IGS

SESSION 6:

LOW EARTH ORBITER

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

1 Introduction

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

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

2 Brief history of IGS LEO

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

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

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

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

- February 2000 <u>Scheduled date for LEO standards outline</u>

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

- April 2000 <u>LEO proposals deadline</u>

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

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

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

- May 2001 Release of CHAMP data

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

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

- June 2001 Inquiry after CHAMP POD processing status among AAC

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

- July - Sep 2001 CHAMP POD implementations at the AAC

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

- September 2001 Call for contributions to CHAMP POD campaign

- October 2001 CHAMP user meeting, Potsdam

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

- Nov-Dec 2001 First results of the POD campaign

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

- January 2002 First CHAMP Science Meeting,

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

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

- Since January 2002 Ongoing improvements in analysis capability

A majority of the AACs contribute updates to their CHAMP campaign results. New gravity fields (EIGEN) and improved estimation methods are bringing CHAMP POD below the 10 cm level.
Inquiry among the AACs after combined LEO + GPS analysis capability suggests that a very small number of centres can already do this.

- April 2002 IGS Workshop Ottawa

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

3 Current status of IGS LEO

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

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

4 IGS LEO charter

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

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

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

IGS LEO Pilot Project Charter

1 Goals

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

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

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

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

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

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

1.1 Assessment of the benefits of LEO data

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

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

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

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

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

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

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

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

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

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

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

	simultaneous processing of GPS and LEO satellites

1.2 Assessment of required means of processing

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

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

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

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

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

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

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

2 IGS LEO Pilot Project structure

The following organisational elements are identified:

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

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

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

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

3 Working plan

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

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

3.1 Succession of analysis projects:

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

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

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

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

   Start of project:
   - Expected for spring - summer 2002

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

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

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

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

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

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

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

Anticipated duration of the Pilot Project

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

4 Initial ideas for an operational phase

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

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

5 Further comments

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

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

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

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

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

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

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

Impact of Different Data Combinations on the CHAMP Orbit Determination

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Abstract

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

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

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

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

LEO Processing Status at AIUB

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

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

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

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

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

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

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

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

LEO Activities at CSR - B. Schutz (CSR)

(Summary by Henno Boomkamp)

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

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

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

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