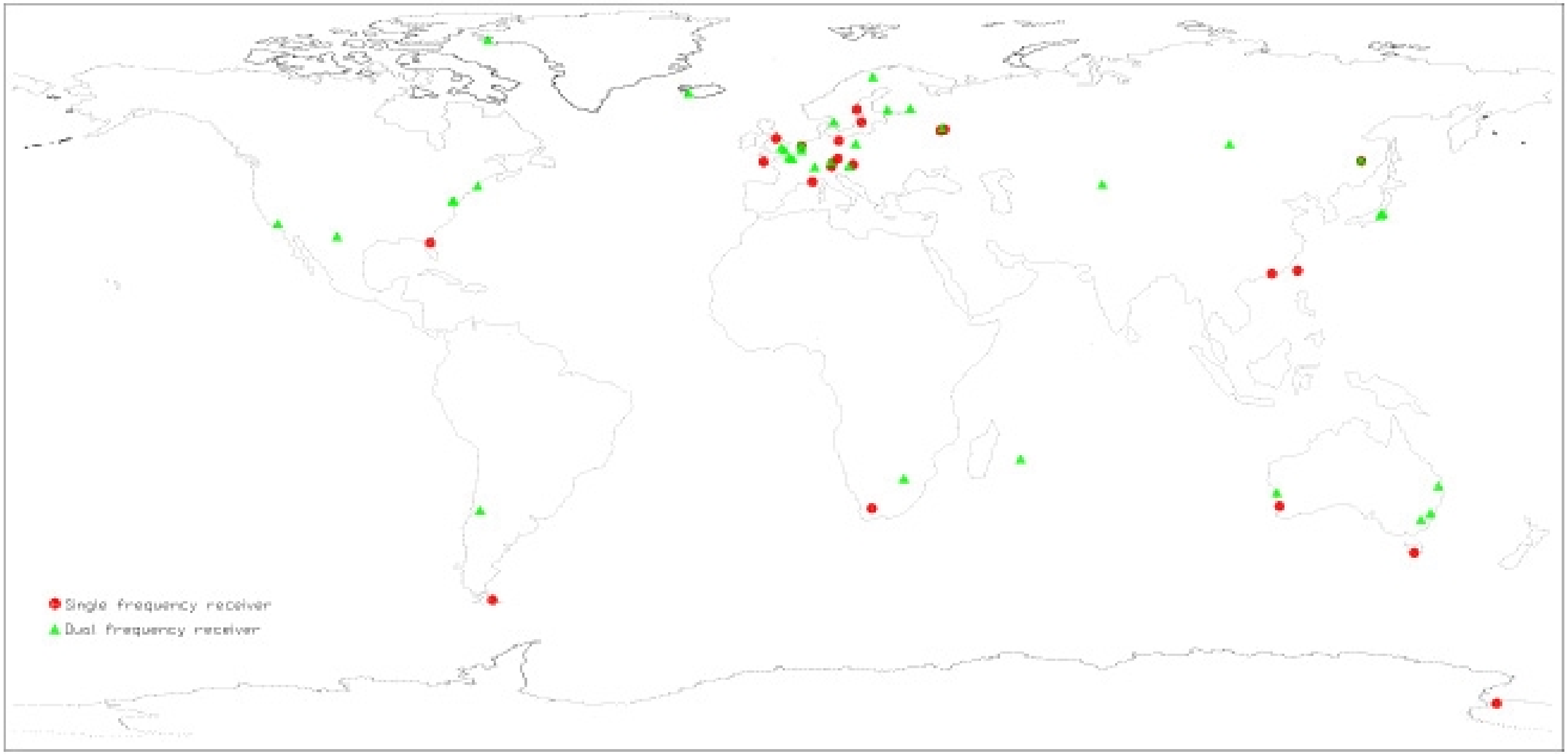
IGEX , basically scheduled as a three months campaign, started in October 1998 and was finally extended until April 1999. The substantial objectives of this project may be summarized as follows:

- to set up a global GLONASS observation network
- to develop and test processing software which enables the combination of GLONASS and GPS data at the observation level
- to estimate GLONASS satellite orbits at the 1 meter level or better
- to determine the time offset between both systems
- to validate the results by means of independent satellite laser ranging observations (ILRS).

International Participation

About 75 organizations, well distributed over the globe, agreed to contribute to IGEX in various areas of responsibility. More than 65 proposals dealt with the installation and operation of permanent tracking sites, comprising slightly more combined dual frequency than single frequency receivers. In the end most of these stations (80%) became operational. Figure 1 shows the status of the IGEX-network on March 24, 1999, just 4 weeks before the end of the official campaign. Of course, the distribution of stations is not really uniform (comparable in number and distribution to the IGS network in 1992) but sufficient to avoid isolated sites.

IGEX-98 Network (Status March 24, 1999)



Two global data centers (CDDIS, IGN) and five regional data center were established to guarantee a smooth data flow. The station representatives were asked to forward IGEX data to the nearest center (according to the data flow diagramm) within 48 hours from the end of the UT-day. These activities were supervised by the IGEX data flow coordinator C. Noll.

An important role for the success of the experiment falls to the Analysis Center (AC) working groups. Eight groups agreed to process the IGEX data and till the end of June 1999 at least six ACs were able to deliver more or less regularly precise GLONASS orbits and station coordinate solutions. The products of BKG (Federal Bureau for Cartography and Geodesy, Germany), CODE (University of Berne, Switzerland), ESA (European Space Operations Center, Germany) and MCC (Mission Control Moscow, Russia) cover the whole duration of the basic Field Experiment. GFZ (Geoforschungszentrum Potsdam, Germany) stopped delivering orbits in GPS Wk 1002, but recently the JPL (Jet Propulsion Laboratory, USA) started calculating ephemeris covering all the weeks in 1999 (since GPS Wk 991). It is worth mentioning that contrary to the remaining centers the MCC solution is solely based on Laser distance measurements.

The AC s base their computation on different basic variables (zero and double differences), different parametrization of the force field and different arc-lengths (3 up to 7 days). Nevertheless, meeting one of the campaign goals, all of them were able to estimate at the start of IGEX GLONASS orbits well below the 1 meter accuracy level. Figure 2 shows the results of a 7-days arc evaluation. Each satellite has been characterized by a state vector and 9 radiation pressure parameters. The stars denote the median value of the coordinate rms calculated from the daily center solutions w.r.t. the long arc.

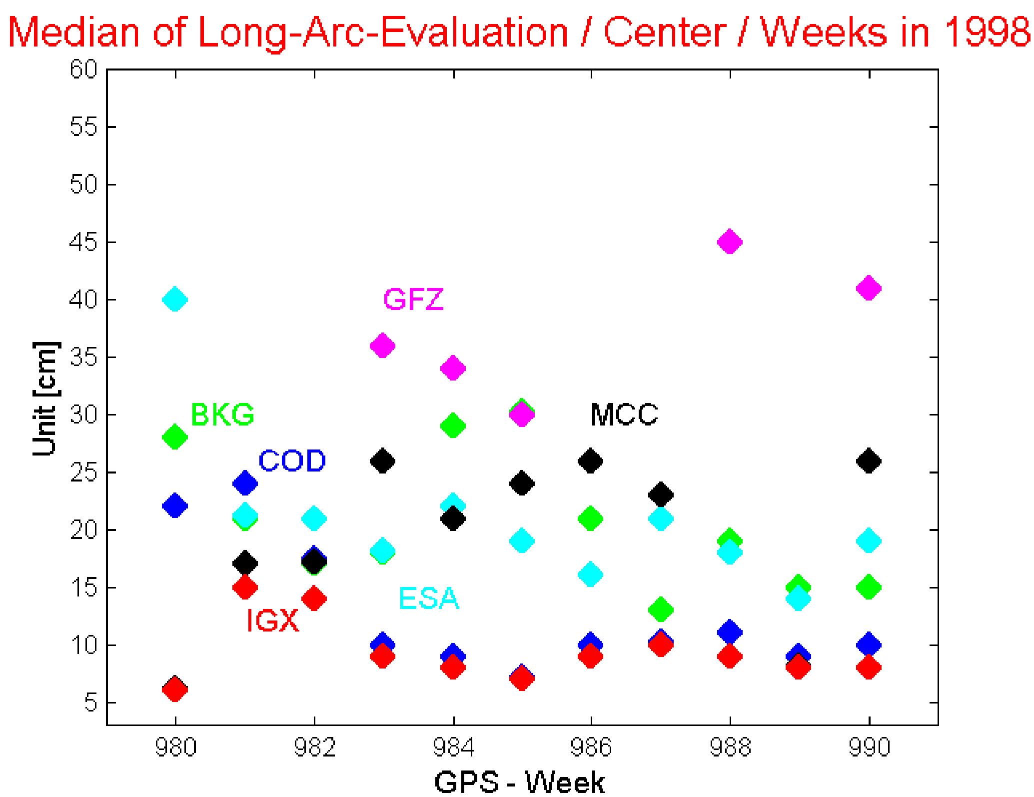


Figure 2

In April 1999 it has been decided to come up, similarly to the GPS orbits, with a combined GLONASS orbit product. The advantage of such a combination is the increased reliability of the orbits and moreover, all satellites included in at least one center solution are considered. This solution, labelled IGX in Figure 2, is calculated from the weighted mean of the center contributions after applying small reference frame corrections. Weights are based on the satellite performance in the long arc evaluation. Contrary to the IGS-GPS combination the satellite clocks given in the IGX SP3 files are broadcast values.

Figure 3 reflects the daily center rms (after a 7 parameter transformation) with respect to the combined orbit over the period of the first 10 weeks of IGEX in 1998.

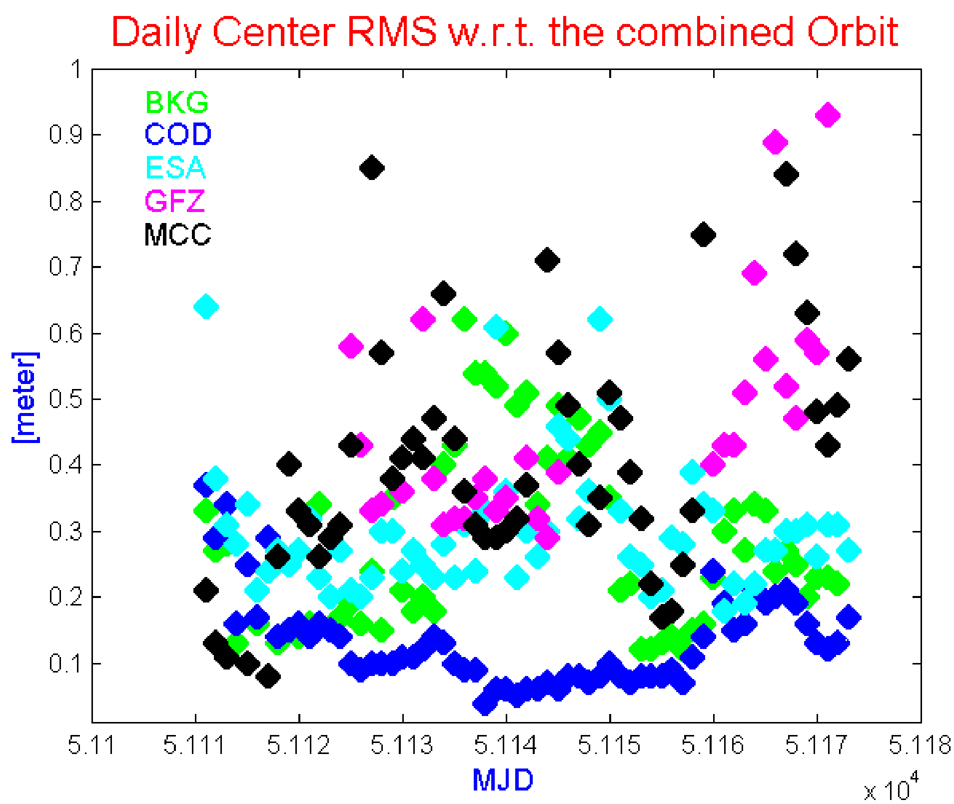


Figure 3

We may summarize, that the IGEX- Analysis Center solutions, comprising precise orbits for 11-15 active GLONASS satellites (note that 3 more satellites have been launched in December 1998) were consistent at the 20-30 cm level. Improvements of that orbit quality as well as studies of systematic differences between mircrowave and laser data are actually hindered due to the low number and spare distribution of tracking sites. The combination strategy will be improved in the very near future essentially to lessen the heavy dependence on the long arc performance (repectively the arc-length in use).

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