IGS PRODUCTS FOR THE IONOSPHERE

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ABSTRACT

In June 1992 the International GPS Service for Geodynamics (IGS) started with the routine provision of precise GPS orbits and earth orientation parameters. In the meantime other products were included into the product palette: rapid orbits, predicted orbits, GPS satellite clock information, station coordinates and velocities (SINEX), and station-specific tropospheric zenith delays.

For a long time the IGS community has been well aware of the fact that the world-wide IGS network offers a unique opportunity to extract ionospheric information on a global scale. At the IGS workshops held in Potsdam in May 1995 and in Silver Spring in March 1996, sub-sessions were dedicated to the ionosphere. Main subject of the ionosphere sub-session in Silver Spring in March 1996 was an intercomparison of ionosphere products provided by several Analysis Centers in order to get an idea of the accuracies that can be achieved. In addition it was identified for the first time, which Analysis Centers are interested to contribute to an IGS ionosphere product.

Since 1996 considerable progress in ionosphere modeling has been achieved at the different Analysis Centers. Today most centers are able (or close to that state) to provide ionosphere information on a routine basis. An official format for the exchange of ionosphere maps, called IONEX, has been developed and approved. It was the main task of the 1998 IGS Workshop to prepare the start of a coordinated routine processing and a combination of future IGS ionosphere products.

INTRODUCTION AND MOTIVATION

Since mid 1996 we are approaching the next solar maximum. Therefore good and fast knowledge about the ionosphere's actual state becomes increasingly important: Users of satellite navigation systems need accurate corrections to remove signal degradation caused by the ionosphere, information on the ionosphere's behavior is of great importance for radio signal propagation applications, scientists will benefit from up-to-date and long-term ionosphere information, as well. ESOC is, for instance, interested to use IGS ionosphere maps to support other ESA missions, like ERS and ENVISAT.

As part of the IGS activities GPS dual-frequency data are collected from a global net of ground stations for years. Due to the fact that the ionosphere is a dispersive medium for microwave signals, dual-frequency GPS data provides thus a direct measure of the ionosphere's activity and can be used to extract global ionospheric information.

Since 1992 the IGS Analysis Centers demonstrate that they are capable to routinely determine orbits, earth orientation and rotation parameters, and other parameters of geophysical interest. In principle, it is a small step for them to derive ionospheric parameters on a regular basis - provided special software for ionosphere modeling is available.

The main motivation for the IGS to get involved in regular ionosphere modeling and mapping is a continuous monitoring of the ionosphere for (at least) the next period of high solar activity and to study in particular the impact of the ionosphere on the "traditional" IGS products (IGS core products).

REVIEW OF IONOSPHERE IGS ACTIVITIES SINCE MARCH 1996

Several of the Analysis Centers participating in the IGS have experience with the evaluation of ionospheric parameters from dual-frequency GPS data and develop corresponding software. Institutions, which do currently not contribute to the IGS with products (like orbits, etc.) but indicated their willingness to contribute routinely to IGS ionosphere products, will be denoted as "Analysis Centers", as well, below. Table 1 gives an overview over all Analysis Centers involved and provides detailed information about their ionosphere modeling.

Looking back over the preceding two years, it can be noticed positively that some of the Analysis Centers have achieved considerable progress and improvement in their ionosphere processing. And, as reaction on an e-mail inquiry initiated in preparation to this 1998 workshop, new Analysis Centers have manifested their interest to enter into future IGS ionosphere activities. It must be noticed, however, that most ionosphere-related efforts of the Analysis Centers dealt with internal improvements. Apart from the intercomparison of ionosphere maps and differential code biases, performed as a part of the 1996 IGS workshop session, and the definition and approval of the so-called IONosphere Map EXchange Format (IONEX) (ref. R3), no significant contributions to a common IGS activity could be registered.

Many Analysis Centers are ready to participate in a routine IGS ionosphere service or are being very close to do so. Therefore, in principle it should only be a small step to start with a routine provision of ionosphere products within the IGS.

POTENTIAL PARTICIPANTS IN A ROUTINE IGS SERVICE FOR IONOSPHERE PRODUCTS

In order to get an overview over the possible participants and their individual ionosphere products, an inquiry via e-mail was initiated prior to the 1998 workshop. The reactions on this inquiry are condensed in the following table:

Analysis Center	CODE	DLR	ESOC	JPL	NOAA	NRCan	ROB	UNB	UPC	WUT
IGS Analysis Center ?	yes	no	yes	yes	yes	yes	no	no	no	no
Extent of ionosphere maps	global & regional (Europe)	regional (Europe)	global	global	regional (US) + global (planned)	regional (Canada) + global (planned)	regional (Belgium)	regional + global (planned)	global	regional
Temporal resolution	24^h / 2^h in preparation	1^h	24^h	15^m	24^h	24^h	15^m		1^h	
Observable(s) used	doubly differenced phase *or* carrier phase leveled to code	carrier phase leveled to code	carrier phase leveled to code	carrier phase leveled to code	GPS phase information	carrier phase leveled to code	carrier phase leveled to code	carrier phase leveled to code	carrier phases and differences	doubly differenced phase
Shell height	*400 km*	*400 km*	*450 km* for 2-d models	*450 km*		*350 km*		*400 km* and calculated from IRI		*400 km*
Elevation cut-off angle	*10°*	*10°*	*20°*	*10°*		*15°*				*15°*
Elevation-dependent observation weighting	yes		yes	yes		yes				
TEC representation	spherical harmonics, n= 12, m = 8	NTCM model	2-d GE-functtions & 3-d Chapman profile models	composition of local basis functions	Site-specific models		Station-specific profiles	spatial linear approximation	3-d tomography models	spherical harmonics, n,m = 3
Grid width	*2.5°*	*2.5° / 5°*	*2.5°*			*3°*				*2.5°*
Differential code biases	yes	yes	yes	yes	no	yes	yes	yes	no	no
Reference frame internally used	sun-fixed / geographic		sun-fixed / geomagnetic	sun-fixed / geomagnetic		sun-fixed / geographic		sun-fixed / geomagnetic	sun-fixed	sun-fixed
Mapping function	$1/\cos z$	$1/\cos z$	$1/\cos z$, integrated in Chapman profile models	elevation scaling function based on extended slab model		$1/\cos z$		$1/\cos z$		$1/\cos z$
Single layer shape	spherical		spherical for 2-d models			spherical		spherical		spherical
IONEX format implemented ?	yes	in preparation	yes	in preparation		planned	no	planned		yes
Ready for routine processing ?	yes	yes	yes	yes	planned	regional: yes global: planned	yes			yes

Analysis Center	CODE	DLR	ESOC	JPL	NOAA	NRCan	ROB	UNB	UPC	WUT
RMS maps provided ?	yes		planned							no
Delay of availability	rapid: 12^h, final: 4^d	2^d	final: 11^d rapid: planned	3^d						

Table 1: Potential participants and their ionosphere products.

The Analysis Center identifiers are in alphabetical order:
CODE (AIUB): Center for Orbit Determination in Europe, Berne, Switzerland,
DLR: DLR/DFD Fernerkundungsstation Neustrelitz, Germany,
ESOC: ESA/European Space Operations Centre, Darmstadt, Germany,
JPL: Jet Propulsion Laboratory, Pasadena, CA, U.S.A.,
NOAA: National Oceanic and Atmospheric Administration, Silver Spring, U.S.A.,
NRCan (EMR): Natural Resources Canada, Ottawa, Ontario, Canada,
ROB: Royal Observatory of Belgium, Brussels, Belgium,
UNB: University of New Brunswick, Fredericton, N.B., Canada,
UPC: Politechnical University of Catalonia, Barcelona, Spain,
WUT: Warsaw University of Technology, Warsaw, Poland.

A blank field indicates that no information is available for the Analysis Center.
The University of New Brunswick (UNB), Fredericton, N.B., Canada, intends (at least in the near future) to contribute with intercomparisons of techniques and scientific findings rather than with routine ionosphere products.

Table 1 shows that the number of methods of ionospheric modeling corresponds to the number of Analysis Centers!

POTENTIAL USERS OF IGS IONOSPHERE PRODUCTS

When developing IGS ionosphere products, potential users of such ionosphere products should be specified. Ionospheric electron density models are of greatest interest to GPS/GLONASS users with single-frequency receivers. The same information may of course be used for other than GPS/GLONASS satellite tracking data, too. Regular information on ionospheric conditions may also be helpful in other fields of radio signal propagation and for scientific interpretation of phenomena in the high atmosphere, the magnetosphere, and solar activity.

Depending on the interests of different users, different kinds of ionosphere products are required. Users may be grouped into two categories:

1) Users interested in fast access to up-to-date ionosphere information, but do not require highest accuracy. We think, e.g., of geodetic survey, navigation applications, road and shipping transport companies. Ionosphere models are only of interest to obtain reasonable corrections for tracking data.

2) Scientists interested in highly accurate ionosphere models. To get precise ionosphere information, this group will accept time delays in having ionosphere products available. Scientists have already signalized their interest in an IGS ionosphere product.

We assume that the majority of potential users will belong to the first category.

PROGRESS MADE AT THE 1998 WORKSHOP

The ionosphere sub-session started with the presentation of the position paper prepared by S. Schaer and J. Feltens. Thereafter contributions covering different aspects relevant for the development of an IGS ionosphere product followed:

- R. Warnant from ROB presented results of a study dealing with the short-term resolution of TEC and its irregularities from GPS data in a regional network.

- N. Jakowski from DLR Neustrelitz reported about their monitoring of the ionosphere over Europe using a model developed at Neustrelitz and discussed its applicability to related ionosphere studies.

- J. Feltens from ESOC presented the basics of a mathematical model to describe the TEC with a 3-d "Chapman profile approach", together with first results obtained - a first attempt in the direction of a 3-d TEC map establishment.

- R. Leitinger from TU Graz pointed out the importance of GPS in ionospheric monitoring, mapping, and nowcasting for atmospheric research. He also pointed out that regional differences are considerable. Nevertheless there is a clear interest in global ionospheric models.

- S. Schaer from AIUB showed long-time series of global TEC parameters and demonstrated that it is possible to predict the parameters of CODE ionosphere maps.

The above presentations and the subsequent discussion revealed that there is a great interest of the ionosphere community in a continuous series of global IGS ionosphere models. However, some of the above presentations indicated that many activities in the ionosphere community are regional in nature. Nevertheless, it was decided that the IGS (at least in a first phase) should stay out of regional ionosphere modeling, but should rather focus on global aspects.

In summary it can be said that the authors and the interested institutions are convinced that the development of an IGS ionosphere product is an important task. A continuous series of IGS TEC maps should be produced at least over one full 11-year cycle of solar activity. It is of particular importance that the IGS TEC maps are covering the next period of maximum solar activity (years 2000-2003).

TOWARDS A COMBINED IGS IONOSPHERE PRODUCT

From Table 1 we can see that ten Analysis Centers are prepared to contribute with ionosphere products to the IGS. The analysis procedures are well established at each center, and they differ considerably. We conclude that it does not make sense for the IGS to come up with very stringent requirements concerning the generation of such products. The IGS should, however, define minimum standards, formats, and deadlines for product delivery. These are the basic considerations underlying the following recommendations which emerged from the Darmstadt workshop:

Recommendations

(1) Initially, the IGS should focus on two kinds of products:
(a) TEC maps in grid form and
(b) differential code biases (DCBs).

(2) IGS TEC maps are global maps. Only global maps will be compared and perhaps combined. This policy may be reviewed after one year of pilot operations.

(3) All TEC maps must be delivered to the IGS in the IONEX format [Schaer et al., 1998]. TEC maps delivered to the IGS thus are "snapshots" of the electron density referring to a particular epoch and to an earth-fixed reference frame.

(4) Global TEC maps from each contributing Analysis Center are given the name *cccGddd0.yyI*, where *ccc* is a 3-figure acronym for the AC (in uppercase), "*G*" says that this file contains global maps, *ddd* is the day of the year, "*0*" indicates a daily file, *yy* specifies the 2-digit year, and the last letter "*I*" stands for "ionosphere maps". Example: *CODG0410.98I* (or *CODG0410.98I.Z*). These files are {compressed} and sent to the IGS Global Data Centers and are available to the interested user. Access Fortran routines are also made available.

(5) The daily IONEX file, as produced by an IGS Analysis Center, should have a 2-hour resolution referring to the epochs *01, 03, ..., 23 hours UT*. RMS files corresponding to the 2-hourly TEC maps may be included in the IONEX files. TEC/RMS maps refer to a two-dimensional grid in a single layer. The height of the single layer should be *450 km* adopting a base radius of *6371 km*. The latitude ranges from *87.5* to *-87.5 degrees* in steps of *-2.5 degrees*; the longitude ranges from *-180* to *180 degrees* in steps of *5 degrees*. TEC/RMS values have to be given in units of *0.1 TECU*.

(6) Daily sets of differential code biases (DCBs) for the GPS satellites are recommended to be included in IONEX files. The exchange of satellite-specific DCBs is IONEX-supported, too. Note that the DCB reference may be chosen arbitrarily and can be taken into account in the combination procedure.

GOALS AND NEXT STEPS

For the near future (about two years) we see the following goals:

(1) Global ionosphere maps (TEC maps) including satellite-specific differential code biases (DCBs) from contributing Analysis Centers are made available in IONEX format through the IGS Global Data Centers. The start of the pilot ionosphere service is scheduled for June 28, 1998 (GPS week 964).

(2) Minimum analysis and performance standards are prescribed:
- Minimum analysis standards are listed in recommendation (5), above.
- Ionosphere products are made available not later than the IGS Final Orbits and EOPs, i.e., 11 days after the observations.

(3) TEC maps and DCB values as produced by individual Analysis Centers are compared by the "IGS Ionosphere Coordinating Center". A weekly report has to be produced.

(4) Individual TEC maps and DCB sets are combined into a preliminary "IGS Combined Ionosphere Product". The weekly report now contains also "rms values" relative to the combined product.

(5) Deadlines for ionosphere product delivery after at least six months of pilot service are reviewed. Define an "IGS Rapid Ionosphere Product".

(6) An "IGS Ionosphere Model" based on the available combined (or individual) time series of IGS ionosphere maps (IGS TEC maps) is developed.

In order to accomplish these goals we propose to establish an "IGS Ionosphere Working Group" proceeding as follows:

- Terms of Reference for the "IGS Ionosphere Working Group":

  A draft for these Terms of Reference will be developed jointly by the authors of this position paper, and, as agreed upon at the Darmstadt Governing Board Meeting, by Gerhard Beutler and John Dow.

- Membership:

  This group should contain representatives of those Analysis Centers which will (with utmost certainty) contribute to the "IGS Ionosphere Service". The list of names will be provided by those IGS parties which intend to participate in the “ionosphere club”.

  From the ionosphere research community representatives will be

  Norbert Jakowski (DLR Neustrelitz),

  Reinhard Leitinger (TU Graz),

  and, as IGS Analysis Center Coordinator,

  Jan Kouba.

  Further participation will be called for through an IGS-mail message (see below).

- Chairperson:

The IGS Governing Board will appoint the first chairperson for the IGS Ionosphere Working Group.

- Announcement, call for participation:

The establishment of the IGS Ionosphere Working Group containing the Terms of Reference, the goals, the next steps, and the list of WG members is published through IGS mail. Further participation is sought in this message. The working group should not have more than 20 members.

- Time frame:

The IGS Ionosphere Working Group should be formally established at the IGS GB Meeting of May 28, 1998 in Boston. This implies that

- draft Terms of Reference for the IGS Ionosphere Working Group and

- draft IGS message containing information and a call for further participation

must be available not later than May 7, 1998 for distribution to the IGS Governing Board.

REFERENCES

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