IGS

LOW EARTH ORBITER MISSIONS (LEO) WORKSHOP

Summary Recommendations of IGS LEO Working Group
Conclusive Actions from the LEO Workshop

Dear LEOWG and interested parties-

Thank you for your attendence and participation in our very productive workshop and Extended LEO Working Group meeting of 12 March. I think it is clear from the questions raised and energy level of the participants that the time is right for the IGS components to take action to prepare for the challenges of the forthcoming LEO data. At the March 12 meeting, the LEOWG agreed on 4 significant draft recommendations and also affirmed a number of recommendations that resulted from the Network Workshop last November. The new recommendations are outlined below. I propose that position papers on each of these 4 recommendations be prepared by the Ad Hoc subcommittees defined in the comments, for presentation at the next IGS AC Workshop in La Jolla in June, 1999 and as preparation for bringing these recommendations from the LEO working group to the Governing Board meeting on June 7.

Best Regards,
Mike Watkins
Chair, IGS LEO Working Group

LEOWG Draft Recommendations from 12 March 1999 Meeting, GFZ Potsdam

R1: The standards for ground stations in the LEO subnetwork be codifed and distributed.

Comment: This recommendation broadens the scope of the LEO ground subnet beyond the planned JPL and GFZ sites for improved redundancy and coverage. We would expect significant involvement by the IGS Infrastructure Committee and IGS Network Coordinator in this task.

Suggested Subcommittee:

Y. Bock (SIO)
M. Caissy (NRCan)
A. Moore (IGS)
J. Zumberge (JPL)
R. Galas (GFZ)

R2: The IGS Analysis Centers should develop a new ultrarapid analysis product (orbit, clock, EOP, and predictions) with a latency of less than 3 hours. This would be demonstrated through voluntary participation in a pilot project to be initiated this summer.

Comment: Some growing applications of GPS data, both ground and flight, require analysis product latencies or prediction accuracies that cannot be met with the current 24 hr daily batch processing paradigm. This pilot project would offer AC's the chance to explore new methods to provide these products. Several existing networks already provide the required data with near global coverage and less than 1 hour latency.

Suggested subcommittee:

P.Fang (SIO)
G. Gendt (GFZ)
T. Springer (CODE)
J. Zumberge (JPL)

R3: A new efficient format should be developed for the 1 Hz ground data.

Comment: The 1 Hz data volume exceeds that of the standard IGS data product by a factor of 30. Even with Hatanaka compression, the volume of data from a 10-30 station LEO network exceeds what Data Centers can easily handle. New binary formats offer the promise of significant reduction in data volume, along with the potential of adding some fields of interest not now in Rinex II, such as improved SNR and channel number. Groups at GFZ and UNAVCO have already proposed some draft formats. The LEOWG would like to propose the creation of the following Format Subcommittee, who will propose a format for use in the Pilot Project of R4 by 1 August 1999:

J. Dean (SIO)
L. Estey (UNAVCO)
R. Galas (GFZ)
W. Gurtner (AIUB)
A. Moore (IGS)
D. Stowers (JPL)

R4: A 3-6 month Pilot Project for the use of flight data from one of Oersted or Sunsat for POD purposes (including effect on the GPS AC products) should begin in August of 1999. The WG further recommends that for the duration of the Pilot Project, the 1 Hz ground data be handled by the network operators and data centers, in the new format described in R3. The Call For Participation will also request additional LEO ground sites following the standards of R1.

Comment: Such a Pilot Project provides the opportunity for the existing AC's to begin LEO positioning and to examine the potentially beneficial effects of including LEO's in their processing. At the same time, it offers the opportunity for new AC's interested and expert at LEO processing to join the IGS community. Finally, it allows the exercise of the IGS data paths and the new format described above

Subcommittee:
Entire LEOWG

Joint IGS - GFZ - JPL Workshop on Low Earth Orbiter Missions: Developing and Integrating Ground and Space Systems for GPS Applications

March 9 - 11, 1999
Potsdam, Germany
GeoForschungsZentrum

This is the first international workshop focusing on end-to-end systems and science aspects for supporting an array of forthcoming Low Earth Orbiter Missions.

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Tuesday, March 9, 1999

Day 1: LEO Missions Overview, Science Goals and Objectives, Infrastructure
Organizers: Ch. Reigber, W. Melbourne

1)	1:00 pm	Welcome	Rolf Emmermann (GFZ/GER)
2)	1:05 pm	Goals of LEO-Workshop	Christoph Reigber (GFZ/GER)
3)	LEO Missions		
	1:15 pm	NASA/DLR/CNES Missions	Tom Yunck (JPL/USA)
	1:45 pm	ESA Missions	Pierluigi Silvestrin (ESTEC/NL)
	1:55 pm	EPS GRAS Mission	Juha-Pekka Luntama (EUMETSAT)
2:10 pm Coffee Break			
4)	Science Goals and Objectives		
	2:30 pm	Gravity Field	Byron Tapley (CSR/USA)
	3:00 pm	Atmosphere	Per Hoeg (DMI/DK)
	3:30 pm	Ionosphere	Norbert Jakowski (DLR/GER)
	4:00 pm	Ocean Reflections	Pierluigi Silvestrin (ESTEC/NL)
5)	4:15 pm	LEO Working Group Goals	Mike Watkins (JPL/USA)
6)	4:30 pm	LEO Infrastructure & the IGS	Ruth Neilan (JPL/USA)
7)	5:00 pm	Discussion	
	6:00 pm	Ice Breaker Party Tuesday Evening	

Wednesday March 10, 1999

Day 2: Flight Instruments, Ground Data Systems, Product Generation
Organizers: J. Dow, R. Neilan, P. Schwintzer

1) GPS Flight Receivers

9:00 am	GPS Flight Receiver	Tom Yunck, Tom Meehan (JPL/USA) Development
9:30 am	ESA's GRAS Receiver	Pierluigi Silvestrin (ESTEC/NL)

2) Ground Infrastructure: Data Flow, H/R Ground Networks, Operations

10:00 am	IGS Ground Network	Angelyn Moore (JPL/USA)
10:30 am	IGS Data Distribution	Carey Noll (GSFC/USA)
11:00 am	Coffee Break	
11:30 am	CHAMP S/C Telemetry, Data Flow & Products	Peter Schwintzer (GFZ/GER)
12:00 pm	H/R Network, JPL Activities	Jim Zumberge (JPL/USA)
12:30 pm	H/R/ Network GFZ Activities	Roman Galas (GFZ/GER)
1:00 pm	Lunch	
2:00 pm	Canadian H/R GPS Ground Data	Mark Caissy (NRCan/CAN)
2:20 pm	CLIMAP: Ground Infrastructure and H/R GPS Stations in Europe	Per Hoeg (DMI/DK)
2:40 pm	Ground Infrastructure for COSMIC	Chris Rocken (UCAR/USA)

3) Mission Operations and Operational Processing Requirements

3:00 pm	CHAMP Mission Operation and Rapid Orbit	Rolf Koenig (GFZ/GER)
3:30 pm	CHAMP Atmosphere/ Ionosphere Processor	Jens Wickert (DLR/GER)
4:00 pm	Coffee Break	

Wednesday March 10, 1999 (cont'd)

4:30 pm	High Rate Data Communication with VSAT	Neil Spriggs (Nanometrics, Inc.) Barbara Perin (UNAVCO/USA)
5:00 pm	LEO/IGS Integration and Benefits For IGS Products	Tim Springer (AIUB/CH)
5:30 pm	GLONASS - Status and Future	D. Ineichen (AIUB/CH)

5) Discussion

6:30 pm	Reception Wednesday Evening

Thursday March 11, 1999

Day 3: Products, User Access, Interfaces, Science Applications
Organizers: N. Jakowski, Ch. Rocken, M. Watkins

1) Atmosphere/Ionosphere Science

9:00 am	Capabilities and Limitations of RO-Measurements for Weather Predictions	Sean Healy (UKMet/UK)
9:30 am	Capabilities and Limitations of RO-Measurements for Ionosphere Monitoring	George Hajj (JPL/USA)
10:00 am	Use of UHF Radio Beacons on board LEOs	Reinhart Leitinger (U Graz/AU)
10:30 am	Gravity Waves	Toshitaka Tsuda (RASC/JAP)
11:00	Coffee Break	
11:30 am	Radio Wave Propagation Effects	Alexander Pavelyev (IER/RUS)
12:00 pm	Climate Change Detection	Elisa Manzini (MPI/GER)
12:30 pm -	Tomographic Use of LEO Data	Guilio Ruffini (IEEC/SP)
1:00 pm	Lunch	

Thursday March 11, 1999 (cont'd)

2) Gravity, Magnetic and Electric Fields and Science Applications

2:00 pm	CHAMP Space Weather Contributions	Hermann Luehr (GFZ/GER)
2:20 pm	CHAMP Gravity Field Related Products	Christoph Reigber (GFZ/GER)
2:40 pm	GRACE Gravity Field Related Products	Srinivas Bettadpur (CSR/USA)
3:10 pm	COSMIC constellation for Gravity Studies	C.K. Shum (OSU/USA)
3:40	Coffee Break	

3) Data Administration and User Interfaces

4:00 pm	CHAMP Information System and Data Centre	Bernd Ritschel (GFZ/GER)
4:30 pm	GENESIS Information System and Data Centre	George Hajj (JPL/USA)
5:00 pm	COSMIC Analysis Centre	Chris Rocken (UCAR/USA)
5:30	Discussion	
6:30 pm	Close of Workshop	Christoph Reigber (GFZ/GER)
7:30 pm	Joint Dinner Thursday Evening	

Friday, March 12, a.m.

Closed Meeting of IGS LEO Working Group -- by Invitation
Organizers: Ch. Reigber, M. Watkins

List of Participants - LEO Workshop
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Use of LEO Satellites for Ionospheric Research and Monitoring

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Abstract

LEO missions such as OERSTEDT, CHAMP, SAC-C, GRACE which are already operating or planned for launch within the next 2 years, can open a new dimension in permanent ionospheric monitoring on global scale. As the first active GPS limb sounding satellite within the GPS/MET program has shown, GPS radio occultations in the ionosphere provide a new and relatively inexpensive tool of profiling the vertical electron density structure.

Due to upward looking GPS phase measurements onboard LEO satellites such as CHAMP, SAC-C and GRACE, valuable information about the topside ionosphere /plasmasphere system is expected. In combination with already available ground-based GPS measurements all over the globe, a comprehensive (up to 4D) analysis of the electronic structure of the ionosphere should be possible.

Scientific objectives are related both to ionospheric research as well as to applications for radio system operations. Major topics are: climatology of the ionosphere, ionospheric perturbations and modeling, improvement and/or development of appropriate probing techniques, space weather contributions.

Introduction

The Earth's ionosphere extends from about 60 km up to the bottom of the plasmasphere at about 1000 km altitude. The ionospheric behaviour is affected by numerous factors such as solar radiation (λ< 130nm) and solar wind, thermospheric composition and neutral winds, electric fields, particle precipitation, electric currents or mass and heat flow. On the other hand, ionospheric processes affect significantly structure and dynamics of thermosphere and plasmasphere/magnetosphere systems.

Future LEO missions carrying a dual frequency GPS receiver onboard and/or radio beacon transmitters, offer a unique chance to improve our knowledge about the ionospheric behavior considerably and to monitor the actual state of the ionosphere on a continuous basis.

The GPS limb sounding technique has been demonstrated to be a powerful tool for remote sensing the Earth's neutral atmosphere and ionosphere by analyzing GPS radio occultation data obtained from the GPS/MET instrument, flown on the Microlab-1 LEO satellite (e.g. Kursinski et al., 1997)

Assuming a spherically layered atmosphere, the Abel inversion method can be used to convert the bending angle profile into a corresponding refractivity profile. Whereas the atmosphere refractivity significantly depends on temperature and water vapor, the ionospheric refractivity depends on the electron density along the occulted ray path and therefore allows to determine the vertical electron density profile of the ionosphere from the bottom up to the satellite height.

Probing the Ionosphere by Satellite Radio Techniques

Radio waves played an important role in the exploration of the ionosphere since the very beginning. Meanwhile numerous probing techniques based on the interaction of electromagnetic waves with the ionospheric plasma have been developed and successfully applied.

Vertical sounding , incoherent scatter and radio beacon techniques can be considered as very powerful sensing methods to get key information about the ionospheric plasma.
From these techniques both the Vertical Sounding as well as the Incoherent Scatter Radar are typical ground-based techniques whereas radio beacon methods use transionospheric propagation of radio waves from satellite-to-ground (SGT) or from satellite-to-satellite (SST).

Radio signals travelling through the Earth's ionosphere are modified in amplitude, phase and polarization due to the interaction of the electromagnetic wave field with the plasma in particular with the free electron gas. Although the plasma resonance frequency in the ionosphere is generally below 20 MHz and the interaction reduces with increasing radio frequency ($1/f^2$), some signatures are still significant in the L- and/or S-band or even higher. The net effect upon the radio wave is proportional to the integrated electron density (total electron content - TEC) along the whole signal path from a satellite to a receiver. So TEC is a key parameter that describes the impact of the ionized atmosphere on the propagation of radio waves.

Satellite – Ground

Radio beacon measurements using satellite signals have played an important role in studying the temporal and spatial structure of the ionosphere practically since the launch of Sputnik I in 1957. Measurements of differential modulation phases (travel time), of coherent carrier phases (differential Doppler) and of Faraday rotation (polarization plane) can be used to derive TEC along the considered ray path.

NNSS

Many observations of ionospheric TEC were/are carried out by using the coherent carrier frequencies at 150/400 MHz transmitted by the satellites of the Navy Navigation Satellite

System (NNSS). This LEO satellite system was extensively used to derive longitudinal profiles of TEC along meridional chains of ground receivers (e.g. Leitinger et al., 1975). Since the potential of such TEC measurements for a tomographic reconstruction of the 2D electron density structure of the ionosphere has been shown by Austen et al., 1986, ionospheric tomography has been studied by many researchers. Although physically reasonable results have been achieved, accuracy and resolution of tomographic reconstructions can essentially be improved when horizontal information as provided by radio limb sounding data is added. Currently some NNSS satellites can still be used for tomographic reconstructions. Some future LEO systems will carry radio beacons for improved tomographic reconstructions of ionospheric electron density.

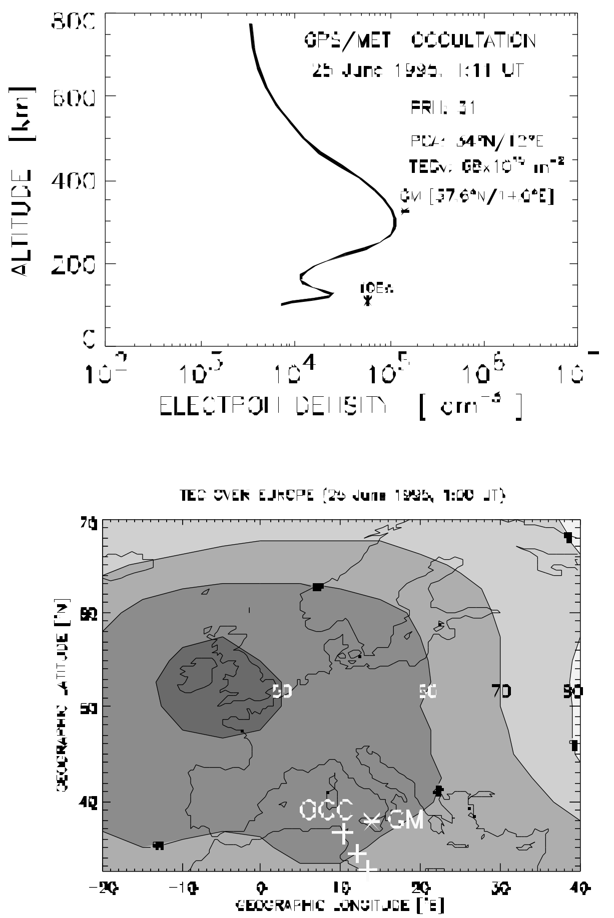

Fig. 1
Retrieved electron density profile using GPS/MET occultation measurements on 25 June 1995, 1:11 UT in comparison with ionosonde data (foEs, foF2 and heights) and the corresponding TEC map over Europe at 1:00 UT (+++ PCA trace, * location of the Gibilmanna ionosonde station, TEC isolines in $10^{15} m^{-2}$).

GPS

Due to the availability of the GPS signals, TEC estimations based on dual frequency GPS measurements provide information on regional and/or global TEC distribution.

To give an example, the GPS measurements of the European IGS network allow the determination of slant TEC values along more than 100 satellite-receiver links over the European area with high time resolution (e.g. Jakowski, 1996).

Using the global IGS network, global TEC maps can be constructed (e.g. Schaer et al., 1996, Mannucci et al., 1998). If accurate enough, GPS based ionospheric monitoring provides an outstanding tool to study large scale processes in the ionosphere (e.g. Jakowski et al., 1999).

Real time ionospheric monitoring and the delivery of TEC maps to GPS and/or GLONASS users should enhance accuracy and integrity of navigation satellite systems.

The ionospheric monitoring technique based on global and regional GPS measurements contributes directly to 'Space Weather' reports and predictions.

Satellite - Satellite

GPS radio occultations in the ionosphere provide a relatively simple and inexpensive tool of profiling the ionosphere. No other profiling technique (bottomside/ topside sounding, incoherent scatter radar) unifies high vertical resolution profiling through the entire ionosphere with global and continuous coverage. However, what has to be taken into account as a limiting factor, is the integration of ionospheric information (electron density) along large distances resulting in a rather poor horizontal resolution (1000 km).

Because the Abel inversion technique is fundamentally based on a spherical symmetry assumption of the refractive index, horizontal gradients or structures in the electron density distribution are principally ignored by applying this technique. Since near the sunrise/sunset hours, in the course of ionospheric storms and/or near the crest region strong spatial plasma density gradients are expected in particular under high solar activity conditions, this assumption cannot be hold in general. A tomographic approach with a spherically layered pixel structure has the advantage that additional information from ground based GPS measurements, models and/or other sources such as peak electron densities obtained at vertical sounding stations can easily be included in the reconstruction of the electron density profile. Solving the system of linear equations for the electron density as a function of the link related TEC and the corresponding geometrical ray path elements through the defined pixel structure, electron density profiles are obtained as illustrated in Fig. 1. One of the most striking features in this Figure is the sensitivity of the analysis to the sporadic E-layer.

As radio occultation data have shown principally, due to strong gradients of the electron density, the sporadic E-layer can cause severe discontinuities in the radio occultation signal (e.g. Yakovlev et al., 1995, Hajj and Romans, 1998). This type of irregularity should have a significant impact on satellite-to-satellite communication links if the link passes the E-layer region or other ionospheric irregularities.

Combinations

Combining LEO- based ionospheric data described above with slant TEC data derived from regional and world wide ground based GPS stations tomographic methods can be applied to reconstruct the three-dimensional structure of the ionosphere/plasmasphere systems (e.g. Rius et al., 1998). This should be attractive especially over good conditioned areas with high dense networks of GPS ground stations such as California, Europe or Japan.

Another unique possibility is the combination of radio occultation with electron content data obtained on ground by measuring dual frequency coherent radio beacon signals transmitted from LEO satellites in the VHF/UHF frequency range as e.g. NNSS satellites (e.g. Leitinger et al.,1997)

Generally speaking, comprehensive tomographic studies on global scale will contribute to explore a number of specific ionospheric phenomena which are not yet fully understood (e.g. equatorial crest, mid-latitude trough, ionospheric storms) in much more detail.

Scientific Objectives

Global monitoring of the ionosphere based on methods discussed in the previous section can contribute directly to study the ionospheric impact on radio system operations (e.g. Bishop, 1994). In particular real-time monitoring of the ionospheric ionization should be capable to control signal degradation and reliability of operational systems.

Since the ionosphere is an integral part of solar-terrestrial relationships, continuous ionospheric monitoring can contribute to space weather predictions, in particular by assimilation of ionospheric data into space weather models (real-time data driven models). Space weather is a rather new discipline based on real-time monitoring and reliable predictions with a strong feedback to operational systems.

An improved understanding of space weather effects, i.e. of solar-terrestrial relationships, can be achieved by studying the large variety of ionospheric phenomena in more detail. Considering the capabilities of SGT/SST measurements discussed in the previous section, the following scientific goals and objectives for ionospheric research and corresponding applications can be summarized as follows:

Climatology of the Ionosphere

Long-term variation of electron density and TEC on global scale ($T \approx 11$ years), long-term trends, seasonal variation, interhemispheric coupling (e.g. semiannual variation), solar and lunar induced variations ($T = 27$ and 29 days, respectively), variability of regular phenomena (e.g. crest)

Ionospheric Perturbations

Large scale ionospheric storms, medium scale phenomena (e.g. TID‘s), small scale phenomena (e.g. bubbles, scintillation effects)

Modelling the Ionosphere and Plasmasphere

Improvement of 4D data base, validation of models (empirical, physical models), development of new models (real-time-data driven models, perturbation models)

Ionospheric Probing and Analysis Techniques

Radio occultation technique (Profiling), LEO radio beacons combined with GPS links (tomography), data assimilation into ionospheric models

Ionospheric Monitoring as a Part of Space Weather Programs

Creation of a SW data pool, data assimilation into space weather models, predictions, warnings

Depending on the concrete scientific task the requirements for accuracy and resolution of TEC measurements are quite different. In any case, an absolute TEC accuracy of at least $3x10^{16}m^{-2}$ should be reached, whereas the relative TEC level should be two orders more accurate. Limb sounding measurements require a sampling rate of at least 1 Hz, whereas topside data should be sampled with 0.1 Hz or faster. In order to have well separated signals from the ionosphere and plasmasphere, LEO orbit heights around 800-1200 km are preferred.

During the next 3 years LEO missions such as OERSTEDT, CHAMP, SAC-C, GRACE, and COSMIC will enable a full use of these new ionospheric probing techniques.

Most of these LEO satellites use topside GPS antennas for navigation and precise orbit determination. It should be mentioned that this type of measurements opens a new area in sensing the topside ionosphere from orbit height up to the plasmasphere. Applying data assimilation techniques, the tremendous amount of data should essentially improve our knowledge about the electron density structure of the outer ionosphere on global scale. As the discussion of current ionospheric models shows (Bilitza, 1994), more data are needed to improve the topside part of current ionospheric models.

Taking into account additional ionospheric/geomagnetic sensors onboard of LEO satellites a more detailed insight into ionospheric processes is possible. So CHAMP provides accurate magnetometer data, in situ electron density along the satellite path derivable from a Langmuir probe and electric field measurements carried out by a digital ion drift meter (Reigber et al., 1996). Substantial enhancement of the horizontal resolution is achievable by multi satellite systems such as COSMIC that is planned to consist of 8 satellites.

Since most of the missions plan to be operational with data latencies of a few hours, the permanent monitoring of the vertical structure of the ionosphere can essentially contribute to space weather monitoring programs.

Conclusions

Ground and LEO satellite measurements discussed here (SGT, SST) can contribute to ionospheric research in different fields such as plasma production, loss, and transport, ionospheric storms, travelling ionospheric disturbances (TID's), small scale irregularities (scintillations), trough, ionosphere/plasmasphere coupling, modeling.

The global network of GPS ground stations as provided by the IGS network allows the permanent monitoring of the total electron content TEC with high temporal resolution on global scale.

The resulting TEC estimates contribute not only to basic research but also to studies of the ionospheric impact on navigation systems under high solar activity conditions.
In particular the vertical structure of the ionosphere up to satellite orbit heights can be studied on global scale. The limited horizontal resolution should be improved by including GPS ground measurements enabling a tomographic reconstruction of the 3D electron density distribution.

Since the radio limb sounding technique is rather young, validation of data products in particular with ionosonde and incoherent scatter data and further improvements of the retrieval technique itself are needed to obtain reliable and accurate solutions. So the next LEO missions will stimulate the development of new data analysis and forecasting tools such as data assimilation into space weather models.

It can be expected that radio occultation measurements onboard satellite missions such as OERSTEDT, CHAMP, SAC-C, GRACE, and COSMIC will essentially contribute to measure the electron density distribution permanently on global scale, probably as part of a space weather monitoring system.

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Distribution of IGS Data

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Background

The IGS collects, archives, and distributes GPS observation data sets of sufficient accuracy to meet the objectives of a wide range of scientific and engineering applications and studies. During the design phases of the service, it was realized that a distributed data flow and archive scheme would be vital to the success of the IGS. Thus, the IGS has established a hierarchy of data centers to distribute data from the network of tracking stations: operational, regional, and global data centers. This scheme, shown in Figure 1, provides for an efficient access and storage of GPS data, thus reducing traffic on the Internet, as well as a level of redundancy allowing for security of the data holdings.

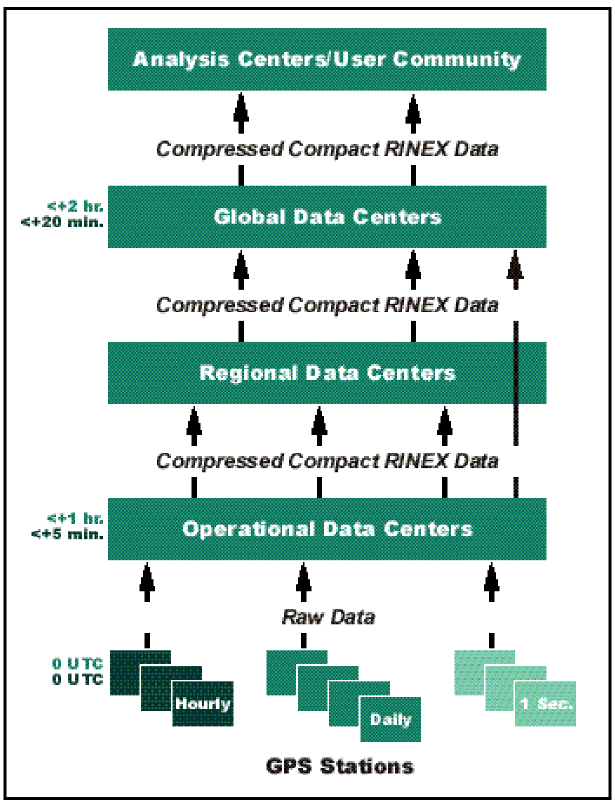

Figure 1. Flow of IGS Data

Description of IGS Data

The "traditional" IGS data product consists of daily observation and navigation data stored in daily files as well as meteorological data from a subset of the network. These data are sampled at a rate of thirty seconds. The raw receiver data are downloaded by the station's operational data center and converted to RINEX format, compacted, using the Hatanaka software (Hatanaka, 1996), and compressed (UNIX compression) prior to shipment to a regional or global data center. Data in compressed compact RINEX format are retained at the global data center level; some data centers also provide data in non-compacted UNIX-compressed RINEX format as a service to the general, non-IGS user community. This set of files containing the thirty-second observation, navigation, and meteorological data average 0.3 Mbytes per site per day in size. Therefore, data from a network of 200 sites would total approximately sixty Mbytes for a single day. Adding non-compacted RINEX data to this list would increase the size to approximately 0.9 Mbytes per site per day. Files containing one hour of thirty-second data average fifteen Kbytes per site per hour. Extrapolating, hourly files of one second RINEX data would average less than one half Mbyte per site per hour in compressed compact format; daily files of one second RINEX data would average ten Mbytes.

Data Center Components of the IGS and Flow of IGS Data

As shown in Figure 1, IGS data flow from a network of tracking stations through various levels of data centers to ultimately reach the IGS analysis centers and user community in general. Figure 2 illustrates this flow on a station basis; this figure shows the number of centers some data flow through before ultimately reaching their destination, e.g., a global data center.

The network of over 200 globally distributed IGS tracking stations that participate on a routine basis are linked in some electronic fashion to enable rapid download. A core set of over eighty sites is analyzed on a daily basis by most centers; these sites are called global sites. At a minimum, all IGS sites must track GPS satellites at a thirty-second sampling rate; many sites, however, track the satellites at a higher rate. The data from these high-rate sites are currently decimated from the one-second data rate down to thirty seconds prior to reaching the data flow chain of the IGS. Station personnel are tasked to report changes in station configuration as well as any operational problems to the IGS Central Bureau. A completed and current site log detailing the station's configuration must be on file at the IGS Central Bureau Information System (CBIS). Data and analysis centers execute software to validate actual data files against the information contained in these logs; therefore, update of these logs is essential to the usability of the data.

Operational data centers (ODCs) are responsible for the direct interface to the GPS receiver, connecting to the remote site daily and downloading the data, ideally within minutes of the end of the day (UTC time) and archiving the raw receiver data. The quality of these data are validated by checking various parameters, such as the number of observations, number of observed satellites, date and time of the first and last record in the file. The data are then translated from raw receiver format to a common format (RINEX), compacted (using Hatanaka software) and compressed (UNIX compression). The Hatanaka compression scheme has proven to reduce the size of the observation file by a factor of eight after compression; this reduction in file size permits more rapid and efficient transmission of data

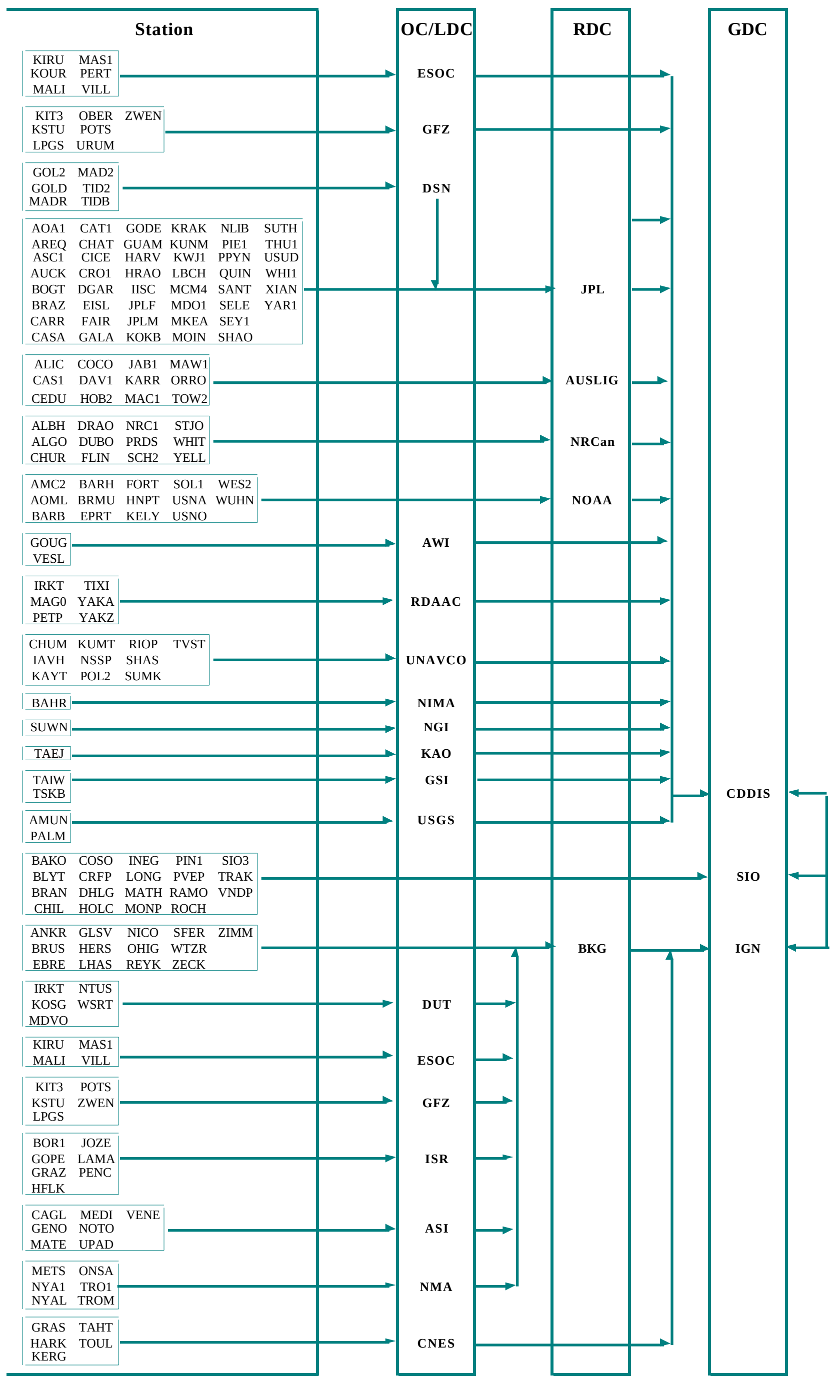

Figure 2. IGS Data Flow by Station

through electronic networks. Both the observation and navigation files (and any meteorological data) are then transmitted to a regional or global data center ideally within an hour following the end of the observation day.

Regional data centers (RDCs) gather data from various operational data centers and maintain an archive for users interested in stations of a particular region. Furthermore, to reduce electronic network traffic, the regional data centers are used to collect data from several operational data centers before transmitting them to the global data centers. Typically data not used for global analyses are archived and available for on-line access at the RDCs. IGS regional data centers have been established in several areas, including Europe and Australia.

The IGS global data centers (GDCs) are ideally the principle GPS data source for the IGS analysis centers and the general user community. These on-line data are utilized by the IGS analysis centers to create a range of products, which are then transmitted to the global data centers for public use. The GPS observation data available through the global data centers consists of observation, navigation, and meteorological files, all in RINEX format. GDCs are tasked to provide an on-line archive of at least 100 days of GPS data in the common data format, including, at a minimum, the data from all IGS global sites. The GDCs are also required to provide an on-line archive of derived products, generated by the IGS analysis centers and associate analysis centers. These data centers equalize holdings of global sites and derived products on a daily basis (at minimum). The three GDCs provide the IGS with a level of redundancy, thus preventing a single point of failure should a data center become unavailable. Users can continue to reliably access data on a daily basis from one of the other two data centers. Furthermore, three centers reduce the network traffic that could occur to a single geographical location. Table 1 below lists the data centers currently supporting the IGS; information on how and who to contact for these data centers is available through the IGS web site.

Timeliness of Data Availability

The rapid availability of IGS data has been an ongoing concern within the service. Data arrival times have been monitored at the various IGS data centers for several years. During 1998 at the CDDIS, for example, forty percent of the 180 sites archived on a daily basis were available to the user community within one hour of the end of the UTC day. Sixty-five percent of the data were available within three hours and seventy-five percent within six hours. These figures are based on arrival times of the full, 24-hour daily file containing thirty-second data. Improvements in these figures still need to be made. It was recommended at the November IGS Network Systems Workshop (Neilan., 1999) that the entire data flow of the IGS be “benchmarked” in order to better understand the data flow on a site by site basis, through each data center, to the data’s final destination (e.g., a global data center). The IGS Central Bureau will study the IGS data flow and map the various data connections during the months to come.

Near Real-Time GPS Data

The IGS Analysis Centers and the user community in general are becoming increasingly interested in near real-time GPS data to be utilized in the generation of near real-time IGS products. Thus, in mid-1998, several data centers began the flow and archive of hourly thirty-second RINEX data files. Table 2 lists the subset of the IGS network currently providing hourly data files to the global data centers as of May 1999. These hourly files are available typically within twenty to forty minutes after the start of the hour, stored in files containing one hour of data in compressed, compact RINEX format, and are retained on-line for three days. In order to ensure the most rapid turnaround at the data centers, no quality validation is performed on these incoming data.

Table 1. Data Centers Supporting the IGS

Operational Data Centers	
ASI	Italian Space Agency
AUSLIG	Australian Surveying and Land Information Group
AWI	Alfred Wegener Institute for Polar and Marine Research, Germany
CNES	Centre National d'Etudes Spatiales, France
DSN	Deep Space Network, USA
DUT	Delft University of Technology, The Netherlands
ESOC	European Space Agency (ESA) Space Operations Center, Germany
GFZ	GeoForschungsZentrum, Germany
GSI	Geographical Survey Institute, Japan
ISR	Institute for Space Research, Austria
JPL	Jet Propulsion Laboratory, USA
KAO	Korean Astronomical Observatory
NGI	National Geography Institute, Korea
NIMA	National Image and Mapping Agency, USA
NMA	Norwegian Mapping Authority
NOAA	National Oceanic and Atmospheric Administration, USA
NRCan	Natural Resources of Canada
RDAAC	Russian Data Analysis and Archive Center
SIO	Scripps Institution of Oceanography, USA
UNAVCO	University NAVSTAR Consortium
USGS	United States Geological Survey
Regional Data Centers	
AUSLIG	Australian Surveying and Land Information Group
BKG	Bundesamt für Kartographie und Geodäsie, Germany
JPL	Jet Propulsion Laboratory, USA
NOAA	National Oceanic and Atmospheric Administration, USA
NRCan	Natural Resources of Canada
Global Data Centers	
CDDIS	Crustal Dynamics Data Information System, NASA GSFC, USA
IGN	Institut Géographique National, France
SIO	Scripps Institution of Oceanography, USA

At then end of the 24-hour period, the daily file containing all 24 hours of thirty second data are forwarded to the data centers through the "normal" data flow channels. The regional and global data centers could execute concatenation software to generate these daily files locally from the individual hourly files. Advantages to this method would be first, a reduction in the amount of data transmitted between data centers each day, and second a possible decrease in latency of the daily file's availability at the data centers. A major disadvantage to this method, however, would be that the designated operational data center for the station would not be generating the RINEX data, and thus two slightly different versions of the station's data could flow in the IGS system. Furthermore, since timeliness of hourly data is crucial, if data for a particular hour were not transmitted to the global data center because of extreme latency, the data center could not include this hour in their version of a daily file. Quality checks on the hourly data (not currently performed) may be required if these data are to be utilized by the global data centers to produce a daily file. Lastly, tests conducted at the CDDIS indicated there are slight differences between the two versions of this daily file, such as lack of a list of satellites in the daily file generated by concatenating the hourly files. Because of these disadvantages, analysts have indicated their preference that this full daily file continue to be generated by the responsible operational data center and forwarded to the designated data centers.

Table 2. IGS Stations Providing Hourly Data

Source	Sites							No. Sites
ESA	KIRU	KOUR	PERT	VILL				**4**
BKG/IGN	BOR1	BRUS*	HOFN	ONSA	REYK	WTZR	ZIMM*	**7**
JPL	AOA1	AUCK	BOGT	CIC1	CRO1	EISL	FAIR	GODE	**28**
	GOL2	GUAM	HRAO	JPLF	JPLM	KOKB	KWJ1	MAD2	
	MCM4	MDO1*	MKEA	NLIB	NSSP	PIE1	PIMO	QUIN	
	SANT	SUTH	TID2	USUD					
NRCan	ALGO	CHUR	NRC1	PRDS	SCH2	STJO	YELL		**7**
Totals:								**46 from 4 data centers**

Note: * indicates site supplying hourly meteorological data

Questions/Issues

New data sets and changes in operational procedures will be required by the IGS in order to support the future low Earth orbiting (LEO) missions with precise, rapidly-available products. The IGS has been transmitting hourly thirty-second data for nearly a year, but the various components have received little feedback as to their utility and timeliness. To support the precise orbit determination requirements of the LEO missions, hourly high-rate (e.g., one second) data will be required. Current data flow paths and data formats may be insufficient to handle the timeliness requirements for LEO missions. For example, a new binary data format may be the best way to transmit these large files. The users must also define the requirements for an acceptable delay and the need for archive and availability of full 24-hour daily files of one-second data. Another area of interest to analysts involved with these LEO missions are the data from the on-board GPS receiver themselves. It is unclear at this time if the IGS data and analysis centers will become involved in the flow, archive, and analysis of this "new" data set or even if these data will in general be available to a global user community.

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Radio Wave Propogation Effects in Radio Occultation Measurements

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Abstract

Analysis of radio wave propagation effects observed in radio occultation measurements of GPS-MET (at λ=19 cm and 24 cm) and "MIR"-GEO (at λ=32 cm and 2 cm) satellites is provided. Radio wave propagation effects including absorption, refractive loss, amplitude, phase and frequency variations of centimeter and decimeter radio waves obtained from data of radio occultation investigations of the atmosphere and ionosphere are revealed. Angular spectrum of radiowave was measured and multibeam propagation near zone radio shadow was discovered using radio holographic method. Sub-Fresnel spatial resolution was achieved and direct evidences of multibeam propagation effects in atmosphere were obtained. The accuracy in angular distance measurements was near 0.002 milliradian and maximum angular distance between different rays was equal to 0.3 milliradian.

The scheme of russian radio occultation experiments is shown in Fig.1. Transmitter installed on orbital station "MIR" emitted radio waves which propagated along two path - (1 and 2 in Fig.1). Direct radio signal (path 1) penetrated through atmosphere was received on GEO and then was retranslated to the Earth based station. Reflected radio waves (path 2) were registered also. According to scheme of radio occultation measurements shown in Fig.1, the terrestrial atmosphere was assumed as being locally spherically symmetrical, with a local centre of curvature O.

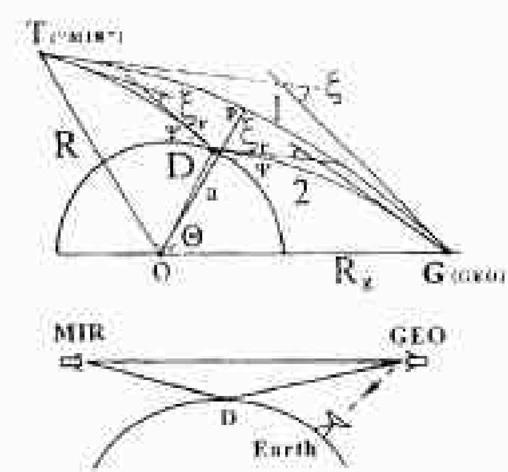

Fig.1. Scheme of radio occultation experiments.

The main physical effects observed during radio occultation experiments are connected with refraction, absorption and diffracion phenomena and may be revealed from observation of time dependences of amplitude, phase, frequency and spectrum of radio wave. In more general sense the radio occultation measurements may be considered as radio holographic registration [3] since the phase, frequency of radio waves are determinated in combination with simultaneous amplitude measurements. Combination of amplitude and phase data obtained during radio occultation may be considered as one dimensional radio hologram of the Earth's atmosphere (and of reflecting part of the terrestrial surface). Effects of radio wave propagation may be observed from analysis of radio hologram including multibeam propagation and diffraction phenomena. Let us consider theoretical background including refraction, absorption effects and their connection with characteristics of radio wave.

Absorption of centimeter and decimeter radio waves may be caused by water vapor and atmospheric oxygen. Differential attenuation of radio wave may be find from expression:

$$\gamma_i(h)=\gamma_k \exp(-h/H_k)+\gamma_w \exp(-h/ H_w), \qquad (1)$$

where γ_i -attenuation of power flux due to absorption, γ_k - attenuation due to absorption in oxygen at h=0 km expressed in db/km, γ_w - attenuation due to absorption in water vapor at h=0 km, H_k, H_w effective altitude for absorption in oxygen and water vapor. Integration along ray path (approximated by straight line) gives the next approximation for integral absorption in atmosphere corresponding to ray path TG [4]:

$$\Gamma(h_p)= (2\pi a)^{1/2} \, [\gamma_k H_k^{1/2} \exp(-h_p / H_k)+ \gamma_w H_w^{1/2} \exp(-h_p / H_w)] \qquad (2)$$

where h_p -minimal distance of ray trajectory from the surface, a-radius of Earth. By means of equation (2) and using experimental data obtained in decimeter and centimeter ranges one may evaluate parameters γ_k , H_k , γ_w, H_w. For winter condition about sea surface in Aleut Island region γ_w=3 10^{-2}db/km, H_w=1.5 km. For summer and continental region (Kazakstan) γ_w=1.6 10^{-2}db/km, H_w=1.5 km. Absorption in oxygen is nearly equal for both region and parameters γ_w , H_w are equal to γ_k=1.5 10^{-2}db/km, H_k=5.3 km. It follows from distinction of effective heights H_k , H_w that integral absorption of oxygen and water vapor is nearly equal for heights lower then 3 km, however for height greater then 5 km oxygen absorption prevailed. Thus using radio occultation measurements in decimeter and centimeter ranges one may control altitude distribution of water vapor. In Fig.2 the dependence of integral absorption of centimeter radio wave due to water vapor on minimum ray altitude is given. The points correspond to experimental data and the curve describes theoretical dependence for water vapor density 7.5 g/m^3 (near the Earth's surface). The results obtained show that for H ≈ 5 km, the signal strength both of centimeter and decimeter radio waves decreases by 2...3 db owing to absorption.

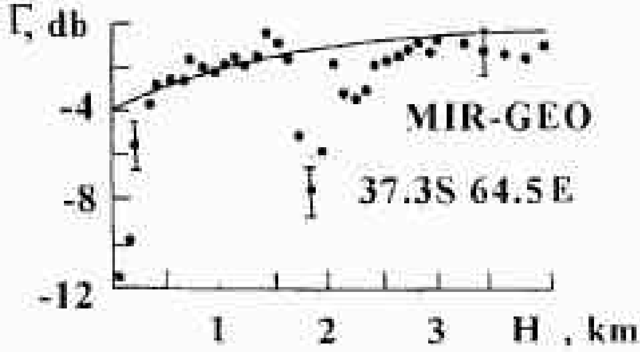

Fig.2. Integral absorption in water vapor at λ =2 cm

Theoretical expression for refraction attenuation of direct signal which is accurate in geometric optics approximation was given in [5] in following form:

$$X^2 (p) = pR^2_d[(R^2-p^2)^{1/2}(R^2_g-p^2)^{1/2}RR_g][\sin\theta\, \partial\theta/\partial p]^{-1} \qquad (3)$$

$$\theta=\pi+\xi(p)\ \ \arcsin p/R-\arcsin p/R_g \qquad (4)$$

For reflected signal the following expressions may used:

$$D^2_s(p_r) = p_r R^2_d[(R^2- p_r^{\ 2})^{1/2}(R^2_g- p_r^{\ 2})^{1/2}RR_g][\sin\theta\, \partial\theta/\partial p_r]^{-1} \qquad (5)$$

$$\theta=\pi+2\xi(p_r)-2\psi(p_r)-\arcsin p_r/R-\arcsin p_r/R_g \qquad (6)$$

where $\partial\theta/\partial p$ is a partial derivative which must be evaluated by conditions that R,R_g are constants, θ - angle between direction OT and OG, R,R_g, R_d- distances OT, OG and TG correspondingly, p_r is impact parameter of reflected signal, $\psi(p_r)$ is sliding angle (Fig.1). Equations (1)-(2) may be used for description of average dependence of amplitude on height in radio occultation data using known function ξ (p). For example in Fig.3 experimental dependence of amplitude A(H) on height H is given. The smooth curve in Fig.3 corresponds to expected dependence A(H) which was computed for standard refraction index profile N(H) with N(0)=280 N-units and dN(H)/dh=0.1265 km^{-1}. Absorption was modelled in the form Γ(H) =1.4 exp(-0.1865H). As it follows from Fig.3 theoretical dependences A(H) is in good accordance with GPS-MET data. As it may be seen in Fig.3 the experimental dependence A(H) includes spikes corresponding to features in temperature and humidity altitude profiles. This spikes may be modelled in geometric optics approximation and using diffraction theory also.

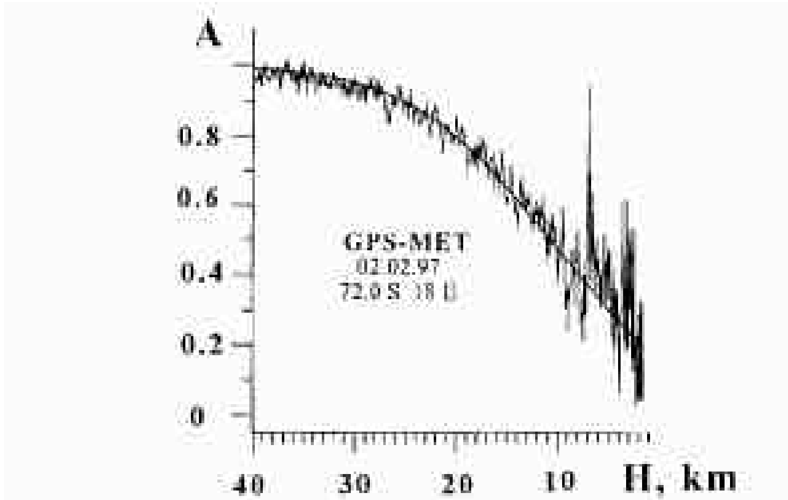

Fig.3. Dependence A(H) at λ =19 cm

Results of applying radio holographic method [6] to multibeam effect observation in GPS-MET and LEO/GEO radio occultation data are shown in Fig.4. Left part of Fig.4 corresponds to radio occultation seance 09 February 1997 16^h 54^m of local time which was held at co-ordinates 15^o South latitude and 145.3^o West longitude. Right part of Fig.4 corresponds to radio occultation seance 25 December 1990 12^h 39^m of local time which was held at coordinates 32.5^o South latitude and 63.9^o East longitude.The power in angular spectrum (arbitrary units) is given on the vertical axis in Fig.4. The data in Fig.4 (right) are shown in succession with time interval between neighboring spectra equal to 1/8 sec. The presence of multibeam propagation may be seen in Fig.4 (two separate maxima). The separation of different ray beams is seen more clearly in right part of Fig.4. This may be connected with more precise phase tracking in MIR-GEO experiments which was achieved using more higher value of discretisation frequency f_d equal to 1 KHz. Phase tracking for GPS-MET data analysis was realised using special phase function corresponding to main beam trajectory calculated by means of radio physical model of atmosphere described in [6]. It follows from Fig. 4 that the achieved accuracy of radio holographic analysis $\delta\beta$ is equal to 0.002-0.005 milliradian. The spatial resolution corresponding to data in Fig. 4 is equal to 100-200 metres. This resolution is more higher then the size of Fresnel zone which was about 0.5-0.7 km in the radio occultation experiments. Thus radio holographic method gives direct evidences of multibeam propagation in radio shadow zone.

Results of the first stage of radio occultation investigations shows necessity of designing international multifrequency radio occultation system for detailed study of small gas constituents of atmosphere (for example, ozone content) and distribution of humidity.

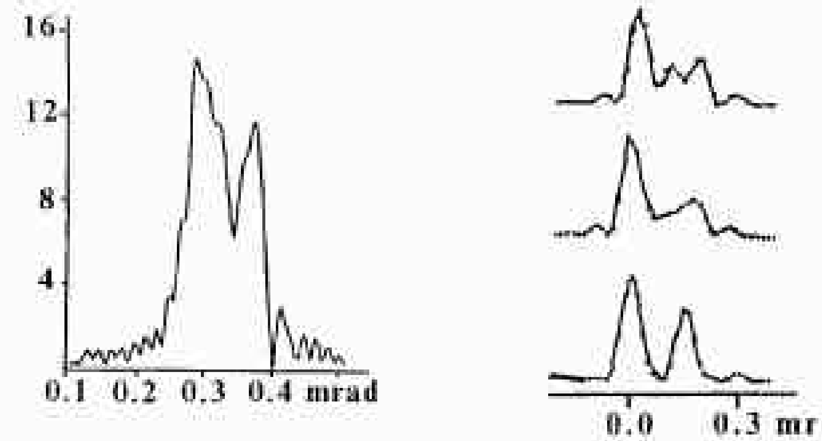

Fig. 4. Angular spectrum
GPS-MET (left) MIR-GEO (right)

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Analysis of the experimental data shows that there is possibility for control the vertical profiles of the refraction and absorption indexes, temperature, humidity and turbulence in regions of the atmosphere corresponding to boundary of radioshadow from measurements in the centimeter and decimeter wavelength ranges.

4-D Distribution of the Ionospheric Election Density Using LEO and Ground TEC Data

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Abstract

In this paper some of our previous work on the use of TEC data for ionospheric modeling is reviewed. We discuss how combining ground and LEO GPS TEC data can result in 4D images of the ionospheric electron content. A grid of "voxels" (3D pixels) is used. We apply this technique to calibrate Topex/Poseidon's ionospheric corrections, which suffer from instrumental biases. For this purpose we show that the direct ingestion of the RA's data into the tomographic model allows for the simultaneous determination of the calibration constant and the electronic density. Since we are also using data from the GPS receiver on Topex/Poseidon, and the ionospheric modeling grid extends above the spacecraft's orbit, plasmaspheric electron content studies are possible.

Introduction

In previous work we analyzed GPS data to extract information about the ionospheric electron density distribution. We can think of this distribution as a field in space-time which we try to represent using the information provided by the data. Since the ionosphere produces delays in the phase and group propagation of radio waves, having an accurate description of the electron content in the ionosphere is essential to any endeavor that uses radio wave propagation (such as tracking and navigating). In this paper we review our tomographic techniques to perform ionospheric imaging using Global Positioning System signal inospheric delay information.

After realizing that the Abel transform approach to analyze ionospheric occultations is limited by unreasonable spherical symmetry requirements, we decided to ingest the LEO data directly into our previous tomographic models, which involved only ground GPS data to that point. For a detailed discussion on the techniques we use to carry out tomography of the ionosphere see the references below. Let us just point out here the salient points. We use voxels (typically with sizes of 9 by 18 degrees by 150 km in latitude and longitude and height), and the solutions are global. We use GPS slant TEC data from ground and LEO receivers as well as Radar Altimeter (Doris is planned next). The data is used "democratically": each ray contributes an equation in the system, weighted by its sigma. A Kalman filter is used to allow for the ingestion of the data time series, typically with a resolution of 1/2 hour; the grid begins at about 100 km over the surface of the Earth and extends about 1000 km beyond the Topex/Poseidon orbit. In the solution, we solve simultaneously for the electronic density at each of the voxels, the instrumental constants of the GPS receivers and transmitters, as well as the instrumental bias in the Topex data. In this way, as a byproduct, we calibrate Topex.

An important problem in tomography is that it is in general an ill-determined problem: the data is not sufficient to uniquely specify a solution. The problem in this case is linear, of the form y= A x. The matrix A is the "integration matrix". It has as many rows as there are data measurements (one for each ray), and as many columns as there are unknowns (one for each voxel plus the bias constants). Its entries, then, are the lengths of the ray portions spent in each voxel, plus a 1 or 0 depending on the satellite and receiver involved (in the bias sector of A). For instance, suppose that a particular ray crosses 2 voxels only, and spends 200 and 180 km in each. Then in the row of A corresponding to this ray, we will find a lot of zeros, then a 200 and a 180 somewhere, and two 1s. corresponding to the receiver and transmitter involved. Similar considerations apply to the case of a Radar Altimeter ray. The corresponding entry in the vector y will contain the ionospheric delay measured. Returning to the initial point, the equation y=Ax is converted into a chi-square problem, and we are to minimize (y-Ax)^2. There are many solutions, however, and this is reflected by the fact A^T A has zero determinant. The approach we take to solve this problem is to add a constraint, and minimize (y-Ax)^2+(Bx)^2. The constraints we use are smoothing constraints. This is a natural choice. If there is data missing in some portion of the grid we ask that the solution interpolates x using the data from other places. Thus, the effective resolution of the solution is not set by the grid, but it can be coarser depending on data availability. It is important to note that the constraint will have strong effect in areas of low data availability, while in areas with abundant data they will not interfere too much. The effective resolution of the system is thus not homogeneous, but will vary depending on the area's data availability.

How much weight should be given to the constraints? The key to this question is in the eigenvalues of the system compared to the expected noise level in the data. Small eigenvalues amplify the noise so that precision in the solution is lost. The effect of giving more weight to the constraints is to bring up the eigenvalues of the system. Therefore, enough constraints should be used to bring up the eigenvalues above a given threshold specified by the noise. No more, no less. This will ensure a good global solution.

Another promising approach is the ingestion of GPS data into models. Climatological models of the ionosphere have existed for a while now, but it is only recently that they have been used to complement other sources of data, such as GPS, in the inversion process. For instance, one can use input from a climatological model such as PIM or IRI to complement GPS data in the inversion process, and to compare the results to other data. The parameters controlling the model are input directly, however, and are not estimated themselves. One could reason, however, that if the models were good enough they could used to infer these parameters given other sources of data, such as GPS ionospheric delay data. The resulting ``best-fit" parameters should be related to the ones one can obtain by independent means. We have ingested TEC data into PIM, using a simple chi-square system, and have obtained pretty good fits (40 cm of post-residual mean, compared to 30 using the tomographic methods, which involve many more parameters). The key for carrying out this idea has been the availability of the integration matrix from the tomographic approach, which has been used as observation operator in the ingestion functional.

Application to Calibration of Radar Altimeters

We now discuss the application of the tomographic techniques discussed before to the calibration of TOPEX/POSEIDON. The tomographic technique should in principle be superior to mapping-function methods, which will introduce biases in the solution if they do not have the correct vertical structure.

IGS and GPS/MET low (0.1 Hz) and medium (1 Hz) rate data (in RINEX format) was processed for February 21st 1997 (A/S off) using our GIST (Global Ionospheric Stochastic Tomographer) software package. We broke the flow of satellite delay data into 3-hour blocks, and smoothness under time evolution was enforced using a Kalman filter. We performed the tomographic inversion in a 6 times 10 times 20-voxel model (totaling 1200 unknowns excluding bias constants), with a resolution of 18 degrees in latitude and 18 degrees in longitude, and consisting of four 150 km-thick layers (extending from 6400 to 7000 km), plus a 700 km layer extending to the T/P orbit height (1336 km above equator, or about 7700 km from the center of the Earth, and then another layer of 700 km as a protonospheric buffer.

In a first iteration we simply compared AVISO/CNES NRA ionospheric correction and DORIS data to our tomographic model estimates. Thus, we were comparing the at-T/P-height TEC predictions from TGPS and DORIS/Bent to the NRA retrieved TEC. Average TGPS TEC fits were quite good, especially when allowing for temporal variations (using a Kalman filter with eight 3-hour batches), while the Center for Orbit Determination in Europe model (CODE), a simple thin-shell model for GPS data analysis, yielded a worse fit. JPL's 15-minute GIM estimates yield an even better fit. We note that DORIS, CODE and JPL estimates may suffer from a bias, however, since they use mapping function techniques to extract TEC estimates, and such models are susceptible to biases due to vertical mismodeling. We have performed a 1-layer fit (100 km layer at 400 km of altitude), equivalent to a simple mapping function such as the one used in CODE, and obtained quite a different bias from the other estimates:

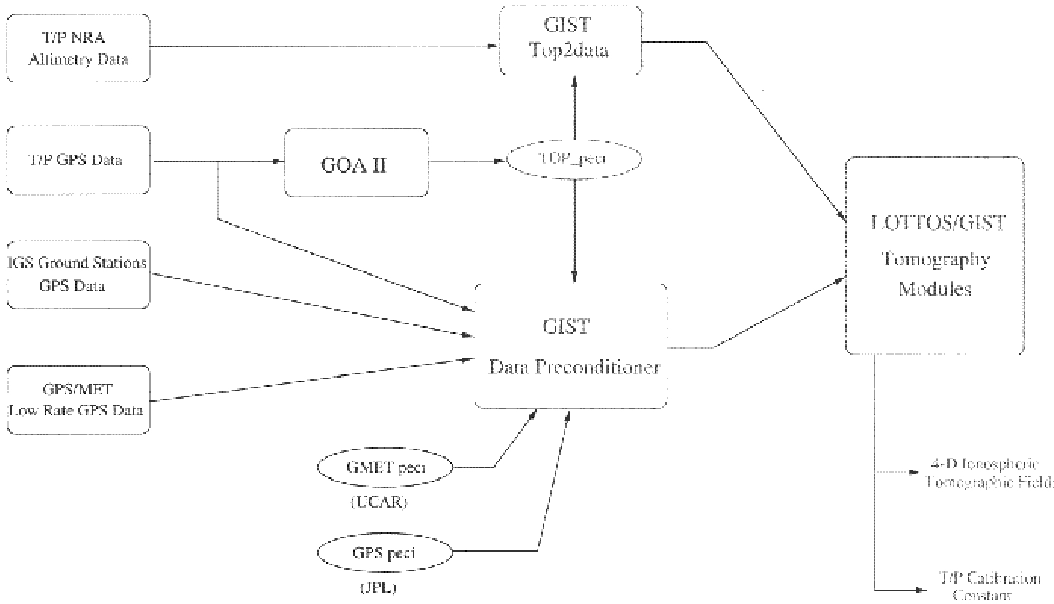
Fit	Bias	RMS
NRA-JPL/15min	0.7	2.5
NRA-RTGPS/24h	3.1	2.9
NRA-DORIS/Bent	4.1	3.0
NRA-TGPS/3h	3.4	3.2
NRA-TGPS/24h	3.2	3.8
NRA-CODE/24h	2.4	4.0
NRA-TGPS/1layer	1.0	4.5
NRA50-TGPS/24h	3.0	0.9

For the purposes of calibration it is best to use the daily TGPS solution (TGPS/24): the bias obtained should be the same whether we use a mean or a high temporal rate solution TGPS solution, and the 24h solution is independent of the random walk drift rate or the a priori guess chosen in the Kalman filter. A potential problem, however, is that it important to smooth out the NRA data in a fashion that resembles as much as possible the temporal and 2D spatial averaging in the TGPS/24h solution, since such filtering may induce a bias. This means taking a time average of the NRA data, as well as a spatial average. We have found that a 50 degrees running average over the orbit produces the smallest RMS and a slope close to 1.0 in the NRA versus TGPS comparison (slope is 0.9). The resulting bias (3.0 TECU) should thus be the most reliable bias. We will return to this point shortly.

As can also be seen in table above, restricting the reconstruction and comparison to the intersection of the T/P and GPS/MET orbits improves the TGPS fit (this solution is called RTGPS/24h, for ``daily Ring TGPS solution''). This behavior is expected, since it is under the GPS/MET orbit where the best vertical resolution is achieved and where, in general, more information is available for the inversion. Since few points of intersection were available for reliable statistics, however, we have not studied the comparisons with RTGPS/3h solutions (the Ring solutions using a Kalman filter with 3-hour batches).

What is the impact of not modeling the protonospheric electron distribution? We can estimate this source of error using simulated data. The Parametrized Ionospheric Model version 1.6 (which uses the Gallaguer plasmaspheric model) was used together with the actual geometric transmitter-receiver ray information for the same day. A full grid extending to the GPS orbit height was used to calculate the simulated delays, and the bias constants where set to zero. The question was then how accurate would the tomographic reconstruction be using a T/P-ceiling grid plus one layer above. It turns our that the reconstruction up to T/P height is quite accurate, with the last layer absorbing part of the protonosphere. Thus, we see that if a layer on top of the T/P orbit is used and the constants are estimated, the sub-T/P distribution reconstruction is quite accurate---there should be little bias (less than a TECU) in TGPS sub-T/P TEC estimates.

In the next iteration to the calibration problem, we ingested directly the Radar Altimeter ionospheric correction data into the tomographic model, treating the RA altimeter as a GPS LEO in the sense that a bias constant was assigned to this source of data. This way, we estimated directly the bias constant, and we did not have to worry about smoothing the data to the solution's spatial resolution as before. In addition, we used GPS data from the up-looking GPS receiver on Topex. It is encouraging to report that we obtained our nicest images yet of the ionosphere, and that the bias constant value (3.0 TECU) was the same to the one obtained with our previous method. It therefore appears that we have a robust approach to calibration. We think the super-T/P reconstruction carries important information about the plasmasphere as well, at least on the plane of the TOPEX orbit.



Block structure of LOTTOS/GIST, the in-house software we use for processing T/P NRA data as well as GPS data from TOPEX, GPSMET and ground. GOA II (JPL's GIPSY OASIS II) is used to obtain orbits when needed. As outputs we obtain electronic density fields as well as calibration constants, including the T/P NRA bias.

Conclusion

In previous work we showed that ground and occultation GPS delay data can be combined successfully to perform ionospheric tomography with a substantial level of vertical resolution. Promising areas of work involve the ingestion of TEC data directly into models. We have seen here that such tomographic TEC estimates can be used for altimeter ionospheric bias calibration at the 1 TECU level using NRA and GPS data from one day. In the simulations we have shown that reconstruction systematics are well below that level, and bias noise can be reduced using averaging. Our results thus suggest that TGPS can be used for absolute ionospheric calibration of radar altimeters.

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CHAMP S/C Telemetry, Data Flow and Products

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Mission, Satellite and Payload Overview

The idea of a small satellite mission was initiated in 1994 by the German Space Agency as a lead project for the East German space industry. The mission goals and the instrumentation for a geoscientific mission, called CHAMP, were defined by scientists of the GeoForschungsZentrum Potsdam (GFZ). The mission was studied in its feasibility, designed and specified under lead of GFZ together with an industrial consortium and the German Aerospace Centre (DLR). After completion of the project's definition and specification phase (Phase B), CHAMP entered into its manufacturing and integration phase (Phase C/D) in January 1997. The launch is scheduled for early 2000 with a Russian COSMOS launcher from the Plesetzk launch site.

CHAMP shall be employed to map both, (a) the Earth gravitational geopotential by the analysis of observed orbit perturbations, and (b) the magnetic geopotential via on-board magnetometry, and in addition shall (c) perform atmosphere and ionosphere profiling by GPS radio occultation measurements.

CHAMP will fly in an 87.3 degrees inclined circular orbit with an initial altitude of 470 km, decaying to about 300 km over the missions lifetime of 5 years. The low altitude orbit supports the spatial resolution of the geopotential field whereas the long mission duration helps to recover temporal field variations.

The satellite consists of a trapezoidal body of 0.6 m height, 4 m length and 1.6 m / 0.4 m bottom/top width and a 4 m long boom in flight direction. The front panel and rear panel are 70 deg and 20 deg, respectively, inclined towards nadir. The mass of the satellite is 500 kg including 32 kg of payload mass. The power consumption will be 150 W of which 45 W is needed to run the instruments.

The satellite will fly in an Earth-pointing mode with all 3 axes stabilized within ±5 deg by a cold gas propulsion system supported by three magnetic torquers. The attitude will be measured by two star sensors each on the body and boom with an accuracy of better than 0.01 deg.

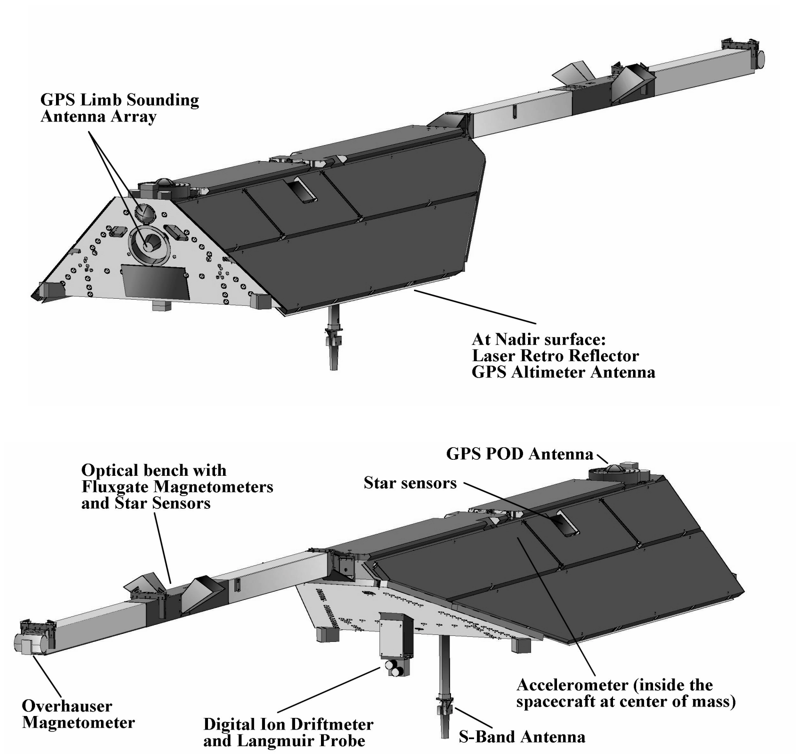

Figure 1. Sketch of the CHAMP satellite and payload accomodation

The CHAMP payload consists of

- a space-borne 16 channel, dual-frequency GPS receiver (JPL, USA) connected to a multi-antenna system for precise satellite-to-satellite tracking between CHAMP and the high-flying GPS satellites (top-antenna: orbit determination, rear-antenna: limb sounding, nadir-antenna: experimental altimetry from surface reflected signals),
- a three-axes accelerometer (ONERA, France) at the spacecraft's center of mass to measure directly the non-gravitational orbit perturbations (air drag, solar and Earth radiation pressure), rigidly connected to two star sensors (DTU, Denmark) for precise inertial orientation information,
- a laser retro-reflector (GFZ Potsdam, HN Berlin, Germany) for additional tracking from ground,
- a magnetometer instrument package consisting of an Overhauser scalar magnetometer (LETI, France) and two Fluxgate vector magnetometers (DTU Denmark), rigidly mounted on an optical bench along the boom together with two star sensors (DTU, Denmark), and
- a Digital Ion Drift Meter (AFRL, USA) to measure the electrical field vector along the orbit.

The satellite structure was integrated by November 1998 and the integration of the payload started in February 1999. The environmental and system tests will commence in May 1999.

Telemetry and Data Flow

CHAMP on-board instruments continuously produce science and instruments' house-keeping data with an overall rate of 10.8 kbit/s, and the satellite adds 2.2 kbit/s of spacecraft house-keeping data, in total 141 MByte/d, which have to be downloaded to the 7.3 m ground antenna of DLR's receiving station in Neustrelitz (53.5 N, 13 E).

With its telemetry bitrate of 1000 kbit/s and a contact time of 28 min/d at 450 km and 20 min/d at 300 km S/C altitude during the three to five passes per day, Neustrelitz is capable to receive 210 MByte/d (at 450 km) and 150 MByte/d (at 300 km), respectively, of dump data. A second ground station, DLR/GSOC's ground station in Weilheim (48 N, 11 E), is operated as the commanding and satellite control station. It receives 'real-time' science and H/K data at a bitrate of 32 kbit/s and sends commands at 4 kbit/s. Weilheim also serves as a back-up station to Neustrelitz, then being capable to switch to a 1000 kbit/s down-link telemetry bitrate.

CHAMP's on-board mass memory unit is organized as a ring buffer and consists of a science data segment of 100 MByte and a H/K data segment of 25 Mbyte storage capacity. The on-board data is written and dumped sequentially controlled by a write and dump pointer. The maximum buffer time (maximum time between two overflights over Neustrelitz) is 13 hours. If, by failure, the buffer runs full, then the oldest data will be overwritten.

CHAMP's **Raw Data Centre** will be established at the receiving station Neustrelitz with the following functions: telemetry data reception (Transfer Frames) and long-term storage in the **Raw Data Archive**, demultiplexing and extraction of science and H/K application packets (level-0 data), immediate transfer of H/K packets to DLR/GSOC, and temporary storage of all level-0 data in the **level-0 rolling archive** for access by the instrument manufacturers and the processing centre at GFZ Potsdam, where the **level-0 long-term archive** is located.

In addition to the spacecraft data, all CHAMP related ground station network data are accessed and archived at GFZ Potsdam: low rate (30 s) and high rate (1 s) GPS ground-based observations from individual stations and data centres, and CHAMP laser tracking data from the international laser data centres. The high-rate GPS ground-station data of the GFZ and JPL subnets are mutually exchanged (about 25 MByte/d in both directions). All data transfer shall be accomplished using the public Internet network.

Product Generation

The products of levels 1 through 4 are generated at the science data processing system GFZ Potsdam within the

- Orbit and Gravity Field Product Generation System,
- Magnetic and Electric Field Product Generation System and
- Neutral Atmosphere Product Generation System,

and at DLR-DFD Neustrelitz within the

- Ionosphere Product Generation System.

Product archiving, administration and retrieval are organized by the CHAMP **Information System and Data Centre** (ISDC), located at GFZ Potsdam, which also is the users' www- and ftp-based interface for access to all scientific products of levels 1 through 4.

CHAMP's standard science products are labeled from level-0 to level-4 according to the number of processing steps applied to the original data. Decommutation and Decoding of level-0 data results in level-1 products. These are dump-related files, associated with each individual instrument and source aboard CHAMP, and the data content is transformed from the telemetry format and units into an application software readable format and physical units. Level-1 products also include the ground station GPS and laser data. Level-2 products are preprocessed, edited and calibrated experiment data supplemented with necessary spacecraft housekeeping data and arranged in daily files. Level-3 products comprise the operational rapid products and fine processed, edited and definitely calibrated experiment data. Finally, level-4 leads to the geoscientific models derived from the analysis of CHAMP experiment data, supported and value-added by external models and observations.

Within the three fields of research and application persued with CHAMP, the following higher level products will be generated:

- Orbit and Gravity Field Products Generation System (GFZ Potsdam)
  - level-2: screened **accelerometer** observations (1 Hz) annotated with calibration parameters, attitude information and thruster firing time events
  - level–3: **rapid science orbits** of CHAMP and the GPS satellites augmented by attitude information and reliability flags and processed within a few hours after data download; CHAMP **orbit predictions** to serve the laser stations
  - level–4: postprocessed **precise orbits** of CHAMP and the GPS satellites; global **Earth gravity field models**, represented by the adjusted coefficients of a spherical harmonic expansion of the static and time varying part of the gravitational geopotential: monthly solutions and progressively accumulated solution

- Magnetic and Electric Field Product Generation System (GFZ Potsdam)
  - level-2: full rate vector data (10 or 50 Hz) of **external magnetic field**; **calibration matrices** derived from the combination of Overhauser and Fluxgate Magnetometer readings; **precise attitude** from Advanced Stellar Compass both for the spacecraft and the boom; **electric field vector**, **ion density** and **temperature** (all selectable between 1 an 16 Hz); preliminary **magnetic activity index** determined along the orbit
  - level-3: **fully calibrated magnetic vectors** (5 Hz)

  - level-4: **main magnetic field models** represented as a spherical harmonic expansion to degree and order 14 derived from the combination of spacecraft and ground-based data, updated once per month; **lithospheric magnetic field model** derived from the coefficients of the spherical expansion for degree and order 15 to 60, separation into a constant and a time varying part by comparison of consecutive models; **magnetic activity indices** indicating the ring current activity, the polar electrojet activity and the global magnetic activity

- Atmosphere/Ionosphere Product Generation System (GFZ Potsdam/DLR Neustrelitz)
  - level-2: list of occultation events **(occultation tables)**; geo-located and time tagged **excess path delays** through atmosphere annotated with SNR for each occultation event
  - level-3: calculated **vertical profiles** of bending angles; Abel-inverted profiles of refractivity: **dry-air** temperature, air-density, air-pressure and, adopting temperature from global analyses, **water vapour** in troposphere and partial water pressure; link-related differential **TEC** (horizontal/upwards) from differential phases; ionospheric profiles of **electron density** from GPS occultation measurements
  - level-4 (tbd): variability studies of atmospheric parameters; seasonal variation at selected areas; 2D, 3D ionopsheric imaging; data assimilation into ionospheric models

Conclusions

CHAMP has got all elements of a GPS LEO mission: Precise Orbit Determination, Gravity and Atmosphere/Ionosphere Radio Occultation

It puts demanding requirements on operating the ground segment and on regular data processing over a 5 years mission duration:

- Operating a dedicated near-real-time delivery high-rate GPS ground tracking network
- rapid and off-line precise orbit determination
- generation of atmosphere and ionosphere profiles from about 200 occultation events per day and demonstration that the 3 hours latency requirement for numerical weather prediction can be met
- generation of monthly gravity and magnetic field model solutions

By this, CHAMP is a pilot mission for coming GPS LEO missions.

CHAMP Atmosphere/Ionosphere Processor

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Abstract

The paper gives an overview of the planned infrastructure needed for the data processing of the Atmospheric/Ionospheric Profiling (AIP) experiment of the German small satellite mission CHAMP. The discussion is focussed on the structure of the AIP processing system. Its main task will be the automatic generation of data products at different processing levels. In addition, operational aspects of the product generation are discussed in view of the challenging future task of providing occultation data for operational weather forecast.

Introduction

The German small satellite project CHAMP is a geoscientific mission for the determination of the Earth's gravity and magnetic field and for GPS-based atmospheric sounding (Reigber et al., 1996). The satellite is scheduled for launch for January 2000.
Within the AIP experiment the data of about 200 aft looking occultations daily will be analyzed to provide global distributed vertical profiles of atmospheric and ionospheric parameters. This task will be done by an automatically working processing system which is under development now. The processing system will receive the input data from several external sources via internet, as occultation measurements onboard the CHAMP satellite, the orbit data of GPS and CHAMP satellites, the measurements of the fiducial GPS ground network and supplementary data. If all these data are available, it will generate the data products using a scientific software package developed in preparation of the CHAMP mission (Jakowski et al. 1998). The processor system has a common interface to the Information System and Data Center (ISDC) which will make the products (vertical profiles of T, p, ρ, N, α) available for the international user community.

The processor is designed to meet future requirements of operational weather prediction services. Therefore the design and the interplay of the processor components are optimized for a fast and effective data processing.

CHAMP Infrastructure for GPS Radio Occultation Experiment

The AIP processing system is part of a complex infrastructure to generate the data needed for atmospheric profiling by means of GPS radio occultation. The entire measurement and processing scenario is sketched in figure 1.

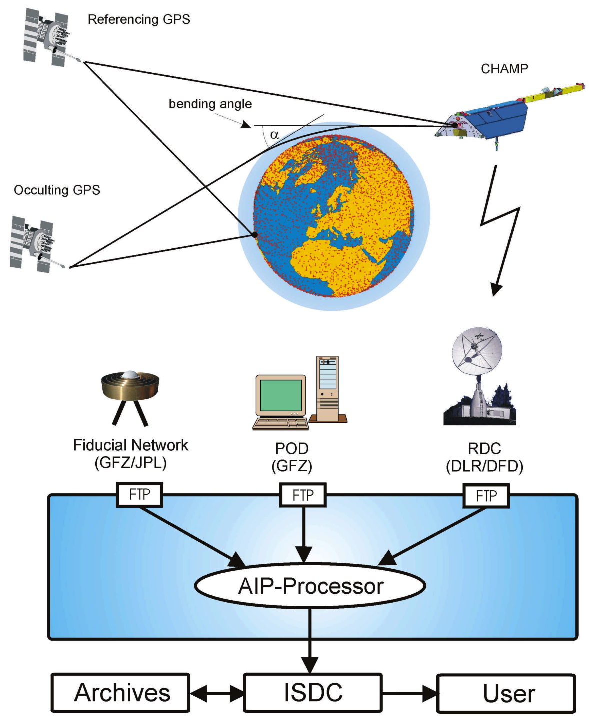

Fig. 1: System of GPS Radio Occultation

During an occultation event CHAMP will receive the high rate (50 Hz) signals of the occulting and the referencing GPS satellites. These Satellite Satellite Tracking (SST) data will be transmitted to the receiving station and archived in the CHAMP Raw Data Center (RDC, provided by DLR/DFD).

In addition a ground station tracks the occulting and referencing GPS satellites enabling the use of double differences for GPS data processing which removes drifts of the clocks in the GPS transmitters and receivers.

To eliminate the relative motion of the CHAMP and GPS satellites from the observed phases the calculation of precise orbit information is necessary (POD). The POD will be done at GFZ Potsdam and the network of fiducial ground stations will be jointly operated by GFZ and JPL (Kang et al. 1997, Reigber et al. 1998). Thereby the dynamic orbit determination procedures itself will be supported by the data of the fiducial network.

After receiving all input data the AIP-Processor will automatically generate the data products with the complementary meta data information and transfer them to the ISDC. The ISDC takes care for dissemination of the data products to external users as well as for their storage in the archive system.

The Atmosphere/Ionosphere Processor

The main task of the AIP processing system will be the automatic generation of data products at different processing levels and their transmission to the ISDC. Therefore the system has to fetch the input data from different sources.

A major problem of the processor operation is the dependence of processing steps on a number of quite different input data. Received input data are mapped to items in a queue of tasks, which have to be processed. When all necessary data arrived, the task will be delivered to its processing module.

The processor system is designed for dynamic configurations allowing simplified upgradings and extensions. Thus, the system consists of separate modules built up by generic components. Then the system will be capable to process input data from other satellite missions (e.g. RSTEDT, SUNSAT, SAC-C) as well as to generate new or modified products.

The AIP processor system is divided into several main components. The generic Input subsystem receives the external data. The design of an efficient and generic interface of the Processing subsystem simplifies the integration of the modules performing the scientific computations. The Data Management subsystem provides the data handling of the processor and a generic interface to the ISDC. It also delivers the retrieval information to the data base for supporting the users. The Controlling subsystem coordinates the work of all modules. The Supervising subsystem watches the system and links the Controlling subsystem and the Operator Interface which supports the controlling of the processor and its components.

The interplay of the main processor components is shown in figure 2.

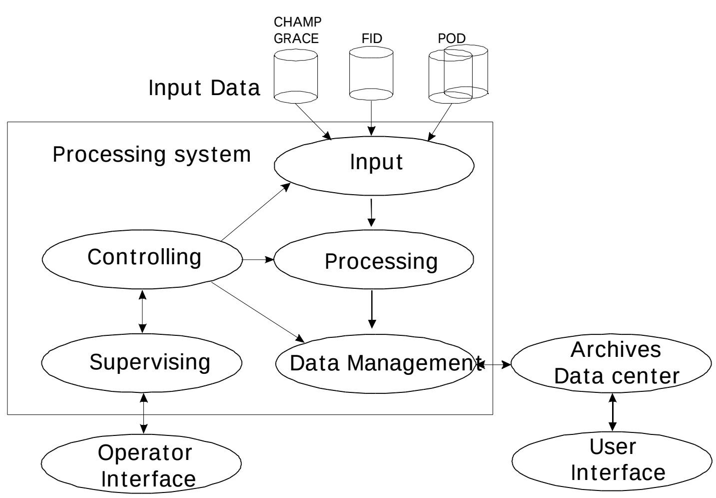

Fig. 2: Main components of the processing system and their interplay

Operational Aspects

Simulations using variational data assimilation techniques by NCAR and ECMWF (Eyre 1994, Zou 1998) have shown that profiles of bending angles from radio occultation experiments can strongly support climate and numerical weather predictions (NWP) analyses. The simulations show that the areas of improvement, if the data are sufficiently dense and timely, range from water vapor distribution in the lower troposphere, predicition of low pressure in cyclogenesis, and weather predictions of temperature, wind fields and water vapor.

The real impact of a single satellite occultation mission as CHAMP on weather predicition is limited by the low density of occultations in space and time. But in near future, systems such as COSMIC and AMORE with more than thousands of occultations per day (Yunck et al., 1999) will meet operational requirements of meteorological services.

Nevertheless, a single satellite mission such as CHAMP is helpful to get first experience in collecting and processing of radio occultation data under operational conditions.
The time schedule of the planned operational scenario for the GPS Radio Occultation System (introduced in figure 1) is illustrated in figure 3. The occultations are nearly evenly distributed over time, but the access to the occultation data is restricted by the number of data dumps to receiving ground stations. In case of only one ground station in middle Europe one has to take into account a data gap up to 11 hours in the worst case.

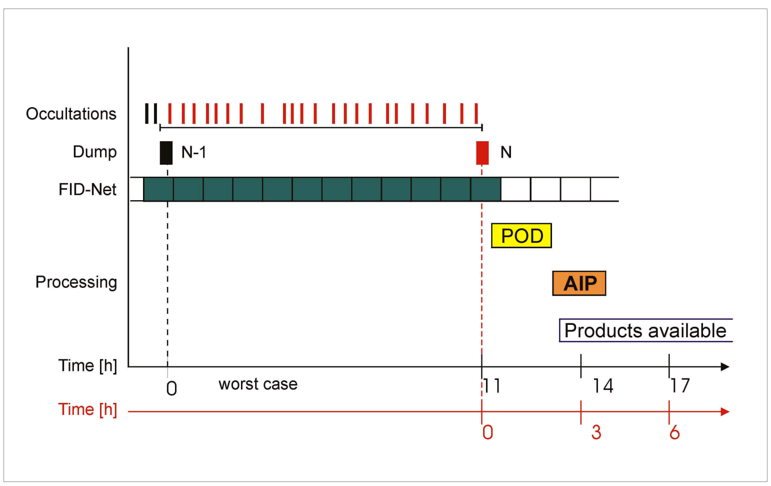

Fig. 3 Operational scenario as expected for CHAMP data processing

Assuming a minimum duration of the POD for the GPS and CHAMP satellites of two hours after receiving the SST data and hourly providing of fiducial network data the sketched time scales for the product generation can be achieved. If the processing time for the occultations is neglected, it follows that the cycle of orbit and fiducial network data provision as well as the periodicity of transmission of the SST data from CHAMP is decisive for the generation time of the atmospheric profiles. Following the course of the sketched events, the time delay for provision of meteorological information derived from occultation measurements reaches from about 3 to 14 hours.

Figure 3 indicates that the delay between two data transmissions from CHAMP is the most limiting factor for operational applications such as weather forecast. To reduce this time interval the operation of a high latitude CHAMP ground station could be an effective solution.

Summary

The general design of the AIP data processing system for CHAMP has been discussed. The processor is the final part of a complex infrastructure needed for GPS radio occultation data processing. The automatic processor works in a data driven manner and is designed for dynamic configurations allowing simplified upgradings and extensions (e.g. for GRACE mission).

The operational meteorology tolerates a maximal time delay between measurement and available atmospheric information of 3 hours (Wergen 1991). To meet this requirement a high latitude receiving ground station is recommended.

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