ILRS Standard for Retroreflector Arrays at GNSS Altitudes

An ILRS Standard for retroreflector arrays at GNSS altitudes should specify a sufficient "effective cross section" to provide enough return signal strength to support robust normal point content by the operational SLR ground stations. The "effective cross-section" is divided by R^{**4} (to account for range) in order to get a measure of return signal strength.

The offset between the LRA phase center and spacecraft center of mass (CoM) should be determined prior to launch to the mm level to maintain parity with our 0.1 ppb goal.

Rationale for the Arrays on GNSS

The primary motivation for placing Satellite Laser Ranging retroreflectors on the GNSS (GPS, GLONASS, and Galileo) satellites is to cross link the observational networks of the International Terrestrial Reference Frame. Improved accuracy for the GNSS satellite orbits and a more stable International Terrestrial Reference Frame (ITRF) will be the result. The accurate co-location of the space borne segments combined with an ongoing plan to insure the accurate collocation of GNSS, SLR, and VLBI ground networks will eliminate uncertainties in the determination of the International Terrestrial Reference Frame which is the agreed to common reference frame for the GPS, Galileo and GLONASS constellations.

The origin of the ITRF is the center of mass of the Earth. The origin and the scale of the ITRF are determined largely from SLR measurements. The figure of the Earth and its deformation is determined largely from the GPS data (and eventually Galileo and GLONASS data). Very Long Baseline Interferometry (VLBI) provides near absolute orientation of the Earth with respect to quasars at the edge of the universe as well as additional information on scale and the figure of the Earth. There are a growing number of geodetic observatories within the ground geodetic networks that incorporate co-located GNSS, SLR, and VLBI instruments. The objective of this co-location is to increase the accuracy and stability of the ITRF. Ranging to the GNSS satellites with SLR equipment while simultaneously observing those satellites with GNSS receivers and VLBI radio telescopes will cross calibrate the three systems through a space based co-location of targets. Again the object is to increase the accuracy and stability of ITRF through better GNSS orbits. It is anticipated that such collocation efforts will be in a campaign type mode to achieve the calibration objectives. Though we will seek retroreflectors on all GPS satellites - ranging to the satellites would likely be episodic according to planned campaigns.

The GNSS and SLR systems have considerable differences, with error characteristics that are in sharp contrast. GNSS depends on radiometric signals from large, complicated targets in high Earth orbits that are significantly perturbed by solar radiation pressure and re-emitted heat. The GNSS signals are considerably affected by water vapor in the atmosphere, multipath, antenna phase center and spacecraft attitude issues, and, in severe cases, ionospheric effects. The knowledge of the GNSS antenna phase center relative to the center of mass has historically been uncertain at the meter level, and only recently has progress been made to reduce it to the few-decimeter level. Because the system is one-way, there is significant correlation between the orbit and clock determination, and no absolute measure of the orbit accuracy is possible from the GPS data itself. The nature of GNSS processing distributes unresolved errors within the solution space and therefore diminishes the ultimate accuracy of the reference frame.

Geodetic SLR systems range to medium-altitude retroreflector mirrors that are small, compact, stable, and require no power. Reference satellites such as LAGEOS are stable, dense cannon ball satellites studded with retro reflectors. Therefore their orbits are much less sensitive than the bulkier GNSS satellites to various surface forces. The laser ranging beams are also relatively insensitive to water vapor and the ionosphere as they range to the orbiting targets. Because the SLR system involves a passive two-way reflection, there is no complication with onboard time determination. It is for this reason that SLR is considered a very accurate direct and unambiguous measure of a satellite's orbit.

GNSS is the positioning and timing system of choice for the majority of users, so it is critical that the origin and scale of the GNSS station coordinates and the precise orbits of the GNSS spacecraft accurately reflect the scale and origin of the ITRF. There is lots of room for improvement in the GNSS positioning capability. GPS and VLBI baseline length time series found that the average drift in vertical positions between these two measurements at

co-located stations was 1.5 mm/yr (MacMillan, 2004). SLR determined ranges to the two retroreflector equipped GPS satellites currently in orbit show discrepancies of 5-6 cm with GPS determined radial orbit positions.

The GNSS and SLR systems have no common components; the ground stations, the targets, and the measurement characteristics are all different. The principal connection between the two techniques is a set of local survey ties between the ground-based components at a limited number of co-located geodetic observatories. Positions of co-located GPS and SLR stations show relative drifts in positions on the order of 3.5 mm/yr according to an IERS, 2005 report. These drifts raise concerns about the accuracy of the ITRF for increasingly important applications of precision positioning including sea-level change, atmospheric remote sensing using GPS limb sounding, gravity measurement, and time transfer.

There are a few laser reflector arrays on low Earth orbiters that carry GPS receivers such as the ocean and ice altimeters. These satellites exhibit biases of several centimeters in positioning between the SLR and GPS only determinations using their on-board GPS receivers. Two older GPS satellites also carry SLR reflectors. However, analysis of this data has been hindered by the small number of GPS targets, the sub-optimal LRA design for the current tracking systems, and night-only tracking ability of the current ground network. Biases of 5-6 cm are observed between GPS and SLR ranging determinations to these satellites.

<u>Retroreflector Specification</u>

Current Satellites

The ILRS currently ranges to satellites from near Earth altitudes (few hundred kilometers) to the moon. Most stations, however, are devoted to satellites at GNSS distances and below. All ILRS stations must range routinely to LAGEOS I and II to be positioned within the Terrestrial Reference Frame and for product quality control. For co-location and network strength, these stations must also be co-located with a GNSS receiver whose data are routinely provided to the IGS for processing.

LAGEOS

The solid cubes in the LAGEOS array have a circular face with 3.8 cm (1.5 inch) diameter; they are uncoated and fabricated with a small vertex offset angle well matched to the velocity aberration. These cubes rely on total internal reflection as do the cubes in the Apollo arrays. The uncoated cubes were chosen to avoid thermal gradients during sun-illuminated periods and to avoid energy losses at the back surfaces.

GLONASS

The GLONASS satellite laser retroreflector arrays were built by the Institute for Precision Instrument Engineering (IPIE) in Russia. Satellites launched prior to 1996 have planar arrays 120 cm by 120 cm with 396 aluminum backcoated, fused-quartz corner cubes 27 mm across flats. All of the GLONASS satellites launched after 1996 tracked by the ILRS (including GLONASS 87, 89, and 95) have 132 corner cubes mounted within a 330-mm radius circular planar array. The presumption is that beam spread due to diffraction accommodates the smaller, yet still significant velocity aberration at GNSS altitudes. This has not yet been measured on the ground to verify performance.

GPS-35 and -36

The retroreflector array on GPS-35 and -36 is a flat panel, 239 mm by 194 mm, with 32 hexagonal-faced corner cubes of the same design as on GLONASS and made by the same company in Russia. The array area is 463 sq cm and mass 1.28 kg (see Figure 1).

ETS-8

ETS-8 has a planar array with 36 round-faced, uncoated quartz corner cubes, 4.06 cm (1.6 inch) in diameter. The array structure is aluminum alloy and the corner cubes are constrained to allow for the differential thermal

expansion of the structure and the quartz corner cubes. The corner cubes have been optimized for velocity aberration at 5320 Angstroms. The array weighs 3.1 kg., and the area is about 780 sq. cm.

From the corner cube and array information the expected return signal strength relative to LAGEOS has been estimated in Table 1. Using these models, the anticipated return signal strengths from GPS-35 and -36, GIOVE-A, and ETS-8 should be nearly the same at zenith and zenith angles of 45 and 60 degrees.

Satellite	Average Range (10 ³ km)	Cross Sec. (10 ⁶ m ²)	Relative Signal Strength normalized to LAGEOS*				
			At Zenith	45 deg. from zenith	60 deg. from Zenith		
LAGEOS	6 - 8	7	1	1	1		
GLONASS 87/89/95	19 - 22	80	0.1	0.14	.185		
GPS-35/36	20 - 23	20	0.021	0.029	.038		
GIOVE-A	24 - 27	45	0.023	0.034	.046		
ETS-8	36 - 39	170	0.017	0.027	.038		

* Cross-Section estimated from the array and corner cube specifications

ILRS Tracking Experience

ILRS Stations routinely range to LAGEOS in both daytime and nighttime. About a dozen stations presently track GPS-35/36, GLONASS-87/89, and GIOVE-A at night. The pass results show that the network acquired about twice as many passes on each of the GLONASS satellites as it did on each of the GPS satellites (See Table 2A and 2B).

Several of the stations have been successful with daylight ranging on the GNSS satellites. The distribution of normal points on the GNSS satellites as a function of local time (see Table 3) shows that the bulk of the daytime data was acquired on the GLONASS satellites.

Although we expect some improvement in both nighttime and daytime ranging with updates in the equipment and procedures now planned for the 2009 -11 timeframe, we will need at least another factor of five increase in the "effective area" over the GPS-35/36 retroreflector arrays to achieve performance comparable to the GLONASS 87 and 89. This is the equivalent of an "effective cross section" of about 100 million square meters at GNSS altitude.

During March 2007, the SLR stations at Koganei, Mt. Stromlo, and Yarragadee ranges successfully to the newly launched synchronous satellite ETS-8. The Yarragadee station acquired nearly 50 pass segment during the first two weeks of test tracking (see Table 4). As a surrogate for return signal strength, the success rate (number of returns verses number of laser firings) was calculated using the full rate date return numbers in the normal point format and the pulse repetition rate used by each of the stations. These results indicate that the return signal strength from ETS-8 is about twice that from GPS-35 and -36.

Although the theoretical calculations in Table 1 show that the return signal strength for ETS-8 should be about the same as GPS, the results here show that the data from ETS-8 is more robust and that an ETS-8 array with uncoated cubes would be a good option to consider for future GNSS satellites.

Table	2A: PA	SS SUM	MARY :	for SEP	TEMBER	2005	
Site Name	Sta.	GP35	GP36	GL87	GL89	GL95	Total
Ajaccio	7848	0	0	0	0	0	0
Beijing	7249	0	0	0	0	0	0
Borowiec	7811	0	0	0	0	0	0
Changchun	7237	0	0	0	2	1	3
Concepcion	7405	0	0	0	0	0	0
Graz	7839	6	7	14	11	7	45
Greenbelt	7105	1	0	1	4	3	9
Greenbelt	7130	0	0	0	0	0	0
Hartebeesthoek	7501	0	0	5	10	0	15
Helwan	7831	0	0	0	0	0	0
Herstmonceux	7840	0	6	8	7	4	25
Katzively	1893	0	0	0	0	0	0
Kiev	1824	0	0	0	0	0	0
Lviv	1831	0	0	0	0	0	0
Maidanak	1864	0	0	5	6	3	14
Matera	7941	0	0	0	0	0	0
Mcdonald	7080	5	6	9	2	2	24
Monument Peak	7110	9	4	8	6	9	36
Mount Stromlo	7825	3	0	9	11	7	30
Papeete	7124	0	0	0	0	0	0
Potsdam	7841	0	0	0	0	0	0
Riga	1884	0	1	0	0	0	1
Riyadh	7832	18	16	9	11	0	54
San Fernando	7824	0	0	0	0	0	0
Simeiz	1873	0	0	1	5	0	6
Simosato	7838	0	0	0	0	0	0
Tanegashima	7358	0	0	1	0	0	1
Urumqi	7355	0	0	0	0	0	0
Wettzell	8834	4	3	10	9	13	39
Wuhan	7231	0	0	0	0	0	0
Yarragadee	7090	19	2	19	14	16	70
Zimmerwald	7810	9	16	16	20	15	76
Totals:		74	61	115	118	80	448

	Table 2B: PASS SUMMARY for 2006							
Site Name	Sta.	GP35	GP36	GL87	GL89	GL95	GIOA	Total
Arequipa	7403	0	0	0	0	0	0	0
Beijing	7249	1	0	0	19	20	1	41
Borowiec	7811	0	0	0	0	1	0	1
Changchun	7237	15	2	75	54	68	28	242
Concepcion	7405	8	8	10	7	0	3	36
Graz	7839	24	50	97	81	79	33	364
Greenbelt	7105	0	0	22	14	19	3	58
Greenbelt	7130	0	0	0	0	0	0	0
Haleakala	7119	0	0	0	0	0	0	0
Hartebeesthoek	7501	0	2	62	19	47	1	131
Helwan	7831	0	0	0	0	0	0	0
Herstmonceux	7840	26	38	59	59	46	28	256
Katzively	1893	0	0	9	10	4	0	23
Koganei	7308	0	0	4	4	0	1	9
Lviv	1831	0	0	0	0	0	0	0
Maidanak	1864	9	3	36	60	36	0	144
Matera	7941	5	5	40	24	4	14	92
Mcdonald	7080	31	30	23	40	28	25	177
Monument Peak	7110	12	6	64	44	17	33	176
Mount Stromlo	7825	69	57	105	86	87	29	433
Papeete	7124	0	0	0	0	0	0	0
Potsdam	7841	0	0	0	0	0	0	0
Riga	1884	0	0	0	0	0	1	1
Riyadh	7832	117	121	89	99	96	11	533
San Fernando	7824	0	0	0	0	0	0	0
San Juan	7406	81	83	96	126	138	57	581
Shanghai	7821	0	0	1	2	0	0	3
Simeiz	1873	0	0	0	1	0	0	1
Simosato	7838	0	0	0	1	2	0	3
Tanegashima	7358	2	2	5	3	3	0	15
Wettzell	8834	36	28	95	75	51	33	318
Yarragadee	7090	125	110	200	196	196	78	905
Zimmerwald	7810	58	61	169	148	127	53	616
Totals:		619	606	1261	1172	1069	432	5159

Table 3. Number of normal points as a function of local time in 1 hour bins(April 1, 2006 ends March 31, 2007)								
Less1 Time	Satellite and Altitude in 1000's of kms							
hours	LAGEOS 6	GPS 20.1	GLONASS 19.1	GIOVE-A 24.0	ETS-8 36			
0	10784	605	1624	483	34			
1	10451	593	1417	585	36			
2	9910	462	1323	602	35			
3	9407	459	1213	501	53			
4	8682	294	896	253	55			
5	8005	244	552	243	20			
6	7158	77	405	112				
7	6904	65	262	68				
8	6455	37	284	31				
9	6115	38	248	32				
10	5244	43	293	50				
11	5163	60	312	48				
12	4532	43	291	34				
13	4753	49	246	23				
14	4687	95	241	37				
15	4789	103	303	63				
16	5246	168	438	103				
17	6527	274	575	137				
18	8134	560	1057	232				
19	10622	591	1397	313	9			
20	11842	744	1324	404	10			
21	10867	603	1089	376	22			
22	9724	635	1061	390	39			
23	10479	666	1290	521	38			

Table 4. Return Success Rate at about 40 degrees from Zenith								
	GPS-35 and -36 ETS VIII							
Station	Pulse Rep Rate	Success Rate	Pulse Rep Rate	Success Rate				
		(returns/fire event)		(returns/fire event)				
Koganei	10	.004	10	.013				
Mt Stromlo	30	.001	30	.002				
Yarragadee	4	.033	2	.066				

Some Options

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As an illustration, several options for the array are examined in Table 5. Other options with other cube sizes are certainly possible.

Option 1. Solid uncoated cubes similar to those on the ETS-8 satellite. The array area and weights in Tables 3A have been estimated by scaling from the cube size, number of cubes, and array weight on ETS-8.

Option 2. Solid, back-coated cubes similar to those provided by IPIE for GPS, GLONASS, and GIOVE-A. The array area and weight for the 160 cube option in Table 3 has been estimated by multiplying the values for GPS-35/36 arrays by a factor of five.

Option 3. Solid, back-coated cubes with 0.5 inch (1.3 cm.) diameter, estimated by scaling from the size and weight of the ETS-8 array which looks like a more efficient design than that of the GPS-35/36.



Option 4. Hollow cubes made from aluminum, glass or Beryllium offer the potential of high gain (reduced area) and lower weight. A hollow cube, although of larger size than being considered here, has already been successfully flown in space on ADEOS-1 and tracked. The ILRS network acquired 175 pass segments on ADEOS-1 during the period 12/14/2002-01/22/2003. Design and performance studies are currently underway at GSFC to determine the viability of an array of space qualified hollow cubes (see Figure 2). The area and weight in table 3 for the hollow cube option are based on those studies.

Table 5Array Options for Effective Cross Sectionof 100 million sq. meters.								
Option	Design	# of cubes	Diameter of cubes (inch)	Approx. Area of the array (sq cm)	Approx. Mass of the arrays (Kg)			
1	Solid – uncoated (scaled ETS)	50	1.3	847	2.3			
2	Solid – coated (scaled GPS)	160	1.06	2300	6.4			
3	Solid – coated (scaled ETS)	400	0.5	1005	1.1			
4	Hollow (analysis)	37	1.4	590	1.2			



Recommendation:

We should endorse an ILRS Standard for an "Effective Cross-Section" of 100 million square meters for satellites at GNSS altitudes.

If the hollow cube option can be made to work, this would provide a factor of five improvement over the arrays on GPS-35 and -36, in an array of 590 sq. cm compared to present 464 sq cm on GPS-35 and -36. Otherwise we should seriously consider a ETS-8 style array with uncoated cubes.