THE IGLOS PILOT PROJECT – TRANSITIONING AN EXPERIMENT INTO AN OPERATIONAL SERVICE

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Abstract

With a constellation of 11 satellites as of December 2003, GLONASS provides a significant complement to the GPS constellation, providing opportunities for enhanced navigation and positioning accuracy, atmospheric modeling, time transfer, and earth orientation estimation. Since 1998, when the IGEX-98 campaign was conducted, there has been a continuously operating global network of GLONASS tracking stations. Subsequently, the IGS made some modifications to its operations to integrate GLONASS stations and GLONASS orbit computation into the IGS standard operations. Four organizations routinely compute precise GLONASS orbits, and combined orbits are generated as well. Time standardization, reference frames, RINEX file formats, and station logs are some of the areas that have been addressed to handle GLONASS and GPS in the same operations. This has been a very successful endeavor, although some problems still exist including delays in production of precise orbits, the uneven global distribution of stations, and uncertainty regarding the long-term viability of GLONASS.

Introduction

In 1998, the International GPS Service (IGS), the Institute of Navigation (ION), the International Association of Geodesy (IAG) and the International Earth Rotation Service (IERS) co-sponsored an experiment that served as a case study for an operational GNSS service. The experiment lasted for six months and essentially expanded the domain of the IGS to include GLONASS. By necessity, the experiment, called IGEX-98, had to address the interoperability, compatibility and operational issues associated with the combined GPS-GLONASS constellations. Since the beginning of IGEX-98, there has been a continuously operating global network of GLONASS tracking stations. Initially set up as a separate "appendage" to the IGS, the GLONASS tracking stations and data products have gradually been integrated into the mainstream IGS operations. This paper discusses the original motivation for IGEX-98, the critical elements that enabled the activity to proceed and succeed, the implementation of the follow-on IGS pilot project, and the transformation that has taken place to assimilate these activities into the normal IGS production scheme. The current state of the GLONASS constellation, tracking network, precise orbits and other data products is discussed. The implications for incorporating another GNSS in the form of Galileo are noted in conclusion.

International GLONASS Experiment (IGEX-98)

There were numerous reasons for initiating a worldwide GLONASS campaign in 1998. A sizeable constellation of satellites was already in place. GLONASS is very similar to GPS so in theory it should be relatively straightforward to modify existing GPS processing software to handle GLONASS data. Rather than view GLONASS as a separate system, the combined GPS-GLONASS systems would represent a significant augmentation to GPS alone. Whereas the GPS P-code was encrypted and available only to authorized users, the GLONASS P-code was open to anyone. GLONASS provided some geometric strength as well, with an orbital inclination of 65 degrees compared to 55 degrees for GPS. Dual-frequency geodetic-quality receivers that could simultaneously track all GLONASS and GPS satellites in view had become available. Both the scientific and navigation communities were interested in exploiting the combined systems. Potential benefits to these communities included real-time navigation and positioning (terrestrial, space), atmospheric monitoring and research, polar motion estimation, satellite integrity monitoring, and time transfer. Finally, the future of GLONASS was uncertain so there was some impetus to do the experiment then or perhaps never have the opportunity.

Motivated by these factors and a significant level of international interest, the IGEX-98 campaign was organized with the following objectives:

- Collect a globally-distributed GLONASS data set over a long time period, using dual-frequency GLONASS receivers collocated with receivers at GPS stations with known ITRF coordinates
- Compute precise orbits (1 meter or better)
- Evaluate receivers
- Develop processing software
- Compare PZ-90, ITRF and WGS-84 reference frames
- Facilitate timing and time transfer
- Stimulate other scientific applications.

The resulting campaign ran from 19 October 1998 to 10 April 1999 and employed 68 receivers at 61 tracking sites in 26 countries. Thirty satellite laser ranging stations in 15 countries also participated, taking advantage of the laser retro-reflectors installed on every GLONASS satellite. During this period, there were 13-14 operational GLONASS satellites. IGEX-98 accomplished a number of "firsts": (a) the first global tracking network for GLONASS, (b) the first extensive use of geodetic-quality dual-satellite receivers capable of tracking all satellites in view, (c) the first precise GLONASS orbits, (d) development of "quasi-production" data processing systems for handling both GPS and GLONASS observations, and (e) five independent determinations of the relationship between the Russian PZ-90 reference frame and WGS-84 and ITRF. [Slater et al., 2000; Weber and Slater, 2001]

IGEX-98 was a success because it was able to take advantage of the existing IGS infrastructure and new receiver technology, and to solve the interoperability issues with GPS. "Timing" also had a lot to do with the success of this project since a couple of years earlier adequate receivers were unavailable, while two years later, there was a marked decrease in the number of operational satellites in the constellation. Thus, the choice of the six-month period in 1998-99 proved to be very fortuitous.

Key Elements Required for Integrating GLONASS into IGS Operations

There were a number of critical elements required to meet the IGEX-98 objectives. Not surprisingly, the same elements were essential to converting the experimental system into a pilot operational system, and ultimately to integrating the GLONASS data processing into routine IGS operations. The key elements were:

- GPS knowledge base
- Receiver hardware and software
- Common geodetic reference frame
- Common time reference
- Standardized data formats
- Data communications and data distribution infrastructure
- Global tracking network
- Tracking station standards
- Data processing software
- Analysis Centers.

It would be hard to overestimate the value of the extensive GPS knowledge base and the existing IGS infrastructure in this endeavor. Most of the potential problems with GLONASS could be anticipated and solved in advance. Data structures, force modeling, and data transmittal protocols used for GPS were adapted to fit GLONASS. Data and documentation standards that had been implemented for GPS such as RINEX and SP3 data formats and station log forms were extended to handle GLONASS. Modifications were made where necessary to accommodate new standardized satellite designations, and receiver and antenna models. IGS procedures for sending GPS data from global tracking stations to regional and global data centers, as well as for storing and retrieving data products, were already in place and were applied to IGEX-98. Similarly, the participating Analysis Centers in IGEX-98 already had software for processing GPS observations and generating precise orbits, which they then modified to work with GLONASS data.

Although some single-frequency and limited dual-frequency GLONASS receivers were available prior to 1998, the introduction of the Ashtech Z18 and Javad Legacy dual-frequency, GPS+GLONASS receivers had a major impact on IGEX-98 and the follow-on pilot project. These receivers can track all satellites in view and output all the GLONASS observations time-tagged to GPS time. The availability of receivers facilitated the creation of the global station network, providing more balanced coverage of the satellites, and therefore more accurate computed orbits. Station coordinates were accurately determined in the ITRF reference frame using GPS. In this way, there was no dependence on the PZ-90 reference frame. The precise orbits were referenced to the ITRF.

The IGS GLONASS Pilot Project

Due to the success of IGEX-98 and the continuing interest of the participants, the IGS decided to set up a follow-on pilot project as a test case for a more permanent GLONASS service comparable to the GPS service. One of the major benefits of this has been to acquire a better understanding of the level of effort required to broaden the scope of the IGS to include multiple Global Navigation Satellite Systems in its routine operations. The International GLONASS Service Pilot Project (IGLOS) was officially started in February 2000. Its goals and objectives were similar to IGEX-98:

- Establish and maintain a global GLONASS tracking network
- Produce precise (10-cm level) orbits, satellite clock estimates and station coordinates
- Monitor and assess GLONASS system performance
- Investigate the use of GLONASS to improve Earth orientation parameters
- Improve atmospheric products of the IGS
- Fully integrate GLONASS into IGS products, operations and programs.

The new requirements for the IGLOS project were the inclusion of only dual-frequency GLONASS receivers, the application of IGS network operations standards, inclusion of SLR observations in the routine production of a combined Analysis Center precise orbit product, receipt of independent orbit, clock and station solutions from Analysis Centers within three weeks of observations, and calibration of GPS/GLONASS receivers and antennas. Much of the groundwork had already been laid during IGEX-98. However, during the four years from 2000-2004, the project has evolved considerably.

<u>GLONASS Constellation</u>

Satellite failures depleted the GLONASS constellation to as few as six satellites after IGEX-98 ended. Russia has launched new satellites annually in 2000, 2001, 2002 and 2003 to maintain the constellation, resulting in a total of 10 operational satellites as of February 2004. Only two of three specified orbit planes are populated with these satellites. The sparseness of satellites is a problem for orbit determination software that depends on double-differenced observations as a data type.

When used to augment the GPS constellation, the GLONASS satellites can significantly increase the overall number of visible satellites, improve satellite geometry and increase the amount of collectible observations. Figures 1a, 1b and 1c show sample visibility plots for three different IGLOS stations – Thule, Greenland, Capoterra, Italy, and Kourou, French Guyana – at 76°N, 39°N and 5°N latitudes, respectively. Each shows the GPS and GLONASS satellites in view and the combined GDOP for 20 February 2004 based on almanac data from 17 February 2004, with an elevation cutoff angle of 5 degrees. The plots include all GPS satellites and 10 active GLONASS satellites. As many as 16 satellites are visible for part of the day from each of the sites. In addition, a visibility plot is shown (figure 1d) for Mattersburg, Austria (47°N) to illustrate the contribution of the GLONASS satellites when obstructions are present up to 20-30° above the horizon. This is a situation typically encountered by surveyors in built-up or mountainous areas.

IGLOS Station Network

The IGLOS station network has been very stable and currently consists of 49 receivers at 47 sites. Thirty-two (33) of these receivers are Javad Positioning Systems equipment and the remainder (16) are Ashtech Z18s. These are all dual-frequency, combined GPS/GLONASS receivers. A map of the tracking network is shown in figure 2. To support the IGLOS project, the IGS changed its site information log form so that it can be applied to GNSS tracking stations rather than solely GPS tracking stations. It is clear from the IGEX-98 and IGLOS project that receiver manufacturers can produce geodetic-quality receivers that track multiple global navigation satellite systems when the signal characteristics are similar. There has been a concerted effort to calibrate the receiver antennas for the GPS frequencies, but a similar set of tests has not yet been carried out to characterize the antenna responses to the GLONASS frequencies.

Since the end of IGEX-98, the International Laser Ranging Service has continued to include three designated GLONASS satellites in its active list of satellites to track. The Russian Mission Control Center (MCC) uses these observations to produce an SLR-only orbit for those satellites.

Data Products

Four Analysis Centers support the IGLOS project – Bundesamt fuer Kartographie und Geodaesie (BKG), Center for Orbit Determination in Europe at the University of Berne (CODE), European Space Agency (ESA) and MCC. All produce precise orbits, although MCC's contribution is based solely on satellite laser ranging (SLR) data from those satellites observed by the ILRS. ESA performs a two-stage process with its GPSOBS/Bahn software. It first computes the precise GPS orbits and clock parameters and related products for the IGS. Then, using the GPS orbits and seven fixed stations to constrain the solution to the ITRF reference frame, ESA processes the GLONASS data as undifferenced observables. Its final GLONASS products are the daily orbit and clock solutions, and a SINEX file of station coordinates. BKG starts with the IGS GPS orbits and clock estimates, and Earth orientation parameters. It fixes the coordinates of seven stations to their ITRF values and then runs the Bernese software on double-differenced phase observations to produce precise GLONASS orbits on a daily basis.

The CODE Analysis Center has done the most to incorporate GLONASS observations into its routine orbit processing. CODE modified the Bernese software so that it can process combined GPS and GLONASS data at one time. Daily orbit estimates are generated for GLONASS, as well as a rapid orbit product. The GLONASS data also contribute to CODE's estimation of ionospheric and tropospheric parameters, and station coordinates. The CODE production operation is the most complete attempt to

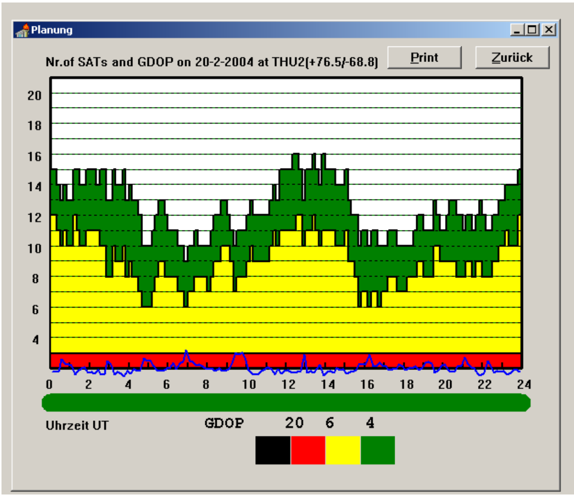

Figure 1a. Satellite visibility and GDOP in Thule, Greenland (yellow=GPS, green=GLONASS, blue=GDOP).

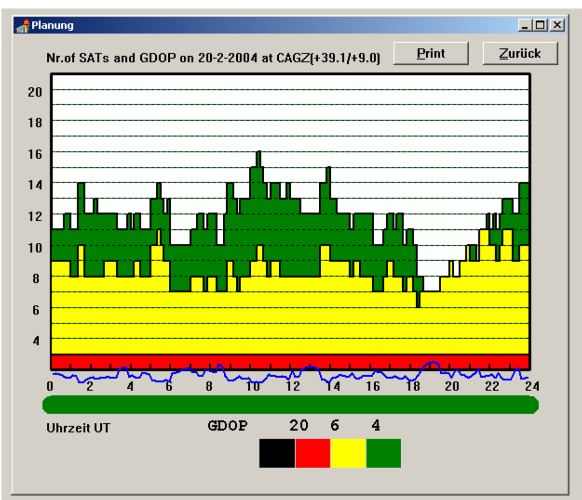

Figure 1b. Satellite visibility and GDOP in Capoterra, Italy (yellow=GPS, green=GLONASS, blue=GDOP).

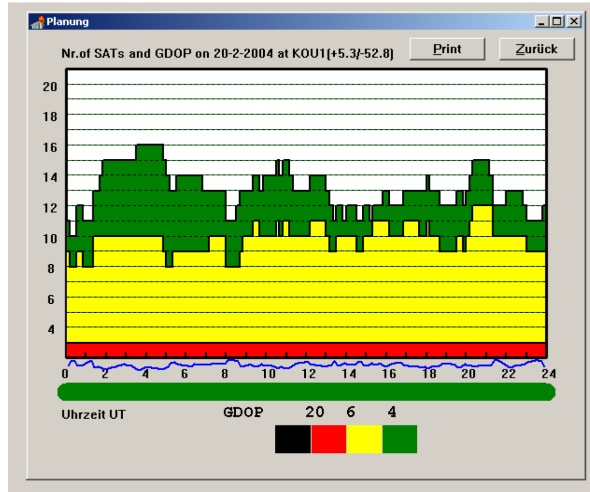

Figure 1c. Satellite visibility and GDOP in Kourou, French Guyana (yellow=GPS, green=GLONASS, blue=GDOP).

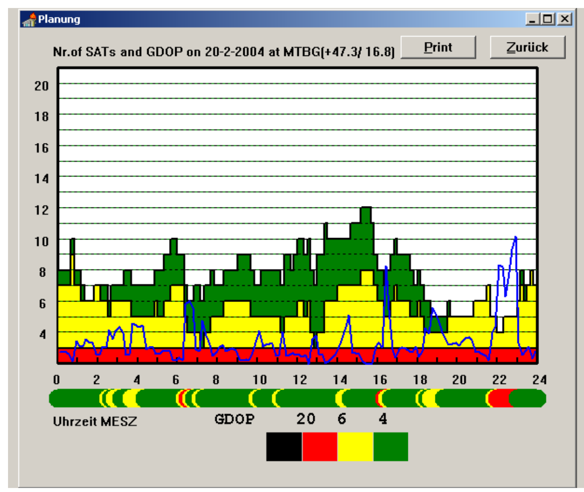

Figure 1d. Satellite visibility and GDOP in Mattersburg, Austria (yellow=GPS, green=GLONASS, blue=GDOP).

integrate GLONASS and GPS data into one processing scheme and to achieve potential improvements in other data products from the addition of the second satellite system's data.

After all the precise orbits are submitted by the four Analysis Centers, a combined orbit is computed in a procedure similar to the one used for the combined GPS orbits. Except for the CODE Analysis Center, there has historically been a considerable delay in obtaining the precise orbits from the other centers, thus

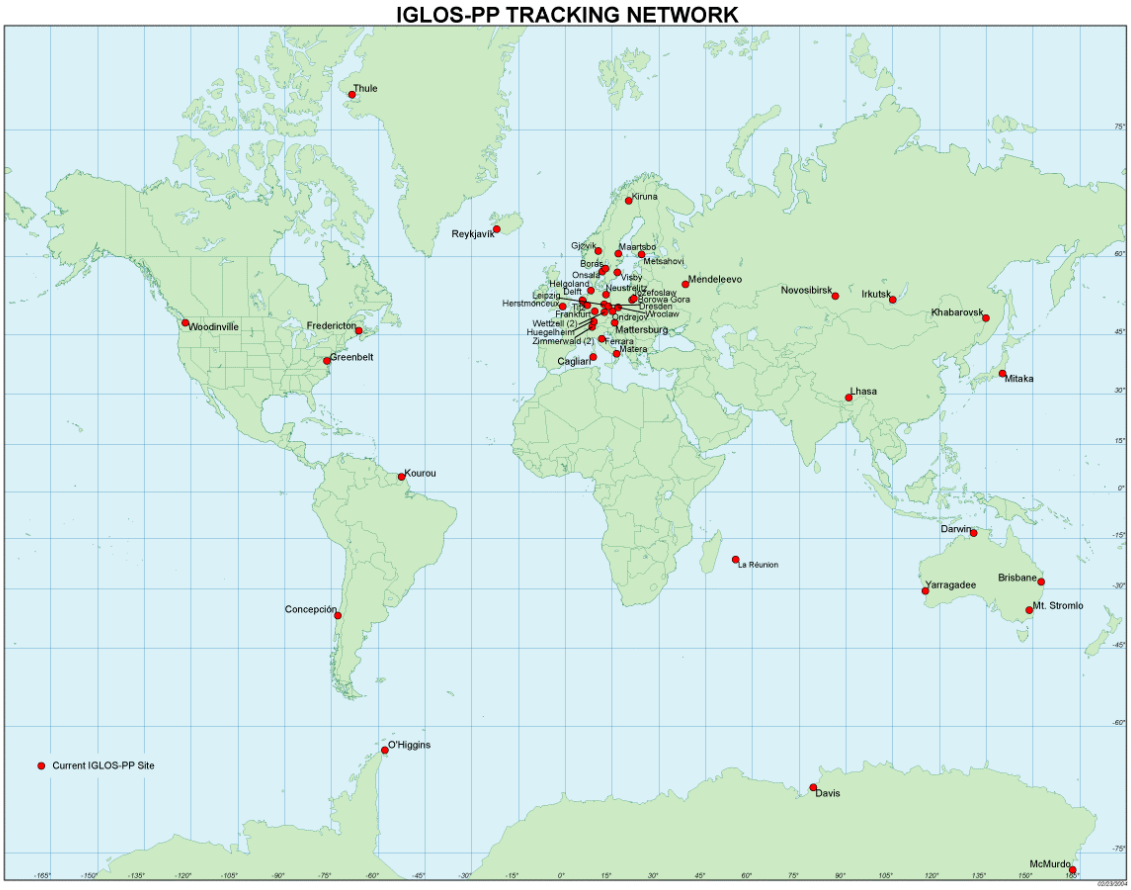

Figure 2. IGLOS tracking station network (February 2004).

delaying generation of the combined orbits. However, the responsiveness of ESA and BKG has improved greatly in recent weeks, which if it continues, will improve the currency of the combined orbits. During IGEX-98, the Analysis Center solutions were consistent at the 20-30 cm level. This accuracy was maintained during the IGLOS project. In June 2003, CODE began producing improved orbits at the decimeter level. The quality of the current GLONASS precise orbits is shown in Table 1. The table gives the RMS residuals for 7-day long arcs fitted to each set of daily orbits submitted by the four analysis centers for eight satellites in GPS Week 1253. Except for one poorly performing satellite (slot 18/plane 3), the fit residuals for BKG, CODE and ESA are all between 4 and 10 cm. The MCC residuals are available only for the three satellites with laser ranging data. The relative performance of the BKG, ESA and MCC orbits compared to the CODE orbits is shown graphically in Figures 3a-3f for GLONASS satellites in slots 3 and 22 for GPS Week 1253. Radial, along-track and across-track components are displayed separately and show the consistency of the orbits produced at the Analysis Centers.

IGLOS Product Usage

Since the GLONASS observations are included with the GPS observations in the RINEX observation files from the Ashtech and Javad receivers, it is not possible to tell which users are retrieving the observation data for GLONASS applications. We can, however, get a rough idea of the users of GLONASS products (e.g., precise orbits) from the records of files downloaded from the NASA CDDIS Global Data Center. Table 2 gives the list of countries and institutional affiliations of this user community for the calendar year 2003. (The IGLOS Analysis Centers have been removed from this tabulation.) Ignoring a one-time download by one user in the United Kingdom, Russia was the biggest user. Twenty-one countries are represented.

Table 1. GLONASS Long Arc (7-day) Residual RMS for Fits to Daily Orbits in GPS Week 1253
(units in centimetres)

Satellite	BKG	CODE	ESA	MCC
Slot 3 / Plane 1	4	10	5	8
Slot 5 / Plane 1	8	10	9	---
Slot 17 / Plane 3	4	6	6	---
Slot 18 / Plane 3	24	19	19	---
Slot 21 / Plane 3	6	9	5	---
Slot 22 / Plane 3	6	6	4	25
Slot 23 / Plane 3	6	6	6	---
Slot 24 / Plane 3	6	6	6	36

Conclusions

If IGEX-98 is considered as a proof-of-concept experiment, IGLOS represents the operational implementation of this concept. The IGLOS pilot project sponsored by the IGS has proven that it is possible to integrate two Global Navigation Satellite Systems, GLONASS and GPS, into a single operational framework. This required some (not insignificant) retooling of GPS data processing software at the IGS Analysis Centers, some relatively minor modifications to GPS data formats, and the application of IGS standards to the incorporation of GLONASS receivers and data in the tracking network and at the data centers. Standardization of data formats, tracking stations, communications protocols and data management, developed over the years by IGS for its GPS operations, was critical to the success of this project. Receiver manufacturers showed that they could produce geodetic-quality equipment and firmware that tracked the two constellations and output the data relative to a single time reference in a standard format. This was certainly helped by the similar characteristics of the GPS and GLONASS broadcast signals. The IGLOS tracking network, now employing exclusively the combined GPS/GLONASS receivers from Ashtech and Javad, has been very stable during the last few years, although there is a very uneven distribution of sites worldwide. Europe has an over-concentration of receivers, while Africa has none, and North and South America and Asia have only a few each. Co-locating the combined GPS-GLONASS receivers at IGS stations tied them to the ITRF reference frame and thereby defined the reference frame for GLONASS products. This solved the reference frame compatibility issue for the IGLOS data processing. However, the broadcast orbits from the GLONASS satellites remain in the PZ-90 reference frame, so predicted orbits based on these still require transformation to ITRF or WGS-84 for compatibility with GPS. For the case when the constellation is sparse, i.e. in the build-up phase or in a depleted state, the use of undifferenced observables rather than double-differenced data in orbit production considerably increases the number of observations available for processing. It also allows as a by-product the direct estimation of satellite clock parameters.

When combined with GPS, even the current 10-satellite GLONASS constellation increases the number of visible satellites to 16 during parts of the day at some sites. In locations where buildings or terrain obstruct lower elevation satellite visibility, the extra satellites can improve satellite geometry for surveying applications. Additional satellites should benefit some IGS products, but the additional data are also an extra burden for the network operations, Analysis Centers and the Data Centers. The data management problem will have to be addressed to ensure that throughput, archiving and retrieval keep up with the data volume.

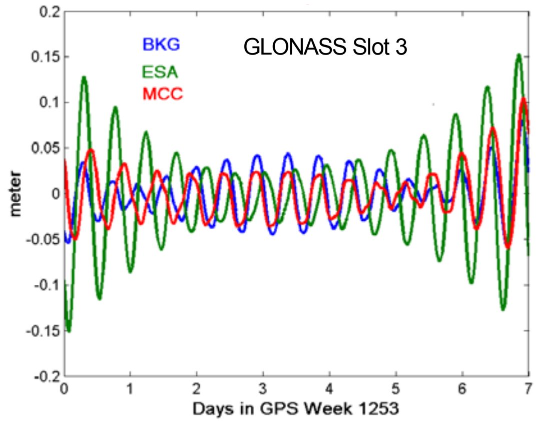

Figure 3a. Radial component with respect to CODE orbit.

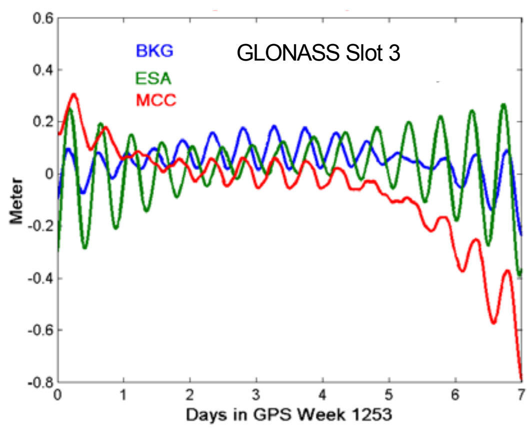

Figure 3b. Along-track component with respect to CODE orbit.

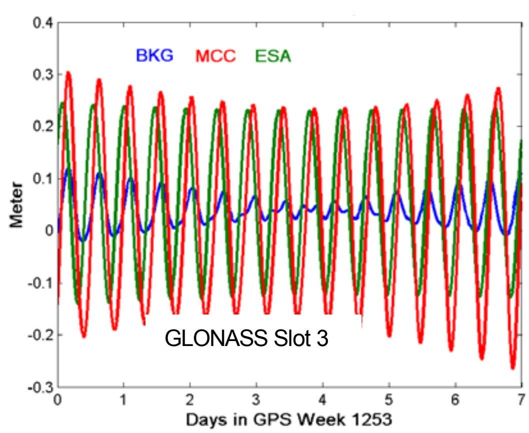

Figure 3c. Across-track component with respect to CODE orbit.

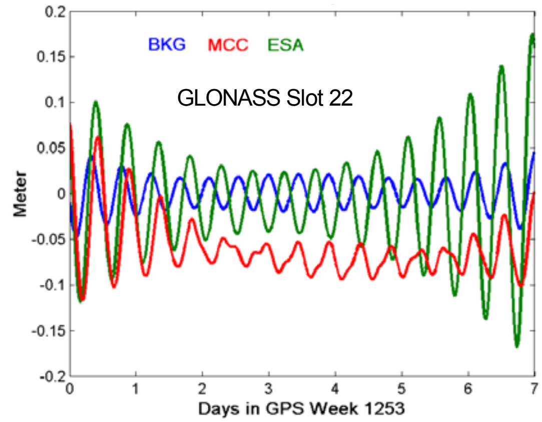

Figure 3d. Radial component with respect to CODE Orbit.

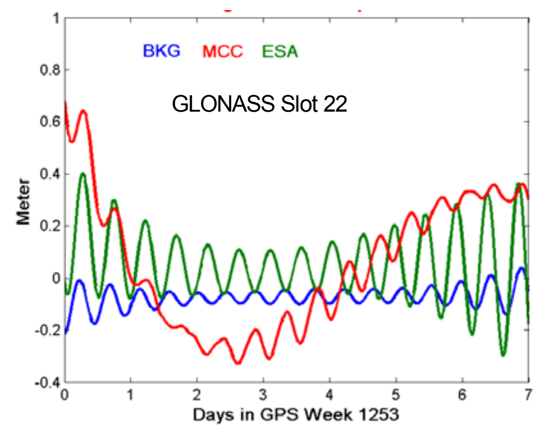

Figure 3e. Along-track component with respect to CODE orbit.

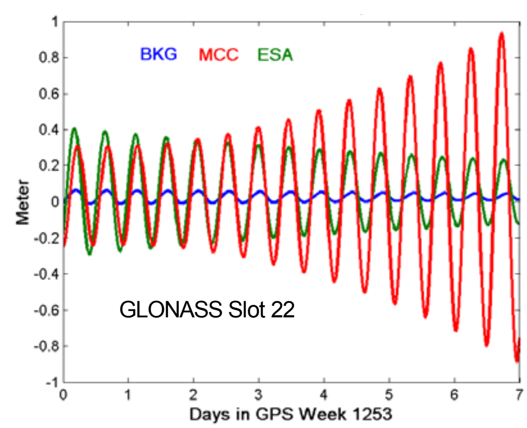

Figure 3f. Across-track component with respect to CODE orbit.

Table 2. Users of GLONASS Data Products (2003)

Country	Institutional Category*	No. of Files	Country	Institutional Category	No. of Files
Algeria	Education	10	Poland	Network	1
Argentina	Education	5	Portugal	Education	1
Argentina	Network	4	Russia	Commercial	1,360
Australia	Government	1	Russia	Education	298
China	Network	54	Russia	Government	4
Czech Republic	Education	1	Russia	Network	2,035
France	Commercial	1	South Korea	Education	3
France	Network	80	Spain	Commercial	26
Germany	Commercial	1	Spain	Education	1
Germany	Education	4	Spain	Network	33
Iran	Network	14	Sweden	Education	8
Italy	Commercial	1	U.S.	Commercial	38
Italy	Education	87	U.S.	Education	26
Italy	Network	4	U.S.	Government	318
Japan	Commercial	7	United Kingdom	Commercial	8
Norway	Education	6	United Kingdom	Government	8,615**
Peru	Network	2	Yugoslavia	Commercial	1

*"Network" implies an internet service provider such as AOL or MSN.
**This was a one-time download of files by one user.

During the last eight months, the CODE Analysis Center has demonstrated that total integration of the two independent GNSS's is possible in the data processing, given the level of integration already achieved in the IGS network operations. GLONASS orbits are being generated at decimeter level accuracies. Ionospheric, tropospheric, Earth orientation and other products are being produced from the combined GPS and GLONASS data.

Thus, the key objectives of the IGLOS Pilot Project have been accomplished. Unfortunately, there is still uncertainty about the long-term viability of GLONASS and this has limited its use in the scientific and navigation communities. Despite this, the lessons learned from the IGLOS project will make the road to Galileo much smoother.

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