IGEX-98

IGS

SESSION 3

NETWORK OPERATIONS

The IGEX Network and Data Processing Organization

Werner Gurtner
Astronomical Institute, University of Berne
Sidlerstrasse 5, CH-3012 Berne, Switzerland

Abstract

The IGEX-98 GLONASS campaign was organized similar to the initial IGS campaign in 1992. Its major components were the network of tracking sites, data centers collecting and redistributing the daily data files, analysis centers for the primary products, additional centers for special investigations and information distribution through e-mail, ftp areas and web pages. The tracking network operated following the guidelines prepared and made available by the campaign steering committee well before the campaign. The major problems concerned the initial difficulties with the number, distribution, and proper functioning of the (dual-frequency) receivers. The extensive support of the campaign by the international laser tracking network (9 satellites were tracked by SLR) provided an excellent opportunity for an independent verification of the computed orbits. An analysis coordinator was elected to cross check the primary products of the analysis centers and to generate combined products if possible.

Introduction

The experiences gathered by the International GPS Service (IGS) during its initial three months campaign in 1992, the subsequent pilot phase and finally the operational service were the basis for the organizational aspects of the IGEX-98 campaign. The major components of the IGEX-98 campaign network consisted of

- The tracking network
- Operational Centers
- Data Centers
- Analysis Centers
- Evaluation Centers
- Coordinators (Data Flow, Network, Analysis)
- Information Exchange Procedures

In addition to the GPS/GLONASS microwave tracking network the International Laser Ranging Service (ILRS) contributed significantly to the success of IGEX-98 by agreeing to extend its tracking list of satellites during the campaign from originally three GLONASS satellites to nine.

In this paper we will concentrate on the tracking network organization, the interface with ILRS and the data preprocessing part.

The Tracking Network

The most important aspects to consider when a tracking network for such a campaign has to be planned are:

- Distribution of receivers
  - Global distribution vs. regional distribution (e.g., Europe only)
  - Balance between northern and southern hemisphere
  - Isolated receivers: No or few common observations with other sites
- Receiver types
  - GPS, GLONASS, combined GPS/GLONASS
  - Code only, code and carrier phase
  - Single-frequency, dual-frequency
- Data exchange formats
- Data flow and latencies
- Information flow

Receiver Distribution

One of the primary goals of the campaign was the computation of GLONASS orbits and to find out the limits and limiting factors for the accuracy of such orbits. Experiences from IGS showed that the better the global distribution and coverage the better the orbits will be. Therefore the call for participation was distributed worldwide with an emphasis on global coverage.

Potential sites in the southern hemisphere were Australia (AUSLIG) and Antarctica (USGS).

Isolated single receivers, or receivers that don't have common observations with other receivers to two or more satellites are of no use for precise orbit computation using carrier phase observations only. Isolated receiver clusters may be of use if at least one of the sites is precisely known in the currently used reference frame (ITRF).

Receiver Types

Major contributors to improved accuracies of orbits and positions are

- the second frequency to allow the elimination of the ionospheric refraction and
- the carrier phase observations with an expected accuracy of about 1 percent of the carrier wavelength (20 cm --> a few mm)

In consequence the highest priority was put to receivers with dual-frequency code and carrier phase observations.

Unfortunately no dual-frequency carrier phase receivers for both GPS and GLONASS were available on the market when the call for participation was issued. In order to guarantee at least a limited success also other receivers were taken into consideration:

· Dual-frequency GLONASS, single frequency GPS receivers (e.g., 3S Navigation receivers)
· Single-frequency GPS/GLONASS receivers (e.g., Ashtech GG24). In this case it was recommended to have a dual-frequency GPS receiver operating on the same site to allow for an easier computation of ionospheric corrections.

At the start of the campaign a first batch of dual-frequency 18-channel Ashtech Z18 became ready and operational, and shortly afterwards the first Javad JPS Legacy 20-channel dual-frequency receivers were announced and installed at a number of IGEX stations. Finally, on a typical day in mid-March 1999 we had the receivers shown in Table 1 operating.

Table 1. Receivers Used by IGEX Stations in March 1999

Receiver	Number	Type
Ashtech Z18	17	GPS+GLONASS, L1+L2
JPS Legacy	5	GPS+GLONASS, L1+L2
ESA/ISN GNSS	1	GPS+GLONASS, L1+L2
3S Navigation R100	14	GPS L1, GLONASS L1+L2
Ashtech GG24	8	GPS+GLONASS, L1
MAN NR-R124	3	GPS+GLONASS, L1
Trimble 4000SGL	1	GLONASS L1
Total	49	

The total number of GPS/GLONASS or GLONASS receivers submitting data for at least part of the campaign was about 70 on 60 different sites.

Data Exchange Formats

<u>Observation Data</u>

RINEX Format

The RINEX Version 2 Receiver-Independent Exchange format, defined in 1990, was already prepared to deal with observations of other satellite systems, too. Early in 1997, after first experiences with geodetic GPS post-processing programs having been modified to process GLONASS observations, too, it became obvious that some small modifications to the original RINEX version 2 definitions had to be done. In discussions with various groups involved in such computations, a GLONASS navigation message file format was generated. Another small format modification was performed in April 1998.

So, when the guidelines for the IGEX-98 were discussed, it was obvious to specify the enhanced RINEX version 2 format as the data exchange format for IGEX-98.

During the second half of 1998 we spent quite some time checking the RINEX files generated by a number of different conversion programs for format compliance and discussing with the software authors the necessary modifications.

Ultimately, about 20 different RINEX converter programs and versions were used.

Table 2. List of RINEX Converter Programs Used to Generate IGEX-98 RINEX Files

ASH_NAV
ASRINEXO V2.9.1 LH
ASRINEXO V2.9.3 LH
ASRINEXO V2.9.3 VM
ASRINEXO V2.9.3 UX
DAYISN2
DAT2RIN 1.01c
GBSS
GEOTRACER GPS Decode
GNSSDatalogger 1.1
GNSSDatalogger 1.2
GN-RINEX 1.0
GPSBASE RINEX CONV.
JPS2RIN 1.00
JPS2RNX v 1.1000
Pinnacle 1.00
S3_RNX
teqc 1999Mar2
TerraSat GeoGenius G
3SRINEXO V3.8
3SRINEXO V4.2

Standard Receiver and Antenna Names

In order to simplify the automated processing and to improve the reliability of the data, standard names for the various GLONASS receivers and antennas used in the IGEX-98 campaign (and not yet known in the respective IGS Tables) have been defined and made available in a text file (http://lareg.ensg.ign.fr/IGEX/ix_recvr.txt). See Table 3.

Table 3. IGEX-98 GPS/GLONASS Receivers and Antennas, December 11, 1998

ASHTECH Receivers	**Description**
ASHTECH xxxxxxxx	xxxxxxxx is the receiver type to be found in the
	receiver-generated S-file, e.g.
	ASHTECH GG24C or ASHTECH Z18

ASHTECH Antennas	**Description**
GPS/GLN KINEMATIC L1	GPS/GLONASS Kinematic L1 (AeroAntenna Techn. Inc)
701073	Dorne Margolin, chokering, GPS/GLONASS
701073 RADOME	Dorne Margolin, chokering, GPS/GLONASS, with radome
700699 L1	700699B_Mar.III_L1

3SNavigation Receivers	**Description**
3SNAV R100 OLD	L1 C/A GPS/GLONASS, 12 ch
3SNAV R101 OLD	L1, L2 C/A and P GLONASS, 4 ch
3SNAV R100-30	L1/L2 C/A and P GLONASS, 2 ch
3SNAV R100-30T	L1/L2 C/A and P GLONASS, 2 ch
L1 C/A GPS/GLONASS, 12 ch	
3SNAV R100-40	L1/L2 C/A and P GLONASS, 4 ch
3SNAV R100-40T	L1/L2 C/A and P GLONASS, 4 ch
	L1 C/A GPS/GLONASS, 12 ch
	All R100: Additional P code GLONASS channels
	available up to total of 12
3SNAV GNSS-300	L1 C/A GPS/GLONASS, 12 ch

3SNavigation Antennas	**Description**
D-MARGOLIN 3S W/O CR	Dorne Margolin without chokering
D-MARGOLIN 3S CR	Dorne Margolin with chokering
M/ACOM 3S	M/Acom helix
TECOM 3S W/O CR	Tecom helix without chokering
TECOM 3S CR	Tecom helix with chokering
AERO 3S W/O CR	Aeroantenna without chokering
AERO 3S CR	Aeroantenna with chokering
TSA-100 3S CR	D.M. chokering, temperature stabilized preamplifier

JAVAD Receivers	**Description**
JPS LEGACY GGD	GPS/GLONASS dual- frequency receiver
JPS LEGACY GG	GPS/GLONASS single-frequency receiver
JPS REGENCY-1 GG	GPS/GLN sngl-freq rcvr with sngl-depth ChR antenna
JPS REGENCY-1 GGD	GPS/GLN dual-freq rcvr with sngl-depth ChR antenna
JPS REGENCY-2 GGD	GPS/GLN dual-freq rcvr with dual-depth ChR antenna

Table 3. (Cont'd)

JAVAD Antennas	Description
JPS LEGANT	Antenna on flat ground plane
JPS REGANT SD	Single-depth choke ring antenna
JPS REGANT DD	Dual -depth choke ring antenna
JPS REGANT-1 SD	Single-depth ChR antenna integrated into Regency-1
JPS REGANT-2 DD	Dual -depth ChR antenna integrated into Regency-2

Antenna Reference Points

To avoid ambiguities in the antenna heights we defined physical reference points for a number of antennae not included in the respective IGS diagrams (see http://lareg.ensg.ign.fr/IGEX/ix_recvr.txt).

Generated Orbits

The format of the orbits generated by the various analysis centers has been decided to be SP3, following of course the guidelines defined and used by the IGS wherever possible.

However, the SP3 as used by IGS did not yet have all necessary extensions to deal with GLONASS satellites. In cooperation with the original author of the SP3 format, Dr. Ben Remondi, the GLONASS modifications have been defined and distributed through IGEXMail #0039.

The original description of the SP3 format can be found at ftp://igscb.jpl.nasa.gov/igscb/data/format/sp3_docu.txt.

Positions and Velocities

The exchange format for resulting three-dimensional positions (and velocities if appropriate) is the Solution-Independent Exchange Format (SINEX), (e.g., see ftp://igscb.jpl.nasa.gov/igscb/data/format/sinex.txt.

Data Flow and Latencies

There is a separate paper about data flow issues by Carey Noll, NASA/GSFC/CDDIS, so only a few general remarks shall be made here:

Among the IGEX-98 tracking stations many IGS sites can be found. Most of the data centers perform the same task for IGS, too. In order not to jeopardize the routine IGS operation we specified a separate data flow for IGEX data. No data of GLONASS or GPS/GLONASS receivers shows up in the official IGS directories at the Data Centers.

The requirements for data latency were not critical because the analysis centers were not requested to provide products within a few days only. Even a delay of a week could have been accepted; we specified 48 hours as goal.

The data flow from the stations to the global data centers has been specified in a separate document (see http://lareg.ensg.ign.fr/IGEX/ix_dflow.txt).

Operational Aspects

Guidelines for IGEX Tracking Stations

In order to guarantee a smooth operation specific guidelines for tracking stations and data centers have been prepared and distributed, available at:

http://lareg.ensg.ign.fr/IGEX/ix_guide.html
http://lareg.ensg.ign.fr/IGEX/ix_datac.html

The guidelines for stations regulate the following issues:

- Connection to ITRF
- Station identification (4-char acronym, DOMES number)
- Station description using special IGEX site log
- Receiver and antenna naming
- Antenna height definitions and measurement
- Sampling rate (30 s), time tags (GPS time)
- RINEX file contents and file naming, compression schemes
- Maximum latency (48 hours)
- Local ties
- Reporting of changes during campaign

A checklist for IGEX stations is also included in the guidelines.

Site Log Files

In order to guarantee a uniform station description and an easy way to report any changes on the site during the campaign, we decided to use a site log form similar to the one used by IGS. In fact we just modified the IGS site where necessary to allow for GLONASS and GPS/GLONASS receivers and added a paragraph to record events that might influence the computed position of the GPS/GLONASS marker.

A blank form of the site log is available at http://lareg.ensg.ign.fr/IGEX/ix_blank.txt.
All the site logs were made available at the IGN ftp server (ftp://lareg.ensg.ign.fr/pub/igex/).

Information Flow

The flow of information within the tracking network but also among all participants and further individuals interested in the IGEX activities occurred mainly using electronic media, namely

- direct e-mail between two parties
- IGEXMail exploder set up at IGN similar to the IGS, EUREF and SLR Mail exploders, allowing easy distribution of mails by individuals to all IGEX addressees
- An IGEX web site set up by the Institut Géographique National (IGN), France (http://lareg.ensg.ign.fr/IGEX) with links to its ftp server (ftp://lareg.ensg.ign.fr).
- IGEX pages linked through the ION web site (www.ion.org) set up by the National Imagery and Mapping Agency (NIMA), USA (http://164.214.2.59/GandG/ion/index.htm)

The IGEXMails were mainly used to announce new stations and configuration changes on existing stations and to distribute weekly summary reports of data holdings at the Data Centers and of the data analyses performed by several IGEX Analysis Centers.

All the IGEXMails are available at the IGEX web site at IGN, France.

SLR Tracking of the GLONASS Satellites

All of the GLONASS satellites are equipped with corner cubes for laser tracking. A few years ago the global satellite laser tracking network included three GLONASS satellites into its list of satellites on a low tracking priority. In order to have a possibility to determine GLONASS orbits completely independently for a larger number of satellites, the IGEX Steering Committee proposed to the CSTG SLR Subcommission Steering Committee to extend GLONASS tracking to nine satellites (three in each one of its three orbital planes) for the three-month duration of the campaign, and to assign the GLONASS satellites a higher tracking priority. This request was granted at the end of August 1998 (SLRMail #0149). The Governing Board of the International Laser Tracking Service (the new organization of the global laser tracking network) agreed in January 1999 to extend GLONASS tracking until the newly assigned end of the IGEX-98 campaign, April 19, 1999.

In addition the Russian Space Agency was asked for permission to observe these satellites by laser tracking. The permission was granted on August 10, 1998 through an e-mail message from Prof. Shargorodsky, Space Device Engineering Corporation, Moscow:

```
From: SMTP%"natali@ricimi.msk.su" 10-AUG-1998 12:18:09.30
To:   gurtner@ubeclu.unibe.ch
Subj: Permission for GLONASS SLR tracking

To: Dr. Werner Gurtner
Steering Committee IGEX98 Campaign
Astronomical Institute
University of Berne

From: Prof.Shargorodsky
Space Device Engineering Corporation Moscow

IGEX98 campaign: GLONASS SLR Tracking Permission
************************************************

Dear Dr.Gurtner,

I addressed to the authorities of Russian Space Agency with your
appeal: "IGEX98 campaign: GLONASS SLR Tracking Permission" and
received the permission for Laser Tracing of ALL operating
GLONASS satellites by Global SLR Network during a first woldwide
observation campaign for mixed GPS and GLONASS receivers
(IGEX98).

You can consider this email as Official Permission to our
inquiry.

Best regards

Victor Shargorodsky
```

The official values for the coordinates of the corner cube arrays on the satellites were provided by Sergey Revnivykh and Vladimir Mitrikas, GEO-ZUP Company on behalf of NPO PM and the Russian Space Agency through IGEXMail #0086 on November 23, 1998.

The following satellites shown in Table 4 were tracked by SLR during the IGEX campaign.

Table 4. Satellites Tracked by Laser Ranging During IGEX-98

Slot	Plane	SLR name	COSPAR number
3	1	Glonass 68	9407601
4	1	Glonass 70	9407603
6	1	Glonass 69	9407602
9	2	Glonass 79	9506803
12	2	Glonass 65	9405001
16	2	Glonass 66	9405002
17	3	Glonass 62	9402101
20	3	Glonass 71	9500901
22	3	Glonass 72	9500902

Table 5 shows the total number of passes observed by the SLR tracking sites during the official duration of the IGEX-98 campaign for one of the nine satellites.

Table 5. Number of GLONASS-70 (Slot 4) Passes Observed by SLR Stations

GLONASS IGEX Campaign
19-OCT-98 - 18-APR-99

Station	Pad ID	Number of Passes
AUSLAS	7839	64
BEJLAS	7249	7
CHALAS	7237	34
CHILAS	7837	20
GFZLAS	7836	12
GRASLLR	7845	64
HOLLAS	7210	26
Kashima	7335	2
Koganei	7328	4
Kunming	7820	5
MD2LAS	1864	6
MLRS	7080	27
MOBLAS-4	7110	128
MOBLAS-5	7090	121
MOBLAS-7	7105	49
MOBLAS-8	7124	16
ORRORAL	7843	3
POLLAS	7811	5
RGOLAS	7840	52
STROMLO	7849	65
Tateyama	7339	4
WLRS01	8834	34
WUHLAS	7236	4
ZIMLAT	7810	34

After the official end of the campaign on April 19, 1999 the SLR tracking network continued GLONASS tracking with a reduced list of satellites (SLRMail #313). See Table 6.

Table 6. Satellites Tracked by SLR After the Official End of IGEX-98

Slot	Plane	SLR name	COSPAR number
4	1	Glonass 70	9407603
9	2	Glonass 79	9506803
22	3	Glonass 72	9500902

Data Processing

Often the raw data of large GPS campaigns are collected by a number of special preprocessing centers where they are checked, supplemented with auxiliary data, converted to RINEX and made available to the Analysis Center(s). However, the scientific goals (see http://lareg.ensg.ign.fr/ IGEX/goals.html) stated that *"The campaign duration of three months is intended to simulate an operational environment, i.e., observations, data transfer, and data analysis have to be performed in a service-like manner (as opposed to a campaign-oriented strategy)."* Therefore such a data preprocessing step was omitted, the data had to be prepared by the tracking stations themselves (or, in the case where several stations were under the responsibility of one agency, this step could be done by this agency only, what IGS calls an *Operational Center*).

The tracking data made available through anonymous ftp servers at the IGEX *Data Centers* were analyzed by various *Analysis Centers*.

An *Analysis Coordinator* cross-compared the primary products, (i.e., the precise GLONASS orbits, and generated a combined IGEX orbit product). The comparisons included also SLR-only orbits. This activity was done under the label *Evaluation Center* as defined in the IGEX-98 call for participation.

Separate papers and reports about the data processing were presented at the IGEX-98 workshop.

IGEX-98 Data Flow

Carey E. Noll
NASA Goddard Space Flight Center
Code 920.1, Greenbelt, MD 20771, USA

Abstract

The International GLONASS Experiment (IGEX-98) was organized to conduct the first global GLONASS observation campaign for geodetic and geodynamics applications. During the initial planning phases, it was decided to utilize, as much as was feasible, the existing infrastructure of the International GPS Service (IGS), which has been operational for nearly five years. This paper discusses the data flow utilized for IGEX-98, data latency, and the various problems that were found and their impact on the service as a whole.

Introduction

The infrastructure created to support the International GLONASS Experiment (IGEX-98) was modeled after that of the International GPS Service (IGS), thus allowing for a logical, efficient flow of data and information. In fact, many of the participants in IGEX-98 were active contributors to the IGS. A hierarchy of data centers, similar to that used in the IGS, was established to promote reduction in data traffic over electronic networks as well as allowing for redundancy and backup of data holdings. A web site (*http://lareg.ensg.ign.fr/IGEX*) was established early in the planning process to facilitate communication, particularly in the dissemination of standards for stations and data centers.

Participation Summary

The overall participation in the IGEX-98 was greater than expected. Although the official IGEX-98 campaign ran from October 19, 1998 through April 19, 1999, the transmission of data began in late August 1998 and continues to this day. During the 182 days of the campaign, 74 receivers at 62 sites sent data to the IGEX data centers. This figure includes 47 dual-frequency and 20 single-frequency GPS+GLONASS receivers and seven GPS-only receivers (for ITRF collocation purposes). Furthermore, thirty SLR stations tracked eighteen GLONASS satellites during the actual experiment time frame. Nearly 6500 passes and 37K normal points were archived for the six-month period. Detailed listings of these data holdings can be found in (Noll and Dube, 1999). At this time, approximately 35 GLONASS receivers continue to operate and send data to the data centers; the global SLR network also continues to track a subset of GLONASS satellites. The tracking station network supporting IGEX-98 during the campaign period and today is shown in Figure 1.

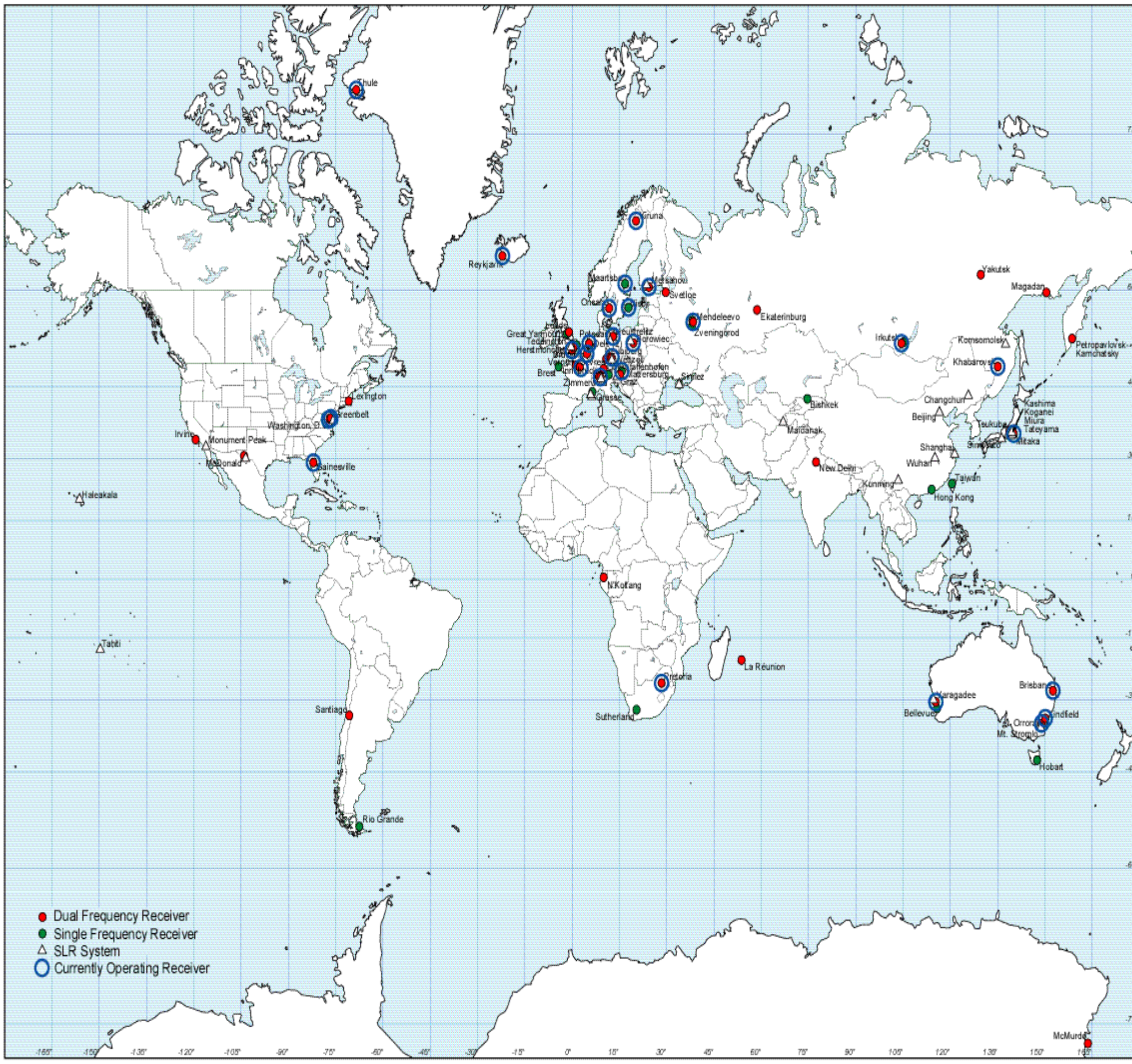


Figure 1. IGEX-98 Network.

IGEX Data Centers and Data Flow

Data centers supporting the IGEX-98 were divided into three categories (as in the IGS): operational, regional, and global. Operational Data Centers were responsible for connecting to the tracking station on a daily basis through automated procedures, downloading the daily file, converting the raw receiver data to RINEX, providing an initial check of the quality of the data, and then transmitting these data to regional or Global Data Centers. This check of data quality should also ensure that the station's data prescribes to published standards for RINEX, information in the header agrees with the site log on file, and that the data are readable. Regional Data Centers gathered data from sites in a particular region (e.g., Europe and Australia), and forwarded selected data then to a Global Data Center. Global Data Centers provided access to IGEX data and products to the Analysis Centers and the user community in general. The major data centers that proposed and participated in the IGEX-98 are listed in Table 1.

Table 1. Principle IGEX-98 Data Centers

Acronym	Full Name	Type
AUSLIG	Australian Land Survey and Information Group, Australia	Operational, Regional
BKG	Bundesamt für Kartographie und Geodäsie (BKG), Germany	Operational, Regional
CDDIS	Crustal Dynamics Data Information System, USA	Global
DLR	Deutsches Zentrum für Luft-und Raumfahrt, Germany	Operational
ESA/ESOC	European Space Agency Space Operations Center, Germany	Operational
GFZ	GeoForschungsZentrum Potsdam (GFZ), Germany	Operational
IGN	Institut Geographique National, France	Global
NCKU	Satellite Geoinformatics Research Center, Taiwan	Operational

A general overview of the flow of IGEX data and information is shown in the diagram in Figure 2. As can be seen from this figure, the Global Data Centers were the prime source of IGEX data and products for the user community. Figure 3 represents the data flow on a site and data center basis. Here it is evident that many institutions were involved in the download of data from the network of over seventy receivers.

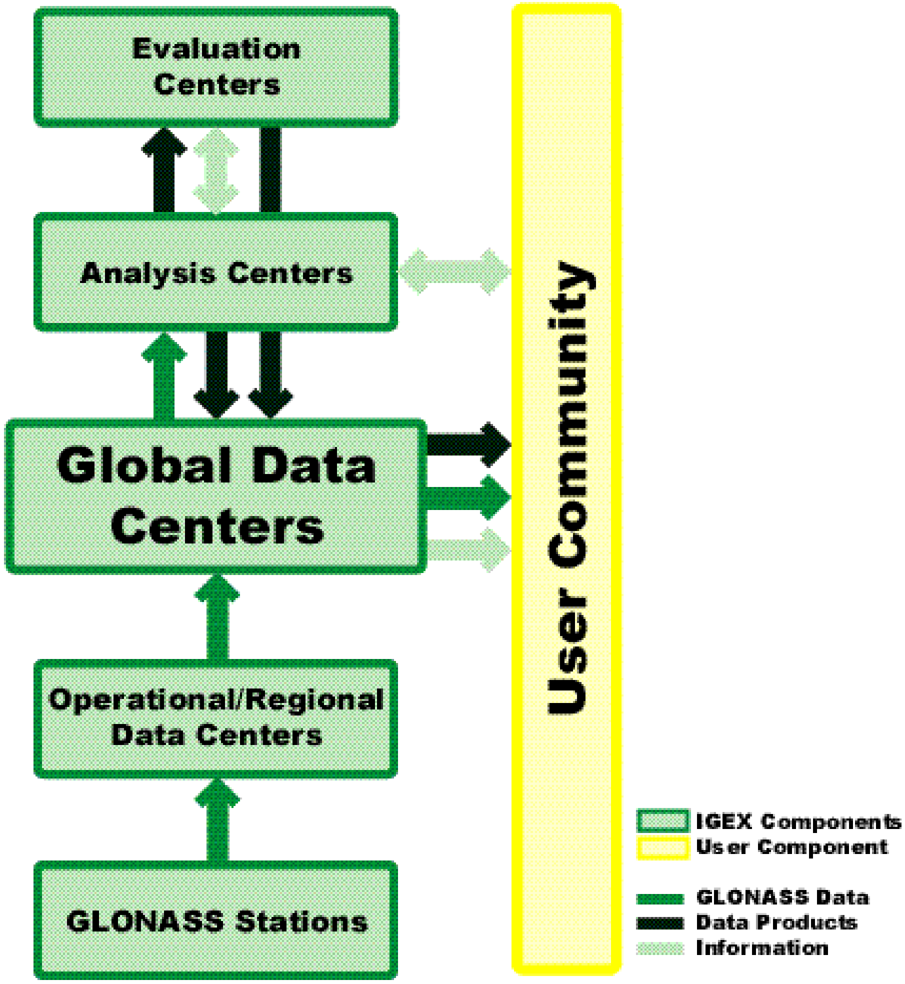
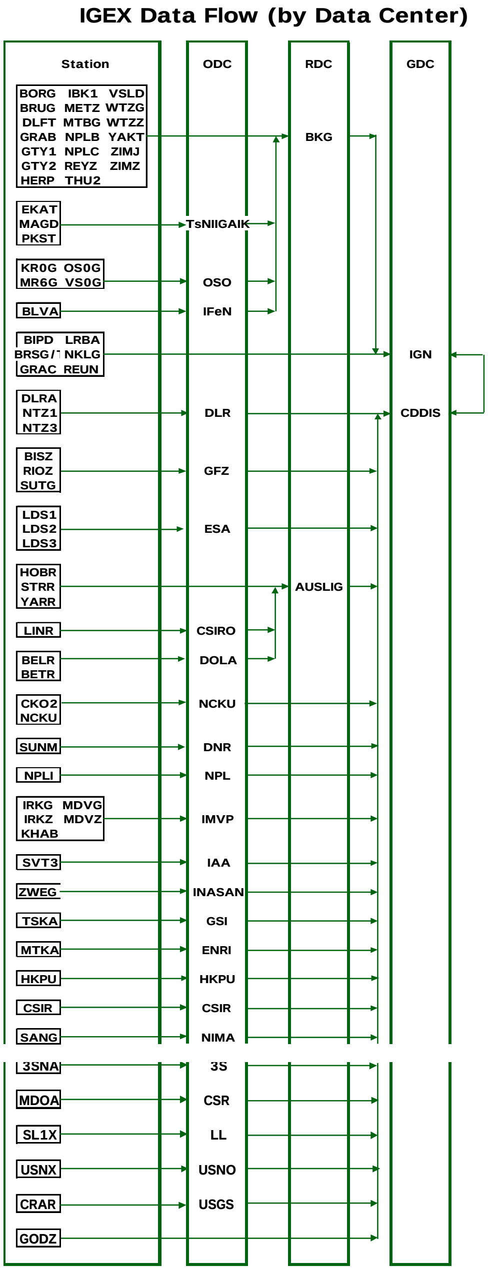


Figure 2. IGEX data flow.



Acronyms

AUSLIG	Australian Land Information Group
BKG	Bundesamt für Kartographie und Geodäsie, Germany
CDDIS	Crustal Dynamics Data Information System, USA
CSIR	Council for Scientific and Industrial Research, South Africa
CSIRO	Commonwealth Scientific and Industrial Research Organisation, Australia
CSR	Center for Space Research, University of Texas at Austin, USA
DLR	Deutsches Zentrum für Luft-und Raumfahrt, Germany
DNR	Department of Natural Resources, Australia
DOLA	Department of Land Administration, Australia
ENRI	Electronic Navigation Research Institute, Japan
ESA	European Space Agency, Germany
GDC	Global Data Center
GFZ	GeoForschungsZentrum, Germany
GSI	Geographic Survey Institute, Japan
HKPU	Hong Kong Polytechnic University, China
IAA	Institute of Applied Astronomy, Russia
IFeN	Institute of Applied Geodesy/University FAF Munich, Germany
IGN	Institut Geographique National, France
IMVP	Institute of Metrology for Time and Space, Russia
INASAN	Institute of Astronomy, Russian Academy of Sciences
LDC	Local Data Center
LL	Lincoln Labs, USA
NIMA	National Imagery and Mapping Agency, USA
NCKU	National Cheng Kung University, Taiwan
NPL	National Physical Laboratory, India
OC	Operational Center
OSO	Onsala Space Observatory, Sweden
RDC	Regional Data Center
TsNIIGAI	Central Research Institute of Geodesy, Aerial Surveying, and Cartography, Russia
UF	University of Florida, USA
USGS	U.S. Geological Survey, USA
USNO	U.S. Naval Observatory, USA
3S	3-S Navigation, USA

Figure 3. IGEX data flow (by data center and station).

IGEX Data and Products

The IGEX data centers provided the user community access to both GLONASS data and the products derived from these data; the IGEX-98 data center at the Crustal Dynamics Data Information System (CDDIS) also archived SLR tracking data from the GLONASS satellites. The GLONASS data (non-SLR) consisted of daily files containing GPS/GLONASS data sampled at a thirty-second rate. In addition to these observation data files, the data centers archived GPS and GLONASS broadcast ephemerides and meteorological data (if available). All data were archived in UNIX-compressed RINEX format, where the observation files were compacted (using the Hatanaka scheme [Hatanaka, 1996]). Each tracking station produced approximately 0.5 Mbytes of data per day in compressed RINEX format. Ideally, the data flowed from the tracking station to the Global Data Centers within 48 hours of the end of the observation day. However, on average, at the CDDIS, ten percent of the data were received within twelve hours; thirty percent within 24 hours.

The GLONASS SLR data consists of round trip pulse time of flight to the satellite. The data points obtained during a typical satellite pass are compressed using sampling over time based upon the presence of some minimum number of data points in the sampling interval, thus creating normal points. These normal point data were available to the user community through the Global Data Centers supporting the International Laser Ranging Service (ILRS) at the CDDIS and the EuroLAS Data Center (EDC) in Germany.

The data files (non-SLR) archived at the IGEX data centers followed the same naming scheme as used by the IGS, **ssssddd#.yyt**.Z where:

- **ssss** is the unique four-character monument ID assigned for the site
- **ddd** is the three-digit day of year
- **#** is a sequence number for multiple files for a single day; this is typically 0, implying the file contains all data for the day
- **yy** is the two-digit year
- **t** is the file type:
  - *o* is an observation file
  - *d* is an Hatanaka-compressed observation file
  - *n* is a GPS navigation (broadcast ephemeris) file
  - *g* is a GLONASS navigation (broadcast ephemeris) file
  - *m* is a meteorological data file
  - *s* is a summary file generated by quality-checking software at the data centers and containing data quality meta-data information
- .Z indicates a UNIX-compressed file

The CDDIS generated daily GPS and GLONASS broadcast ephemeris files; each file contained all navigation messages for the GPS (filename *brdc**ddd**0.**yy**n.Z*) and GLONASS (filename *igex**ddd**0.**yy**n.Z*) satellites recorded by the tracking receivers for that day. Analysts utilized these two files rather than downloading all individual broadcast ephemeris files.

IGEX products were generated operationally by six Analysis Centers (as shown in Table 2) as well as the IGEX Analysis Coordinator. These products consisted of daily GLONASS precise ephemerides (in SP3 format), satellite clock information, and station coordinates (in SINEX format). The files were transmitted to the Global Data Centers for archive and distribution to the general user community. As with the GLONASS data files, the product files utilized the same naming conventions established by the IGS, **ssswwww#.typ**.Z where:

- **sss** is the acronym for the Analysis Center
- **wwww** is the four-digit GPS week
- # is the day of the week, e.g., 0 for Sunday, 6 for Saturday, and 7 indicating the data span the entire week
- **typ** is the data type:
  - *sp3* is an orbit file in SP3 format
  - *eph* is an orbit file in SP3 format
  - *pre* is an orbit file in SP3 format
  - *erp* is Earth rotation parameter data
  - *snx* is a file containing precise coordinates in SINEX format
  - *ssc* is a file containing precise coordinates in SINEX format without supporting matrices
  - *sum* is a summary file detailing analysis information
- .Z indicates a UNIX-compressed file

All filenames used at the data centers (for both data and products) are in lowercase, with the exception of the .Z indicating a UNIX-compressed file.

Table 2. IGEX-98 Analysis Centers Supplying Results to the CDDIS

Acronym	Source	Time Period
BKG	Bundesamt für Kartographie und Geodäsie (BKG), Germany	Weeks 0980 through present
COX	Center for Orbit Determination (CODE), AIUB, Switzerland	Weeks 0979 through present
ESX	European Space Agency Space Operations Center (ESA/ESOC), Germany	Weeks 0980 through present
GFX	GeoForschungsZentrum Potsdam (GFZ), Germany	Weeks 0983 through 1001
JPX	Jet Propulsion Laboratory (JPL), USA	Weeks 0991 through present
MCC	Mission Control Center (MCC), Russia	Weeks 0980 through present
IGX	Combined IGEX Solution, University of Technology, Vienna, Austria	Weeks 0981 through 0989

Problems Encountered

As with the start of any new program, numerous problems were identified by the data centers while archiving the data sets and making them available to the user community. These problems are summarized in Table 3. A majority of these problems were due to non-conformance to published IGEX-98 documentation, such as missing or incomplete site logs and RINEX header information. Although operators may have considered these discrepancies "minor", conformance to the standards enables data centers, analysis centers, and users to analyze the IGEX data in an efficient, automated fashion and ensures consistency among results from multiple disciplines.

Many of the problems could have been diagnosed by Operational Data Centers prior to transmission to the IGEX data flow. For the most part, these problems where detected by the CDDIS when quality-control software, in particular UNAVCO's TEQC (Estey, 1998), failed and thus required human intervention in otherwise automated routines. When these problems were diagnosed at the CDDIS, messages were sent to the station or its Operational Data Center detailing the nature of the problem and requesting a re-supply of all files.

Table 3. IGEX-98 Data Problems Encountered at the CDDIS

Problem "Category"	Description/Examples
Missing site logs	CK02, EKAT, GATR, MAGD, NCKU, NPLI, PKST, YAKT
TEQC	Required modification for GLONASS data type Required modification to handle manufacturer-supplied RINEX converters
File format problems	Compression (GZip used instead of UNEX compress) ASCII used instead of binary in file transfers Extra <CR>s in files
File naming conventions	Upper case instead of lower case .Z not used or used incorrectly to indicated UNIX compressed file Misnamed files (d instead of o)
Empty files transmitted	
RINEX headers	Non-conformance to published standards Missing required lines
Receiver/antenna naming	Non-conformance to recently-published IGS standards
RINEX version	V1 instead of V2
Satellite number 0	Valid output for GG24 receiver Invalid for RINEX format
RINEX converter problems	Time regression error with 3S converter Field overflow (phase data) in Z-18 converter

Conclusions/Recommendations

In general, the flow of GLONASS data and products in IGEX-98 performed well given the diverse nature of the community involved in the experiment. Some recommendations, however, are in order should IGEX-98 continue in some form in the future:

- Tracking stations should follow prescribed guidelines, thus ensuring timely, automated processing of data by both data and analysis centers.
- Operational Data Centers should be clearly identified and perhaps consolidated to ensure timely and efficient flow of data. Responsibilities of these centers need to be clearly identified. These data centers should perform a more rigorous check on data quality, perhaps standardizing the use of such software packages as UNAVCO's TEQC throughout the IGEX infrastructure.

- Global Data Centers need to ensure consistency among themselves, thus ensuring equalized data holdings for the user community and for backup purposes.

References

Estey, L. (1999). TEQC Summary, in *Proceedings IGS 1999 Network Systems Workshop*, Annapolis, Nov. 2-5, 1998, pp. 343-345, JPL.

Hatanaka, Y. (1996). Compact RINEX Format and Tools, in *Proceedings IGS 1996 Analysis Center Workshop*, Mar. 19-21, 1996, pp. 121-129, JPL.

Noll, C. E., M. P. Dube (1999). The IGEX Data Center at the CDDIS, in *Proceedings IGEX-98 Workshop,* Nashville, Sept. 13-14, 1999, JPL.

BKG´s Operation of GPS/GLONASS Receivers and Its Regional IGEX Data Center

Heinz Habrich
Bundesamt fuer Kartographie und Geodaesie
Richard-Strauss-Allee 11, D-60598 Frankfurt / Germany

Abstract

Four dual-frequency combined GPS/GLONASS receivers have been operated by the Bundesamt fuer Kartographie und Geodaesie (BKG) during the IGEX-98 campaign. The new receiver types were set up at the observation sites for continuously tracking the satellite signals. The GPS/GLONASS observation data were automatically transferred to BKG using communication links similar to those used by the IGS service.

A regional IGEX data center for Europe has been established at BKG, before the beginning of the IGEX-98 campaign. The IGEX observation and navigation files of the European IGEX stations were uploaded from the observation sites to that data center. All data transfers were performed by the usage of the RINEX data format and the combined GPS/GLONASS observation files were successfully compressed into the "compact RINEX" format. Following the IGEX data flow structure the RINEX files were then uploaded to the global IGEX data center at the Institut Geographique National (IGN) in Paris, France. Due to the additional observations of GLONASS satellites the size of the observation files increases compared to the files of IGS stations. This was recognised in the duration of the file transfer, but was not critical. Statistics of the data holdings, latencies and quality control at BKG will be shown in the following.

Operation of GPS/GLONASS Receivers

BKG owns six dual-frequency combined GPS/GLONASS receivers, in detail four Ashtech Z-18 and two 3S-Navigation R-100. Four of this receivers were at least partly operated during the IGEX campaign.

Two Ashtech Z-18 are permanently operating in Wettzell (Germany) and Reykjavik (Iceland). They are connected to a PC with Internet connection, that is running the "GPS-Base" software from the Terrasat company. A fully automated data flow comparable to that used within IGS has been established. The two 3S-Navigation R-100 receivers were set up in Wettzell and Ankara (Turkey) before the beginning of the IGEX-98 campaign. Because of the lack of remote control capabilities, concerning the receiver and communications to the site, the receiver in Ankara was shipped back to BKG shortly after the beginning of IGEX-98, when the firmware had to be updated. This receiver could not be re-installed in Ankara during the official IGEX-98 observation period. The 3S-Navigation R100 receiver in Wettzell is connected to an external frequency standard (Hydrogen-Maser) which guarantees a stable receiver clock. Since two different receiver types are simultaneously operated in Wettzell their observations may be used to compare both receiver types.

Although, the IGEX-98 campaign has officially ended on April 19, 1999, BKG continues the operation of its GPS/GLONASS receivers. Two more Ashtech Z-18 receivers are available at BKG and their permanent installation is in preparation. One of this receivers will be installed in Lhasa (Tibet) in November 1999, whereas the site location of the second receiver is not yet decided.

IGEX Data Center Structure

In order to establish a regional IGEX data center for Europe we use a structure very similar to that of the existing IGS data center. We use the Internet for all data transfers and have implemented the "push" strategy to transfer the files from the observation stations to BKG and from BKG to the global IGEX data center at IGN. All observation files since the beginning of the IGEX-98 campaign are "online" available for anonymous ftp users.

The "RINEX compact" data format (Hatanaka compression) could successfully be generated for combined GPS/GLONASS files. Separate RINEX navigation files (G-files) have been created at the observation sites and transferred to BKG, which include the broadcast ephemerides of the GLONASS satellites. This new file type was required because the GLONASS broadcast ephemerides parameters are different from that of the GPS satellites. If the "RINEX compact" GPS/GLONASS observation files are compressed with the "Z-compression" algorithm, they show up a file size of approximately 600 kbyte in the average. Corresponding IGS observation files (GPS observations only) have a size of approximately 350 kbyte. Due to the additional GLONASS satellites the size of the combined GPS/GLONASS observation files increases significantly. However, no problems caused by the increased file size could be detected in the data transfer and holdings at our data center.

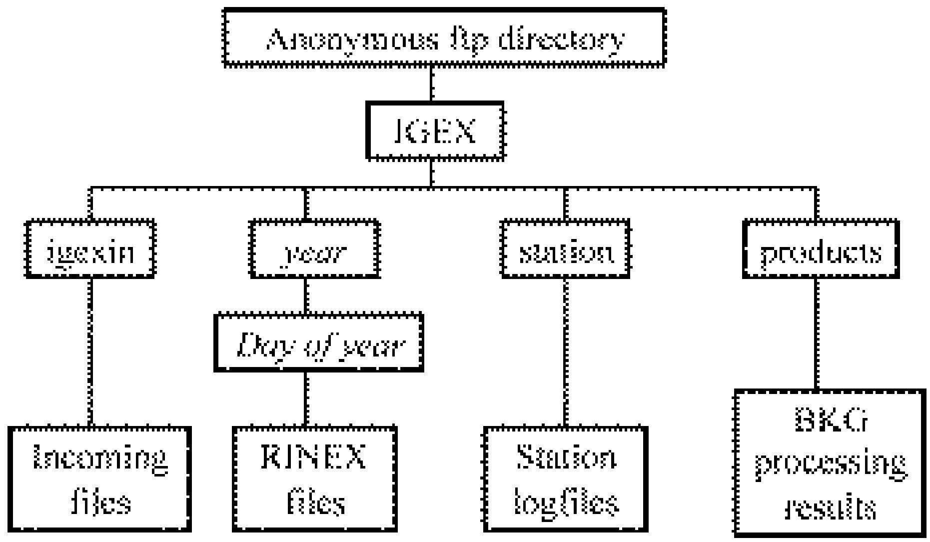


Figure 1. Structure of the IGEX Data Center at BKG

The file structure of the IGEX data center at BKG is shown Figure 1. The *anonymous ftp login* on the host 141.74.240.26 (igs.ifag.de) will show the *IGEX* directory, which includes 4 subdirectories. The *igexin* subdirectory is used by the observation stations for the temporary storage of all uploaded IGEX data files. BKG moves the files to daily subdirectories using the *day of year* as directory names. The station log-files could be found in the *station* directory. BKG not only operates the regional data center, but also acts as an IGEX analysis center. The processing results of BKG (precise orbits of GLONASS satellites, daily transformation parameters between PZ-90 and ITRF 96, and receiver-specific estimates of the system time difference between GPS and GLONASS) are stored in the *products* directory.

Hourly RINEX Files

In October, 1998 BKG started to transfer hourly RINEX files from selected IGS stations as a test project. When the GPS/GLONASS observations of the Ashtech Z-18 receiver in Wettzell became available, these observations were included in the hourly data transfer, too. Thus, hourly GPS/GLONASS observation files from the station Wettzell are available at the data center at 6 min after the full hour. The observations may be used for near real-time estimations of troposphere and ionosphere parameters.

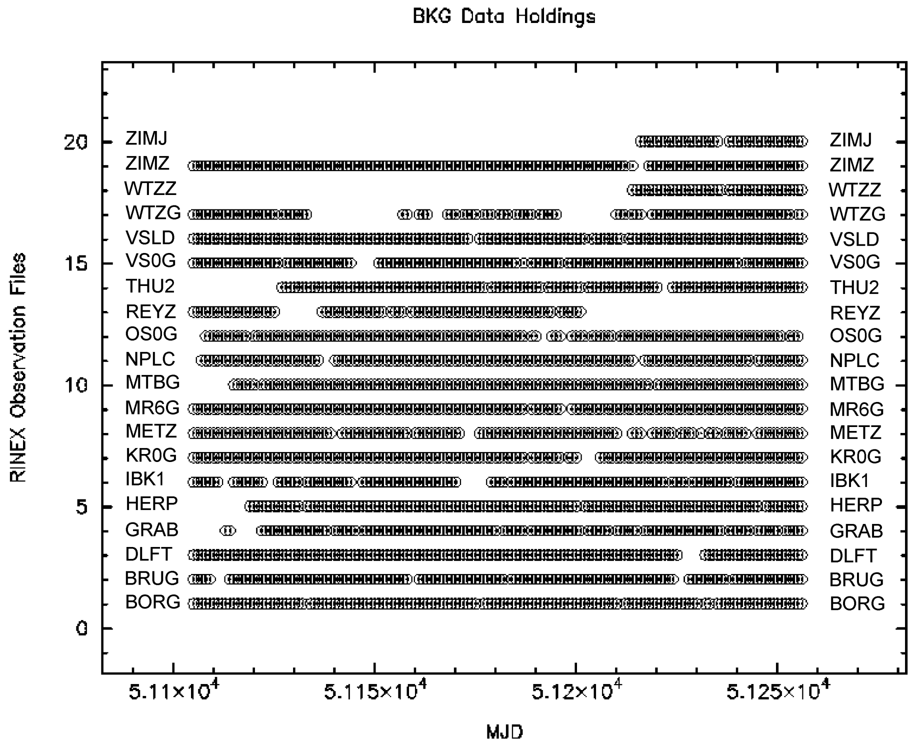


Figure 2. Summary of observation files October 19, 1998 – April 19, 1999.

Data Holdings

Figure 2 shows a summary of all GPS/GLONASS observation files, which have been submitted to BKG during the official period of IGEX-98. A total number of 20 observation stations have sent their files routinely to BKG with no, or only very few interruptions for most of the stations. The stations ZIMJ and WTZZ has started the operation in the second half of IGEX-98 as may be seen in Figure 2. A summary of the observations for the period April 20, 1999 to August 16, 1999 is given in Figure 3. Although, the IGEX-98 campaign has ended before this period, most of the stations continue with the operation of GPS/GLONASS receivers and the file transmission. A list of all stations and the corresponding receiver types is given in Table 1.

Table 1. Station List

Abbr.	Station Name	Receiver	Receiver Type
BORG	Borowiec, Poland	3S-Navigation R100-30T	L1/L2, GPS/GLONASS
BRUG	Brussels, Belgium	3S-Navigaton R100-30T	L1/L2, GPS/GLONASS
DLFT	Delft, Netherlands	Ashtech GG24C	L1, GPS/GLONASS
GRAB	Graz, Austria	Ashtech Z18	L1/L2, GPS/GLONASS
HERP	Herstmonceux, UK	3S-Navigation R100	L1/L2, GPS/GLONASS
IBK1	Insbruck, Austria	Ashtech GG24	L1, GPS/GLONASS
KR0G	Kiruna, Sweden	Ashtech Z18	L1/L2, GPS/GLONASS
METZ	Metsahovi, Finland	Ashtech Z18	L1/L2, GPS/GLONASS
MR6G	Maartsbo, Sweden	Ashtech GG24	L1, GPS/GLONASS
MTBG	Mattersburg, Austria	Ashtech GG24C	L1, GPS/GLONASS
NPLC	Teddington, UK	3S-Navigation R100-40T	L1/L2, GPS/GLONASS
OS0G	Onsala, Sweden	Ashtech Z18	L1/L2, GPS/GLONASS
REYZ	Reykjavik, Iceland	Ashtech Z18	L1/L2, GPS/GLONASS
THU2	Thule, Greenland	Ashtech Z18	L1/L2, GPS/GLONASS
VS0G	Visby, Sweden	Ashtech GG24	L1, GPS/GLONASS
VSLD	Delft, Netherlands	3S-Navigation R100-40T	L1/L2, GPS/GLONASS
WTZG	Wettzell, Germany	3S-Navigaion R100	L1/L2, GPS/GLONASS
WTZZ	Wettzell, Germany	Ashtech Z18	L1/L2, GPS/GLONASS
ZIMZ	Zimmerwald, Switzerland	Ashtech Z18	L1/L2, GPS/GLONASS
ZIMJ	Zimmerwald, Switzerland	JPS Legacy GGD	L1/L2, GPS/GLONASS

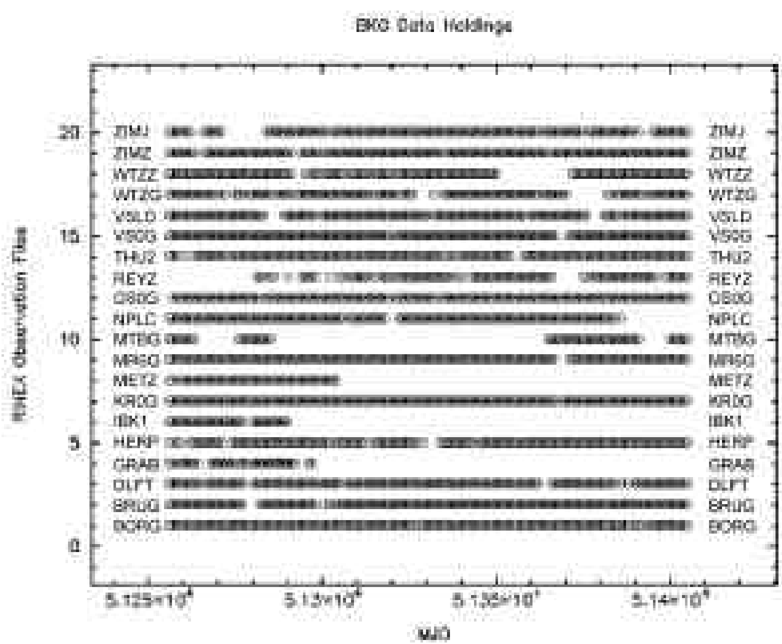
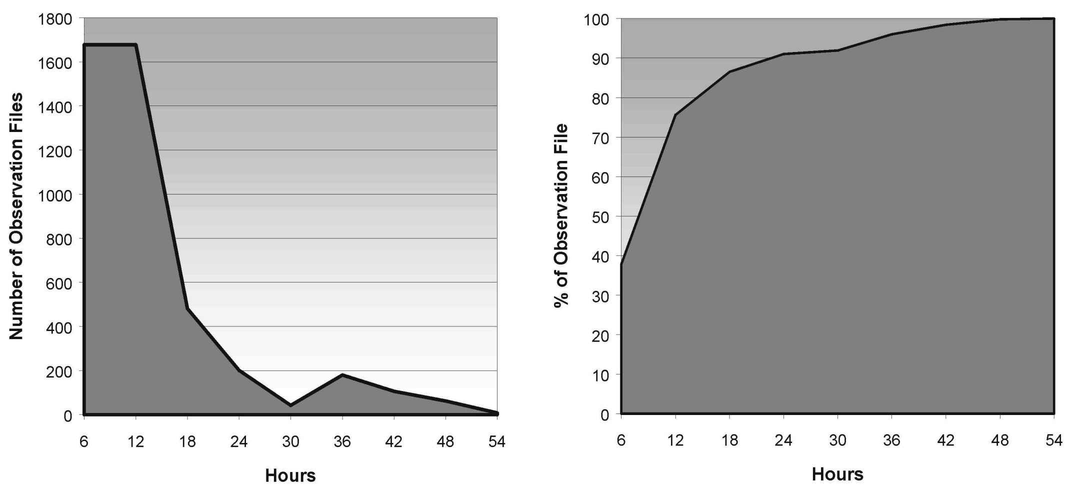


Figure 3. Summary of observation files, April 20, 1999 – August 16, 1999.

Data Latency

Daily observation files, each begins at 0:00 UT and ends 0:00 UT of the following day, have been created and transferred during IGEX-98. Because no manual interaction was required for the data transfer of most of the observation stations, the daily files could be uploaded to BKG within a few hours after the end of the observation for those stations. Figure 4 a) shows the time when the observation files were available at BKG in hours since the end of the observation day. It is given the total number of observation files for the period day 292, 1998 to day 228, 1999. Most of the files have been transferred within 18 hours. The number of transferred files increased at 36 hours after the observation end, again. This is about noon of the day following the observation end in Europe and leads to the assumption, that the files with a latency of about 36 hours have been submitted manually. The percentage of the files received at BKG as a function of the latency is shown in Figure 4 b). More than 90 % of the observation files have been transferred within the first day after the observation end.



a) b)

Figure 4. Latency of observation files Day 292, 1998 to Day 228, 1999.

Daily mean values of the data latency of all stations are shown in Figure 5. These mean values vary between 8 and 28 hours for the period day 292, 1998 to day 228, 1999. Figure 5 shows a linear trend of the mean values, also, which shows a data latency of about 14 hours at the beginning and that slightly decreases to about 12 hours at the end of the period.

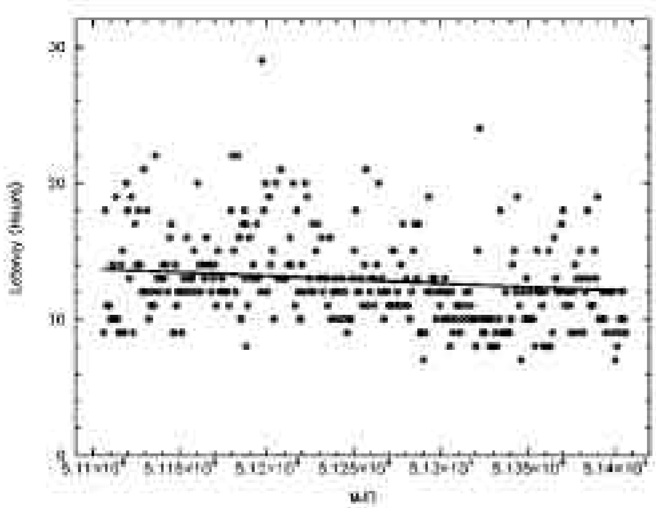


Figure 5. Latency of observation files, mean of all stations, Day 292, 1998 to Day 228, 1999.

Conclusion

Although the official period of IGEX-98 has ended, BKG will continue its operation of 4 GPS/GLONASS receivers and will set up 2 additional receivers, soon. A regional IGEX data center has successfully been established at BKG similar to the existing IGS data center. The statistics of the IGEX data holdings and latencies are comparable to that of the IGS service. This demonstrates that a routine GLONASS tracking network may be established and the observation data may be used by the analysis centers with a data latency of smaller than one day.

Integrity Monitoring Software for GPS/GLONASS Reference Stations

Kees de Jong and Niels Jonkman
Department of Mathematical Geodesy and Positioning, Delft University of Technology
Thijsseweg 11, 2629 JA Delft, The Netherlands

Abstract

Delft University of Technology (DUT) has traditionally been involved in research towards quality control of (geodetic) observations. Originally applied to conventional surveying techniques, the quality control procedures developed at DUT are also utilized within the context of the Dutch permanent GPS array. The dual-frequency GPS receivers at the reference stations of the array all employ dedicated integrity monitoring software based on DUT's quality control theory, to insure the quality and reliability of their observations. Recently, in view of the participation of DUT in the IGEX-98 campaign, this integrity monitoring software has been extended to incorporate dual-frequency GLONASS observations as well as GPS observations.

The integrity monitoring software aims to detect anomalies in the GPS/GLONASS data in real time. To that end, the software employs a recursive Kalman filter and DUT's recursive DIA (Detection, Identification and Adaptation) validation procedure. As the software does not require any external information, like satellite and receiver positions, velocities and clock behavior or information on the atmospheric effects, it can be executed independent of the application for which the data was originally collected. The software is able to detect slips of one cycle in the carrier data in real time, even for relatively long observation intervals of 30 seconds. Moreover, as a by-product, the software also produces precise estimates of the absolute ionospheric delay.

DUT's integrity monitoring software could be a valuable pre-processor for IGEX and IGS GPS and GLONASS observations. To facilitate its evaluation, the software is freely available to the scientific community. It is written in standard Ansi C and can therefore be compiled and run on any operating system. In this contribution a description is given of the integrity monitoring software that is running at DUT's GPS/GLONASS reference station. In addition to the underlying theoretical models, integrity monitoring results are given for two IGEX-98 stations, their data spanning the period March to mid-August 1999.

Introduction

With the development of the Russian GLONASS, a second satellite navigation system has become available for high-precision positioning and timing applications. The combined use of GPS and GLONASS is expected to greatly enhance the availability and reliability of space based navigation systems. In The Netherlands the potential benefits of GLONASS were recognized, resulting in a joint research project of the Survey

Department of the Ministry of Transportation and Public Works (MD) and Delft University of Technology (DUT). Purpose of this project is to gain insight in the performance of GLONASS and in the possibilities of GPS/GLONASS integration for precise positioning applications.

In July 1998 a single-frequency GPS/GLONASS receiver was installed at DUT in Delft. Although the primary aim of this receiver was to gain experience with combined GPS/GLONASS observations, the receiver was also used to participate in the International GLONASS Experiment 1998 (IGEX-98). The IGEX-98 campaign aims to collect geodetic quality GLONASS data from a global network of stations in order to compute amongst others precise GLONASS satellite orbits and an accurate transformation between the GPS and GLONASS reference frames. In view of the favorable results obtained with the combined GPS/GLONASS observations and the prolongation of the IGEX-98 campaign, the single-frequency receiver was replaced with a dual-frequency GPS/GLONASS receiver in February 1999.

The dual-frequency GPS/GLONASS receiver currently installed in Delft has been equipped with real-time integrity monitoring software. The software was originally developed at DUT for the reference stations of the Active GPS Reference System for The Netherlands (AGRS.NL), the Dutch permanent GPS array (de Jong, 1996). Primary aim of the software is to detect and correct errors in the observations and to detect errors in the satellite transmitted broadcast ephemeris. As the software operates in real-time, it allows the AGRS.NL operator to immediately discern and act upon problems with the receivers at the AGRS.NL stations as well as with the GPS satellites. This is of particular importance as the AGRS.NL stations are in principle able to provide real-time differential and kinematic positioning services.

The use of the integrity monitoring software however is not restricted to the AGRS.NL stations alone nor to just the spotting of anomalies in the data. As the integrity monitoring software does not necessarily require a receiver to be installed at a known position, it can also be used at a roving receiver. The software would then act as a sophisticated Receiver Autonomous Integrity Monitoring (RAIM) package. If however a precise position is available for the receiver, the integrity monitoring software can also be used to generate differential GPS and GLONASS corrections. Moreover, as the receiver would in that case be stationary, two other options of the software, adaptive multipath modeling and ionosphere estimation, could then also be employed (de Jong and Jonkman, 1999).

In this contribution, the most recent version of the integrity monitoring software capable of handling both GPS and GLONASS data will be described in more detail. In the second section, the models on which the software is based will be explained and a brief theoretical evaluation of the error detection capabilities of the software will be given. For IGEX-98 large amounts of data were processed for a number of tracking stations, covering almost the entire time span of the experiment so far. Part of these results will be presented and discussed in the third section.

Integrity Monitoring of GPS and GLONASS Observations

In this section, the theoretical concepts on which the integrity monitoring software for GPS/GLONASS data is based, will briefly be explained. The approach implemented in the software consists of two steps. In the first step the measured code and carrier phases are validated, while in the second step the satellite ephemeris and clock parameters are checked. Both steps of the procedure will be discussed, but the first step will be emphasized, as it is by far the more intricate. For a more detailed description of the software, the reader is referred to (de Jong, 1996).

Step 1: Validating the Observations

The discussion of the code and carrier phase observation validation starts in the first subsection with a brief review of testing and reliability theory. The observation and dynamic models to which this theory is applied are introduced in the second subsection. Finally, in the third subsection results of a limited series of design computations are briefly discussed, illustrating the strength and efficiency of this first step.

Testing and Reliability

The validation of the code and carrier phase observations is based on the recursive Detection, Identification and Adaptation (DIA-) procedure (Teunissen, 1990), running in parallel to a Kalman filter (Kalman, 1960); see Figure 1. The DIA-procedure aims to detect possible misspecifications in the observation model of the Kalman filter by means of statistical hypothesis testing. The procedure consists of the following steps:

1. *Detection:* An overall model test is carried out to diagnose whether unspecified model errors have occurred.

2. *Identification:* If a model error is detected, its potential source is identified by testing the nominal observation model against models extended with bias parameters.

3. *Adaptation:* After the identification of the most likely source of the model error, the observation model is adapted to eliminate the biases in the filters' state vector.

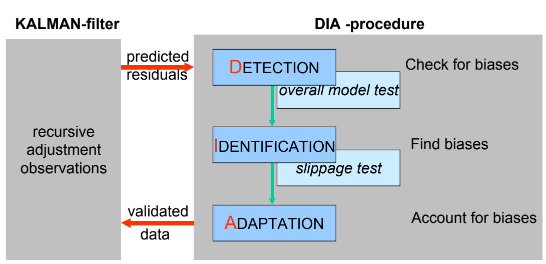


Figure 1. Kalman filter and DIA procedure.

The original or nominal observation model is indicated as the observation model under the null-hypothesis; the models extended with bias parameters are indicated as models under alternative hypotheses. In the integrity monitoring software only one-dimensional alternative hypotheses, describing outliers or integer cycle slips in the observations are considered. These biases are assumed to be described by a known vector c_k and an unknown scalar , as c_k .

The test statistics associated with the DIA-procedure are based on the filter's predicted residuals or innovations sequence v_k, and its corresponding covariance matrix Q_{v_k}. The predicted residual is defined as the difference between actual and predicted observations. Under the null-hypothesis, the expectation of v_k is zero; under the alternative hypothesis the expectation equals c_k .

With these test statistics, the Detection and Identification step of the DIA-procedure can be described in the following manner. A model error is detected and the null-hypothesis is rejected in the Detection step, if the overall model test statistic exceeds a certain critical value. The critical value is set, based on the distribution of the overall model test statistic under the null-hypothesis. In the subsequent Identification step, the test statistics of the alternative hypotheses, indicated as the local slippage (LS) test statistics, are computed and the alternative hypothesis corresponding to the largest statistic is said to describe the most likely misspecification of the observation model. For this misspecification to be sufficiently likely however, the LS test statistic also has to exceed a critical value, which again is set based on the distribution of this statistic under the null hypothesis. If the largest slippage test statistic remains smaller than the critical value, then a misspecification other than the ones described by the alternative hypotheses is thought to be present.

The size of the model error that can be detected in the Identification step with a probability γ, the so-called power of the test, is referred to as the Minimal Detectable Bias (MDB) (Salzmann, 1991). The MDBs can be computed once two reference probabilities have been specified: the probability of rejecting the null-hypothesis when it is actually true (α_0) and the probability of rejecting the null-hypothesis when an alternative hypothesis is true (γ_0). The probabilities α_0 and γ_0 determine the value of the non-centrality parameter λ_0. With this non-centrality parameter the MDB is expressed as

$$MDB = \sqrt{\frac{\lambda_0}{c_k^T Q_{v_k}^{-1} c_k}} \qquad (1)$$

MDBs provide an important diagnostic tool for inferring how well particular model errors, such as outliers and cycle slips, can be detected. The MDBs are said to describe the internal reliability of a system. In the section entitled "Design Computations," the

MDBs will be presented for different observation scenarios to illustrate the performance of the integrity monitoring functions.

Measurement and Dynamic Models

The approach to integrity monitoring presented in this paper is based on the philosophy that it should be applicable irrespective of the application(s) for which the data may originally have been collected. The integrity monitoring software does therefore not require any external information, like satellite and receiver positions, velocities and clock behavior or information on atmospheric effects. In this subsection, the Kalman filters' observation and dynamic models are derived that manage to realize the aim of this philosophy.

A total number of five basic observables are available from the GPS and GLONASS satellites: two carrier observations (L1, L2) and three code observations (P1, P2, C/A). In addition, for GPS with Anti-Spoofing switched on, a derived code observable, consisting of the difference between the encrypted P1 and P2 codes, may be available instead of the P2 code observation. The reconstructed P2 code observation is then obtained as the sum of the C/A and P2-P1 observations, resulting in (additional) correlation between the C/A and P2 code observation, see (Teunissen et al., 1998). The receiver tracking scenarios considered in this paper are summarized in Table 1.

Table 1. Receiver Tracking Scenarios. Cn (n=3,4,5) Refers to Code-Correlation, X4 to Cross-Correlation Tracking**.**

	Carrier		Code				
No. of obs.	L1	L2	C/A	P1	P2	P2-P1	Identifier
3	×	×	×	-	-	-	C3
4	×	×	-	×	×	-	C4
4	×	×	×	-	-	×	X4
5	×	×	×	×	×	-	C5

Assuming all five code and carrier observations C and ϕ are available at time k, the observation or measurement model for these five observations can be written as

$$\begin{pmatrix} C_1 \\ \phi_1 \\ \phi_2 \\ C_2 \\ C_{C/A} \end{pmatrix}_k = \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} L_k + \begin{pmatrix} 1 \\ -1 \\ -\kappa \\ \kappa \\ 1 \end{pmatrix} I_k + \begin{pmatrix} 0 \\ \lambda_1 N_1 \\ \lambda_2 N_2 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} \eta_{C_1} \\ \eta_{\phi_1} \\ \eta_{\phi_2} \\ \eta_{C_2} \\ \eta_{C_{C/A}} \end{pmatrix} \tag{2}$$

where $L = \rho + c\left(\delta^s t + \delta_r t\right) + \Delta T$ indicates the sum of the geometric distance ρ between satellite and receiver, the satellite and receiver clock errors, $\delta^s t$ and $\delta_r t$, multiplied by the speed of light c, and the combined effect ΔT of the biases due to the troposphere, orbital errors and Selective Availability (SA); I is the first order L1 ionospheric effect; N_1, N_2 are the L1 and L2 carrier ambiguities; η are hardware delays (assumed constant for a satellite pass of several hours); λ_1, λ_2 are the wavelengths of the L1 and L2 carriers; the coefficient κ, finally, equals $\kappa = \left(\lambda_2 / \lambda_1\right)^2$. For GPS, we have $\kappa \approx (9/7)^2$, whereas for GLONASS $\kappa = (9/7)^2$ for all satellites.

The parameters L and I are functions of time. Due to the presence of the receiver-satellite range, the receiver clock bias and, for GPS, the effect due to SA, it is not possible to describe the time-dependent behavior of the first parameter by, for example, a low order polynomial, for time intervals greater than a few seconds. It should therefore be eliminated from (2). This can be accomplished simply by subtracting observation C_1 from the other observations. Or, formally, by applying the transformation, defined by the transformation matrix

$$T = \begin{pmatrix} -1 & 1 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 \\ -1 & 0 & 0 & 0 & 1 \end{pmatrix} \tag{3}$$

For the ionospheric parameter I a linear polynomial model is introduced. Unknown parameters are the ionospheric effect itself and its rate of change $\dot{I}$. Substitution of this model into measurement model (2) and eliminating parameter L yields

$$\begin{pmatrix} \phi_1 - C_1 \\ \phi_2 - C_1 \\ C_2 - C_1 \\ C_{C/A} - C_1 \end{pmatrix}_k = \begin{pmatrix} -2 & 0 \\ -\kappa - 1 & 0 \\ \kappa - 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} I \\ \dot{I} \end{pmatrix}_k + \begin{pmatrix} \lambda_1 N_1 \\ \lambda_2 N_2 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} \eta_{\phi_1} - \eta_{C_1} \\ \eta_{\phi_2} - \eta_{C_1} \\ \eta_{C_2} - \eta_{C_1} \\ \eta_{C_{C/A}} - \eta_{C_1} \end{pmatrix} \tag{4}$$

The dynamic or transition model for the ionospheric parameters is given as

$$\begin{pmatrix} I \\ \dot{I} \end{pmatrix}_k = \begin{pmatrix} 1 & \Delta t_{k,k-1} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} I \\ \dot{I} \end{pmatrix}_{k-1} \tag{5}$$

with $\Delta t_{k,k-1} = t_k - t_{k-1}$.

Model (4) is singular, i.e. not all parameters are estimable. The unknown parameters are therefore transformed according to

$$\begin{pmatrix} \dot{I}_k \\ I_{1,k} \\ I_{2,k} \\ I_{3,k} \\ \Delta \end{pmatrix} = \underbrace{\begin{pmatrix} 0 & 1 \\ 1 & 0 \\ 1 & 0 \\ 1 & 0 \\ 0 & 0 \end{pmatrix}}_{\begin{pmatrix} T_I \\ 0^T \end{pmatrix}} \begin{pmatrix} I \\ \dot{I} \end{pmatrix}_k + \begin{pmatrix} 0 \\ -\dfrac{\lambda_1 N_1}{2} - \dfrac{\eta_{\phi_1} - \eta_{C_1}}{2} \\ -\dfrac{\lambda_2 N_2}{\kappa + 1} - \dfrac{\eta_{\phi_2} - \eta_{C_1}}{\kappa + 1} \\ \dfrac{\eta_{C_2} - \eta_{C_1}}{\kappa - 1} \\ \eta_{C_{C/A}} - \eta_{C_1} \end{pmatrix} \tag{6}$$

After applying this transformation the measurement model reads

$$\begin{pmatrix} \phi_1 - C_1 \\ \phi_2 - C_1 \\ C_2 - C_1 \\ C_{C/A} - C_1 \end{pmatrix}_k = \begin{pmatrix} 0 & -2 & 0 & 0 & 0 \\ 0 & 0 & -\kappa - 1 & 0 & 0 \\ 0 & 0 & 0 & \kappa - 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \dot{I}_k \\ I_{1,k} \\ I_{2,k} \\ I_{3,k} \\ \Delta \end{pmatrix} \tag{7}$$

The corresponding dynamic model for the parameters related to the ionosphere is given by

$$\begin{pmatrix} \dot{I} \\ I_1 \\ I_2 \\ I_3 \end{pmatrix}_k = \begin{pmatrix} 1 & 0 & 0 & 0 \\ \Delta t_{k,k-1} & 1 & 0 & 0 \\ \Delta t_{k,k-1} & 0 & 1 & 0 \\ \Delta t_{k,k-1} & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \dot{I} \\ I_1 \\ I_2 \\ I_3 \end{pmatrix}_{k-1} \tag{8}$$

The above measurement model is valid for any of the receiver tracking scenarios given in Table 1. For example, for scenario C3 the parts which apply to the parameters I_3 and Δ are simply omitted from measurement model (7).

In addition to the above-mentioned parameters, it is also possible to include a dynamic model to describe biases in the code observations (Jin, 1996; de Jong, 1996). These biases are mainly due to multipath, see also (de Jong, 1999) for more details on the influence of multipath on the parameters estimated by the integrity monitoring functions.

The extended integrity monitoring functions are an objective means to evaluate the susceptibility of a site's environment to multipath. It may therefore serve as a useful tool when selecting a point for a reference station receiver.

Stochastic Model

The stochastic model is specified by the covariance matrix of the observations and the process noise matrix of the dynamic model for the ionosphere. If Q_y is the covariance matrix of the original measurement model (2), the covariance matrix of model (7) follow from applying the covariance law. It is given as $TQ_{y_k}T^T$. The subscript k indicates the covariance matrix may be time-dependent. For example, the precision of the observations may depend on the elevation of the satellites (Euler and Goad, 1991; Jin and de Jong, 1996). Here, however, we assume these precisions to be constant. In addition, correlations between the observations of the original model (2) are assumed to be absent for non-cross-correlating receivers. For cross-correlation data (receiver tracking scenario X4) correlation is introduced due to the reconstruction of the L2 observations from L1 and L2-L1 data. This correlation is taken into account by the integrity monitoring functions.

Table 2. Parameters Used for the Computation of MDBs and for Actual Data Processing

Standard deviations (m)		Spectral density	
φ_1	0.005	$q_I^{(2)}$	5×10^{-9} m^2/s^3
φ_2	0.005		
C_1	2.0	Testing parameters	
C_2	2.0	α_0	0.001
$C_{C/A}$	2.0	γ_0	0.80
$C_{P2\text{-}P1}$	2.8$^{(*)}$		

$^{(*)}$St. dev. σ computed as: $\sigma_{C_{P2-P1}} = \sqrt{\sigma^2_{C_1} + \sigma^2_{C_2}}$

The dynamics of the ionospheric effects are assumed to consist of a zero-mean white noise process with process noise matrices Q_k^I, characterized by the spectral density $q_I^{(2)}$. The spectral density is taken as a constant for an entire satellite pass. The process noise matrix for the transformed ionospheric parameters, see (6) is given by $T_I Q_k^I T_I^T$.

Elevation dependent weighing of observations is not yet implemented in the integrity monitoring functions. Therefore, in order not to falsely identify observations as being biased, where they actually have a high noise level, the a priori standard deviations in the analyses which follow, have to be on the safe side. The a priori values for the stochastic model are given in Table 2.

Design Computations

In this subsection the theoretical performance of the integrity monitoring software will be briefly analyzed by means of the Minimal Detectable Bias (MDB)-measure introduced in the subsection on testing and reliability. MDBs will be given for the four receiver tracking scenarios of Table 1. Default parameters used for the computations are given in Table 2.

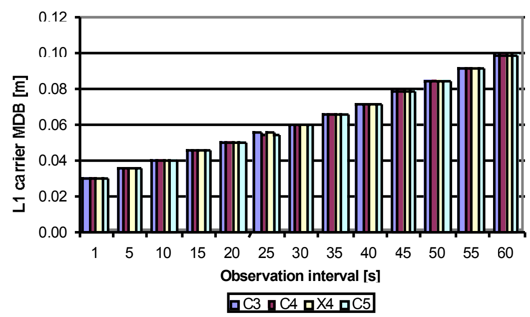


Figure 2. Carrier MDBs as function of the observation interval.

It appears that the code MDBs are roughly equal to four times the standard deviations of the code observations. The carrier MDBs are mainly a function of the observation interval, the spectral density of the ionospheric model and the standard deviations of the carrier observations (de Jong, 1998). Shown in Figure 2 are the carrier MDBs as a function of the observation interval. It can be concluded from this figure that even for observation intervals, or data gaps, as large as 60 seconds, the carrier MDBs are small enough to find even the smallest cycle slip, bearing in mind that a cycle corresponds to approximately 20 cm.

Step 2: Validating the Satellite Ephemeris and Clock Parameters

In the first step of the integrity monitoring approach, the code and carrier phase observations are validated. For real time navigation applications however, one has to make use of parameters of the satellite transmitted navigation message, i.e., satellite ephemeris and clock correction parameters, in addition to the observations. Hence, these parameters need to be validated as well, particularly as they are known to contain gross errors on occasion.

The second step of the integrity monitoring is dedicated to the validation of the parameters in the navigation message, using the validated observations from the first step. With the satellite ephemeris and clock parameters and the reference station's known position, the distance between satellite and receiver can be computed. The difference between observed (and validated) and computed code range consists of the receiver clock bias, tropospheric and ionospheric effects and biases due to orbit errors and SA. The tropospheric and ionospheric effects can be removed using one of the many available models and by forming a linear combination of the L1 and L2 code observations. The most significant remaining term (for GPS) is the effect due to SA. It is assumed that this bias is small compared to biases due to errors in the broadcast parameters. Therefore, parameter ΔT can be ignored. The corresponding measurement model for m satellites therefore reads

$$\begin{pmatrix} C^1-\rho^1-c\delta^1 t \\ \vdots \\ C^m-\rho^m-c\delta^m t \end{pmatrix} = \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix} c\delta_r t \qquad (7)$$

If two satellites are tracked, it is possible to detect errors, if more than two satellites are tracked, it is also possible to identify the satellite(s) with the erroneous navigation data. Detection and identification of biases is again based on statistical hypothesis testing, similar to DIA-procedure of the first step.

Results

The integrity monitoring software, as described in the previous section was used to analyze the data of several stations participating in the IGEX-98 campaign, in order to demonstrate the capabilities of the software and evaluate the performance of both GLONASS and some of the dual-frequency receiver types involved in the campaign. The results for two of these stations, ZIMJ and ZIMZ, will be discussed in some more detail in this section.

The ZIMJ and ZIMZ stations are located closely together - less than 10 meters apart - at the Zimmerwald site of the Astronomical Institute of the University of Berne in Switzerland. The ZIMJ-station is equipped with a JPS Legacy receiver, while the ZIMZ station is equipped with an Ashtech Z18-receiver. In order to allow a fair comparison between the two receivers, only data collected between February 19th (day of year (doy) 50) and August 18th (doy 230) were taken into consideration for both stations. Moreover, the data were processed with a hard-limiting cut-off elevation of 10 degrees.

Cycle Slip and Outlier Detection

The carrier phase cycle slips and code outliers detected by the integrity monitoring software in the ZIMJ and ZIMZ data were accumulated into daily slip and outlier counts. The average daily slip and outlier counts for the half-year period considered in the analyses are shown in Figures 3 and 4. As can be seen from Figure 3, there exists a reasonable consistency between the average daily number of cycle slips detected in the data of the ZIMJ JPS receiver and the ZIMZ Ashtech receiver. For most GLONASS satellites, less than 5 slips are found per day, with four notable exceptions, i.e. the satellites at slots 8, 10, 14 and 16. The satellites 10 and 16 are known to suffer from

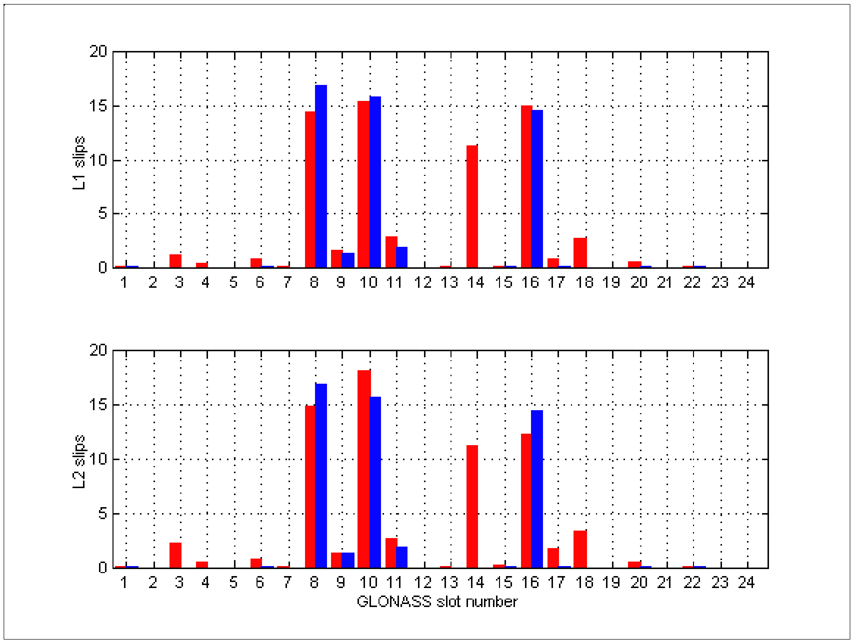


Figure 3. Average number of L1 and L2 frequency carrier phase cycle slips per day, top and bottom respectively, for station ZIMJ (light gray) and station ZIMZ (dark gray).

frequent signal interruptions or severe signal fading; see (Cook, 1997) and (Zarraoa et al., 1997). Satellite 8, which is one of the three satellites launched in December 1998, appears to have developed similar signal problems. Satellite 14 finally, is an exceptional case as it has only recently been put into operation after an outage of almost two years. Since its reintroduction into the constellation in July 1999, the satellite has shown considerable problems with in particular its transmissions on the L2 frequency. The Ashtech receiver does as a consequence not provide any L2 frequency observations for this satellite, while the JPS receiver only collects a small number of observations of very poor quality.

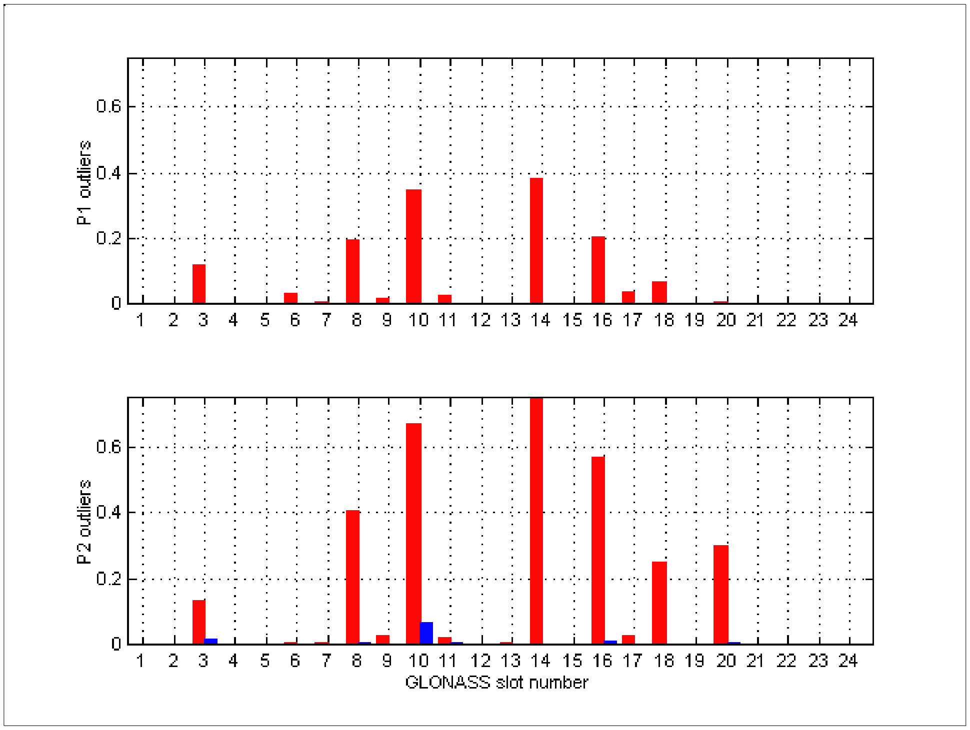


Figure 4. Average number of P1 and P2 code outliers per day, top and bottom respectively, for station ZIMJ (light gray) and station ZIMZ (dark gray).

The average number of code outliers per day, depicted in Figure 4, does not show the same measure of agreement between the ZIMJ JPS receiver and the ZIMZ Ashtech receiver. Whereas in the Ashtech code data hardly any outliers are detected, the JPS data code does seem to contain quite a few. However, an average number of code outliers of the order of 0.3 still only implies that an outlier was detected in the ZIMJ JPS data once every three to four days. Then again, the ability to detect code outliers is also very limited as witnessed by the code MDBs which are about 8 meters, conform the section entitled "Design Computations."

It should in addition be noted from Figure 4, that the average number of P2 code outliers detected in the JPS data of GLONASS satellite 14 - almost 10 per day - is exceptional. This indicates an acute tracking problem of the L2 frequency signal of this satellite. As the Ashtech receiver did not provide L2 frequency data for satellite 14, its observations were not validated by the integrity monitoring software, and the number of slips and code outliers for this receiver is consequently omitted from Figures 3 and 4.

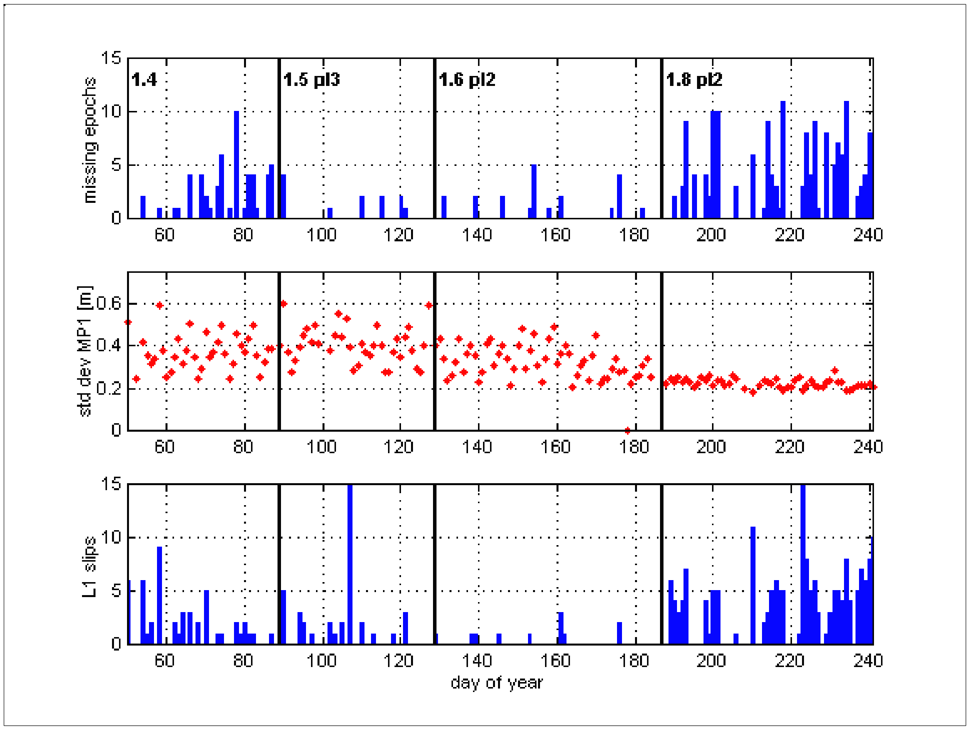


Figure 5. Daily missing epoch count, daily estimates of the P1 code multipath combination and daily L1 frequency carrier phase cycle slip count, top, middle and bottom respectively, for GLONASS satellite 4, determined from the JPS Legacy data collected at station DLFT. The black lines indicate receiver firmware upgrades, the number at the top of the lines the firmware version.

The slightly larger number of code outliers detected in the JPS data can be put into perspective by considering time series of daily missing epoch and cycle slip counts and time series of daily code multipath combination standard deviation estimates. Such time series are shown in Figure 5 for the JPS receiver in Delft, The Netherlands (DLFT). The daily number of missing epochs is determined by counting the number of observation epochs missing between consecutive epochs with full dual-frequency data, i.e. receiver tracking scenario C5. The code multipath combination is a linear combination of code and carrier phase observations from which the time varying parameters like range, clock errors and atmospheric effects are eliminated. The noise of the resulting constant time series is dominated by the noise of the code observations, and if present by code-multipath.

As can be seen in Figure 5, the daily statistics for the JPS receiver show a distinct dependence on the receiver firmware version. Between February and August 1999, four firmware versions were released and each new version resulted in rather dramatic changes in the missing epoch and slips counts and the multipath combination standard deviation estimates. Some of the versions, 1.4 and 1.8, score well on code precision, but not so well on the number of missing epochs and slips, while for the other versions, 1.5

and 1.6, it is the other way round. Hence, the JPS receiver appears to be still very much under development.

Navigation Message Anomaly Detection

In order to demonstrate the ability of the integrity monitoring software to detect anomalies in satellite transmitted navigation messages, in this section we will briefly discuss the GLONASS navigation message validation results of the ZIMZ-station. This station was one of the first operational stations of the IGEX-campaign, and its data spans a period of approximately 11 months, starting early September 1998.

In Table 3 a summary is provided of the navigation message anomalies detected by the integrity monitoring software in the ZIMZ data. Only four instances were found of navigation message rejections. In two cases the anomalies were accounted for in the Notices Advisory for GLONASS Users (NAGU). The two other cases were analyzed in some more detail, in order to establish the cause of the anomaly.

Table 3. GLONASS Navigation Messages Rejected During Processing of ZIMZ Data. (Indicated are the date and Time of Ephemeris (TOE or tb in GLONASS nomenclature) of the rejected messages, as well as the time of first detection. The last column contains a brief summary of the applicable NAGU, if available.)

date (doy)	**SVR**	**TOE**	**time detection**	**NAGU** number / outage summary
17 Nov 1998 (321)	09	22:15:00.0 22:45:00.0	22:15:00.0 22:45:00.0	-
23 May 1999 (143)	09	5:15:00.0	5:15:00.0	NAGU NUMBER: 039 (ADVS) 23.05/0510-UNFINISHED NAGU NUMBER: 040 (ADVS) PUT INTO OPERATION 29.05/1830
19 Jul 1999 (200)	13	2:45:00.0 3:15:00.0 3:45:00.0 4:15:00.0	2:40:00.0 3:15:00.0 3:45:00.0 4:15:00.0	NAGU NUMBER: 056 (ADVS) UNUSABLE 18.07/1911-19.07/0416
20 Jul 1999 (201)	13	13:45:00.0	13:45:00.0	-

One of the two cases that were unaccounted for in the NANUs, the anomaly in the messages of satellite 9 starting November 17th, 1998, was already spotted by the staff of MIT's Lincoln Laboratory, see IGEX mail no. 80. The source of the anomaly was indicated as an off-schedule change of satellite clock bias and rate parameters to erroneous values. An inspection of the GLONASS RINEX navigation files of the ZIMZ-station, allows us to be somewhat more specific: from 22:15 UTC onward, satellite 9 transmitted the clock parameters of satellite 15; see Table 4. Note in Table 4 that the clock rate parameter in the anomalous message transmitted by satellite 9 is exactly the same as the rate parameter in the message shown for satellite 15, while the difference in the clock bias parameters is consistent with the clock drift of satellite 15 over the 15-hour period that separates the messages. A similar case of possible mistaken identity by the control segment has been described in (Cook, 1997).

Table 4. Navigation Messages of GLONASS Satellites 9 and 15, Extracted from RINEX GLONASS Navigation File of Station ZIMZ (The messages show the change of the clock parameters for satellite 9 to incorrect values, probably those of satellite 15.)

satellite at slot 15

```
15 98 11 17  5 45  0.0 0.609047710896D-04-0.545696821064D-11 0.198000000000D+05
   -0.626687011719D+04-0.267974376678D+01 0.931322574615D-09 0.000000000000D+00
    0.887535986328D+04-0.168138027191D+01 0.000000000000D+00 0.400000000000D+01
    0.230565717773D+05-0.886440277100D-01-0.186264514923D-08 0.200000000000D+01
```

satellite at slot 9

```
 9 98 11 17 21 45  0.0 0.141195021570D-03 0.909494701773D-12 0.774000000000D+05
    0.167495493164D+05 0.131936454773D+01 0.186264514923D-08 0.000000000000D+00
   -0.153474038086D+05-0.891745567322D+00 0.279396772385D-08 0.600000000000D+01
    0.115610678711D+05-0.309737873077D+01 0.000000000000D+00 0.100000000000D+01
 9 98 11 17 22 15  0.0 0.606067478657D-04-0.545696821064D-11 0.792000000000D+05
    0.184032075195D+05 0.521919250488D+00 0.186264514923D-08 0.000000000000D+00
   -0.167196318359D+05-0.590189933777D+00 0.279396772385D-08 0.600000000000D+01
    0.561003076172D+04-0.347185993195D+01 0.000000000000D+00 0.100000000000D+01
```

The second unreported case, the anomaly in the messages of satellite 13 on July 20th, 1999, was also caused by incorrect clock parameters. This time however, rather than transmitting the parameters of the wrong satellite, satellite 13 started to transmit zeros in the clock parameter data block from 13:45 UTC onward; see Table 5.

Table 5. Navigation Messages of GLONASS Satellite 13, Extracted from RINEX GLONASS Navigation File of Station ZIMZ (The messages show the change of the clock parameters to zero.)

```
13 99  7 20 13 15  0.0-2.454780042171D-05-9.094947017729D-13 4.770000000000D+04
   -6.726183593750D+03-2.747117996216D+00 9.313225746155D-10 0.000000000000D+00
    8.650967773438D+03-1.542927742004D+00 0.000000000000D+00 6.000000000000D+00
    2.306361572266D+04-2.170295715332D-01-1.862645149231D-09 0.000000000000D+00
13 99  7 20 13 45  0.0 0.000000000000D+00 0.000000000000D+00 4.950000000000D+04
   -1.174619677734D+04-2.781394004822D+00 0.000000000000D+00 0.000000000000D+00
    6.296288574219D+03-1.058659553528D+00 0.000000000000D+00 6.000000000000D+00
    2.178959130859D+04-1.189256668091D+00-1.862645149231D-09 0.000000000000D+00
```

To conclude the third section we would like to stress that in spite of what is reported in this and the previous subsection, GLONASS is maintained at a very high level of integrity and the GLONASS satellites do provide excellent data compared to GPS if they are healthy.

Conclusions

In this contribution a description was given of the integrity monitoring procedures, developed for GPS/GLONASS reference stations. These procedures were developed to detect and identify biases in dual-frequency code and carrier observations and are based on the recursive DIA (Detection, Identification, Adaptation) theory, which runs in parallel with a Kalman filter. After validating the observations, the navigation messages transmitted by the satellites, are checked for anomalies and biases. This is done using an approach similar to the DIA procedure.

Results were presented from analyzing data, collected within the framework of IGEX-98. Data was processed for several stations, covering almost the entire campaign so far. The data analysis revealed peculiarities in particular of the GLONASS satellites but also of the different receivers used at the IGEX-stations. Delft University of Technology is willing to continue its analysis of single-station dual-frequency data on a regular basis as an analysis center in the sequel to the IGEX-98 campaign.

Acknowledgments

The support of the Survey Department of the Ministry of Transportation and Public Works is gratefully acknowledged.

References

Cook, G.L. (1997). GLONASS Performance, 1995-1997, and GPS GLONASS Interoperability Issues, *NAVIGATION- Journal of the Institute of Navigation,* Vol. 44, No. 3, pp. 291-300.

Euler, H.-J., C. C. Goad (1991). On Optimal Filtering of GPS Dual-Frequency Observations Without Using Orbit Information, *Bulletin Géodésique,* Vol. 65, pp. 130-143.

Jin, X.X. (1996). *Theory of Carrier Adjusted DGPS Positioning Approach and Some Experimental Results,* PhD thesis, Delft University Press, Delft, ix+163 pp.

Jin, X.X., C.D. de Jong (1996). Relationship Between Satellite Elevation and Precision of GPS Code Observations, *Journal of Navigation,* Vol. 49, No. 2, pp. 253-265.

de Jong, C.D. (1996). *Principles and Applications of Permanent GPS Arrays,* PhD thesis, Department of Geodesy, Technical University of Budapest, vii+96 pp.

de Jong, C.D. (1998). A Unified Approach to Real-Time Integrity Monitoring of Single- and Dual-Frequency GPS and GLONASS Observations, *Acta Geodaetica et Geophysica Hungarica*, Vol. 33 (2-4), pp. 247-257.

de Jong, C.D. (1999). The Influence of Code Multipath on the Estimated Parameters of the Geometry-Free GPS Model, Accepted for publication in *GPS Solutions.*

de Jong, C.D., N.F. Jonkman (1999). A Permanent GPS/GLONASS Reference Station in The Netherlands, Presented at the Sixth International Conference on Integrated Navigation Systems, St. Petersburg, Russia, 24-26 May 1999.

Kalman, R.E. (1960). A New Approach to Linear Filtering and Prediction Problems, *Journal of Basic Engineering, Transactions of the ASME,* Vol. 82, pp. 35-45.

Salzmann, M.A. (1991). MDB: A Design Tool for Integrated Navigation Systems, *Bulletin Géodésique*, Vol. 65, No. 2, pp. 109-115.

Teunissen, P. J. G. (1990). An Integrity and Quality Control Procedure for Use in Multi Sensor Integration, *Proceedings ION GPS-90,* Colorado Springs, Sept. 19-21, 1990, pp. 513-522. Inst. of Navigation.

Teunissen, P. J. G., C. C. J. M. Tiberius, N. F. Jonkman, C. D. de Jong (1998). Consequences of the Cross-Correlation Measurement Technique, *Proceedings 2nd European Symposium on Global Navigation Satellite Systems GNSS 98,* Toulouse, Vol. 2, Paper No. IX-0-11, 6 pp.

Zarraoa, N., W. Mai, A. Jungstand (1997). Long Term Evaluation of GLONASS Performance, *Algemeine Vermessungs Nachrichten,* Vol. 8-9, pp.313-318.