IGS

1996 ANALYSIS CENTER WORKSHOP

)-21, 1996

International GPS Service for Geodynamics

Association Internationale de Géodésie

Union Géodésique et Géophysique Internationale

International Association of Geodesy

International Union of Geodesy and Geophysics

IGS Central Bureau

Jet Propulsion Laboratory

California Institute of Technology

Pasadena, California U.S.A.

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ABSTRACT

Components of the IGS — International GPS (Global Positioning System) Service for Geodynamics — have operated a GPS tracking system for several years. The network now contains more than 100 stations and has produced a combined GPS ephemeris that has become the standard for geodesists and geophysicists worldwide. IGS data and products are freely available to all, thanks to the cooperation and participation of all the IGS members. The IGS has initiated development of several new products, and technical issues permitting greater accuracy of IGS products have been identified. The IGS convened a workshop in March 1996 in Silver Spring, Maryland, USA, to coordinate these developments and to examine technical problems and solutions. The following topics were addressed: orbit/clock combination; Earth orientation; antenna calibration; SINEX and densification of the International Terrestrial Reference Frame (ITRF) using the GPS; receiver standards and performance; and atmospheric topics.

ACKNOWLEDGEMENT

This publication was prepared by the Jet Propulsion laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. It contains material from contributors in United States Government agencies, agencies of other governments, and universities.

FOREWORD

Gerald L. Mader
Silver Spring, MD, June 1996

For the past several years, the IGS has operated a global GPS tracking network, now numbering over 100 stations, and has produced a combined GPS ephemeris that has become the standard for geodesists and geophysicists around the world. IGS data and products are easily and freely available to all thanks to the cooperation and participation of all the IGS members.

As a consequence of this success and its acceptance by the scientific community, the IGS has initiated the development of several new products. In addition, technical issues permitting even greater accuracy of IGS products have been identified.

In order to more effectively define and coordinate these developments and to examine in detail technical problems and solutions, the Analysis Centers of the IGS convened a workshop which was held March 19-21, 1996 in Silver Spring, Maryland, USA. The Workshop was hosted by the National Oceanic and Atmospheric Administration (NOAA) and was jointly organized by NOAA and the Geodetic Survey Division, Geomatics Canada.

As these Proceedings demonstrate, there were significant contributions made by the presenters on the primary themes of this workshop. The discussions, which were central to the plan of the workshop, led to numerous specific recommendations which are also documented in these Proceedings.

The workshop's success followed primarily from this balance between presentations and discussions. In most of the sessions, about half the scheduled time was devoted to discussions focused on the specific issues of that session. The physical arrangement of the workshop was designed to encourage these discussions. The participants from the analysis centers and the invited speakers were seated facing each other around a "U-shaped" arrangement of tables. The remaining participants and interested observers, of which there were many, were seated in an audience section of the conference room. This design, which drew an overwhelmingly favorable reaction, contributed to the informal atmosphere and close interaction necessary to productive discussions while allowing a large number of persons to feel involved.

I would like to thank all the session chairpersons for the time and effort that went into organizing their sessions and for preparing their session position papers and summaries. Ruth Neilan and Gerhard Beutler deserve special mention for ensuring that our discussions stayed on track and led to the numerous productive recommendations contained herein. I also want to thank my co-convenor, Jan Kouba, who, while he was unable to attend, was certainly present in spirit and whose energetic contributions to the IGS are an inspiration to us all.

INTRODUCTION

Ruth E. Neilan
IGS Central Bureau,
Jet Propulsion laboratory, California Institute of Technology
Pasadena, California, September 1996

We hope that you find these proceedings from the Silver Spring Analysis Center Workshop a valuable resource within the family of IGS documentation. The meeting hosted by NOAA proved to be very stimulating, and ensuring that these technical developments and directions of the IGS are documented is a key responsibility of the Central Bureau. Certainly the level of editing is less formal than the IGS Annual Report Series, especially this year when the Central Bureau was involved with both documents simultaneously. However, the papers included in these workshop proceedings will be of great benefit to many colleagues, students, and institutions, and so the effort of each contributing author is greatly appreciated.

I would like to especially recognize the efforts of Priscilla Van Scoy at the Central Bureau who assisted in organizing the document and routing it through its various stages to completion. I also want to thank the co-chairs of each session for reviewing and commenting on the document, and with special thanks as well to Gerhard Beutler, Jan Kouba, Gerry Mader, Jim Ray and Tim Springer.

IGS

C O N T E N T S

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Orbit/Clock Combination

GPS Earth Orientation

GPS Antenna Calibration

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Orbit/Clack Combination

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Atmospheric Trends

Other Contributions

EXECUTIVE SUMMARY [†]

G. **Beutler**
Chair, IGS Governing Board

Dear Colleagues,

The 1996 IGS Analysis Center Workshop took place March 19-21, in Silver Spring, MD. Gerry Mader and Jon Kouba, who organized this meeting, arranged it as a real workshop. The setup was perfect to focus the discussion, and I believe that everybody enjoyed a very fruitful three days at the NOAA facilities.

On Friday, 22 March, a business meeting of the IGS Governing Board with the session chairs as guests was organized with the goal to come up with the appropriate action items.

It was a shock for the participants to learn immediately before the start of the workshop that Jan Kouba, IGS Analysis Coordinator, could not attend the workshop due to a very sudden health problem, which virtually immobilized our Coordinator for a week. I am convinced that everybody is relieved to hear now that Jan — according to his own diagnosis — is in perfect shape again, and that he continues his coordinating task far the IGS with the same energy as before.

Let us now try to summarize the sessions and some events of the workshop.

The fallowing topics were addressed, where each topic was introduced by a position paper prepared by the session chairpersons:

- Orbit/Clock Combination — Chair: *Kouba/Beutler*
- Earth Orientation — Chair: Ray/McCarthy
- Antenna Calibration — Chair: *Mader/Rothacher*
- SINEX, Densification of the ITRF using the GPS — Chair: *Blewitt*
- Receiver Stondords and Performance — *Chair: Zumberge/Gurtner*
- Atmospheric Topics — Chair: *Feltens/Gendt*

The position papers were available before the beginning of the workshop. They will serve os a first draft for the session summary, including all recommendations and decisions, which will be included into the workshop proceedings. let me go through the individual sessions now.

Orbit/Clock Combination Chair: *Kouba/Beutler*

Currently the best AC's and the combined IGS solutions are approaching the 5cm(orbits)/0.5ns(clocks) precision level. Combinations, comparisons, evaluations and free exchange of information within the IGS and amongst the IGS AC's are essential to the health and growth of the IGS.

The development of the IGS orbit quality showed that orbit parameterization became an important issue even if the arc length is only one day. The weekly analyses of the IGS coordinator made it also clear that different orbit modeling techniques led to different estimates (or realizations) of the ITRF origin. This is why it was recommended that "all AC's make every effort to align their orbit, station and EOP solution to conform to the ITRF origin. It was shown that this could be effectively achieved by means of stochastic orbit modeling or radiation pressure modeling. "

Recently the ITRF94 was made available by the ITRF section of the IERS (Boucher and Altamimi). It was recommended that the ITRF94 should replace the ITRF93 within the IGS, provided the tests performed by the

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[†] *Distributed as IGS Mail* Message *#1266, dated* March 29, *1996.*

IGS AC's in collaboration with the IERS clearly indicate the superiority of the ITRF94. The IGS AC Coordinator will coordinate these activities with the IERS.

Today all IGS AC's take part in yet another IGS combination, called the "IGS Preliminary orbit/clock combination" which is now approaching a precision of about 10cm/1 ns and is made available with a delay of 38 h only. In order "to economize and to minimize the IGS combination effort and to speed up the delivery of the IGS Final orbits/clocks it is recommended that starting on 30 June, 1996 (day 182, start of GPS week 860) the IGS Final combination be discontinued, the current Rapid IGS combination becomes the IGS Final and the IGS Preliminary (IGP) becomes the IGS Rapid (IGR) combination. This way the most precise Final orbits/clocks will become available within 11 days and the IGS Rapid orbits/clocks will be available within about 1 day." It was moreover decided that the 38h deadline for the (now really) rapid orbit will be replaced by a 23h deadline, allowing it to make available the official IGS Rapid Orbit with a delay of 24h. This is of course only possible if the data are available at the AC's about 6 hours after midnight UT (!). Again these changes shall be implemented on 30 June, 1996.

It became clear at the workshop that there is considerable interest in 1-2 day predicted orbits. This is why IGS Analysis Centers will start producing 1- and 2- day predicted orbits. The interest in predictions became even more apparent at the business meeting, which is why the IGS AC-coordinator will be asked to study options leading to the production of an official IGS predicted orbit.

Mike Watkins from JPL presented a very encouraging agreement of few centimeters of SIR measurements to GPS satellites (PRNs 5 and 6 are equipped with a laser reflector) with distances derived from individual and the combined IGS orbits. He addressed in particular the importance of modeling the actual attitude of the GPS satellites during eclipse phases. It was also agreed that SLR data at present would have little impact on IGS orbits, but that more SLR data would be most desirable for calibration purposes. There were indications that a concentrated and coordinated SLR observation campaign of PRNs 5 and 6 might take place in fall 1996.

Clyde Goad from OSU presented a very elegant and most efficient triple difference algorithm which was successfully used for orbit determination and estimation of erp-series. It was pointed out that the approach is equivalent to o correct double difference scheme (without ambiguity resolution) because mathematical correlations of the triple differences are modeled correctly.

Tim Springer from CODE presented first experiences using the "new" orbit model developed in Bern. There are indications that the model is particularly well suited for orbit predictions.

Earth Orientation Chair: Ray/McCarthy

The session was opened with a review of the method developed and applied by the IGS Analysis Coordinator to produce the combined IGS EOP series. The review was presented by Pierre Tetreault. In the next presentation by Marshall Eubanks we were reminded that the IGS combined EOP series agree very well with the VLBI derived values. Periodic variations seen in the differences "IGS - IERS EOP series" could be attributed to smoothing effects in the IERS series which disappeared after a review of the IERS algorithms to produce the combined series.

Only the x- and y- components of IGS polar motion series have been extensively used by the IERS. The GPS-based length of day (LOD) or UT1 -UTC drift values have not been given much weight by the IERS so far. The presentations by Jim Ray and Daniel Gambis revealed that much more attention is given to that topic now. It became clear that GPS-derived LOD values are biased (because of correlations with the dynamical orbit parameters); it became also clear on the other hand that much very valuable information is contained in the IGS-derived 10D series. We will undoubtedly observe in the future that these IGS products will play a more important role in the determination (and the prediction) of the IERS UT1 -UTC series. This might become true in particular if the correlation between these drift parameters and the (empirical) radiation pressure parameters becomes more clearly understood.

Dennis McCarthy and Tam Herring pointed out that sub-diurnal EOP variations play a crucial role for the EOP series derived by the IGS Analysis Centers. It is true on the one hand that the effects are minimized if constant EOP values are derived for time intervals covering one or several of these periods. But in view of the fact that the amplitudes may reach the 1 mas level, biases of the order of 0.1 -0.3 mas still may remain in such series. Tom Herring also pointed out that such effects are difficult for IGS analysts to see because they maybe absorbed by the estimated radiation pressure parameters. It was argued that the well established diurnal and semi-diurnal terms should be applied by all IGS Analysis Centers.

The oral presentations were concluded by a review of the existing and a preview of the new IERS standards. It was argued that IGS Analysis Centers should follow more closely the IERS standards. If departures from these standards cannot be avoided this fact should emerge from the AC's processing specifications (AC questionnaire).

The recommendations of this session really emerged from the oral presentations: All Analysis Centers are asked to follow the IERS conventions (standards) to the extent possible (something which is facilitated by making available software source code), all AC's are urged to update their AC questionnaire (available at the IGS Central Bureau Information System) at least once per year and the AC coordinator is asked to review these schemes in the IGS annual report. It was further recommended that the general users use the IGS rapid and preliminary polar motion series (in future rapid and final) together with the corresponding final and rapid, resp. IGS orbits. The IERS further asks the IGS Analysis Coordinator to develop a method to combine submitted LOD/UT1 results with the goal to form an official IGS series of such values. The series of recommendations was concluded by the requests to take into account 12h- and 24h- terms in EOP series using the latest tidal model of Richard Ray (to be made available by the IERS) and to document the actual procedures of the AC's (which is of particular importance in this case). Of course such terms have to be taken into account in all transformations between the terrestrial and the celestial frames.

Antenna Calibration *Chair: Mader/Rothacher*

The "state of the ort" in anechoic chamber measurements was introduced by two papers, namely Chuck Meertens from UNAVCO and Bruce Schupler from NASA/GSFC. This underlines the broad interest in absolute precise phase center information. These presentations were complemented by discussions of the "in situ" techniques focusing on the differential antenna behavior (relative to one antenna or one antenna type) by Gerry Mader from NOAA and by Markus Rothacher from CODE.

It became apparent that "in situ" calibrations from different groups are in good agreement and are well suited to correct relative antenna biases. Some inconsistencies still exist, however, between these in situ and the chomber test results. Using the (absolute) chamber test models to correct the phase center of the Dorne-Margolin antennas leads to an unexplained and significant scale bias of about 0.015 ppm in global GPS analyses.

It was therefore recommended to make available to all parties interested the relative antenna phase center models for (if possible) all commercially available geodetic antenna types stemming from in situ measurements. Provided that the final tests performed with this set are successful the IGS Analysis Centers will start using these relative models on 30 June, 1996, at the latest. This will remove obvious discrepancies, e.g., for sites equipped with Trimble antennas, in solutions which did not yet account for such relative models. The amount of work invested by all involved parties is amazing, and it was acknowledged that all efforts are necessary to come to a satisfactory model, eventually.

It was acknowledged that the scale effect resulting from the use of absolute chamber tests needs to be directly addressed in the future.

SINEX, Densification of the ITRF *Chair: Blewitt*

We are now in the middle of the IGS pilot project "densification of the ITRF through regional GPS networks."

In September 1995 the IGS AC's started submitting to the global dato centers so-called free network solutions in a still experimental version of the SINEX format (Software Independent EXchange format). Today such series are available from all seven AC's. Three institutions (JPL, MIT, University of Newcastle) are analyzing and combining these weekly products. The procedures of each of the centers were presented and discussed in the session. It became obvious that the philosophy and the actual procedures were quite different. The "final" products, on the other hand, agree amazingly well. Is this possibly a consequence of the Central limit Theorem formulated by C.F. Gauss? The consequence of these weekly analyses is remarkable: a consistent set of coordinates (referring to the ITRF) far all the sites analyzed by at least one AC are openly available! It is generally expected that these activities will make the updating of the ITRF (GPS part) much easier.

In any case one could draw the conclusion that this first phase of the pilot project was quite successful. The second phase, where the products of regional Associate Analysis Centers will be included into these weekly comparisons, too, is scheduled to start on 30 June, 1996. It was initiated by the call for participation in January 1996. The proposals are now evaluated; the "new players" will be introduced by IGS mail soan.

It also became clear that there was too much flexibility in the SINEX format in the past. A working group is now revising the SINEX format with the goal to have the weekly AC and AAC contributions transmitted in the SINEX Version 1.0, starting 30 June, 1996. The AC coordinator is responsible for finalizing this version, of course in close contact with the AC's and the new associates!

All recommendations of this session were related to the SINEX format; most of them were very technical in nature. There was, however, the recommendation to include the EOP information into the SINEX file which will require some additional thought. In view of the variety of methods used by the AC's to implement a priori information and to parametrize the EOP series, the implementation seems to be non-trivial at first sight. There is little doubt, on the other hand, that the AC coordinator in collaboration with the AC's will come up with a solution that makes sense. It was the general understanding that the inclusion of this information shall NOT serve the generation of a "new" IGS polar motion series, but allow it to remove reference frame inconsistencies between solutions in a more rigorous way.

Receiver Standards and Performance *Chair:* Zumberge/Gurtner

The network performance and in particular data latency were reviewed by Werner Gurtner and Jim Zumberge. These analyses were based on statistics routinely made at the global data centers and at some of the AC's. The result was encouraging in the sense that with a "minor" organizational effort, it actually should be possible to make the observations (at least of a sub-net) available to the AC's early in the morning (UT) which actually would allow them to turn out rapid products within 24h.

Data quality was not well monitored so far within the network. The goal, to my understanding, is to have a short information concerning quality available together with the RINEX data files coming in. Such tools are prepared right now.

A very interesting and (at least for me) surprising presentation was given by Dr. Hatanaka from the Geographical Survey Institute (GSI) of Japan. He presented an algorithm (based on forming differences of the observable) allowing it to compress the data before transmission by about a factor of 2.4 (in addition to the compression that is already used today). First experience with the algorithm made by some of the IGS components is positive.

The following recommendations concluded the session:

A set of stations will be identified by the Central Bureau together with the AC Coordinator and the AC's for which data have to be available at the AC's at 6 a.m. UT. This implies that the data must be available at all Global Data Centers before 5 a.m. UT. Obviously such stations have to be operated in a fully automatic way. Data of sites which are used for the final products must be made available to the AC's within 48 hours.

Should this step be successful, we would undoubtedly see the (currently rapid, but future) final IGS orbits and EOPS with a delay of much less than the 11 days guaranteed so for.

The Central Bureau prepares procedures for the "Hatanaka compression" to be made available for extensive tests.

The need for improved mechanisms for problem detection and reporting was clearly seen by the network specialists. A routine monitoring of the entire network must be put in place by the CB. It was also requested that not only negative, but also positive feedback should flow back to operating agencies.

Atmospheric Topics *Chair: Gendt/Feltens*

The issue of using the IGS network for modeling the troposphere and the ionosphere was first addressed within the IGS at the 1995 Potsdam Workshop. Meanwhile a brood discussion of this topic inside and outside the IGS was taking place. It becomes clear by now that the IGS actually must play an active role in these fields.

Troposphere aspects were first looked at from the user's point of view: Eugenia Kalnay from the USA National Centers for Environmental Prediction was particularly interested in data stemming from satellites of the type GPS-MET. It seems clear that temperature profiles with a high spatial density are of greatest use in meteorology y.

The IGS is not actively involved in the GPS-MET experiment, at present. It may make available total tropospheric delays which, if accompanied by high accuracy barometer and temperature measurements, may be transformed into the "total precipitable water content. " The IGS network and the IGS Analysis Centers have the potential to make available such information with a high temporal and spatial resolution (of its tracking network) on a routine basis to the atmospheric physicists. Many are convinced that such time series are relevant for climatological purposes, and, if indeed rapid orbits of the "new kind" (see above) become routinely available, for weather prediction.

That the IGS is "in principle" ready for such a development was one conclusion from Neil Weston's presentation about the CORS network. MET doto ore transmitted in near real time for selected sites within this US-wide GPS network; the MET data are processed together with the receivers' code and phase observations to generate the information required by the meteorologists. A presentation prepared by Rocken (and presented by Meertens) demonstrated how well GPS-derived water contents agree with WVR results; Gerd Gendt's analysis showed that the tropospheric delays as derived by different IGS AC's are consistent on the level of a few millimeters now. That the issue of weother prediction is taken seriously by IGS AC's was underlined by presentations from JPL (Bar Sever discussing methods to use predicted orbits for meteorological studies) and S10 (Fang presenting methods for near real time meteorology and crustal deformation using GPS).

It was recommended that MET stations of a defined high quality should be deployed — at least in a part of the IGS network. MET information already available at the stations or becoming available in the near future shall be sent routinely in MET RINEX files to the IGS dota centers, where they will be available for scientific purpose, Steps leading to the deployment of the appropriate MET equipment will be taken before the end of 1996.

It was also recommended that IGS tropospheric delay estimates should be studied and combined by special Associate Analysis Centers. GFZ is ready to build up such a center (hopefully) by the end of 1996. Other parties will be invited through a call far participation.

Ionosphere models using data from the IGS network were developed by Schaer et al. from CODE, by Wilson et al. from JPL, by Feltens et al. from ESA, by Komjathi et al. from University of New Brunswick, and by Jakowski et al. from DIR Neustrelitz. A data set of five weeks of the year 1995 was used (and is still used) by the "ionosphere groups." It became clear that different groups have different goals in mind: pure GPS-internal use (to correct, e.g., single frequency data or to help ambiguity resolution) is one goal, calibration of altimetry data another, pure ionosphere research a third goal. Methods and models are very different, too. It seems, however, that we are now reaching a state where the models of different groups maybe effectively compared.

Such comparisons were presented by the ESA- and the Neustrelitz- groups using a two-dimensional grid in the single layer electron shell. I personally believe that the level of agreement [few TECUs) and not (yet) unexplained biases are amazing. It is fair on the other hand to state that we are still far from the consistency level we have reached, e.g., in modeling the troposphere. Consequently the recommendations are more modest for the near future: In a first step the analyses of the 5-week event and the comparisons emerging from it will be concluded. In a next step a common format for the exchange of ionosphere models is created. A first draft for this format, with the tentative name IONEX, will be available soon. Only in the more distant future (one year from now?) a pre-operational production of IGS ionosphere products is envisaged.

Final Remarks

Although the above summary is rather long it can only give an incomplete picture of the workshop. It was a meeting deserving the name (label) workshop and I have no doubt that important decisions and new directions were the direct result of the considerable amount of work invested in the preparation of this workshop. let me therefore thank all the contributors to this workshop, and let me congratulate Gerry Mader and Jan Kouba for the organization of this fine IGS event.

A G E N D A

IGS Analysis Center Workshop

A Workshop
Sponsored by

National Oceanic and **Atmospheric** *Administration*

19-21 March **1996**
Silver Spring, Maryland **USA**

Tuesday Morning, 19 March

08:00–08:30		**Opening Activities/Welcome**	

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Orbit/Clock Combination, Modeling & Discussion
Session Choirs: G. *Beutler & J. Kouba*

08:30	**M. Wotkins**	GPS/SLR **Orbit Comparisons: Two GPS SVS** (PRN **5** & **7) ore equipped with SIR reflectors ond hove been observed by** several SLR stations **for** several **yeors. Comparisons done routinely** at JPL, apart **from** JPL **orbits** olso **include the IGS and other AC orbit solutions. These comparisons provide onother, truly independent check ond** quality **testing for the GPS orbits. They** olso indicate **ond confirm peculiarities of some AC solutions in** regard **to the origin ond orientation, in** particular.
08:50		**Discussion**
08:55	**C. Good**	**A Triple Difference Approoch to** Global **GPS** Analysis: **Triple** differencing **when used properly, i.e. with the corresponding** var-cov. **motrix (due to the triple** differencing), **produces identical results to the corresponding undifferenced ond double difference** traditional approaches. **The triple** differencing **hos significant** advantages **in doto editing ond intuitive** under-standing **of the significance of** ambiguity **fixing in** global **GPS** analysis.
09:15		**Discussion**
09:20	**T. Springer** **E.** Brockmann M. Rothacher **G.** Beutler	**Towords a New Orbit Model: From 1992 until 1995 the orbit models as used by individual** IGS **AC's evolved considerably. Todoy o number of "different" models ore** actually **in use,** ranging **from purely deterministic to stochastic models in the** Kalman **filter sense; they include** empirical **force models os they underlie, e.g., the** "long-arc **analysis" performed weekly by the IGS** analysis **coordinator. The models ore critically reviewed; the** impact **on non-orbit pyrometers (e.g.** LOD) **is studied. The contribution is** meant **to** stimulate **the discussion which eventually might** lead **to new** "standards" **for the** modelling **of individual AC ond IGS orbits.**
09:40		**Discussion**
09:45	**J. Koubo** **G.** Beutler **Y.** Mireault	**Position Poper Summery ond Discussion Points: Mony** important **issues need to be roised, discussed ond opprooches ogreed on: for** example **the** useful-**ness ond necessity of the** IGS Final **combination (when IGS preliminary** (24-**36h) and IGS Ropid** (**1 doy** delay)) **ore** operational **ond in place. A com-plete review of reference frome** realization **for IGS, the smell incompatibilities [e.g., in origin ond orientation), solutions reporting,** formats, **harmonizing SINEX ond IGS** orbits/EOP, **etc.**
10:05		**BREAK**

10:30		General Discussion of Orbit/Clock Modeling & IGS Combination Issues, Recommendations, Resolutions, etc.
12:00		End of Session

Tuesday Afternoon, 19 March

GPS Earth Orientation, Combinations & Discussion

Session Choirs: J. Roy & D. McCarthy

13:00	J. Kouba	IGS Combination of GPS EOP Results
13:20		Discussion
13:30	M. Eubonks	Comparison of GPS ond VLBI Polar Motion with AAM
13:50		Discussion
14:00	J. Ray	Comparison of GPS and VLBI 10D Results
14:20		Discussion
14:30	D. Gombis	Multi-technique EOP Combinations by the IERS
14:50		Discussion
15:00		BREAK
15:30	D. McCarthy	Daily/Semi-daily EOP Voriotions ond Time Stoles
15:50		Discussion
16:00	T. Herring	Consequences of Subdoily EOPS for GPS Orbits
16:20		Discussion
16:30	D. McCarthy	New IERS Standards & Conventions
16:50		Discussion
17:00		General Discussion of EOP Issues, Recommendations, Resolutions, etc.
17:30		End of Session
17:30		Open Discussion on Extended, Continuous VLBI Compoign
19:00-21:00		Analysis Center Poster Presentations & Reception Holidoy Inn

Wednesday Morning, 20 March

GPS Antenna Calibration & Discussion

Session Choirs: G. Mader & M. Rothacher

08:30	C. Meertens C. Rocken	Anechoic Chamber Measurements by UNAVCO
08:50	T. Clerk B. Schupler	Anechoic Chomber Measurements by NASA/GSFC
09:10	M. Rothacher	In Situ Antenno Measurements by AIUB
09:30	G. Moder	In Situ Antenna Measurements by NOAA

09:50	J. Johannson	IAG Special Study Group on GPS Antennas
10:00		BREAK
10:30		Discussion: Anechoic Chamber Measurements Field Measurements Phose Centers Standard Antenno Tables for IGS

Wednesday Afternoon, 20 March

SINEX & Discussion

Session Choirs: G. *Blewitt* & *Y.* Bock

13:00	G. Blewitt	Pilot Project, Densification, SINEX Documentation
14:00	G. Blewitt M. Watkins T. Herring	Global Network Associate Analysis Center - Discussion
	R. Ferland	SINEX Document
15:00	V. Hotanaka	RINEX Compression Algorithm
15:30		Discussion

Receiver Standards and Performance

Session Chairs: *J.* Zumberge & W. *Gurtner*

16:00	J. Zumberge	Review of Data latency and Quality
16:10		Other Speakers and Discussion
16:40	W. Gurtner	Review of Documented (IGS Mail) Receiver Problems
16:50		AC Concerns (1 Overheod per AC)
17:10–17:30		Other Speokers ond Discussion
19:00		Workshop Dinner - Holiday Inn

Thursday Morning, 21 March

Atmospheric Topics

Session Chairs: G. *Gendt* & *J. Feltens*

Part 1 — Troposphere

08:30	S. lord	The USA National Centers for Environmental Prediction Operational Atmospheric Data Assimilation System and Prospects for Usage of GPS Data
08:45	N. Weston	The NGS Continuously Operating Reference Station (CORS) Network
08:55	C. Rocken T. VonHove F. Solheim C. Alber R. Wore C. Meertens	Near-Real-Time Estimation of Atmospheric Water Vapor from GPS

09:05	P. Fang Y. Bock	Rapid GPS Meteorology for Weother Forecasting and Crustal Deformation
09:15	Y. Bar-Sever	Strategies for Near Real Time Estimation of PWV
09:25	G. Gendt	Comparison of IGS Troposphere Estimations
09:35		Discussion
10:00		BREAK

Part II — Ionosphere

10:30	S. Schaer G. Beutler M. Rothacher (presented by M. Rothacher)	Daily Global Ionosphere Mops Based on GPS Carrier Phase Data Routinely Produced by the CODE Analysis Center
10:45	A. Komjathy R. Langley (presented by A. Komjathy)	An Improved Algorithm for High Precision Ionospheric Modelling
11:00	B. Wilson A. Mannucci D. Yuan M. Reyes (presented by B. Wilson)	Global Ionospheric Mapping: Validation ond Preliminary Comparisons
11:15	G. Hajj et 01. [invited paper) (presented on behalf of G. Hajj by B. Wilson)	Ionospheric Profiling Using GPS/MET Dots
11:30	J. Feltens J. Dow T. Mortin-Mur C. Garcia-Martinez (presented by J. Feltens)	Verification of ESOC Ionosphere Modeling ond Status of IGS Intercomparison Activity
11:45		Discussions

[N. Jakowski ond E. Sardon: "Comparison of GPS-Derived TEC Values from Several Groups with Other Ionospheric Probing Techniques." No oral presentation-paper will be delivered for the proceedings only.]

Thursday Afternoon, 21 March

13:00–15:30	J. Dow P. Fang	Contributed Papers Issues Not Covered in Workshop Prospective Topics for Next Workshop
16:00–17:00	G. Mader J. Kouba	Wrap Up: Session Summaries Action Items Recommendotians

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SUMMARY RECOMMENDATIONS

Silver Spring Workshop
March 1996

A) Orbits

1. **All AC's make every effort to align their orbit, station and EOP solution to conform to the ITRF origin. It was shown to be effectively achieved by means of stochastic orbit or R_p modeling.**

2. **The ITRF94 (PO 1) coordinates of the 13 ITRF stations ore used for the IGS realization of ITRF starting on June 30, 1996 (Wk 0860).**

3. **To economize and to minimize the IGS combination effort and to speed up the delivery of the IGS Final orbits/clocks, it is recommended that starting on June 30, 1996 (Wk 0860), the IGS Final combination be discontinued, the current Rapid IGS combination become the IGS Final and the IGS Preliminary (IGP) become the IGS Rapid (IGR) combination. This way the most precise Final orbits/clocks will become available within 11 days, and the IGS Rapid orbits/clocks will be available within about 1 day.**

4. **Timely data delivery is crucial for rapid and precise IGS products, so it is requested that IGS data delivery deadlines be more effectively observed, in particular for a number of selected global stations. For these stations an 8 hour (maximum) delay could be acceptable, providing that IGS global data center equalization does not add more than 2 hours. (See recommendation E. I.)**

5. **It is recommended that the current submission deadline of 36h for IGP be shortened to 23h (after the last observation), starting on June 30, 1996 (Wk 0860). If all the participating AC solutions have orrived prior to this deadline, the IGS combination is to be completed within an hour after the last submission. (Dependent on A.4 & E. I.)**

B) Earth Orientation Parameters

1. **IERS Conventions Adopted for General Use**

   To ensure the highest degree of compatibility of results from the individual Analysis Centers and with other techniques, it is recommended that all IGS Analysis Centers incorporate the IERS Conventions (Standards) into their data analysis procedures to the greatest extent possible.

   Whenever departures from the IERS Conventions are deemed necessary, Analysis Centers are encouraged to document the alternative procedures in their reports to the IGS, IERS, and in updated AC Questionnaires. The new version of the IERS Conventions will be available in printed form by late spring 1996. Some parts will be available sooner as source code.

2. **Reporting IGS Analysis Center Models and Methods**

   To ensure the highest quality of results from the IGS combinations and to avoid misunderstandings, it is essential that the models and methods used by the Analysis Centers be fully understood by the users. It is particularly important that departures from the IGS and IERS Standards and Conventions be noted. Therefore, it is recommended that all IGS Analysis Centers provide updated versions of their AC Questionnaire at least once per year and every time that significant changes are made.

   The Analysis Center Coordinator will review the scope of the current Questionnaire, making suitable revisions, and will provide a standard format at the IGS Central Bureau. New responses should be filed by all Analysis Centers by July 1, 1996.

3. **IGS Combination of GPS Polar Motion Results**

   Based on the demonstrated high quality of the weighting methods used by the IGS for its polar motion combination, it is recommended that outside users of GPS polar motion results use the IGS Rapid combination polar motion values.

For those applications requiring more rapid turnaround, it is recommended that the IGS Preliminary combination values be used.

Given the high quality of current polar motion estimates from GPS and considering the potential value for excitation studies, Analysis Centers are encouraged to include and report polar motion rate parameters in their data analyses, in addition to polar motion offset parameters.

4. IGS Combination of GPS LOD/UT1 Results

For near real time applications, where the only UT 1 information available is from predictions, it is recommended that the IGS Analysis Center Coordinator devise a method to combine submitted LOD/UT1 results from the GPS Analysis Centers to form a preliminary UT 1 -UTC estimate.

This new UT1 combination will be used to align the IGS Preliminary orbits rather than IERS Bulletin A predictions. Because the GPS LOD/UT1 errors do not seem to be related to the satellite orbit errors in a simple way, a new method is needed far the combination, different from that used for polar motion. The Analysis Center Coordinator will fully document the UT1 combination procedure adopted.

5. Modelling Sub-daily EOP Variations

To account for variations in Earth orientation at nearly 24-h and 12-h periods, it is recommended that the IGS Analysis Centers follow the IERS Conventions and account for these effects in modelling GPS observable using the tidal model of Richard Ray.

This model should be used in the transformation between inertial and Earth-fixed coordinates (and vice versa) for all transformations used in GPS processing. Specifically, the diurnal and semi-diurnal terms need to be included in the transformation of the inertial GPS orbits into the Earth-fixed frame for submission to the IGS.

About 50% of the errors in this adopted model will "project" into the inertial orbits, and of course the total error will be in the transformation from inertial into Earth-fixed coordinates. The one issue still to be addressed is: do these contributions tend to cancel each other or do they add constructively?

6. Reporting EOP Values

With respect to diurnal and semi-diurnal variations, it is recommended that when Earth orientation parameters are estimated, the procedures for reporting EOP values adhere to the IERS Conventions and guidelines, which are still to be determined. In particular, users must know how to relate the reported EOP values to the corresponding total values (including all tidal contributions] at the associated UTC epoch.

The relationship between reported EOP values and the corresponding total EOP values should be explained in the Analysis Center Questionnaire.

C) **Antenna** Sessions

1. Two sets of phase calibration corrections (PCC) Tables are put together by a small group (Mader, Meertens, Rothacher) to be used by the IGS and by IGS users:

   a) A set of "mean" phase center offsets for 15 and/or 20 degrees cut-off.

   b) A set of elevationdependent PCC and offsets relative to the Dome Margolin T Antenna.

2. After checks (e.g., UNAVCO, MIT,...) the correction tables are made available at the CBIS tagether with an official SINEX name.

3. IGS AC's and Regional AC's start using the official PCC tables on July 1, 1996.

4. Different antenna types have to be uniquely identified (model & serial numbers).

D) **Pilot Densification Project & SINEX**

1. AC's strive to correct SINEX discrepancies, as reported by AAC's as soon os possible.

2. SINEX version 1.00 to be adopted as the first official release version with format description to be made available at IGSCB.

3. AC's and AAC's adopt SINEX v. 1.00 (see Appendix 1) by June 30, 1996.

4. IGS request SSG 1.156 to study the use of IGS products and to report back with recommended usage for high precision regional analysis. Blewitt (President of SSG1 . 156) will provide initial instructions on use immediately.

5. AC's strive for a wide global distribution of stations: New stations which improve coverage should be given preference to existing stations in dense regions.

6. AC's should include Earth rotation parameters in their weekly SINEX files. The AC Coordinator will work with the AC's to ensure that each AC produces compatible sets of parameters. Combine station & EOP parameters in consistent fashion.

7. AC's should strive to ensure that information in the SINEX file and information used in the analysis come from the same source.

E) Network

1. Data of sites for rapid orbits available at all AC's at 06:00 UT.
   Available at all Global Data Centers (GDC) before 05:00 UT.

2. Data of sites for final products available at all AC's within 48 hours

3. CB (+ ACS) prepares:
   a) List of "6^h-sites," data available within 6 hours
   b) list of "48^h-sites."

4. OC'S and DC's improve data flow to meet deadlines.

5. CB prepares procedures for the "Hatanaka" - compression to be made available for extensive tests.

6. Need improved mechanisms for problem detection and reporting.

7. Routine network monitoring by CB
   a) Feedback to stations.

F) Atmospheric

1. The IGS-sites are asked to install MET-Stations with the below given characteristics until the end of 1996. The meteorological data (reduced to the GPS-antenna location, RINEX format) should be sent simultaneously with the RINEX observations to the Global Data Centers. In a pilot phase, o time delay of a few days is acceptable for the Met RINEX files.

   Proposed characteristics of the MET-Stations:

Pressure:	$\leq$0.5 mbar, very stable $\leq$0.5 mbar throughout 2 years
Temperature:	$\leq$0.5 K
Humidity:	$\leq$10%
Sampling rate:	<10 minutes

2. Climate Research

Starting by the end of 1996, the Analysis Centers compute series of total zenith path delay (ZPD) with o default sampling rote of minimum 2 hours. (Data intervals starting at 00:00 GPS-time.)

An associate IGS processing center combines the individual time series of delay to an IGS Mean series of ZPD and converts the delays to estimates of precipitable water vapor (PWV). By the end of 1996 GFZ will be ready to act as an associate processing center. Other agencies will be invited through a call of participation.

Formats for exchange and distribution of results should be defined. For the exchange between the AC's and the associate processing center, the SINEX format, and for distribution of results the RINEX format, should be used. Necessary extensions or modification of both formats must be discussed.

3. Weather Forecasting

The contribution of IGS to the weather forecast will be restricted by orbit computation, rapid orbits with 23-hour delay and predicted orbits.

If data from the IGS network are needed, the analysis centers engaged in weather forecast should make bilateral agreements for nearly real-time data transfer with tracking sites of interest.

G) Ionospheric

1. Complete the 5 weeks comparison in process.
2. Agree on common standards, e.g., on format (IONEX). Working group established.
3. Continue e-mail discussion of results and agree on future work.
4. Prepare a pilot phase in which ionosphere products should be computed, compared and checked under pre-operational conditions.

H) Other

The IGS Stations that use external frequency standards (especially MASERS) need information on frequency standard performance and Epoch timing derived by IGS. AC's are requested to transmit such data obtained from routine analysis to the stations and groups responsible for the operation of the frequency standards.

The IGSCB begin to develop a database for monumentation details and local surveys (geophysical and geodetic) at IGS sites, in order to (i) allow AC's and AAC'S to make a more informed choice of sites, and (ii) provide geophysicists/geodesists with data to enhance interpretation of results.

1) Recommended Topics for the Next Workshop

Calibration of IGS orbits using SLR (Denser Tracking, Different Software...)

New Analysis Methods

Parameterizations of Orbit Model

LOD/UT1 from GPS

Experience with Sub-Daily Tidal Model of EOP'S

New IERS 1996 Standards

Phase Centre Correction Models (+GPS Spacecraft ??)

longer Term Global SINEX Analysis

Regional SINEX Analysis

Near Real Time Orbits and Supporting Data Flow

Monuments/Stability

Possible Role of GLONASS in IGS

Troposphere

Ionosphere

Spaceborne Arrays

ORBIT/CLOCK COMBINATION

GPS ORBIT/CLOCK COMBINATIONS AND MODELING

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INTRODUCTION

Since October 1993 a close and productive cooperation between the seven IGS Analysis Centers (ACs) resulted in an unprecedented increase of precision, reliability and the delivery speed of individual AC and combined IGS orbit/clock solutions. Currently the AC and IGS solutions approaching the 5cm(orbits)/0.5 ns(clocks) precision are available within hours or days after observations rather than weeks or months. Combinations, comparisons, evaluations and exchange of information within the IGS are essential to continuous improvements of the service. The recent precision advances are mainly due to (a) modeling and analysis innovations and (b) better global deployment of receivers rather than instrumentation improvements as was the case during the initial stages of IGS. The modeling advances and innovations have been brought about by the AC cooperation and competition. With increasing solution precision and processing speed more emphasis should be put on analysis of possible solution biases to increase accuracy. The focus should be on multi-technique comparisons and analyses as individual, single technique solutions for station positions, velocities and EOP are susceptible to systematic effects.

The main focus of this position paper is to suggest ways how to increase precision, accuracy and efficiency of the IGS data processing and products. Antenna, tropospheric and ionospheric (error) modeling are not dealt with here as they are addressed in other sessions of this workshop.

ORBIT AND ERROR MODELING

Global GPS analyses effectively “absorb” some systematic effects. In particular solution parameters pertaining to solar radiation pressure and initial phase ambiguities can effectively either absorb or produce systematic biases. For example, a small constant change of a few cm in all satellite or receiver antenna offsets is effectively absorbed, with no effect on the solution scale or height.

The IGS combination/evaluation detects small orientation and origin differences for individual AC solutions. For example, a y-coordinate shift of about 5cm, noticed for JPL solutions at the end of 1994 (GPS Week 770), was later confirmed to be real and in fact aligned the JPL solutions closer to the real (ITRF) geocenter (Figure 1). This alignment also resulted in a better statistics in the IGS long-arc analyses and GPS-SLR comparisons (Watkins, 1996).

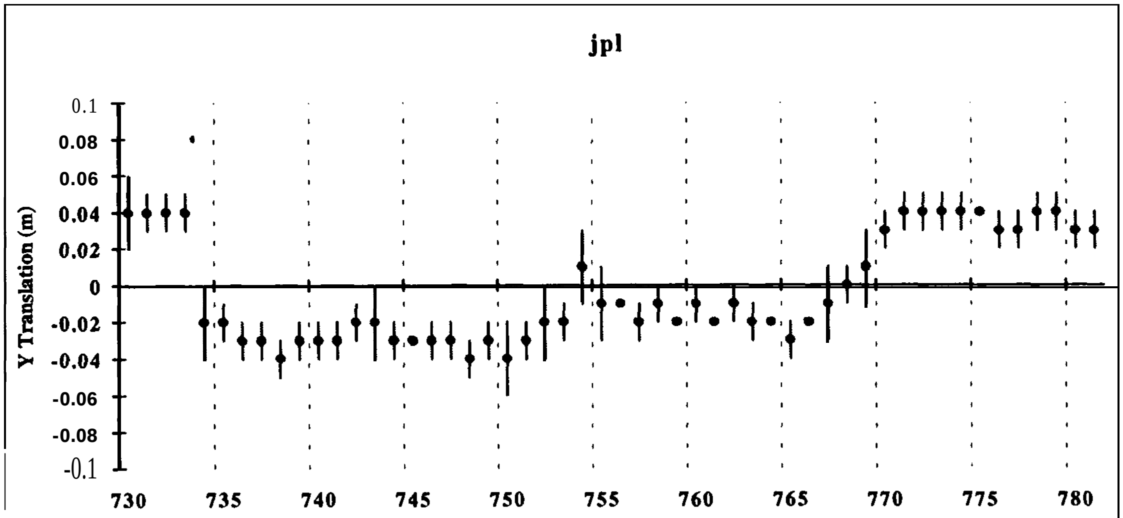

Figure 1. JPL 1994 Weekly Mean Y translations (meters) from IGS Final Orbits. For more details see the 1994 IGS Annual Report (Zumberge et al., 1995).

Subsequently, two additional ACS followed JPL and aligned their solutions with the geocenter, namely CODE in June 1995 by introducing small stochastic velocity changes once per revolution and S10 in November 1995 by introducing independent Rp scales for each revolution. Although the stochastic orbit/Rp modeling can effectively remove the coordinate origin bias, the cause may be different, e.g. a regionally biased tropospheric modeling and/or an unsuitable station distribution. The effect on unconstrained station solutions is even more pronounced: (a) y-coordinate shifts of up to 15cm have been detected in the weekly GNAAC (Global Network Associate AC) SINEX analyses, (b) a y-pole misalignment of about 0.5 mas has been also detected. Considering that these effects are almost an order of magnitude larger than the respective formal errors, and could bias combination solutions, it is strongly recommended that:

RECOMMENDATION # 1:
"All ACS make every effort to align their orbit, station and EOP solution to conform with the ITRF origin. It has been shown to be effectively achieved by means of stochastic orbit or Rp modeling. "

Furthermore, the most significant precision/accuracy improvements are likely to be achieved by processing longer arcs than the current 1 to 3 days. This will only be possible with either improved or stochastic models, for radiation pressure in particular. Increased research effort in this direction is strongly recommended.

It must be pointed out that each change in the "dynamical modeling" has implications on the estimation of the parameters defining the "change" of the reference frame during the time interval of the arc. Such parameters are UT1 -UTC drifts (or length of day), drifts in the nutation in obliquity and elliptical longitude. These aspects have to be carefully studied before any changes of the dynamical orbit models. For more information we refer to Rothacher et al. (1996) and Springer et al. (1996).

ITRF REALIZATION

Ideally an unbiased IGS combination solution for station coordinates, properly aligned with ITRF and spanning at least one year should be used as the day to day ITRF reference for the IGS data processing. In the past two years all IGS ACS have been fixing or tightly constraining the same 13 station ITRF92 or ITRF93 coordinates. This has the advantage of clear ties to ITRF which incorporates contributions by other space techniques, but it introduced discontinuities and may have caused distortions due to small GPS/ITRF inconsistencies and errors. An alternative, consistent but potentially biased realization might be achieved by selecting a combined GPS/IGS solution properly oriented and positioned with respect to the official ITRF.

Both approaches should converge with decreasing GPS biases and increasing ITRF accuracy. For the time being a compromise approach is to constrain rather than fix ITRF coordinates according to their estimated ITRF sigmas. For example, constraining the ITRF93 to 20 mm (1 sigma) produces virtually no relative position inconsistencies with respect to the corresponding free GPS solutions (note that unconstrained GPS solutions are not necessarily unbiased !). Considering that ITRF94 coordinates for the 13 stations have significantly improved while showing more realistic, larger formal errors, both approaches to ITRF realizations are expected" to produce similar results. Figure 2 and Table 1 compare the ITRF94 solutions (P01 in Figure 1 and PO1, P02, P03 in Table 2) to a 16 week average of the MIT SINEX weekly station combinations (MIT95P01(SNX)):

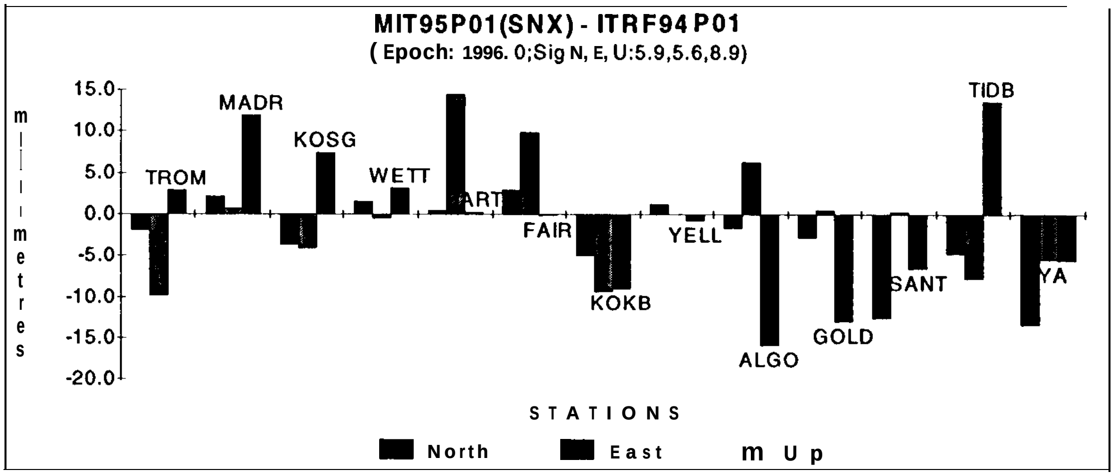

Figure 2. POSITION DIFFERENCES FOR THE 13 ITRF STATIONS USED BY IGS FOR ITRF REALIZATION

Table 1. ITRF94 PO1 ,P02,P03 coordinate differences (after a 7 parameter transformation) for the 13 ITRF stations used by IGS for ITRF realization. (Epoch 1996.0; PO1 - ALL techniques+ GPS(COD,EMR,JPL); P02 - GPS(COD,EMR,JPL); P03 - ALL techniques except GPS(COD,EMR,JPL))

	DX	DY	DZ	N	E	up	
Mean (mm)	2.7	4.0	-3.4	-3.0	0.4	-1.2	MIT95P01-ITRF94 Pol
Sigma (mm)	5.0	7.4	6.8	5.1	6.7	8.9	
Mean (mm)	0.4	5.1	-1.4	-1.6	-2.4	-0.1	MIT95P01-ITRF94 P02
Sigma(mm)	7.0	7.1	6.2	4.9	9.0	7.1	
Mean (mm)	7.2	-2.6	-11.9	-7.5	-4.9	0.5	MIT95P01-ITRF94 P03
Sigma(mm)	10.9	8.6	14.9	15.1	7.5	15.6	
Mean (mm)	3.5	0.8	1.2	2.2	1.0	-0.1	MIT95P01-ITRF93 C02
Sigma(mm)	5.9	9.5	8.8	8.8	4.7	10.6	
Mean (mm)	-1.4	1.9	-4.3	-5.0	-1.1	-0.7	ITRF93C02-ITRF94 PO1
Sigma(mm)	8.4	10.4	8.6	9.0	7.1	11.1	

More than 13 stations and a better distribution are needed for an improved ITRF realization. A close examination of the ITRF94 solution, similar to the examination of thepreviousITRF solutions inthepast, has notreveal any suitable additional stations due to weak station velocity solutions. Therefore, itis suggested that:

RECOMMENDATION # 2:
"TheITRF94(POl) coordinates of the 13 ITRF stations are used for the IGS realization ofITRFstarting onJune30, 1996 (Wk 0860)."

To mitigate the small discontinuities on June 30, 1996 (ITRF94/ITRF93) and January 1, 1995 (ITRF93/ITRF92) it is also recommended that IGS provides appropriate parameters fortransformation ofthe IGSproducts.

IGS ORBIT/CLOCK COMBINATIONS

The IGS orbit/clock combinations were originally implemented in two phases: the first, so called Rapid orbit/clock combination, was initially produced within 15 days and based on the IERS(Bull. A) EOP; it is now completed within 11 days and averaged directly in the ITRF (without external EOP alignment). The second and final phase, known as the Final combination is based on the IERS(Bull. B) EOP and is available with a delay of about two months. The main reason for the Final combination was to benefit from the final IERS EOP combination and its stability, and to allow the ACS to revise and resubmit their solutions.

Since January 1, 1996, six ACS have provided input for generating an IGS Preliminary orbit/clock combination which is now approaching precision of about 10cm/1 ns with a delay of only 38 h .

During 1995 systematic differences were noticed between both IERS EOP (i.e. Bull. A and B) and the IGS pole combination series. It has been shown that the above differences are mainly due to smoothing procedures employed in the production of the IERS series. Furthermore, GPS/VLBI comparisons show 0.1 mas precision for the IGS pole coordinates (see IGSMAIL#1 072). The smoothed out signal of the IERS series was as high as 1 mas which may affect significantly the Final Orbit precision. The ACS rarely resubmit their solutions since the preliminary processing has been initiated and the IGS Rapid Orbits are now as precise and stable as the IGS Final ones, we therefore propose:

RECOMMENDATION # 3:
"To economize and optimize the IGS combination efforts and to reduce delays in the IGS Final orbits/clock production it is recommended that starting on June 30, 1996 (Wk 0860) the current IGS Rapid combinations become the IGS Final product and the IGS Preliminary (IGP) product replaces the IGS Rapid (IGR) combination. In this way the precise IGS Final products will become available within 11 days and the IGS Rapid orbits/clocks will be available in about 1 day. "

PRELIMINARY/RAPID ORBIT/CLOCK COMBINATIONS

Since January 1, 1996 up to six ACS (COD, EMR, ESA, GFZ, JPL, S10) have been providing input for the IGS Preliminary orbit/clock computations. Despite the initial difficulties, like data delivery delays and INTERNET problems, this IGP project has exceeded expectations. Delays in data availability are driving the ACS solution precision rather than the number of stations, since often the remote stations providing required station geometry, are most prone to data delays. Table 2 gives a summary of IGP statistics and solution delays. The standard deviations (std) for orbit rms and delivery delays indicate variations in precision and processing delays. Also shown in Table 2 are number of days when AC's input has not been available or had to be excluded .

Table 2: IGS Preliminary orbit/clock combination statistics for days between January 14 to February 29, 1996. (Delays are in hours since the last observation)

CENTER	DELIVERY(h)		ORB RMS(cm)		MISSED/EXCL
	mean	std	mean	std	days
COD	14	4	23	16	1
S10	18	4	19	8	10
EMR	21	5	15	10	2
JPL	21	4	12	3	2
ESA	26	7	25	8	12
GFZ	30	4	13	10	7

Prompt and reliable station tracking data availability and AC solution input also during weekends and holidays are very important to this project; it is therefore proposed:

RECOMMENDATION # 4:
"Timely data delivery is crucial for rapid and precise IGS product generation and it is therefore essential to meet IGS data delivery deadlines particularly for the selected global stations. For these stations a 6 hour maximum delay should not be exceeded and the data equalization of the IGS Global centers should not require more than 2 hours. "

From the above table it is apparent that the current 36h submission delay deadline can be reduced substantially, thus:

RECOMMENDATION # 5:
"It is recommended that the current submission delay deadline of 36h for IGP be reduced to 23h after the last observation as of June 30, 1996 *(Wk 0860). If all participating AC solutions arrive prior to this deadline the IGS combination is to be completed within an hour after the last submission. "*

There is also considerable interest in IGS orbit predictions to be available in real time, or with delays much shorter than 1 day. There are at least two alternatives to such IGS predictions, one is completely analogous to the current IGS combination, i.e. a weighted average of AC predictions. The second, potentially more reliable and precise, is to use an advanced orbit model to fit several preceding days of IGS orbits and to generate IGS orbit predictions. Benefits and feasibility of different orbit prediction approaches will have to be, first discussed and evaluated by all AC.

More research is required in order to make the satellite clock solutions more robust and precise. Additionally, precise external time comparisons at stations equipped with very stable HM clocks are needed to assure continuity and compatibility with the international time standards. For more details and results of IGS orbit/clock combinations see the poster at this workshop.

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Evaluation of IGS GPS Orbits with Satellite Laser Ranging

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Abstract

The accuracy with which orbits for the Global Positioning System (GPS) spacecraft can be computed directly affects the accuracy of the resulting site coordinates and polar motion. Several groups routinely analyze GPS ground tracking data to compute precise orbits and terrestrial reference frame solutions. In this paper, we infer the accuracy of the orbits of two of the GPS satellites by comparing to independent laser ranges of subcentimeter accuracy obtained by a small but reasonably well distributed network of tracking sites. We find that all seven international GPS Service for Geodynamics (IGS) analysis centers achieve range residual root mean square (rms) errors at or below the 100 mm level. The best orbit solutions, from JPL, CODE, and the IGS combined product, yield a residual rms of about 50 mm. These residuals are consistent with three dimensional orbit errors of less than 150 mm. Intimating yaw rates for the spacecraft during shadow events, and using these estimates to compute the laser residual, significantly improves the fit. A small mean residual value of — 15 to —30 mm seems to exist for most centers and laser sites which is not fully explained at present, but may be due to uncertainties in the corrections to the laser data, such as the reflector to spacecraft center of mass vector or small reference frame differences between the SLR sites and the GPS orbits.

Introduction

Until the launch of GPS35 (PRN 5) in August, 1993, no other tracking type was available for the GPS spacecraft. GPS35 used a laser retroreflector array (LRA) derived from that used on the Russian GLONASS system navigation satellites which are routinely tracked in Russia with SLR. The LRA is on the nadir (earth pointing) side of the GPS spacecraft, with offsets from the center of mass of 0.8626, –0.5245, and 0.6584 meters in the spacecraft x, y, and z axes, respectively [*Degnan and Pavlis*, 1994]. An identical system was used for GPS36 (PRN36) which was launched in March, 1994. We have used this SLR data to evaluate the accuracy of the GPS orbital ephemerides from the 7 IGS Analysis Centers and the IGS combined orbit. The discussion is a summary of the detailed discussion in [Watkius et al., 1996].

Each SLR observation is actually a five minute normal (average) point of higher rate data to reduce the random noise component in the measurements. Each range normal point should be accurate to about 10 millimeters, with the limiting error sources being tropospheric refraction and uncalibrated rauge biases in the laser system. For the period studied in detail in this paper, 1 Jan 1995-30 November 1995, a total of 469 passes (4464 points) for GPS35 and 36 were obtained from 11 sites, presented in Table 1 with both geographic location and Crustal Dynamics Project ID. Note that although the first few sites dominate the observations, they are thankfully well distributed. Because of the sparseness of the SLR tracking of GPS35 and 36, we have elected not to actually fit spacecraft orbits to this data. Instead, we will use the data as an external check on ephemerides computed using only GPS data. This will give a unique and independent assessment of the orbit error derived from the routine analysis of GPS data, and hence present in the solution for site positions and Earth orientation. Because of the high altitude of the GPS spacecraft, observations from the ground, even down to low elevation, are still nearly radial from the spacecraft point of view. In fact, the largest departure from the truly radial direction is about 13 degrees, and so the range residual is a measure primarily of the radial component of orbit error. Thus, a scale factor may be computed to calibrate the radial overlap that may be applied to the cross-track (orbit normal) and alongtrack (transverse) components to approximate the true three dimensional orbit accuracy.

Results

We have taken the orbits from each of the seven analysis centers and from the IGS combined orbit for the period 1/1/95 - 11/30/95 and computed SLR residuals for each using the GIPSY-OASIS 11 software developed at JPL [*Webb and Zumberge, 1995*]. The models used for the SLR processing generally adhere to the IERS Standards of *McCarthy* [1992]. These include solid tides, ocean tidal loading, and we have additionally modelled the subdaily Earth orientation variations due to ocean tides. Since the sp3 files are expressed in the Earth fixed frame, no daily Earth orientation values are required to evaluate the laser residuals. We have fixed the coordinates of the laser sites to the ITRF93 values and used the marker eccentricities of the CSR94L01 solution [*Eanes and Watkins, 1994*]. Note that no parameters are adjusted from the laser data during the evaluations. The orbits were interpolated to the times of the SLR data using a tenth order polynomial, which has millimeter accuracy compared to a numerical reintegration of the orbit. Finally, since only J PL adjusted the GPS spacecraft yaw rates, we have chosen to feed the JPL estimates back for all centers. These corrections are only applicable during eclipsing periods, which during our data span are 15 June – 31 July for GPS35 and 5 March - 26 April and September - October for GPS36. The fits are summarized during three orbit regimes. The first, denoted in Table 2 as SUN, are those observations obtained when the GPS spacecraft is not in eclipse season. Those denoted ECL are in eclipse season, but not in eclipse during the particular observation. Finally, those denoted SHA are either actually in shadow or within 30 minutes of shadow exit at the time of the SLR observation, and may be maneuvering according to the model described in *Bar-Sever* [1995 a, b]. The resulting fits over all data for each center and each regime are presented in Table 2. We have edited outlier laser residuals which exceeded 300 mm.

Discussion

Several conclusions can be drawn from Table 2. The first is that the radial orbit error for the GPS spacecraft is as low as 50 mm. We say radial here because, as mentioned above, the geometry of the GPS orbit makes the laser data typically within 10 degrees of the radial direction as seen from the spacecraft. Interestingly, this figure is actually slightly lower than the average radial overlap for the GPS spacecraft, and indicates that the overlaps are pessimistic indicators of orbit accuracy. Scaling the radial overlap fit to radial orbit error and applying that scale factor to the other components yields implied orbit errors of 50, 70, and 100 mm in the HCL components. We conclude then that the three dimensional orbit error typically does not exceed 150 mm.

Another conclusion that can be drawn is that the fit rms is indeed degraded during eclipse season, and more so during a shadow event. The JPL orbit, which is the only one estimated simultaneously with GPS s/c yaw rates during eclipse, suffers by far the least degradation. Note that two separate effects cause the range error reflected in the SLR evaluation in the ECL and SHA regimes; a kinematic effect stemming from errors in the applied yaw rates which cause the computed LRA position to be in error, and a dynamic error in the GPS ephemerides due to radiation pressure mismodelling from attitude errors on shadow exit.

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Table 1. SLR Data for GPS35 and GPS36

Site	ID	Passes GPS35	Passes GPS36
Haleakala, USA	7210	56	56
Monument Peak, USA	7110	61	32
Yaragadee, Aust.	7090	32	42
Wettzell, Germany,	8834	35	28
Royal Greenwich Ohs, U.K.	7840	22	14
Graz, Austria,	7839	16	10
McDonald Ohs., USA	7080	15	6
Greenbelt, USA	7105	9	9
Orroral, Aust.,	7843	3	6
Greenbelt, USA	7918	4	0
Quincy, USA	7109	4	0

Table 2. SLR Data Fit to GPS Ephemerides

Center	SUN 3685 pts. mean	SUN 3685 pts. rms	ECL 729 pts. mean	ECL 729 pts. rms	SHA 50 pts. mean	SHA 50 pts. rms
JPL	–24	51	–9	45	–34	57
CODE	–20	52	–17	70	–16	103
IGS	–11	55	15	72	–3	96
SIO	6	66	58	116	0	125
GFZ	13	77	13	95	–16	88
EMR	–14	82	19	96	–29	130
NGS	–14	92	21	122	0	150
ESA	–1	91	–56	191	–10	250

All units are millimeters

This preprint was prepared with the AGU LaTeX macros v3.1. File slr'igs formatted 1996 September 6.

Using the Extended CODE Orbit Model
First Experiences

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Abstract

The Extended CODE Orbit Model, an empirical orbit model proposed by *Beutler et al. [1994]*, was used for the first time in the actual parameter estimation procedures (using the Bernese GPS Software), to model the orbits of the GPS satellites at the CODE Analysis Center of the IGS. Apart from six Keplerian elements this orbit model consists of nine instead of the usual two parameters to take into account the deterministic part of the force field acting on the satellites.

In this article we focus on the optimum use of this Extended CODE Orbit Model for the CODE IGS activities. Of particular interest are the generation of *rapid orbits*, with only 12 hour delay after the last observation, and (IGS) orbit prediction.

Introduction

The Center for Orbit Determination in Europe (CODE), is one of at present seven Analysis Centers (AC's) of the International GPS Service for Geodynamics (IGS). CODE has been formed as a joint venture of the Astronomical Institute of the University of Bern (AIUB), the Swiss Federal Office of Topography (L+T), the German Institute for Applied Geodesy (IfAG), and the French National Geographical Institute (IGN). CODE is located at the AIUB in Bern.

Since the start of the IGS in June 21, 1992, CODE has produced ephemerides for all active GPS satellites and daily values for the earth rotation parameters. Starting January 2, 1994, all the individual AC orbit (and clock) solutions have been evaluated and combined into official IGS orbit/clock solutions by the Analysis Center Coordinator, [*Beutler et al.*, 1995; *Kouba*, 1995]. The IGS combinations/evaluations, summarized in weekl y IGS reports, clear] y demonstrate the steady improvements in both, precision and reliability, for all AC'S.

The CODE orbit position RMS, compared to the combined IGS orbit, reached the 10 cm level by the end of 1994. By the end of 1995 the RMS had decreased to a level of 6 cm.

Thanks to this improvement of the orbit quality it has become clear that the classical orbit model, using eight parameters, is not accurate enough to guarantee an orbit quality below the 10 cm level. Different AC's solved this problem in different ways by either using deterministic or stochastic orbit models. At CODE the estimation of small velocity changes (pseudo-stochastic pulses) for all satellites at noon and midnight was implemented, starting June 4, 1995, to deal with the model deficiencies of the, classical orbit model. However, by mid 1995 it also became clear that the Extended CODE Orbit Model as proposed by *Beutler et al. [1994]* and used in the IGS orbit comparisons for the long-arc analysis [*Beutler et al.,* 1995] should also be capable of producing orbits better than the 10 cm level RMS. Therefore, in early 1996, the model was finally fully implemented into the Bernese GPS Software Version 4.0 and first experiences were gathered.

We will first show some results of the initial tests performed to get a better understanding of the mode]. We will then discuss two interesting applications of the Extended CODE Orbit Model. Apart from using the new model for our normal processing method (overlapping 3-day arcs) we also apply the new model for the production of our rapid orbits (12 hour delay) and for orbit predictions.

The Extended CODE Orbit Model

In *Beutler et al. [1994]* and *Rothacher et al. [1996]* the new orbit model is discussed in detail, therefore here only the basic characteristics are summarized.

For the Extended CODE Orbit Model the acceleration $\vec{a}_{rpr}$ due to the deterministic part of the solar radiation pressure model is written as:

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

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

$$\begin{aligned} \vec{a}_D &= [a_{D0} + a_{DC} \cdot \cos u + a_{DS} \cdot \sin u] \cdot \vec{e}_D = D(u) \cdot \vec{e}_D \\ \vec{a}_Y &= [a_{Y0} + a_{YC} \cdot \cos u + a_{YS} \cdot \sin u] \cdot \vec{e}_Y = Y(u) \cdot \vec{e}_Y \\ \vec{a}_X &= [a_{X0} + a_{XC} \cdot \cos u + a_{XS} \cdot \sin u] \cdot \vec{e}_X = X(u) \cdot \vec{e}_X \end{aligned} \quad (2)$$

where $a_{D0}, a_{DC}, a_{DS}, a_{Y0}, a_{YC}, a_{YS}, a_{X0}, a_{XC}$, and a_{XS} are the nine parameters of the Extended model, and

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

The Extended CODE Orbit Model clearly is a generalization of the standard orbit model which is, at this time, still used for the official CODE solutions,

To gain experience with the model a test data set of 4 weeks was selected (GPS weeks 0836–0839). Several different 3-day solutions and a couple of 5-day solutions were performed. Furthermore, a test solution, based on the complete (15 parameter) model, was added to the variety of solutions in our reprocessing experiment of the 1995 IGS data,

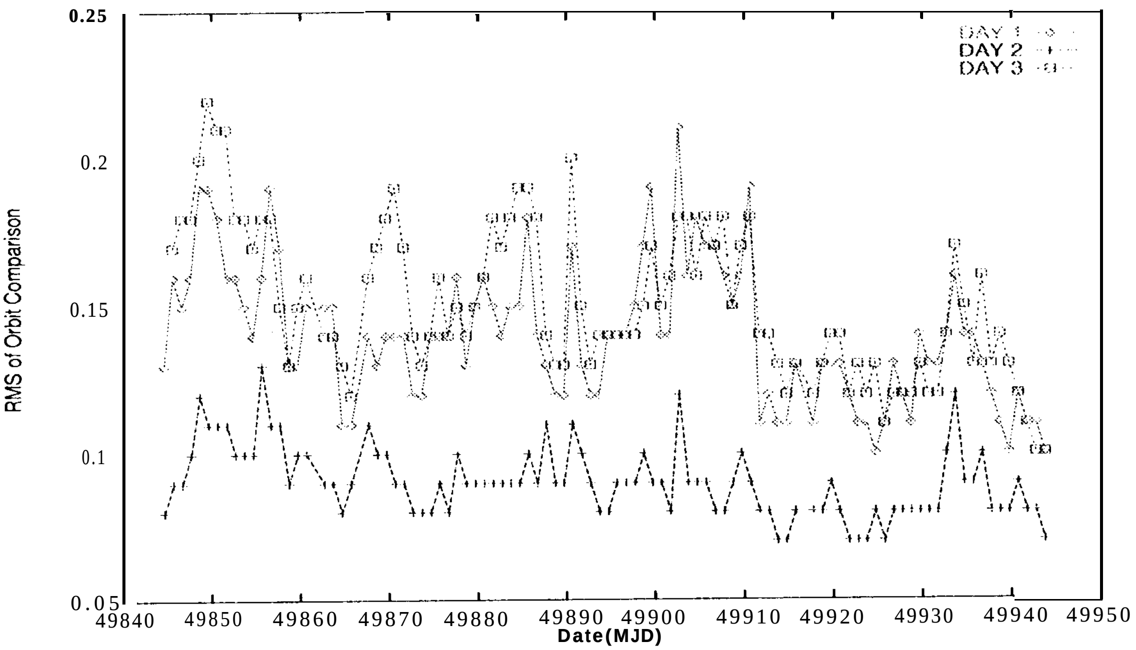
First Results

The most striking result stems from our 1995 reprocessing experiment where we created two different types of solutions. One was based on our current IGS routine strategy estimating the conventional (8 parameter) orbit model and 2 pseudo-stochastic pulses per day for all satellites in the along-track and radial directions. This means that for each satellite five of these pulses are estimated over a 3-day arc, all in all ten additional parameters per satellite. So, for each satellite 18 parameters are estimated: 6 Keplerian elements, 2 radiation pressure coefficients and 10 velocity changes. The second type of solutions used the Extended CODE Orbit Model where pseudo-stochastic pulses were estimated only for the eclipsing satellites and satellite PRN23, which has a solar panel defect. This means that 25 parameters were estimated for the eclipsing satellites and satellite PRN23, but only 15 parameters for all other satellites.

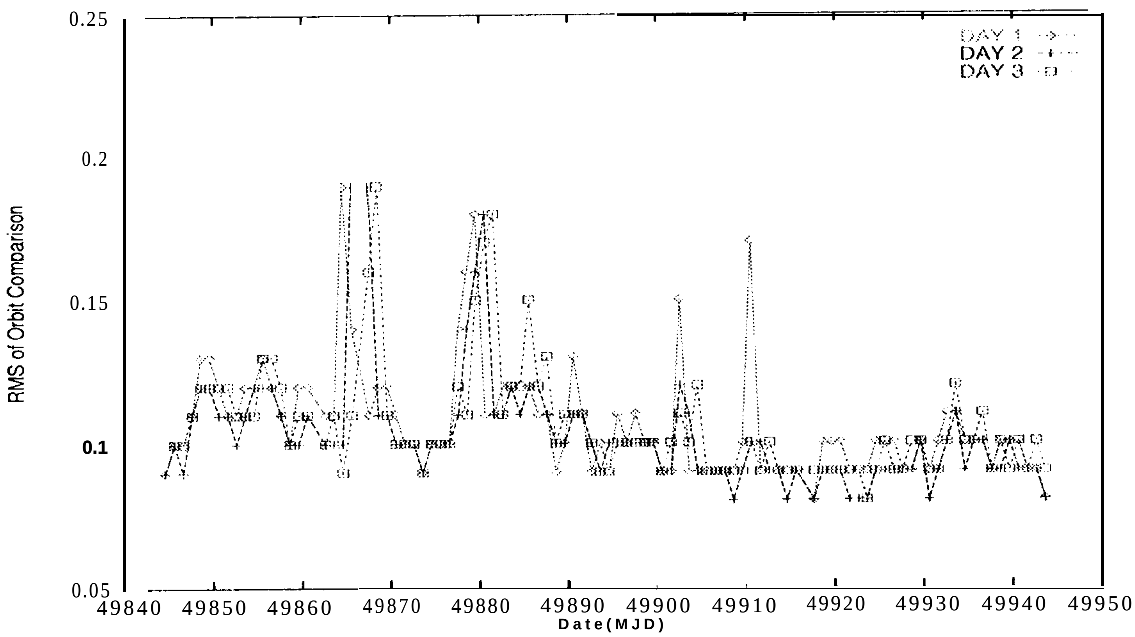
For both types of 3-day solutions individual precise orbit files were created for each day of the 3-day arcs. These (daily) precise files were then compared to the IGS final orbits. The RMS errors of the comparisons, using 7 parameter Hehnert transformations (w.r.t. the IGS final orbits), are shown in Figure l for the 1995 reprocessing. Clearly the first and third day show a significant decrease of precision when using the conventional orbit model whereas with the Extended CODE Orbit Model all days are of the same high quality.

That the middle clay of the conventional orbit model shows a smaller RMS than the middle day of the Extended model is most likely explained by the fact that this solution is very similar to the CODE solution which was taking part in generating the IGS final orbit. However, a detailed analysis using fully independent Satellite Laser Ranging (SLR) data, seems to indicate that using the complete mode] for the 3-day solutions actually leads to a slightly less accurate orbit solution for the middle day. Different tests using the 4-week data set indicated that for 3-day arcs the Extended model provides too many degrees of freedom. Not all nine parameters should be estimated using an arc length of “only” three days. Correlations between the orbit parameters but also with other parameters, like UT1-UTC, are significant. With 5-day arcs the correlations seem to decrease to an acceptable level. We should note that no tests were performed using a priori constraints on the orbit parameters. If a certain orbit parameter was setup it was estimated without any constraints.

One of the aims of the tests with the 4-week data set was to determine how to make optimum use of the Extended Model for 3-day arcs which we are using for our official IGS



(a) Conventional Orbit Model



(b) Extended CODE Orbit Model

Figure 1. Unweighted RMS values of the orbit comparisons of the3 individual days of a 3-day arc with the final IGS orbits.

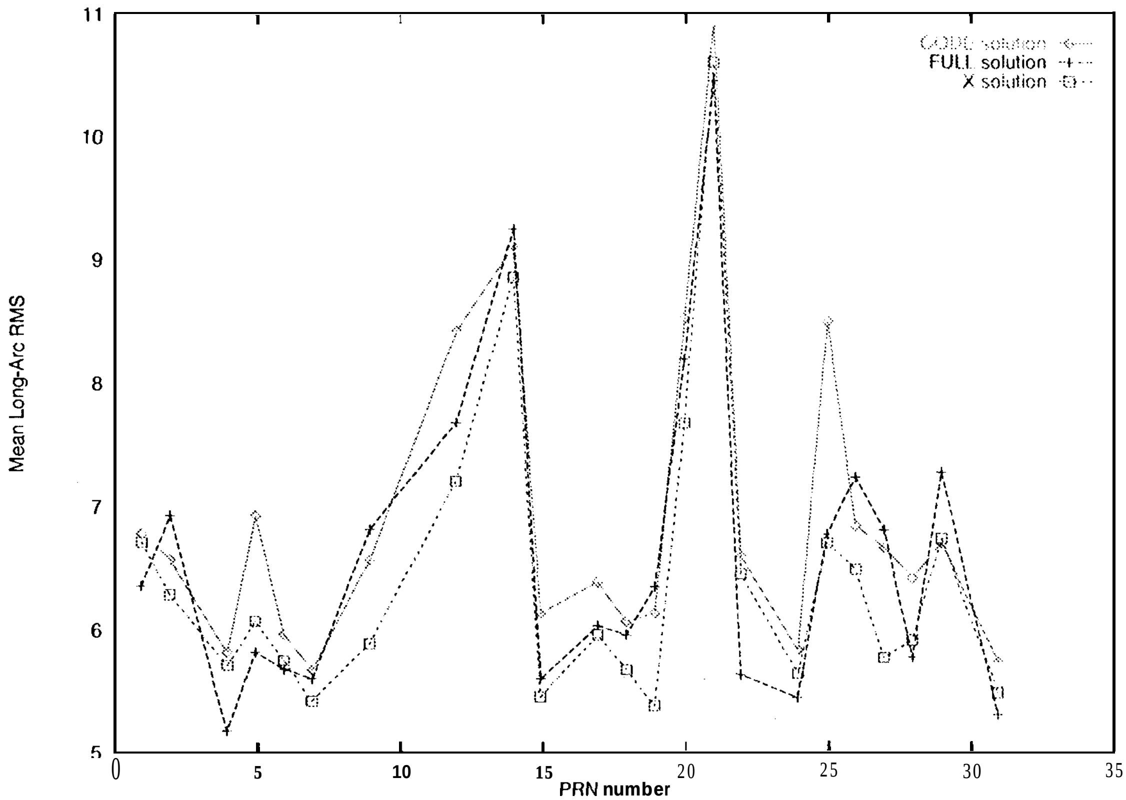


Figure 2. Mean long-arc RMS values over the 4-week test period.

contributions since 1992. The best strategy we have found so far is to <u>not</u> estimate any "X" terms (a_{xo}, a_{xc}, a_{xs} in (2)) of the Extended model and still use five pseudo-stochastic pulses over three days for each satellite. Figure 2 shows the quality, per satellite, of the official CODE solution, a solution using the full Extended model (labelled "FULL") and a solution using the Extended model without estimating any X-terms (labeled "X"). The RMS is the mean of all the long-arc (7-day) orbit checks performed for the 4-week test data set. Clearly the X-solutions perform better than both other solutions for most satellites. Only for a few satellites the "FULL" solution performs better than the "X" solution.

The stochastic pulses seem to absorb certain (orbit) model deficiencies more efficiently than the parameters of the Extended model, in particular for eclipsing satellites. The directions of the stochastic pulses are based on an orbit specific coordinate system (along-track, radial and out of plane components), whereas the components of the Extended model are defined as described in (2). Furthermore these pulses are estimated every 12 hours which makes them almost exactly "once per revolution" terms. They should therefore have a similar effect as the perturbation model proposed by *Colombo [1989]* which is well suited to absorb (gravity related) periodic unmodeled forces. In 1994 it was clearly shown [*Beutler et al., 1994]* that the Extended model performs much better than the Colombo model.

However, at that time the orbit accuracy, based on a 7-day arc fit, was of the order of 15 cm whereas today we are reaching the 5 cm level. With these orbit accuracies it is possible that the errors in the earth gravity field model (GEM-T3 model truncated to degree and order eight) are becoming significant.

It is clear that the modeling of the orbits of eclipsing satellites should be further improved. Implementing the "attitude" model [*Bar-Sever*, 1995] would improve the model for the eclipsing satellites, but other methods might be useful, too. An alternative method, to solve the modeling problems of the eclipsing satellites, might be a kind of "kinematic" solution for the motion of the satellite antenna phase center during the eclipse phase and for a time period of 30 minutes afterwards.

Applications of the Extended CODE Orbit Model

Rapid Orbits

Since January 1, 1996, the IGS is making available rapid combined orbits with a 36 hour delay. CODE participates in this new IGS activity with orbits which are available within 12 hours. The limiting factor for the accuracy of the rapid orbits is the availability of station data with a good geographical distribution. Especially with our 8 hours deadline, and the bad internet performance between Europe and America during office hours, the available data tend to have a bad geographical distribution. A good way to solve this problem is to use longer arcs. We have to keep in mind however, that we wi ll have to use the last day of an n-day arc as rapid orbit product. With the conventional model the last day would be significantly less accurate than the middle day of the same arc, see Figure 1 The fact that with the Extended model all days of an n-day arc (n= 1,2..5) are of the same qua] ity makes it possible to use longer arcs for the rapid orbit computations thereby making the rapid orbit product much less sensitive to the geometry of the available data.

Figure 3 shows the quality of our rapid orbits since January 1, 1996. Around MJD 50130 (February 17) we started to use the Extended Orbit Model to produce 5-day arcs, the last day of this 5-day arc being our official IGS rapid orbit contribution. One clearly sees that, after some initial problems, the 5-day solution (the last day of a 5-day arc) is performing much better than the 1-day solution. In reality the performance is even better because here the unweighed RMS is given which is dominated by satellites with modeling problems, which are of course more pronounced in the 5-day arcs than in the 1-day arcs. The peaks, which show up in the 1-day solutions due to a bad station geometry, are hardly visible in the 5-day solution, although the 5-day arcs are based on exactly the same observations (apart from using more days, of course).

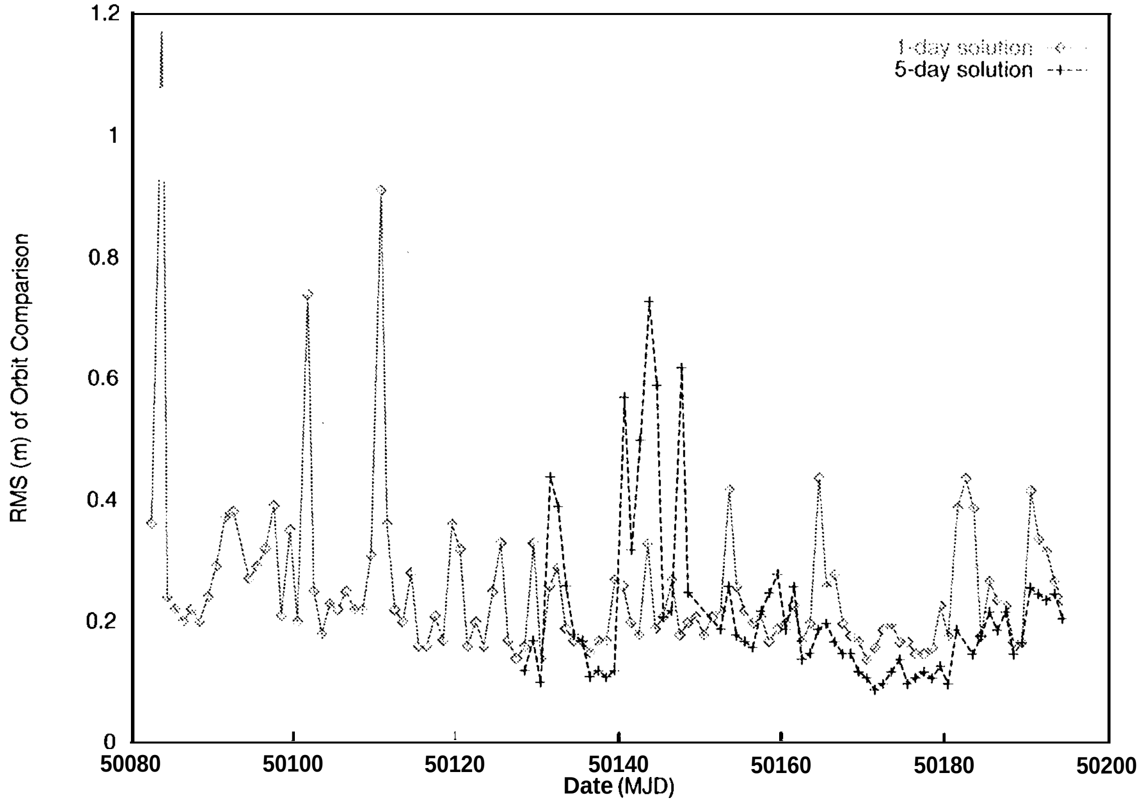


Figure 3. Unweighed RMS values of orbit comparisons showing the quality of the 1 -day and 5-day rapid orbits. CODE orbits were used as reference.

Orbit Predictions

Everyone famil iar with the weekl y summaries of the IGS orbit combination is aware of the fact that the Extended CODE Orbit Model (used for the long-arc analysis of the IGS orbit combination) is capable of modeling the orbits of the GPS satellites over seven days at the few centimeter level. This indicates that the model should also be well suited to generate accurate orbit predictions.

At CODE we create 24- and 48-hour predictions based on our 1-day routine solutions for internal use. The 24-hour predictions are used as a priori orbits in the IGS routine processing rather than the broadcast ephemerides since the predictions have a better accuracy. After the implementation of the Extended model into our software we noticed a significant improvement of our predictions. Figure 4 shows the qual ity difference of the orbit predictions using the conventional and the Extended model. With the conventional (8 parameter) orbit model our 24-hour predictions had a quality around the 75 cm level and the 48-hour predict ions around the 130 cm level. With the Extended (15 parameter) model the quality of the predicted orbits is now around the 25 and 60 cm level for the 24- and 48-hour

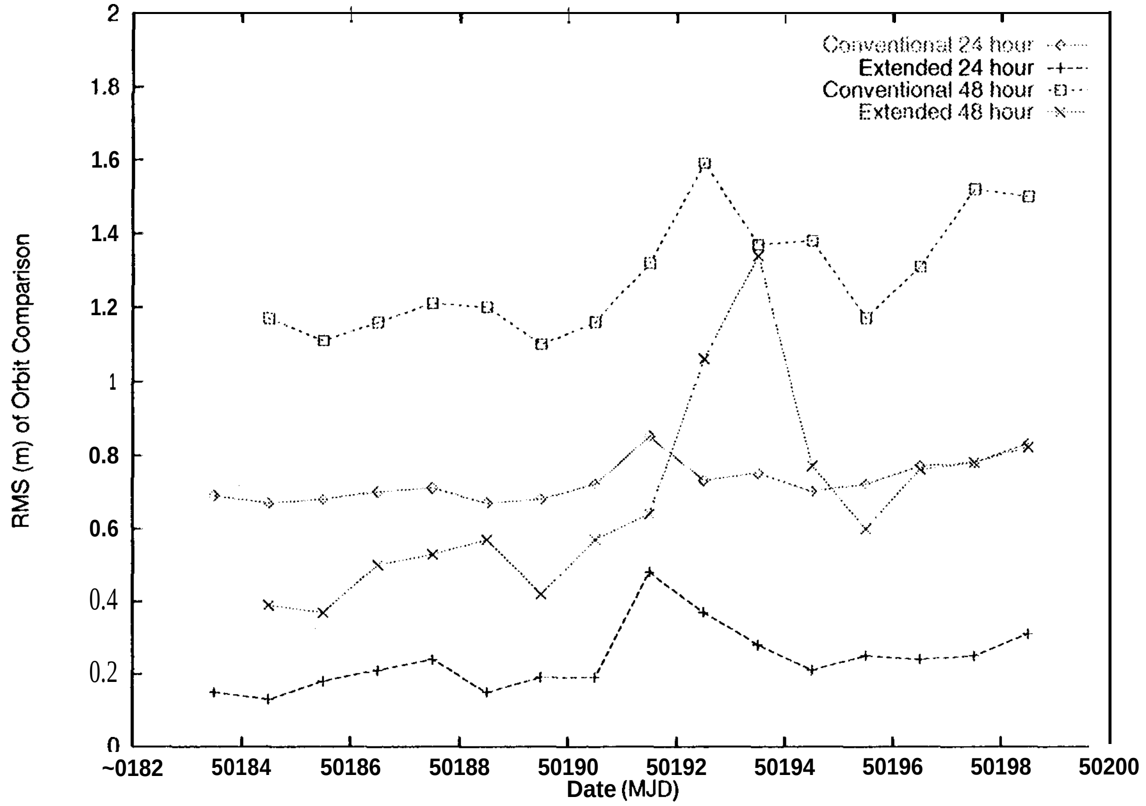


Figure 4. Unweighed RMS values of orbit comparisons showing the quality of 24- and 48-hour orbit predictions using the conventional and Extended orbit model. CODE orbits were used as reference.

predictions respectively. As expected the Extended model is better suited for predictions than the conventional model. The 48-hour predictions of the Extended model are even better, in most cases, than the 24-hour predictions of the conventional model!

At these accuracy levels, and for real-time purposes, the extrapolation of the Earth Orientation parameters starts to play an important role. For predictions to be used in real-time data analysis, based e.g. on the IGS 36-hour orbits, it will be mandatory to predict the Earth Orientation parameters with an accuracy of about 1 mini arc second.

Summary and Outlook

Our first tests revealed that the Extended CODE Orbit Model is very well suited the CODE IGS activities but also for long-arc analyses (arcs longer than 3 days). Furthermore, we have shown that the model gives an important contribution to the generation of high precision rapid orbits and orbit predictions. Our rapid orbits, based on the Extended model, have an accuracy of approximately 10 cm. Prediction quality is at the 20 and 60 cm level for 24- and 48-hour orbit extrapolations, respectively.

For short arcs, 1- to 3-days, one has to be aware of correlations between some of the parameters of the Extended model. It may not be necessary, and possibly even harmful, to solve for all nine parameters of the Extended model. The best 3-day arc solutions were obtained by not estimating any "X" terms of the Extended model but st i ll estimating five pseudo-stochastic pulses for each satellite in the along-track and radial directions. These pseudo-stochastic pulses, as implemented for the CODE IGS orbit products since June 4, 1995, seem to be capable of absorbing certain (orbit) model deficiencies more efficiently than the parameters of the Extended model. This aspect will be studied in more detail in the near future.

Long arcs are interesting from a scientific point of view but they are *not* practical for the routine IGS analysis as preformed at CODE. Currently we are therefore focusing on how to best implement the Extended model for 3-day arcs as we are using them in our IGS analysis. However, in the more distant future we might consider generating weekly 7-day arcs as our official IGS products.

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GPS EARTH ORIENTATION

GPS EARTH ORIENTATION COMBINATIONS AND RESULTS: SESSION SUMMARIES AND RECOMMENDATIONS

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INTRODUCTION

This session consisted of seven presentations to review the status of current GPS determinations of Earth orientation and to consider further refinements. Brief summaries of each are given in the following sections. The first, by J. Kouba, reported the results of the Analysis Coordinator for the combined IGS time series of daily polar motion (PM) values, a by-product of the regular orbit combinations. The IGS results were compared with similar GPS-only series compiled by the IERS Central Bureau and by the U.S. Naval Observatory (USNO) and with the multi-technique combinations in IERS Bulletins A and B. The accuracy of the IGS PM series, recently estimated to be about 0.1 mas (McCarthy and Luzum, 1995), is now sufficient to reveal the effects of over-smoothing applied in the IERS combined series. While this is roughly comparable to the accuracy of weekly VLBI PM determinations, T.M. Eubanks showed in the following presentation the power of continuous GPS observations to monitor a previously predicted, but undetected, mode of atmospheric excitation. He encouraged the estimation of PM rate parameters, as some Analysis Centers (ACs) already do, to improve excitation studies further.

J. Ray and D. Gambis *et al.* gave largely contrasting views of the information content of GPS determinations of Universal Time (UT 1) and length-of-day (LOD). Using direct comparisons with VLBI, Ray characterized the LOD measurements of the seven IGS ACS, noting the significance of pervasive biases, and assessed the potential value for monitoring UT1 variations. Gambis *et al.* synthesized combined UT1 time series using VLBI for the low frequency behavior and GPS for high frequency. Both studies agreed that GPS estimates of UT 1 should be valuable when VLBI data are unavailable, such as for near real time applications. Rotational alignment of the very rapid IGS Preliminary orbits, produced daily with only 1,5-day delay, are such an application.

The effects of sub-daily Earth orientation variations were discussed by D. McCarthy and T. Herring. McCarthy examined the consequences for estimated PM values, showing that neglect of the effect leads to aliased errors at longer periods which can approach the 0.1 mas level when data arc lengths are not even multiples of 24 hours. He stressed the importance of understanding the data analysis procedures implemented by the ACS and the precise Earth orientation quantities reported to the IGS. Herring showed that diurnal and semi diurnal errors are effective y absorbed into the orbit and orientation parameters. Both speakers agreed that current models for sub-daily Earth orientation variations are sufficiently accurate that the effects should be fully incorporated into GPS data analyses.

In the closing presentation, McCarthy reviewed new standards soon to be adopted by the IERS. These include a tidal model for sub-daily Earth orientation variations which

IGS ACS are strongly encouraged to use. Adoption of a general convention for reporting EOP values, whether to include tidal contributions or not, was discussed but was not resolved. The results of this session have been distilled by the participants into a set of six recommendations, which are listed in the final section below. These incorporate revisions made based on discussions at the Workshop.

IGS COMBINATION OF GPS EARTH ORIENTATION PARAMETERS
-- J. Kouba

During the IGS Rapid orbit/clock combination, daily GPS-based PM values (IERS series designation: EOP(IGS)95 P 01) are produced weekly since January 1, 1995 with an 11-day delay. They are computed as weighted means from solutions submitted by the seven IGS ACS. Most ACS and the IGS Rapid (IGR) PM solutions have better than 0.5 mas precision, and, in direct comparisons, clearly show the effects of smoothing applied to both IERS series (Bulletins A and B) for periods less than 10 days. Similarly, since January 1, 1996, another daily PM series (EOP(IGS)96 P 01) based on the IGS preliminary (IGP) orbit/clock combination is produced daily with only a 1.5-day delay. Currently, six IGS ACS are contributing to this IGP combination. The IGP PM precision is approaching the IGS Rapid PM precision level. These two PM series imply *Rx, Ry* orientations of the respective IGS orbit combinations, The *Rx, Ry* orbit rotations can be effectively used to evaluate orbit reference frame and PM consistency of the IGS and individual AC solutions. The orbit/PM consistency has improved slightly during 1995 and it is at or below 0.1 mas for IGS combined and most AC solutions. The IGR PM combinations (EOP(IGS)95 P 01) was compared to the IERS and USNO GPS-based PM combinations. All three combined GPS PM series were found to be consistent at the 0.1 mas rms precision level, subject only to small offsets not exceeding 0.4 mas.

COMPARISON OF GPS AND VLBI POLAR MOTION WITH AAM
-- T.M. Eubanks

In a paper by Eubanks *et al. (1988),* circularly polarized quasi-periodic polar motions with "periods of -10 days and inferred polar motion amplitudes <1.0 mas" were predicted based on the existence of an atmospheric normal mode. These retrograde oscillations have now been observed in highly accurate PM results from GPS and VLBI data, with (peak to peak) amplitudes of 0.5 to 1.0 mas. These data are now in fact sufficiently accurate to provide continuous monitoring of this phenomenon. Excellent agreement is found between the geodetic data and Atmospheric Angular Momentum (AAM) estimates from numerical weather forecast assimilation models, with the observed polar wobble being almost entirely driven by atmospheric pressure forcing. The agreement between geodetic and AAM estimates of the PM excitation is better if the "inverted barometer" oceanic effect is ignored, implying that the ocean surface does not compensate pressure loads at these high frequencies.

The normal modes of a linearized barotropic atmosphere model can be separated into two classes, the linearly polarized sub-diurnal gravity modes, and the Rossby-Haurwitz modes, which are always westward propagating, or retrograde circularly polarized. The observed 10-day polar wobble is due to a Rossby-Haurwitz mode, one of only 3 normal modes expected to cause polar motions. The other two such modes, a 1.2-day period Rossby-Haurwitz mode and a 0.6-day period gravity mode, are much smaller, with predicted PM amplitudes of order 50 μas or less, and are not currently geodetically observable. Atmospheric normal mode periods depend on the thermal structure of the atmosphere, and continued geodetic monitoring of the 10-day mode will thus provide a resource for long term studies of climate change.

There is a general need for a clearer description of the smoothing/filtering and *a priori* ties applied in the GPS data analysis, both to the EOP, and, in addition, to the orbit analysis, As the estimated orbits provide the framework with respect to which the EOP is measured, a clear understanding of the orbital constraints (including any *a priori* ties to, e.g., Earth rotation predictions) is needed to better interpret the GPS EOP estimates, especially at high frequencies,

GPS MEASUREMENTS OF LENGTH-OF-DAY: COMPARISONS WITH VLBI AND CONSEQUENCES FOR UT1 -- **J.R. Ray**

Length-of-day (LOD) estimates from the seven GPS ACS of the IGS have been compared to values derived from VLBI for a recent 16-month period. All GPS time series show significant LOD biases which vary widely among the Centers, Within individual series, the LOD errors show time-dependent correlations which are sometimes large and periodic. Clear correlations between ostensibly independent analyses are also evident. In the best case, the GPS LOD errors, after bias removal, approach Gaussian with an intrinsic scatter estimated to be as small as -21 μs/d and a correlation time constant of perhaps 0.75 d. Integration of such data to determine variations in UT1 will have approximately random walk errors which grow as the square-root of the integration time. For the current best GPS performance, UT1 errors exceed those of daily 1-hour VLBI observations after integration for -3 d. Assuming the stability of LOD biases can be reliably controlled, GPS-derived UT1 can be useful for near real time applications where otherwise extrapolations for several days from the most current VLBI data can be inaccurate by up to -1000 μs.

DENSIFICATION AND EXTENSION OF VLBI UT1 SERIES WITH SATELLITE TECHNIQUES -- D. **Gambis,** M. **Feissel,** and **E.** Eisop

The GPS technique has recently shown its capability of monitoring PM. Due to the difficulty of determining with accuracy the long-term behavior of the non-rotating system realized through the orbit orientation, Universal Time UT 1 cannot be accurately derived from GPS technique since it is affected by long-term errors. Still, on time scales limited to a couple of months the high-frequency signal contained in the GPS UT determination can be used for densifying the series obtained by the VLBI technique and also for UT predictions in non-availability of the operational VLBI solution on a quasi real-time basis. In that case accuracies of about 200 μs on 10 days and 300 μs on 20 days are currently obtained. These analyses have recently led to the development of operational procedures for both densification of Universal Time and use of GPS UT determinations in non-availability of VLBI solution.

DAILY & SEMI-DAILY EOP VARIATIONS AND TIME SCALES; NEW IERS STANDARDS & CONVENTIONS -- **D.D.** McCarthy

Accuracy of Earth orientation information derived from the analysis of GPS orbits is limited currently by systematic errors. If ACS could agree on standard models and practices this situation could be improved, For example, it is now evident that high-frequency variations in Universal time andpolar motion can be observed, However, a consensus on the application of existing models in the analysis of observational data has not yet been reached. Another example is the use of *a priori* information on the motion of the celestial ephemeris pole in an inertial reference frame (precession/nutation).

Questions remain on the model to be used as well as the procedure to be used in treating daily and sub-daily variations. Resolution of these problems is important now, both in the analysis of the observations and in reporting the derived Earth orientation. The IERS is in the process of adopting the theoretical sub-daily model of Richard Ray for the forthcoming IERS Conventions. This model will be available in the form of source code.

In comparing Earth orientation values from different analyses for a specified set of epochs, a clearer understanding of the EOP contributions included is also required. Should these values be reported as an estimate of the total instantaneous Earth orientation at that epoch (including all tidal components) or should they report only the estimated non-tidal contributions presumably averaged over the data span?

CONSEQUENCES OF SUB-DAILY EOP VARIATIONS FOR GPS ORBITS
-- T. A. Herring

Sub-daily Earth rotation variations, in principle, have two effects in the analysis of GPS data: (1) the rotation of the gravity field will perturb the orbits of the GPS satellites; and (2) the effect the transformation from inertial to Earth-fixed coordinates.

The former of these is an extremely small effect and can be neglected, (As a rough order of magnitude estimate, we take the total C20 perturbation on a GPS satellite which is approximate y 10-5 m/sec^2. The diurnal and semidiurnal changes in the direction the C20 harmonic is oriented in inertial space would change this perturbation by $5 \bullet 10^{-9}$ resulting in accelerations of less than 10^{-13} m/sec^2. The resultant orbit perturbation is <0.2 mm.)

The latter effect on the transformation between the inertial and Earth-fixed coordinate systems is the most important effect. The neglect of the diurnal and semidiurnal rotations has itself two impacts: (1) Because of error in the mathematical model, the estimators will be affected (i.e., parts of the semidiurnal and diurnal rotations will be aliased in station coordinate estimates, atmospheric parameter estimates, the orbital parameter estimates, and the post-fit residuals), and (2) The direct transformation effects.

Analyses which we have done for (1) suggest that the diurnal and semidiurnal terms alias into the orientation and rate of change of orientation terms (about 50% of the total terms) and into the inertial orbit parameters (also about 50%). There appears to be only small decreases in the post-fit residuals and changes in station position (of order a few millimeters).

The effects of the direct transformation can be easily accounted and for 1 mas amplitude diurnal or semidiurnal term would result in -10 cm changes in the satellite positions in the Earth-fixed frame. (The aliasing contribution from the estimator appears to be about 5 cm for this magnitude term.) The aliasing contribution is smaller when pole position and UT 1 are not estimated (provided the *a priori* values are accurate).

When the diurnal and semidiurnal terms are not included in the mathematical model, Earth-fixed GPS orbits will have diurnal and semidiurnal rotations in them (because the motion of the Earth in the inertial frame of the orbit is not accounted for). The amplitude of these errors is of order 10 cm and will vary with the beat frequencies between the major terms in the semidiurnal and diurnal model. The major beat frequency is 13.7 days.

It should also be noted that the effects of phase center models appear to be about 3 times larger than the effects of the diurnal and semidiurnal models used in the analysis; i.e., changes in semimajor axis when the diurnal and semidiurnal models are used are -8 cm when PM/UT 1 estimated, - 4cm when PM/UT 1 are not estimated. The phase center models change the semimajor axis by -20 cm.

RECOMMENDATIONS

[1] IERS Conventions adopted for general use

To ensure the highest degree of compatibility of results from the individual Centers and with other techniques, it is recommended that

> all IGS Analysis Centers incorporate the IERS Conventions (Standards) into their data analysis procedures to the greatest extent possible.

Whenever departures from the IERS Conventions are deemed necessary, Analysis Centers are encouraged to document the alternative procedures in their reports to the IGS, IERS, and in updated AC Questionnaires. The new version of the IERS Conventions will be available in printed form by late spring 1996. Some parts will be available sooner as source code.

[2] *Reporting IGS Analysis Center models & methods*

To ensure the highest quality of results from the IGS combinations and to avoid misunderstandings, it is essential that the models and methods used by the Analysis Centers be fully understood by the users. It is particularly important that departures from the IGS and IERS Standards and Conventions be noted. Therefore, it is recommended that

> all IGS Analysis Centers provide updated versions of their AC Questionnaire at least once per year and every time that significant changes are made.

The Analysis Center Coordinator will review the scope of the current Questionnaire, making suitable revisions, and will provide a standard format at the IGS Central Bureau, New responses should be filed by all Analysis Centers by 01 July 1996.

[3] *IGS combination of GPS polar motion results*

Based on the demonstrated high quality of the weighting method used by the IGS for its polar motion combination, it is recommended that

> outside users of GPS polar motion results use the IGS Rapid combination polar motion values.

For those applications requiring more rapid turnaround, it is recommended that

> the IGS Preliminary combination values be used.

Given the high quality of current polar motion estimates from GPS and considering the potential value for excitation studies, Analysis Centers are encouraged to

> include and report polar motion rate parameters in their data analyses, in addition to polar motion offset parameters.

[4] *IGS combination of GPS LOD/UT1 results*

For near real time applications, where the only UT1 information available is from predictions, it is recommended that

> the IGS Analysis Center Coordinator devise a method to combine submitted LOD/UT1 results from the GPS Analysis Centers to form a preliminary UT1-UTC estimate.

This new UT1 combination will be used to align the IGS Preliminary orbits rather than IERS Bulletin A predictions. Because the GPS LOD/UT1 errors do not seem to be related to the satellite orbit errors in a simple way, a new method is needed for the combination, different from that used for polar motion. The Analysis Center Coordinator will fully document the UT 1 combination procedure adopted,

[5] *Modelling sub-daily EOP variations*

To account for variations in Earth orientation at nearly 24-h and 12-h periods, it is recommended that

> the IGS Analysis Centers follow the IERS Conventions and account for these effects in modelling GPS observable using the tidal model of Richard Ray.

This model should be used in the transformation between inertial and Earth-fixed coordinates (and visa versa) for all transformations used in GPS processing. Specifically,

> the diurnal and semidiurnal terms need to be included in the transformation of inertial GPS orbits into the Earth-fixed frame for submission to the IGS.

About 50% of the errors in this adopted model will "project" into the inertial orbits and of course the total error will be in the transformation from inertial into Earth-fixed coordinates, The one issue still to be addressed is do these contributions tend to cancel each other or do they add constructively.

[6] *Reporting EOP values*

With respect to diurnal and semidiurnal variations, it is recommended that

> when Earth orientation parameters are estimated, the procedures for reporting EOP values adhere to the IERS Conventions and guidelines, which are still to be determined. In particular, users must know how to relate the reported EOP values to the corresponding total values (including all tidal contributions) at the

associated UTC epoch.

The relationship between reported EOP values and the corresponding total EOP values should be explained in the Analysis Center Questionnaire.

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McCarthy, D., and B. Luzum, Changes in USNO GPS-only combination procedure, IGS Electronic Mail #1072, http: //igscb.jpl.nasa. gov/igscb/mail/igsmail/igsmess. 1072, 28 Sept. 1995.

IGS COMBINATION OF GPS EARTH ORIENTATION PARAMETERS(EOP)

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ABSTRACT

During the IGS Rapid orbit/clock combination, daily GPS based polar motion (PM) values (IERS designation: EOP(IGS)95 P 01) are produced weekly since January 1, 1995 with an 11 day delay. They are computed as weighted means from solutions submitted by the seven IGS Analysis Centers (ACs). Most ACS and the IGS Rapid (IGR) PM solutions have better than 0.5 mas precision, and clearly show smoothing effects in both IERS series (Bulletin A and B) for periods less than 10 days. Similarly, since January 1, 1996, another daily PM series (EOP(IGS)96 P 01) based on the IGS preliminary (IGP) orbit/clock combination is produced daily with only a 1.5 day delay. Currently, six IGS ACS are contributing to this IGP combination. The IGP PM precision is approaching the IGS Rapid PM precision level. These two PM series imply *Rx*, *Ry* orientations of the respective IGS orbit combinations. The *Rx*, *Ry* orbit rotations can be effectively used to evaluate orbit reference frame and PM consistency of the IGS and individual AC solutions. The orbit/PM consistency has improved slightly during 1995 and it is at, or below 0.1 mas for IGS combined and most AC solutions. The IGR PM combination (EOP(IGS)95 P 01) was compared to the IERS and USNO GPS based PM combinations. All three combined GPS PM series were found to be consistent at the 0.1 mas rms precision level, subject only to small offsets not exceeding 0.4 mas.

INTRODUCTION

Since January 2, 1994 orbit/clock solutions submitted by seven IGS Analysis Centers (ACs) have been combined into two classes of IGS orbit/clock solutions: the IGS Rapid and the IGS Final combinations. The IGS Rapid (IGR) combination is produced typically within 11 days since the last observation and was initially based on the IERS Bull.A, while the IGS Final combination is based on the IERS Bulletin B and is typically available within one to two month delay. For more details on both IGS combinations see the 1994 IGS Annual Report (Kouba et al., 1995).

Since January 1, 1996 a third IGS preliminary orbit/clock (IGP) combination was initiated with the participation of six ACS and with a much faster production cycle of less than a 38h delay. Since the IGP combination has proven to be successful and to economize the IGS combination efforts, as well as to speed up the delivery of IGS products, it has been recommended that as of June 30, 1996 (Wk 860) the IGP will replace the IGS Rapid combination and the current IGS Rapid will become the IGS Final orbit/clock combination. Both combinations will be carried out directly in the ITRF (Kouba et al., 1996).

EOP/ORBIT CONSISTENCY

The IGS orbit combinations were designed to mitigate small EOP errors and reference frame inconsistencies of individual Analysis Center (AC) solutions. Each AC orbit solution is first rotated to a common reference pole direction by applying appropriate PM differences. An unweighed mean orbit is then computed and AC solutions are further aligned by 7 parameter transformations before the final weighted orbit is generated (Beutler et al., 1995; Kouba et al., 1995). The IERS Bull. B PM, corrected for the IERS-ITRF misalignment, is used as the reference direction of the IGS Final orbit combinations, A high degree of reference frame consistency is ensured by all ACS using the same set of 13 ITRF station positions and velocities. The combination procedure also facilitates checking of orbit/EOP consistencies for all the submitted AC solutions by comparing AC orbit *Ry* and *Rx* rotations with the corresponding PM *x* and y differences . In other words, the AC PM solutions are compared with the IERS Bulletin B directly and by means of orbit alignments. Both comparisons should agree, provided that the AC PM and orbit solutions are consistent. Similarly the consistency of station coordinates and PM solutions could be analyzed; recently IGS and AC station solutions have become available.

The AC orbit orientation and PM solution differences with respect to Bull. B during 1994 and 1995 are summarized in Table 1 and 2, respectively. One can observe a good orbit/PM consistency and especially for 1995, most likely due to a more consistent reference frame (ITRF93), additional stations and AC processing improvements. The average PM and orbit orientation differences are similar and the corresponding sigmas are also consistent for most ACS. There are some y-coordinate differences between PM and orbit orientation in particular in 1994. These may be due to differences in ITRF station constraints, i.e. the sigmas and the number of constrained stations (ACS are free to constrain/fix more than the 13 ITRF stations), as well as in modeling, observation weighting, station distribution (geometry), etc.

Table 1: IGS Final Orbit orientation and IERS (Bull. B) PM differences during 1994.
(corrected for the IERS-ITRF92 misalignment; units: mas)

Center	IGS Final Orbits				IERS (Bull. B)				Difference (IGS-IERS)			
	x	sig	y	sig		sig	y	sig	x	sig	y	sig
COD	-.17	.37	-.32	.37	- .1;	.31	- .50	.36	.01		.18	
EMR	.08	.40	-.28	.47	.04	.39	-.41	.48	.04		.13	
ESA	-.18	.46	-.06	.43	-.14	.42	-.08	.44	-.04		.04	
GFZ	.39	.45	-.69	.52	.28	.30	-.40	.30	.11		-.29	
JPL	-.26	.36	-.28	.38	-.21	.35	-.31	.36	-.05		.03	
NGS	.23	.87	-.63	.68	.13	.80	-.84	.76	.10		.21	
S10	.49	1.04	-.41	1.13	.53	.52	-.16	.65	-.04		-.25	
MEAN	.08	.11	-.38	.08	.06	.10	-.38	.09	.02	.02	.01	.08

Initially, the IGS Rapid (IGR) and Final orbit/clock combinations were generated in the same way using the IERS Bull. A or B respectively for the combined orbit orientation. Since May 28, 1995 (GPS Week 0803), the IGR orbit combinations are no longer aligned to the Bull. A, but are directly combined in the ITRF93. This was made possible by the better orbit consistency between ACS in 1995 as discussed above. EOP series, consistent with the new IGR orbits have been produced as a weighted average of AC PM solutions by applying the orbit weights while preserving the Bull. A UT1 -UTC values. For completeness, the new IGS (IGR) EOP series (IERS designation: EOP(IGS)95 P 01), together with the new IGS Rapid orbit/clock combinations,. were subsequently reprocessed back to Jan. 1, 1995. The differences of the new IGR EOP series (with respect to Bull. B) are summarized in Table 2. One can also see a high degree of consistency between the Final Orbit and the IERS(Bull. B) differences. The IGR EOP combination (EOP(IGS)95 P 01) was used for AC pole comparisons in the next section.

Table 2: IGS Final Orbits and IERS (Bull. B) PM differences during 1995. (corrected for the IERS-ITRF93 misalignment; units: mas)

Center	IGS Final Orbits				IERS (Bull. B)				Difference (IGS-IERS)			
		sig	y	sig	x	sig	y	sig	x	sig	y	sig
CODE	-.:5	.29	-.39	.24	-.04	.31	-.35	.29	-.01		-.04	
EMR	-.06	.31	-.03	.38	-.04	.37	.04	.40	-.02		-.07	
ESA	.14	.41	.29	.42	.20	.43	.37	.42	-.06		-.08	
GFZ	.11	.25	-.21	.20	.18	.32	-.14	.26	-.07		-.07	
JPL	.04	.28	-.49	.25	.05	.31	-.34	.26	-.01		-.15	
NGS	.28	.41	-.31	.38	.25	.46	-.20	.43	.03		-.11	
S10	-.15	.65	.04	.61	-.17	.70	.03	.63	.02		.01	
MEAN	.04	.05	-.16	.10	.06	.06	-.08	.10	-.02	.01	-.07	.02
IGR (EOP(IGS)95 P 01)					.05	.29	-.14	.22				

The last two lines of Table 2 also demonstrate the level of consistency between the IGS Final and Rapid orbit combinations during 1995. The largest differences in PM orientation are smaller than 0.2 mas which is well within the expected stability of both the IGS and IERS PM series.

INDIVIDUAL AC POLE SOLUTIONS

While performing routine evaluation of the IGR PM, significant and sometimes periodic differences approaching 1 mas with periods between 5-10 days (see e.g. Fig. 1), with respect to both IERS combinations (Bull. A, B) have been observed, After examining and eliminating a number of potential systematic effects (e.g. the sub-daily PM, interpolation, etc.) it was concluded that the differences between the GPS and the IERS PM series are due to smoothing applied to both IERS PM series. The GPS PM variations correspond to atmospheric PM effects as predicted almost a decade ago by Eubanks et al. (1988), (Eubanks, 1996). It has been detected for the first time thanks to the IGS. Subsequently both USNO and the IERS Central Bureau have adopted much weaker smoothing schemes for the IERS Bulletin A and B.

The differences with respect to the Bull. B (i.e. EOP(IERS)C04) for the IGR PM combination and the individual AC pole solutions (with respect to IGR) are shown in Figures 1-2. The smoothed out atmospheric signal is clearly visible for the IGR PM as the EOP(IERS)C04 in 1995 did not yet employ the new smoothing scheme. The IGR standard deviations in Table 2 (0.2-0.3 mas) are mainly due to the atmospheric signal smoothed out in the Bull . B, as pointed out above.

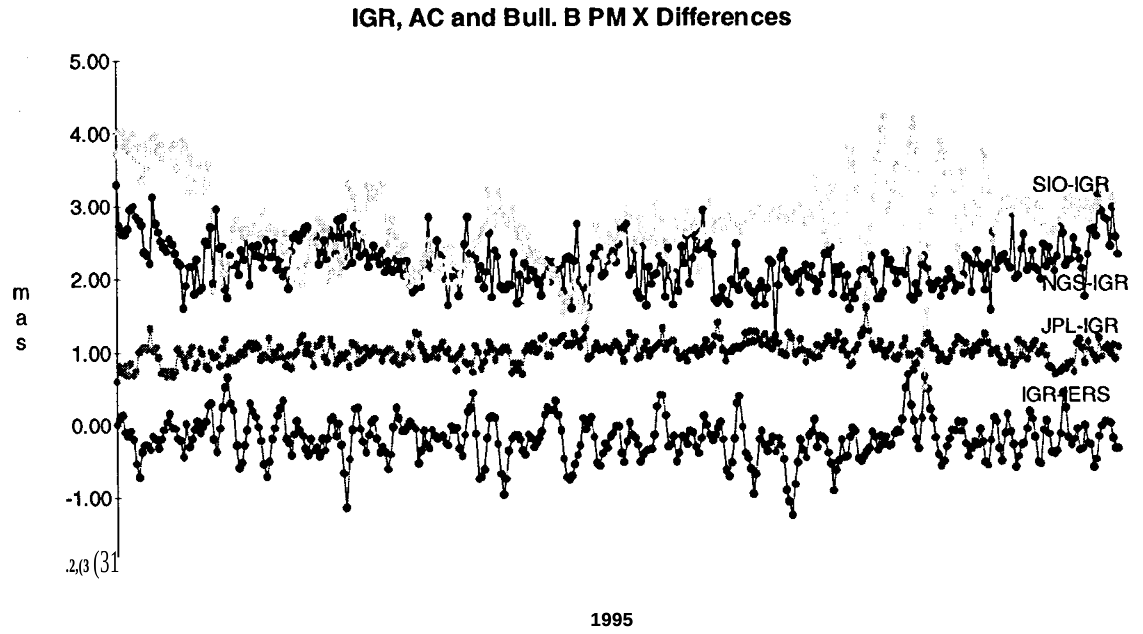

Fig. 1a. Polar Motion (PM) X Coordinate Differences for IGR (EOP(IGS) 95 P 01) with respect to the IERS (Bull. B), and JPL, NGS, S10 (offset by 1,2,3 mas, resp.) with respect to IGR

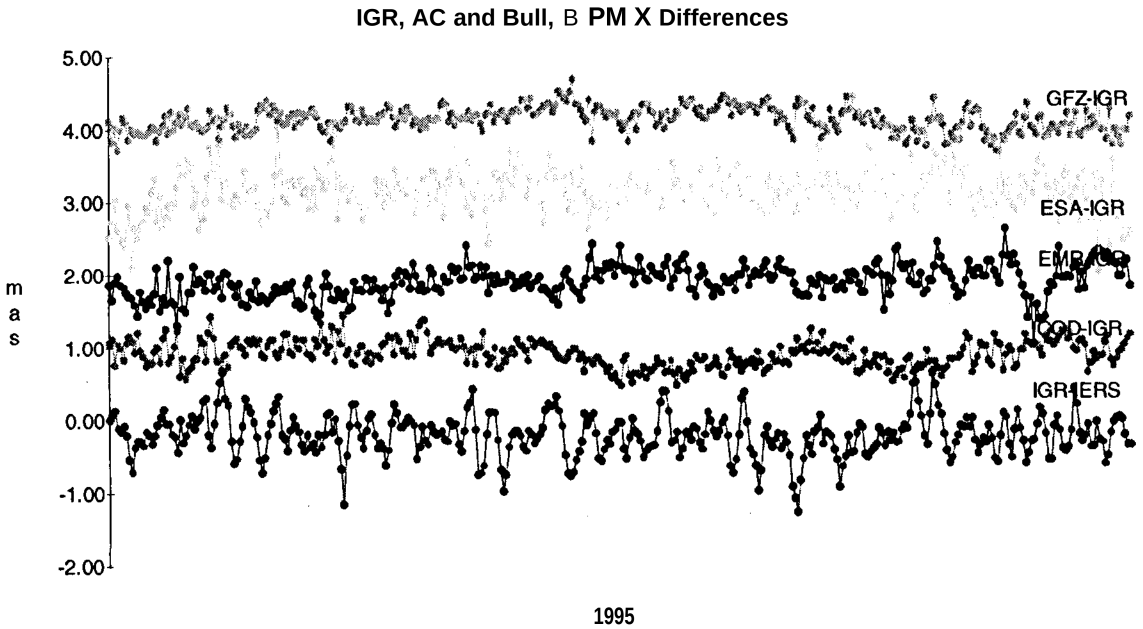

Fig. lb. Polar Motion (PM) X Coordinate Differences for IGR (EOP(IGS) 95 P 01) with respect to the IERS (Bull. B), and COD, EMR, ESA, GFZ (offset by 1,2,3,4 mas, resp.) with respect to IGR.

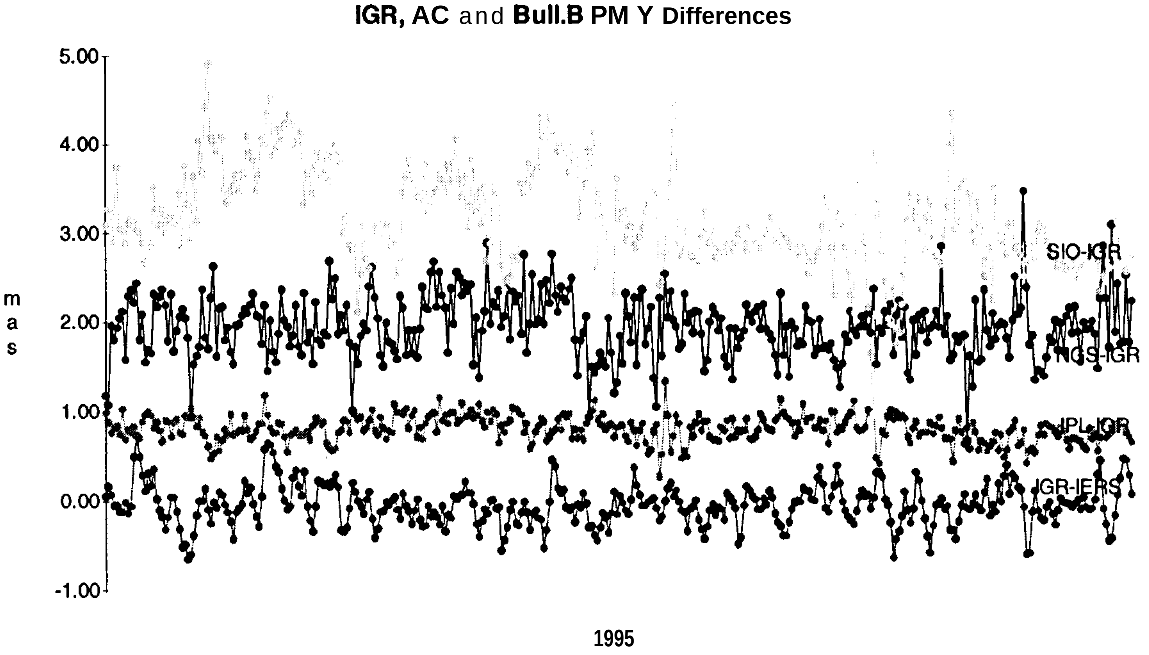

Fig. 2a, Polar Motion (PM) Y Coordinate Differences for IGR (EOP(IGS) 95 P 01) with respect to the IERS (Bull. B), and JPL, NGS, S10 (offset by 1,2,3 mas, resp.) with respect to IGR

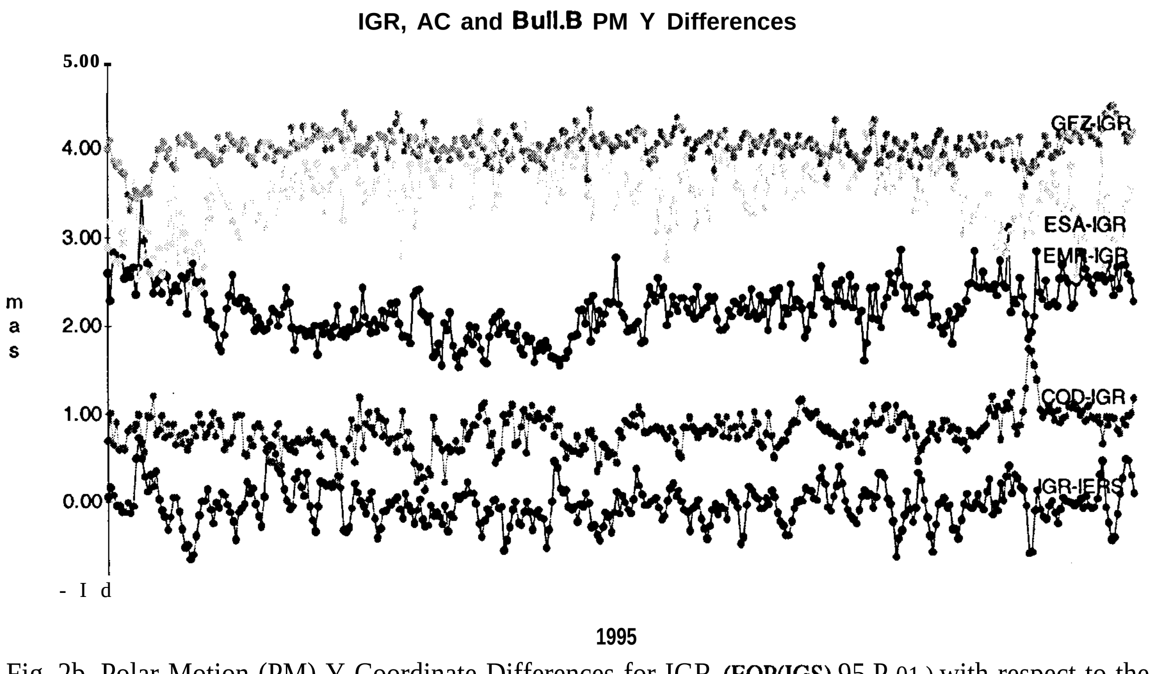

Fig. 2b. Polar Motion (PM) Y Coordinate Differences for IGR (EOP(IGS) 95 P 01) with respect to the IERS (Bull. B), and COD, EMR, ESA, GFZ (offset by 1,2,3,4 mas, resp.) with respect to IGR.

COMPARISON OF GPS PM COMBINATION SERIES FOR 1995

Currently there are three GPS PM combination series: IGR, USNO and IERS. The IGR (EOP(IGS)95 P 01) and IERS combinations utilize identical input series (i.e. the 7 IGS AC EOP solutions), whereas USNO adds its own GPS PM solution. The three PM combinations use different editing, bias removal and smoothing. In the case of the IGR PM combination, it employs the IGR orbit weights and editing, but no biases or smoothing are applied (Kouba, 1995). It is oriented to ITRF93 as realized by the 13 ITRF93 station positions of date. The differences between the three GPS PM combinations and the IERS Bull. A and Bull. B (EOP(IERS)C04) are shown in Table 3. This comparison does not introduce any data filtering, weighting, biases removal, nor the IERS-ITRF93 alignment,

Table 3: Differences for IERS, USNO and IGS GPS PM combination series for 1995 (mas):

Difference	Mean X	sig	Mean Y	sig
IGS GPS -EOP(IERS) C04	-.20	.29	-.04	.22
IERS GPS-EOP(IERS)C04	.08	.29	.02	.24
USNO GPS-EOP (IERS)C04	.17	.29	-.20	.23
BULL A -EOP(IERS)C04	.17	.24	-.22	.27
IGS GPS -BULL A	-.38	.15	.17	.18
IERS GPS -BULL A	-.10	.18	.22	.19
USNO GPS-BULL A	.00	.13	.02	.16
IERS GPS-IGS GPS	.28	.10	.06	.10
USNO GPS-IGS GPS	.37	.08	-.15	.09
IERS GPS-USNO GPS	-.10	.12	.21	.10

Assuming no correlation between the three GPS combined series, the following rms estimates are obtained for the three PM combinations (Table 4):

Table 4: Estimated rms for the GPS PM combination series for 1995 (mas) .

Series	Pole X	Pole Y
IERS	.097 mas	.080 mas
USNO	.076	.065
IGS	.038	.061

The differences for the three combined PM series are also plotted in Figure 8. Small differences in smoothing, stability as well as biases can be observed. The biases between IERS and IGS PM, to a large extent, can be explained by the misalignment between the IERS EOP and ITRF93 as published in the 1993 IERS Annual Report (Table II-3, p. 11-19).

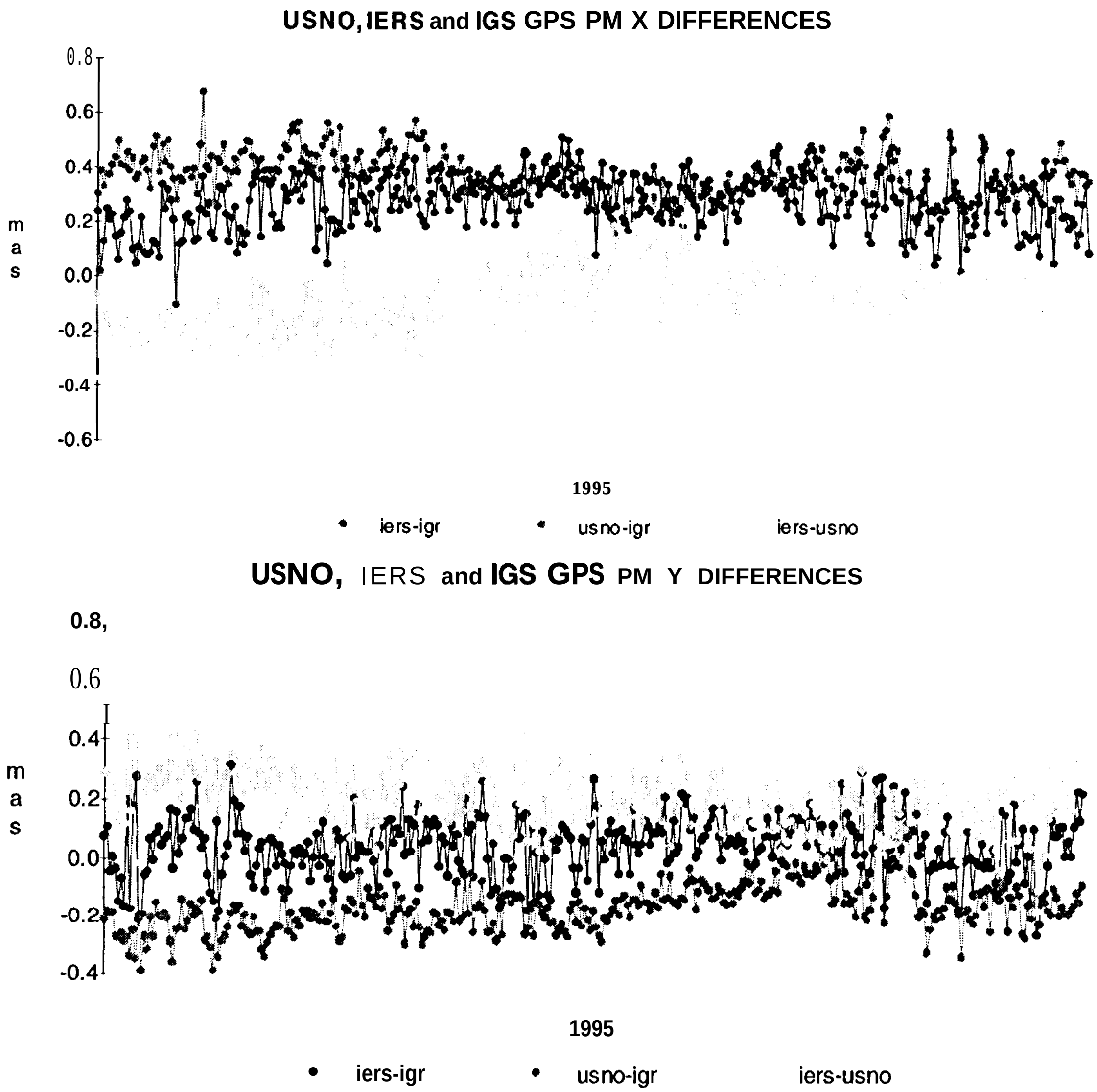

Fig. 3. IERS, USNO and IGR (EOP(IGS)95 P 01) GPS PM combination differences.

IGS PRELIMINARY COMBINATION

The IGS Preliminary (IGP) combination, initiated in January 1996, employs the same strategy as the IGS Rapid (IGR) combination, but it is produced within 38h after the last observation and uses six AC preliminary solutions. The precision of preliminary AC solutions might be affected by an absence of some geometrically important stations which are not available at the time of processing (Kouba et al,, 1996). Figure 4 compares the IGP PM (EOP(IGS)96 P 01) to the current Bull. A for the first two months of 1996 and shows rms below 0.5 mas.

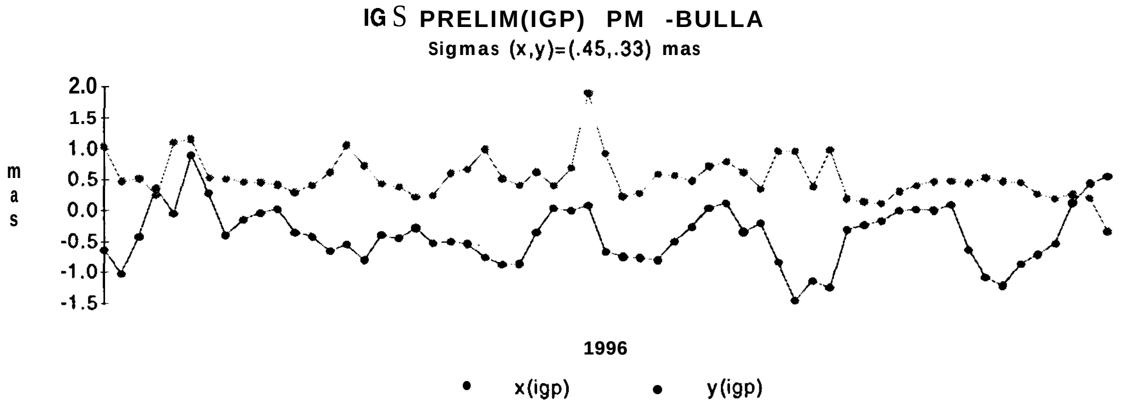

Fig. 4. IGS Preliminary (IGP) PM combination (EOP(IGS)96 P 01) differences with respect to the IERS Bulletin A for January - February, 1996.

Similarly as for the IGR series, UT1 -UTC is obtained from the IERS Bull. A, available at the time of combination which are usually predictions of more than one week, This is clearly visible in Figure 5 where IGP UT 1 -UTC is compared to the IERS Bull. A which already include results from daily VLBI observations. The systematic trend with increasing prediction periods and regular weekly resets produce the saw tooth effect. Also shown in Figure 5 is a simple arithmetic average of the six AC solutions *(UT1(IGS))* and the same average corrected for a drift averaged over the two months *(UT1c(IGS))*, to show the feasibility and desirability of IGS UT1-UTC combinations. Ray (1996) examines GPS UT 1 -UTC solutions and possible combinations in more details.

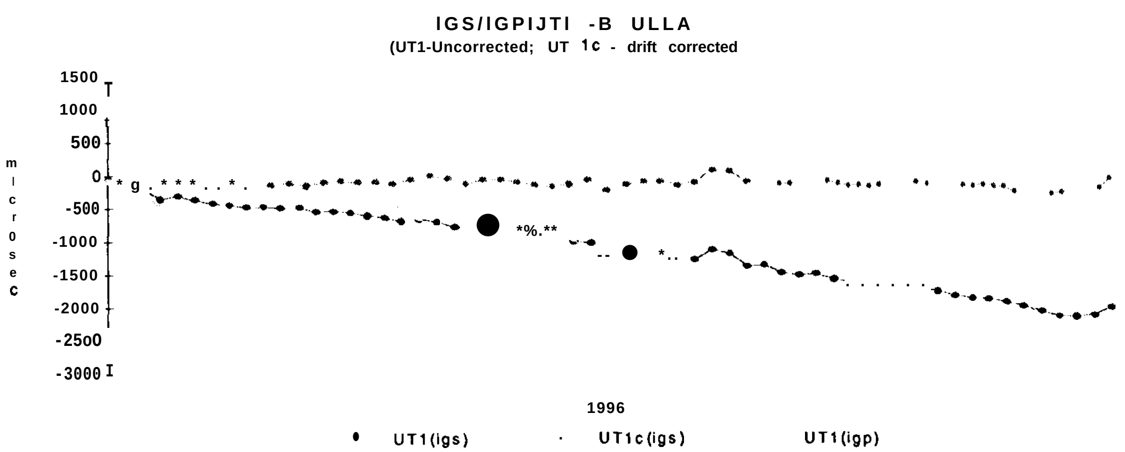

Fig. 5. IGS Preliminary UT1-UTC combination differences with respect to the IERS Bulletin A for January - February, 1996. *UT1(igs)*- a simple average of 6 AC UT] solutions; *UT1c(igs)* - drift corrected UT 1 (igs); *UT1 (igp)* - the Bull. A prediction used in EOP(IGS)96 P 01.

CONCLUSIONS

The IGS combined and most individual AC PM solutions showed steady improvement in precision and consistency approaching the 0.1 mas level during 1994 and 1995. The IGS Final and Rapid orbit orientations were consistent within 0.1 mas in 1995 and thus no significant orientation discontinuities are expected when the current IGR orbit combination will become the IGS Final products on June 30, 1996.

The IGR PM solutions show real PM variations with 2-10 day periods which have been related to atmospheric effects. The current daily GPS PM solutions produced by AC are typically 24h averages, largely independent from day to day. Any signals with periods less than 24h, such as sub-daily tidal effects are effectively averaged out. As a simple average of sub-daily PM model values over a 24h (UTC) period is typically less than .002 mas, 24h average PM solutions are reported regardless of whether the sub-daily PM is applied or not. This should clarify the matter for most IGS users.

The IGS Preliminary (IGP) combinations, which are soon to replace the IGS Rapid combinations, are producing useful and timely PM and UT 1 -UTC. The need for improved IERS (Bull. A) predictions, or an IGS UT1 -UTC combination is also apparent,

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GPS MEASUREMENTS OF LENGTH-OF-DAY: COMPARISONS WITH VLBI AND CONSEQUENCES FOR UT1

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ABSTRACT

Length-of-day (LOD) estimates from the seven GPS Analysis Centers of the IGS have been compared to values derived from VLBI for a recent 16-month period. All GPS time series show significant LOD biases which vary widely among the Centers. Within individual series, the LOD errors show time-dependent correlations which are sometimes large and periodic. Clear correlations between ostensibly independent analyses are also evident. In the best case, the GPS LOD errors, after bias removal, approach Gaussian with an intrinsic scatter estimated to be as small as -21 μs/d and a correlation time constant of perhaps 0.75 d. Integration of such data to determine variations in UT1 will have approximately random walk errors which grow as the square-root of the integration time. For the current best GPS performance, UT 1 errors exceed those of daily 1-hour VLBI observations after integration for -3 d. Assuming the stability of LOD biases can be reliably controlled, GPS-derived UT1 can be useful for near real time applications where otherwise extrapolations for several days from the most current VLBI data can be inaccurate by up to -1 ms.

INTRODUCTION

The rate of spin of the Earth about its polar axis varies on all observable timescales by up to a few milliseconds (ins) per day. Currently, the average day length exceeds 86400 s (as measured by atomic time or TAI) by roughly 2 ms, with variations over the previous year of more than 1 ms. The related quantity Universal Time (UT1) is the conventional measure of the instantaneous angle of rotation of the Earth, relative to the "fixed" stars, and is expressed in time units. Excess length-of-day is then defined as

$$LOD = - d(UT1-TAI)/dt$$

(For reference, 1 m of rotation of the Earth at its equator corresponds to a change in UT1 of 2.15 ins.) Tidal distortions of the Earth's moment of inertia induced by the gravitational attractions of the Sun and Moon cause UT 1 variations at the 2 ms level which are accurately predictable (Yoder *et al.,* 198 1). However, unpredictable UT1 variations of comparable or larger magnitude are produced by a variety of geophysical processes (Hide and Dickey, 199 1). To maintain accurate knowledge of the current orientation of the Earth in inertial space therefore requires periodic measurements of the positions of reference celestial objects from known points on the Earth's surface. Historically, this function was performed by timing the meridional transits of stars. In addition to their practical value, accurate UT 1 measurements are used to evaluate the bulk geophysical properties of the Earth independently of viscoelastic models (e.g., Robertson *et al.,* 1994) and to study the Earth's excitation mechanisms for angular momentum exchange (e.g., Dickey *et al.,* 1992).

With the development of space geodetic techniques beginning in the late 1970s, the accuracy of UT 1 measurements was improved by about two orders of magnitude (Carter et *al.*, 1985). Very long baseline interferometry (VLBI) has demonstrated highly accurate and stable determinations of UT 1, in large part because its very precise observations of extragalactic radio sources provide access to a nearly inertial celestial reference frame. Lunar laser ranging (LLR) is also capable of determinating Earth rotation but its measurement history has been sparse and significantly less accurate. It has long been expected that radio observations of satellites in the Global Positioning System (GPS) could be used to determine daily UT 1 or LOD values to supplement and eventually to replace, partially, those from VLBI. Indeed, the satellite laser ranging (SLR) technique has already shown that a satellite-based method can provide rapid and frequent estimates of UT 1 although the results have not been sufficiently accurate or stable enough to reduce the need for VLBI. GPS offers the potential of improved UT 1 or LOD results with higher time resolution and reduced operations costs owing to the more robust constellation of 24 satellites and a dedicated global ground tracking network (Beutler *et al.*, 1994). Improved measurements of high-frequency LOD variations could help resolve remaining discrepancies in the Earth's angular momentum budget in the subseasonal range (Dickey *et al.*, 1992).

All satellite-based techniques are handicapped in their ability to observe UT1 by the fact that the rotation of the Earth is indistinguishable from a uniform rotation of the satellite orbit nodes. Hence, if the satellite orbits are not already accurately known and must be estimated from the same data used to monitor Earth rotation, the problem is singular without applying additional constraints. LOD, on the other hand, can be determined together with the satellite orbit elements. A time series of continuous LOD values can then be integrated to yield UT 1 variations as a function of atomic time. However, any unmodeled forces acting on the satellites which affect the rate of change of the satellite nodes will contaminate the LOD estimates. If the systematic errors are constant, the resulting LOD bias can be determined empirically by comparison with VLBI results and corrected. If the unmodeled satellite forces are random, producing LOD estimates with a white noise error distribution, then integration will give UT 1 estimates with a random walk error distribution. In reality, a combination of the two cases is expected. Current SLR analyses, for example, have shown UT 1 variations can be tracked at 3-day intervals with root-mean-squared (rms) residuals $<100\ \mu s$ while applying constraints to VLBI-based UT 1 for periods longer than -60 days (Eanes and Watkins, 1994).

This report examines the quality of LOD results from the seven operational Analysis Centers of the International GPS Service for Geodynamics (IGS) (Beutler *et al.*, 1994) for a recent 16-month period, compared with VLBI determinations. The statistical properties of each GPS time series are characterized and the prospects for their use in multi-technique programs to monitor Earth rotation are evaluated. Following common practice, all UT 1 and LOD times series used here have been adjusted to remove zonal tide contributions (for periods up to 35 d) (Yoder *et al.*, 1981; McCarthy, 1992) leaving the purely non-tidal UT 1 R and LODR components for analysis.

REFERENCE LODR TIME SERIES FROM VLBI

To best characterize GPS-based LOD estimates, we seek an independent time series of clearly superior stability and accuracy sampled at least as frequently as the daily GPS values. VLBI is the only technique both fully independent and sufficiently accurate to qualify for such a reference series; see, for example, IERS (1995). Unlike GPS, however, VLBI does not operate continuously. A single large VLBI network, organized by the National Earth Orientation Service (NEOS), runs for 24 hours once per week specifically to monitor all components of Earth orientation (Eubanks *et al.*, 1994). Estimates of UT1 and LOD from each weekly session have formal uncertainties of -5 μs and -10 μs/d, respective y. To monitor subweekl y UT 1 variations, a separate series of 1-hour VLBI sessions runs nearly daily using a single east-west baseline between the eastern U.S. and Germany (Ray *et al.,* 1995), These abbreviated VLBI sessions cannot determine LOD but do give UT 1 estimates with formal uncertainties of roughly 20 μs. In addition to the sessions to monitor Earth orientation, a variety of other VLBI networks operate for 24-hour periods at irregular intervals, mostly organized by NASA for such purposes as crustal motions studies. While some of these determine UT 1 and LOD as well or better than the NEOS network, others are geometrically weak.

We have considered all available VLBI sessions during a recent 16-month study period (489 days from 03 Jul. 1994 to 03 Nov. 1995; see following section) and used the homogeneous analysis performed operationally by the U.S. Naval Observatory (USNO) referred to as series ‘ ‘n9504”. This series was submitted to the International Earth Rotation Service for its 1994 annual compilation (IERS, 1995). During the study period, 196 estimates of UT 1 and LOD are available from 24-hour VLBI sessions with average formal uncertainties of 8 μs and 17 μs/d, respectively. An additional 310 UT 1 determinations, with an average formal uncertaintyof21 μs, are contributed by the quasi-daily 1-hour sessions. Following tidal correction, these data have then been fit to cubic splines to interpolate LODR values for each daily noon epoch in the study period. Individual spline segments are fit to the UT1 R values available between successive 24-hour sessions with the slopes at each end constrained to equal -LODR from the 24-hour sessions. LODR at each noon epoch is simply the negative derivative of the UT 1 R spline fit. To avoid sometimes erratic behavior, it is necessary to edit the input data to cull poorly determined sessions and to eliminate data points spaced close together in time. The editting criteria were to omit UT 1 R and LODR values with formal uncertainties greater than 100 μs and 50 μs/d, respectively, and to delete data points closer together than 0.8 d based on larger formal uncertainty. Figure 1 (top) shows the resulting LODR time series, which is dominated by a large annual variation caused predominantly by the seasonal exchange of angular momentum between the atmosphere and the solid Earth (e.g., Hide and Dickey, 1991).

Errors have also been interpolated in an attempt to estimate the accuracy of the resulting daily time series of LODR values, First, the formal UT 1 R and LODR uncertainties from the VLBI analysis were resealed by a factor of 1.35 to account for likely underestimation of the true errors and an error floor of 15 μs was applied to the UT 1 R estimates from the 1-hour sessions; see Ray *et al. (1995)* for a discussion of these issues. Interpolation of the adjusted VLBI errors to the daily noon epochs of the LODR time series generally follows the development of Morabito *et al. (1988).* They have shown that LODR variations can be represented by an integrated white noise process (i.e., a random walk) driven by changes in atmospheric angular momentum; thus UTIR varies as an integrated random walk. Using their formulation, errors will grow as

$$\sigma_{LODR} = Q^{1/2}\, t^{1/2} = (60\ \mu s/d)\ t’”$$
$$\sigma_{UTIR} = (Q/3)^{1/2}\, t^{3/2} = (34.6\ \mu s)\, t^{3/2}$$

where t is the time (in days) since the last known values of UT 1R and LODR, respective?. Q is the power spectral density of the underlying white noise process, equal to 3600 μs /d according to Morabito *et al.* Since our case involves interpolation between two observed values of UT 1 R and/or LODR, the above error propagations have been

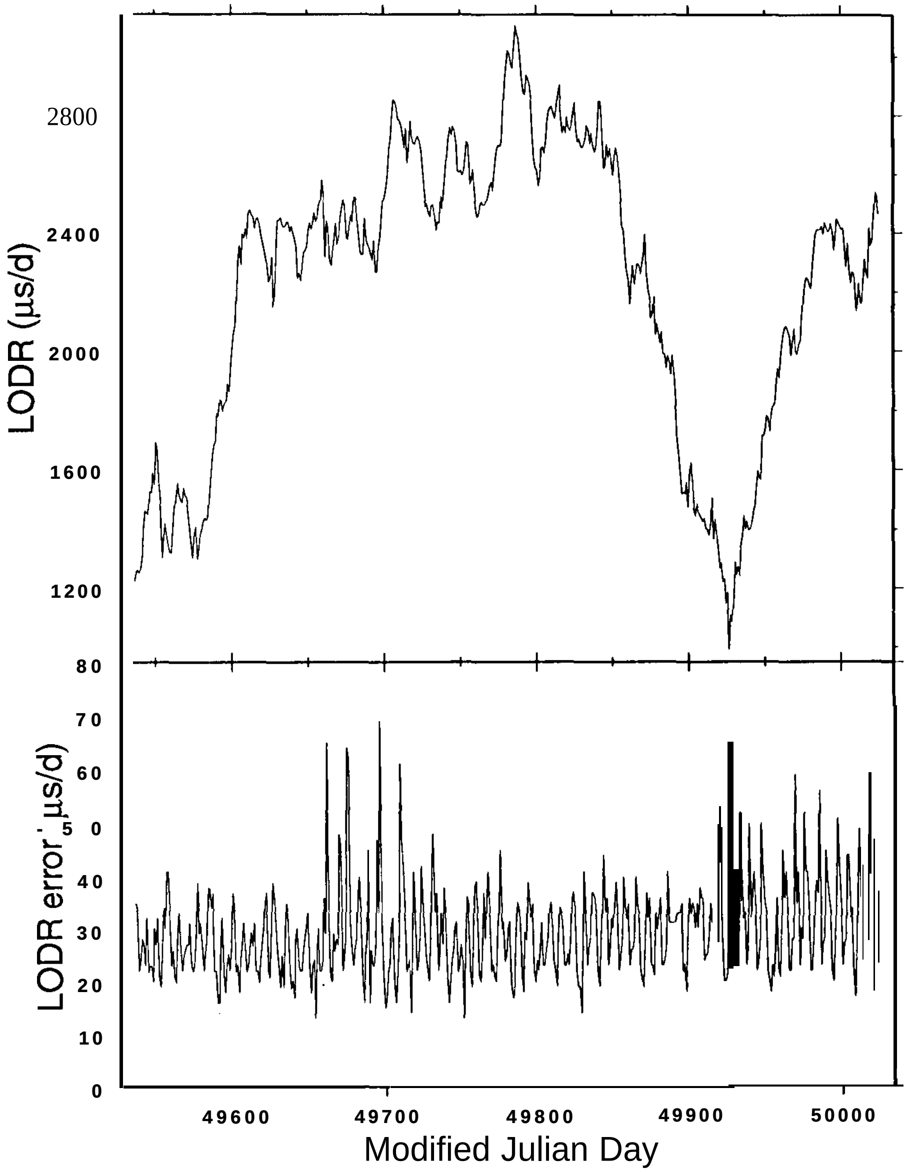

Fig. 1 LODR values (top) determined by a spline fit to UT1 and LOD estimates from VLBI data analysis by USNO. The corresponding LODR errors (bottom) are derived using the A AM excitation model of Morabito *et al. (1988)*.

reduced by a factor of √2. Finally, the adopted error of each interpolated LODR value has been taken to be the minimum of the interpolated LODR errors from each of the nearest LODR measurements; the errors in the time rate of change of UT 1 R interpolated from each of the nearest UTIR measurements. The resulting time series of LODR errors is plotted in Figure 1 (bottom). The average LODR error over this 16-month period is **26.2** µs/d. The 7-day modulation of the LODR errors evident in Figure 1 is due to the weekly interval between the robust, 24-hour VLBI sessions.

The methodology above may over-estimate interpolated LODR errors somewhat. The power spectral density value of Morabito *et al.* was derived from fits to daily atmospheric angular momentum estimates and may not apply for periods less than -2 d. Eubanks and Archinal (1996) offer evidence of an *upper limit* for Q which is about one-fourth the Morabito *et al.* estimate for periods under a day.

LODR TIME SERIES FROM GPS

The GPS data processing functions of the IGS (Beutler *et al.,* 1994) are performed independently by seven Analysis Centers (ACs), each of which receives raw observational data from a set of globally distributed, continuously operating receivers and produces daily estimates of the GPS satellite ephemerides, Earth orientation parameters (EOPs), station coordinates, and other products. The individual orbit results are then combined by the Analysis Center Coordinator to form a single IGS ephemeris for each GPS satellite. All products from the ACS and the IGS combinations are available from the IGS Data Centers. Table 1 lists the IGS ACS together with their three-letter code signifier. Each AC uses its own data analysis software except that JPL and EMR both use the JPL-developed GIPSY package, Four ACS (COD, ESA, NGS, and S10) analyze the GPS carrier phase data as double-differences while the other three Centers (EMR, GFZ, and JPL) use undifferenced data. Descriptive reports from each AC, together with additional information about IGS operations, are contained in the *IGS 1994 Annual Report* (IGS, 1995).

Table 1. IGS Analysis Centers

Code	Institution
COD	Center for Orbit Determination in Europe (CODE), Astronomical Institute, University of Bern, Bern, Switzerland
EMR	Natural Resources Canada (NRCan), Ottawa, Canada
ESA	European Space Agency, European Space Operations Center, Darmstadt, Germany
GFZ	GeoForschungsZentrum, Potsdam, Germany
JPL	Jet Propulsion Laboratory, Pasadena, California, USA
NGS	National Oceanic and Atmospheric Administration (NOAA), Silver Spring, Maryland, USA
SIO	Scripps Institution of Oceanography, La Jolla, California, USA

For this study we assume that the LODR (and UT1 R where available) estimates of the IGS ACS are strictly independent of the LODR and UTIR values determined by USNO from VLBI observations. Conceivably, this assumption could be violated if constraints were applied in any of the GPS data analyses relative to a priori UT 1 information from, for example, an IERS combination UT 1 time series or prediction series, dominated by the VLBI contribution. We have no evidence that such constraints are significant.

Earth orientation product files for each AC have been retrieved from the IGS Global Data Centers for the 16-month time period from 03 Jul. 1994 (MJD 49536.5) through 03 Nov. 1995 (MJD 50024.5), a span of 489 days. The starting date corresponds to the implementation of a standard IGS format for reporting Earth orientation results. EOP results are nominally reported for each 24-hour span at UTC noon epochs. Two ACS did not report LODR results for the full period: S10 omitted two weeks (MJD 49921.5-49927.5 and 49956.5-49962.5); NGS began reporting LOD on 06 Aug. 1995 so that only

90 days are available. Where necessary, tidal corrections were applied to reported LOD values.

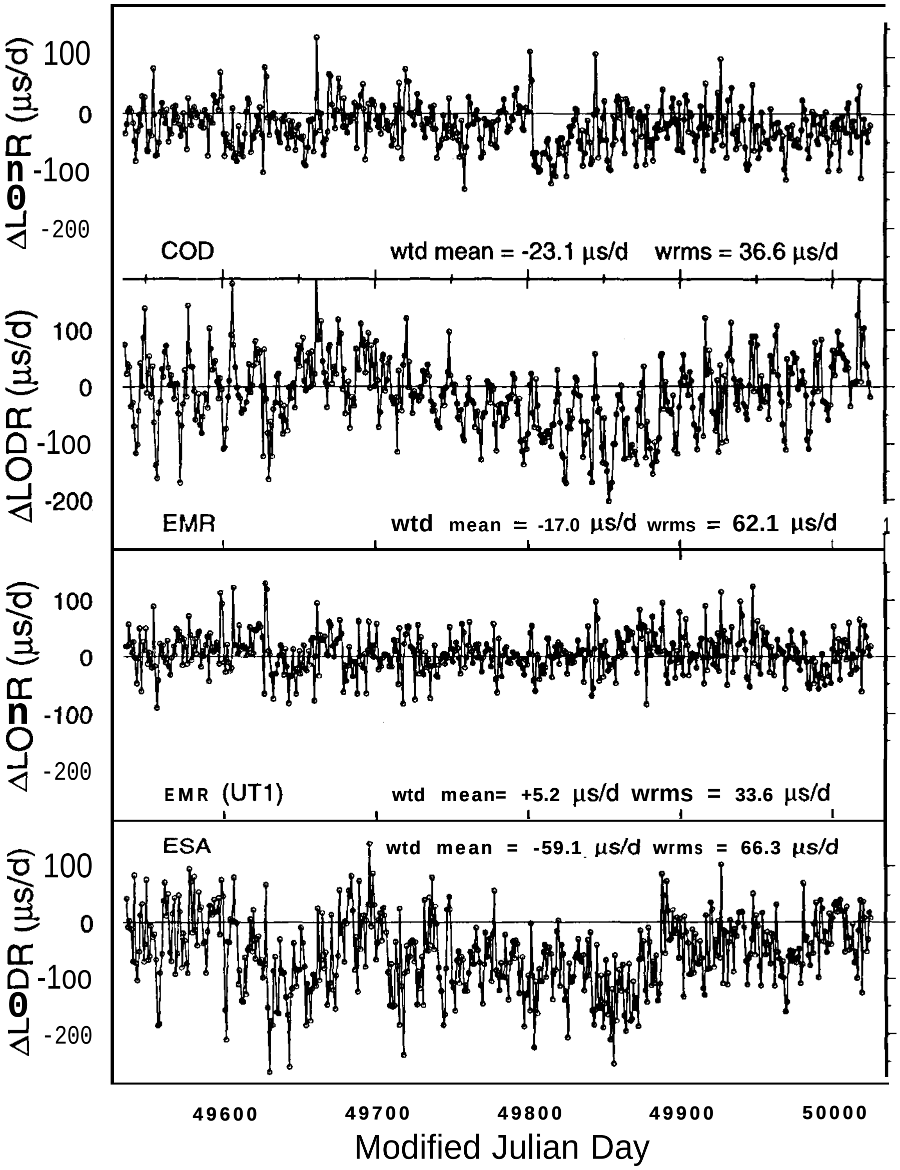

Fig. 2a LODR differences of each GPS time series relative to the VLBI-derived values shown in Figure 1. For each GPS series, weighted mean LODR differences and weighted rms scatters are listed using the VLBI-derived errors only.

EMR is a special case in reporting independent LOD and UT1 time series. (COD and JPL also report UT1 values but theirs are integrals of the estimated LOD values.) Stochastic modeling of the orbit parameters coupled with *a priori* constraints on the initial satellite states (based on the previous day's orbits) permits EMR to determine UT 1 and the satellite nodes simultaneously (Tétreault et *al.*, 1995). In order to include the EMR UT 1 series in this study the data were converted to LODR by first removing the tidal variations, then fitting with a cubic spline, and evaluating the spline derivatives at each

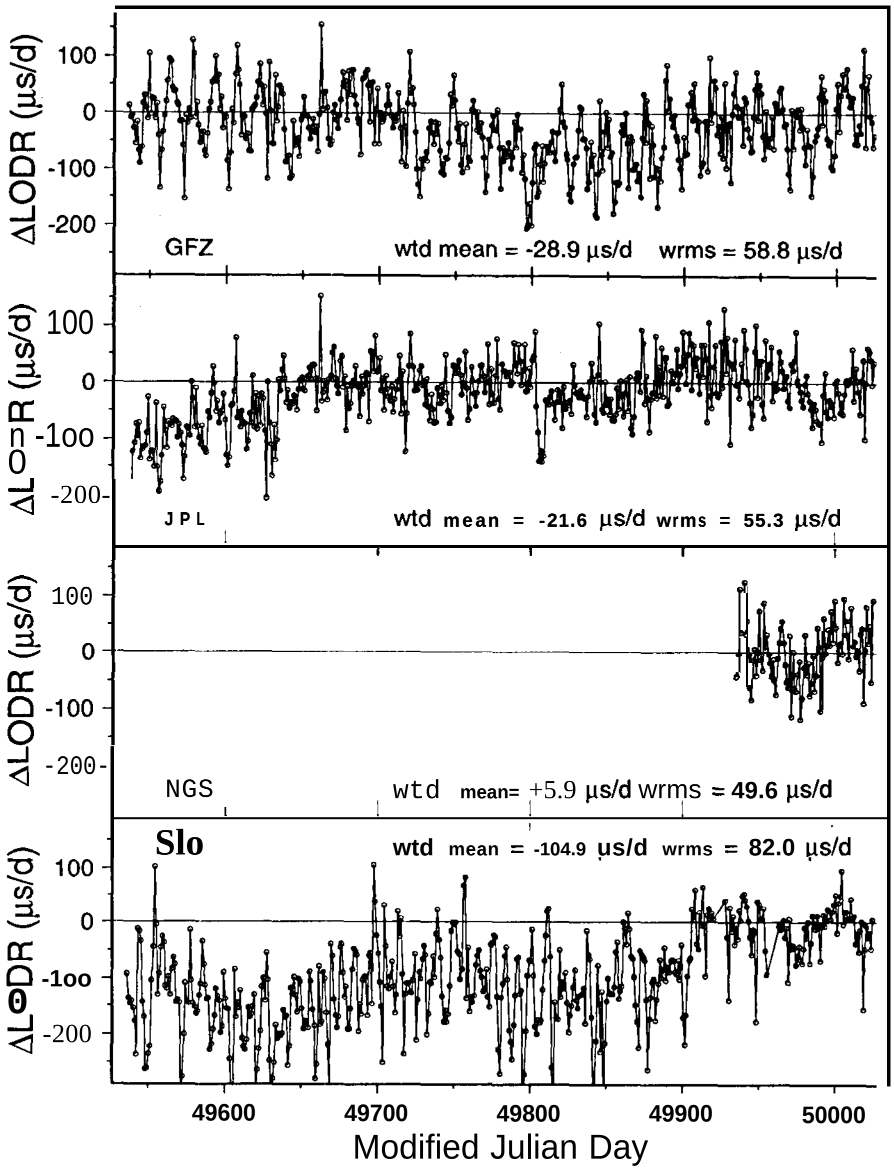

Fig. 2b Continuation of Figure 2a,

UT 1 epoch, In the following sections, this derived LODR series is distinguished from EMR's directly estimated LODR series by being labelled ' 'EMR (UT1)".

Figures 2a and 2b plot the differences of each GPS-based LODR time series with respect to the reference LODR series derived from VLBI data (shown in Figure 1). The weighted means of the differences and the weighted rms (wrms) scatters about the means are also shown. In computing these statistics, the LODR differences have been weighted using the estimated LODR errors of the VLBI-derived series onl y. The formal LODR uncertainties reported by the IGS ACS are very uniform in time and unrealistically small, ranging from an average value of 1.4 μs/d for COD to 17.9 μs/d for ESA, For this reason, the GPS formal uncertainties have been ignored,

IERS TIME SERIES C04

The IERS generates a continuously updated time series of daily EOP values referred to as C04, which is a combination of independent results from a variety of techniques and analyses. It is described as "slightly low-pass filtered" and suited for "all applications where an accurate model of the Earth orientation irregularities is needed" (IERS, 1995). Because this series is often used as a reference for comparison, its differences have also been computed relative to the VLBI-derived LODR series and the results shown in Figure 2c. Note, however, that C04 is not independent of the other series, having incorporated the n9504, COD, and EMR (UT1) series, among others.

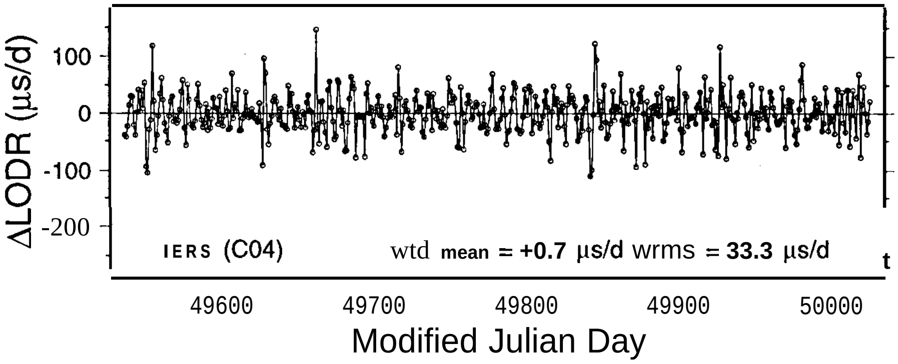

Fig. 2c LODR differences of IERS multi-technique combination series C04 relative to the VLBI-derived values shown in Figure 1. The weighted mean and rms scatter values shown use weights from the VLBI-derived errors only.

DISCUSSION OF LODR DIFFERENCES

A number of interesting observations can be drawn from inspection of the LODR differences plotted in Figures 2a and 2b. Most important is the fact that all GPS series show significant LODR biases relative to VLBI and usually the biases drift considerably with time. A constant LODR bias is equivalent to a linear time-dependent (UT 1 R - TAI) error (see further discussion below). Among the ACS, EMR (UT 1) has the smallest and most stable bias with an overall wrms of 33.6 μs/d. COD shows the next best scatter with a wrms of 36.6 μs/d but with a larger bias and an abrupt bias shift around MJD -49803 (27 Mar. 1995). The remaining series are more variable although most show indications of improvement in the more recent data, particularly JPL and S10.

Another important feature is the occurrence of correlated differences between series. Because a common VLBI-derived LODR reference has been used for all the differences, correlations are to be expected at some level. However, some correlations appear more likely to reflect errors common to one or more of the GPS series. Figure 3 illustrates such a case. In the top part of the figure are plotted expanded views of the LODR differences for the COD, EMR (UT1), and JPL series relative to VLBI. From MJD 49802.5 to 49803.5 (26-27 Mar. 1995) all three series show large changes in ALODR: -127, -99, and -132 μs/d, respectively. It is entirely possible that part of these abrupt shifts is caused by inaccuracies in the reference series. The bottom part of Figure 3 shows an expanded view of the daily VLBI-derived LODR series from Figure 1 while the middle part of the figure shows the distribution of available VLBI data (after editting) and their associated errors (after the adjustments discussed previously), It can be seen that the ALODR shifts fall near the middle of a 3.7-d gap in the VLBI data during which an are extremum of the LODR variation occurs. Thus the VLBI-derived LODR values around MJD 49803 are sensitive to the spline fit and may be suspect. On the other hand, the COD and JPL series show persistent LODR bias changes following the abrupt shift, whereas EMR (UT 1) does not. More than 20 days pass before the COD series returns to its previous bias level; the independent JPL series is similar altough the detail behavior appears more complex. It is perhaps noteworthy that the Analysis Center Coordinator reported orbit modelling problems by all ACS for eight GPS satellites during the week 26 Mar. -01 Apr. 1995 (Kouba *et al.,* 1995).

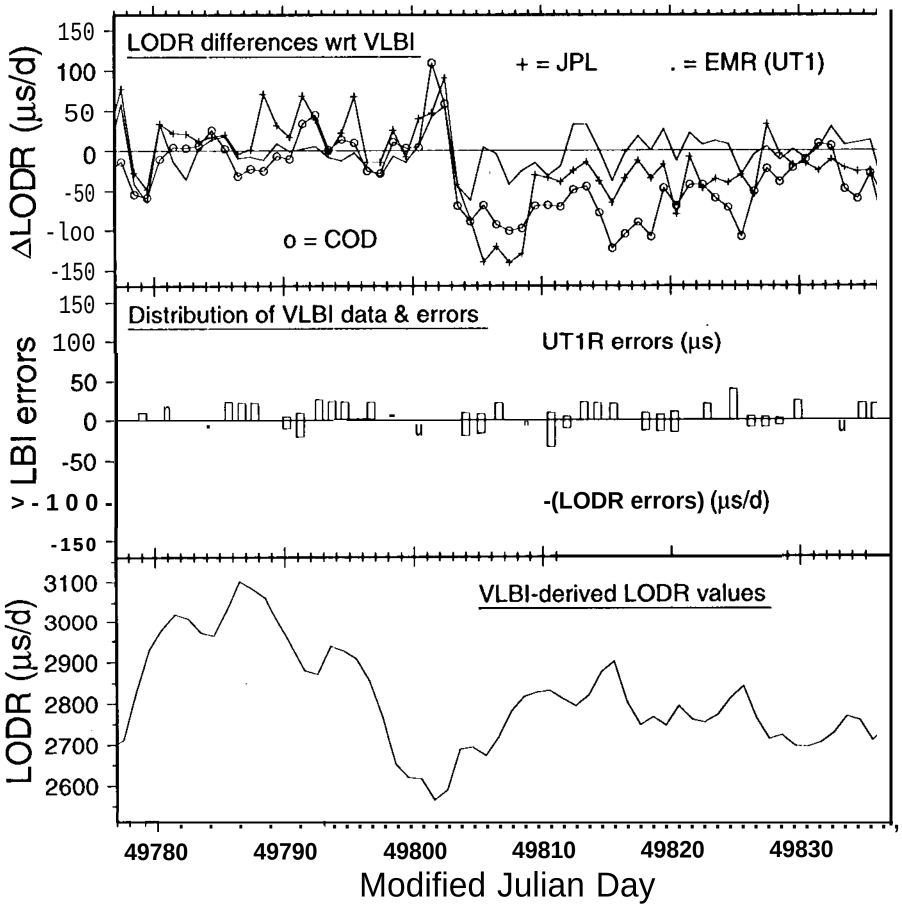

Fig. 3 Expanded view of LODR differences for COD, EMR (UT 1), and JPL during March-April 1995 (top), Corresponding VLBI-derived LODR values shown in the bottom with the distribution of VLBI data and errors shown in the middle.

An even more striking example of correlated errors between ostensibly independent GPS time series is shown in Figure 4, which is an expanded view of the last 125 days of ALODR time series for EMR (see Figure 2a) and GFZ (see Figure 2b). Both display large, systematic LODR variations that appear quasi-periodic and are highly correlated. This behavior characterizes the full study period, not just the range expanded for Figure 4. In contrast, the EMR series derived from their directly estimated UT1 series, EMR (UT1), has a very different behavior (see Figure 2a). Presumably, some aspect of the satellite orbit modelling by EMR and GFZ allows similar error leakage into their LODR estimates even though their analysis systems are independent.

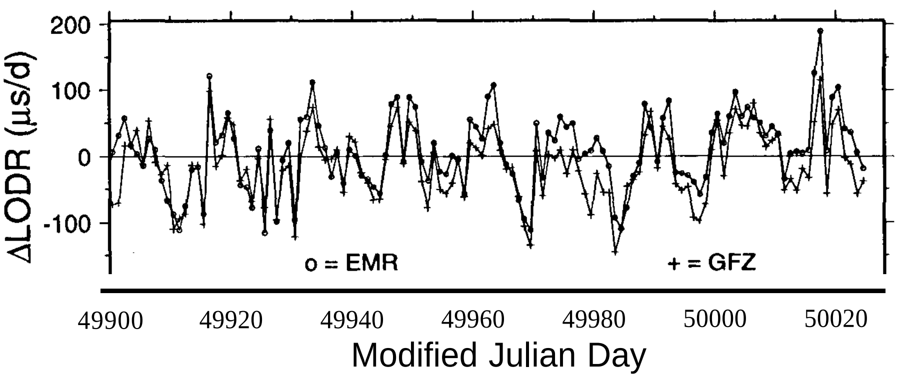

Fig. 4 Expanded view of LODR differences from Figures 2a and 2b for EMR and GFZ showing highly correlated variations.

These ALODR time series are direct evidence that: non-zero LODR biases area natural consequence of the GPS data analysis; LODR bias values and stability range widely depending on the analysis procedures used; LODR bias values are correlated in time for individual analyses and vary over a wide range of timescales; and large LODR errors may be correlated between nominally independent analysis systems. These characteristics must be taken into account if GPS LODR results are to be combined successfully with those from other techniques.

Finally, Figure 5 shows an expanded view of the LODR differences between IERS combined series C04 and VLBI (from Figure 2c). It is evident that the differences are not random and that there appear to be distinct periodicities. Since the n9504 VLBI data are common to both time series the differences should reflect the different styles for interpolating the observational results to an even time grid and the effects of other contributors to the C04 combination. According to IERS (1995), the UT 1R and LODR values in series C04 have been smoothed over periods <20 d; the filter response is -50% at 9-d periods. Thus, it seems reasonable to attribute much, if not most, of the systematic differences between C04 and VLBI to the smoothing applied in the C04 combination. This is important to note when characterizing LODR variations at the few-day level, as

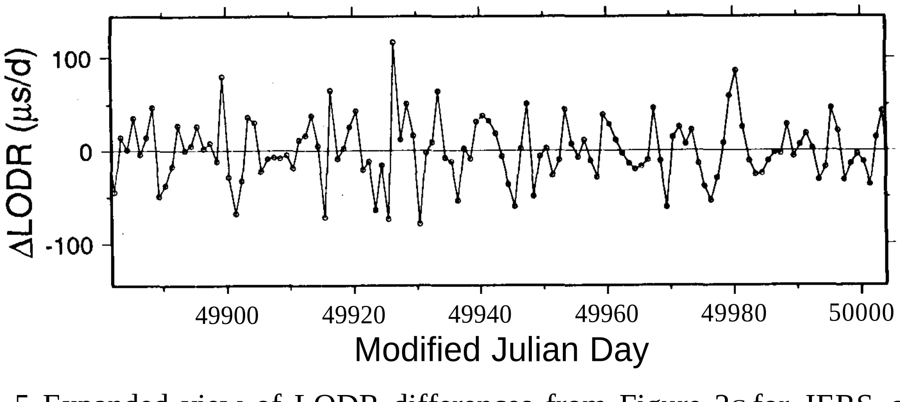

Fig. 5 Expanded view of LODR differences from Figure 2c for IERS combination series C04 showing systematic, quasi-periodic variations probably due to smoothing applied in the combination.

we are here. The C04 series is, however, unbiased relative to VLBI LODR over few-week periods.

ANALYSIS OF SCATTER OF GPS-DERIVED LODR ESTIMATES

Because the bias levels of GPS-derived LODR time series vary with time, a single wrms statistic for the entire 16-month study period does not adequately convey the performance over shorter intervals. To address this, wrms values for each ΔLODR time series have been recomputed using variable intervals over which to remove mean LODR biases. Figure 6 is a plot of the results for each AC and the IERS combination series C04. (The NGS data have been omitted here and in subsequent discussions due to their limited span.) At the longest interval, the wrms values are those shown in Figures 2a, 2b, and 2c. For a time series with stable LODR bias and random ΔLODR differences, the trend in Figure 6 would be flat with no dependence on bias interval. Only the IERS combination series C04 has an approximately flat trend, down to about 1-month intervals. EMR (UT1) and COD show the least influence of bias shifts among the GPS series. JPL, GFZ, EMR, ESA, and S10 all display steady declines in wrms ΔLODR scatter for shorter bias intervals, revealing the significance of LODR bias drifts.

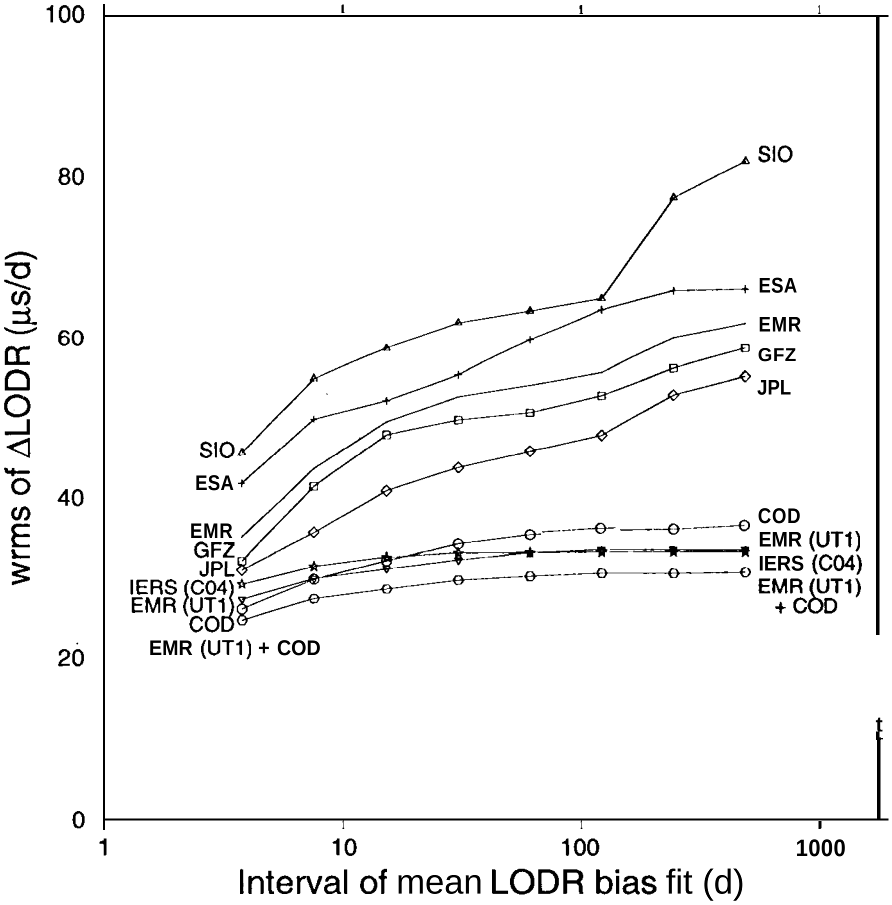

Fig. 6 Scatter of LODR differences for variable intervals used to fit mean LODR biases. Shown in addition to each IGS time series is the IERS combination C04 and an average GPS series formed by EMR (UT1) and COD.

Interestingly, while the wrms of the EMR (UT1) series is only very slightly greater than IERS C04 over the longest spans, it is less over intervals of -60 d and shorter. At - l-week periods EMR (UT 1) agrees significantly better with VLBI than does IERS, wrms differences being 29.9 μs/d versus 31.4 μs/d. This is evident by comparing Figure 2c with Figure 2a where is can be seen that EMR (UT1) tracks VLBI LODR variations very closely for extended periods, a pattern which is less apparent in the IERS LODR differences. Similarly, the COD series also agrees better with VLBI than does IERS over intervals shorter than -20 d, Again, we attribute the poorer short-term agreement for IERS to smoothing applied in forming the C04 combination series.

Motivated by the encouraging performances of EMR (UT1) and COD, it is worth evaluating an LODR series formed from the combination of those two. If their errors are largely independent, then such a combination should have improved performance. Such a series has been formed by simple averaging and its stability is included in Figure 6 labelled as ' 'EMR (UT1) + COD". This GPS combination LODR series has a weighted mean LODR difference relative to VLBI of -8.8 μs/d and a wrms of 30,8 μs/d. It has a smaller wrms ALODR scatter than IERS C04 over all intervals, by 2.5 μs/d over the longest spans increasing to 4,6 μs/d at -4 d. This is a clear indication that the information content of the various contributors (including VLBI, EMR (UT1), and COD) has not been optimally utilized in forming the IERS combination, probably due mostly to smoothing.

Tests with forming GPS-only LODR combinations using additional series have been less successful. While the results will depend to some extent on the scheme used to weight the ACS, only the addition of JPL to the EMR (UT 1) + COD combination gives a scatter smaller than the EMR (UT 1) series alone, and only very slightly. (See further discussion on GPS combinations below.)

If we accept the validity of the VLBI-based LODR error distribution shown in Figure 1 (where the average error is 26.2 μs/d) and assume that all other errors are independent (which is clearly not true for IERS C04) and Gaussian (also not true over short spans, at least) then wc can infer the noise-like "error" of each of the other series, after bias correction, averaged over the 16-month span: COD 25.5 μs/d, EMR (UT 1) 21.0 μs/d, EMR 56.3 μs/d, ESA 60.9 μs/d, GFZ 52,6 μs/d, JPL 48.6 μs/d, S10 77.7 μs/d, and IERS C04 20.6 μs/d. These results imply a noise-like error of 16.5 μs/d for the EMR (UT1) + COD combination. Since the VLBI errors are likely to be pessimistic, the inferred error estimates for the other series are actually lower limits.

IMPLICATIONS FOR MONITORING UT1

Despite the striking statistical agreement presented above between VLBI and some GPS determinations of LODR, the implications for monitoring UT1 remain unclear at this stage. Consider an ideal GPS-derived LODR time series which is unbiased and which has a small, random noise error, σ_{LODR}. Then integration will provide estimates of (UT1R - TAI) variation as a function of time t following some initializing epoch. If the LODR errors are white noise distributed, the error in the derived (UT 1 - TAI) will grow as a random walk, that is, as $t^{1/2}$. If there is an uncorrected LODR bias, then the UT1 error will have an additional linear drift contribution proportional to time. Rather than having a single well defined bias, if occasional bias shifts occur, then the resulting UT 1 will tend to follow a series of roughly linear segments connected by sharp changes in drift overlaying a random walk pattern.

Compare this expectation with actual results of integrating the differential LODR time series for COD, EMR (UT 1), IERS (C04), and EMR (UT 1) + COD, shown in Figure 7. (The other GPS series give much larger and more erratic ΔUT1R variations.) In each case the overall LODR bias has been removed before integration, producing the inferred variation of (UT 1 -TAI) relative to the VLBI n9504 time series, For clarity, the curves have been offset from one another by 500 μs. Because the mean LODR difference has been removed from each series (equivalent to removing an overall UTIR drift), ΔUT1R values are equal to zero at the beginning and end of each. Integration of IERS (C04) yields a ΔUT1R trend which is flat with relatively small scatter. It does not follow a random walk because the IERS LODR series was presumably derived by differentiating the C04 UTIR series. Integration merely restores the original UTIR variation and shows that differencing of the IERS LODR series with VLBI has not introduced any unexpected artifacts.

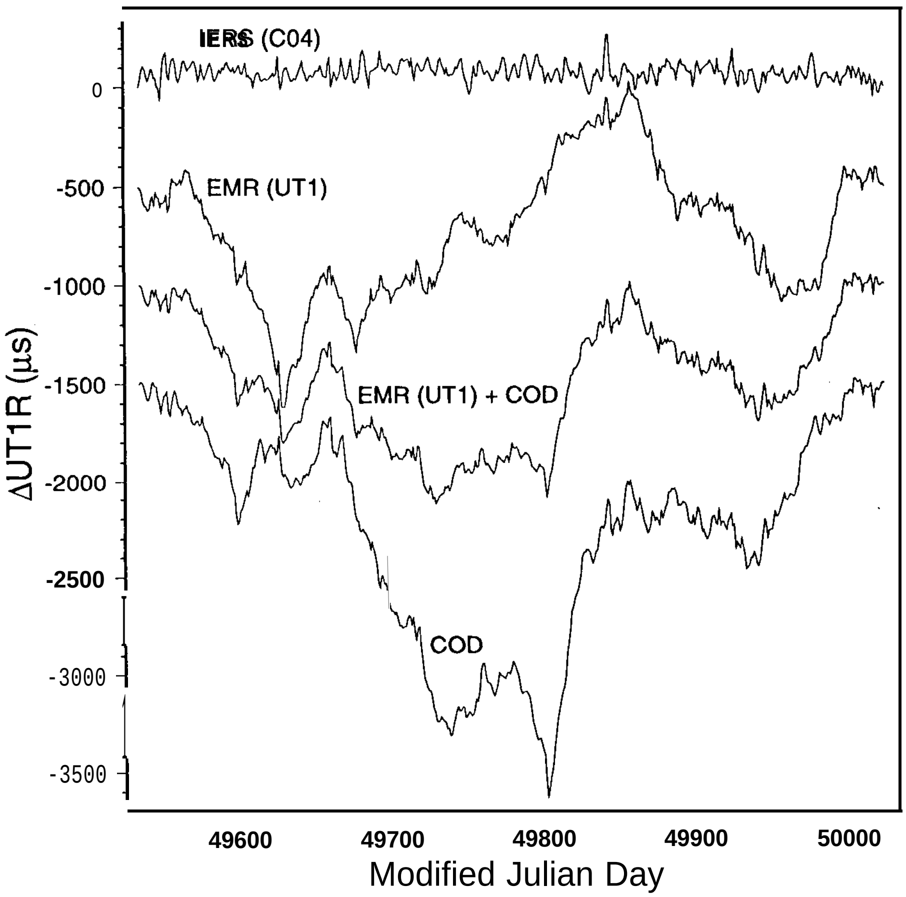

Fig. 7 UTIR variations, relative to VLBI, from integrating LODR differences for the COD and EMR (UT1) series, their average, and the IERS combination C04. Trends have been offset from one another by 500 μs.

The trends of the GPS-derived ΔUT1R series more closely resemble random walks. The excursions for COD, more than 2100 μs, are distinctly larger than for EMR (UT1), -1100 μs despite similar inferred LODR "noise" estimates of 25,5 and 21.0 μs/d. This difference in behavior is not likely to be related simply to the random walk effect of integrating white noise. Inspection of Figure 2a shows that the COD LODR differences are not random, even apart from the bias shift at MJD -49803. There are clear trends in the LODR bias level with time. Computing LODR bias fits at 1-month intervals, gives values ranging from -2,8 μs/d to -53.3 μs/d, compared with the overall bias of -23.1 μs/d. Over 1-month periods, such biases will accumulate to UT1 excursions of -600 μs to +900 μs relative to the overall trend, as observed in Figure 7. The range of month-long LODR bias drifts is smaller for EMR (UT1), from -13.0 μs/d to +23.8 μs/d about the overall mean of +5.2 μs/d, and better distributed about the overall mean bias, as evident in Figure 2a. The derived ΔUT1R for EMR (UT1) could be considered roughly consistent with the random walk model although the effects of small LODR bias shifts are still apparent. However, considering this series was originally estimated directly as UT1, then differentiated for this study before being integrated back to UT1, the behavior should resemble IERS C04. That it does not, but is closer to a random walk, indicates that the EMR analysis procedure actually models this parameter more as an integrated LODR than a true UT 1, as expected for a satellite-based technique.

Based on these results, a Gauss-Markov process is probably a better model for the LODR errors of the GPS estimates (after bias correction) than is pure white noise. For this case, the autocorrelation function for a time lag t is $\sigma_{LODR}^2 \exp(-|t|/\tau)$ where τ is a characteristic correlation time constant, For comparison, the autocorrelation function for white noise is a Dirac delta function. Upon integration, the variance of the resulting

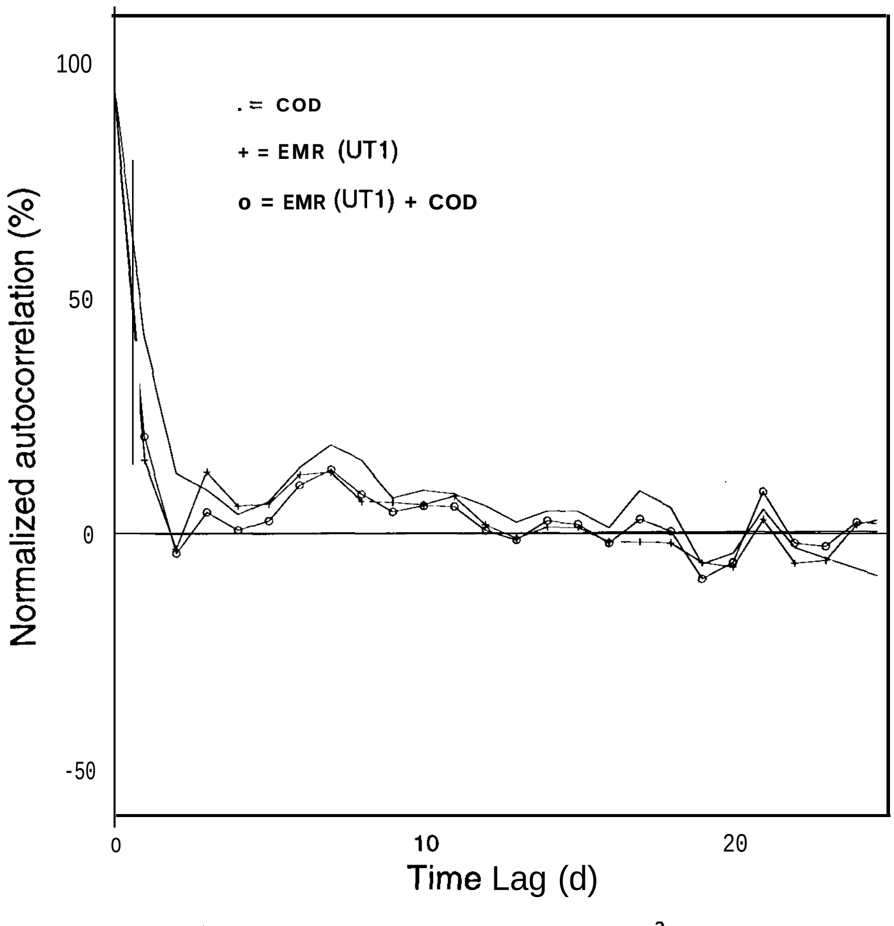

Fig. 8 Autocorrelation functions, normalized by σ_{LODR}^2, for the LODR differences of the COD and EMR (UT 1) series, and the average of those two.

UTIR will then be

$$\sigma_{INT\text{-}LODR}^2 = \int_0^t \int_0^t \sigma_{LODR}^2 \exp(-|u-v|/\tau)\, du\, dv$$
$$= 2\,\tau\,\sigma_{LODR}^2\,[t - \tau + \tau \exp(-t/\tau)]$$

as a function of the length of integration t. (Refer to Brown and Hwang (1992) for background.) Now, to evaluate correlation time constants τ for the best GPS series, Figure 8 shows autocorrelation functions (normalized by σ_{LODR}^2) for COD, EMR (UT1), and the combination EMR (UT 1) + COD. It can be seen that τ is slightly greater than 1 d for COD and about 0.75 d for the other two series. Autocorrelation functions for the remaining series (not shown) are not well re presented as Gauss-Markov processes, sometimes having large periodicities and with e^{-1} time constants of several days.

To put these results into context, Figure 9 shows the expected UT1 R errors due to integration of an unbiased LODR series with Gauss-Markov errors (plotted as the solid lines) compared with the estimated errors of the current operational VLBI program (plotted as "+' '). A full 24-hour VLBI session occurs weekly with daily l-hour sessions in between (see prior discussion). The VLBI errors plotted are the average values for the data used in this study, resealed as described previously. For the hypothetical GPS-derived UTIR error, we assume a time series of LODR measurements which have been bias-corrected (presumably based on some prior history of measurements) and have a long-term scatter of σ_{LODR} = 16.5 μs/d, the estimated value for the EMR (UT1) + COD combined LODR series. The GPS-determined LODR series is then integrated and the intial UT 1 R value set to the result of one of the weekly 24-hour VLBI sessions. Three different values are considered for the LODR correlation time constant τ, 0.1, 1, and 10 d. For the best observed GPS performance, where $\tau \approx$ 1, the UTIR error exceeds that of the 1-hour daily VLBI sessions after 2-3 d of integration and it exceeds 100 μs after 20 d. If τ were improved to -0.1 d, the resulting UT1 R error would exceed that of the daily VLBI sessions after -2 weeks of integration, It must be stressed that these results assume

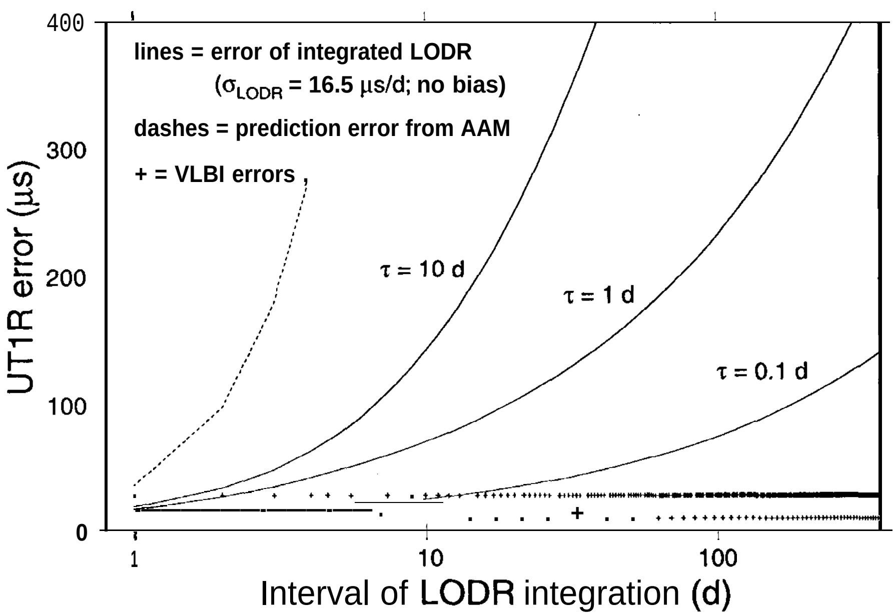

Fig. 9 Growth of inferred UT1 R error from integration of hypothetical GPS-derived LODR time series (three cases), compared with current VLBI and prediction.

that the LODR bias has been well determined and removed, and that no changes in bias occur during the integration period.

A STRATEGY FOR IGS LOD/UT1 COMBINATION

The current IGS strategy for combining polar motion results, which weights the individual AC contributions using their weights from the orbit combination, is less likely to be appropriate for combining LOD or UT1 results because of the indistinguishability of UT1 changes from a net node shift. A better strategy would probably rely on the statistical performance of each LOD series, relative to the combination, as determined over a recent time span, For example, consider forming a combined LOD series from the LOD estimates of all the ACS for the most recent N days. Based on the results seen above, particularly in Figures 2a and 2b where LOD biases are shown to sometimes vary systematically over few-week periods, N should probably be chosen to be at least 30 d. For EMR, the differentiated UT1 series should be used instead of the directly estimated LOD series. The LOD combination would be done iteratively, first forming an unweighed mean series for all epochs with data from all ACS. The LOD bias and rms for each AC can then be computed and used to next form a weighted mean LOD series. Iterating, weighted LOD biases and weighted rms values can then be computed and used to recompute the combination series.

The IGS weighted mean LOD series can then be compared to the most recent IERS Bulletin A series to determine and remove the LOD bias and to initialize the UT1 value. (Clearly, the series length N must be sufficiently long to provide adequate overlap with Bulletin A.) This could most simply be done by identifying two recent adjoining days in Bulletin A having accurate UT 1 values, then interpolate UT 1 to the midpoint noon epoch and use LOD = -AUT 1 to evaluate the LOD bias of the IGS series.

Test LOD combinations have been made using the 16-month data sets described above, with N = 30, 60, and 120 d. In addition, the relative AC weighting was tested using $(1/wrms)^2$ and $(1/wrms)^4$ weights. Compared with the VLBI-derived LOD series, the mean IGS combination is not sensitive to either the weighting factor or the data span, with wrms LOD differences between 30.7 and 31,7 μs/d. This compares with a wrms value of 30.8 μs/d for the simple average series of EMR (UT1) + COD.

CONCLUSIONS

First and foremost, it can fairly be said that GPS does not measure LOD (or UT1) proper, but rather ' 'pseudo-LOD" in analogy with "pseudo-range". All of the GPS-derived LOD time series examined here possess significant biases relative to VLBI determinations and the biases vary widely among the different IGS Analysis Centers. Within individual series, there are time-dependent variations in the LOD bias levels which are in some cases large and periodic and in other cases abrupt. In addition, there are clear correlations between the results of ostensibly independent GPS analyses suggesting the effects of similar choices in data modelling. Taken together, these results demonstrate the critical importance of analysis procedures in influencing LOD bias and stability. Until such time as the sources of LOD bias are understood and corrected, GPS determinations much be regarded as biased estimates and adjustments applied accordingly. In practical terms this can only be done by comparing overlapping LOD time series from VLBI and GPS and computing empirical corrections for GPS. For a retrospective analysis, such a procedure is straightforward, In an operational environment, such as near real time EOP monitoring and UT 1 prediction, accurate VLBI values may not be readily available thus allowing the possibility of undetected LODR bias shifts and substantial UT1 errors.

In the best cases, GPS LOD time series have wrms differences of -34 μs/d compared with VLBI. If the VLBI errors have been estimated accurately here and all errors were Gaussian and uncorrelated, then the intrinsic error of the GPS estimates, after bias correction, approaches -21 μs/d. By combining LOD results from the two best GPS series (EMR's UT 1 -derived and COD's) an even smaller scatter of perhaps -16.5 μs/d can be achieved. However, if such a series is integrated to give UT], its errors will grow at least as fast as $t^{1/2}$ from the epoch when UT1 is initially fixed, The resulting UT1 error coefficient depends on the LODR error correlation time constant, which is -0.75 d in the best case. Given the current VLBI operational mode, the expected UT1 error from integration of GPS LOD, even in the best case, will exceed that of the daily 1-hour VLBI sessions after -3 d. This observation makes it highly questionable whether GPS can currently contribute much, if any, useful information to the current sequence of UT 1 measurements made by VLBI. Indeed, this conclusion is compounded if allowance is made for even small shifts in LOD bias, which give rise to changes in UT 1 drift rate and which appear pervasive. The evidence thus indicates that combinating GPS results with VLBI-derived UT1 would most likely degrade the quality of a VLBI-only solution. A contrary conclusion has been reached by IERS (1995), which has included the EMR (UT1) and COD GPS series in their combination C04, and by Boucher and Feissel (1995) who present filtered GPS comparisons to C04. However, we have shown above that the smoothing applied in forming the C04 combination renders it unsuitable for assessing UT 1 variations for periods under -20 d, precisely the regime where GPS is expected to be most useful. Resolution of this issue would be aided by a comparison campaign using multibaseline VLBI sessions to observe both UT 1 and LOD continuously for an extended period, say 6 months or longer.

Where GPS LOD measurements may stand to be most valuable is for near real time applications and UT 1 prediction. Processing delays for global GPS data sets are now only a few days, already usually shorter than for operational VLBI data, and are expected to approach real time in the near future. Near real time LOD estimates from GPS can certainly be more accurate than extrapolation of prior UT 1 time series considering that gaps of 5 d and 10 d from the most recent data lead to a UT1 errors of -387 μs and -1094 μs (Morabito *et al.*, 1988), respectively; see Figure 9. However, as stressed before, the reliability of such a service will depend critically on maintaining a high level of stability for LODR biases.

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MULTI-TECHNIQUE EOP COMBINATIONS

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ABSTRACT

The IERS Central Bureau regularly combines independent estimates of EOP values, mainly based on SLR, VLBI and GPS, to derive its operational series and also for long-term analysis. The contribution of these 3 techniques to geodynamics is important for their complementarily but also for some aspects linked to redundancy in order to eliminate systematic effects. For polar motion these 3 techniques give approximately the same accuracy (about 0.30 mas).

The determination of Universal Time is based on the VLBI technique. Still, satellite techniques (SLR, GPS) give information on the high-frequency UT1 behaviour on time scales limited to a couple of months; this signal can be used for densification of the UT1 series as well as for UT1 extensions on a quasi-real-time basis from the current VLBI available value. In that case errors are limited to about 200 microseconds over one week and 500 over 2 weeks. This represents an improvement of an order of magnitude with respect to the current prediction of UT1.

INTRODUCTION

Until 1972, Astrometry based on a network of optical instruments was the only technique able to monitor the Earth orientation. Since, various techniques have shown their capability for this purpose, doppler observations of navigation satellites, laser ranging to the moon and to dedicated satellites, VLBI and more recently GPS and DORIS. Various phenomena are perturbing the Earth Rotation on time scales ranging from a few hours to centuries and their understandings require extended and continuous series. The different EOP solutions are unequal in time length, quality, time resolution, which supports the concept of combined solutions benefiting of the various contributions. The realization of such series must take advantage of the qualities of the independent series at the various time scales. For practical reasons also linked to statistical applications, these series are given at equidistant intervals (1 day). They should contain no jump and negligible systematic errors; at least 3 independent techniques are thus highly desirable for that purpose. Table 1 shows the evolution of the uncertainty of one single value since 1962.

Table 1. Uncertainty of one daily value of EOP (IERS) C 04.

Period	1962-1967	1968-1971	1972-1979	1980-1983	1984-1995	1996 --
X (mas)	30	20	15	2	0.5	0.3
Y (mas)	30	2(I	15	2	0.5	0.3
UT1(0.1 ms)	30	20	15	2	0.5	0.3
dPsi (mas)	12	9	5	3	0.5	0.3
dEps (mas)	2	2	2	2	0.5	0.3

Table 2. Characteristics of the smoothing adopted for EOP(IERS) C 04. Variations with periods smaller than the values are smoothed out.

Period	1962-1967	1968-1971	1972-1979	1980-1983	1984-1995	1996 --
x	40d	40d	30d	15d	8d	3d
Y	40d	40d	30d	15d	8d	3d
UT1	17d	17d	15d	10d	8d	3d
dPsi					8d	3d
deps					8d	3d

In order to eliminate the white noise, the series are smoothed. The filtering characteristics have evolved (Table 2) according to the improvement of the series accuracies and to the temporal resolution. The present cutoff period corresponds to 2.5 days.

Another main aspect is the maintenance of the IERS reference systems. The transformation between the terrestrial and the celestial reference frame is performed via a product of matrices connected to EOI' parameters. The inconsistency of the IERS EOP of Bulletin A and B with the IERS reference frames is given by the values printed on Table 3.

Table 3. The value to add to the EOP time series in order to make them consistent with 1994 realization of the IERS terrestrial reference systems (ITRF94) is A+A' (t-1993.0), t in Besselian years.

	x	Y	UT1
	0.001"	0.001"	0.0001s
A	+0.05 (0.28)	+0.76 (0.29)	0.42 (0.16)
A'	+0.12 (0.07)	+0.11 (0.07)	0.04 (0.05)

MULTI-TECHNIQUE EOP COMBINED SOLUTION

The first step in the general procedure for deriving the IERS/CB multi-technique combined solution is the evaluation for each solution of the correction of systematic errors, bias and drift in order to translate it into the IERS system. The formal uncertainties estimated by the analysis centers being an internal consistency value, an external calibration has to be made in order to reflect the real uncertainty of the estimates. This is done using a pair variance analysis. Consequently a scaling factor is given to the series. Weights of the series entering the combined solution are thus estimated.

Figure 1 gives the rough percentage of the contribution of the various techniques for the different EOP parameters. Note that the 3 main techniques (VLBI, SLR and GPS) have about the same contribution in the polar motion series whereas for UT and celestial pole offsets the quasi unique contributor is VLBI. Figure 2 shows for the y-pole component the differences of the main series entering the solution with C04. Table 4 represents the RMS agreement of these series with C04 for both components.

Table 4- RMS agreement with EOP (IERS) C04

	x pole (mas)	y pole (mas)
EOP(IERS) 95 P 01	.17	.12
EOP (USNO) 96 R 04	.17	.13
EOP (IAA) 95 R 01	.18	.16
EOP (CSR) 95 L 01	.18	.18
EOP (USNO) 96 C 01	.17	.14

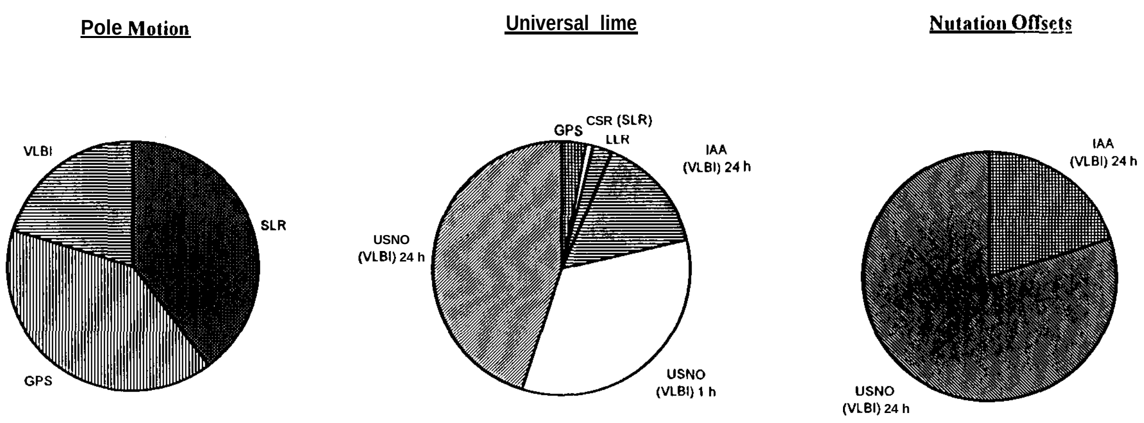

Figure 1. Percentage of the contribution of techniques in the combined EOP.

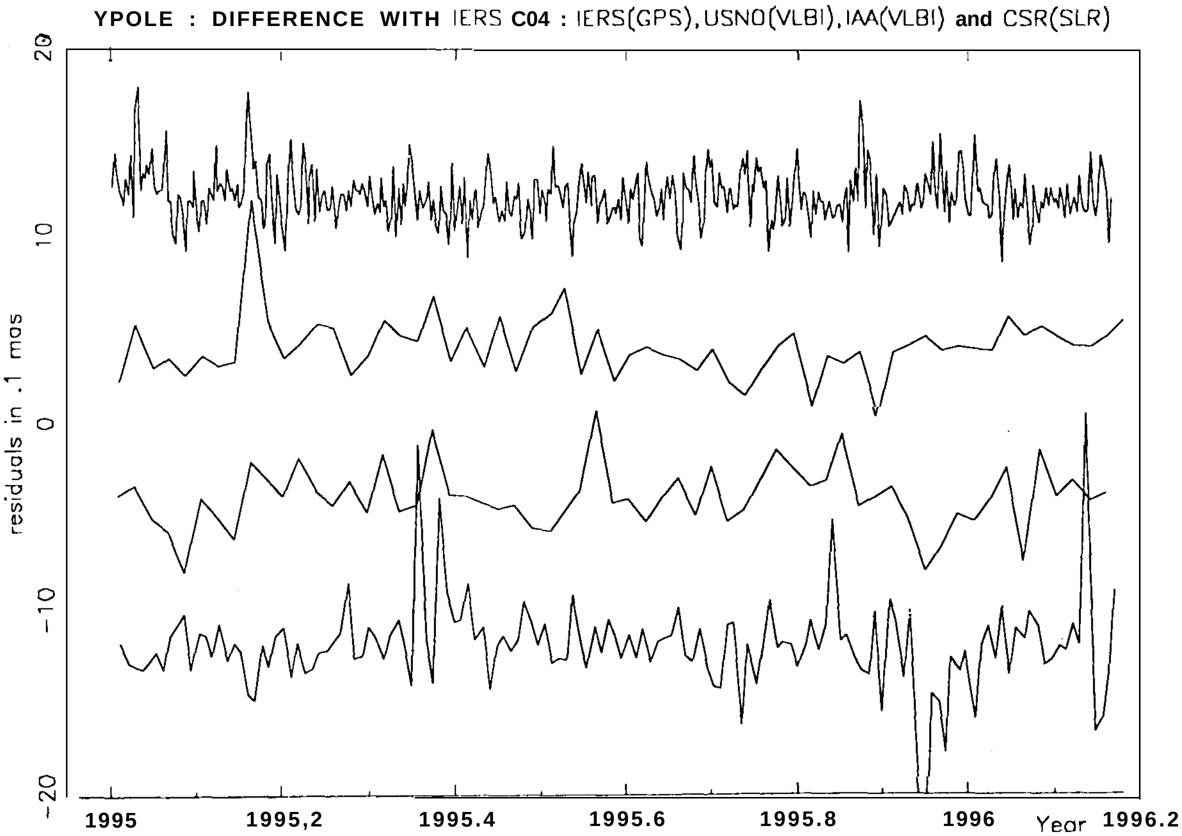

Figure 2. Differences (in 0.1 mas) of the main series entering the solution with IERS C04 for y pole. The biases are arbitrary.

UNIVERSAL TIME BASED ON BOTH VLBI AND GPS TECHNIQUES

So far, the operational Universal Time solution C04 was based on VLBI series (USNO 24h, USNO 1h and IAA 24h) with a small high-frequency contribution from the SLR technique. Due to the difficulty of determining the long-term behaviour of the non rotating system realized through the orbit orientation, Universal Time UT1 cannot be accurately derived from GPS technique. Still, on time scales limited to a couple of months the high-frequency signal contained in the GPS UT determination can be used for densifying the series obtained by the VLBI technique and also for UT extension from the last available current VLBI estimate.

Data

The UT1 series used in the present analyses are currently collected within IERS; they range from beginning 1995 to the present.

VLBI

EC) (USNO) 96R 04:	24h sessions based on a regional network
EOP(USNO) 96 R 05:	1 h sessions on an E-W baseline
EOP(IAA) 951<01:	24h sessions based on a regional network

GPS

EOP(CODE) 95 P 01:	continuous daily
EOP(EMR) 95 P 01:	continuous daily
EOP(JPL) 95 P 01:	continuous daily

SLR

EOP(CSR) 95 L 01:	continuous, approx 3-d intervals calibrated on VLBI, except for the last month

Combined IERS

EOP(IERS) C 04:	continuous 1-d solution principally based on VLBI.

Figure 3 shows the differences of these series to the reference series (here C04); note the long-term behaviour of the residuals series except for CSR which is tied to VLBI. Figure 4 shows the amplitude spectrum of the differences of the series to EOP(USNO) R05. A bimodal structure appears for GPS series with spectral power appearing for low frequencies. Based on these results, low and high-frequency signals have been separated using a Vondrak smoothing (cutoff perod : 1 month). Figure 5 represents the high-frequency content (< 1 month) of GPS, USNO (lb) and CSR series showing very similar behaviour. The correlation between these series are given on table 5.

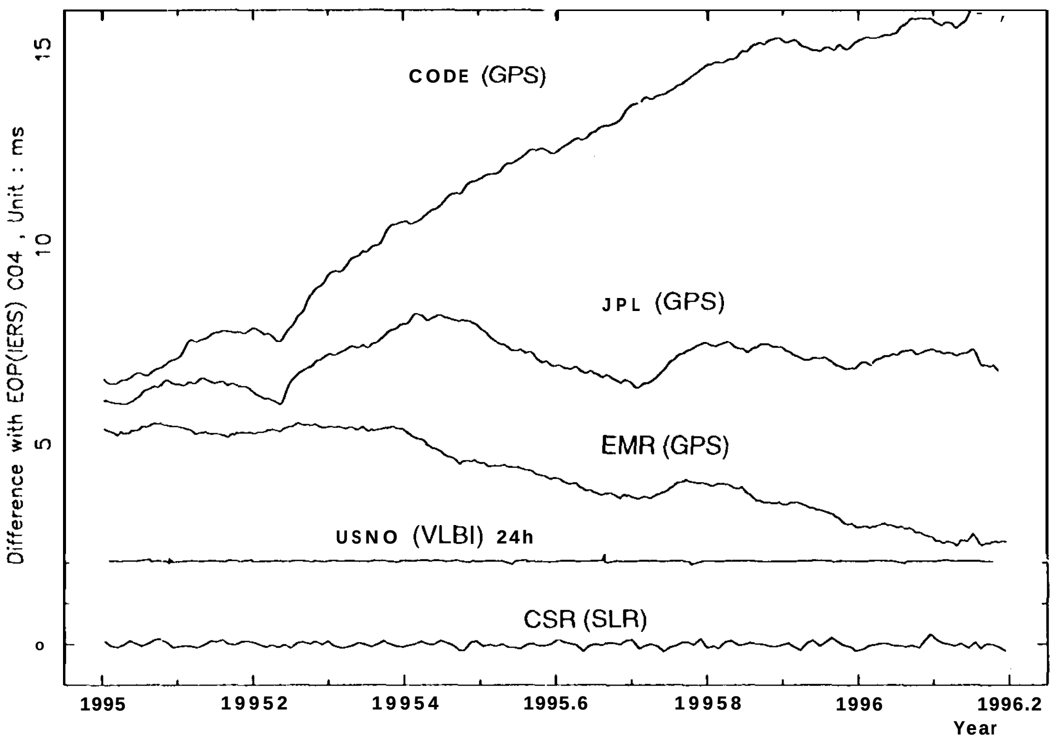

Figure 3- Raw "UT1" derived from GPS analysis present large systematic low-frequency errors relatively to an external series (here IERS combined solution C04) which prevents their direct use in current analyses.

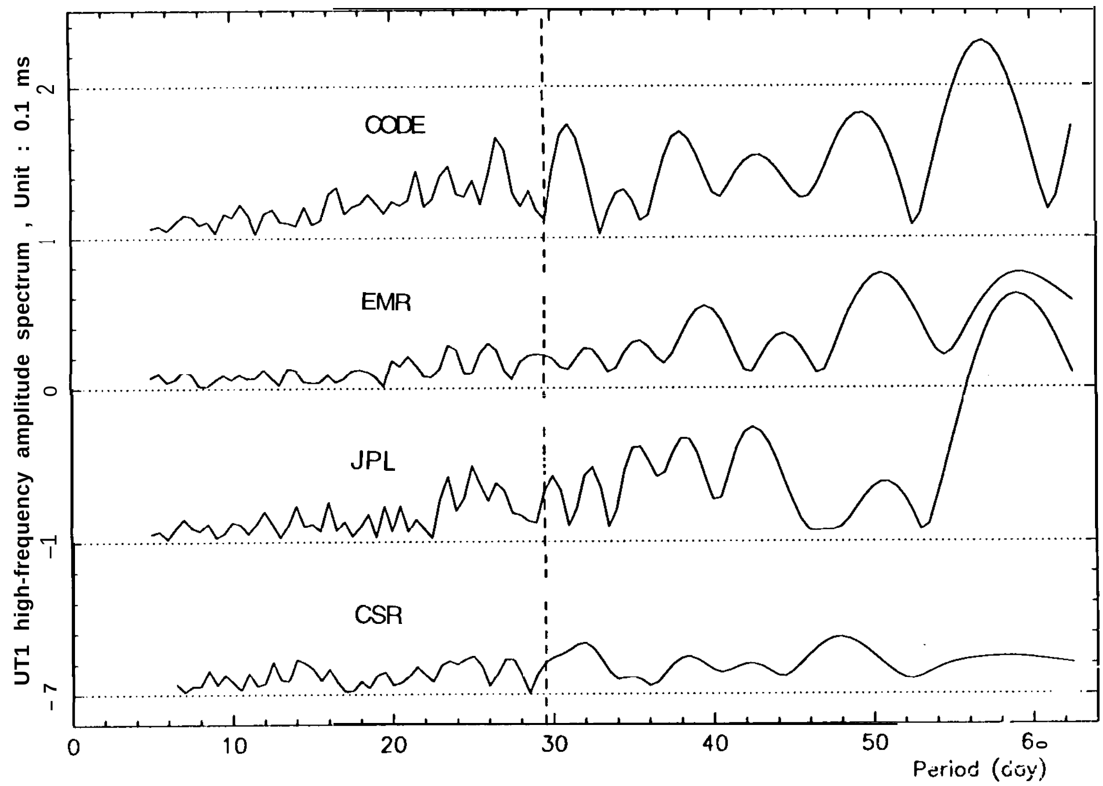

Figure 4 - Amplitude spectrum of the differences of UT1 GPS series with EOP(USNO) 96R 05. This analysis gives the threshold for smoothing characteristics determination.

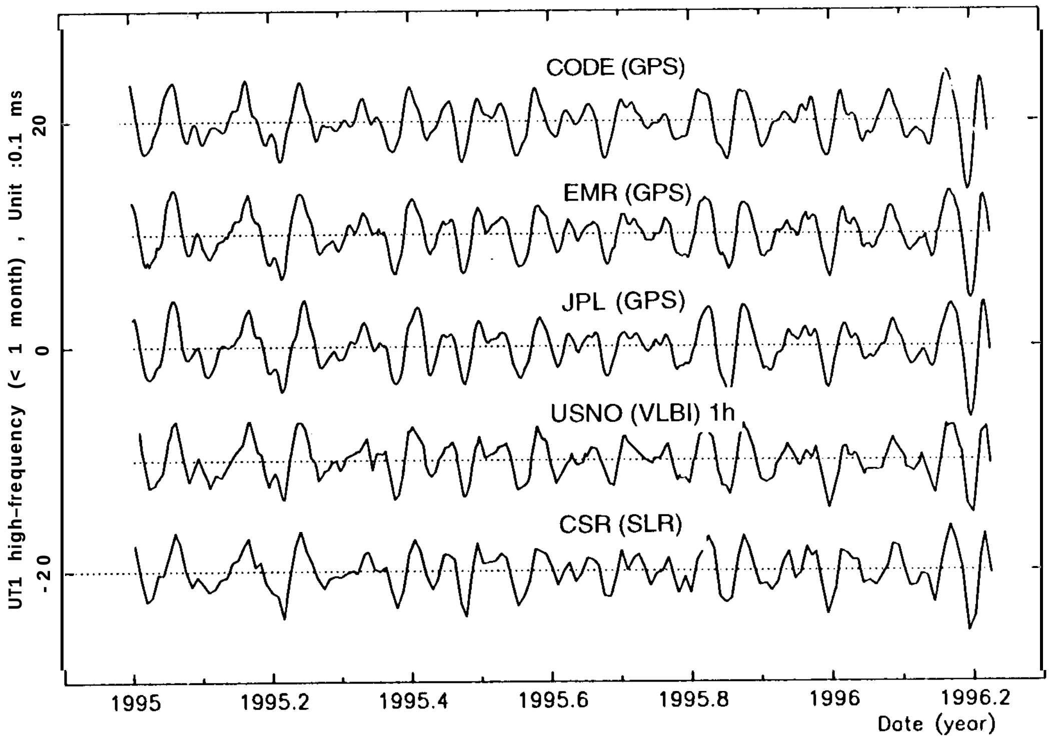

Figure 5 - High-frequency content of the various series. Variations with periods larger than 100 days have been smoothed out.

Table 5. Correlation of VLBI, GI'S and SLR UT1 data for periods under one month

	VLBI(1h)	CODE	EMR	JPL
GPS (CODE)	0.89			
GPS (EMR)	0.91	0.96		
GPS (JPL)	0.89	0.94	0.97	
SLR (CSR)	0.89	0.86	0.89	0.87

Combination

Long-term variations of the reference series are merged with the high-frequency signal of the GPS series. For a practical reason, C04 is here used for reference since it is given at one-day intervals. 3 independent series based on CODE, EMR and JPL have been derived and mixed to give a "UT1 GPS combined solution". In the processing, a variance analysis performed on the whole interval leads to the weighting of these 3 series in the combination. The weights take into account the formal uncertainties of the series scaled by an external factor.

The rms agreements between this series and the various series entering or not in the solution are given on Table 6. The uncertainty of the combined solution is about 0.03 ms for a single value which is a slight improvement compared to those of the independent series (about 0.04 ins). A significant correlation (about 0.6/0.7) appears between these 3 residuals series.

Table 6. RMS agreement of various solutions with respect to EOP(IERS) 95 PO1.

Series	RMS agreement (0.0001 s)
USNO 24h	0.22
USNO 1 h	0.28
IAA 24h	**0.21**
GPS(CODE)	0.23
GPS(EMR)	0.17
GPS((JPL)	0.24
SLR	0.61
C04	**0.23**
NEOS	0.23
SPACE	0.21

Use of UT1 **GPS** estimates for near real time applications

Another application of LOD (or UT1 integrated series) derived by GPS is the estimation of Universal Time from the last VLBI estimation. We have tried in this analysis to answer the 2 following questions:

1) What is the error of the UT extrapolation based on GPS estimates from the last current VLBI data compared to the usual prediction performed using VLBI data?

2) What is the evolution of the errors with respect to the horizon (1, 2 and 3 weeks in advance)?

Based on the structure of the trends of GPS UT1 shown in Figure 3, we estimate as prediction model a linear term, corrected locally by the re-adjustment of a bias. This estimation is performed over some time span ranging from 50 to 200 days preceding the last VLBI solution. A series of simulations have been performed over the interval 1995-1996.3. Prediction errors are given on Table 7 for the 3 GPS solutions CODE, EMR and JPL. Comparison is also given in the last column with the performance reached when no adjustment of this model is made. (GPS UT1 estimates are in this case only put at the end of the VLBI UT1 solution).

We can notice that there is only a significant improvement in the case of CODE. A better knowledge is needed concerning the sources of long-term errors of the various GPS UT1 series.

Table 7- RMS error out to 1, 2 and 3 weeks, with drift and bias estimated on time spans ranging from 50 to 200 days. Unit :0.0001 s. Last column gives the RMS error with no long-term prediction estimated.

Horizon: 1 week

Series	50	100	**150**	**200**	no model estimated
CODE	2.3	2.1	2.1	1.9	2.5
EMR	1.5	1.5	1.5	1.4	1.2
JPL	1.5	1.4	1.2	1.3	1.3

Horizon :2 weeks

Series	50	100	**150**	**200**	no model estimated
CODE	3.4	2.9	2.9	2.8	2.5
EMR	2.2	2.2	2.2	2.0	1.7
JPL	3.6	2.8	2.5	2.7	2.6

Horizon: 3 weeks					
Series	50	100	150	200	no model estimated
CODE	4.6	3.4	3.6	3.5	4.7
EMI<	2.9	2.6	3.1	2.7	2.4
JPL	4.0	2.5	2.0	2.5	2.2

Note that the uncertainty average is about 0.2 ms over one week for GPS solution. The degradation of the performance is small over time spans of 2 and 3 weeks (respectively 0.3 and 0.4 ins). These results can be compared to the UT1 predicted values based on VLBI data on the same analysis interval. Inaccuracies are 1.2 ms over one week and respectively by 4 and 7 ms for 2 and 3 week predictions (Table 8).

Table 8. RMS errors (in ms) of the Universal Time solution based on GPS and compared to prediction.

UNIT :1 ms	1 week	2 weeks	3 weeks
Pure Prediction	1.15	4.05	7.20
GPS estimates	.1.5	.25	**.30**

CONCLUSIONS

independent techniques are highly desirable to monitor the Earth rotation for their complementarily aspects but also partly for their redundancy allowing to separate true geophysical signals from systematic fluctuations. This can be for instance illustrated by the 40-50 day oscillation which was only detected when other techniques than astrometry (Doppler tracking and Lunar laser ranging) began to contribute.

Although the internal UT1 series derived from GPS determinations are not directly usable for Earth Orientation monitoring, its high-frequency information can be used together with an external long-term calibration (VLBI or C04) to derive a mixed solution which may be used both for scientific (densification). The combination of independent UT1 (GPS) solutions improves the final solution by elimination of white noise. Integration of the operational USNO 1 h solution to this series is under investigation.

GPS-derived UT1 can be also useful for near real time applications from the last currently availbleVLBI estimate. In that case the improvement of the solution is a factor 8 for 1 week and respectively 16 and 24 for 2 and 3 weeks compared to a predicted series.

GPS UT1 results are still in their infancy, and further improvements may be expected both in the short term accuracy and in the long term stability of GPS UT1 determinations; their comparison with VLBI intensive series should bring better understanding of errors on both sides. Nevertheless they already contribute to analysis and operational solutions in the frame of IERS/BC. VLBI will remain the ultimate reference for the motion of the satellite orbit node. When the error budget in the GPS determination is better known, lower acquisition rates may become acceptable for operational work. However, due to the non-dynamical character of its reference direction for UT1, VLBI is also in principle the most accurate technique for high frequency determinations of UT1. The potential high frequency systematic errors in satellite-based UT1 are independent from those that may arise in single baseline VLBI. Scientific investigations of the high frequency structure of the Earth's rotation should benefit from the continuity of the satellite results added to the accuracy of VLBI results.

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DAILY & SEMI-DAILY EARTH ORIENTATION PARAMETER VARIATIONS AND TIME SCALES

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ABSTRACT

Theoretical models of daily and semi-daily variations in Earth orientation due to tides are now in close agreement. Observations indicate that these variations do exist. It is important that the IGS and IERS agree on a convention for the publication of observations in order to avoid confusion among users of these data. The current practice of the IERS is to provide daily smoothed estimates at Oh UTC. These contain no daily/semi-daily information. IGS Analysis Centers provide daily estimates of polar motion which do not currently take into account the daily/semi-daily variations in their analyses. Therefore, the observations reported by the IGS Centers may, in fact, contain small systematic errors depending on the length of the arcs used in the orbit determinations. It is recommended that all organizations reporting Earth orientation data provide to the user the information required to transform between a celestial and terrestrial reference frame including the daily/semi-daily variations. The details regarding this problem will be the subject of a forthcoming paper

INTERNATIONAL EARTH ROTATION SERVICE CONVENTIONS (1996)

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ABSTRACT

The accuracy with which reference systems and Earth orientation data can be defined are limited by the systematic errors which arise in the treatment of astronomical and geodetic observations. Constants and models must be re-evaluated and improved, if possible, as measurement precision improves. Both the astronomical and geodetic communities will maintain sets of conventional standards which change slowly with time as well as "current best estimates" for high-precision users of reference systems. These will be available electronically and updated as required. The International Earth Rotation Service (IERS) Conventions are discussed from the theoretical and applied points of view. Specific constants and models are described.

INTRODUCTION

The IERS Conventions is a document intended to define the standard reference system used by the International Earth Rotation Service (I ERS). It is based on the Project MERIT Standards (Melbourne *et al.,* 1983) and the IERS Standards (McCarthy, 1989; McCarthy, 1992) with revisions being made to reflect improvements in models or constants since the previous IERS Standards were published.

The recommended system of astronomical constants corresponds closely to those of the previous IERS Standards with the exception of the changes outlined below. The units of length, mass, and time are in the International System of Units (S1) as expressed by the meter (m), kilogram (kg) and second (s). The astronomical unit of time is the day containing 86400 S1 seconds. The Julian century contains 36525 days.

SYSTEMATIC ERRORS IN CURRENT OBSERVATIONS

Modern observational methods are able to achieve precision on the order of ±0.1 millisecond of arc in the determination of Earth orientation parameters. Physical phenomena that are modeled in the analyses of these observations affect the data with magnitudes many times larger than the precision. Errors in these models or use of inconsistent models may produce systematic errors in the Earth orientation parameters derived from modern methods. These systematic errors do, in fact, limit the accuracy of the modern observations. It follows that a concerted effort should be made to use the most representative constants and models to achieve the highest possible accuracy.

CONTENTS OF THE IERS CONVENTIONS

To provide the highest accuracy in its data, the IERS periodically publishes a compendium of the best models and constants to be used in the analyses of its data and in the application of the data to meet user requirements. The contents of the new IERS Conventions document, the final draft of which is being completed, are listed below. It is intended that the models and constants of the IERS Conventions be consistent with the International Astronomical Union (IAU) "current best estimates." All of the IERS Conventions document will be available electronically and on the World Wide Web.

CONVENTIONAL CELESTIAL REFERENCE SYSTEM

Both the equator and origin of right ascension are described in the first chapter of the new IERS Conventions. The accuracy of the definition of the celestial reference system is shown, and procedures are given to obtain the most recent realization of the frame.

CONVENTIONAL DYNAMICAL REFERENCE FRAME

The dynamical frame of the IERS Conventions is defined by the DE 403 ephemeris of the Jet Propulsion Laboratory (Standish *et al.,* 1995). The constants consistent with this frame are listed and procedures are given to obtain the ephemeris electronically.

CONVENTIONAL TERRESTRIAL REFERENCE SYSTEM

Definitions of the Conventional Terrestrial Reference System are shown, and the process to follow in obtaining the most recent realization of the terrestrial frame are given. The chapter lists the transformation parameters to be used to relate this frame to other world coordinate systems and datums. Should observational estimates of station motions not be available, the NUVEL no-net-rotation plate motion model (De Mets *et al.* 1994) is recommended for use and is described,

NUMERICAL STANDARDS

Consistent numerical constants to be used with IERS data are listed. These are current best estimates, and will be updated electronically as required,

TRANSFORMATION BETWEEN THE CELESTIAL AND TERRESTRIAL SYSTEMS

A chapter is devoted to the proper procedures to be followed in transforming between terrestrial and celestial reference systems, It provides two methods, the first being the traditional system making use of the concept of the equinox. The second method involves the "non-rotating-origin" approach. The International Astronomical Union (IAU) 1980 Theory of Nutation (Seidelmann *et al.,* 1982), which is the current standard of the IAU, is provided along with new definitions of the astronomical arguments (Simon *et al., 1994)* to be used in implementing the theory. Also presented here, for the first time, is a new model of nutation consistent with the most modern astronomical observations. It is based on an analysis of Very Long Baseline Interferometry (VLBI) observations (Herring, 1995). The IAU model remains the standard and the new IERS model is to be used only for those applications requiring high-precision *a priori* estimates of the nutation angles. A consistent convention to be used to standardize the description of prograde and retrograde motions is presented. A formulation for geodesic nutation is also provided.

GEOPOTENTIAL

In addition to the procedures to be used to obtain the adopted geopotential field electronically, models describing the effect of solid Earth tides are given. A standardized method to account for the permanent tide is provided, and the effect of the ocean tides on the geopotential is described.

LOCAL SITE DISPLACEMENT

Corrections to the positions of observing sites participating in the IERS are required to achieve the highest possible precision. These corrections take into account the effects of ocean loading, solid Earth tides, rotational deformation due to polar motion, antenna deformation, atmospheric loading, and postglacial rebound. Frequency-dependent Love Numbers are given.

TIDAL VARIATIONS IN THE EARTH'S ROTATION

Current observations indicate that high-frequency variations in the Earth's rotation and polar motion occur. These appear to be due to the action of tides on the Earth. A standardized theoretical model of tidal effects on the Earth's orientation is presented for use in the analyses of observational data,

TROPOSPHERIC MODEL

A chapter of the IERS Conventions is devoted to models of the effects of the troposphere on observations made using satellite laser ranging, very long baseline interferometry, and the global positioning system.

RADIATION PRESSURE REFLECTANCE MODEL

One source of systematic error in the analysis of observations of the satellites in the Global Positioning System (GPS) is modeling the effect of radiation pressure on the satellite orbits. A standardized model consistent with current observations is presented.

GENERAL RELATIVISTIC MODELS FOR TIME, COORDINATES AND EQUATIONS OF MOTION

Relativistic equations of motion for an artificial Earth satellite are shown as are equations of motion in the barycentric frame. The effect of relativity on time scales is discussed.

GENERAL RELATIVISTIC MODELS FOR PROPAGATION

A rigorous "consensus model," taking into account relativity, is available to model time delays in VLBI observations. This includes the effects of gravitational delay, geometric delay, and observations close to the Sun, Relativistic propagation corrections are also given for satellite laser ranging.

DIFFERENCES BETWEEN THE IERS CONVENTIONS OF 1995 AND PREVIOUS IERS STANDARDS

Most chapters of IERS Technical Note 13 have been revised, and known typographical errors contained in that work have been corrected in the new edition. There are some major differences between the current version of the IERS Conventions and the past IERS Standards. The following is a brief list of the major modifications.

IERS DYNAMICAL REFERENCE FRAME

In Chapter 2, the JPL DE 403 ephemeris (Standish, 1995) replaces the DE 200 model of IERS Technical Note 13.

IERS TERRESTRIAL REFERENCE SYSTEM

The NUVEL NNR- 1 A Model (DeMets *et al.*, 1994) for plate motion has replaced the NUVEL NNR-1 Model of IERS Technical Note 13.

NUMERICAL STANDARDS

Numerical values are now given only for the most fundamental constants along with their uncertainties and references. Constants which have been changed include the astronomical unit in seconds and meters, precession, obliquity, equatorial radius, flattening factor and dynamical form factor of the Earth, constant of gravitation, geocentric and heliocentric gravitational constant.

TRANSFORMATION BETWEEN CELESTIAL AND TERRESTRIAL REFERENCE SYSTEMS

An empirical model to be used to predict the difference in the celestial pole coordinates between those published by the IERS and those given by the IAU model is added. The model (Herring 1995) is based on the analysis of fourteen years of VLBI data by the Goddard Space Flight Center and the Souchay and Kinoshita Rigid Earth nutation series (Souchay and Kinoshita, 1995) re-scaled to account for the change in the dynamical ellipticity of the Earth implied by the correction to the precession constant. Terms with duplicate arguments in the Souchay and Kinoshita series have been combined into single terms. The model includes the effects of the annual modulation of geodetic precession and the effects of planetary perturbations of the lunar orbit from Williams (1994). Since it appears that the free core nutation (FCN) varies in time, the Central Bureau will publish in the IERS Annual Report its current best estimate of the FCN representation. The precession constant will change (from the IAU- 1976 value) to be consistent with the IERS nutation model, as will the rate of change of the obliquity. FORTRAN code to generate this series will be available by anonymous ftp.

GEOPOTENTIAL

The JGM3 model replaces the GEM-T3.

LOCAL SITE DISPLACEMENTS

The printed table of the components of site displacement due to ocean loading is no longer included. References to machine-readable files are given. Love Numbers are revised, and atmospheric loading and postglacial rebound are included.

TIDAL VARIATIONS IN EARTH ORIENTATION

The subdaily and daily tidal variations in Earth orientation due to the effect of ocean tides have been added. The model of R. Ray (1995) is recommended.

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IGS

GPS ANTENNA CALIBRATION

Calibration of GPS Antennas

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Introduction

As geodetic techniques using the Global Positioning System (GPS) continue to improve, the calibration of the antennas used to track GPS data becomes increasingly important. The establishment of the International GPS Service and by several agencies of continuously operating reference stations (CORS) provides a convenient means to incorporate reference network data into a user's solution for either local or regional geodetic baselines. However, the antennas used by these reference networks will very often not be the same as those employed by the user at his end of the baseline. Moreover, different CORS networks may use different antennas and different antennas may also be found within the same network.

Two antenna characteristics which are frequently not noticed when identical antennas are used, may now become a significant source or error when the antennas at either end of a base line are different. A GPS geodetic solution fundamentally provides the vector between the phase centers of the two antennas. To relate this vector to permanent monuments on the ground, the location of the phase center with respect to an external feature of the antenna structure must be combined with the location of this reference feature with respect to the monument. Since the baseline vector is a relative measurement, errors in phase center location cancel out when identical antennas are used. However, different antennas generally have different phase center locations. Mixed antennas at a minimum require knowledge of the relative positions of the antenna's phase centers and ideally the absolute location of each antenna's phase center.

The antenna phase centers defining a baseline vector are actually average phase center locations for the data used to produce that baseline vector. A real antenna does not have a single well-defined phase center. Instead the phase center is a function of the direction from which it receives a signal. For GPS antennas, the dominant variation occurs with elevation. Since baseline measurements usually include GPS observations distributed over all elevations above some cutoff value, this effect may not always be noticeable, even when using mixed antennas. However, these phase center variations with elevation, if large enough, can be noticeable on mixed antenna baselines as an apparent change in height with elevation cutoff.

In addition, high precision on longer baselines requires an estimation of the tropospheric scale height along with the baseline components. The estimation of this parameter, which is highly correlated with height, depends on the variation of phase residuals with elevation. If this variation includes an effect that arises from the antennas in addition to that from the troposphere, the scale height parameter, and the height, can be significantly in error. The complete calibration of GPS antennas includes determining this phase center variation as well as the average phase center location.

Calibration Procedure

Previous calibrations of GPS antennas have been in an anechoic chamber. When properly done, these measurements should provide precise descriptions of the phase center and variations with elevation and azimuth. Such measurements have been reported by Schupler et al. (1994) and Meertens et al. (1996) for a number of antenna types. However, scheduling and funding constraints for these test facilities and the ever increasing number of GPS antenna types suggests that an alternate means of antenna calibration would be useful. Furthermore, the signal characteristics and other idiosyncrasies of the anechoic chamber suggest that a means of measuring antenna characteristics in situ would be a valuable comparison.

The calibration procedure used here will determine in the field the relative phase center position and phase variations of a series of test antennas with respect to a reference antenna. The phase characteristics of the reference antenna are assumed known from chamber measurements and will allow the phase characteristics of the test antennas to be separately determined.

To perform these antenna calibrations, a test range has been established at the National Geodetic Survey's Corbin facility. This test range consists of two stable 6 in. diameter concrete piers rising about 1.7m above ground. On the tops of these piers, antenna mounting plates are permanently attached. The piers are separated by 5m and are located in a flat grassy field about 21m from the nearest building, a l-story block structure with asphalt roof. Identical length antenna cables connect these piers to the building. These piers lie along a north-south line and are designated the north and south piers. Leveling data show that the south pier is 3.4mm taller that the north pier. The north pier will be used as the reference pier and the south pier used as the test pier.

The average phase center location can be found by using a standard reference antenna on the reference pier and determining the relative position of a test antenna. Because the baseline length is so short, tropospheric and ionospheric effects may be ignored and separate L1 and L2 solutions estimated. These solutions provide the vector for the L1 and L2 phase centers from the reference antenna to the test antenna and allow the L1 and L2 offsets for the test antennas to be determined.

The variation of the phase center is found by constraining the test antenna to its L1 or L2 position and using single difference phase residuals over a 24 hr period to estimate the relative clock at each epoch, the satellite phase biases and a polynomial for the phase residuals as a function of elevation. Separate polynomials are estimated for L1 and L2 and azimuth variation is ignored. The polynomials go to fourth order in elevation. A constant term for the polynomial is not estimated since it is not readily separated from the clock values. This inability to determine a constant phase offset does not inhibit the determination of the more important phase variations and may be completely ignored when differencing observations.

The reference antenna used for all these calibration measurements is a Dorne/Margolin choke ring antenna, type T. This is the antenna used with the Trubo Rogue receivers and in standard use throughout the network of the International GPS Service. It's characteristics have been measured in the anechoic chamber by Schupler et al., and Meertens et al., making it a good candidate for the reference antenna.

All test antennas had a north azimuth marker which was oriented toward the north. Several days of data were collected for each antenna pair at a 30s sample rate using Trimble 4000 SSE receivers for the first series of tests and Ashtech 212 receivers for the second series of tests. Both receivers used a common external rubidium frequency standard. The test antennas calibrated so far are listed in Table 1.

The first step in processing the calibration data was to estimate the L1 and L2 baselines from the reference antenna to the test antenna. These solutions were done using double differences, a 10 degree elevation cutoff, and no tropospheric scale height adjustment. These initial phase center estimates did not use any phase variation data for either antenna.

These phase center positions were then used to estimate the variation of phase center with elevation. This was done with the NOAA program ANTCAL. ANTCALuses single frequency, single differences to estimate a polynomial describing the phase residuals as a function of elevation along with phase biases, and clock offsets.The test antenna position is constrained to the previously determined value. ANTCAL accepts as input a file containing antenna phase variation values. This file contained the elevation dependent phase corrections derived by Rocken et al., but resealed to the standard L1/L2 offsets of O. 110m and O. 128m for the Dorne/Margolin Choke Ring antenna. These phase corrections were applied to the reference antenna data only. No phase corrections were applied to the data from the test antenna. This procedure allowed the phase corrections found for the test antenna, though fundamentally a relative measurement, to be expressed as an absolute correction.

Table 1. Test Antennas
Ashtech 700829
Ashtech 700718
Ashtech 700228 w/ notches
Ashtech 700228 w/ holes
Ashtech 700936
Dorne/Margolin Choke Ring Type T
Leica SR299
Leica SR399
Micrometer 4647942
Topcon 72110
Trimble 14532
Trimble 22020 w/ ground plane
Trimble 22020 w/o ground plane
Wild AT202

The initial step of estimating the L1 and L2 phase center offsets was repeated but this time using the phase corrections for the reference antenna and those for the test antenna just determined. This iteration made only a slight change to the original offsets but these values will be used to give the final antenna offsets.

Results

The position of the north reference pier was determined from a solution to the IGS station GODE at Goddard Space Flight Center in Greenbelt, MD, approximately 100km from Corbin. This reference position is given in Table 2.

Table 2. Pier Positions

	X *(m)*	*Y* (m)	Z (m)	Lat (d,m,s)	Lon (d,m,s)	Height (m)
North	1097042.0569	-4897241.6777	3923122.3574	38127.6906	-772224.5840	36.1406
South	1097042.6579	-4897244.6983	3923118.4514	38127.5293	-772224.5871	36.1445

The Dorne/Margolin test antenna data was used to establish the position of the south pier with respect to the north pier. These solutions yield a height difference between the two piers of 3.9mm which agrees favorably with the leveled height difference of 3.4mm. The south pier and north pier positions, given in Table 2, define the vector between the two Dorne/Margolin L1 and L2 phase centers. This south pier position was then used as the a priori value for all subsequent data processing to yield test antenna phase center positions relative to the Dorne/Margolin antenna. These relative differences were then combined with the L1 and L2 Dorne/Margolin Choke Ring offsets of 0.1 10m and O. 128m to find the vertical offsets of the test antennas. The horizontal offsets of the Dorne/Margolin Choke Ring antennas was assumed to be zero. The horizontal offsets of the test antennas were also estimated.

The L1 and L2, horizontal and vertical offsets for each test antenna are summarized in Table 3. Wherever more than one measurement was made for a particular antenna model, the separate results have been averaged together in this Table. The vertical offset is always with respect to the bottom-most surface of the antenna structure - i.e. the surface that would contact the tribrach mount.

The polynomials describing the phase variation with elevation have been used to generate the phase corrections in 5 degree elevation increments for both L1 and L2. These L1 and L2 phase corrections are also listed in Table 3. These corrections extend from the zenith down to 10 degrees elevation, below which there was too little data to use reliably.

In practice, these phase correction tables are used within the GPS adjustment software to provide interpolated phase corrections at each epoch for the particular antenna types in use. From Table 3, the corrections would be subtracted from the observed phase to remove the elevation dependence introduced by the antenna,

The phase variation can easily be seen by plotting the single difference phase residuals, after the clock variations have been removed, as a function of elevation. These variations maybe seen for L1 and L2 for each of the test antennas in Figures 1-7. The polynomial fit is also shown as a solid line.

These figures also show quite clearly sinusoidal variations with elevation. These variations are due to multipath from ground reflections and are proportional to 2hsin(elv) where h is the height, in wavelengths, of the phase center above the ground. All the mixed antenna pairs show essentially the same multipath pattern, particularly at the lower elevations. Even though the figures show single difference residuals, the multipath is satisfactorily modeled from the height of the test antenna alone. This is because the multipath amplitude is different for the antenna pairs. If the multipath amplitude at the two antennas was the same, the resultant single difference should practically cancel out the multipath. The only remaining multipath would be proportional to the few centimeter height difference between the two phase centers and would be negligible.

Table 3. GPS Antenna Offsets and Phase Variations

Format Description

VENDOR MODEL # DESCRIPTION YR/MO/DY

[north] [east] [up 1 | L1 Offset (m)

[901 [851 [801 [751 [701 [651 [601 [551 [501 [45] | L1 Phase at

[401 [351 [301 [251 [201 [151 [101 [51 [0] | Elevation (mm)

[north] [east] [up 1 | L2 Offset (mm)

[901 [851 [801 [751 [701 [651 [601 [551 [501 [451 | L2 Phase at

[401 [351 [301 [251 [201 [151 [101 [51 [0] | Elevation (mm)

Calibration Results

ROGUE SNR-8000 96/03/18

0.0 0.0 110.0

10.0 10.0 9.0 7.0 5.0 3.0 1.0 -2.0 -3.0 -5.0

-5.0 -6.0 -7.0 -7.0 -5.0 -4.0 -3.0 0.0 3.0

0.0 0.0 256.0

3.0 3.0 2.0 2.0 1.0 1.0 0.0 -1.0 -2.0 -2.0

-3.0 -4.0 -4.0 -3.0 -2.0 -1.0 0.0 3.0 6.0

Ashtech 700829 96/03/18

-0.8 0.4 89.4

0.0 1.0 1.7 1.9 1.8 1.4 0.5 -0.6 -2.0 -3.6

-5.4 -7.1 -8.9 -10.4 -11.5 -12.2 -12.2 0.0 0.0

-0.1 -1.0 61.7

0.0 -2.2 -4.0 -5.5 -6.9 -8.2 -9.4 -10.5 -11.5 -12.3

-12.9 -13.1 -12.8 -11.8 -9.8 -6.8 -2.4 0.0 0.0

Ashtech 700718 96/03/ 18

1.0 0.6 83.7

0.0 0.4 0.6 0.6 0.2 -0.4 -1.2 -2.4 -3.8 -5.3

-6.9 -8.6 -10.2 -11.6 -12.6 -13.2 -13.2 0.0 0.0

-0.1 -1.9 63.8

0.0 -2.5 -4.5 -6.1 -7.5 -8.7 -9.8 -10.9 -11.8 -12.6

-13.2 -13.4 -13.2 -12.2 -10.4 -7.6 -3.3 0.0 0.0

Ashtech 700228N (not ches) 96/03/18

-0.2 -1.0 79.5

.0 .2 -.5 -1.7 -3.4 -5.2 -7.0 -8.8 -10.4 -11.7

-12.8 -13.5 -14.0 -14.2 -14.2 -14.1 -14.0 0.0 0.0

-1.9 3.7 77.4

.0 -1.3 -2.2 -2.8 -3.2 -3.7 -4.1 -4.7 -5.4 -6.1

-6.8 -7.5 -7.9 -7.9 -7.3 -5.9 -3.3 0.0 0.0

Ash tech 700228R (rings) 96/03/18

-1.9 0.0 85.3

.0 1.1 1.2 .5 -.8 -2.4 -4.1 -5.9 -7.6 -9.2

-10.4 -11.4 -12.1 -12.4 -12.6 -12.6 -12.5 0.0 0.0

-3.8 3.4 77.9

.0 -1.6 -2.6 -3.1 -3.4 -3.7 -4.0 -4.5 -5.1 -5.8

-6.6 -7,4 -7.9 -8.1 -7.6 -6.2 -3.6 0.0 0.0

```
Ashtech      700936                                              96/03/ 18
      0.8      -0.7     112.9
   0.0 0.5  -0.3 -1.9 -4.0  -6.5 -8.9 -11.3 -13.2 -14.8
  -15.8 -16.2 -16.1 -15.4 -14.2 -12.6 -10.8 0.0 0.0
      0.2       1.7     135.1
   0.0 0.7  1.0 0.9 0.6 0.0 -0.8 -1.6 -2.6 -3.5
   -4.2  -4.7 -4.8 -4.5 -3.6 -2.0 0.5 0.0 0.0

Trimble      22020-00                                            96/03/18
      0.6      -1.9      77.2
    .0   1.4   3.4   5.3   6.6   7.2   6.8   5.6   3.6   1.2
  -1.4  -3.9  -6.0  -7.5  -8.3  -8.1  -7.1   0.0   0.0
     -1.1       1.2      70.5
    .0   -.1    .1    .5    .8   1.0   1.0    .6    .0   -.9
  -1.9  -2.9  -3.8  -4.4  -4.4  -3.5  -1.4   0.0   0.0

Trimble      22020-00     w/o GP                                 96/03/18
      2.9      -0.5      88.5
    .0  .8  1.8 2.9 4.0 5.0  5.9 6.6 7.0 7.1
   6.9 6.4  5.5 4.2 2.6 .7 -1.4  0.0 0.0
      0.7       2.2      86.8
    .0  -.6  -.6 -.2 .3 1.0 1.7 2.3  2.8 3.0
   3.0 2.7 2.0 1.0  -.2 -1.8 -3.6 0.0 0.0

Trimble      14532-00                                            96/03/18
      0.8      -2.2      84.0
   0.0   3.5   6.5   8.8   10.2   10.6   10.1   8.8   6.8   4.5
   2.0  -0.4  -2.4  -3.9   -4.7   -4.7   -3.8   0.0   0.0
     -2.0      -0.1      79.1
   0.0    0.6    1.1    1.6    1.8    1.8    1.6 1.1 0.3 -0.6
  -1.4  -2.4  -3.1  -3.4  -3.1  -2.1   0.1   0.0   0.0

Macrometer   4647942                                             96/03/18
      1.4       0.1     133.9
    .0   0.6   2.2   4.4   6.3   8.1   9.8  12.4  14.5  13.6
  10.3  4.9  -0.4  -6.5  -9.9  -12.7  -15.0  0.0  0.0
      2.2       1.2     100.2
    .0  -0.2  -0.6  -1.0   0.9   3.7   5.9   7.3   6.8   4.7
   1.4  -1.8  -4.4  -5.3  -6.1  -4.8  -2.7   0.0   0.0

Topcon       72110                                               96/03/18
      1.3       4.7     139.9
    .0  -.9  -1.5 -2.0 -2.4 -2.7 -3.1 -3.6 -4.3 -5.2
  -6.3  -7.7 -9.5 -11.6 -14.2 -17.2 -20.6  0.0 0.0
      2.1       2.4     121.5
    .0  .9  1.3  1.4  1.3  1.0  .6  .1   -.4   -.9
  -1.4  -1.8 -2.2 -2.5 -2.7 -2.9 -3.0  0.0 0.0
```

The clarity with which the multipath is visible in these figures using data from satellites at all azimuths is also good evidence for the azimuthal symmetry of these antennas, validating the modeling of antenna corrections by elevation only. Any azimuthal asymmetry in antenna response or multipath reflections would tend to wash out these sinusoidal patterns.

These results include several measurements of identical antenna model numbers. Where repeated measurements are available, the separate results are shown in Figures 8-12. These figures show that the phase variations repeated within a few millimeters for several different antennas within the same model type. The horizontal and vertical offsets also generally repeated within a few millimeters.

These results are also compared with those from Meetens et al. and Rothacher 1996 where possible. These comparisons are shown in Figures 13-16. Though Rothacher used double differences, a spherical harmonic representation for both elevation and azimuth variation, and entirely different data sets, the two in situ measurement type agree fairly well. The results from anechoic chamber tests, designated "Rocken", appear to agree well with the two in situ measurements at L1 but less well at L2. Thus far there is no explanation for this difference.

Summary

The determination of antenna phase centers and phase variations with elevation using very short baseline measurementsin the field appears feasible. The success of this technique depends on accurate phase characterization of a standard reference antenna which may be done independently in an anechoic chamber.

Identical model antennas were tested and yielded vertical phase center offsets that repeated within a few millimeters at L1 and L2. These differences are greater than the measurement errors but constitute too small a sample to confidently indicate the variation that might be expected within a particular antenna type.

Horizontal offsets up to 3mm were measured for some of these antennas. However, these offsets may be unique to the particular antennas being tested. The measurement of horizontal offsets is particularly important but will require additional antennas of the same type to get a better indication of the repeatability of this offset.

The phase variation with elevation has been determined and has been shown to repeat within a few millimeters for several antenna types tested. These phase variations have been used to effectively remove the effects of mixed antenna differences on the determination of tropospheric scale height and antenna height.

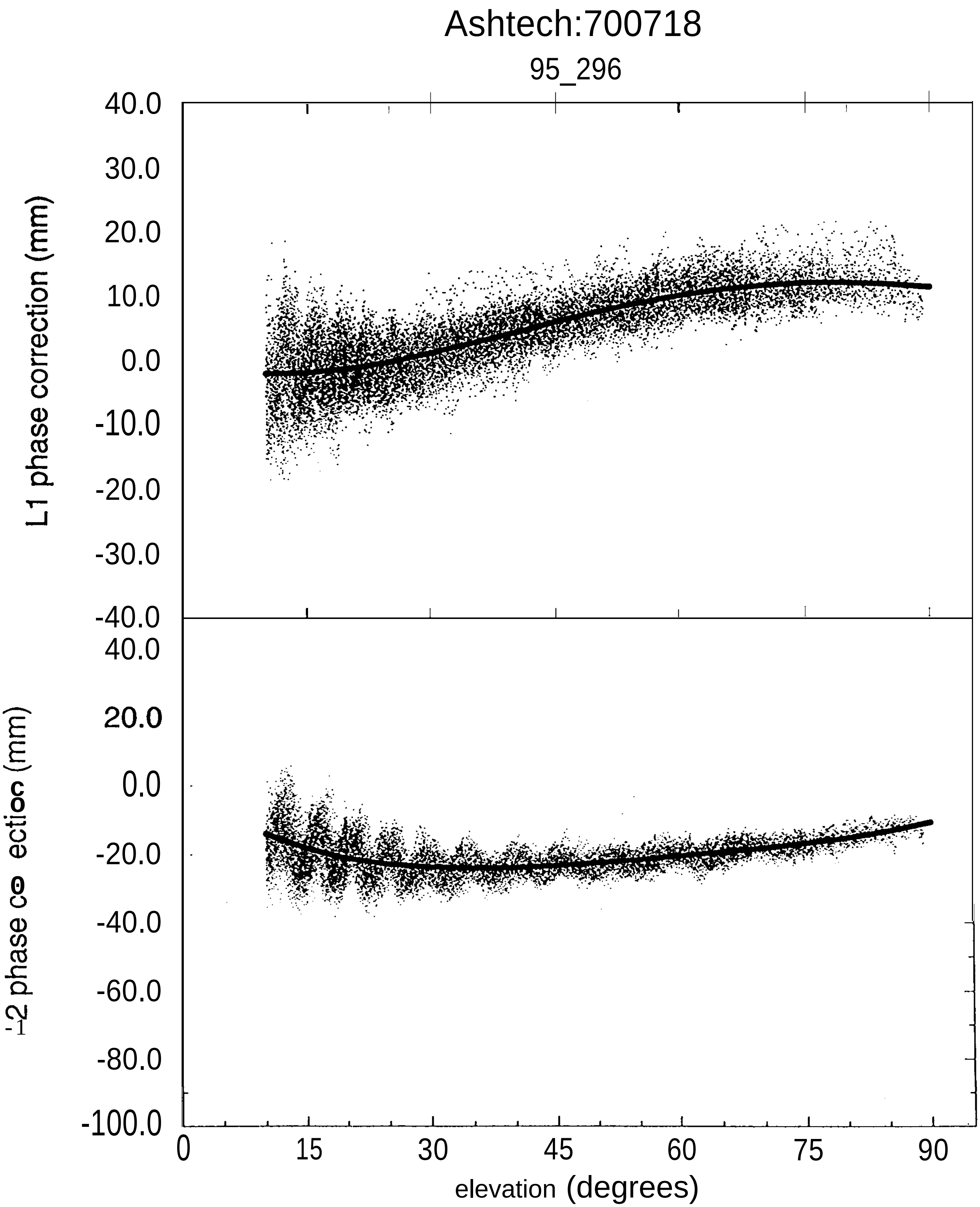
References

Schupler, B. R., Allshouse, R. L., Clark, T.A., Journal of the Institute of Navigation, Vol. 41, Number 3, p. 277, Fall 1994.

Meertens, C., Rocken, C., Braun, J., Exner, M., Stephens, B., Ware, R., IGS Analysis Centers Workshop Proceedings, Silver Spring, MD, 1996.

Rothacher, M., IGS Analysis Centers Workshop, Silver Spring, MD, 1996.

Figure 1



Ashtech:700718
95_296
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
-30.0
-40.0
L1 phase correction (mm)
40.0
20.0
0.0
-20.0
-40.0
-60.0
-80.0
-100.0
0
15
30
45
60
75
90
elevation (degrees)

Figure 2

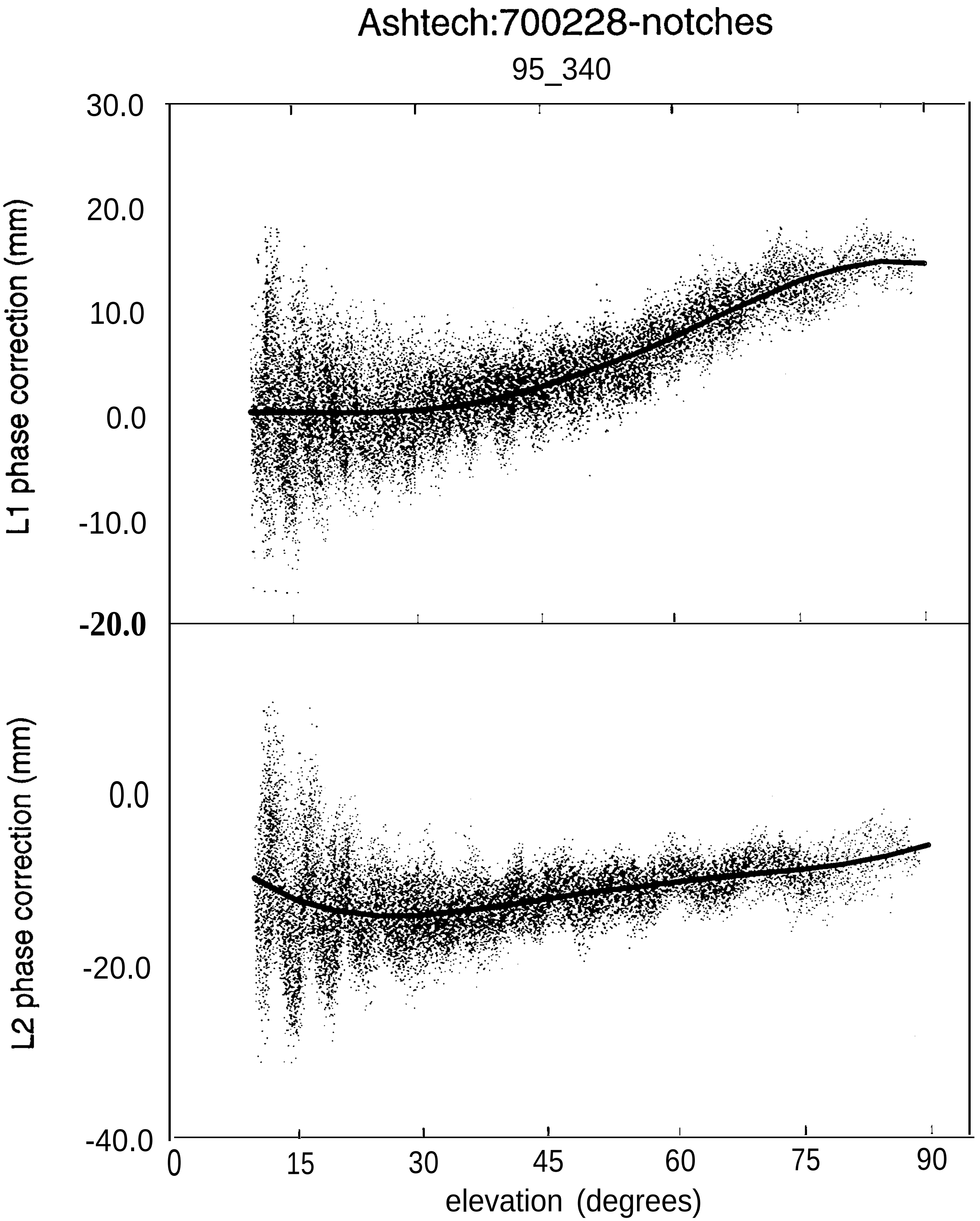

Ashtech:700228-notches
95_340
L1 phase correction (mm)
30.0
20.0
10.0
0.0
-10.0
-20.0
L2 phase correction (mm)
0.0
-20.0
-40.0
0
15
30
45
60
75
90
elevation (degrees)

Figure 3

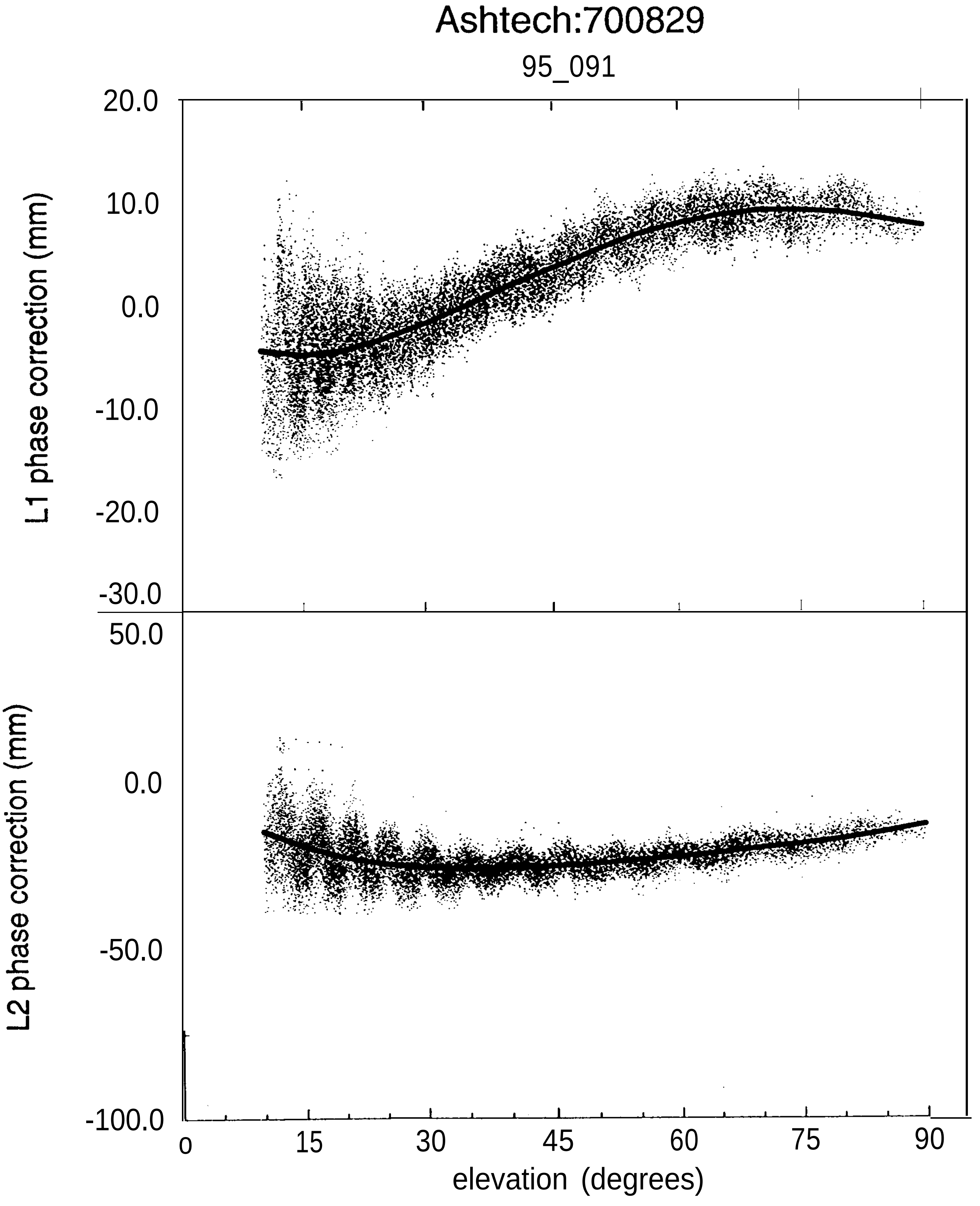

Ashtech:700829
95_091
20.0
10.0
0.0
-10.0
-20.0
-30.0
L1 phase correction (mm)
50.0
0.0
-50.0
-100.0
L2 phase correction (mm)
0
15
30
45
60
75
90
elevation (degrees)

Figure 4

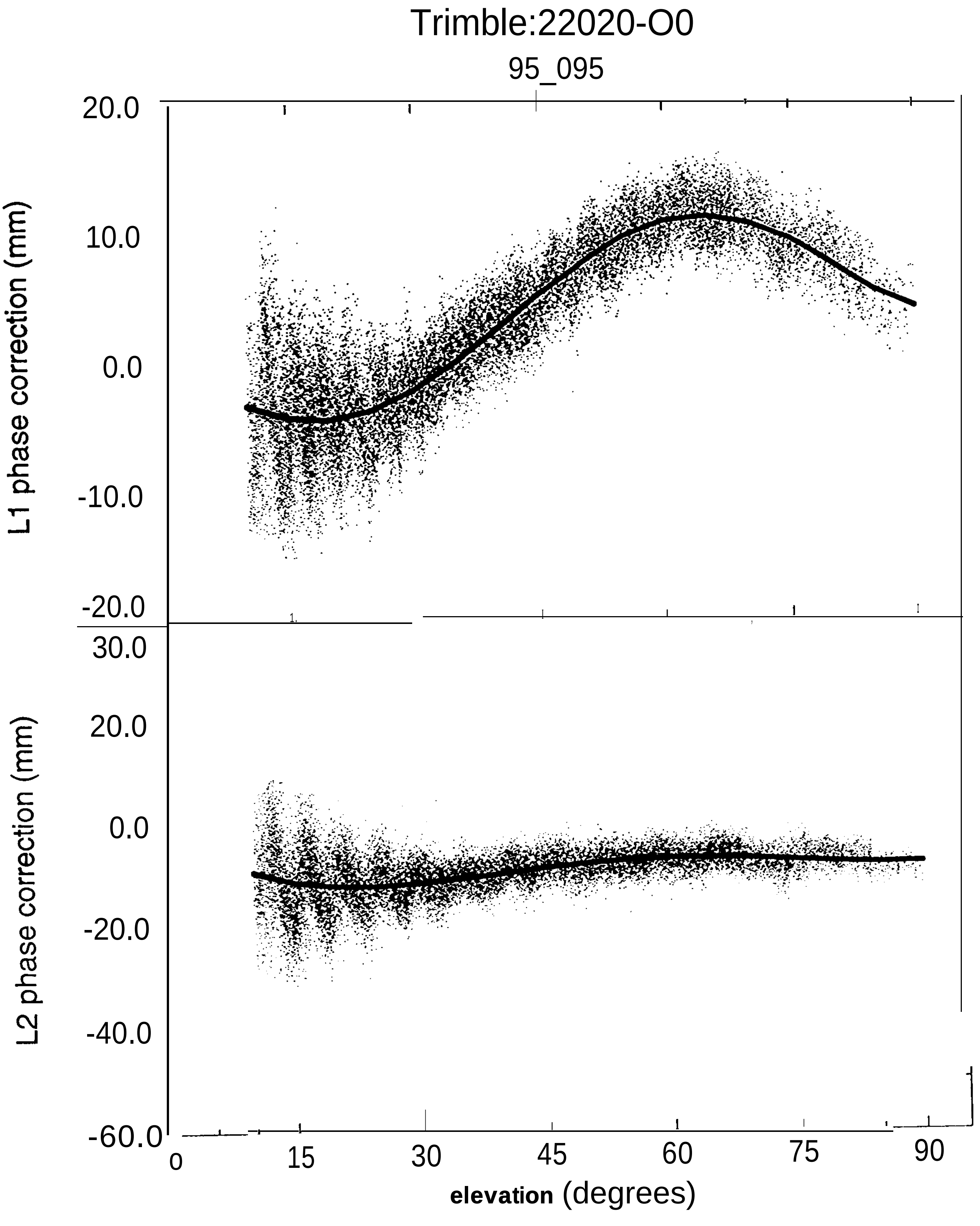

Trimble:22020-O0
95_095
20.0
10.0
0.0
-10.0
-20.0
L1 phase correction (mm)
30.0
20.0
0.0
-20.0
-40.0
-60.0
L2 phase correction (mm)
0
15
30
45
60
75
90
elevation (degrees)

Figure 5

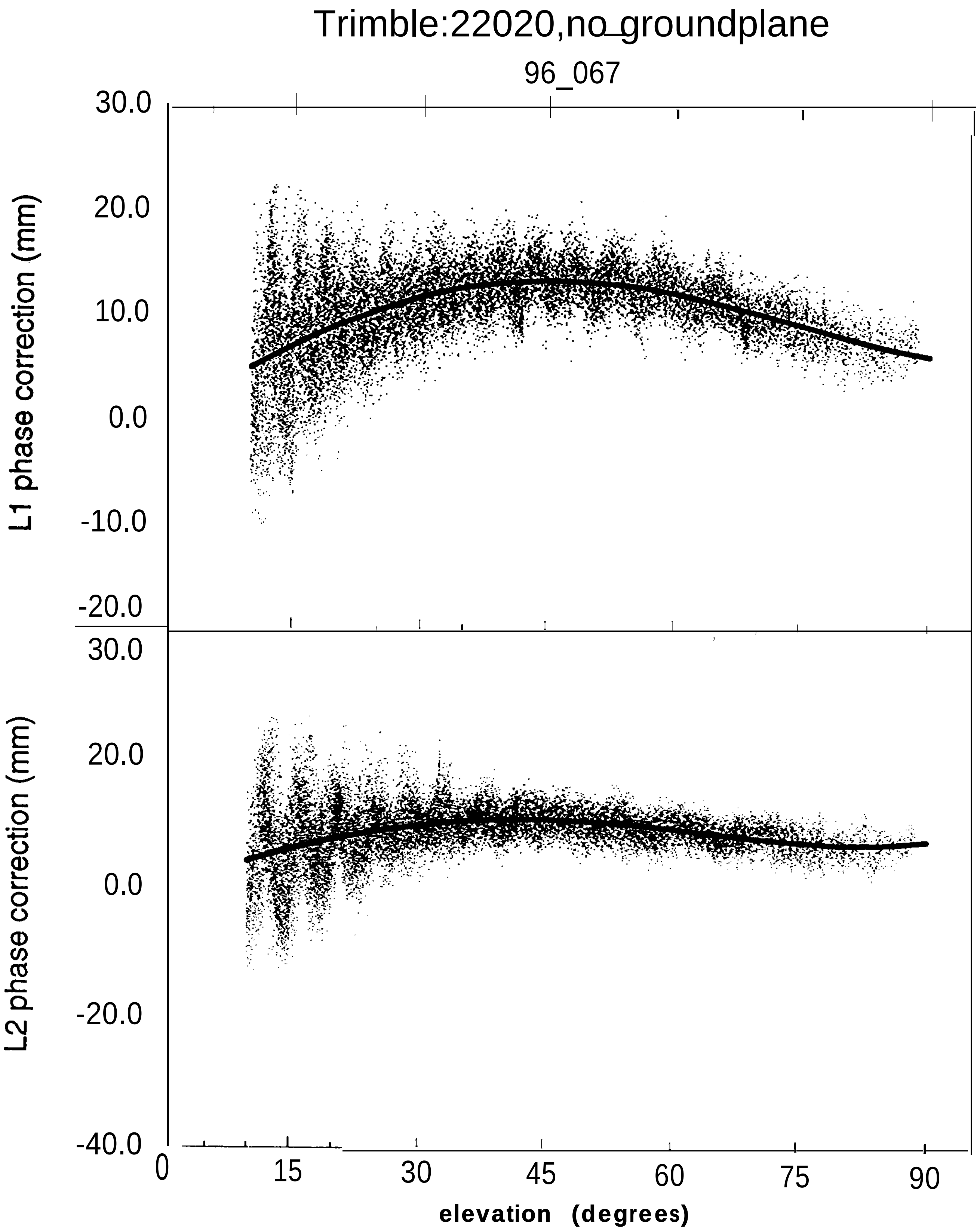
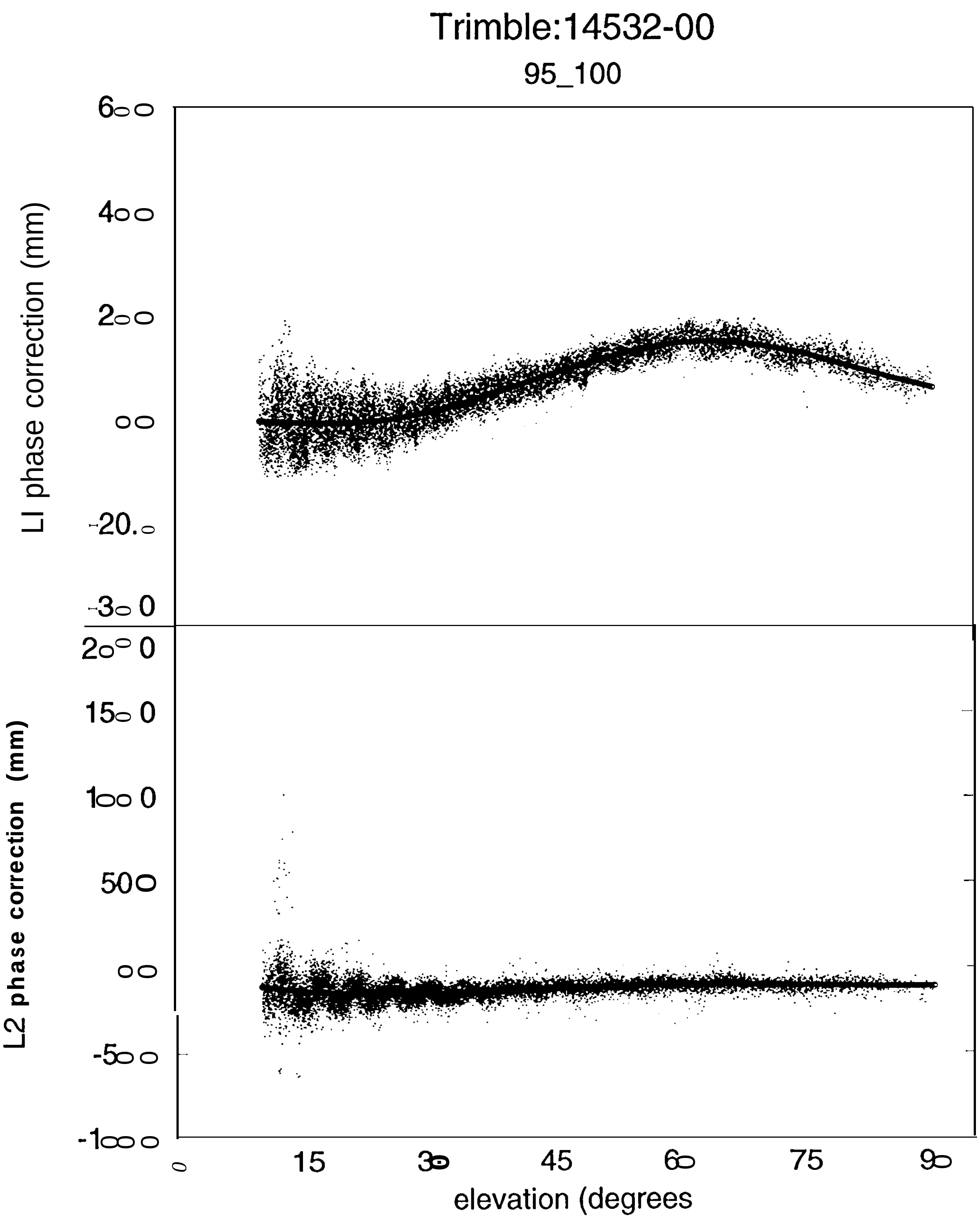

Trimble:22020,no_groundplane
96_067
30.0
20.0
10.0
0.0
-10.0
-20.0
L1 phase correction (mm)
30.0
20.0
0.0
-20.0
-40.0
L2 phase correction (mm)
0
15
30
45
60
75
90
elevation (degrees)

Figure 6



Trimble:14532-00
95_100
LI phase correction (mm)
L2 phase correction (mm)
elevation (degrees

Figure 7

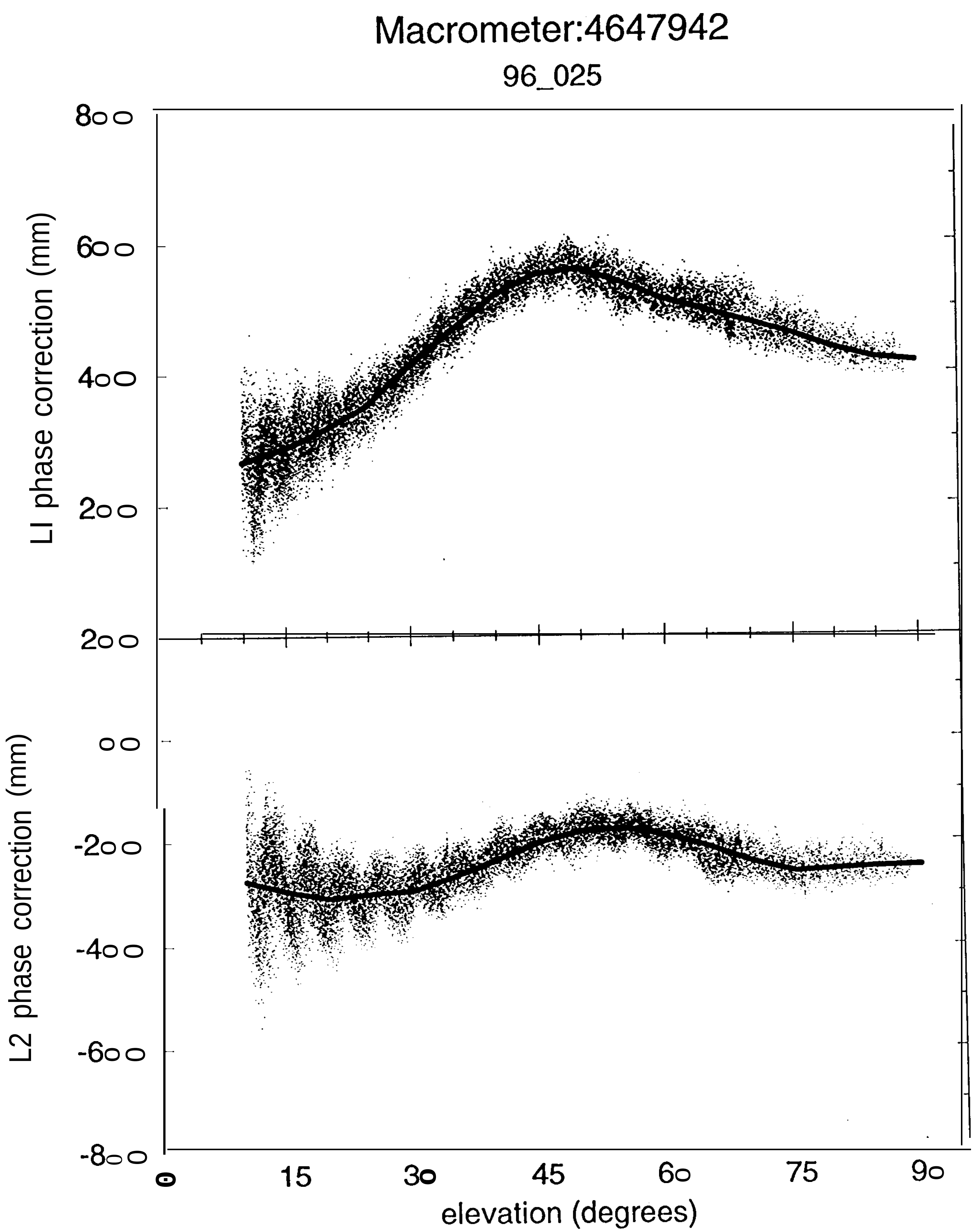
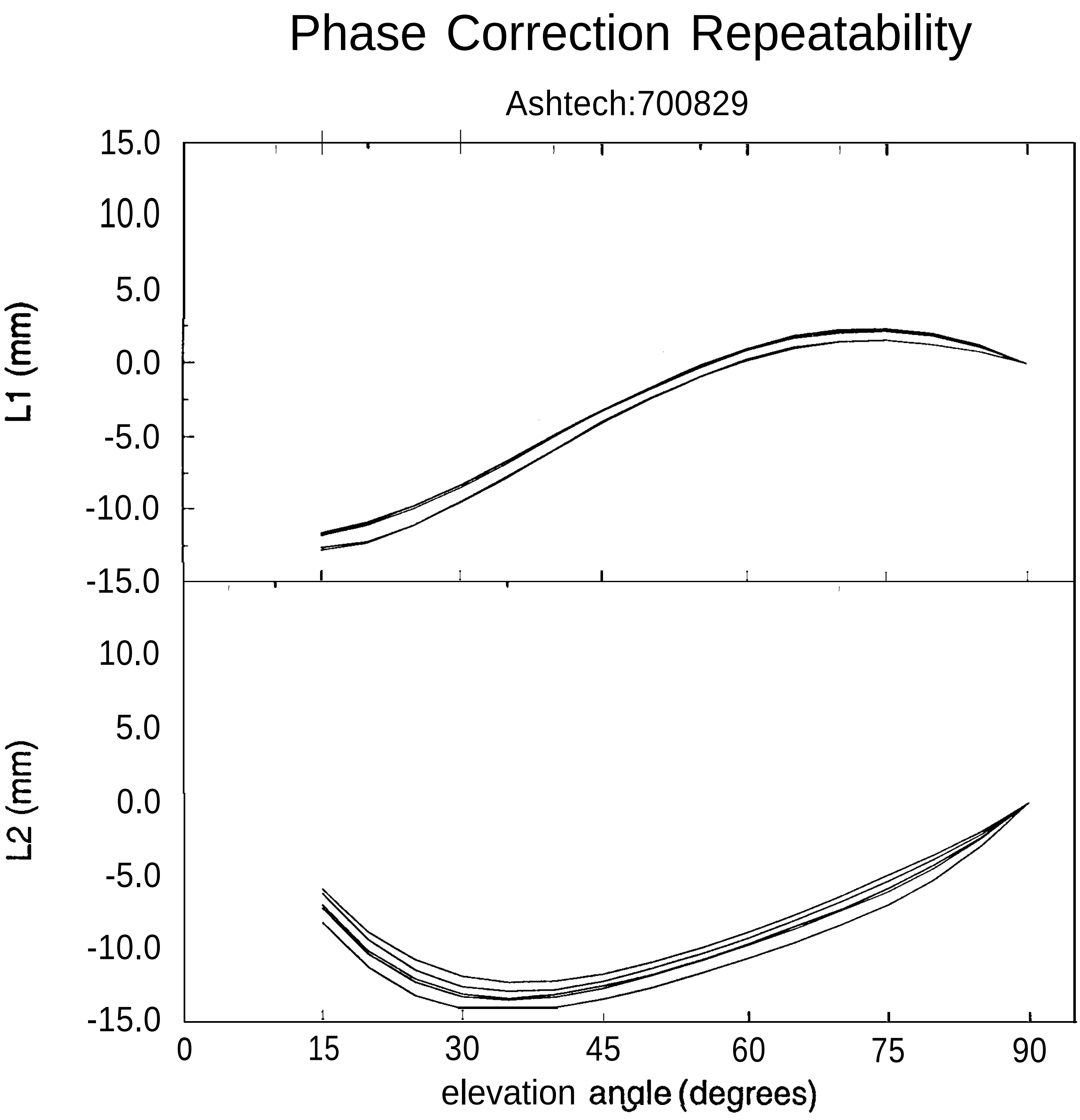

Macrometer:4647942
96_025
LI phase correction (mm)
L2 phase correction (mm)
8oo
6oo
4oo
2oo
2oo
oo
-2oo
-4oo
-6oo
-8oo
0
15
3o
45
6o
75
9o
elevation (degrees)

Figure 8



Phase Correction Repeatability
Ashtech:700829
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
L1 (mm)
10.0
5.0
0.0
-5.0
-10.0
-15.0
L2 (mm)
0
15
30
45
60
75
90
elevation angle (degrees)

Figure 9

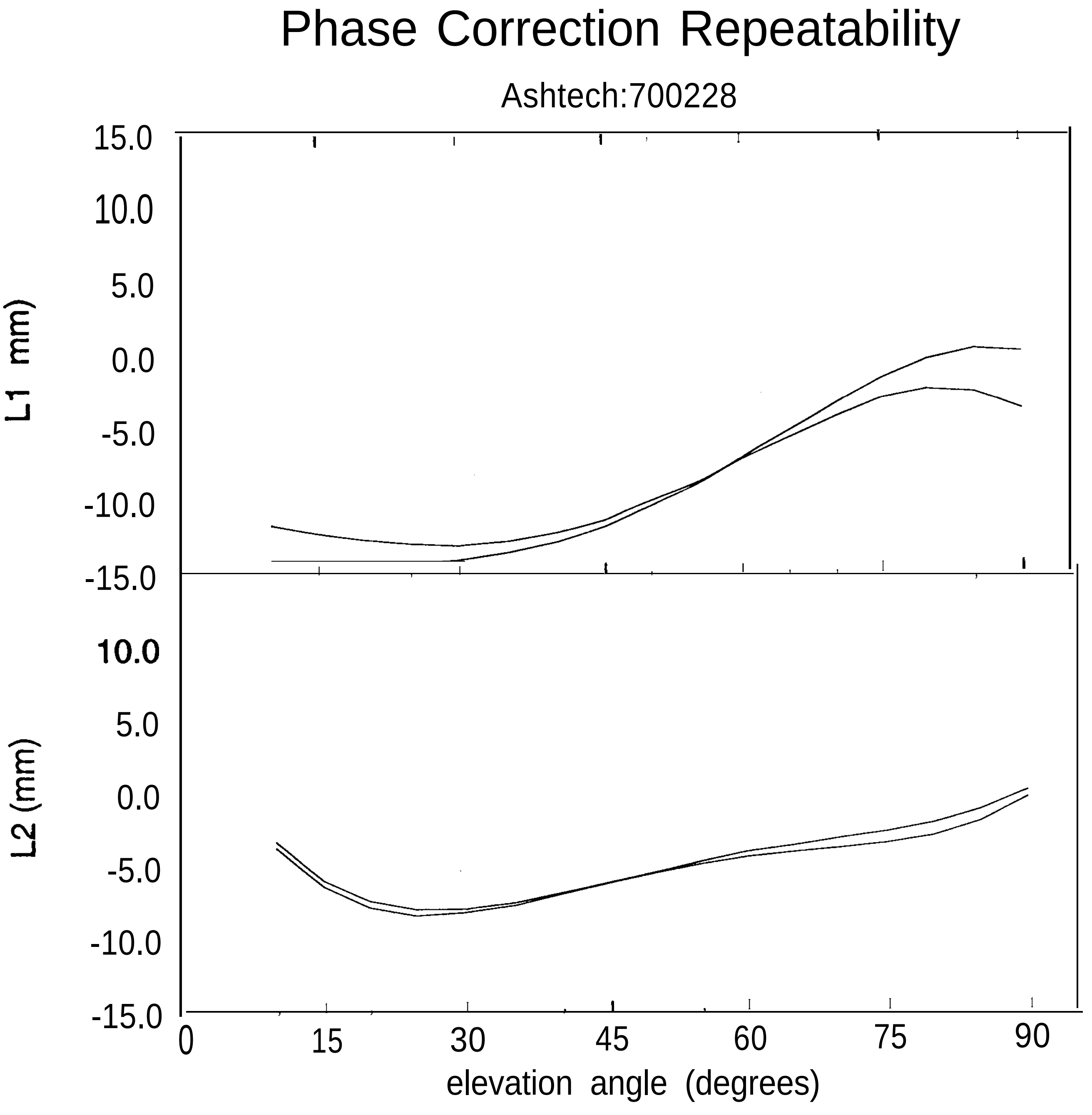
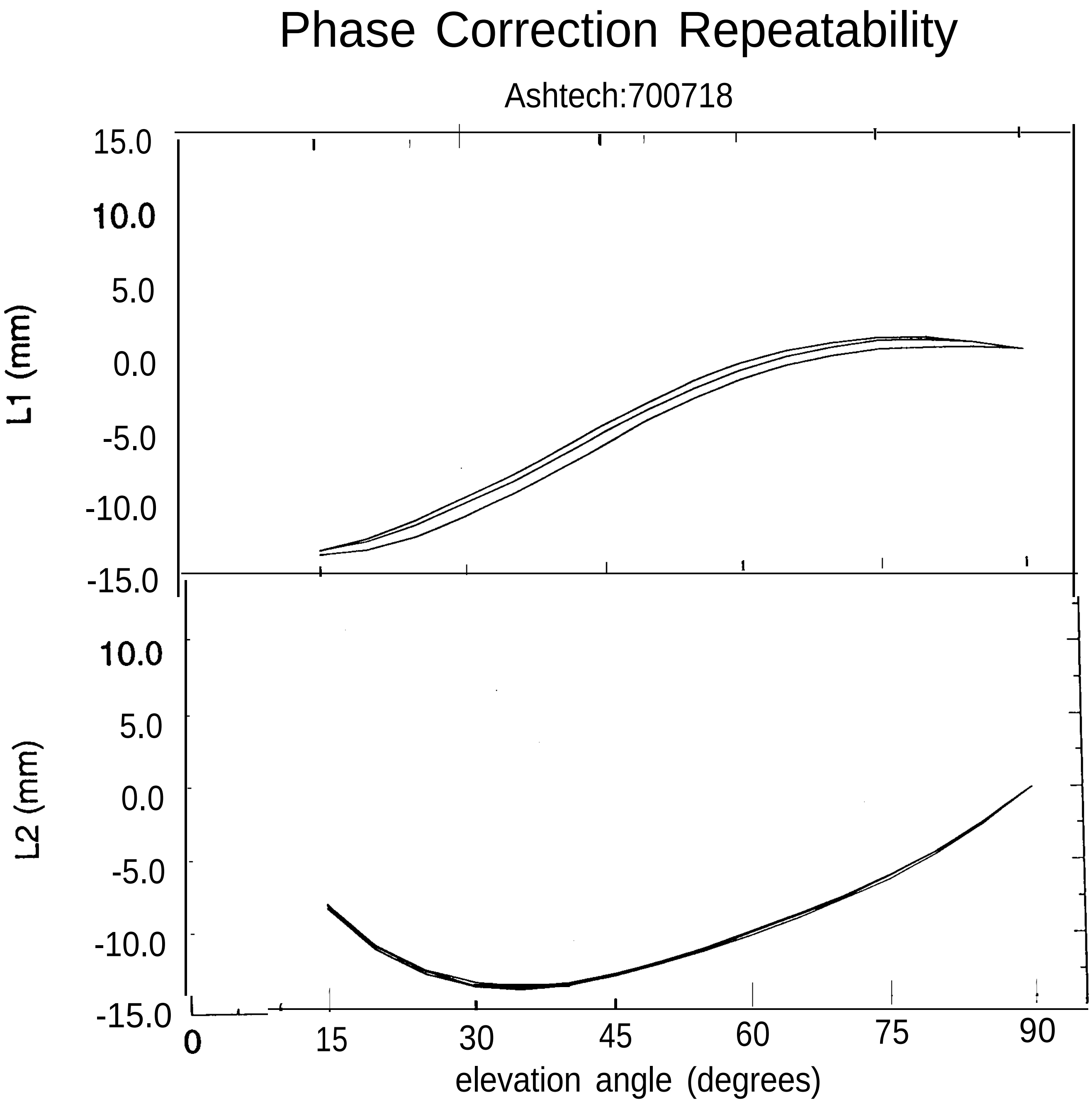
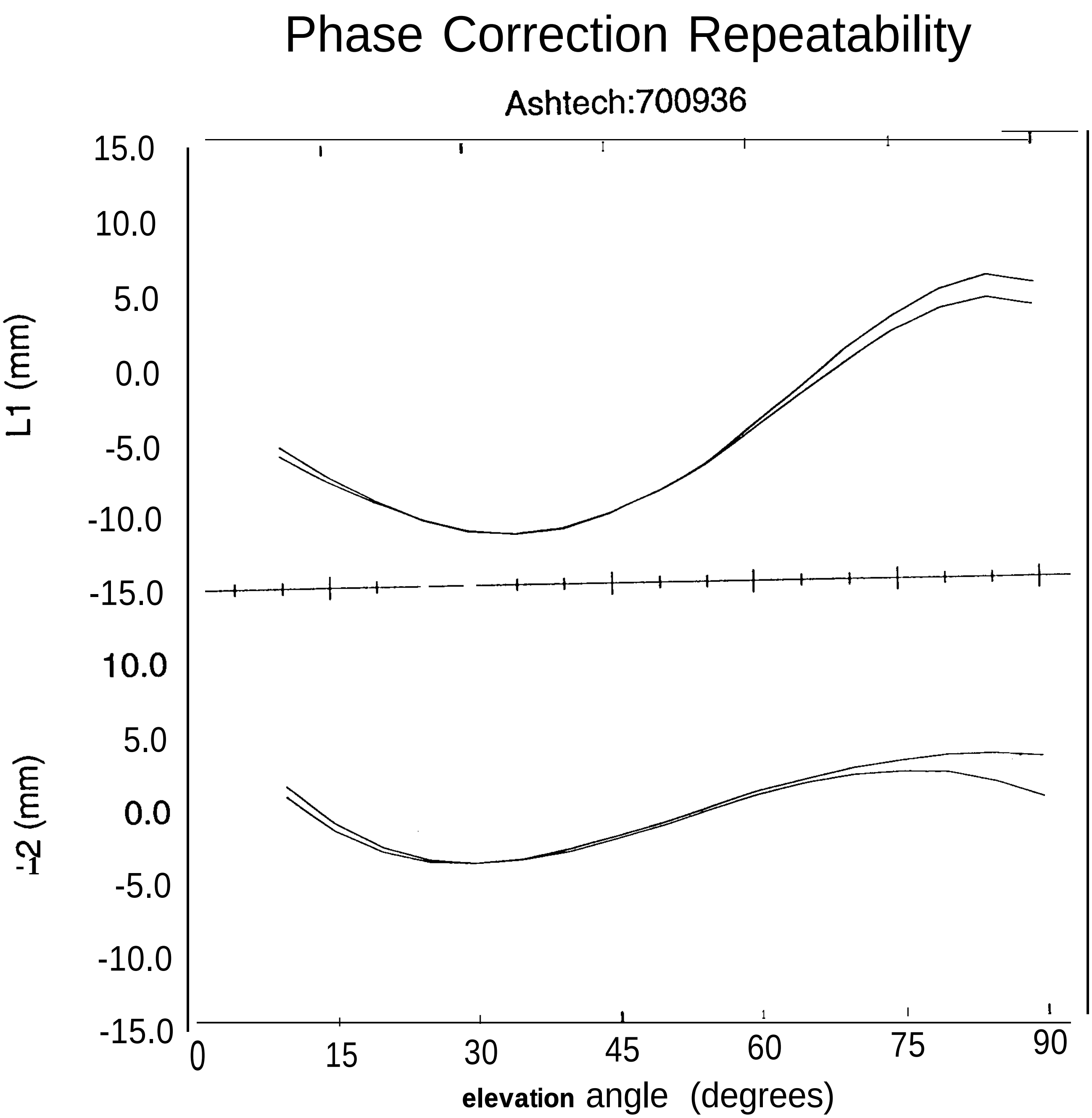

Phase Correction Repeatability
Ashtech:700228
L1 mm)
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
L2 (mm)
10.0
5.0
0.0
-5.0
-10.0
-15.0
0
15
30
45
60
75
90
elevation angle (degrees)

Figure 10



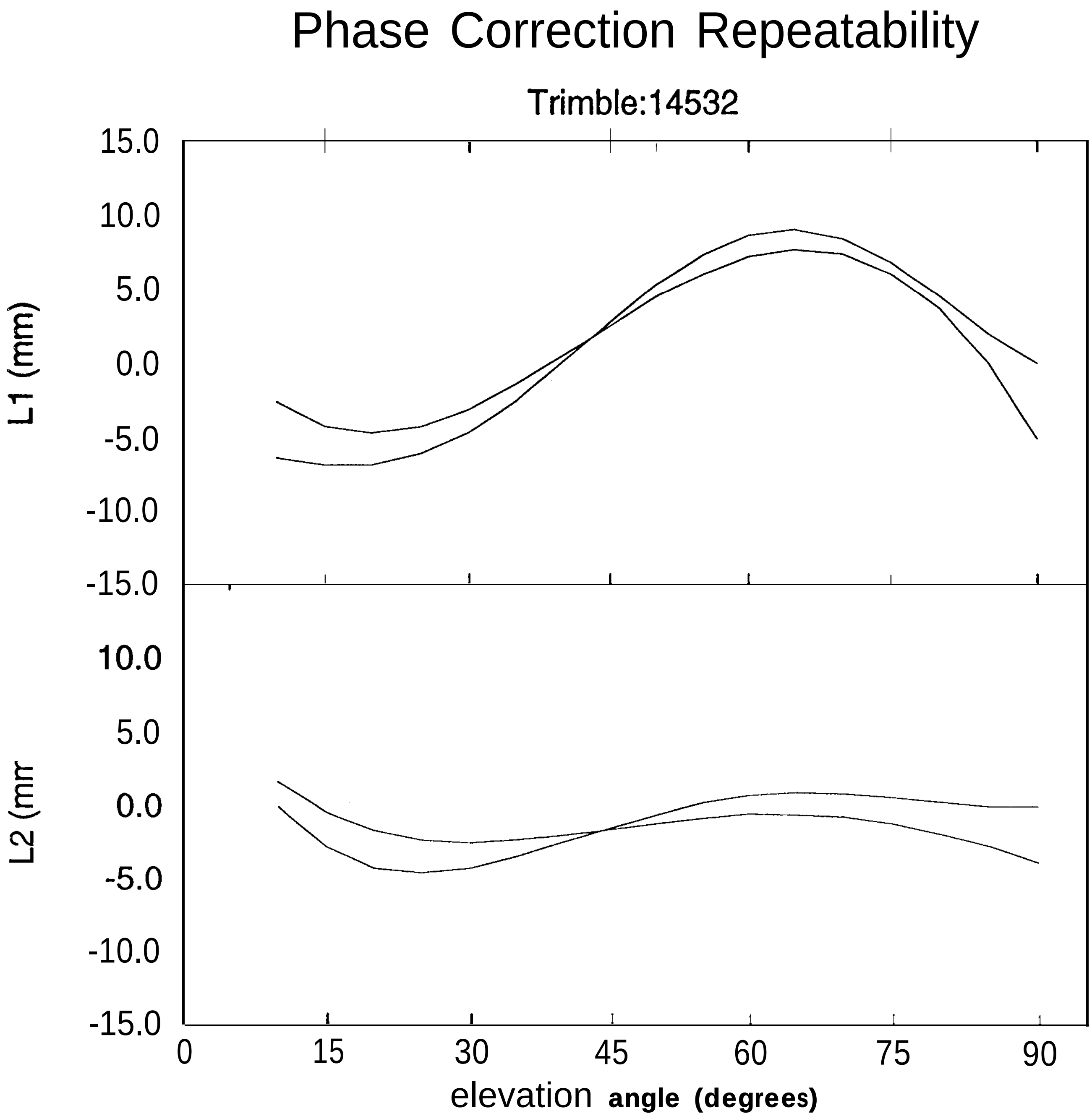
Phase Correction Repeatability
Ashtech:700718
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
L1 (mm)
10.0
5.0
0.0
-5.0
-10.0
-15.0
L2 (mm)
0
15
30
45
60
75
90
elevation angle (degrees)

Figure 11



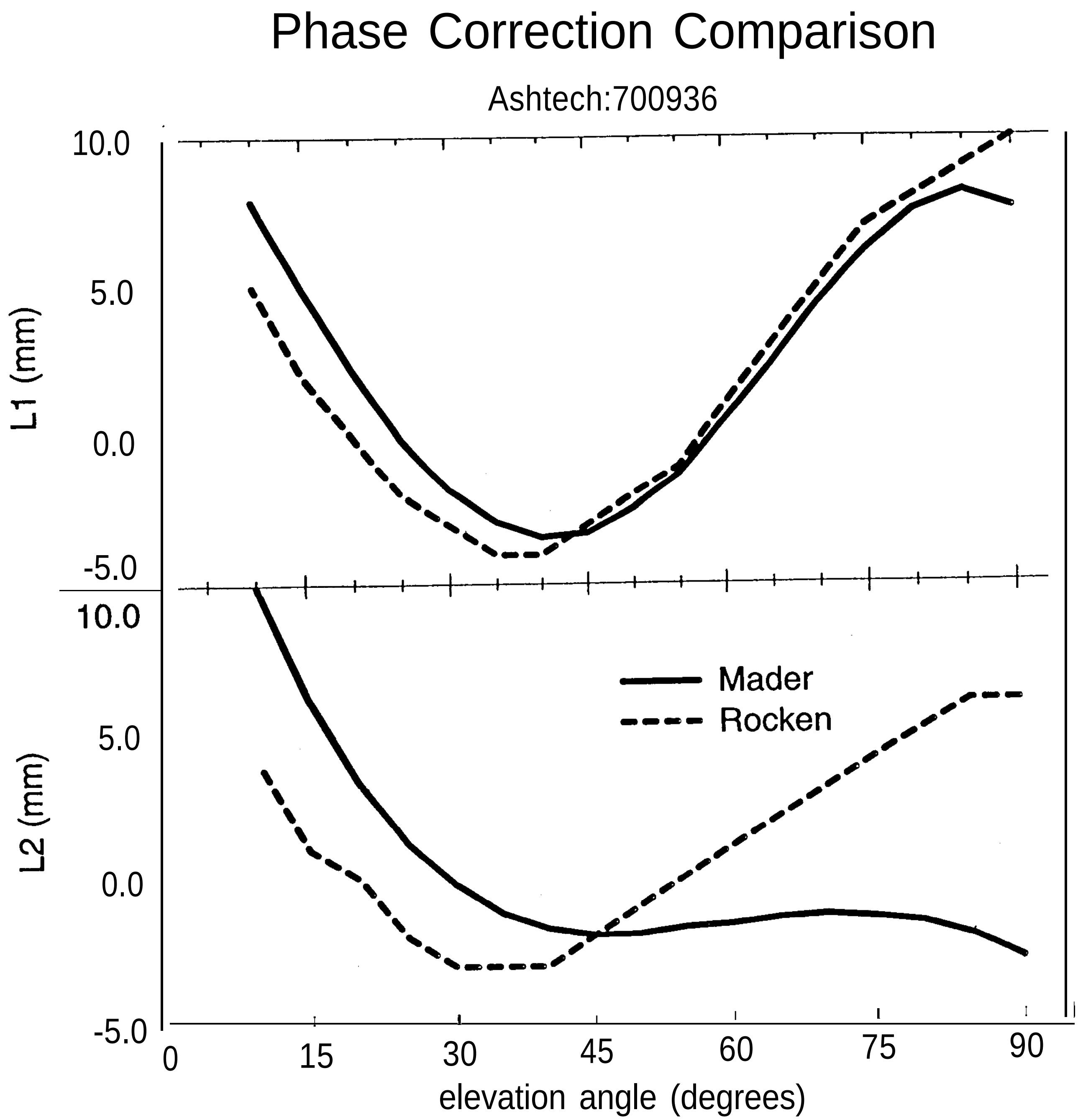
Phase Correction Repeatability
Ashtech:700936
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
L1 (mm)
10.0
5.0
0.0
-5.0
-10.0
-15.0
0
15
30
45
60
75
90
elevation angle (degrees)

Figure 12



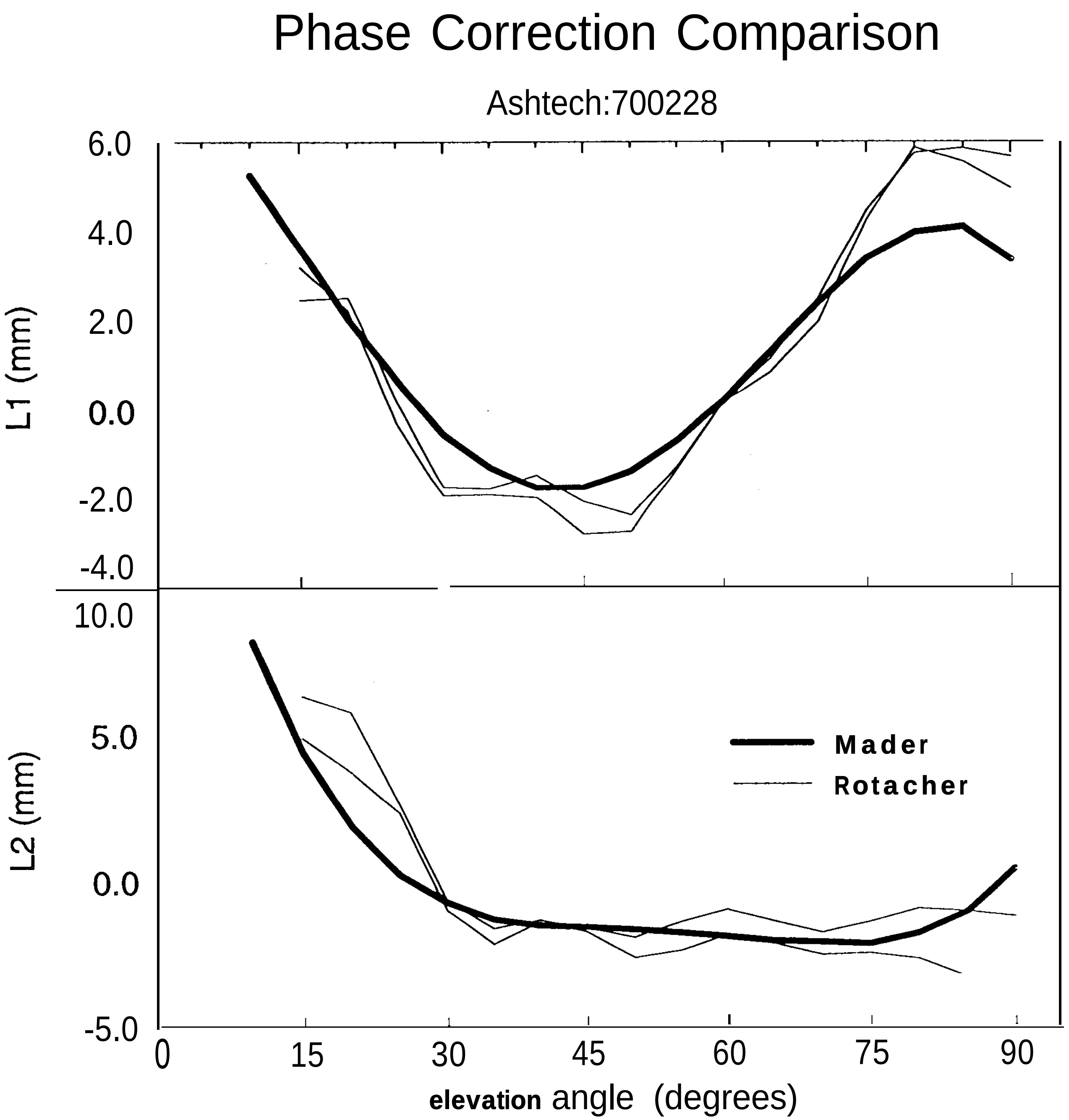
Phase Correction Repeatability
Trimble:14532
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
L1 (mm)
10.0
5.0
0.0
-5.0
-10.0
-15.0
L2 (mr
0
15
30
45
60
75
90
elevation angle (degrees)

Figure 13



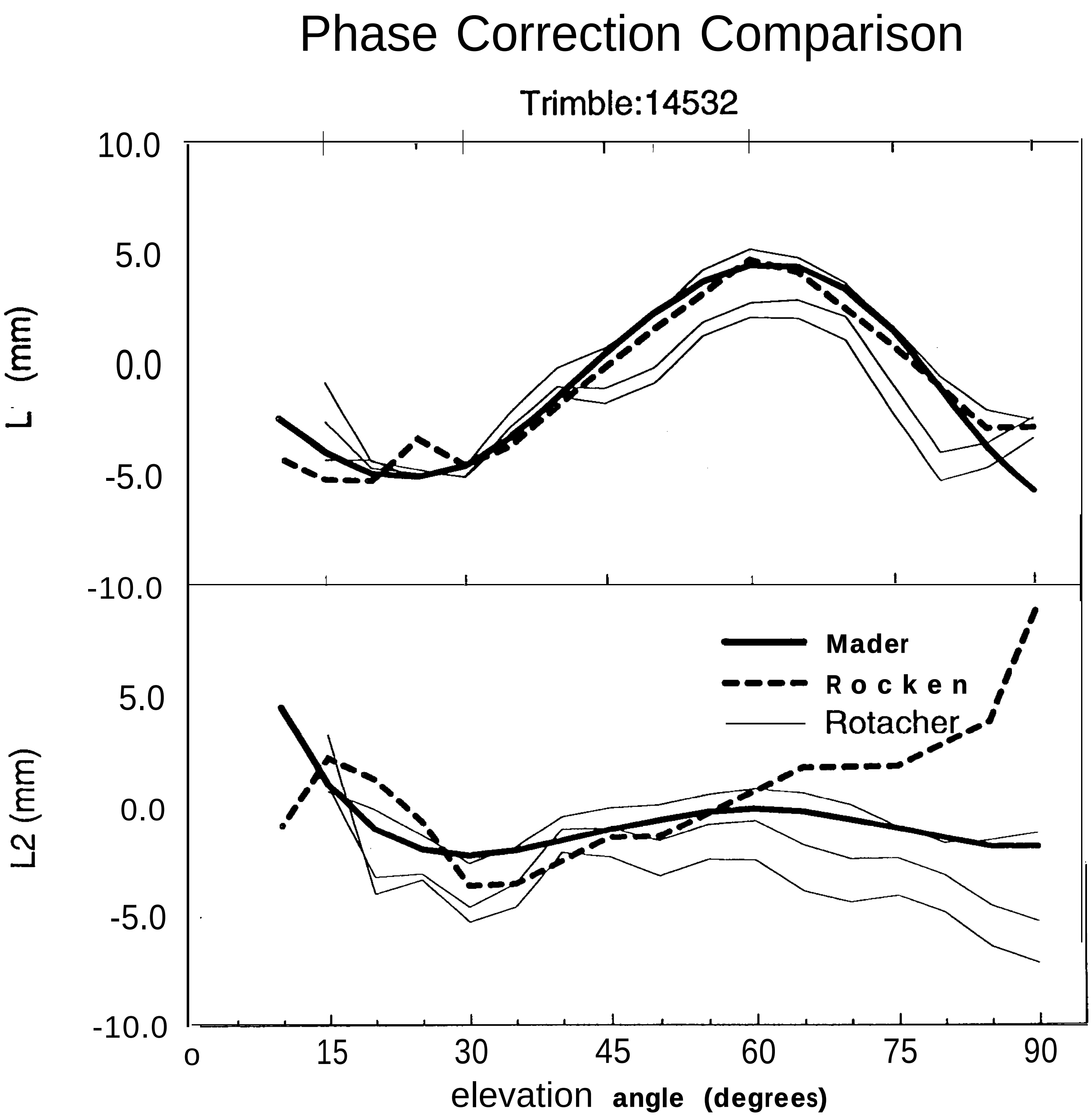
Phase Correction Comparison
Ashtech:700936
10.0
5.0
0.0
-5.0
L1 (mm)
10.0
5.0
0.0
-5.0
L2 (mm)
Mader
Rocken
0
15
30
45
60
75
90
elevation angle (degrees)

Figure 14



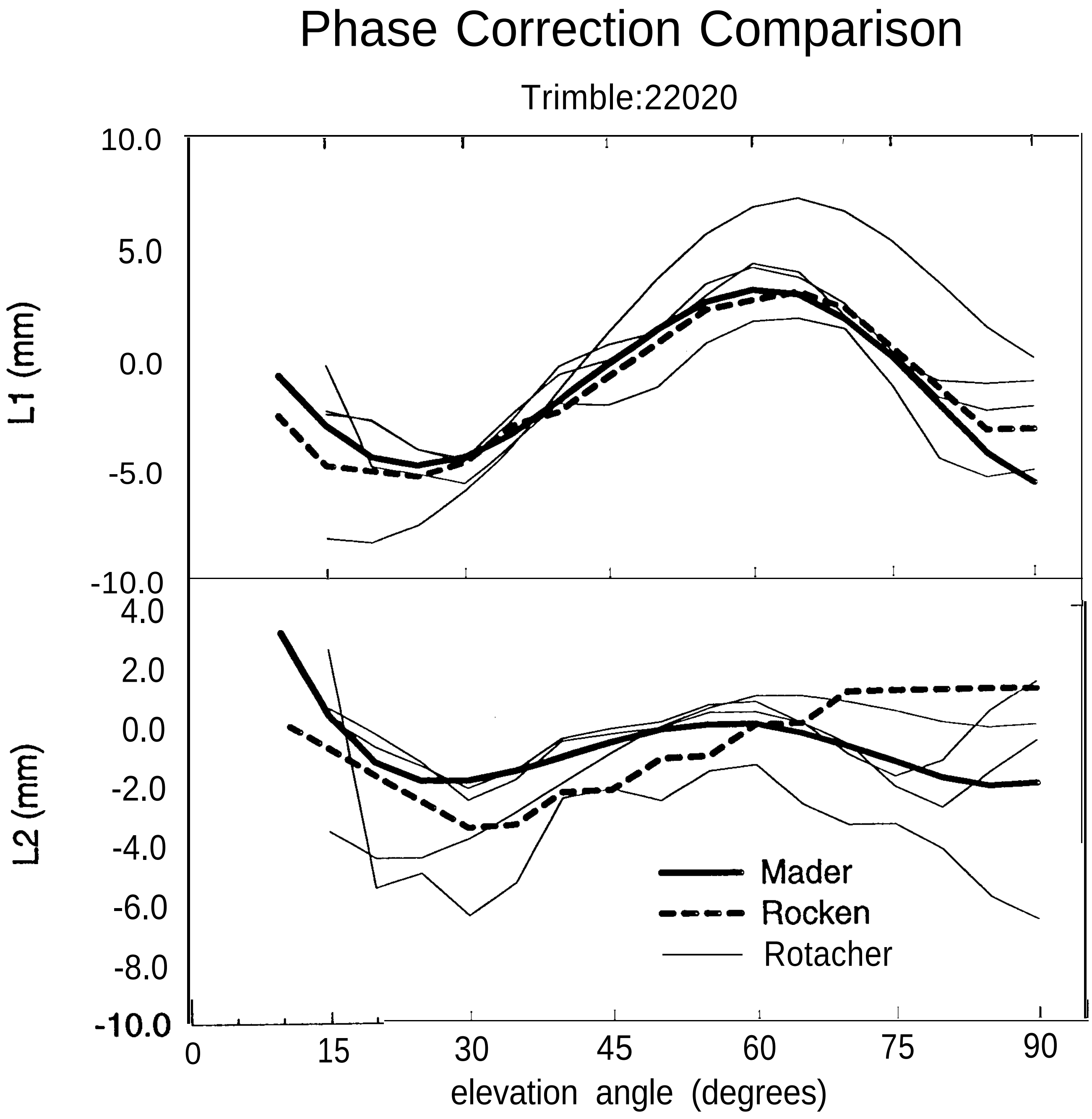
Phase Correction Comparison
Ashtech:700228
6.0
4.0
2.0
0.0
-2.0
-4.0
L1 (mm)
10.0
5.0
0.0
-5.0
L2 (mm)
Mader
Rotacher
0
15
30
45
60
75
90
elevation angle (degrees)

Figure 15



Phase Correction Comparison
Trimble:14532
10.0
5.0
0.0
-5.0
-10.0
L (mm)
5.0
0.0
-5.0
-10.0
L2 (mm)
Mader
Rocken
Rotacher
o
15
30
45
60
75
90
elevation angle (degrees)

Figure 16


Phase Correction Comparison
Trimble:22020
L1 (mm)
10.0
5.0
0.0
-5.0
-10.0
L2 (mm)
4.0
2.0
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
Mader
Rocken
Rotacher
0
15
30
45
60
75
90
elevation angle (degrees)

Field and Anechoic Chamber Tests of GPS Antennas

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University Navstar Consortium (UNAVCO)

M. Exner, University Corporation for Atmospheric Research (UCAR)

P. Kolesnikoff, Ball Aerospace

IGS Meeting, Silver Spring, MD, 20 March 1996

The accuracy of GPS surveys between different GPS antenna types and mounts can be improved using antenna calibration corrections. These corrections range from the 1 mm level to the 100 mm level for commonly used geodetic quality antennas and mounts. In order to calibrate a variety of geodetic antennas and mounts, tests were conducted on short baselines in the field and in a state-of-the art anechoic antenna chamber. Antennas included in the testing, with available IGS names in parentheses, were the Allen Osborne Associates choke ring T (DORNE MARGOLIN T) and AOA Rascal, Ashtech choke ring (DORNE MARGOLIN ASH) with cover installed, Leica SR399 external (EXTERNAL), and Trimble 4000 SST(4000ST L1/L2 GEOD) and Trimble Geod L1/L2 GP (TR GEOD L1/L2 GP) called in this report the SSE or SS1 antenna[1]. The results summarized here are described in detail in the UNAVCO Academic Research Infrastructure (ARI) Receiver and Antenna Test Report[2] (*http://www.unavco.ucar.edu/community/ari/report*). Also examined here are the effects of high and low antenna height, snow at the site and protective antenna covers.

Anechoic Chamber Measurements

Antennas can be characterized by phase center offsets and by phase and amplitude patterns for L1, L2 and L3 (ionosphere free) tracking as a function of azimuth and angle. We define the *offsets* as the average phase center locations relative to a physical reference point (typically used in RINEX files) on the antennas, and the *patterns* as the azimuth and elevation dependence of the phase centers and amplitudes. We measured these antenna properties in the Ball Aerospace anechoic test range chamber located in Broomfield, Colorado.

We ran the chamber tests using the antenna and low-noise-amplifier (LNA) combinations provided by the manufacturers. The chamber source transmitted at 9 frequencies near L 1 and L2 to simulate GPS spread spectrum modulation. We observed at 5 degree intervals over all azimuths and over ±120 degrees of elevation. Thus, more than 60,000 digital phase measurements were recorded for each antenna. The centers of rotation of the antennas with respect to the chamber mount were determined using a laser. The detail and high precision of the testing done in this state-of-the-art chamber may account for any disagreement between the results presented here and previous results (Schupler and Clark, 1991, 1994). The L 1 phase patterns for various antenna-LNA combinations are shown in Figure 1.

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1. The SSE and SS1 antennas are identical.
2. SST antennas were tested but the results were not included in the ARI test report because SST antennas were not offered as an ARI purchase option.

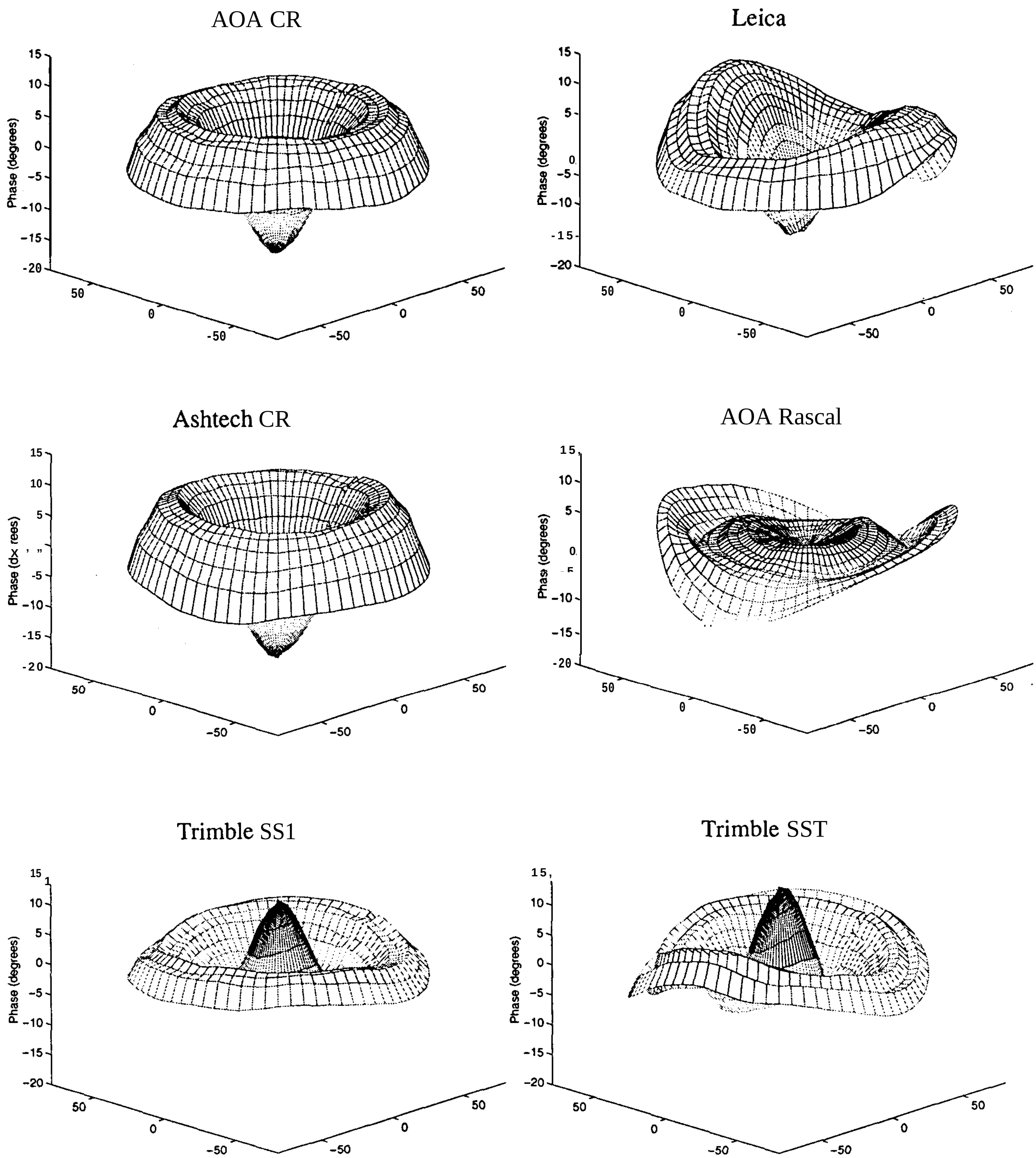

Figure 1: L1 phase center patterns are shown for several antennas (10 degrees of L1 phase is approximately 5 mm). Each of the *sombrero plots* shows zenith values in the center and 5 degree steps outward ending at 10 degrees above the horizon.

Antenna Field Tests

We conducted two types of field tests on Table Mountain near Boulder, Colorado, to validate antenna calibration parameters determined by the chamber tests. First, antenna rotation tests were conducted using antennas of the same type aligned to north on one mount and to the south on another mount, and then each antenna was rotated by 180 degrees. The observed difference in baseline length is equal to four times the average horizontal phase center offset from the rotation axis of the antenna. UNAVCO has conducted antenna rotation tests since 1989 on available antennas including the Trimble SD, SDT, SST and SS1, the Ashtech XIIM, TI-4 100, FRPA, and the AOA Dorne-Margolin T with choke ring. The results are available in a series of UNAVCO technical reports (*ftp: unavco/pub/rec_test*). In the second field test, calibration corrections determined by the chamber tests were used in surveys between mixed antenna types on known baselines.

Antenna Rotations

The Ball chamber-measured horizontal phase center offsets are as large as 3 mm (L I) and 4 mm (L2) with an uncertainty of 0.5 mm, yielding as large as 8 mm horizontal offsets for L3 (Figure 2). These offsets agree within 1 mm for L1 and L2 with offsets determined by field rotation tests for the AOA choke ring and Trimble SS1 antennas (Figure 3) as well as for the Trimble SST (not shown). The UNAVCO/Ball results offer for the first time a confirmation with chamber measurements of the horizontal offsets observed in the field antenna rotation tests.

The antenna rotation tests results shown here address only the phase center offset. It is possible to estimate phase patterns from field GPS data on short baselines (Mader and MacKay, 1995; Rothacher and others, 1995). This technique has the advantage that possible local site multipath and scattering effects can be accounted for. The results are, however, relative to a reference antenna for which a precise absolute calibration must exist (and the reference antenna must be setup to minimize multipath effects). We do not elaborate on these tests here since we have not compared them to chamber tests.

Field Antenna Mixing with Chamber-Derived Offset and Pattern Corrections

We found that L3 mixed-antenna, offset-corrected measurements with no tropospheric estimations were in error by 20 mm or less in the vertical (Figure 4, plus symbols on left panel) and by 1 mm or less in the horizontal. If hourly tropospheric estimations are included in the L3 solutions, the vertical error increases to as much as 87 mm for the Trimble SS1 to Ashtech choke ring (Figure 4, plus symbols on right-hand panel).

Application of offset and pattern corrections reduces the vertical error for troposphere corrected Trimble SS1 to AOA and Ashtech choke ring antenna mixes to 13 mm or less. The least successful application of the offset and phase center pattern corrections has been with the Trimble SST antenna where the residual error is as large as 50 mm. SST mixing results can be found in UNAVCO reports available via ftp (*unavco/pub/rec_test*).

UNAVCO/BALL Anechoic chamber

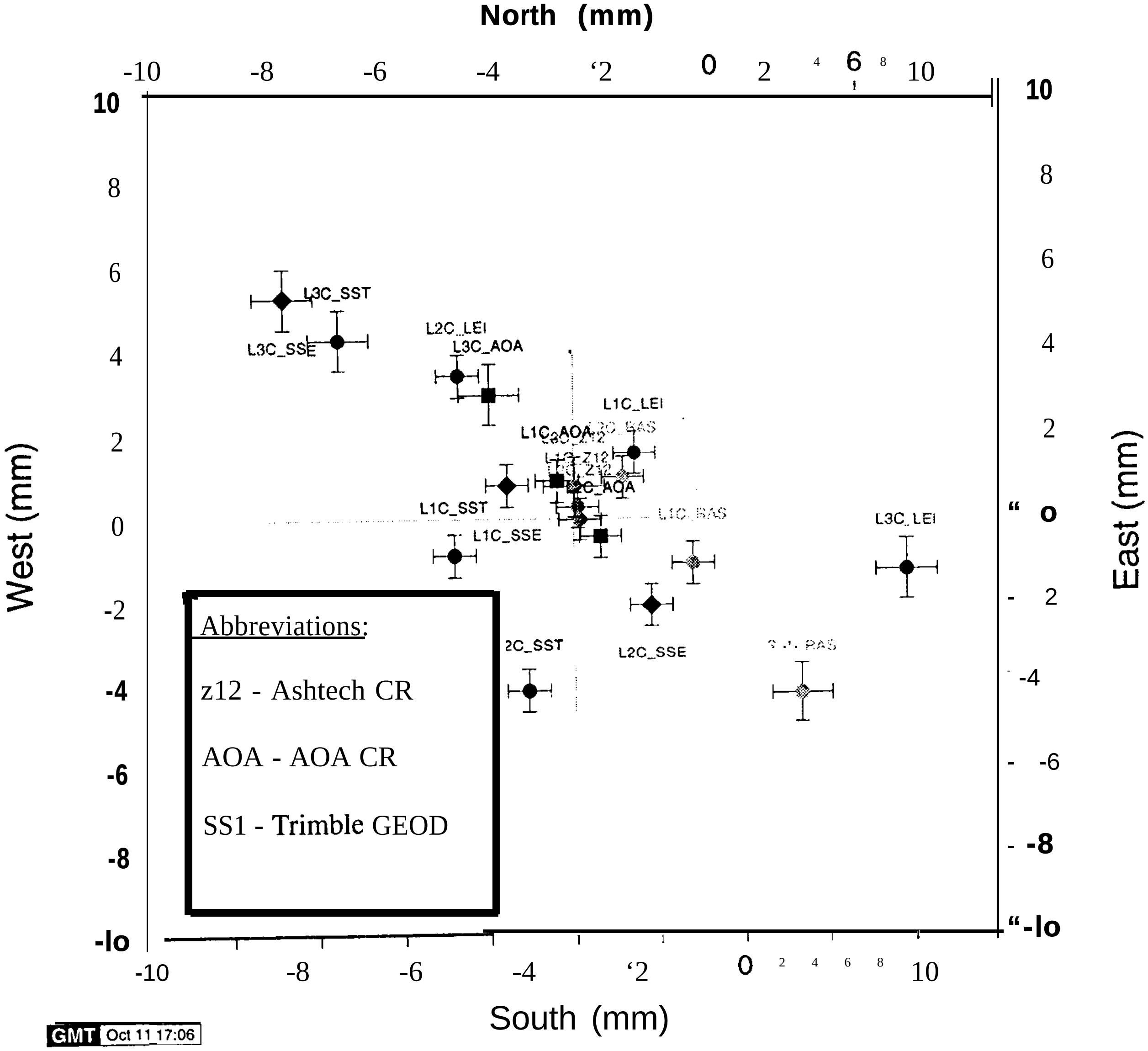

Figure 2: Horizontal phase center offsets (labeled L1C, L2C, and L3C) determined from chamber tests. The antenna axis of rotation is the zero point. Error estimates are ±0.5 mm for the measured L1 and L2 offsets.

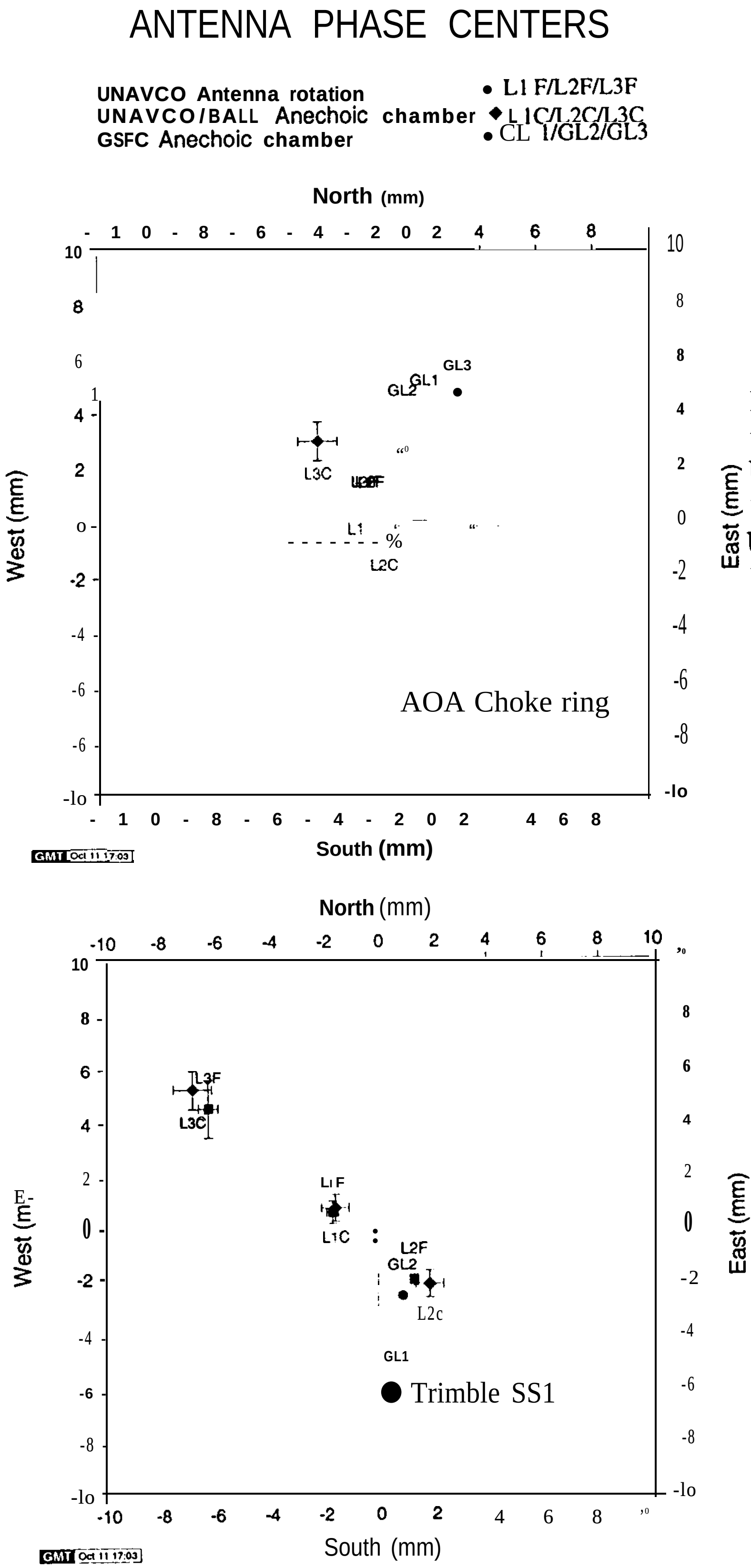

Figure 3: Horizontal phase center offsets derived from UNAVCO field antenna rotation tests (L IF, L2F, L3F), UNAVCO/Ball anechoic chamber tests (L1C,...), and Goddard/Bendix anechoic chamber tests (GL1,...).

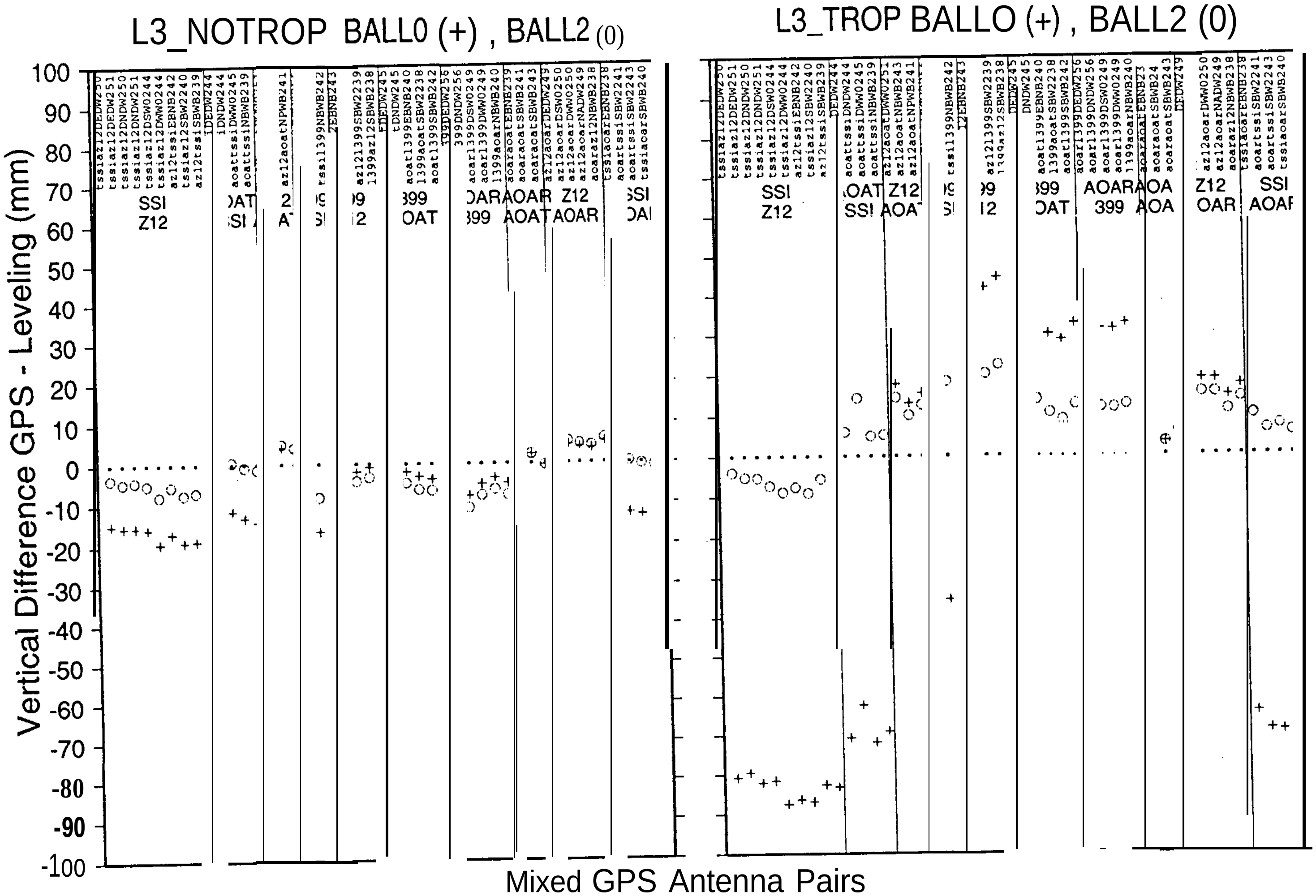

Figure 4: Summary of mixed-antenna vertical solutions with offset corrections only (+ symbols) and offset plus phase center pattern corrections (o symbols). L3 solutions are shown with tropospheric estimation (right panel) and without tropospheric estimation (left panel). The columns, separated by vertical lines, show 10 different antenna mixes. Ground truth is indicated by the dotted line,

In general, mixed antenna baseline solutions show vertical errors of 12 mm or less without tropospheric estimation, and up to 50 mm with tropospheric estimation. This compares with 1 mm errors achieved with unmixed antennas on short baselines with no tropospheric estimations. The antenna mixing error has several possible sources. First, an anechoic chamber provides an *ideal* low multipath environment whereas observations in the field are influenced by local site conditions including multipath and monument effects[1]. Second, differences in phase patterns between mixed antennas can be easily confused with tropospheric delay, particularly at low elevation angles. These effects are described in the following section.

Effects of High and Low Antenna Height Mounts

In order to investigate the effect of antennas heights on baseline accuracy, we conducted tests at Table Mountain where antennas could be easily mounted near to the ground over rod monuments set in concrete. Monuments were occupied with high (1.5 m) and low (less than 0.5 m) antenna tripod mounts with various GPS receivers and antennas. Baseline results using Trimble SSE GPS receivers and Trimble SST antennas with high and low antenna heights had vertical errors as large as 17 mm when tropospheric parameters were estimated. The horizontal components were not affected. The results of the antenna height tests are summarized in Table 1.

Table 1: Vertical solutions using high (1.5 m) and low (less than 0.5 m) antenna heights

Antenna heights	No tropospheric estimation (rms in mm)	With tropospheric estimation (rms in mm)
low-low	**0.9**	**7.4**
low-high	1.3	**5.6**
high-high	1.4	**4.1**

We found that multipath at the low antenna can be easily mismodeled as tropospheric delay. The multipath phase error generated by a low antenna can correlate to tropospheric delay for large intervals of elevation. Specifically, the L 1 phase error for a low antenna is long period (more than 1 hour) and often correlates to tropospheric delay, particularly at low elevation angles (15 to 30 degrees) where multipath and tropospheric delays are strong. This can lead to vertical errors of several cm in daily solutions. Based on a simple multipath model and experimental results at

]. We have shown, for example, that even with identical antennas, the use of low antenna mounts can seriously degrade vertical accuracy when tropospheric parameters are estimated. Nevertheless, it should be possible to map and correct for local multipath effects and any phase center pattern distortions resulting from the site antenna mount. This could be accomplished using a zero (or very low) multipath antenna with a well known antenna and mount phase center pattern. Variations in solutions between the zero and site antennas could be stacked for a number of days. Variations that persist in sidereal time could be used to correct for combined multipath and phase pattern effects. However, changes in local environment caused by snow, rain, plant growth, or modification of man-made structures could degrade the accuracy of this correction.

Table Mountain, we conclude that: (1) GPS antennas should not be placed near the ground because the scattering from the ground causes low frequency multipath that can be mismodeled as tropospheric delay resulting in vertical errors as large as several cm, (2) measurements using GPS antennas mounted on tripods at 1.5 m height are generally more accurate because they are subject to high frequency multipath (high frequency multipath is not easily confused with tropospheric delay). Details of the UNAVCO high-low antenna tests are described in *http:// www.unavco. ucar.edu/dots/science/l 995_ant_tests/tblmtn.*

It is important to note that for pillar monuments there is the possibility of an additional effect- scattering from the horizontal surface of the pillar immediately below the antenna (Elosegui, and others, 1995). In this case the horizontal top of the monument is the main scatterer and the separation between the antenna and the top of the pillar is important, independent of the height of the monument above the ground. The scattering effect may be enhanced by the presence of a metal plate at the top of the pillar.

Snow and Tropospheric Estimation Effects

Multipath effects have been demonstrated to affect vertical accuracy in the high-low antenna set-ups described above. In addition, changes in multipath conditions, such as snow at the site, can affect vertical baseline solutions when tropospheric delays are estimated. Such an effect was found using two Trimble SSE antennas on a 55 m baseline with 1 m 0.5 m antenna heights (Chris Alber, doctoral thesis in preparation). Vertical results for one day with snow cover and one without are given in Figure 5.

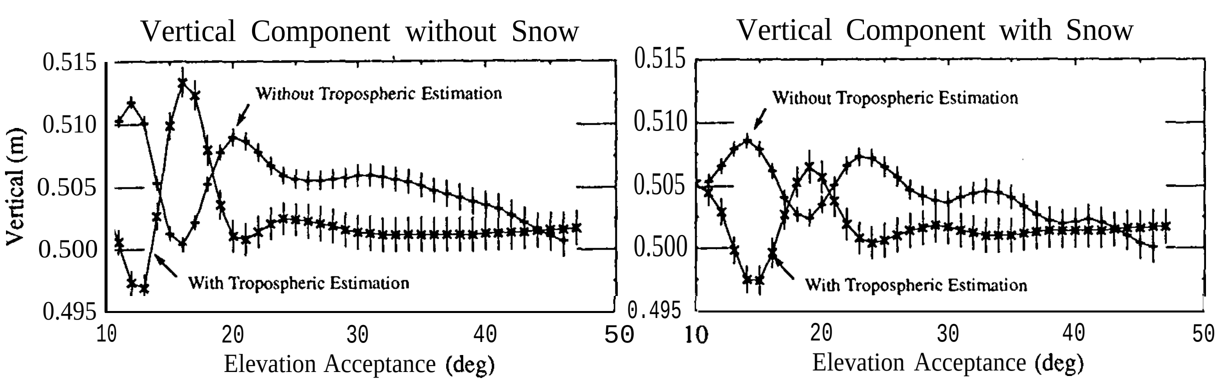

Figure 5: GIPSY processed vertical solutions are shown as a function of minimum satellite elevation acceptance for a day without snow and a day with snow, with and without tropospheric estimation. Each point represent a 24-hour solution using data from all satellites above the minimum elevation mask. Error bars show the formal solution error.

Each point represents the vertical baseline component solution from GIPSY processing using 24 hours of data and all satellites above the minimum elevation mask. The vertical baseline components for no-snow and snow are shown with and without stochastic tropospheric estimation. The results show a sensitivity at the 1 to 2 cm level to minimum elevation acceptance which is caused by multipath effects and is responsible for the errors and variability in vertical solutions from high-low antenna setups. Of note in this test, however, is the reversal in the sign of the effect when there is snow cover, indicating a large phase change in observed multipath. This effect is enhanced by the low height of one of the antennas. Similar effects were observed with 1-3 meter high monuments in the Swedish permanent network at least part of which was attributed to buildup of ice and snow on one side of the protective cover over the antenna (Elosegui, and others, 1995).

Improved GPS Geodetic Antennas

For the highest accuracy applications such as vertical deformation studies or atmospheric sensing, multipath effects can be a limiting error source. Multipath effects can to some extent be minimized by careful site selection and installation, but can also be reduced by using an antenna with higher multipath suppression, and through software algorithms such as multipath stacking and prediction. One approach to improved antenna design is the addition of a 1 meter choke ring to the JPL/AOA choke ring antenna. This approach is attractive since it could be used to retrofit choke ring antennas currently installed in the IGS global network. Details of this design are described in *http://www.unavco. ucar.edu/docs/science/geo_antenna.* Improvements in multipath reduction using a 1 meter ground plane with the AOA choke ring have also been demonstrated (Mader and Schenewerk, 1994).

Effects of Antenna Protective Covers

The anechoic chamber tests showed differences between the AOA choke ring and the Ashtech choke ring with protective cover. Subsequent field tests have confirmed that antenna covers significantly influence the vertical solutions. For example, using an Ashtech compressed styrofoam conical cover on only one end of a short baseline causes a 10 mm vertical error in the baseline vector when the tropospheric delay parameter is estimated. Preliminary results of an 1/8 inch thick acrylic dome cover shows a smaller, 2 mm vertical offset. UNAVCO is conducting further tests with a 1/4 inch acrylic cover used with AOA choke ring antennas at many IGS sites.

Summary

Antenna mixing as well as site and antenna height dependent multipath effects may effect GPS accuracy at the level of a few mm to 10 cm (Table 2). Progress is being made by measuring and correcting for mixed antenna effects (using field and chamber data), by moving toward *standard* antennas (JPL-designed choke rings with Dorne-Margolin antenna elements are now available from AOA and Ashtech and will soon be available from Trimble), and by avoiding tropospheric estimation errors associated with low antennas.

Using antenna phase pattern and offset corrections derived from anechoic chamber tests, the accuracy for mixed Trimble SS1 (patch antenna with removable ground-plane) and Ashtech and AOA choke ring antennas, with tropospheric estimation, is 12 mm or less in the vertical. Mixing results for other antennas are as high as 5 cm in the vertical. Additional work is needed to reduce antenna mixing errors down to the 1-mm level, to evaluate mixing of similar antennas made by different manufacturers (including different preamplifier designs), and to calibrate monument and cover effects.

References

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Table 2: SUMMARY OF ANTENNA AND ANTENNA MOUNTING ISSUES

Antenna Phase Center Variations

PROBLEM	STATIC POSITION ERROR LEVEL	POSSIBLE SOLUTION
Mixed Antenna Types	up to 8 mm horizontal up to 90 mm vertical	< 3 mm horizontal chamber/ insitu <10 mm to 30 mm anechoic chamber corrections <10 mm insitu GPS calibration (Mader and others)
Like Antenna types with long baseline separation ("see" same satellite at different elevation)	up to 0.015 ppm scale factor (Rothacher and others)	Insitu GPS calibration, better anechoic chamber corrections

Multipath and Scattering Effects

PROBLEM	ERRORLEVEL	POSSIBLE SOLUTIONS
Low antenna setup (<0.5 m)	up to 20 mm vertical	setup antenna <1.5 m or flush with the ground, use lower multipath antenna
Snow at site	up to 20 mm vertical	install higher or use lower multipath antenna; keep antenna clear of snow and ice
Protective Covers	2 mmto 15 mm vertical	eliminate cover or use thinner, more micro-wave transparent cover (best to date is 1/8" acrylic give 2 mm vertical error)
Pillar Signal Scattering	up to 10 mm vertical	microwave absorber under antenna; reduce cross-section of pillar; reduce metal plate under antenna; make pillar more microwave transparent (e.g. carbon fiber)

SINEX AND PILOT PROJECT

Compact RINEX Format and Tools

(beta-test version)

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Abstract

A data format and software tools are developed for compression of RINEX II observation files based on two basic ideas: (1) eliminate tile redundant information by recording only the variation between adjacent epochs for the epoch date time, event flag, satellite list, LLI, and signal strength, and (2) decreasing the digits of the phase, pseudorange, Doppler and receiver clock data by taking 3rd order differences of those data between adjacent epochs. The size of the files can be reduced 1/8 of the original RINEX files by combining with standard file compassion commands.

Introduction

Accompanied with the recent rapid increase of GPS permanent sites in the world, the amount of the data has become huge. We can find the data of nearly 100 stations in the archive at the IGS data centers which exceed 50 Mb/day. This situation causes the long dui alien time and expensive cost of data transmission by using telephone line or satellite communication or Internet.

An effective GPS file compression format and software tools arc developed. Since the RINEX format (Gurtner et al., 1989, 1990) is currently used widely to exchange the GPS data, the compassion format is designed to keep complete compatibility with RINEX II observation file format (with a few trivial exception, see the section of Incompleteness). The format is ASCII type, so it can be compressed more by using standard file compassion tools on UNIX or DOS. It can be used as an useful tool to reduce data traffic on internet or telephone line and to save the storage space.

Principles

Two basic ideas are used to reduce the size of RINEX file: (1) To eliminate redundant information by recording only the variation of the information. (2) To decrease the digits of the numerical data by taking triple difference of data arc.

(1) elimination of redundancy

Looking into RINEX 11 observation file format, we notice that some of the information is redundant. For example, the date of epochs, number of satellites, Loss of Lock Indicator (LLI), and signal strength are almost invariant from epoch to epoch. We can reduce the

redundant information if we record only the variation of those information. Comparing the characters of those data between adjacent epochs, the unchanged character is replaced with blank. If some character changes to blank,
'&' is recorded.

(2) Reduction of digit of numerical data by taking 3rd order difference of the time series
Fig. 1 shows how the magnitude of the data is reduced by taking multiple order differences. The time series of the data such as phase and pseudorange have strong correlation between epochs. We can [reduce the digit of the data by using this property. By taking differences between adjacent epochs, the digit of the data can be reduced and correlation becomes lower. Similar algorithm is used for the compression of seismogram data (Takano, 1990). By repeating the difference operation to the several times, we can reduce the digit more. Table I shows the average number of digit of the differenced data for each data type. (Signs and decimal points are not counted in this table). Empirically, the average number of digit is minimized when we take 3rd order difference which is close to random noise. The algorithm of processing is shown in Appendix I. This algorithm is applied for the data arcs of receiver clock offset and those of each data type of each satellites. This algorithm can be used in real time, since it doesn't need the data of future epoch to make the differences of current epoch. Therefore it's possible to implement this algorithm in the receiver firmware.

Table 1 The average number of digits of the difference data
(Ashtech Z- 12, sampling inter-vat : 30s)

order of difference	L1	L2	C1	P1	P2	D1	D2
0	10.7	10,6	11.0	11,0	11,0	6.7	6.6
1	8.0	7,9	7,5	7,5	7.5	4.5	4.4
2	5,9	5,9	5.1	5.1	5.1	2.8	2,7
3	4.3	4,2	3.6	3.6	3.6	2.9	2.8
4	4,3	4.2	3.7	3.6	3.6	3,2	3.1

Description of Compact RINEX format

In the RINEX format, 3 digits are used for fractional part phase, pseudorange and Doppler data (and 9 digit for receiver clock offset). in the Compact RINEX format, those data are multiplied by 1000 (receiver clock offset by 1000000000) to eliminate decimal points. The numerical data should be dealt as integer values to avoid round error in the calculation.

The Compact RINEX format consists of following lines.

(1) The 1st and 2nd lines shows the Compact RINEX format version and name of software.
(2) The header lines in the original RINEX file are follows without any modification.
For every epoch:
(3) (A32,nA3) : The line of EPOCH/SAT or EVENT FLAG (date, time, satellites, etc.), n is number of satellites and can be more than 12

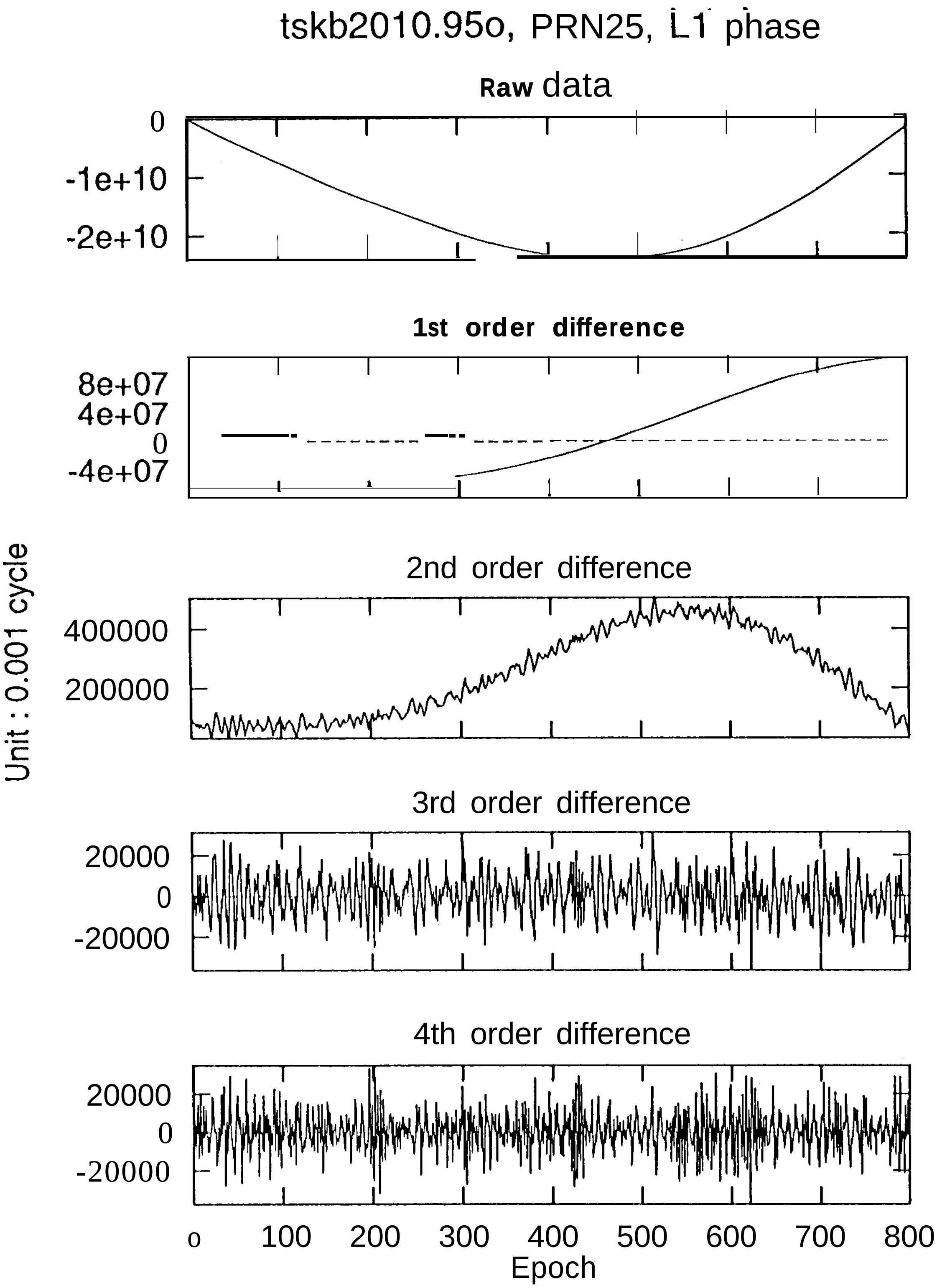

Fig. 1 Raw and differenced data for L1 phase of PRN25 in tskb201 0.950

(4) (Iv) : differenced data of the receiver clock offset. 'v' mans that the length of the integer format is variable and is O when the data field is blank in the original RINEX file. When a data arc is initialized, (Iv) is replaced with (I1,"&'',Iv) in which '1 I' is for the order of differences for the arc.

For every satellite:

(5) (n(Iv,x),n(A1,A1)) : differenced observations for all n data types (Iv) followed by change in LLI and signal strength (Al ,A1) for all data types. When a data arc is initialized, (Iv,x) is replaced with (I 1,"&'',Iv,x) in which 'I 1' is for the order of differences for the arc.

Lines (5) is repeated for every satellite, and lines (3)-(5) is repeated for every epoch. Only the characters changed from the corresponding field of previous epoch are recorded for (3) and LLI and signal strength in (5). If's character changed to a space, '&' is placed to record this 'disappearance'. Because of this procedure, most of characters are disappeared from those lines. Finally, the spaces at the end of each line of (3)-(5) have to be truncated.

The format allows the arbitral order of the differences (<1 O) for generality.

When the event flag (> 1) is set, the event information lines (such as change of wave length factor) are followed by adding '#' at the first column.

(6) ("#",A) : event information lines inserted

The definition of the data arc is important for the differential operation. A data arc of receiver clock offset or each data type/satellite is initial ized

(a) at the first appearance of the corresponding data in the file (mandatory),
(b) after the epoch of which the original data field is blank (mandatory),
(c) when event flag (>1) is set (mandatory), and
(d) at arbitrary epoch (optional).

The feature (d) makes the format more robust, but should not be abused since the compression performance will be worse, The feature (d) will work when the size of difference data become big by a large cycle slip or reset of clock.

An example of Compact RINEX file and it's original RINEX II file arc shown in Appendix 11 and 111, respectively.

Usage of the reducing/recovering software

A source code written in C language (ANSI) for reducing/recovering the RINEX file arc developed.

rnx2crx. c : convert RINEX to Compact RINEX
crx2rnx. c : recover RINEX file from Compact RINEX file

I'o see the usage of the command, type

RNX2CRX -h

(The executable file name RNX2CRX is assumed.)

Each software can be used as a command or filter
[example 1]

RNX2CRX rinex.file

will create Compact RINEX file with the file name rinex. file cr

[example 2]

cat rinex. file | RNX2CRX

outputs the Compact RINEX data to standard output

Numerical value of the data is dealt as integer in these software to avoid round error so that the recovered values arc completely the same as the original one.

Compression Rate of the Format and Speed Performance of the Tools

By combining the reduction of RINEX file and use of UNIX compress command, the size of the file can be reduced to about 1/8 of the original RINEX file. This size is even much smaller then binary format provided by each receiver manufacture. The 'l'able shows an example by using data of TurboRogue receiver.

Table II comparison of performance (in the case of being applied to tskb3000.95o)

	SIZE (Mb)	RATE (%)
① CONAN BINARY	(),387	20.9
② RINEX	1.848	100.0
③ ② + compress	0.597	32,3
④ Compact RINEX	0.546	29.5
⑤ ④ + compress	().215	11.6

We can scc that the Compact RINEX format realizes smaller file size than UNIX 'compress' command even without using binary coding. Moreover, the size of the compressed Compact RINEX is about 53 % of CONAN binary file (but without navigation message).

Th proccessing time for above file is about 4 seconds by 111'9000/73 5, 22 seconds by Sun SS2, and 10 seconds by Sun SS 10. Those are just approximate values since the processing speed may depend on the mashine type, OS, compiler, compiler option, etc.

Fig 2 shows the performance of the software when being applied to all data of IGS archive on Jan 1, 1996 (89 station), The total size of the compressed Compact RINEX files is about 40 % of the current archive to which only the UNIX compress command is applied.

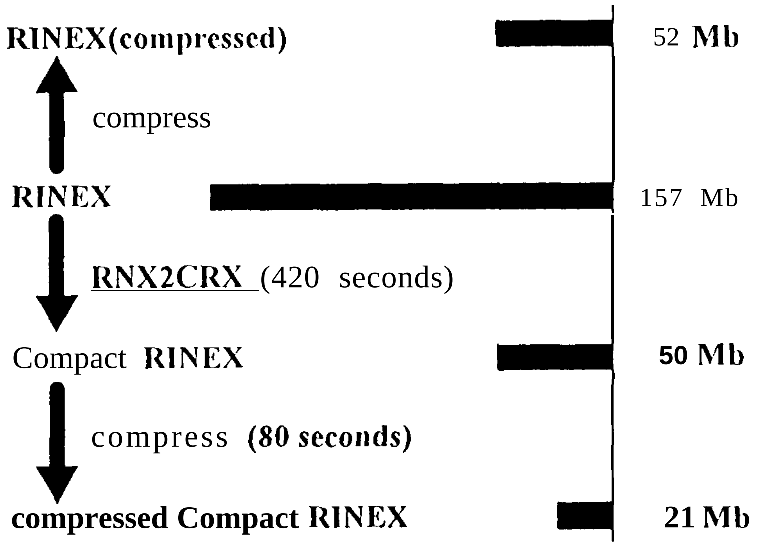

Fig. 2 Performance of the data compression tools when being applied to whole IGS data on Jan 1.1996 (89 stations). The processing times arc for the case of HP9000/735.

Incompleteness

The following information in the original RINEX files will be lost by transforming into Compact RINEX format.:

(1) meaningless space at the end of each line

(2) distinguish between numerical format: **for example "-O. 123" and "-. 123".**

Although the recovered RINEX file can be different from original one for them, the changes don't affect the numerical values at all.

Availability

The source code of current version of the software and sample data are available from

ftp://terras.gsi-mc.go.jp/pub/software/RNXCMP

References

Gurtner, W., G. Mader, D. MacArthur (1989), A Common Exchange Format for GPS Data, GPS Bulletin, Vol.2, No.3, 1-11.

Gurtner, W., G. Mader (1990), Receiver Independent Exchange Format Version 2, GPS Bulletin, Vol.3, No.3, 1-8.

Takano, K. (1990), Data Compression Method for Seismic Waves, Program and Abstracts, The Seismological Soceiety of Japan, 1990 No. 1, C32-04 (in Japanese).

Appendix 1 Algorithm for taking the n-th order differences

Let's consider an arc of the GPS data containing a RINEX II file (for example, the P 1 pseudorange data of the satellite PRNO I).

$$Y0[i],\ i=1,2,3,\ldots,n$$

The order of the range data is more than tens of thousands of km in most cases, but the size of the differences between adjacent epochs is much smaller:

$$Y1[i] = Y0[i] - Y0[i-1],\quad i=2,3,4,\ldots,n$$

The digits can be reduced more if we take difference one more time:

$$Y2[i] = Y1[i] - Y1[i-1],\quad i=3,4,5,\ldots,n,$$
$$Y3[i] = Y2[i] - Y2[i-1],\quad i=4,5,6,\ldots,n.$$

Empirically, the minimum digits can be achieved when we take 3rd-order-difference for GPS data, We can define the new sequence of the differenced data as follows:

$$Y0[1],\ Y1[2],\ Y2[3],$$
$$Y3[i],\ i=4,5,6,\ldots,n$$

The resulting data sequence preserve whole information in the original time series so that we can recover the original data arc Y0[i] from them by following calculation:

$$Y2[i] = Y2[i-1] + Y3[i],\quad i = 4,5,6,\ldots,n,$$
$$Y1[i] = Y1[i-1] + Y2[i],\quad i = 3,4,5,\ldots,n,$$
$$Y0[i] = Y0[i-1] + Y1[i],\quad i = 2,3,4,\ldots,n.$$

In general, the order of difference to take can be arbitrary, so the algorithm to take m-th order differences are as follows;

$$Y_j[i] = Y_{j-1}[i] - Y_{j-1}[i-1],\qquad i=j+1,\ldots,n;\ j=1,\ldots,m.$$

We can save the following data sequence which preserve whole information in the original time series.

$$Y_{j-1}[j],\ j=1,\ldots,m,$$
$$Y_m[i],\ i=m+1,\ldots,n.$$

The original data arc Y0[i] is recovered from them by following algorithm;

$$Y_{j-1}[i] = Y_j[i] + Y_{j-1}[i-1],\qquad i=j+1,\ldots,n;\ j=m,\ldots,1.$$

Appendix 2 An example of Compact RINEX file

```
REDUCED RINEX VER .   0.3beta
PGM To REDUCE         RNX2CRXVer.e.1. 4beta
    2                 OBSERVATI ON DATA    c (GPS)         RINEX VERSION / TYPE
RGRINEXO V2.4.2  Vw   EMR                 22-NOV-95 21:00  PGM / RUN BY / DATE
BIT 2 OF LLI (+4] FLAGS DATA COLLECTED UNDER 'AS  CONDITION COMMENT
       .000000000000         HARDWARE CALIBRATION (S)      COMMENT
       .00000021 8620        CLOCK OFFSET (S)              COMMENT
STATION INFORMATION UPDATED 1995 10 7                      COMMENT
ANTENNA :DELTA H (HEIGHT) BELOW REFERS TO THE BOTTOM OF    COMMENT
ANTENNA - ADD .110 M FOR L1 AND .128 M FoR L2 PHASE CENT   COMMENT
algo CACS-ACP 883160 ALGONQUIN PARK, ONTARIO, CANADA       MARKER NAME
40104M002                                                  MARKER NUMBER
AUTO - DOWNLOAD       NATURAL RESOURCES CA                 OBSERVER / AGENCY
226                   ROGUE SNR-8000      TURBO 3.2.32.1   REC # / TYPE / VERS
173                   DORNE MARCOLIN T                     ANT # / TYPE
   918129.6000  -4346071.2000  45619 ?7. 8000              APPROX POSITION X72
        .1000          .0000          .0000                ANTENNA : DELTA H/E/N
     1     1                                               WAVELENGTH FACT L1 /2
     5    cl    L]    L2    P2    P1                       # / TYPEs 0? OBSERV
    30                                                     INTERvAL
  1995    11    22     0     0     .000000                 TIME OF FIRST OBS
                                                           END or HEADER
 9 5 1 1 2 2 0 0   .0000000 0 6 25 18 14 28 29 22
3&23483304611 3&-6922742757 3&-5394331641 3&23483302945     74s4
3&21877048460 3&-14051925969 3S-10949548024 3&21877047035    9454
3&24215557627 34-2595202746 3&-2022292768 3S242155S714S     6444
 3&-12445464816 3&-9697760203 3&22375464751 3&2237 5466230   7 8
3&20706081053 3S-21439520675 3L-16706I11050 3&20706078869    9464
3&20455520061 3&-20561689014 3&-16022079901 3&20455 518464   9464
                    30

16809664 88341417 68837416 16810379
-12769309 -67104297 -52289052-12769483
18281939 960711s1 74 S60629 18280910          3
 -88677557 -69099356 -16874458-16874808         9
-1676041 -8807682-6863128 -1676137
8639385 45399387 35376147 8639385
                 1 &&

3037e 153253 119451 29116
88777 469294 36568388661
21953 11S916 90288 25103
 337318 262869 63891 64069
110915 583410 454608 111269
74594 393548 306664 74789
                    30                   29 14 e

-2208 -9585 -7483 -2082
-2618 -17907 -13956 -1568
4241 20994 16352 3S02
305 2543 2040 -5S70            4
 2700 2050 612 e73
-1057 -7836 -6109 -1276
                 2 &&            7    29 18       31 22

-162) -4314 -3433 961
.7 0 3 -3011-2343-100
-3 0 6 3 -12857-10014-4335
-5 4 0 -8018-62613147          3
 2789 2169 1165 197
3&24544245672 3&-60136-129 3L24544248105        16534
497 3725 2898 240
                    30                  18 5 29

-310 -6510 -5071 -296
-4138 -12393 -9592 -1599
-988 -4386 -3415 -1117
-6019 -22017 -17197 -4838
```

```
 2892 2302 -444 599
-22541669 -118452695 -92300728 -22543843 & 4
-992 -5637 -4384 -696
              3 &&

-3597 -17040 -13286 -3637
2730 7068 54e3 -5469
-2922 -16283 -12687 -323S
-1326 -18138 -14113 -7859
 2795 21e2 1306 523
1311 6104
-1124 -5587 -4360 -875
                 30

3553 21557 168 00 3592
3164 12022 9396 7115      6
-5 Eel -31603 -24634 -5814
-1525 1399 1112 3413
 2614 2057 423 456
26e5 9455
881 34e9 272o 475
              4 &&

3826 18701 14573 S194
1510 -1201 -954 2672
-3615 -17138 -13342 -3251
1018 -3153 -2458 3317
 2679 2034 247 907
-924 -5243
543 2926 2281 e43
                 30

560 424e 3323 -815
-3190 906 694 -2738
3570 15668 12201 3476
1306 13907 10819 -3916
 2S'97 2256 770 91
-2032 7193
-1652 -6049 -4713 -2303
              5 &&

4046 18101 14094 4900
3764 17402 13573 -1470
1571 12992 10122 1343
5595 22322 17448 8248
 2867 2261 454 813
5807 13903
159 -2463 -1918 809
                 30

1982 9993 77e2 410
-425 -e60 -689 6227
3149 16838 13125 3933
-525 7133 5481 3e4
 279e 2170 450 268
-2536 -11633 3&-64 5879073 3&243 86514671        434
-1582 -6495 -5061 -1550
              6 &&

-949 -856 -666 708
2447 3206 2532 291
3021 16081 12526 26S3
-1196 -6095 .4743 -1504
 2479 1917 536 860
-443 6683 -92201717 -22516369
53 -329 -261 -181
```

Appendix 3 The original RINEX file for the Compact RINEX file shown in Appendix 2

```
     2              OBSERVATI ON DATA    G (GPS)              RINEX VERSION / TYPE
RGRINEXO V2 .4.2 VM EMR               22-NOV-95 21:00         PGM / RUN BY / DATE
BIT 2 OF LL1 (*4) FLAGS DATA COLLECTED UNDER 'AS CONDITION COMMENT
        .000000000000          HARDWARE CALIBRATION (S1       COMMENT
        .000000218620          CLOCK OFFSET (S)               COMMENT
STATION  INFORMATION  UPDATED 1995 10 7                       COMMENT
ANTENNA: DELTA H [ HEIGHT) BELOW REFERS TO THE BOTTOM OF      COMMENT
ANTENNA - AOD .110 M FOR L1 AND .128 M FOR L2 PHASE CENT      COMMENT
algo CACS-ACP 883160 ALGONQUIN PAM. ONTARIO. CANADA           MARKER NAME
40104M002                                                     MARKER NUMBER
AUTO- DOWNLOAD         NATURAL RESOURCES CA                   OBSERVER | AGENCY
226                    ROGUE SNR-8000     TURBO 3.2.32.1      REC # / TYPE / VERS
173                    DORNE MARCOLIN T                       ANT # / TYPE
  918129.6000 -6346071.2000 4561977 .8000                     APPROX POSITION XYZ
        .1000          .0000          .0000                   ANTENNA: DELTA H/E/N
    1    1                                                    WAVELENGTH FACT L1/2
    5    C1    L1    L2    P2    P1                           # / TYPES OF OBSERV
   30                                                         INTERVAL
 1995    11    22    0    0     .000000                       TIME OF FIRST OBS
                                                              END OF HEADER
 9S  112200   .0000000 0 6 25 18 14 28 29 22
 23483304 .611    .6922742 .757 1  -5396331.64145 234 83302 .9454
 21877048.460    -14051925 .?69 9 -1094 ?548. 024C5 21 877047 .0354
 24215557.627    -25?5282.146  6  -2022292.76944  24215557.1454
                 -12445464.816 7   -9697760.203 8  22375464.751     22375466.230
 20706081.053    -2143 ?520.67S 9 -16706111.05046 2070607 8.8694
 20455520.061    -20561689.014 9 -16022079.90146 204 S551S.4644
 95 11 22 0 0 30.0000000 0 6 25 18 14 28 29 22
 23500114.275     -6034401.340  7  -5325494.22545  23500113.3244
 21864279.151    -14119030.266  9  -11001837.07645  21864277.5524
 24233 839.566    -2499211 .595 6   -1947432.13943  24233838.0554
                 -12534142.373  7  -97666'59.559  9  22358590.293    22358591. 422
 20704405.012    -2144 8328.357  9  -16712974.17046  20704402.7324
 20464159.446    -20516289.627  9  -15986703.75446  20464157.8494
 9 5 1 1 2 2 0 1   .0000000 0 6 25 18 14 28 29 22
 23516954.317     -6745906.670  7   -5256537.35845   23516952.8194
 21 S51590.619    -14195665.269  9  -11053760.44545  21851596.7304
 24252143.458     -2403024.520  6   -1872481.22243  24252144 .0684
                 -12622482.612  7   -9 835696.046 9  22341779.726     223417 80.683
 20702839.886    -214 S6552 .629 9  -16719382 .69846  20702837.0644
 20472873.425    -20470496.692  9  -15951020.94346  20472972.0234
 95 11 22  0 1 30.0000000 0 6 2S 18 29 14 28 22
 23533822.529     -6657268.332  7   -5187468 .52345 23533 819.3484
 21839004.246    -14251848 .885 9 -11105332 .08745 21 839003 .0014
 20701389.916    -21464172.497  9  -16725320.25846  20701387.7674
 24270469 .608     -230671 ?.002  6   -1797437.97744   24270469.6144
                 -1271 0482.833 7    -9904267.614  9  22325033.662     22325034.886
 20491660.941    -20424318.045  9  -15915037.57746  204  I31659.7104
 9 5 1 1 2 2 0 2   .0000000 0 7 25 29 18 14 28 31 22
 23550717.290      -6 S69490.640  7   -5118291.15345  235  50713. 8724
 20700054.399    -21471190 .?72 9  -167307 89.20146  20700052.3414
 21826492 .969    -14317593.971  9  -11156562.01645  21826492.0304
 24288817. 476     -2210303 .035 6  -172230 8. 66543  24288817 .8404
                 -1279 8140.247  7   -9972572.094  9   2230 8353 .266     22308354 .228
 24544245.672              -.601)6           -.12953   24544248. 1054
 20490522.493    -20377749,961 9 -15878750.75846  20490521.1504
 95 11 22   0 2 30.0000000 0 7 18 25 29 14 28 31 22
 21 814064.478    -14392907.037 9 -11207455.30345   21814063.5214
 23567634.462     -6479585.987 1    -5049014 .84045 23567634 .7924
 20698832 .347    -21477612.440  9  -16735792.94246  20698 830.4694
 243071 81 .043     -2113792.644  6   -1647110.49343   24307 183.9084
                 -128? 5451.962 7 -10040607,184 9 22291738.094       22291739.300
 24521704.003      -118453.296  6      -92300 .85743   24521704.2624
 20499457.083    -2033079 8. 077 9 -15942164.87046    20499455.6474
 9 5 1 1 2 2 0 3   .0000000 0 7 18 25 29 14 28 31 22
 21801715 .176    -14447805.123 9 -1125 8025 .23445   23801713,8374
 23584576.775      -6390547.305 7    -4079 $34, ]0]45   23594576.6394
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                  -13059027.296  7  -10175860.591  9  222 58707.763     2225 8708.707
 24476627 .2e3      -355330.919  6
 20517542.902     -20235756 .181 9  -15768106.24746  20517541.6624
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                  -13145205.622  7  -10243074.817  9  22242293.274     22242294.389
 24454093.993      -473751.635  6
 20526695.553     -20107659.754 9 -1573062 8.51146 20526694.4984
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 24380774.251      -1727065.378  6   -1345760.06843   24380774.5234
                  -132311 87.264 7  -10310011.124  9  22225946.755     22225947.786
 24431561.743       -592154 .842 6
 20535919. 894    -20139194.748 9  -15692855 .77846 2053591 8. 5314
 9 5 1 1 2 2 0 5   .0000000 0 7 18 25 29 14 28 31 22
 21753174.070     -14702 889.046 9  -11456791.89745  21753172.9904
 236 S2632.331      -6032919.153  6   -4700962.99445 23652630.7954
 20694312.013     -21501367.782  9  -16754303.58946  20694310.0194
 24399214.844      -1630163.284  6   -1270251.94143   24399214.5254
                  -13316729.355  7  -10376667.251  9  22209668.660     22209669.711
 24409036.340       -710  S26.637  6
 20545216.084     -20090333.626 9  -156547 e9.96646  20545214.5704
 95 11 22 0, 5 30.0000000 0 7 18 25 29 14 28 31 22
 21741265.536     -14765470.704 9  -11505556.81745 21741263 .S324
 23669719.742      -5943118 .358 6    -4630988.42245   23669718.6134
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 24417675.679      -1533149.296  6   -1194656.65543   24417675.9564
                  -13401909.097  7  -10443041.028  9  22193459.439     22193460.432
 24386515.248      -828878.653 6     -645879.07343    24386514.6714
 20554582.541     -20041112 .8S3 9  -15616436.13646  20554581.0654
 9 5 1 1 2 2 0 6   .0000000 0 7 18 25 29 14 2e 31 22
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 206932 54. 855   -21506921.950 9  -1675 8631.51046 20693252 .70e4
 24436155.560      -1436029.509  6   -1118978.95343   24436157.3124
                  -13486724. 011 7 -10509130.538 9  22177319.628     22177320.809
 2436399  S.024      -947204.201  6     -730080.79043   24363990  .>024.
 20564019.318     -19991522.848 9  -1 S577794 .54946 20564017.8354
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POLYHEDRON ASSEMBLY AT NEWCASTLE
METHOD AND INITIAL RESULTS

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ABSTRACT

A Global Network Associate Analysis Centre of the IGS was established at the University of Newcastle in 1995 as part of the IGS Pilot Project for Densification of the ITRF. With this project now eight months old, this paper describes in detail the analysis method used at Newcastle to create a weekly G-Sinex solution, the Global component of the integrated IGS Polyhedron. A method of attaching Regional networks to the Global component is also proposed. Some statistics summarizing the combined network are presented, and the coordinate repeatability in a recent eleven-week series is assessed and compared to that of the individual Analysis Centre networks. It is found that the median station coordinate standard deviation in the series of free combined networks is 3.6mm in height and under 3.2mm horizontally, exceeding any AC network on this statistic. This relies on imposing the IGS requirement for a Global station: that it is estimated by at least three Analysis Centres.

INTRODUCTION

In the Pilot Project for the construction of the densified IGS Polyhedron by distributed processing, the Global Network Associate Analysis Centres (GNAACS, previously known as a Type Two AACS) have the weekly task of assembling the Polyhedron from its component coordinate solutions (Blewitt et al [1993b], Blewitt et al [1995]). This is undertaken in two stages:

- The Analysis Centre weekly solutions (from now on called A-networks) are obtained from A-Sinex files, compared and combined to form the GNAAC Global component (from now on called the G-network) which is made available as a weekly G-Sinex file.

- Weekly Regional solutions (R-networks) are attached to the Global component (without further adjustment of the G-network). The resulting set of consistent Polyhedron components (the P-network) will be made available in P-Sinex files.

The second item relies on the IGS weekly orbit combination (Beutler et al [1993], Goad [1993], Kouba [1995]). The stations which go into the combined G-network should be those used by the ACS for rigorous orbit and earth orientation estimation, which hence define the primary frame of the Polyhedron and lead to the IGS Orbit. This sparse station set should be deployed as uniformly as possible over the globe (as discussed by Zumberge et al [1995]).

Each A-Sinex currently includes 30-70 stations, with about 20 being estimated by all ACS, and about 60 positioned by at least three ACS. The estimation redundancy of the A-network stations defines the reliability of the G-network (i.e. the ability of a GNAAC to detect outliers and discrepancies in A-networks). Figure 1 below shows station redundancies in the A-networks of a typical week. The IGS definition of a Global station requires that it be positioned by at least 3 ACS, so the two dozen stations in the first two columns of the chart do not qualify, only appearing in one or two A-networks each week.

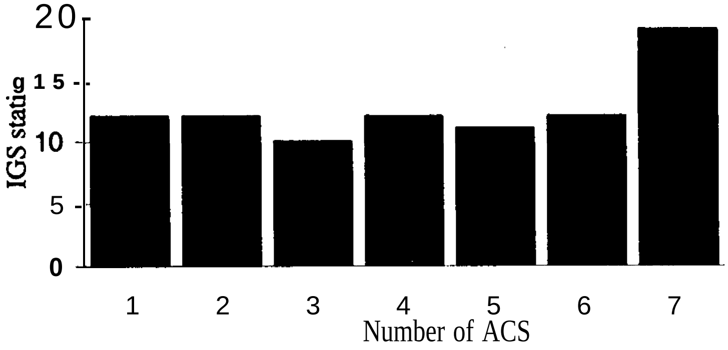

Figure 1- A-network stations grouped by number of ACs estimating each.

In this paper I focus on the first GNAAC task, G-network assembly. The methodology employed in this analysis is given in section 2, and some results of this are summarised in section 3, where a short time-series of G-networks is presented. Section 4 briefly discusses the second GNAAC task, suggesting a procedure for the attachment of Regional networks.

2 G-NETWORK ANALYSIS

2.1 Parameter matching to a Sinex catalogue

Each Analysis Centre delivers a weekly A-Sinex file. The first step is to extract the set of A-networks from A-Sinex files with a common parameter numbering. Because Sinex is a complex format, this is a rather involved task. Each GPS site has a unique four-character identifier; at each site there may be multiple monuments which within a particular Sinex file are identified by letters A, B, etc. For monuments listed in the ITRF, the unique DOMES code is given. For each monument, multiple station estimates may be given in a Sinex file - this occurs when the monument is estimated at distinct epochs, for instance, or when more than one antenna is operating at the monument. For each station, one or more records are given in each of a set of station attribute tables, describing the antennae, receivers and local tie vectors used during the period of observation. Each of these records includes an epoch range. Sinex format is detailed by Kouba [1996].

A catalogue Sinex file is maintained, giving the same information types for all the stations which might occur in the incoming A-Sinex files. In a series of automatic matching stages, each A-Sinex station is assigned the parameter numbers of a catalogue station. Any discrepancies between the station information in the A-Sinex and that in the catalogue are recorded, and non-unique matches are reported on. If unknown or ambiguous stations are found, the catalogue is updated. By setting the epoch ranges, etc., of the catalogue stations, and flags governing the matching criteria, the analyst can process Sinex files in various analysis contexts.

The result of this for each A-network is:

- an estimate parameter vector y (of coordinate triplets) with a full covariance matrix Σ_y,
- an a priori parameter vector z with covariance matrix Σ_z,
- parameter reference lists for both vectors to the catalogue Sinex.

'inner constraints' generalised inversion of the normals. The constraints on all the 'loose' A-networks are chosen so estimable quantities differ negligibly from the truly 'free' network case.

2.3 Combination of loose A-networks

The combination of the loose A-networks is a 'sparse matrix' application, in that the overall covariance matrix of the observations (the A-network coordinates) is a block diagonal - no correlation is modelled between the A-networks, making the combination feasible. A normal equations 'block' is formed for each A-network, which in a separate software module are added and solved. The 'observations' and 'parameters' are the same quantities so the first-order design matrices of this Least Squares operation are of the binary incidence type - for this reason the process can also be regarded as a weighted ANOVA.

Firstly, a combination parameter list is formed automatically from the catalogue parameter lists of each A-network, allowing exclusion of A-network parameters flagged as outliers in a previous iteration (see section 2.4 below) or excluded due to discrepancies with the catalogue, and the exclusion of parameters unique to single blocks if required. Let the combined parameters be $\mathbf{p}$ with covariance matrix $\boldsymbol{\Sigma}_\mathbf{p}$, and the excluded parameters for normal equation block i be $\mathbf{u}_i$ (total n blocks). The subscript notation for the binary incidence matrices **A is** used as before:

$$\mathbf{P}_i = \mathbf{A}_{x_i-p}\,\boldsymbol{\Sigma}_{\mathbf{x}_i}^{-1}\,\mathbf{A}'_{\mathbf{x}_i-\mathbf{u}_i}\left(\mathbf{A}_{\mathbf{x}_i-\mathbf{u}_i}\,\boldsymbol{\Sigma}_{\mathbf{x}_i}^{-1}\,\mathbf{A}'_{\mathbf{x}_i-\mathbf{u}_i}\right)^{-1}\mathbf{A}_{x_i-u_i}\,\boldsymbol{\Sigma}_{\mathbf{x}_i}^{-1} \tag{4}$$

$$\mathrm{N}_i = \mathrm{A}_{x_i-p}\,\boldsymbol{\Sigma}_{\mathbf{x}_i}^{-1}\,\mathbf{A}'_{x_i-p} - \mathbf{P}_i\,\mathbf{A}'_{x_i-p} \tag{5}$$

$$\mathbf{d}_i = \mathbf{A}_{x_i-p}\,\boldsymbol{\Sigma}_{\mathbf{x}_i}^{-1}\mathbf{x}_i - \mathbf{P}_i\mathbf{x}_i \tag{6}$$

$$\boldsymbol{\Sigma}_\mathbf{p} = \left(\sum_{i=1}^{n}\sigma_i^{-2}\mathbf{N}_i\right)^{-1} \tag{7}$$

$$\mathrm{p} = \boldsymbol{\Sigma}_\mathbf{p}\sum_{i=1}^{n}\sigma_i^{-2}\mathbf{d}_i \tag{8}$$

where σ_i^2 is a variance component (scaling factor) applied to each block (see 2.4 below). The values of $\boldsymbol{\Sigma}_{\mathbf{x}_i}^{-1}$ are carried over from eqn. 2, and the bracketed inversion in eqn. 4 is relatively small. Also, note that the **A** matrices are notational only - fast reparameterisation routines are used in the software. In fact, the inversion of the normal equations of common parameters (eqn. 7) is the only major computation here. This can be rapidly carried out by Cholesky decomposition (N = LL', L triangular) - I also use the Singular Value decomposition (N = UDV' , D diagonal, U and V orthogonal) which provides the matrix eigenvalues indicating the regularity of the inversion.

2.4 Residual Analysis

The direct LS coordinate residuals for observation block i given by $\mathrm{v}_i = \mathbf{A}_{p-v_i}\mathbf{p} - \mathbf{A}_{x_i-v_i}\mathbf{x}_i$ (where the parameter list of vi is the intersection of those of **p** and xi) are of little interest, because they are biased by the datum differences of the A-networks. A-network orientation is arbitrary, and the geocentric origin is observed inaccurately (compared to the precision of inter-station 'baselines). Therefore it is appropriate to remove a seven-parameter similarity transformation between each A-network and the combined G-network, giving post-fit residuals which are independent of the A-network datum. A question arises over appropriate weight matrices for this estimation when the networks have full covariance matrices. The dispersion of pre-fit residuals (the 'observations' of the estimation) is described by the biased covariance matrix

$$\Sigma_{v_i} = \underset{x_i - v_i}{A} \Sigma_{x_i} \underset{x_i - v_i}{A'} - \underset{p - v_i}{A} \Sigma_p \underset{p - v_i}{A'} . \qquad (9)$$

This matrix is dependent on the A-network loose constraints, which I control by the parameters of eqn. 2. I take the reciprocals of the diagonal elements of eqn. *9* to form a diagonal weight matrix, then iteratively compute the similarity parameters S_i and post-fit residuals O_i. This weighting method and alternatives are still being tested. Blewitt et al [1992] have in a related context explicitly projected the covariance matrix orthogonal to the space deftned by the linearised mapping matrix of the 7-parameter transformation, hence obtaining an estimable basis. This is equivalent to fixing all 7 similarity transformation parameters to the estimate coordinates.

The full Σ_{v_i} is used to compute the covariance matrix of o_i, which is required for outlier detection and other statistics. If the linearised mapping matrix of the transformation at convergence of the estimation is B_i then

$$\Sigma_{o_i} = \Sigma_{v_i} - B_i (B' \Sigma_{v_i}^{-1} B)^{-1} B_i' . \qquad (10)$$

The post-fit residuals of each A-network are used for two important residual analyses: variance component estimation (VCE) and outlier detection. These two tasks are mutually dependent, since each relies on the correct fulfillment of the other. A circular problem is ameliorated by assuming that the variance component applied to each Analysis Centre has continuity between weekly epochs, whereas outlying observations do not. A careful balance is nonetheless required between these two objectives in the testing of residuals, which to some extent must involve *ad hoc* modelling choices.

The variance component estimation method I use is a slow-converging variant of Helmert's iterative method (Grafarend et al [1979], Sahin et al [1992)) in the Helmert blocking setting. In this method one discards the off-diagonal elements of the Helmert matrix (Ziqiang [1989]), making the component for each block dependent on the partitioned residuals for that block only. At convergence, this is equivalent to the full Helmert method and to iterated MINQE and Maximum Likelihood derivations. The scale factor update ρ_i^2 for each block i is given by

$$W_i = \sigma_i^{-2} \underset{p-v_i}{A} N_i \underset{p-v_i}{A'} \qquad (11)$$

$$\rho_i^2 = \frac{o_i' W_i o_i}{m - \mathrm{tr}(W_i \underset{p-v_i}{A} \Sigma_p \underset{p-v_i}{A'})} , \qquad (12)$$

where W_i is the weight matrix of the ith reduced observation block and m is the number of estimated parameters. The 'slow convergence' of this expression has not caused problems, even when the initial σ_i's are far from the final values. Because these factors are highly sensitive to outliers, the A-network scale factors are in practice held fixed from week to week so iterating the G-network formulae (eqns. 4-8) to convergence of eqn. 12 is not a regular requirement - executing eqn. 12 once is sufficient to indicate weekly deviations in variance components.

Outlier detection is carried out using the full-matrix form of Baarda's w test (Cross [1994]) on the coordinate triplet of each station observation in turn. Before computing this, each A-network block is scaled by the overall unit variance (chi square per degree of freedom) of the G-network estimation. The Baarda statistic for the *j*th station of block *i* is:

$$w_{ij} = \frac{\mathbf{a}'_j \mathbf{W}_i \mathbf{o}_i}{\mathbf{a}'_j \mathbf{W}_i \boldsymbol{\Sigma}_{\mathbf{o}} \mathbf{W}_i \mathbf{a}_j} \tag{13}$$

where $\mathbf{a}_j$ is a binary incidence vector, the elements of which are unity that correspond to the three parameters of the station *j* under test, otherwise zero.

In the absence of outliers and if variance scaling is correct, the $\mathbf{w}_{ij}$ should be normally distributed with zero mean and unit standard deviation. We can assess the normality of the $\mathbf{w}_{ij}$ using skewness and kurtosis values or the Kolmogorov-Smirnoff goodness-of-fit test. For the series presented in the next section, I remove observations whose $\mathbf{w}_{ij}$ lie in the outermost 1 % of the normal distribution (i.e. 99% confidence level) to improve the 'robustness' of the estimation. Due to the multiple outlier 'masking' effect and the uncertainty in variance scaling increasing the possibility of type I and type II errors, this procedure is by no means perfect. Observations flagged as outliers are excluded from an iteration of eqns (4-8) and the residual analysis steps are repeated.

The Weighted Root-Mean-Square (WRMS) summary statistic is calculated for each A-network with respect to the G-network, and also between each pair of A-networks, and between each A-network and ITRF coordinates. The WRMS values are included as a triangular table in the GNAAC analysis report (see Table 2 below). Because it takes account of parameter weighting, this can be a more useful and stable statistic than a simple RMS when a range of station variances are present in a network.

2.5 GNAAC Products

After residual analysis on the loose solution I constrain the G-network to the conventional Core network of 13 stations in ITRF94. It is this constrained solution and its constraints which are written to the G-Sinex file (with station information provided by the Catalogue Sinex) and delivered to an IGS Global Data Centre (CDDIS). The loose solution can be regained from the G-Sinex by removing constraints (eqns. 2, 3).

A GNAAC analysis report is also produced each week, deposited at CDDIS and distributed to the IGSREPORT email list. This gives information on A-Sinex discrepancies and residual summaries comparing the A-networks, combined G-network and ITRF *Core.*

3- A G-NETWORK SERIES

The procedure is now illustrated with some statistics from an eleven-week series of G-networks (GPS Weeks 0840-0850, 1 lth February - 27th April 1996). Sections 3.3-3.5 provide a simple indication of G-network performance.

The G-networks used here differ from those submitted weekly to CDDIS in that only stations positioned by at least three ACS were included. This is the IGS stated requirement for Global stations (IGS Terms of Reference) so it was applied in this study. The weekly G-network I submit in the Pilot Program currently includes all the A-network stations, regardless of which column of Figure 1 they belong to. In the GPS weeks used here, 55-60 stations each week met the 3-AC requirement. The six Analysis Centres producing weekly A-networks were included - COD, EMR, ESA, GFZ, JPL and S10. I do not include the daily Sinex from NGS.

A constant variance component was used for each Analysis Centre to obtain this series. To initialise these components the iterative VCE formula (eqn. 12) was applied to the loosely-constrained A-networks to generate a variance scale factor for each AC in each of the weeks analysed, after removal of the most extreme outliers. The constant variance component for each AC was set to the average of the Centre's components over the series. These factors are listed in Table 1.

COD	EMR	ESA	GFZ	JPL	S10
47	19	27	42	17	2.4

Table 1- Variance components applied to ACS

3.1 Residual Analysis

The presence of outliers tends to make the values in Table 1 too large. The A-networks are affected differently by this because some ACS regularly have far-outliers in their A-networks while others do not, The numbers of station observations removed each week using the Baarda statistic at the 99% confidence level (eqn. 13) are given in Figure 2 (unit variance scaling was applied before the outlier test.) The G-network solutions were iterated with outliers removed. Because Table 1 was unchanged in the iteration, the unit variance after the outlier removal tends. to be below unity, as shown in Figure 3.

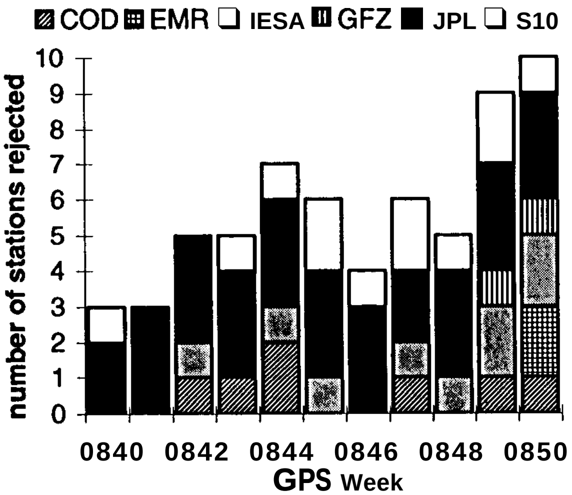

Fig 2- Outliers at 99% confidence level

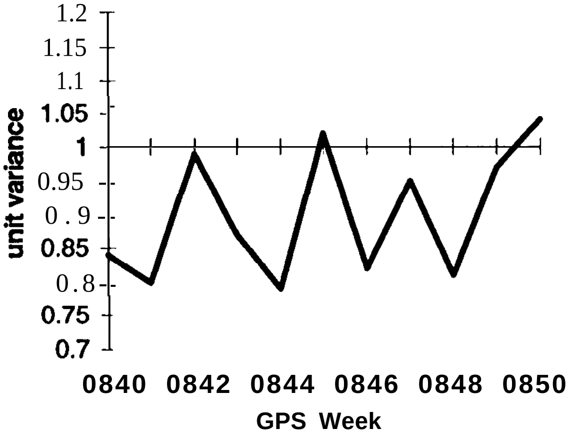

Fig 3- Unit variance series after outlier rejection

We can examine the deviation in individual AC variance components for each week by computing eqn. 12 after overall unit variance scaling (although eqn. 12 is an iterative expression, the components are already close enough to their correct values to make a single evaluation useful). This results in figure 4.

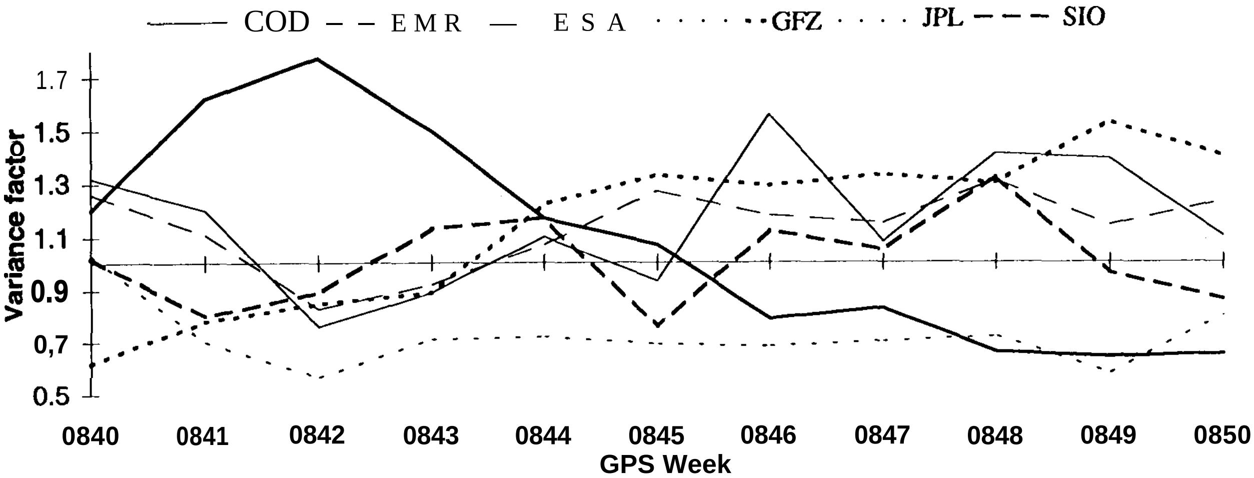

Fig 4- Weekly variance factor deviations for each AC

Note how the ACS with several outliers removed each week (notably JPL) have variance factor deviations consistently below unity - this is because the initial variance components were influenced by these outliers. It would be wrong to apply these factors in each week, because of their outlier-masking effect. Rather, the long trend in Figure 4 is examined and variance components adjusted over a period of time. Using this approach, the variance components are a function of the outlier detection test used and the confidence level chosen for outlier removal.

3.2 **WRMS of postfit residuals**

The weighted root-mean-square of post-fit residuals after weighted similarity transformation was calculated between A-network pairs (Table 2), and between A-networks and the G-network (Figure 5).

EMR	ESA	GFZ	JPL	SIO	G	
8.2	11.3	11.0	8.8	10.3	3.5	COD
	14.9	9.9	6.9	7.9	5.9	EMR
		14.5	13.3	11.5	10.9	ESA
			9.7	9.9	10.5	GFZ
				14.9	5.5	JPL
					3.6	SIO

Table 2- Week 0848 WRMS (mm) of postfit residuals after weighted similarity transformations between each pair of A-networks, and the G-network (code G)

Examination of the residuals and their standard deviations for individual stations in the pairwise comparisons of Table 2 is helpful because they are independent of the combination - they can for instance be used in ad hoc methods for locating outliers. However, to assess G-network consistency we need to examine the variation in the series of independent estimates.

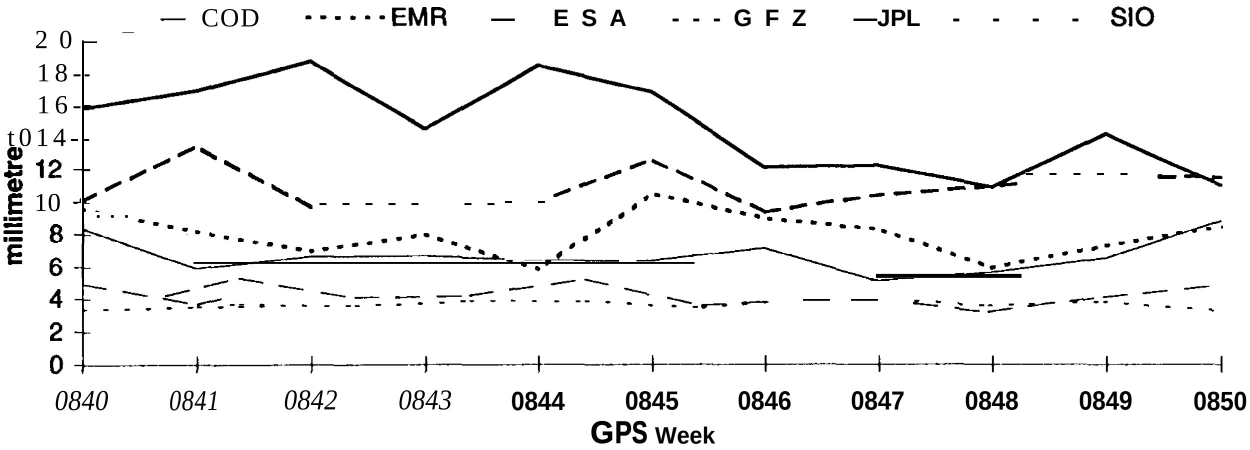

Fig 5- WRMS of post-fit residuals between each A-network and the G-network in each week.

3.3 Coordinate variation in the G-network series

To look at the coordinate variation in this series of free G-networks I imposed the conditions of no net rotation, translation or scale on a ten-station subset with respect to a G-network in the middle of the series (week 0845). The ten stations selected are estimated by all or almost all Analysis Centres in each week of the series, have a worldwide distribution and are among the best-performing stations. I estimated the unweighed 7-parameter similarity transformations for these ten stations between each G-network in turn and the reference week network, and applied these transformations to obtain the aligned G-networks. The transformation parameters are omitted here - see Table 4 below (ITRF comparison) for an indication of G-network datum variability.

I then took the difference in coordinates for each station between each G-network and the reference network, and obtained this difference in Up, North and East components. For each station, this gives a random-looking scatter of residual components. The variation in each of these residual series can be summarised by its standard deviation, which is independent of the network used as the reference for the alignment step. The standard deviation in (U,N,E) components was calculated for each station. The three sets of SDS are shown in the histograms of figure 6.

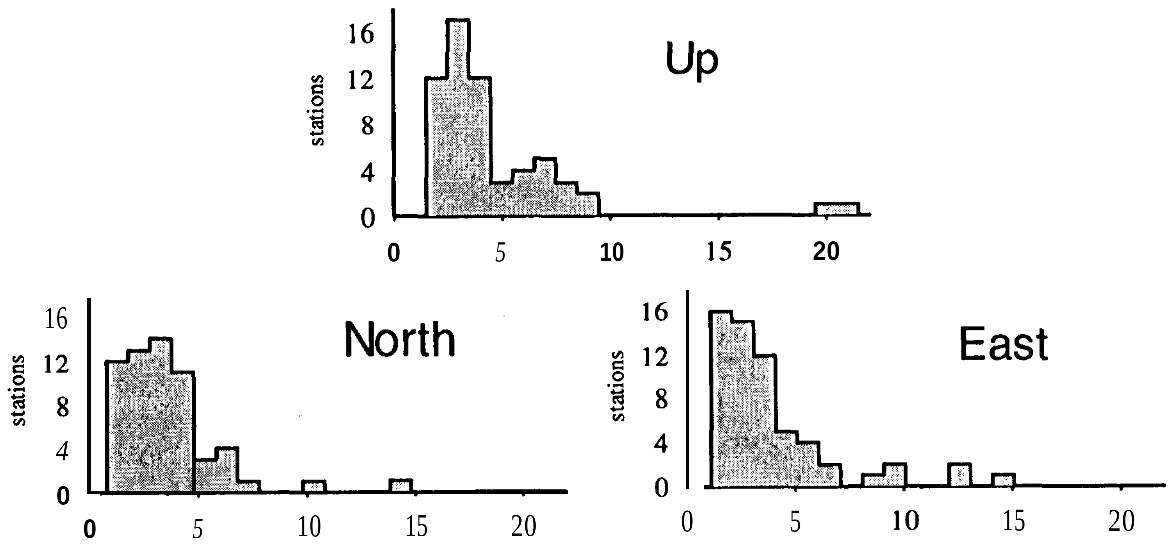

*Figure 6- histograms showing distributions of standard deviations of station coordinate variation **(nun)***

The standard deviations in height tend to be slightly larger than in horizontal components, also the East component tends to have less variability than the North (global GPS estimates vector lengths parallel to the pole less well than those perpendicular to it). Here one can clearly see the 'bad stations' with coordinate variability well beyond the main group - these are also a feature of A-network series (see table 3 below). There is also a clear secondary modal group of stations, with the main group of stations centred around 2-4mm standard deviation and the secondary group around 5-8mm.

3.4 Repeatability comparison with A-networks

I repeated the alignment procedure for the loose A-networks from each Analysis Centre using the same set of ten stations, and calculated the standard deviation of the component differences for each station in the same way. To present the results in a compact form, I show the quartiles of the set of station standard deviations in Up, North and East components for each Analysis Centre and the G-network (Table 3).

NET		MIN	25%	50%	75%	MAX
COD	U	0.91	2,92;	4.74	7.24	24.59
AC	N	1.30	2.41	4.00	5.74	13.91
	E	1.62	2*71	3.74	6.82	24.44
EMR	U	3.44	4.89	6.14	8.05	21.97
AC	N	1.93	3.88	5.59	7.29	12.07
	E	0.90	3.89	5.78	8.23	19.29
ESA	U	3.89	7.33	12.46	22.91	138.66
AC	N	1.71	6.00	9.98	15.25	39.52
	E	2.97	6.82	10.25	18.01	73.23
GFZ	U	3.79	5.55	7.22	10.52	37.48
AC	N	1.74	3.44	5.23	7.21	17.78
	E	1.54	3.78	6.52	10.20	23.65
JPL	U	1.41	3.25	4.40	5.75	90.49
AC	N	1.02	2.58	3.51	5.02	23.78
	E	1.35	2.89	3.80	5.43	141.51
S10	U	2.58	3.81	4.95	7.23	27.67
AC	N	1.12	2,01	3.88	4.57	15.29
	E	1.71	2.49	4.21	6.46	16.05
G-	U	1.48	2.51	3.61	5.49	21.07
NET	N	0.82	1.94	3.17	4.37	14.59
	E	1.10	1,91	3.04	4.15	14.31

Table 3- Quartiles of distributions of standard deviations (in mm) of station coordinate variations in series of aligned free-networks, A-nets compared to combined G-net.

Table 3 shows that the values of the 25, 50 (median) and 75 percentiles of the distributions of standard deviations are lower for the G-network than for any of the A-networks - this is true in Up, East and North components. The MAX and MIN columns give the extreme standard deviations in each case (note that the U, N and E components do not necessarily refer to the same station) - in both the G-network is comparable to the highest-repeatability A-networks.

Most A-networks include a few stations with a large dispersion in repeated coordinate estimates, as can be seen by the great difference between the 75 percentile and the maximum in most rows of

Table 3. The **ESA and JPL networks especially** feature greatly **varying** station estimates. It should be remembered that not all the A-Sinex data went into the G-networks - only those stations estimated by at least three ACS. The results in Table 3 are only possible given this level of data redundancy, which allows the G-network to function as an effective 'data screen'.

3.5 Comparison with ITRF Core

A 13-station subset of ITRF IGS stations is designated the 'IGS Core network' and is conventionally used for network constraint by IGS agencies. Data from one of the Core stations was unavailable during the period, so only twelve stations were included in this comparison. A weighted similarity transformation between each week's G-network and **ITRF94** at the mid-week epoch was estimated - below are shown the transformation parameters and the postfit residual SD and WRMS series. The scale and rotation parameters have been multiplied by the earth radius to give all parameters in **millimetres.** The arbitrary **metre** level differences in orientation are quite acceptable.

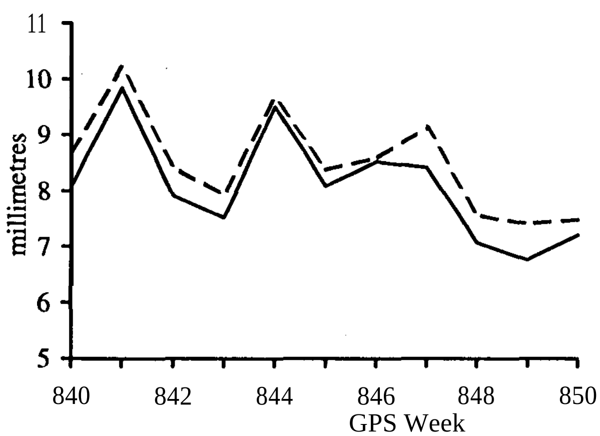

*Figure 7- Standard deviation (dashed **line**) and **WRMS** (solid line) of post-fit residuals between **G-**network and **ITRF94** for Core stations.*

Wk	t_X	t_Y	t_Z	r s	r r_X	r r_Y	r r_Z
0840	-6	-17	-3	7	1147	-60	**-1897**
0841	-21	1	-8	8	518	921	-1113
0842	-11	-15	**12**	11	3416	-698	-2458
0843	-15	-12	14	9	**182**	-79	-150
0844	**-12**	**-12**	25	**11**	1352	-367	-865
0845	-24	-25	16	9	**581**	-193	-384
0846	-24	-23	41	**10**	324	-121	-240
0847	-23	-27	51	8	-432	70	156
0848	-13	-24	37	10	-231	**11**	86
0849	-17	-29	33	6	83	9	-263
0850	-10	-25	41	12	29	-56	-83

*Table 4- estimated frame parameter differences (nun) between weekly G-network and **ITRF94 for** Core stations, where r is the earth radius*

4 ATTACHMENT OF R-NETWORKS

It is hoped that Regional Network Associate Analysis **Centres** will begin to submit Regional network solutions **(R-Sinex)** in the second half of 1996, which GNAACS will integrate with their G-Network to assemble a Polyhedron solution. **R-Sinex** files will state constraints and station information in the same way as **A-Sinex** files, so I anticipate applying the procedures described in sections 2.1 and 2.2 in much the same way. Each R-Network will include three or more Global 'Anchor stations' disposed so as to form good fiducial control for the regional network. The attachment of the **R-**network to the G-network should be such that the Anchor coordinates coincide with the G-network, with the parameters and covariance matrix of the R-network adjusted appropriately. The G-network should not be affected by this step.

One way to accomplish this involves borrowing (not for the first time) from terrestrial geodetic adjustment theory. The principle is that of estimating the local (unshared) parameters of a component network in a **multiple-block** estimation. **In** this case the common parameters are the Anchor station coordinates, with however the R-network estimates of these being excluded from the

G-network estimation. Assuming a very loosely constrained Regional solution has been obtained as described in section 2.1, giving ‘free’ coordinates r (including Anchor stations) with **covariance** matrix Σ_r**,** the Polyhedron coordinates n of the non-Anchor stations and their **covariance** matrix can be obtained by: (Cross [1994] p. 122)

$$\mathbf{P} = \underset{r-n}{\mathbf{A}}\,\Sigma_r^{-1}\,\underset{r-n}{\mathbf{A}'} \tag{14}$$

$$\mathbf{Q} = \underset{r-n}{\mathbf{A}}\,\Sigma_r^{-1}\,\underset{p-r}{\mathbf{A}} \tag{15}$$

$$\mathbf{n} = \mathbf{P}^{-1}(\underset{r-n}{\mathbf{A}}\,\Sigma_r^{-1}\mathbf{r} - \mathbf{Qp}) \tag{16}$$

$$\Sigma_n = P^{-1} + \mathbf{P}^{-1}\mathbf{Q}\Sigma_p\mathbf{Q}'\mathbf{P}^{-1} \tag{17}$$

Since Σ_r^{-1} is known from the constraint removal step, and P is small (there are only a few Anchor stations), this is a rapid calculation. **Eqn.** 17 assumes that r and p are **uncorrelated,** the same assumption that was previously made for the A-network combination. The result is equivalent to a simultaneous LS computation in which the Regional estimates of the Anchor stations have been ascribed zero weight.

5 CONCLUSION

The G-network is a high-reliability primary frame for Polyhedron assembly, with the same advantages for GPS networks as a rigorously-estimated highly redundant primary control network had in the days of terrestrial surveying. The repeatability results presented here are evidence of this, and are likely to continue to improve for some time to come. The IGS redundancy requirement of a Global station (at least three independent weekly estimates) is considered basic to a sound Global solution. An interesting extension to this paper would be a quantitative reliability assessment to establish this, e.g. by computing marginally detectable errors with different levels of A-network station set overlap.

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IGS

ATMOSPHERIC TRENDS

IGS TROPOSPHERIC ESTIMATIONS
-SUMMARY-

Gerd Gendt

Since the monitoring of the atmosphere using the IGS components was first addressed during the 1995 Potsdam Workshop there were a lot of activities on this topic, as examples should be mentioned (i) quality assessment of water vapor determination using ground based GPS measurements (ii) establishment of infrastructure and development of software and technology for GPS contributions to weather forecast. These investigations are of course relevant for climatological studies too.
The aim of this session on ground based GPS meteorology was to give an insight into these activities, to get information from possible customers, to discuss the role of IGS within this topic and to define the next steps.

Eugenia Kalnay from the USA National Centers for Environmental Predictions gave an overview on input data types, data flow and software components used for weather forecast. The quality of weather prediction has been steadily improved during the last decades. This was mainly reached by using more and more data from earth orbiting satellites. Nevertheless, the ocean region lack in data density even today. This gap could partly be filled by GPS/MET, which are especially interesting by its vertical profiles for temperature or water vapor. Ground based derived precipitable water vapor was not tested up to now, but the predictions can benefit from each kind of information given with high quality.

Comparisons of GPS derived vertical integrated water vapor content with water vapor radiometer and radiosonde measurements show a high agreement of about ±1 mm in precipitable water vapor. This accuracy is sufficient to start using ground based GPS receivers in meteorology. If the global IGS network is equipped with meteorological packages IGS will be capable to contribute to global climate research without great additional effort. By this way, the meteorological community could benefit from cheap (using receivers already installed for other purposes) and continuously derived series.
Comparisons of the zenith path delay series computed by all IGS Analysis Centers (ACs) show a very high consistency corresponding to 1.3 mm precipitable water vapor, but on the other hand these show also systematic differences which have to be investigated. The elimination of systematic errors is especially important for climate research, were we are looking for small signals over long time periods.

Whereas the existing IGS components can contribute to climate studies, many additional efforts have to be made for contributing to weather forecast. With the CORS network a network with real-time transfer of GPS observations and meteorological data was developed and put into operation. This network could provide real-time monitoring of atmospheric water vapor with high quality if good orbit predictions based on super rapid orbits from the IGS ACS will be available.

In different institutions various technologies are under development that could be used for real-time atmospheric monitoring.
The complexity of the atmosphere requires for precise weather forecast a high spatial density of information about the atmospheric parameters. “The resulting density of GPS networks will be so high that these networks cannot be analyzed by the IGS. Further on this is not a global problem, and the requirements for a real-time data transfer can only be fulfilled concentrating on each region. That means regional MET-ACS for tropospheric analysis will be installed, which will benefit from the following IGS products:

Data from the global IGS network, which are relevant for this region.
The download interval etc. should be arranged bilateral between the MET-ACs and the sites of interest, It is reasonable to have nearly real-time data transfer only for those data, which will actually be used by MET-ACs.

Predictions based on super rapid IGS orbits.
These predictions could be computed by IGS using the long arc orbits (e.g. 3-day orbits), because these are more stable than the orbits from the last day only.

Although there are no stringent demands for an IGS water vapor product at the moment, IGS should take the initiative and start to offer such a new product. After a pilot phase IGS may recapitulate and decide whether to continue with such a product.

RECOMMENDATIONS

1, The IGS-sites are asked to install MET-packages with the below given characteristics until the end of 1996. The meteorological data (reduced to the GPS-antenna location, RINEX format) should be sent simultaneously with the RINEX observations to the Global Data Centers.
In a pilot phase a time delay of a few days is acceptable for the Met RINEX files.

Installation of MET-packages in the IGS network with the following characteristics:

Pressure	: ≤0.5 mbar, very stable s0.5 mbar throughout 2 years
Temperature	: <0.5 K
Humidity	: ≤10 %
Sampling rate	: ≤ 10 minutes

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2. For Climate Research

2.1. Starting from the end of 1996 the Analysis Centers compute series of total zenith path delay (ZPD) with a sampling rate of minimum 2 hours. (Data intervals starting at 00:00 GPS-time).

2.2. An associate IGS processing center combines the individual time series of delay to an IGS Mean series of ZPD and converts the delays to estimates of precipitable water vapor.
By the end of 1996 GFZ will be ready to act as an associate processing center. Other agencies will be invited through a call of participation.

2.3. Formats for exchange and distribution of results should be defined. For the exchange between the ACS and the associate processing center the SINEX format and for distribution of results the RINEX format should be used. Necessary extensions or modification of both formats must be discussed.

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3. For Weather Forecast
The contribution of IGS to the weather forecast will be restricted on the orbit computation, rapid orbits with 23-hour delay and predicted orbits.

If data of the IGS network are needed the analysis centers engaged in weather forecast should make bilateral agreements for nearly real-time data transfer with tracking sites of interest.