GLONASS Orbit Determination at the Center for Space Research

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Abstract

In this article we review the contributions of the Center for Space Research to the International GLONASS Experiment 98 (IGEX-98) campaign. These include 1) the temporary establishment of a GPS/GLONASS receiver at the IGS GPS site at McDonald Observatory in west Texas; 2) the evaluation of GLONASS orbits computed by different centers using Satellite Laser Ranging (SLR) data; 3) the computation of GLONASS orbits using SLR data and the CSR's UTOPIA software, and 4) the computation of GLONASS orbits using radiometric data and the Jet Propulsion Laboratory's GIPSY software. When used directly to compute range residuals relative to each center's radiometric orbit, we find the SLR data to be a very effective discriminator of the radial orbit accuracy. We also find that the mean of the SLR range residuals has a value of -5 cm, similar to what has been observed in SLR/GPS comparisons. Results from our SLR-determined GLONASS orbits shows the presence of a mean radial acceleration (positive away from Earth) of 4–5 nm/s^2. We examine whether any of this acceleration can be attributed to a "radiation rocket" force caused by the transmission of navigation signals from the satellites towards the Earth.

Introduction

The Center for Space Research at the University of Texas at Austin made several contributions to the International GLONASS Experiment 98 (IGEX-98) campaign. We temporarily established a Javad Legacy GPS/GLONASS dual frequency receiver and single-depth choke ring antenna near the IGS GPS site at McDonald Observatory in west Texas. In addition, we have been computing GLONASS orbits using the Jet Propulsion Laboratory's GIPSY analysis software and the dual-frequency radiometric data from the global network supporting the IGEX-98 campaign. We have also analyzed satellite laser ranging (SLR) measurements to a half dozen of the GLONASS satellites to ascertain the accuracy of the GLONASS radiometric orbits, as well as for the determination of orbits based on the SLR measurements alone. It is this last contribution that is reviewed in this paper.

Radiometric Orbit Evaluation Using SLR Data

The most direct technique for evaluating the relative accuracy of the GLONASS orbits computed using the radiometric data is to compute the RMS difference of these orbits with the SLR measurements. The SLR ranges from the better stations have an absolute accuracy at the cm-level, and the station coordinates are also known to similar accuracy.

Therefore, the SLR residuals can be a very effective discriminator between different orbits computed using different software packages and/or different analysis techniques. They are primarily an indicator of the radial accuracy, as the measurements are not as sensitive to transverse and normal orbit variations for a satellite at the GLONASS altitude. Tables 1 and 2 show the weighted RMS of observed (SLR) minus computed (radiometric orbit) range residuals for GLONASS orbits computed by various IGEX analysis centers. We evaluated satellites 3, 6, 13, 16, 20, and 22, since these are the satellites that received tracking priority by the International Laser Ranging Service (ILRS) during the IGEX-98 campaign. SLR data were employed in the computation of the MCC orbits, and thus these results in Table 2 cannot be considered an unbiased estimate of orbit accuracy. In general, the best orbits (CODE and GFZ) appear to have a radial accuracy at around the 10-cm level. Exceptions to this are satellites 13 and 16, which seem to behave anomalously relative to the other satellites. Also note that the mean residual is roughly –5 cm (with the exception of satellites 13 and 16 on occasion).

Table 3 shows the same results for the IGEX combined orbit, which is a weighted average of the orbits from each IGEX analysis center. With the exception of satellites 13 and 16, the range residual RMS is less than 10 cm and the mean range residual is about –5 cm.

Table 1. Weighted RMS residuals (cm) using GLONASS sp3 orbit files from each IGEX center. Data from 20 SLR sites were used (CSR95L01 station coordinates) covering 1/24/99–2/20/99 (GPS weeks 994-997).

	CODE			ESA			JPL			GFZ		
SAT	# pts	Avg	rms	# pts	Avg	rms	# pts	Avg	rms	# pts	Avg	rms
3	518	-5.1	7.7	518	-9.6	19.1	517	-10.0	22.0	518	-5.4	10.0
6	570	-5.5	11.1	570	-9.1	13.2	567	-11.7	23.9	564	-6.8	11.6
13	385	3.2	10.5	385	-4.9	20.0	385	-8.9	17.8	385	-4.7	9.8
16	393	0.9	12.0	369	-6.2	41.7	393	-7.3	34.0	296	1.8	37.8
20	697	-6.3	9.4	697	-7.7	15.3	696	-9.0	21.5	697	-3.3	9.8
22	657	-8.1	10.4	657	-9.6	14.8	654	-14.9	26.1	658	-8.0	16.0

Table 2. Weighted RMS residuals (cm) using GLONASS sp3 orbit files from each IGEX center. Data from 20 SLR sites were used (CSR95L01 station coordinates) covering 11/1/98 – 12/19/99 (GPS weeks 982-988).

	CODE			ESA			BKG			MCC		
SAT	# pts	Avg	rms	# pts	Avg	rms	# pts	Avg	rms	# pts	Avg	rms
3	890	-2.9	9.0	890	-1.5	14.8	890	-4.6	17.1	890	-2.6	8.6
6	1173	-1.0	11.1	1173	-4.9	17.5	1173	-3.0	15.9	1173	-3.5	9.7
13	663	-5.5	33.0	663	-8.2	12.5	596	-0.3	43.3	663	-4.8	12.0
16	824	-4.5	36.3	632	-13.3	39.4	744	-1.4	42.5	841	-5.5	20.7
20	1456	-4.0	9.6	1456	-11.2	17.2	1456	-1.0	9.9	1456	-3.9	7.9
22	1488	-7.6	9.7	1488	-9.1	12.8	1488	-6.5	13.3	1488	-7.3	8.8

Table 3. Weighted RMS residuals (cm) using GLONASS sp3 orbit files for the IGEX combined orbit. Data from 20 SLR sites were used (CSR95L01 station coordinates) covering 11/1/98 – 12/19/99 (GPS weeks 982-988).

	IGEX		
SAT	# pts	Avg	rms
3	890	-3.2	7.5
6	1173	-2.4	9.4
13	663	-6.7	16.7
16	846	-5.8	24.0
20	1456	-3.9	7.9
22	1488	-7.3	8.8

Orbit Computations Using SLR Data

We computed orbits for GLONASS satellite 3, 6, 13, 16, 20, and 22 using the available SLR data. CSR's UTOPIA software was used for these computations. CSR97L01 station position and velocities were employed, along with the IERS C04 polar motion series. The JGM-3 gravity model was employed [*Tapley et al.*, 1996] along with a GM value of 398600.4415 km^3/s^2. Solar and Earth radiation pressure were both modeled with a satellite reflectivity coefficient of 1.4. Because of the lack of availability of a detailed satellite model, we used values of 24 and 15 m^2 for the satellite cross-sectional area in the solar and Earth radiation pressure models, respectively. The latter value represents an approximate average of the variable cross-sectional area presented by the spacecraft towards the Earth. The mass of each satellite was assumed to be 1413 kg, and the offset of the laser retroreflectors with respect to the center-of-mass was assumed to be 0, 0, -151 cm in the satellite-fixed xyz frame.

A 7-day arc length was used to analyze the SLR data. Over each arc, we estimated the initial position and velocity vectors, mean accelerations in the radial and transverse directions, and once/revolution accelerations (cosine and sine components) in the radial and normal directions. As shown in Figure 1, the RMS of the SLR normal point residuals was approximately 3 cm, although there was considerable variation from one week to the next. Figures 2 and 3 show the weekly values for the estimated radial once/revolution accelerations. Note that they tend to be quite coherent. The sine component tends to be the same for satellites occupying the same orbit plane, suggesting that the empirical acceleration are probably accommodating the mismodeled solar radiation pressure forces. Figure 4 shows the weekly values of the mean radial acceleration. Possible explanations for the 4.5 nm/s^2 mean of these apparent accelerations will be discussed in the next section.

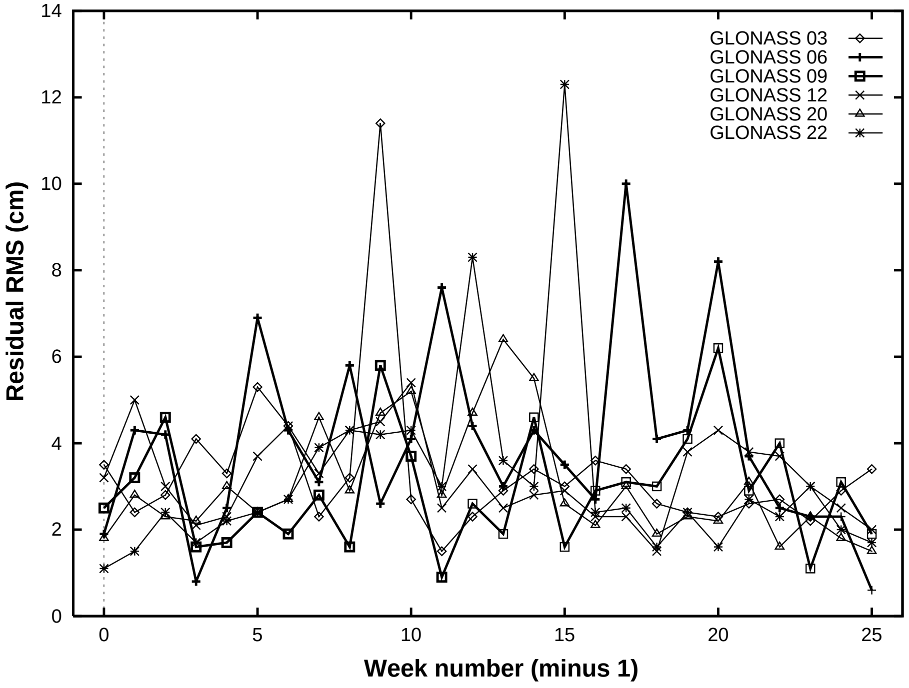

Figure 1. RMS of laser range residuals for GLONASS weekly arcs starting 13 Oct 1998

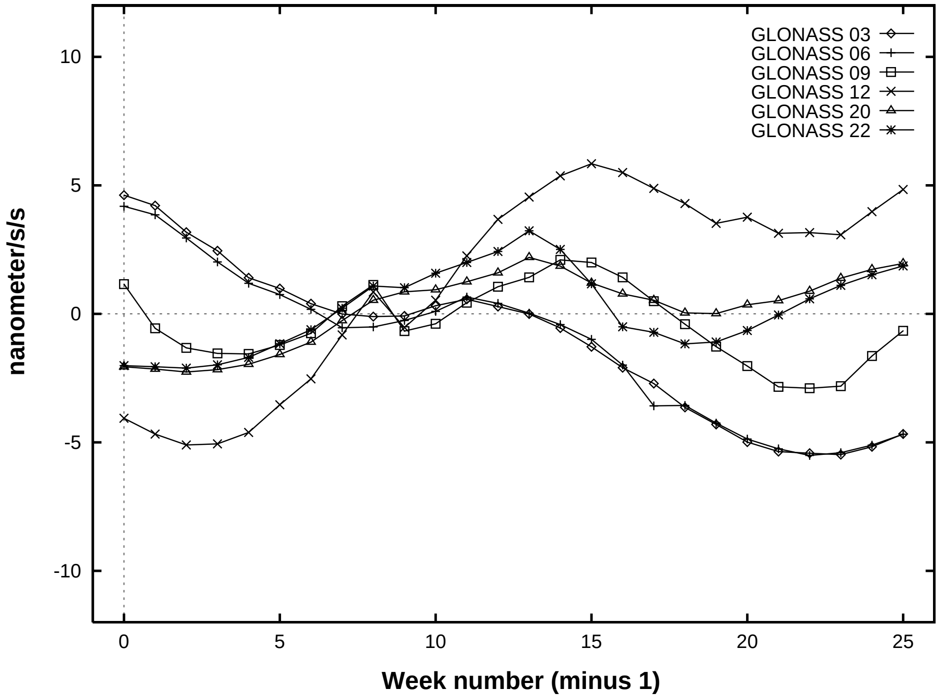

Figure 2. Cosine term of 1-cpr radial acceleration for GLONASS weekly arcs starting 13 Oct 1998

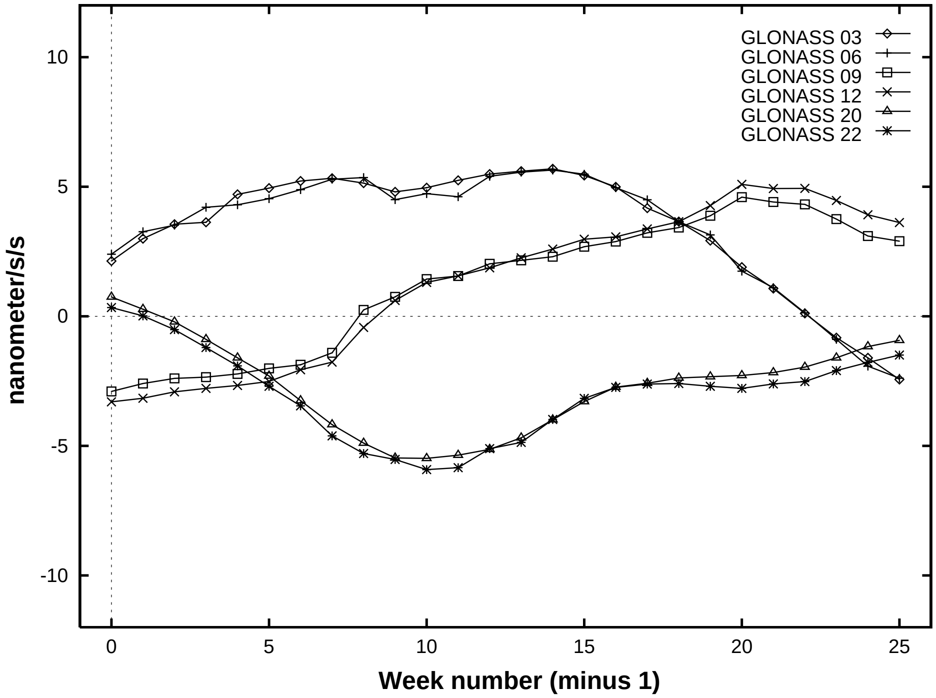

Figure 3. Sine term of 1-cpr radial acceleration for GLONASS weekly arcs starting 13 Oct 1998.

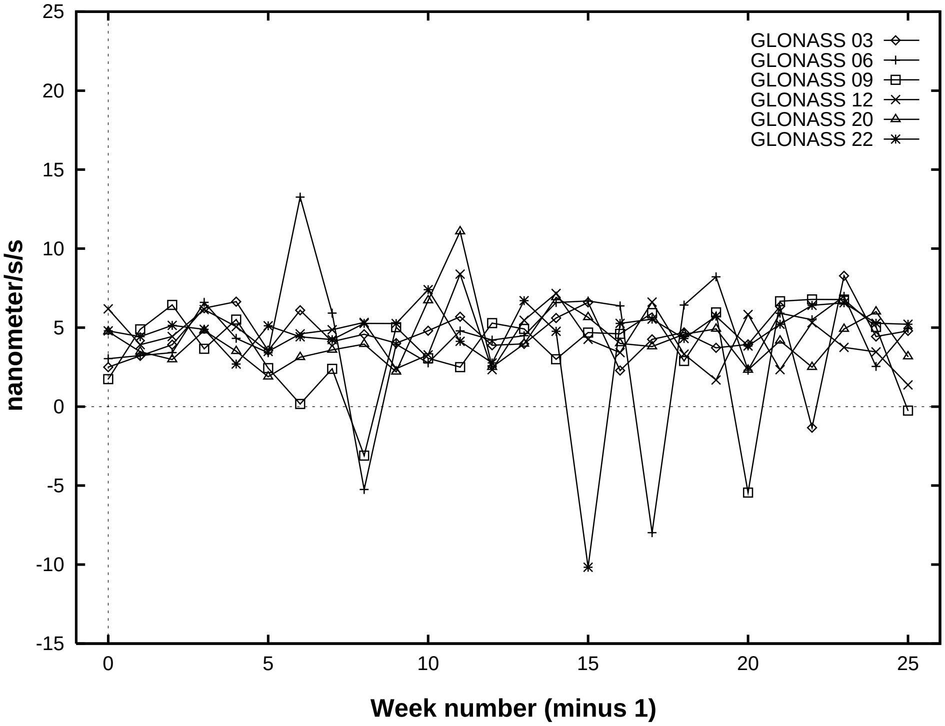

Figure 4. Mean radial acceleration for GLONASS weekly arcs starting 13 Oct 1998

We compared the SLR GLONASS orbits with the radiometric GLONASS orbits computed by each of the IGEX analysis centers. The radial-transverse-normal RMS orbit differences were typically ~10 cm, 40 cm, and 45 cm respectively, with an overall 3-D position RMS of ~60 cm. It is difficult to use the SLR orbits to evaluate the accuracy of the radiometric orbits because the SLR orbit accuracy can be highly variable within a 7 day arc; anywhere from less than 10 cm when tracking coverage is good to over a meter when the coverage is poor. The mean radial difference of the SLR minus radiometric orbits varies considerably, but is consistently negative from center to center and week to week. The mean was approximate –7-8 cm, except for satellite 13 and 16, where the mean was a few centimeters smaller. A mean radial difference between the SLR and radiometric orbit occurs because we estimated a mean radial acceleration, and the recovered value for this acceleration is significantly different from zero.

GLONASS and GPS "Radiation Rockets"

We estimated a mean radial acceleration for the GLONASS SLR orbits because the power contained in the L-band signals being broadcast by the satellites is not insignificant. As a consequence, an outward (radial) force was probably acting on the satellites, as illustrated in Figure 5. This idea was originally suggested by *Milani et al.* [1987], although their description of the resulting effect on the orbit is not what is observed in orbit determination strategies, since all the orbit elements will adjust to accommodate the tracking observations in a least squares sense. It should be noted that the radiometric data alone does not have the strength to reliably estimate a mean radial acceleration because the estimation of other parameters (clock offsets, ambiguities, troposphere, etc.) dilutes the radial information content of the data.

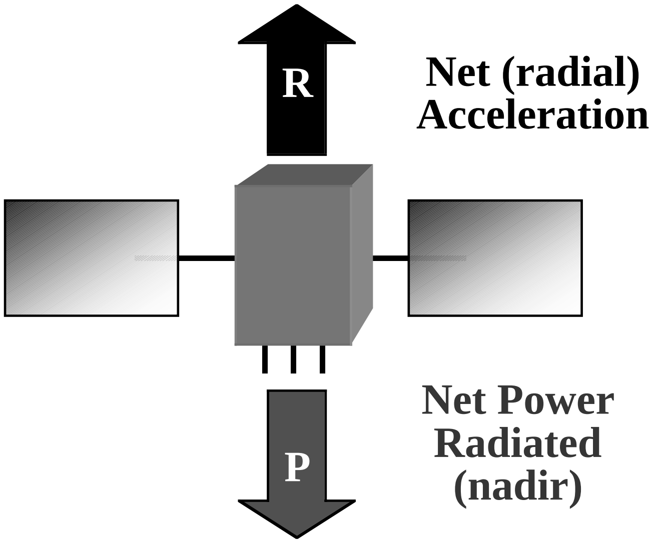

Figure 5. “Radiation Rocket” for GPS and GLONASS satellites

We have little information on how much power is being transmitted by the GLONASS satellites, so we have used the GPS satellites as a model and assumed that the GLONASS satellites would be similar. The mean radial bias between the SLR and radiometric orbits was actually first detected on the GPS satellites [e.g. *Springer et al.*, 1998]. Table 1 shows the power being transmitted by the GPS satellites. We do not know how much power is being transmitted on the L3 or S band frequencies, but power is probably not transmitted continuously in these bands in any case. In our original analysis, we used the power values provided by Langley (1998), which led to a total transmit power estimate of 1092 Watts. As illustrated in Figure 5, the radial acceleration (R) on the satellite may be computed from the transmitted power (P) as R = P/(c x mass). For a 1413-kg satellite like GLONASS, the radial acceleration is 2.6 nm/s^2, whereas for a GPS satellite (1000 kg), it is 3.6 nm/s^2. This is clearly a large fraction of the observed radial acceleration on the GLONASS satellites. For GLONASS, 1 nm/s^2 is roughly equivalent to 1.2 cm of radial orbit bias. However, it was pointed out that the values given in Langley (1998) included the effect of antenna gain. The actual transmit power is considerably less (Aparacio et al., 1995), as shown in the last column of Table 1. This reduces the radiation rocket effect to 0.09 nm/s^2 for the GLONASS satellites, equivalent to only 0.1 cm of radial bias.

Table 3. Power transmitted by the GPS satellites [Langley, 1998; Aparicio et al., 1995].

	Transmitted Power		
Signals	dBW	Watts (with effect of antenna gain included)	Actual Watts
P Code on L1	23.8	240	10.7
P Code on L2	19.7	93	6.6
C/A Code on L1	28.8	759	21.9
Other (L3, S, ?)	?	?	?
Total		1092	39.2

Part of the radial biases observed in the orbits of the IGEX analysis centers may be caused by not modeling Earth radiation pressure, which contributes about 1 nm/s^2 of radial acceleration. Since Earth radiation pressure was modeled in our computations and the radiation rocket from the transmitted signals is too small, we must invoke other explanations for the remaining radial acceleration. One possibility is that the value of GM we employed is too large. If we reduce our GM value by 1-_ (0.0008 km^3/s^2) (Ries et al., 1992), this would explain 1 nm/s^2 of the observed mean radial acceleration. An error in GM much larger than this is considered to be unlikely.

Another possibility is an error in the modeled offset of the laser retroreflector array (LRA) from the satellite center-of-mass. It is impossible to evaluate the uncertainty in the location of the LRA without detailed information on the satellite dimensions and center-of-mass changes, and we have no information about the effect of the LRA design on the laser range biases. We hesitate, however, to attribute the apparent radial bias entirely to an error in the LRA location, since it is unlikely that the error would be similar for both the GPS and GLONASS satellites.

Conclusions

We have used SLR measurements and a precise set of station coordinates/velocities to evaluate the accuracy of the GLONASS radiometric orbits computed during the IGEX-98 campaign by the analysis centers. The orbits computed by the CODE and GFZ groups generally have a radial accuracy on the order of 10 cm, although the accuracy can be several times larger on occasion. The mean of the SLR range residuals is ~ -5 cm, indicating the radiometric orbits are 5 cm too high.

We have also computed GLONASS orbits independently using the SLR measurements only. We have observed a persistent 4–5 nm/s^2 outward radial acceleration that can fully explain the 5-cm bias in the SLR range residuals. It appears that the satellite broadcast signals are not large enough to be causing the observed radial acceleration after all. We might attribute a part of the apparent acceleration to an error in GM and the correction for the center-of-mass offset of the laser retroreflector array, but a source of several nm/s^2 acceleration is required to explain the rest. Failure to model Earth radiation pressure can contribute an additional 1 nm/s^2 to the apparent radial acceleration.

The relative insensitivity of GLONASS and GPS radiometric data to radial accelerations should be investigated further, as it may help explain some of the "common-mode" signals observed in time series of station positions. Further study of the forces acting on the GLONASS and GPS satellites is recommended. A carefully constructed error budget for the location of the LRA phase center for the GPS and GLONASS satellites is also essential to limit this area of uncertainty.

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