IGEX-98

IGS

SESSION 1

INTRODUCTION, OVERVIEW, AND GLONASS OPERATIONS

The GLONASS IGEX-98 Campaign: From Its Genesis to Its Realization

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Abstract

In October 1998, a worldwide GLONASS observation campaign, named IGEX-98, was organized and is in fact still continuing. First of all some specifications were written by a Steering Committee, leading to an international Call for Participation followed by many proposals. Several groups have been very active in providing geodetic observations (GLONASS, GPS, SLR) and in analyzing these data for different purposes (precise orbit estimations, point positioning, clock comparisons). In total, around 68 GLONASS receivers were installed worldwide (including 48 dual-frequency GLONASS geodetic receivers). All GLONASS receivers were collocated with GPS receivers (if not already combined GLONASS/GPS receivers). Many of these sites are also in collocation with other space geodetic techniques (VLBI, SLR, DORIS, PRARE). The purpose of this paper is to present the scientific goals that led to the organization of such a large experiment and also to present the organization of this campaign giving a general overview of the research activity.

Introduction

From October 1998 to April 1999, an international GLONASS campaign (IGEX-98) was successfully organized thanks to a large international involvement. A network of 75 receivers was deployed worldwide and the data were processed regularly by six analysis groups for different scientific investigations: precise GLONASS orbit determination, terrestrial reference frame issues and time transfer. The goal of this paper is to present not only the campaign itself but also to explain the different steps that were taken in order to go from the original ideas and goals to the results themselves that were presented by all the analysis group at the IGEX-98 Workshop (Nashville, USA, September 1999).

The Genesis of the IGEX-98 Campaign

In 1997, there was a lot of discussion about the possible interest of GLONASS for civil applications (e.g., Langley, 1997).

The system itself seemed to be quite attractive:

- the technology was close to GPS (allowing possible combined GPS/GLONASS receivers),
- the GLONASS P-code was available to civil users without any military degradation (allowing precise applications for real-time applications such as navigation and time transfer),
- all GLONASS satellites were equipped with large laser retro-reflectors allowing possible laser tracking for precise orbit determination.

On the other hand, there were also several problems or questions that needed to be investigated:

- the future of the GLONASS constellation was not (and is still not) extremely bright and even certain,
- the relationship between the GLONASS-related PZ-90 terrestrial reference frame and the GPS-related terrestrial reference frame was not determined and several (incompatible) transformations were given by the manufacturers themselves,
- the relationship between the GLONASS time and the GPS time was not investigated,
- there were no precise GLONASS orbits available for scientific post-processing applications,
- there were very few combined GPS/GLONASS receivers and real data available to the scientific community to investigate these issues.

Taking all these aspects into consideration, and after a fruitful discussion between G. Beutler and P. Willis at the Scientific Assembly of the International Association of Geodesy (IAG) in Rio de Janeiro (September 1997), it was decided to organize a worldwide GLONASS campaign in order to investigate all these points and to understand if GLONASS could be useful to the civil community.

Since no components were operating, and because we had no idea of the feasibility itself of such an ambitious campaign, it was decided to organize the experiment within the IAG Commission VIII (Coordination of Space Techniques for Geodesy and Geodynamics) and more specifically within its sub-commission "precise satellite microwave systems", chaired by P. Willis at that time. This campaign was called IGEX-98 (International GLONASS Experiment - 1998) and was planned initially for a three-month duration.

A small number of scientists were contacted and kindly agreed to form a Steering Committee in order to organize this IGEX-98 campaign: G. Beutler, W. Gurtner (network coordinator and liaison with the laser community), G. Hein, C. Noll (data flow coordinator), R. Neilan (liaison with the IGS), J. Slater (liaison with the ION and the navigation community in general), P. Willis (chair).

The Original Goals

The original goal of IGEX-98 was to establish a worldwide network of dual GLONASS/GPS receivers observing for at least a three-month period, to collect these data on an almost daily basis and to make them available through data centers for processing at the analysis centers. All the GLONASS receivers were to be collocated with GPS receivers. In several cases they were in fact collocated with other space geodetic techniques of the International Earth Rotation Service (IERS).

Several scientific goals were foreseen and could be summarized as follows (as presented by Willis et al., 1999):

- upgrade existing scientific GPS software to allow possible GLONASS data processing,
- obtain precise GLONASS orbits (at a sub-meter level or better),
- evaluate or improve this orbit using SLR measurements,
- investigate the datum transformation between PZ-90 and WGS 84 (ITRF),
- obtain precise station positions (at a few decimeters or better),
- evaluate or improve these positioning results using the collocated GPS measurements,
- estimate the GLONASS satellite clocks and estimate the time difference between GLONASS and GPS time,
- investigate possible receiver calibration problems and compare the performances of the available GLONASS receivers.

It is obvious from this list that our goals were quite ambitious and broad, leading to potential major interests from several communities (e.g., geodesists, navigation users, time transfer metrologists, etc.).

Several organizations were interested in such an international GLONASS campaign and proposed to sponsor the IGEX-98:

- the IAG Commission VIII (CSTG)
- the International GPS Service (IGS)

- the Institute of Navigation (ION)
- the International Earth Rotation Service (IERS).

The Preparation of the Campaign

During the fall of 1997, the IGEX-98 Steering Committee started to draft several necessary technical documents (station requirements, data flow monitoring) and also an international Call for Participation. This part was done in a very short time due to the high degree of expertise of the writers and also the fact that we were trying to follow the organization of the IGS which had already been operational for several years.

Those documents were circulated broadly (in particular using a new Web site: http://lareg.ensg.ign.fr/IGEX) at the Institut Géographique National (IGN) in France. They were also submitted (and accepted after some minor modifications) to the IGS and the IERS Governing Boards in December 1998.

At that time, an international Call for Participation was issued making use of several Bulletin Boards (IGS Mail, IERS Gazette, etc.) and also published in the IAG Newsletter (Willis et al., 1998).

In June 1998, the Steering Committee, which previously worked only by e-mail, had its one (and only) meeting at IGN in Marne-la-Vallée in France in order to review all the answers to this Call for Participation. At that time, it became clear that the number of answers was exceeding (by far) our most optimistic goals. It also become clear that some operational aspects could not be solved before the start of the campaign (initially planned for September 19, 1998): some receivers would not be in the field at that time, or even purchased; some technical problems still remained in the RINEX conversion; the data flow was far from being operational for some stations. It was then decided to postpone the campaign by one month and to start by October 19, 1998.

In order to keep the IGEX-98 community informed about the plans and also about the on-going operational, a bulletin board (IGEX Mail) was created at IGN. The distribution list has rapidly grown to 470 and since October, around 40 messages are issued every month.

The IGEX-98 Campaign

During the entire span of the campaign (October 1998 to April 19, 1999), 75 receivers were deployed at 61 sites, involving 26 countries:

- 48 dual-frequency GLONASS receivers,
- 20 single-frequency GONASS receivers,
- 7 GPS-only receivers

Note that all the GLONASS receivers were either combined GPS/GLONASS receivers or closely collocated with a dual-frequency GPS receiver. A concerted effort by the newly created International Laser Ranging Service (ILRS) led to 30 SLR stations, tracking 9 GLONASS satellites. A more detailed description of the campaign itself can be found in (Slater et al., 1999).

All of the GPS and GLONASS data are freely available to the scientific community through two global data centers - NASA’s Crustal Dynamics Data Information System (CDDIS) and IGN). Twenty-one centers (from 12 different countries) proposed to analyze these data and six centers were able to produce results in an almost timely manner. At that time, R. Weber was appointed as a new member of the Steering Committee in the role of Analysis Coordinator in order to evaluate (and combine) the IGEX-98 precise orbits (see Weber and Fragner, 1999).

Preliminary Results

Results will be presented during the IGEX-98 Workshop. Basically, precise GLONASS orbits were obtained with an accuracy of about 20 cm in the radial component as summarized by (Weber and Fragner, 1999). From these precise orbits, station positions were obtained at the few millimeter level using only GLONASS (and its limited constellation). See, for example (Ineichen et al., 1999).

The terrestrial reference frame issue is addressed by several participants, either using the tracking stations approach as done by (Boucher et al., 1999), or using the satellite orbits themselves as done by (Mitrikas et al., 1999). As for the time transfer issue, some work still needs to be done in order to make proper use of the IGEX-98 precise orbits (Lewandowski, 1999).

The Post-Campaign Period

Looking at these results, it would have been quite a pity to stop the campaign without any plan for the future. On the other hand, the participants only answered the Call for Participation in view of a limited campaign (three months originally). At the conclusion of the campaign, it was decided to ask the participants to continue on a "best effort basis" until a decision about continuing the project could be made at the IGEX-98 Workshop. It was also suggested that only the dual-frequency GLONASS equipment should be maintained operational in order to decrease the analysis burden.

Since the end of the campaign, the network has been less dense, but 20 to 30 receivers are still operational (with large gaps in the Southern hemisphere, especially in South America and at a lesser level in Africa). However, four analysis groups are still analyzing these data on a regular basis.

It is likely that the IGEX-98 campaign will be followed by a new organization, as proposed by (Beutler et al., 1999), in order to generate new types of IGS products, as long as the GLONASS constellation is still maintained (even with a limited number of satellites).

Conclusions

In conclusion, the IGEX-98 campaign was quite a challenging experience. Thanks to the expertise gained by the geodetic community with the International GPS Service, organizing the IGEX-98 campaign was not too difficult. This campaign led to a large international cooperation, merging people from different fields such as geodesy, navigation and time transfer metrology.

The results of the campaign (20-cm orbit, centimeter accuracy positioning) exceeded the scientific expectation of most participants. It is then quite logical that such a campaign would continue, within the umbrella of IGS, if the GLONASS system remains viable for future years.

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The GLONASS System – Status and Prospects

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Abstract

The paper outlines the current status of the GLONASS constellation and efforts of the Russian Federation government aimed at sustaining and further developing the GLONASS system. The latest governmental decrees and other directives relevant to GLONASS are provided. The paper also discusses the main points of the program for maintaining and developing the GLONASS system over the next three years, the readiness of GLONASS for Y2K problem resolution, and some key issues of international cooperation in the field of GLONASS technology, including the declared willingness of the Russian Federation to make the GLONASS system available as a base for creating an international global navigation satellite system.

Introduction

The global navigation satellite system GLONASS is a government dual-purpose space system, designed to meet the needs of the Ministry of Defense and civil users. Toward this end, a high accuracy channel (1.2/1.6 GHz range) is earmarked for users in the Ministry of Defense, and a standard accuracy channel (1.6 GHz range) is for civil use.

The first launch of a GLONASS satellite took place on 12 October 1982. On the basis of Decree No. 658-rps of the President of the Russian Federation dated 24 September 1993, the system was accepted into operation as a first-stage constellation (twelve satellites) with the proviso that the standard constellation (24 satellites) be deployed by 1995. At the end of 1995 the GLONASS constellation was expanded to its full complement (24 satellites, eight each in three orbital planes in circular orbits with a height of 19,100 km and an inclination of 64 degrees).

GLONASS has gained universal recognition as a full-fledged component in the world-wide infrastructure for global provision of coordinates and time. GLONASS is an actually existing and actually functioning system performing on a high technical level, a fact repeatedly confirmed by independent foreign experts. In addition, GLONASS has great potential for having its performance improved to a level capable of meeting the future needs of its users.

Current Status of the GLONASS System

Due to a lack of funds, the constellation of satellites has not been added to for two years. This means that at the present time (10 September 1999), the constellation is composed of a total of 16 GLONASS satellites, as shown in Table 1, of which:

- Eleven (11) are being used for the intended purpose. In this case, eight satellites are outside the guaranteed life expectancy (three years); of these, two have been in operation since 1994, and six since 1995.
- Five (5) are not being used for the intended purpose; documents have been prepared to discontinue operation of two of them (763, 762); one (770) has been temporarily shut down for passage through shaded regions of the earth and moon; and the reasons the other two (758, 765) have malfunctioned are being investigated. Plane and slot number locations for these are shown in Figure 1.

Table 1. GLONASS Constellation Status on 13 September 1999

GLONASS Number	KOSMOS Number	Plane (Slot)	Frequency Number	Launch Date	Date Put Into Service	Status of Satellite	Date Taken Out of Service
758	2275	3 (18)	10	11.04.94	04.09.94	out of service	05.03.99
770	2288	2 (14)	09	11.08.94	04.09.94	out of service	24.08.99
775	2289	2 (16)	22	11.08.94	07.09.94	in operation	
762	2294	1 (04)	12	20.11.94	11.12.94	out of service	04.09.99
763	2295	1 (03)	21	20.11.94	15.12.94	out of service	27.07.99
764	2296	1 (06)	13	20.11.94	16.12.94	in operation	
765	2307	3 (20)	01	07.03.95	30.03.95	out of service	10.09.99
766	2308	3 (22)	10	07.03.95	05.04.95	in operation	
781	2317	2 (10)	09	24.07.95	22.08.95	in operation	
785	2318	2 (11)	04	24.07.95	22.08.95	in operation	
776	2323	2 (09)	06	14.12.95	07.01.96	in operation	
778	2324	2 (15)	11	14.12.95	26.04.99	in operation	
782	2325	2 (13)	06	14.12.95	18.01.96	in operation	
779	2364	1 (01)	02	30.12.98	18.02.99	in operation	
784	2363	1 (08)	08	30.12.98	29.01.99	in operation	
786	2362	1 (07)	07	30.12.98	29.01.99	in operation	

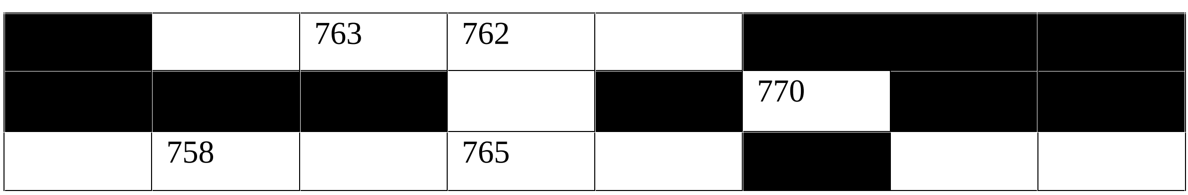

Figure 1. Plane and slot number locations of "out of service" satellites. (Top row is plane 1, slots 1-8; middle row is plane 2, slots 9-16; bottom row is plane 3, slots 17-24.)

Currently the average coverage of the earth (defined as the percent of time during which a user has in view no less than four satellites with an acceptable relative position geometry) has been reduced to 60% or less, which is causing a corresponding deterioration in the system's basic operating characteristics (availability, reliability and accuracy). To complete and maintain the GLONASS constellation, it is necessary to conduct no fewer than two launches (three satellites each) yearly, and this requires significant financial outlays.

Government Policy Relative to the GLONASS System

Acknowledging that GLONASS is the national property of Russia, the President of the Russian Federation, by his Decree No. 38-rp dated 18 February 1999, committed the government of the Russian Federation to adopt measures to unconditionally preserve and develop the GLONASS system. To carry out this decree, the government of the Russian Federation adopted Declaration No. 346 dated 29 March 1999, concerning: “Measures to carry out Decree No. 38-rp of the President of the Russian Federation dated 18 February 1999”, which affirmed “A provision to fix the limits of responsibility of federal executive agencies with respect to maintenance, use, and development of GLONASS”, and which sanctioned a “Plan of immediate measures to maintain and develop GLONASS”.

In accordance with this plan, the most important and urgent problems are to work out an interagency program to maintain and develop GLONASS and to do so within the next three years. The plan provides specific measures to maintain and expand the system with the mandatory condition that they be fiscally responsible. Such a program must by nature guarantee the possibility of future application of GLONASS for a wide circle of users at the federal and regional levels, and must subsequently also be the basis for joining forces with other ministries and agencies interested in preserving and expanding the system.

One of the program’s fundamental goals is to implement a mechanism for shared financing of complex dual-purpose systems by interested ministries and agencies, and also to create conditions for bringing in sources of financing that are outside the budget.

The program envisions two steps in the maintenance and development of GLONASS. In the first step — until the end of 2001 — the plan is to complete and maintain the constellation at the minimum level necessary to provide navigation support to its users. In this case, a minimally required level is taken to be a constellation of 15 to 18 satellites, assuring a three-dimensional positioning accuracy of no worse than 100 meters over 90% of the earth’s surface. Maintaining such a constellation requires four launches of blocks of three GLONASS satellites.

The plan calls for a concurrent acceleration of work to modernize GLONASS. In the second step — from the end of 2001 to 2003 — the plan is to expand the GLONASS-M system to the standard configuration.

At all steps of the program, a solution of the three-part problem of joint expansion of the constellation, the ground-based control system, and the infrastructure of users is proposed. Presently the Russian Ministry of Defense has in reserve two GLONASS satellites (guaranteed service life, three years) with equipment for insertion into orbit. A third satellite is 50% ready. One modernized GLONASS-M satellite with a guaranteed service life of five years is basically finished and is in the final stage of assembly at the “Polet” Industrial Association (Omsk).

Program for Maintaining and Developing GLONASS

The goal of this interdepartmental program is to:

- assure preservation of GLONASS as a basic space system having important defense, social and economic implications;
- promote introduction of space navigation technologies into the national economy;
- attract foreign investments to finance work on GLONASS by making it available as the basis for building an international global navigation satellite system.

The direction of the work is to:

- maintain the GLONASS Constellation;
- deploy the GLONASS-M Constellation;
- modernize GLONASS satellites;
- modernize the ground-based control complex;
- develop the infrastructure of users and the equipment to operationally enhance the GLONASS system;
- expand international cooperation in the realm of satellite navigation.

Sources and mechanism for participation in financing:

- Government defense law;
- Federal space program;
- Federal special program for using GLONASS in the interests of civil users;
- Other budgetary sources and sources outside the budget, drawn together by special resolutions of the government of the Russian Federation and governmental customers of GLONASS.

GLONASS and the Y2K Problem

The date and time on board a GLONASS satellite are recorded by loading a time program in which relative time is given in seconds (relative to 00 hours 00 minutes 00 seconds of 1 January of the most recently passed leap year) in a four-year cycle. A new four-year cycle for counting time begins at the start of each leap year (00 hours 00 minutes 00 seconds on 1 January).

Since the GLONASS satellites began operation with the last two modifications of the on-board computer, (that is, since 25 May 1988), there have been two transition dates from cycle to cycle — 1 January 1992 and 1 January 1996. All 36 satellites that were used in the GLONASS system at this time passed these dates without any problems.

In connection with the fact that relative time is established on GLONASS satellites, to them 1 January 2000 is no different than 1 January 1992 or 1 January 1996. Consequently, as the transition is made to the year 2000, GLONASS satellites will operate stably.

An updated version of the special software, which completely solves the Y2K problem for the ground-based control complex, will undergo comprehensive testing in November of this year. Once the tests are completed, a final conclusion will be drawn about how prepared the space and control segments of GLONASS are to provide proper operation as we pass over into the year 2000.

GLONASS and International Cooperation

International cooperation in global satellite navigation in large measure influences and can be influenced by the successful solution of many problems, in particular:

- shielding the frequency range of satellite radio navigation from currently deployed systems of Mobile Satellite Services (MSS);
- introducing international standards of use of global satellite navigation (e.g., ICAO, GNSS, SARPs) and bringing them into agreement with already existing normative documents of different governments;
- switching to a new generation of satellites on condition that the constellation and operating features of the system be maintained at the stated level;
- taking into account the growing need of users for reliability and accuracy of the coordinate and time services, etc.;
- bringing time and coordinate reference systems into agreement when GPS and GLONASS are used in combination;
- resolving issues of military and civil interaction for managing and using global navigation systems.

In execution of Decree No. 38-rp of the President of the Russian Federation dated 18 February 1999, which speaks of the “willingness of the Russian Federation to make the GLONASS system available as a base for creating an international global navigation satellite system”, a concept is currently being worked out to use GLONASS in this capacity with due regard for the country’s defense and security.

At the aerospace conference of the ICAO in Montreal in September 1991, a resolution was adopted about using GLONASS and GPS as components of a global navigation satellite system (GNSS), as was a recommendation about using these systems at the same time in order to increase accuracy, reliability and integrity of the navigation service. In 1996 agreements were reached between the Russian Federation, the ICAO and the IMO about using GLONASS as a component of a GNSS together with the U.S. GPS. At the present time, within the framework of the ICAO, the Russian Federation is taking part in developing Standards and Recommended Practices for a GNSS, and drawing up other documents necessary for using GLONASS and GPS.

Conclusion

On the basis of the country's current scientific and technical potential, the Russian Federation is implementing a policy to broaden the use, maintenance and improvement of GLONASS for the purpose of safeguarding the interests of national security and increasing the efficiency of transportation and other branches of the economy along the following lines:

- strengthen and maintain national security;
- increase operating efficiency and safety of transportation and other branches of the economy through application of GLONASS;
- maintain the scientific and technical potential of the Russian Federation in the area of space navigation systems;
- maintain and develop GLONASS as a base for a Federal navigation system and the equipment for operational enhancements aimed at increasing its utility for all users;
- provide for the wide-scale introduction of GLONASS into different spheres of activity;
- actively advance GLONASS for acceptance by the world community as the standard navigation system for civil, commercial and scientific application;
- universal concurrence on an international agreement regarding use of GLONASS;
- promote mass production of equipment for GLONASS users;
- attract foreign investments to finance work on GLONASS by making it available as a base for creating an international global navigation satellite system.

The Russian Federation intends to maintain and improve GLONASS, ensuring the announced basic technical characteristics for a period of no less than 15 years, subject to sufficient guaranteed special financing in accordance with the legislation in force in the Russian Federation.

A standard accuracy signal on a permanent global base will be made available without levying direct fees for civil, commercial and scientific use. There is no suggestion that any methods of encoding or degrading the standard accuracy signal will be used.

The GLONASS system, as well as the auxiliary facilities that raise its performance and are located in the Russian Federation, are government property and will be managed by competent government agencies.

The Russian Federation intends to further cooperation with other governments and international organizations in the matter of civil use of GLONASS, and also its auxiliary facilities, with due concern for the interests of national security and the foreign policy of the Russian Federation.

The Russian Federation intends to follow a path to future use of GLONASS and its auxiliary facilities as a component of international global navigation satellite systems.

The Russian Federation intends to universally encourage the quickest possible introduction of GLONASS into all spheres of activity; support development and manufacture of necessary equipment; acquire sufficient equipment for GLONASS users as well as auxiliary facilities. It will not take actions aimed at limiting commercial activity in the area of expanding the use of GLONASS. The above pledges will be valid as long as they do not go against the country's national security and economic interests.

The Russian Federation intends to offer assistance and grant licenses and privileges to domestic manufacturers of navigation equipment, users and investors, and also to encourage all types of mutually advantageous collaboration with foreign governments and companies in the field of satellite navigation technologies.

Appendix 1

Index of Government Documents Defining Policy with Respect to the GLONASS System

- *Decree No. 658rps of the President of the Russian Federation dated 24 September 1993 concerning introduction into operation of the GLONASS global navigation satellite system;*
- *Declaration No. 237 of the Government of the Russian Federation dated 7 March 1995: "Conducting operations using the GLONASS global navigation satellite system in the interests of civil users";*
- *Declaration No. 1435 of the Government of the Russian Federation dated 15 November 1997: "Federal program for using the GLONASS global navigation satellite system in the interests of civil users";*
- *Charge No. Pr-1451 of the President of the Russian Federation to the Government of the Russian Federation dated 4 November 1998 (concerning development of an action plan for the unconditional maintenance and development of GLONASS);*
- *Declaration No. 3348-PGD of the State Duma of the Russian Federation dated 9 December 1998: "Measures to ensure operation of the GLONASS global navigation satellite system";*
- *Decree No. 38-rp of the President of the Russian Federation dated 18 February 1999;*
- *Declaration No. 346 of the Government of the Russian Federation dated 29 March 1999: "Measures to implement Decree No. 38-rp of the President of the Russian Federation dated 18 February 1999"*

  (this declaration affirmed the "Provision to fix the limits of responsibility of federal executive agencies with respect to maintenance, use, and development of GLONASS"; endorsed the "Declaration of the Government of the Russian Federation; and approved the "Plan of immediate measures to maintain and develop GLONASS");
- *Declaration No. 896 of the Government of the Russian Federation dated 3 August 1999: "The use of navigation satellite systems in the Russian Federation for transportation and geodesy".*

Note: texts of the documents are available on the Internet on the home page of the Coordination Scientific Information Center (KNITs) at http://www.rssi.ru/SFCSIC/SFCSIC-main.html.

Appendix 2

Declaration of The Government of The Russian Federation

The global navigation satellite system GLONASS has been created, deployed and put into operation in the Russian Federation. The purpose of the system is to continuously provide users with coordinate and time information at any point on the earth.

Taking into consideration the great importance of the satellite navigation system for effective solution of problems in transportation, geodesy, and other scientific and practical applications, as well as the objective need for widespread implementation of new combined information systems with users' satellite navigation equipment, on 18 February 1999 the President of the Russian Federation adopted a resolution on Russia's movement up to a new level of international cooperation. This means offering the Russian navigation satellite system GLONASS as a basis for creating and developing international global navigation satellite systems.

Realization of this proposal will promote strengthening of the degree of trust and openness in international relations; maintain international stability; and widen scientific and technical relations between countries.

In this connection, the government of the Russian Federation approved measures aimed at assuring operation of the orbital grouping of the GLONASS global navigation satellite system in the required configuration and at concentrating the efforts and abilities of concerned ministries and agencies to further improve the system. The Russian Space Agency is responsible for application and development of GLONASS in the interests of civil users, as well as for international cooperation in this field.

GLONASS Constellation Maintenance, 1998-1999

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Abstract

Amid troubled economic and political times, the Russians have struggled to maintain a useable constellation of satellites. The outlook for the GLONASS constellation seemed very bleak at ION GPS-98. Over a three year span without launches, the number of useable satellites dwindled to eleven. Ailing satellites were kept on board even when very unreliable. However, 1999 has seen the introduction of three satellites launched at the end of 1998, a long awaited activation of the spare satellite in plane 2, and more recent efforts to revitalize another existing satellite long thought dead. This paper examines some of the maintenance problems noted during the last 1.5 years and some of the success stories. Individual and historical satellite accuracies are examined to determine how well the new satellites are doing.

Introduction and Background

Observations of GLONASS operations over the past year give mixed impressions of the overall program status. Encouraging signs were the launch of three new satellites, activation of the spare, and reactivation of an older satellite once thought dead, thereby adding five usable satellites. Meanwhile, three satellites were withdrawn from service, and presently five others, including the reactivated one are unusable, resulting in a net loss to the user. The GLONASS control segment was very persistent in trying to extend the life of failing satellites, but seemed to be less consistent in day-to-day maintenance of the satellite onboard information than in past years. This paper examines some of the maintenance related activities of the past year and a half in particular, and draws from historical data to put the observations in context. Discussions begin with a comparison of the constellation in September 1999 versus September 1998. The new launch and activation of the spare are discussed, followed by observations about the failed/failing satellites. While an aging constellation would be expected to require more vigilant maintenance procedures to assure satellite integrity and reliability, there is evidence of neglect. During the past year and a half there have been several instances in which none or few of the satellites received ephemeris or clock uploads for several days. Some idiosyncrasies of "old" clock and ephemeris data are discussed. There is some historical evidence that maintenance procedures, and possibly accuracy, were better several years ago than they are today.

Sequoia Research Corporation (SRC) has operated a GPS-GLONASS receiver in support of the Federal Aviation Administration to monitor GLONASS operation and performance since 1992. An integrated GPS-GLONASS receiver is run on a 24-hour basis except for data downloads and maintenance. For diagnostic purposes, all data possible are collected on all

GLONASS satellites, whether or not they are declared healthy. This is done by overriding receiver defaults and in some cases placing custom almanacs in the receiver. The receiver is an 8-16 channel (depending on settings) model R-100 GPS-GLONASS C/A-code receiver built by 3S Navigation. A cesium clock is used for frequency/time reference and allows assessment of individual satellite errors (Cook, 1997). Because the R-100 does not offer dual frequency data, SRC was not an active participant in IGEX. However, IGEX data have been used to augment on-site collections.

GLONASS Status, September 1998 and 1999

As of 10 September 1999, there are eleven usable GLONASS satellites (Notice, 1999). Five other satellites are listed as operational, but unhealthy, and several of those have been unusable for some time. Table 1 shows the status a year ago and present, along with some comments.

Table 1. GLONASS Constellation Status, September 1998 and 1999 (Holmes, 1998)

Plane	Slot	Launch Date	Sep 98	10 Sep 99	Comments on Present Status
1	1	12/30/98	-	Healthy	Launched 12/30/98
	2	-	-	-	
	3	11/20/94	Healthy	Unhealthy	Last Transmitted 7/27/99
	4	11/20/94	Healthy	Unhealthy	Last Transmitted 9/3/99
	5	-	-	-	
	6	11/20/94	Healthy	Healthy	
	7	12/30/98	-	Healthy	Launched 12/30/98
	8	12/30/98	-	Healthy	Launched 12/30/98
2	9	12/14/95	Healthy	Healthy	
	10	7/24/95	Healthy	Healthy	
	11	7/24/95	Healthy	Healthy	
	12	-	Healthy	-	Last Transmitted 11/5/98;Withdrawn 2/3/99
	13	12/14/95	Healthy	Healthy	
	14	8/11/94	Unhealthy	Unhealthy	Transmitted from 4/29/99 to 8/24/99
	15	12/14/95	Healthy	Healthy	Old satellite replaced by spare on 4/26/99
	16	8/11/94	Healthy	Healthy	
3	17	4/11/94	Healthy	-	Last Transmitted 7/3/99;Withdrawn 9/9/99
	18	4/11/94	Healthy	Unhealthy	Unusable 3/5/99; shuts down during eclipses
	19	-	-	-	
	20	3/7/95	Healthy	Unhealthy	Only brief transmission on 9/10/99
	21	-	-	-	
	22	3/7/95	Healthy	Healthy	
	23	-	-	-	
	24	-	-	-	

Satellites Added to the Constellation

Launch of Slots 1, 7, and 8

Satellites from the 30 December 1998 launch were placed in Slot 7. As depicted in Figure 1, two of the satellites were then transferred into Slots 1 and 8. Satellites in Slot 7 and 8 began transmitting in mid January and were brought into the active constellation on 29 January 1999. The satellite in Slot 1 did not stabilize its orbit until early February, but by 18 February 1999 it, too, was operational. There may have been problems with that satellite, as the time from launch until operational status was somewhat longer than normal. As shown in Figure 1, the new satellites are all very close to the locations specified in the Interface Control Document (ICD). It would appear that little or no station keeping is done, so one may note some of the older satellites have drifted a few degrees off the ICD-specified station.

Spare Replacement of Slot 15

The spare satellite, which had been listed in Slot 9, was activated in Slot 15 in April 1999. The former Slot 15 had stopped operating in December 1998 but was just listed as unhealthy until April 1999. The spare had been steadily drifting forward in Plane 2 since its launch in December 1995, and had just crossed the Slot 15 station around January 1999. In mid-April, its drift was reversed to place it back in Slot 15. After a brief checkout, it was declared healthy in almanacs and on the internet on 26 April 1999. The onboard satellite health bit did not appear healthy until 27 April.

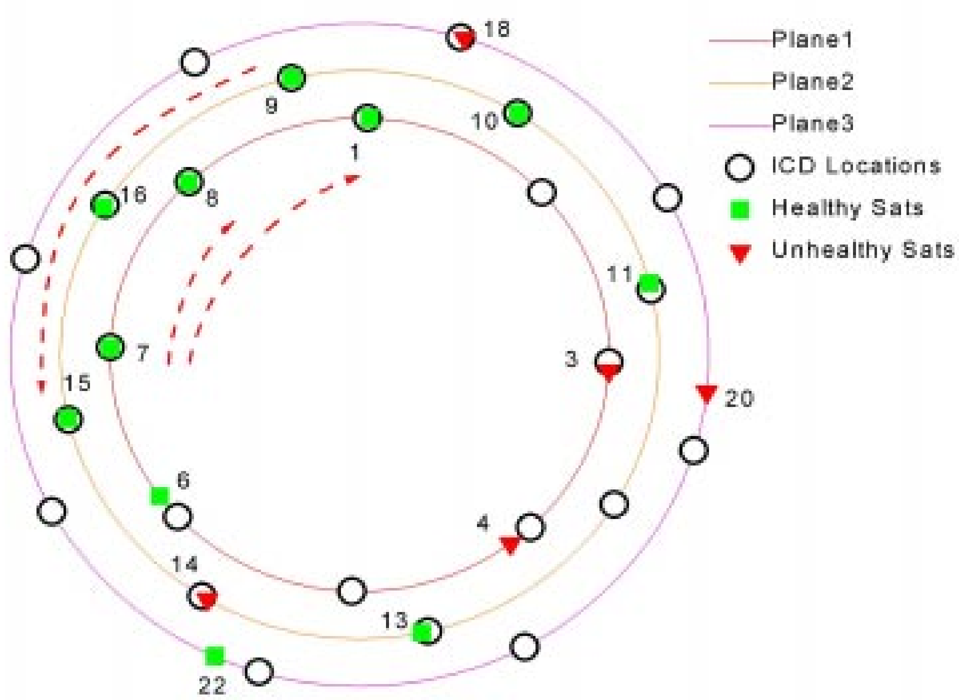

Figure 1. GLONASS constellation, September 1999.

Failed/Faltering Satellites

Slot 12

Slot 12 stopped transmitting on 5 November 1998 and was formally withdrawn from service on 3 February 1999. Although the satellite had some problems in late 1997, those seemed to have been resolved, and the satellite had been operating normally through the day before it stopped transmitting. It looked as though only one clock was used on this satellite, and since there are supposed to be three redundant clocks on the satellites, it would seem some other subsystem must have failed.

Slot 15

Slot 15 (NORAD 23620) went unhealthy for the last time on 3 December 1998, stopped transmitting on 4 December, and was withdrawn from service in April 1999. Figure 2 shows range errors derived from pseudorange measurements, as well as the transmitted clock bias and frequency (derived from daily first differences of the bias, without relativistic compensation). The satellite was down a number of times for clock resets and/or changes. In later months it was particularly unreliable, and the lack of a stable frequency reference probably led to the decommissioning of the satellite.

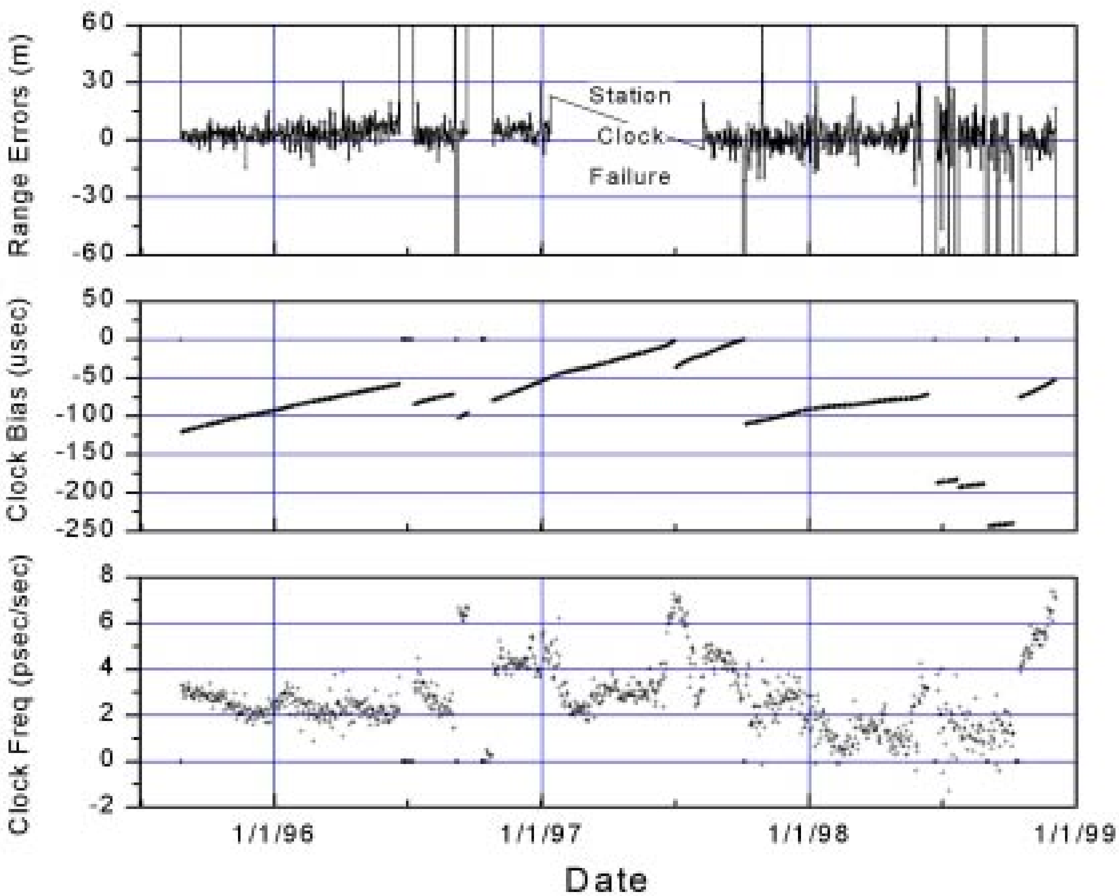

Figure 2. Slot 15 range errors and clock parameters.

Slot 17

Slot 17 stopped transmitting on 3 July 1999 while the SRC receiver was tracking it, and was withdrawn from service on 9 September 1999. The internet page said the satellite was operating between 13 and 30 July, but none of the satellite almanacs indicated it was healthy during that period. The satellite had generally performed well during its lifetime, and no persistent problems had been noted before it stopped. The satellite appeared to have only used two clocks and the second seemed stable when the satellite quit, so the failure would not seem clock related.

Slot 18

Slot 18 has not been usable since 5 March 1999. Prior to this outage, it had been down for six weeks every six months during its eclipse season. It continues to transmit, although the message fields are all zeros. Almanac ephemeris data for it in the other satellites are valid, but the frequency number has been zeroed out. Range errors and clock parameters are shown in Figure 3. Although clock phase was reset after each outage, the frequency history looks continuous until a discontinuity in early 1998. It looks like the satellite may have only used two clocks, but it was probably plagued by power problems all its life. Given the ground segments continual efforts to use satellites to the end, Slot 18 will probably not be withdrawn for a while.

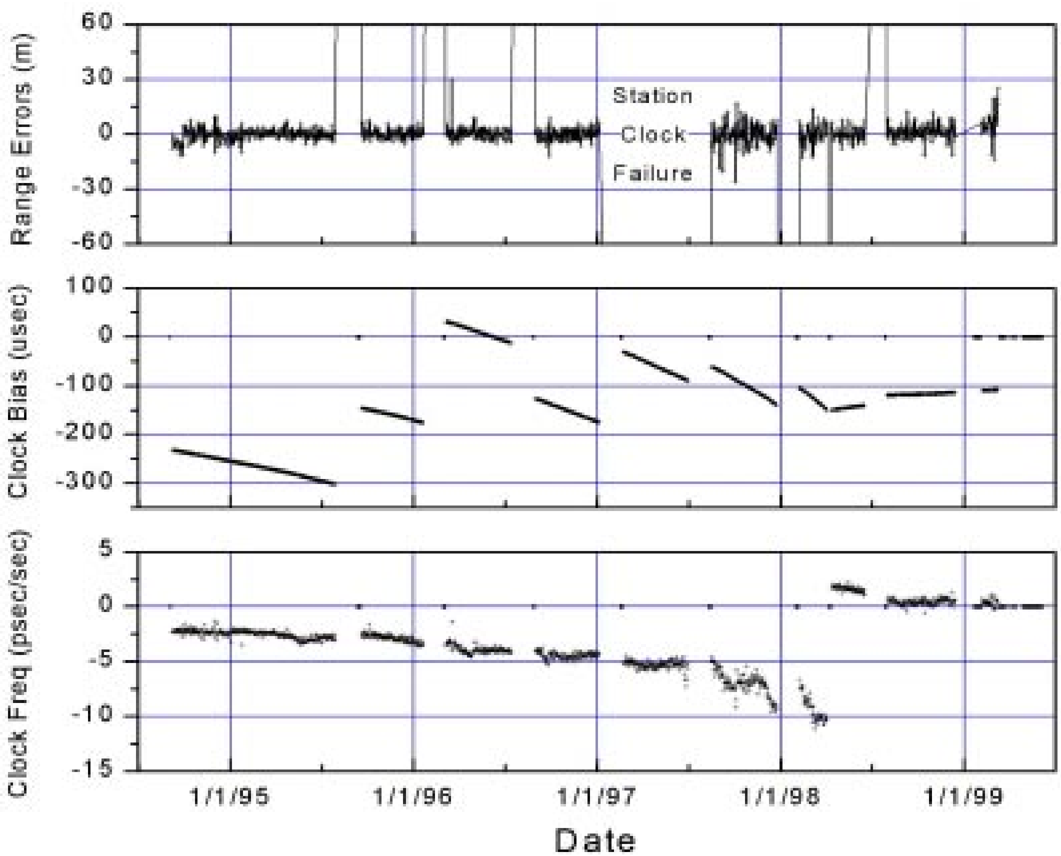

Figure 3. Slot 18 range errors and clock parameters.

Slot 14

The reactivation of Slot 14 came as a surprise. That satellite stopped transmitting in November 1997, and came back in January 1998 to transmit in an unhealthy, unusable status with all zero data fields until March 1998. In March, it went off the air again, and in May 1998, the ephemeris data for Slot 14 in all other satellite almanacs were replaced by a default (unrealistic) set of elements. That had usually been an indicator the satellite would be withdrawn, so SRC receiver tasking for Slot 14 was stopped. However, the satellite was never dropped from the operational list on the internet web page.

On 15 April 1999, other satellite almanacs indicated realistic ephemerides for Slot 14, instead of the default ones, but its frequency number remained zero. On 29 April, a custom almanac with the previous frequency number was inserted in the SRC receiver, and the receiver picked up the satellite on its next pass. At that time, the transmitted status was unhealthy, but data messages were valid, and pseudorange measurements indicated the satellite could have been used. Although seemingly usable, it remained unhealthy and unannounced from April until 8 July, when it was declared healthy in other satellite almanacs and on the internet. Presumably the long period of successful, but unannounced operation was a confidence building measure, given the long outage.

It is interesting that something went wrong on Slot 14 that took over a year to fix, and it could be fixed from the ground. Many observers had believed the satellite was dead and needed to be replaced by the spare. As stated before, the ground segment seems to have been persistent in trying to preserve the assets they have.

Slot 14 appeared to stop transmitting on 24 August 1999 and has not been detected as of the writing of this report. The internet page says it is down for maintenance for an undetermined time.

Slot 3

Slot 3 appeared to stop transmitting on 27 July 1999. It had changed to a third clock in April 1999. On 16 June, 11 July, and 13 July 1999 there appeared to be some minor problems with the satellite, but those seemed to have been corrected. The satellite is simply listed as unusable on the internet, and is still listed in satellite almanacs as unhealthy.

Slot 4

Slot 4 stopped transmitting on 4 September 1999. It is still listed in satellite almanacs with a valid frequency and valid ephemeris data. It was on its second clock and appeared to be operating well before it quit. It is too early to tell if it will come back or not.

Slot 20

Slot 20 appeared to only transmit briefly on 10 September 1999 during a pass visible to SRC, and it was declared unhealthy on the internet. No additional information is available as of this printing.

Age of Data, 1998-1999, and Maintenance Lapses

The regularity of ephemeris and clock refreshment (uploads) can give an indication of how well the GLONASS system is being maintained. The GLONASS ICD states that clock uploads will be done twice a day and ephemeris data will be done "periodically". Based on SRC and others' observations, the general schedule was clock uploads every orbit, and ephemeris uploads approximately every other orbit (Misra et al. 1993). The age of clock information is difficult to directly discern, as there is no age word directly associated with it, but an ephemeris age word increments by one at the Moscow day rollover. Thus it is easy to tell if the satellite ephemeris data are being routinely maintained.

Figure 4 shows ephemeris age data for all the satellites since the beginning of 1998, with the age words color- and size-coded. The bottom plot shows age words for individual satellites, while the top plot shows all satellites overlaid. An age of 0 or 1 (in green, smallest symbol) is considered normal, 2 (in red) is somewhat unusual, and 3 or greater (in blue, largest symbol) is highly uncommon. Several blue areas can be detected, but February 1998 and June 1999 stand out because nearly all the GLONASS satellites indicate an ephemeris age of 3 or greater for a period. The summer months of 1999 show more red areas (age of 2) than previous times.

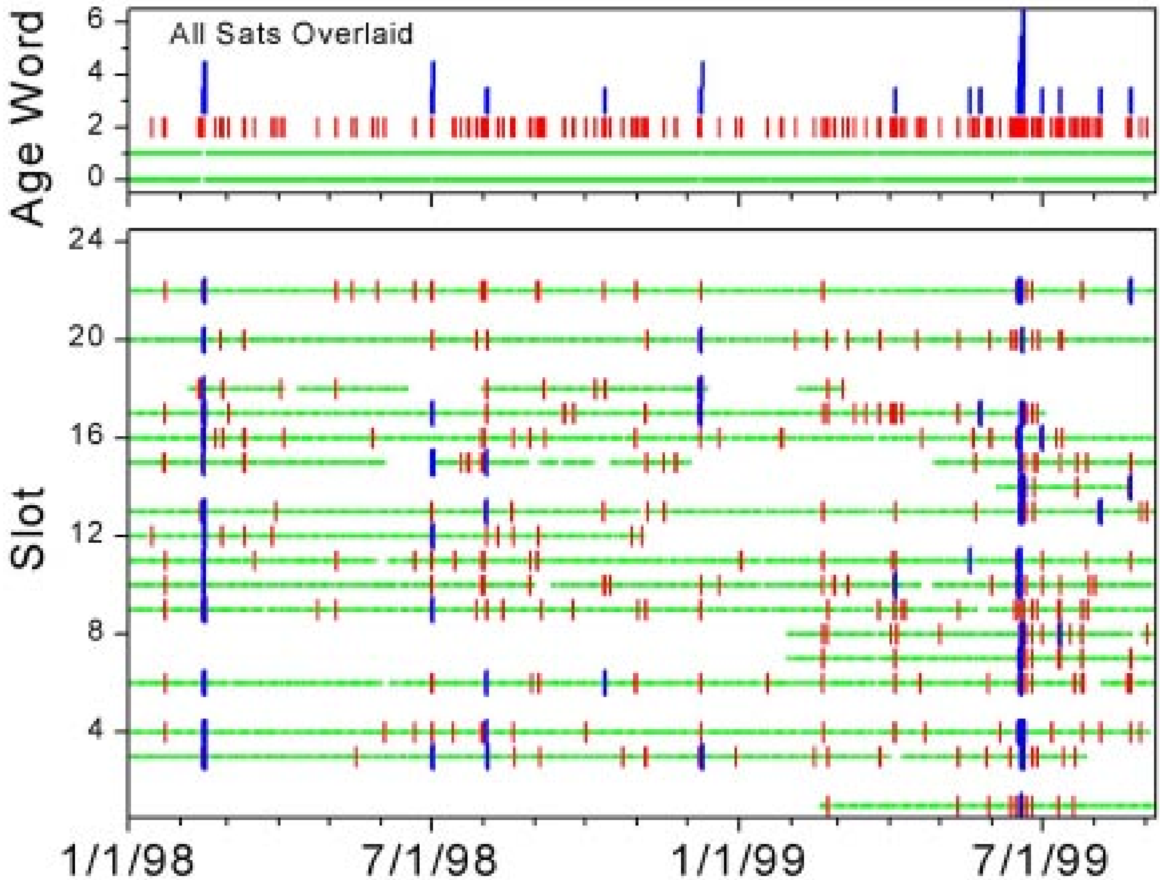

Figure 4. GLONASS Age of Data words, 1998-1999.

Missing Uploads, February 1998

Figure 5 shows a blowup of the data in February 1998 with increased resolution of the color and size coding of Age and with detected clock uploads, based on SRC collections. It does not look like any ephemeris uploads were made between late on 12 February and sometime on 15 February. Some of the satellites did not receive ephemeris data until 16 February. No such lapse of ephemeris uploads had been observed in prior data collected at SRC.

Although clock age is more difficult to discern, many clock uploads are observed directly at SRC. The ones detected are shown with a small black triangle/mark above the bars showing coverage in the figure. By inspection, one can note that the regularity of uploads was suspended at about the same time as when ephemeris data were not being uploaded. One exception is an upload to Slot 6, which just happened to have one of the most troublesome clocks during this period. It is possible that the control segment was monitoring the satellite and trying to keep errors within certain bounds. Surprisingly, the observed impact on range errors during this period was small, and was not very significant in statistical terms.

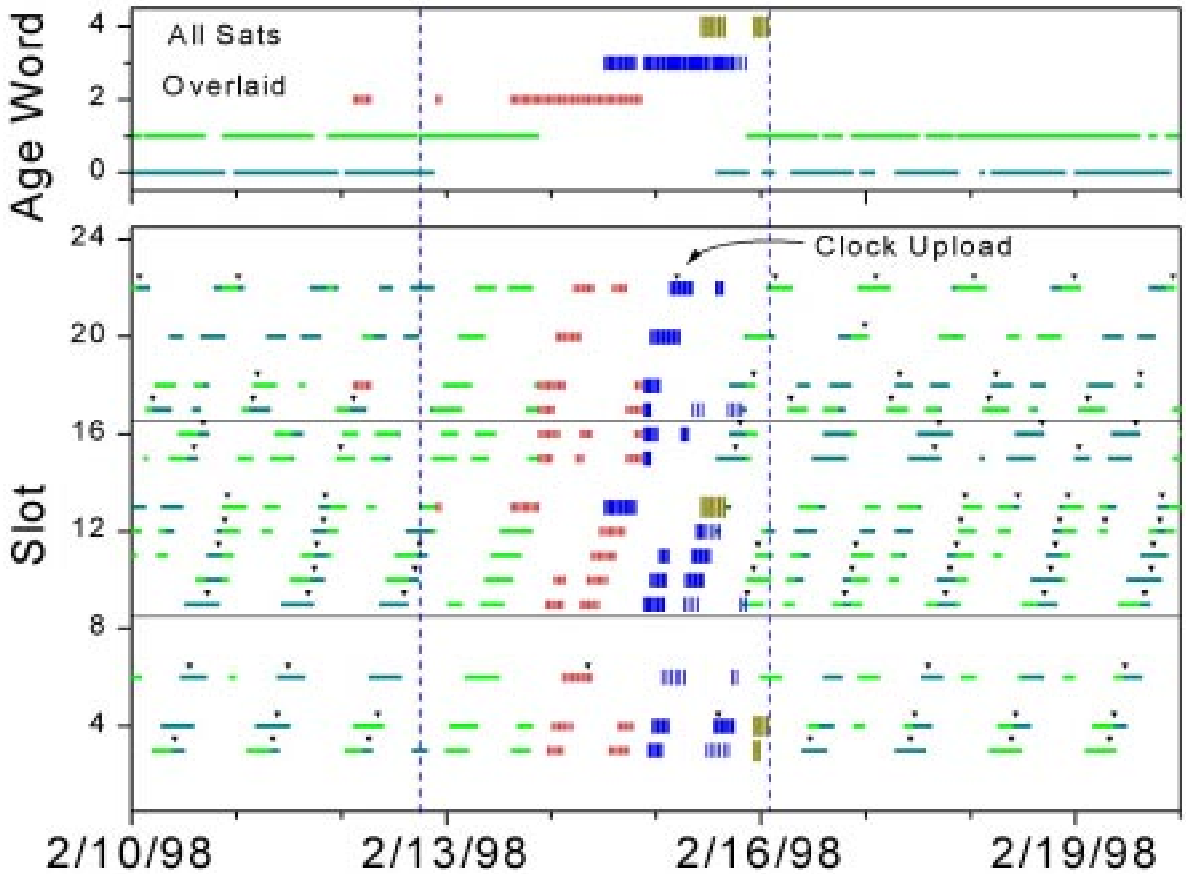

Figure 5. GLONASS Age of Data, February 1998.

No mention of this activity was made on the internet page. One could argue that since accuracy was within specifications, no notice was required. At the time, it was difficult to understand if the lapse in uploads was due to some problem with the ground segment, or possibly a demonstration that less frequent uploads were acceptable. Our speculation would be that the ground segment was distracted with some local problems.

There was an interesting idiosyncrasy that occurred as time went on during the lack of uploads, due to the lack of synchronization of clock and ephemeris uploads. The clock and ephemeris states are uploaded separately, and if there is an upload in the middle of the half hour period, the new values for the respective upload are immediately inserted in the navigation message. In other words, one will observe clock or ephemeris states change in the middle of the half-hour period, with the same epoch, or time word, before and after the upload. (As an aside, the RINEX specification does not say which state vector to record, and some manufacturers provide the first one observed within a half hour, and some provide the second. It would be good to record both.)

Generally at 0 and 30 minutes after each hour, each GLONASS satellite begins to transmit its predicted clock and state vector data, which are effective at 15 and 45 minutes after the hour, respectively. Those data are rebroadcast every 30 seconds (civil code) unless there is an upload of new predictions to the satellite. While the half-hour effective interval for each state vector is the norm, the ICD makes provision for hourly data, along with a transition from half-hourly to hourly data. The ICD does not really explain it, but this transition usually occurs when the satellite has gone about three days without an upload. (As will be shown in the next section, the precise point of transition varies somewhat.)

Because the clock and ephemeris data are uploaded separately, the half-hour to hour transitions occur at different times for clock and ephemeris data. Only one effective epoch is transmitted, and it applies to the ephemeris, as does the age of information word. During the period when the clock and ephemeris intervals are different, the clock effective time is 15 minutes before or after the ephemeris effective time. Both half-hourly clock with hourly ephemeris and vise versa have been observed. If the clock drift is very large, using the wrong time can cause a noticeable error, but one might make the point that after three days without upload, the error in clock predictions will probably be large also. This transition from half hourly data to hourly data has been observed a number of times when satellites went unhealthy due to clock failure or otherwise, if the satellite continued to transmit data during that time. Some of this activity was observed in the February data, but by itself the SRC receiver does not observe all that is going on.

Missing Uploads, June 1999

Between 15 and 20 June 1999, the GLONASS constellation went through another extended period with very few uploads. Figure 6 shows the Age of Data and clock uploads for all the satellites during this period. This time IGEX data were used, allowing nearly continuous coverage, except for Slot 14 for which SRC data were used. The uploads shown are from the SRC data, because same-epoch double clock values were available. As in February 1998, very few clock uploads were detected during the period when the age of data values were growing. Unlike the February 1998 maintenance lapse, several of the satellites developed significant range errors as the result of no uploads. Slot 15 had range errors of around 40 meters on 15 June, and the errors grew to over 85 meters before the satellite was set unhealthy on 18 June. It was corrected about half a day later with fresh clock and ephemeris data. Only the period when the satellite was set unhealthy was noted on the internet. Slot 16 developed errors of over 70-80 meters on 17 and 18 June before it was corrected, but nothing for that period was mentioned on the internet.

There were some age anomalies that could indicate a quality control problem with the IGEX data. Age values for Slot 10 on 18 June toggle about 4-3-4-0-3-0. The same satellite toggles 1-6-1 on 20 June. Jumping by more than 1, or decreasing without going to zero should not happen, unless the age word is uploaded, and old data are uploaded. Some concurrent SRC coverage indicates some of the IGEX data are in error on 18 June, but no attempt was made to isolate the erroneous station.

There was, however, an instance of concurrent IGEX and SRC coverage which indicates slightly old data were uploaded. On 20 June, Slot 4 Age of Ephemeris word dropped from 6 to 1 instead of to 0 in both data sets. That may have indicated the computations were made on 19 June, but not uploaded to the satellite until the next day.

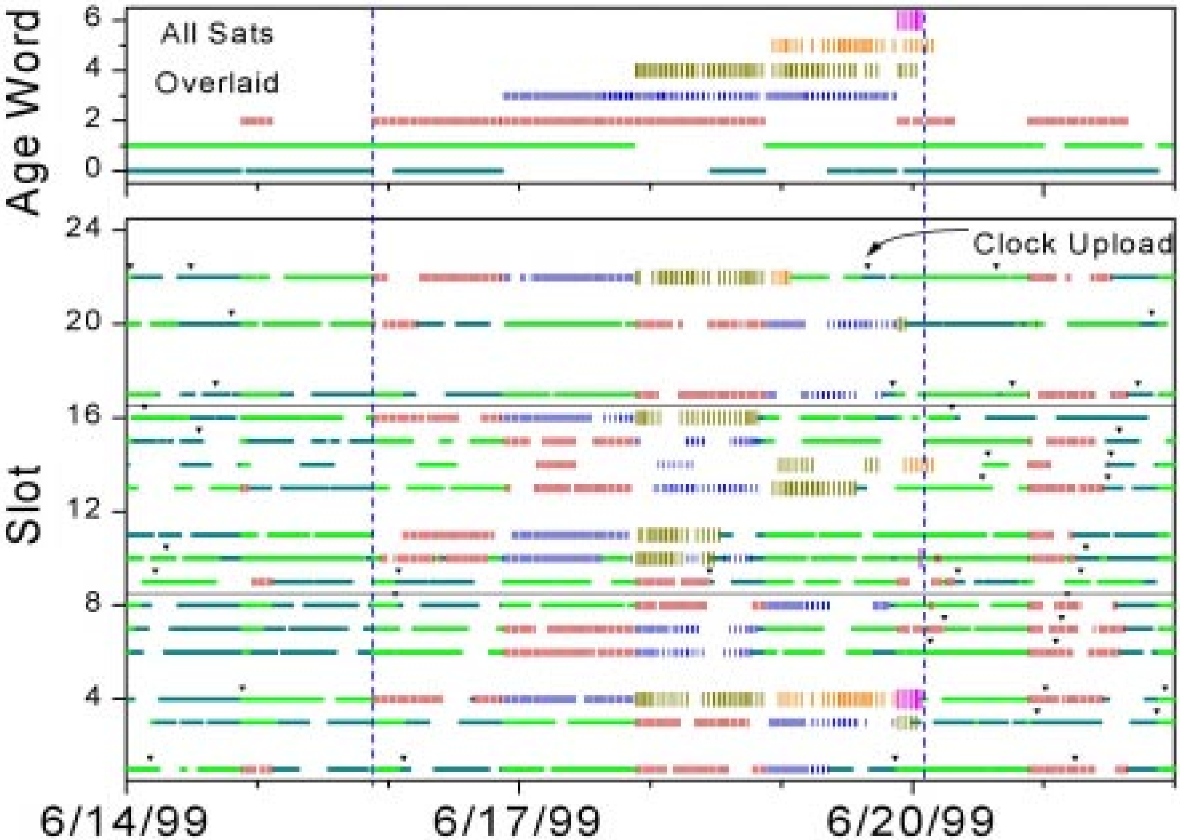

Figure 6. GLONASS Age of Data, June 1999.

Once again, the inconsistency of the clock data with the ephemeris time word was observed when the data became older. Figure 7 shows a two and a half day set of clock data for Slot 17. The top plot shows the clock data transition from half hourly to hourly data and back again. When the ephemeris data were changing every half hour but the clock every hour, one could note the same clock value at two different times, as is emphasized in the inset plot. The lower part of the figure shows the residuals to a linear fit of the clock data, and emphasizes the time tag mismatch of the data. The errors caused by the mismatch are small, about +/- 5 counts or less than 2 meters. They are on the same order of magnitude as the general relativistic correction to clock phase, which can be seen superimposed on the residual plot. Elevations to Moscow and Ussuriysk (a potential eastern Russian control site) are shown (Feairheller, 1994). Note that there is a clock discontinuity on 17 June that could not have been an upload from either site, and the data transition to hourly values a few hours later, also indicating the discontinuity was not an upload.

Figure 8 shows just the residual plot for Slot 17 over a larger time span. On 14 June, clock corrections are uploaded just about when the satellite reached its peak elevation relative to Moscow, and a small discontinuity is observed. While it might be tempting to say there was a clock upload at the discontinuity on 17 June, the transition to hourly data argues against it, as does the fact the satellite was below the Moscow and Ussuriysk horizons at the time. It would appear the buffered data in the satellite are from two sets of predictions. In other satellites it seems very clear that the sparser (hourly) data are from an older set of predictions.

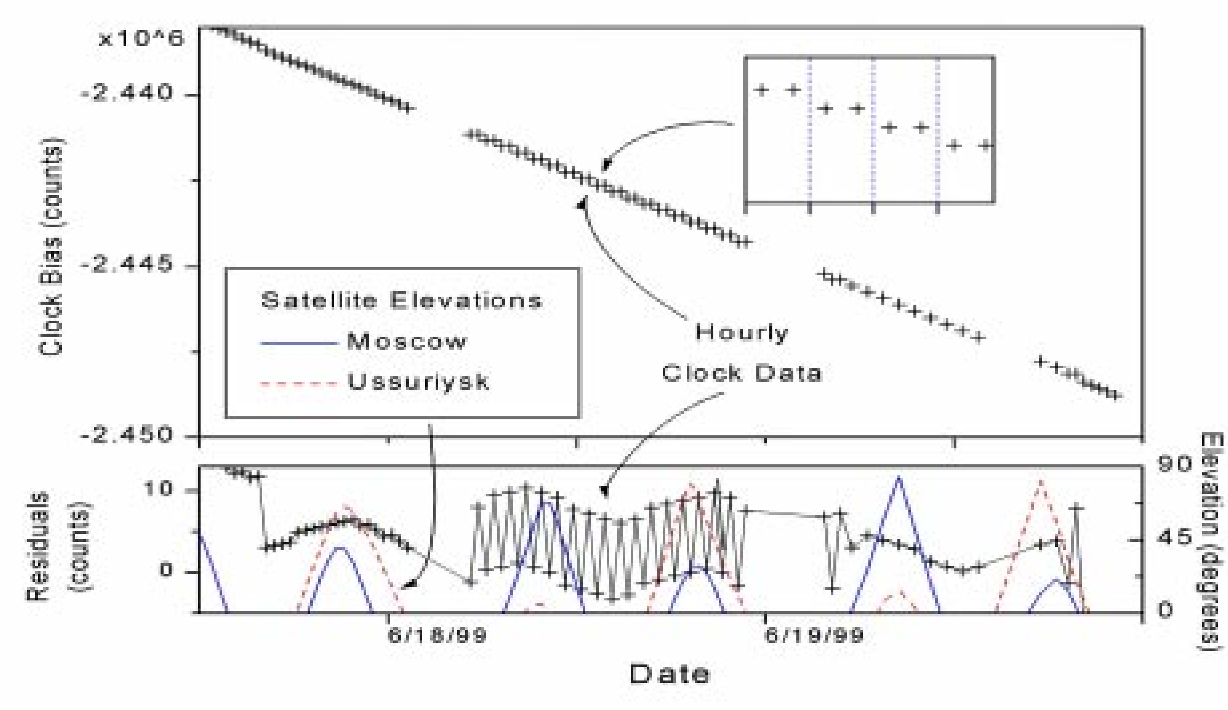

Figure 7. GLONASS Slot 17 clock corrections, 17-19 June 1999.

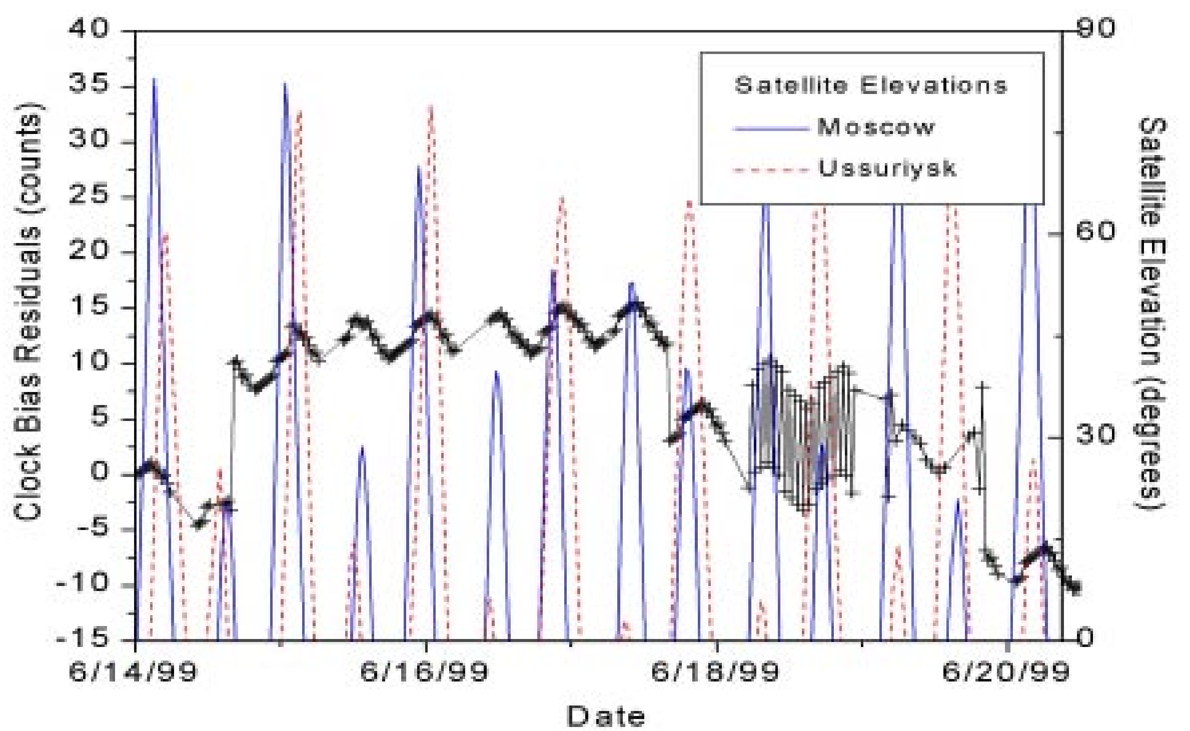

Figure 8. GLONASS slot 17 clock corrections, 14-20 June 1999.

Clock Failure and Erroneous Upload, Slot 8, 22-23 August 1999

In a separate incident, but relating to maintenance activities, Slot 8 experienced a clock failure on 22 August 1999, but was allowed to broadcast for more than two orbits before it was declared unhealthy. Figure 9 shows the onset of the clock failure as observed at SRC at about 13:30 UTC on 22 August. Two passes later, the range errors had grown to over 6 kilometers, but the satellite had not been declared unhealthy by 13:04 UTC on 23 August, when it went below the SRC elevation mask. The internet web page listed the satellite as unhealthy at 13:35 UTC, 23 August. A troubling observation is that the satellite was uploaded with new clock data at 11:20 UTC, 23 August, but the upload discontinuity was only 5 meters, as though the tracking system had not detected the failure, or had not included any recent data in the computation of predictions. Perhaps the clock tracking filter had thrown all the data out, but it should have raised a flag somewhere to indicate the satellite was unhealthy.

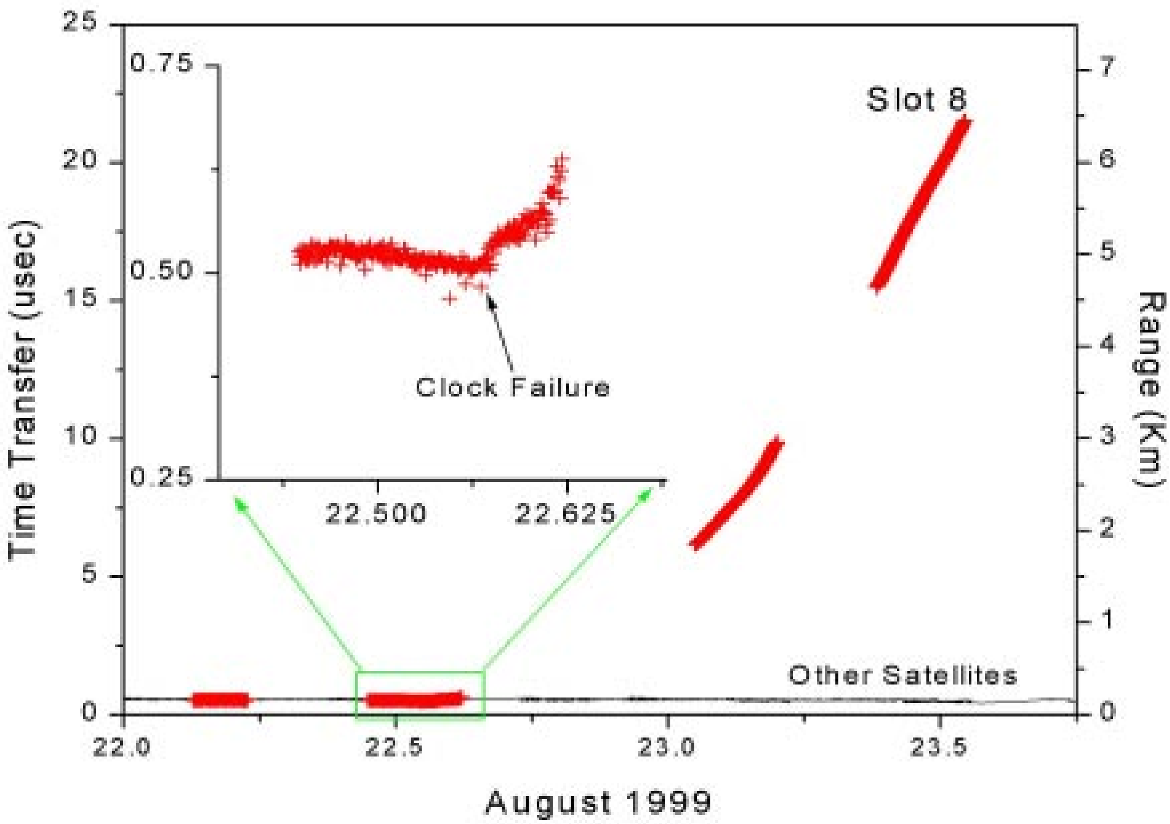

Figure 9. GLONASS slot 8 range data showing clock failure, 22 August 1999.

Change of Maintenance Routines?

There is some historical evidence that there was a relaxing of attention to satellite uploads back as far as 1995. The bottom part of Figure 10 shows the aggregate number of occurrences of ephemeris age greater than or equal to two each quarter since the start of

1993. If the satellite were uploaded every other orbit, age should not have exceed one. Counting rules applied were if a healthy satellite had an age of data greater than one during any time SRC could see it during a day, the quarterly count was increased by one. Before 1995 it was rare to see an age of data greater than one on a healthy satellite, but the constellation was about the same size as it is today. Summer quarters since 1996 have had higher incidences of old data, and the overall trend is toward less routine maintenance.

The top part of Figure 10 shows a 1-2 meter increase in the magnitude of the upload discontinuities observed at SRC since about 1997. This measure has been shown to correlate with pseudorange derived clock/ephemeris errors (Cook, 1997), which also indicate a gradual rise. Since atmospheric errors still dominate the error budget, the overall accuracy of GLONASS when the satellites are healthy remains comparable to GPS without Selective Availability. However, changes in the maintenance procedures may have contributed to slightly poorer GLONASS user range errors. It is possible that the Russians are convinced that augmentation systems are necessary for the safe operation of satellite navigation systems, and they will rely on the augmentation system to reduce errors to small values and provide the essential integrity checks of the system.

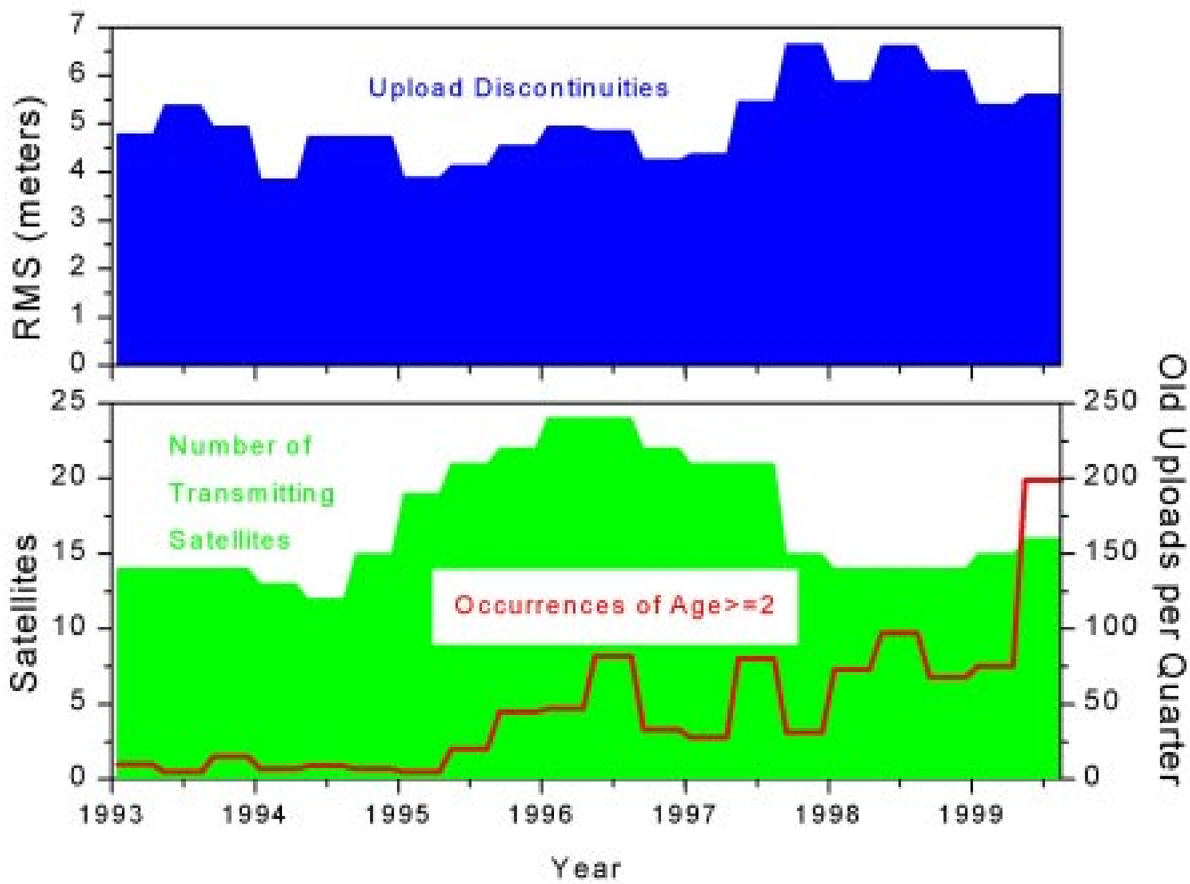

Figure 10. Occurences of Age of Data > 1, 1993-1999.

Conclusions

While the ground segment of GLONASS works hard to keep its limited assets in the space segment working, it does not always appear to be diligent in doing the routine day to day operations. Thus, they were able to revive a satellite after a year and a half silence (although its fate is now in question), but they allow satellites to go unattended for days at a time. It is difficult to understand why a lack of updates for four to six days is allowed. It is also difficult to understand how the procedures are so insensitive to a bad satellite that it can go two orbits without being corrected, or at least marked unhealthy. On the other hand, a ground based augmentation system might provide the integrity and accuracy required for many applications.

Acknowledgements

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GLONASS and the International Terrestrial Reference System

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Abstract

The first results of the IGEX-98 campaign provide significant materials to illustrate the mutual benefits of the GLONASS system and the realization of the International Terrestrial Reference System (ITRS). This paper reviews the various relations and their synergy with the GPS system, especially in the frame of the International GPS Service (IGS). Three points are particularly discussed:

- results of the IGEX-98 for terrestrial reference frame
- possible inclusion of GLONASS as a new technique for the realization of the ITRS by the International Earth Rotation Service (IERS)
- GLONASS as an active realization of the ITRS, in conjunction with GPS or the planned Galileo system.

GLONASS and ITRS

The realization of the International Terrestrial Reference System is based on a global combination of individual terrestrial reference frames provided by the IERS analysis centres. These realizations are basically:

- Annual realizations labeled ITRFyy, where y indicates the year of the most recent data included in the combination
- ITRF2000 which is under preparation
- A pilot experiment of Terrestrial Reference Frame time series.

In addition to the 4 IERS techniques (VLBI, SLR, GPS and DORIS), GLONASS could theoretically be considered as a candidate technique for the realization of the ITRS. On the other hand, GLONASS could be also used as an operational realization of the ITRS, using either GLONASS broadcast orbits in PZ-90 and then conversion into the International Terrestrial Reference Frame (ITRF) or by fixing IGS related orbits which lead to a direct expression into ITRF.

The IGEX-98 campaign should provide significant results for TRF issue. The contribution of GLONASS could be seen as:

- An improvement of the ITRS network: new sites, new collocations which should follow the criteria of the International Space Geodetic Network;

– Input solutions to ITRF combinations as pure GLONASS solutions or multi-technique; together with GPS or SLR.

Some TRF Results from the IGEX-98 Campaign

Figure 1 shows the IGEX and ITRF97 collocation sites, identifying those where local ties are available, missing or dubious.

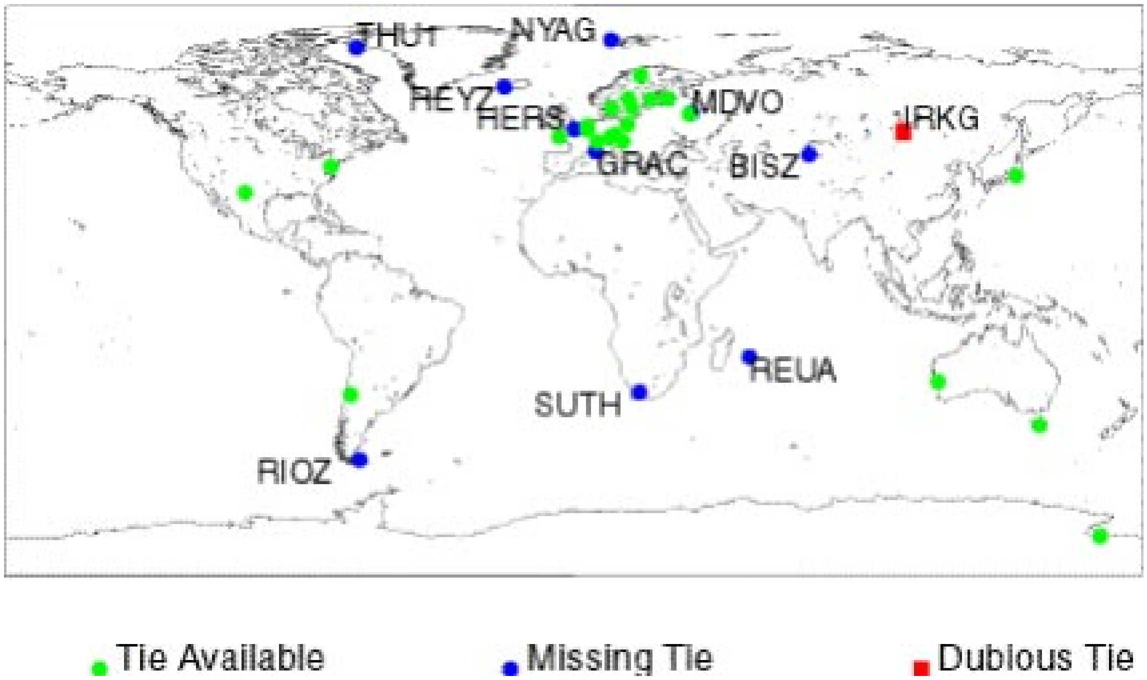

Figure 1. IGEX/ITRF97 collocation sites.

For this paper, the IERS Terrestrial Frame Section has received two types of solutions provided by GFZ and JPL.

GFZ Solutions

GFZ provided 11 weekly SINEX files corresponding to GPS weeks 991 to 1001. These solutions were derived with the following properties:

– GLONASS as well as GPS data for mixed dual-frequency receivers were used
– GPS orbits from the IGS final solution are introduced and fixed (except eclipsing GPS satellites)
– Earth rotation parameters are fixed to the estimated values of IGS
– Coordinates of only one station are fixed to their initial values in the determination of orbits.

JPL Solutions

JPL provided two types of daily solutions using over 100 days of data:

- station position solutions computed from GPS dual-frequency tracking data by fixing the GPS satellite orbit and clock to IGS/FLINN solution. The reference frame for this set of solutions is the one defined by the IGS/FLINN orbit solutions, that is ITRF96. In these solutions, station position, receiver clock and tropospheric delay for individual sites are solved for, station by station.
- station point position solutions computed from GLONASS dual-frequency tracking data by fixing the GLONASS satellite orbit and clock values to the broadcast ephemeris and clock values file; the reference frame for this set of solutions is the one defined by the GLONASS broadcast orbit, which is PZ-90. In these solutions, the broadcast orbit is first smoothed by a dynamic fit (trajectory fit) to remove outliers and gross errors. The 3-D RMS error of the fit is around 5 meters. Station position, receiver clock and tropospheric delay are then solved for individual sites by fixing the orbit to the smoothed orbit file and fixing the transmitter clock to the broadcast ephermeris clock file.

Analysis of the Received Solutions

Comparisons of the above described solutions were performed with respect to ITRF97. The following plots (Figures 2, 3, and 4) summarize the 7 transformation parameters between each individual solution and ITRF97. Table 1 lists the 7 transformation parameters between ITRF97 and PZ-90 (to be used with the equation given below) as derived from JPL point positioning daily solutions. Note that the scale is given in meters, assuming that 1×10^{-8} corresponds to a station height error of 6 cm. Table 1 shows that the most significant parameters are the Z-translation and the rotation around the Z-axis.

Table 1. Transformation Parameters from ITRF97 to PZ-90

Tx m	Ty m	Tz m	D m	Rx "	Ry "	Rz "
-0.3 ±0.1	0.0 ±0.1	0.9 ±0.1	0.1 ±0.2	0.002 ±0.03	0.012 ±0.04	-0.354 ±0.04

$$\begin{pmatrix} X_{pz90} \\ Y_{pz90} \\ Z_{pz90} \end{pmatrix} = \begin{pmatrix} X_{itrf97} \\ Y_{itrf97} \\ Z_{itrf97} \end{pmatrix} + \begin{pmatrix} Tx \\ Ty \\ Tz \end{pmatrix} + \begin{pmatrix} D & -Rz & Ry \\ Rz & D & -Rx \\ -Ry & Rx & D \end{pmatrix} \begin{pmatrix} X_{itrf97} \\ Y_{itrf97} \\ Z_{itrf97} \end{pmatrix}$$

Conclusion

A preliminary 7-parameter transformation between ITRF97 and PZ-90 was estimated in this paper. It is obvious that more results and post-analysis from the IGEX-98 campaign are needed for a more rigorous estimate.

Acknowledgement

The authors thank the analysis groups at GFZ and JPL for providing their IGEX-98 station position solutions.

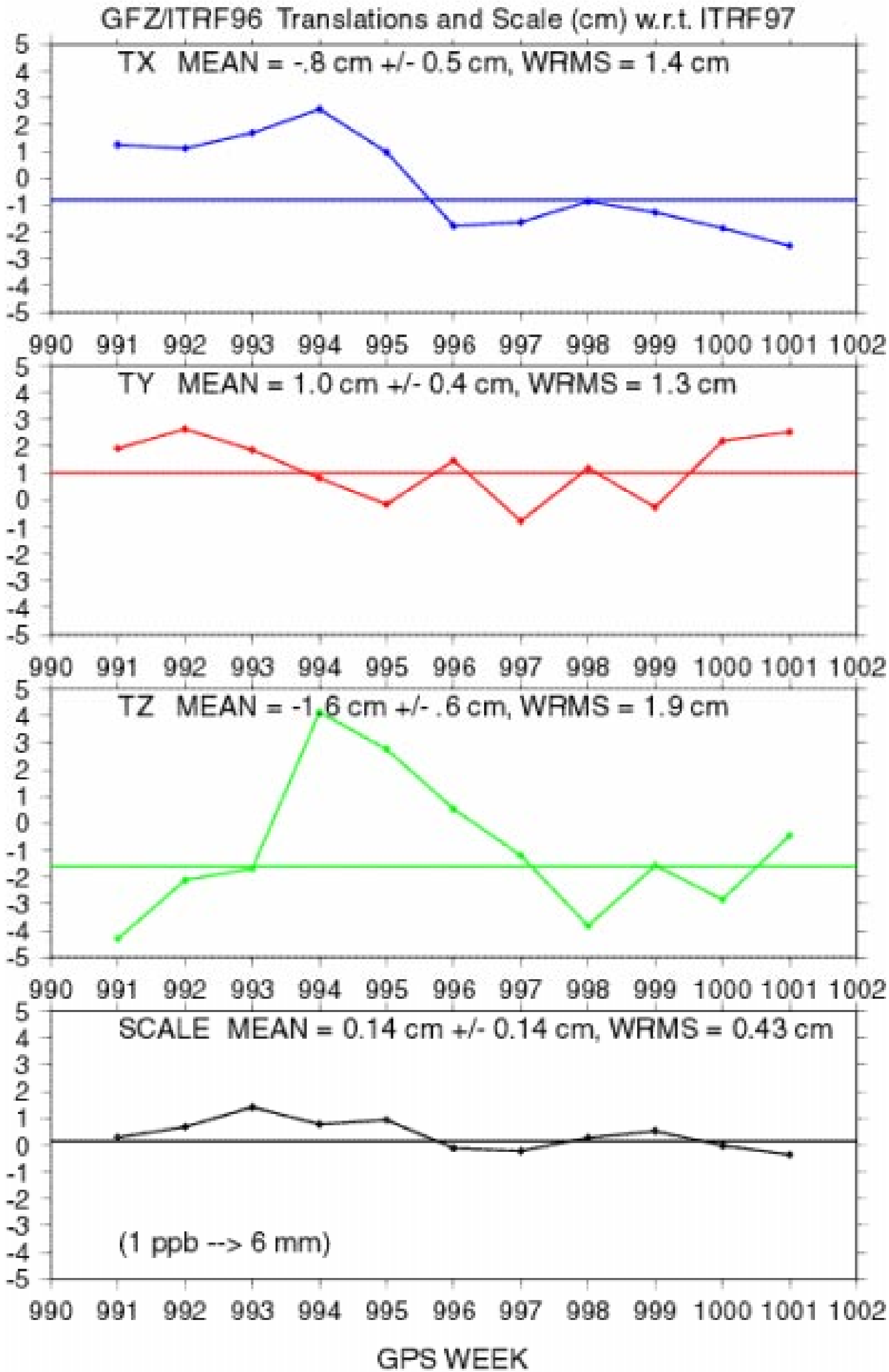

Figure 2. 7-parameter transformations relating GFZ/ITRF96 positions to ITRF97.

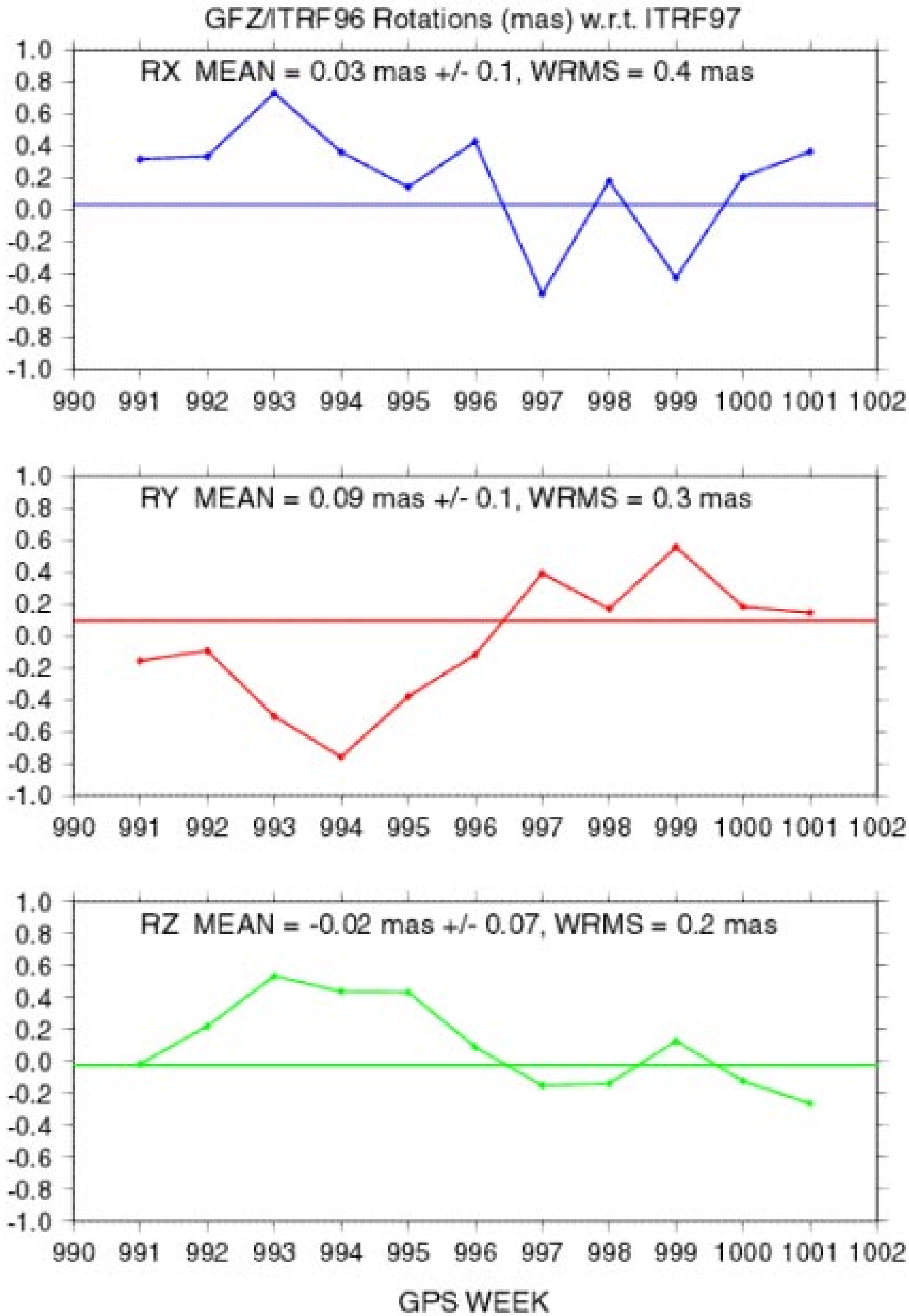

Figure 2. (Cont'd)

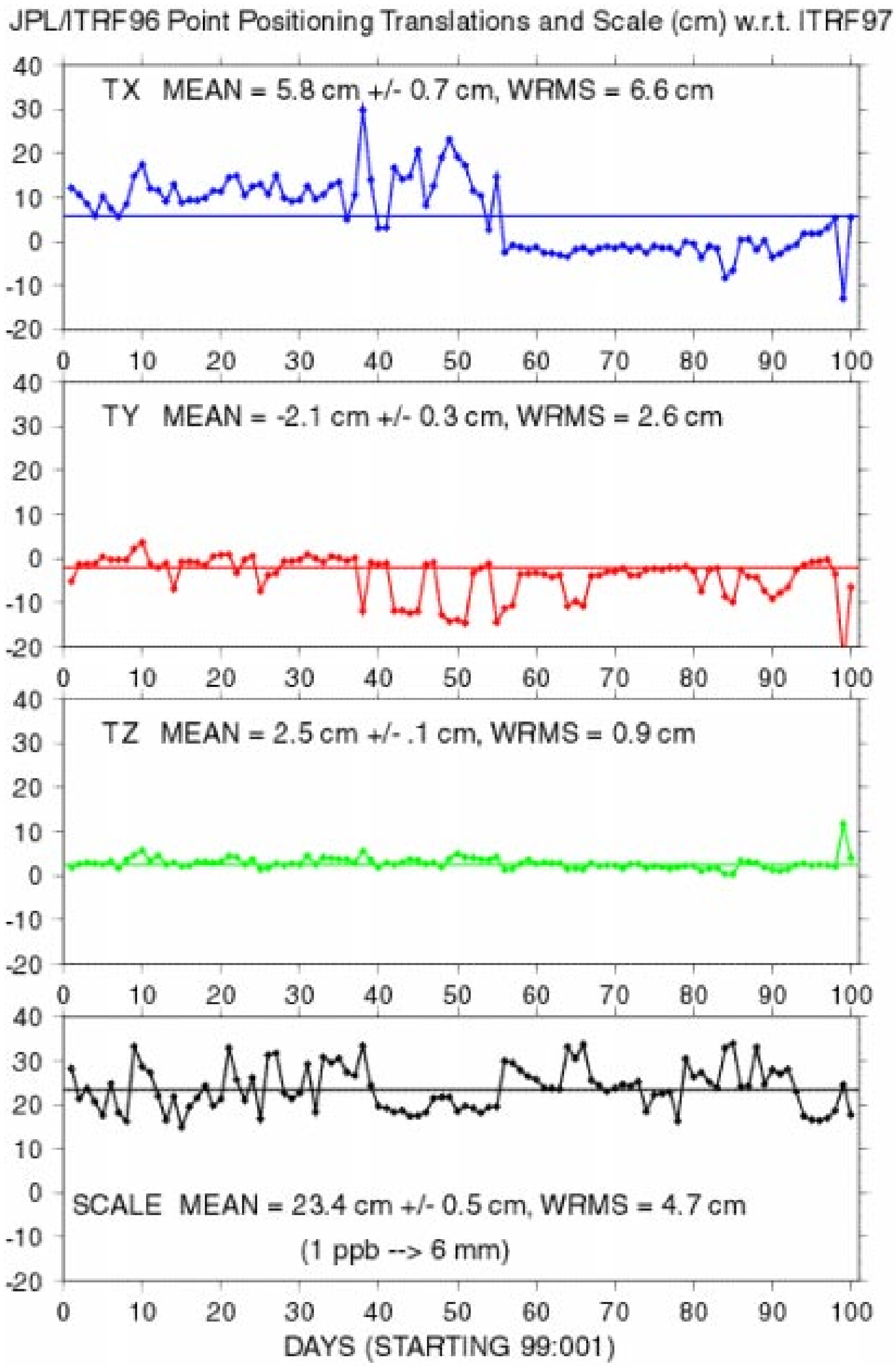

Figure 3. 7-parameter transformation relating JPL/ITRF96 positions to ITRF97.

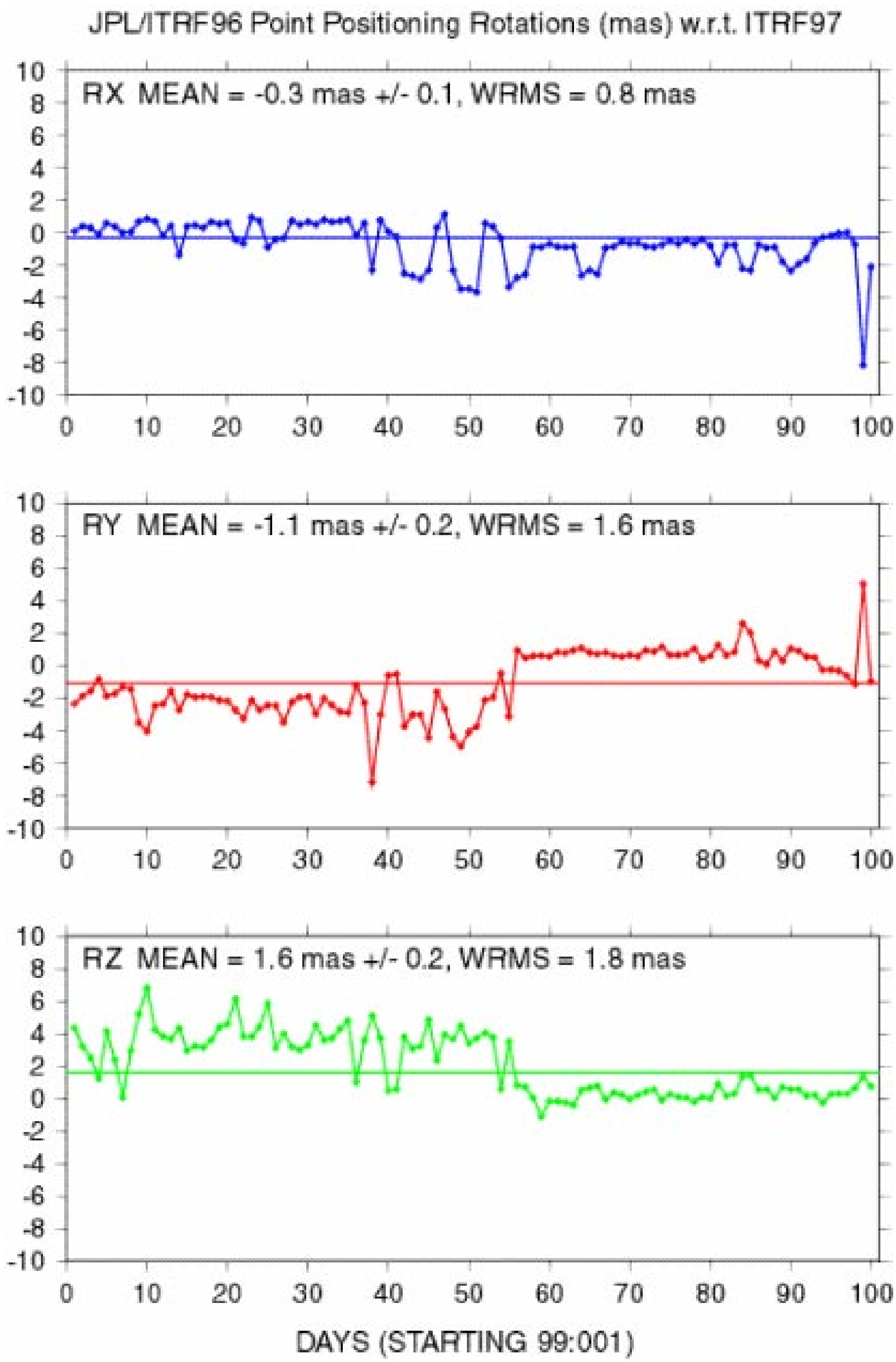

Figure 3. (Cont'd)

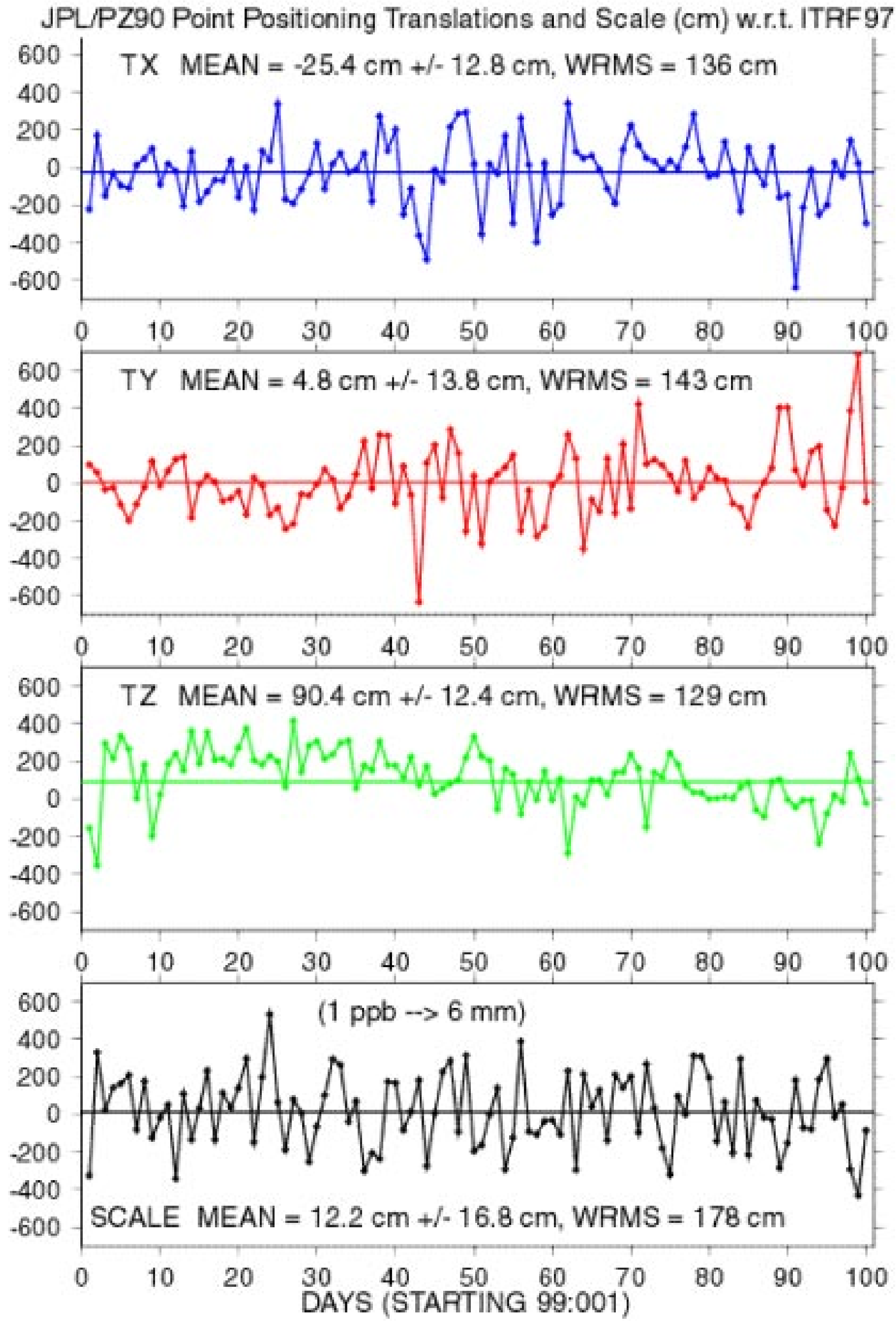

Figure 4. 7-parameter transformation relating JPL/PZ90 positions to ITRF97.

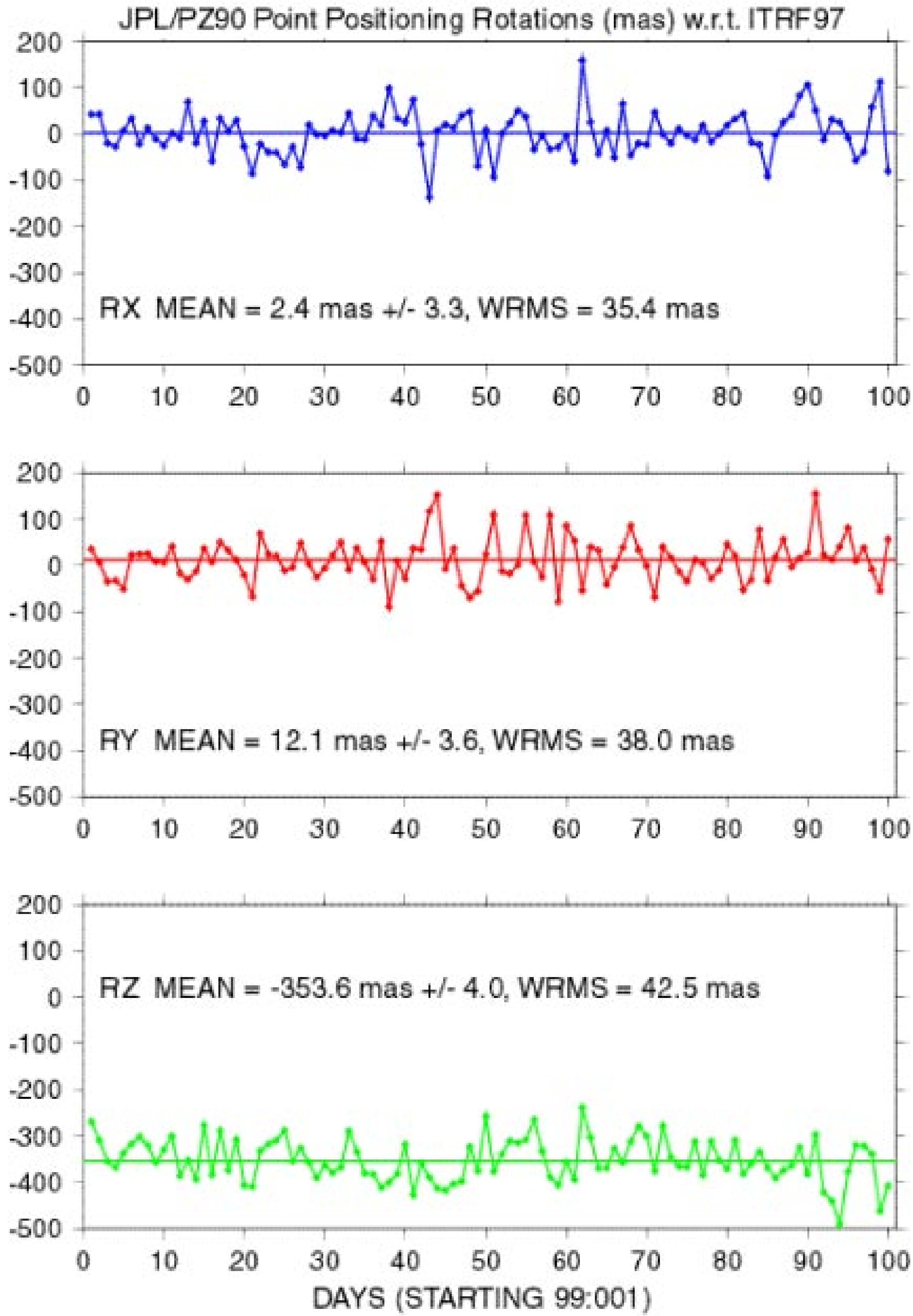

Figure 4. (Cont'd).