High Precision Determination Of Station Heights Of The Keystone Satellite Laser Ranging Network:- Developing Optimum Observation Requirements.

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Summary:

The KSP network, comprising the co-location of VLBI, SLR and GPS space geodetic techniques, was established in 1996 by the Communications Research Laboratory (CRL) to monitor regional crustal deformation in the Tokyo metropolitan area. The pre-requisite for the scientific objectives and outcomes of the KSP network to monitor any pre-cursory / pre-seismic crustal movement is the ability to determine tracking station positions at a precision and accuracy of one mm. or better using a very short time span of observations; one week to one month. The rationale for the study, therefore, was to establish an "observation budget" and develop computation strategies for the Keystone SLR network that would meet the geodetic precision requirements of the specifications. Several factors limit the size of the observed data that is produced by any given SLR station. For the purposes of the study, observation scenarios were adopted which were both realistic and matched well with the output of some of the most productive SLR stations currently operating in the world. Several computation procedures were employed comprising single and multiple satellite solutions, with varying arc lengths, of Lageos-1, Lageos-2, Ajisai and Etalon-2.

It was determined that the "observation budget" of greater than 1100 observation normal points of range data, comprising observations to several geodetic satellites (Lageos-1, Lageos-2, Ajisai, Etalon-1, Etalon-2) for a one-month arc can meet the KSP geodetic precision requirements of 1 mm. in the station height component. The optimum "observation budget" of 1600 range normal points per station per month translates into a combined total of 45 complete Lageos-1 and Lageos-2 passes together with 20 complete Ajisai or 10 Etalon passes.

For the small network (KSP), short arc solutions (several days), the precision of the estimated station height component approaches 1.5 to 2.0 mm. for a Lageos-1 / Lageos-2 solution for an eight to ten day arc; with earth Orientation Parameters estimated. This has the potential to improve with the inclusion of data from the other high altitude geodetic satellites such as Etalon-1 and Etalon-2. It is therefore recommended that (i) this study be expanded to incorporate the Etalon satellites in the small network short arc solutions and (ii) that the KSP give equal observation priorities to the Etalon satellites as for the Lageos satellites.

The October 1997 results of the initial observed data from the KSP stations Kashima and Koganei showed rms of the post-fit residuals at the one centimeter level; which is compared to Greenbelt (3 mm.), Monument Peak (5 - 6 mm.) and Yaragadee (4-5 mm.) for the concurrent data.

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1.0 Introduction:

The KSP network, comprising the co-location of VLBI, SLR and GPS space geodetic techniques, was established in 1993 by the Communications Research Laboratory (CRL) to monitor regional crustal deformation in the Tokyo metropolitan area. Figure 1.1 shows the relative locations of the Keystone (KSP) Satellite Laser Ranging (SLR) Network of stations. Table 1.1 gives the approximate distances (from 35 to 135 km) between the stations.

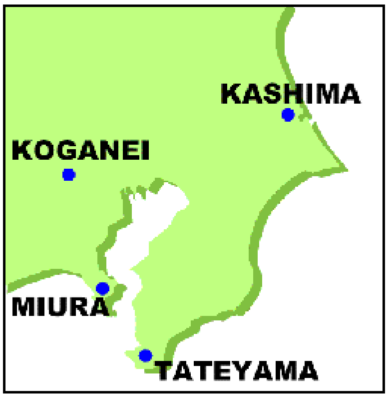


Figure 1.1 Relative Locations of Keystone SLR stations

Table 1.1 Approximate Distances (Kilometers) between Keystone Stations

Station/Monument ID	Koganei	Miura	Tateyama
Kashima/73357201	109.121	123.475	134.875
Koganei/73287101		57.775	91.837
Miura/73377301			34.951
Tateyama/73397401			

The general design specifications of the main components of the KSP generation of SLR stations are listed in Table 1.2 (CRL, 1996):

Table 1.2 Design Specifications for KSP generation of SLR Stations.

Laser Wavelength	532 nanometers
Laser Pulse Width	30 picoseconds
Laser Repetition Rate	10 to 1000 Hz.
Laser Pulse Energy	50 mJoules (max.)
Telescope Aperture	75 cm.
Telescope Focus	Coude
Telescope Mount	Azimuth - Elevation
Telescope Tracking Accuracy	2.5 arcseconds
Telescope Driving Speed	12 degrees/second
Photodetector	Single Photon Avalanche Diode (SPAD) and Micro Channel Plate (MCP)
Time Measurement:	GPS (Current) Hydrogen Maser (planned), Master Ranging Control System (MRCS) Epoch Counter

With these specifications the expected precision of a normal point of the observed SLR ranges is 8 mm (Kunimori, (1997) - personal communication).

The pre-requisite for the scientific objectives and outcomes of the KSP network to monitor any pre-cursory / pre-seismic crustal movement using space geodetic techniques is the ability to determine tracking station positions at a precision and accuracy of one mm. or better using a very short time span of observations; one day to several weeks. The rationale for the study, therefore, was to establish an “observation budget” and develop computation strategies for the Keystone SLR network that would meet the geodetic precision requirements of the specifications – a determination of the height component at a precision of 1 mm. or better. Several factors limit the size of the observed data that is produced by any given SLR station; such as weather and cloud cover, satellite elevation/availability/visibility, work practices [number of shifts (24-hour operation), length of shifts, weekend and public holiday operations, station maintenance, etc.]. For the purposes of the study, observation scenarios were adopted which were both realistic and matched well with the output of some of the most productive SLR stations currently operating in the world. Figure 2.1 shows examples of the quantity of data produced by some of these global stations in USA, Europe and Australia.

Several computation procedures, described in Section 2.0, were performed comprising single and multiple satellite solutions, with varying arc lengths, of Lageos-1, Lageos-2, Ajisai and Etalon-2. Although, several geodetic satellites are available for SLR, the Lageos satellites were selected because of their global observation priorities, and Ajisai because of its observation priorities in Japan. A limited experiment was undertaken with Etalon-2 in order to demonstrate its potential to produce some of the best geodetic solutions and that it is convenient for use in “near real time” computations since, as in the case of the Lageos satellites, due to its altitude there are no atmospheric drag effects. Although currently there is a very low data volume for the Etalon satellites, compared to Ajisai, it has the advantage that current daily magnetic and solar flux values (which generally has a one month delay in its distribution) are not required.

The initial approach was to simulate data for all the Western Pacific Laser Tracking Network (WPLTN) stations (in addition to the Keystone stations)– and study the influence of added data and added quality on the precisions of the estimated geodetic parameters – in a global sense. However, the excessive computational load led to the abandoning of this approach (temporarily – only for the purposes of this study) and confine the study to the Keystone stations.

2.0 Computation Procedure:

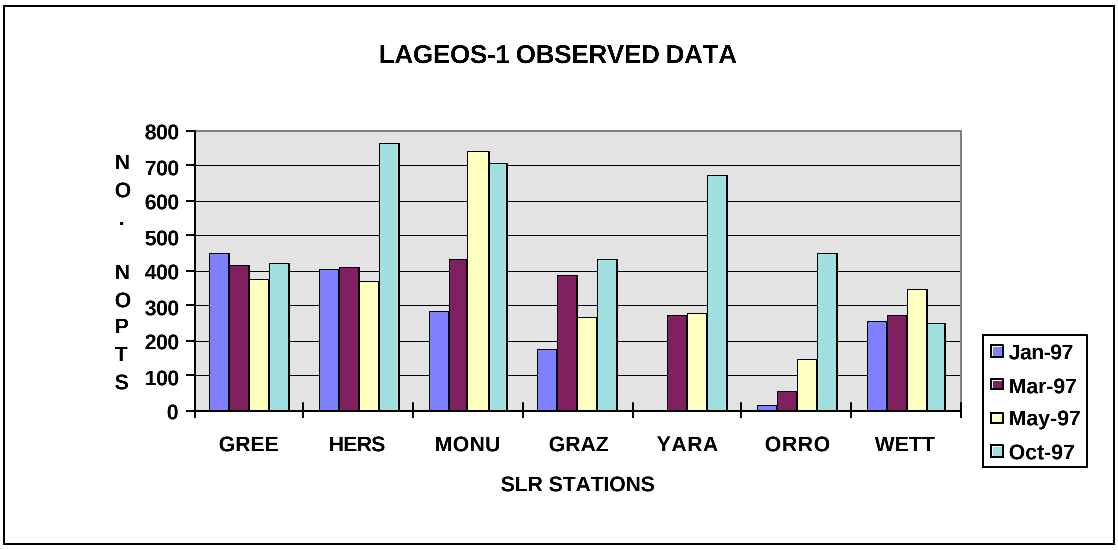
Initially, Lageos-1 and Lageos-2 observed data for January, March and May 1997 was processed for Precise Orbit Determination (POD) of these satellites, determining the quality of the solutions obtainable from the observed global data set and overall performance standards of the observing stations in terms of the quality (precision) and quantity of data; providing an indicator for realistic expectations of data quality (measurement uncertainty and added noise) and quantity for the current generation of SLR stations, that is Keystone, based on the performance of the current best stations in the world – as indicated by these solutions. The locations and distribution of the global set of SLR stations that observed at some stage during the months January, March, May and October 1997 are shown in Figure 3.1. In addition, the satellite trajectories generated from these POD solutions were used to manufacture the simulated data for the Keystone SLR sites. Similarly, Ajisai data for May 1997 was also processed for POD and simulated data produced for the four Keystone sites. For Etalon-2 however, the state vector for the predicted satellite orbit was used to generate the trajectory and the simulated data.

In general, the orbit parameters that were estimated over 30-day arcs for each satellite comprised the state vector, one solar radiation pressure scale coefficient, constant and periodic (once per revolution) general acceleration in along and cross track once every five days and for, Ajisai only (1490 km. altitude), one atmospheric drag coefficient. Measurement biases (range and time) were estimated for every pass.

The station coordinates at epoch are determined from the positions and velocities of the University of Texas, Center for Space Research (UT/CSR) solution SSC(CSR)95L01 in ITRF94. These coordinates were held fixed for the POD process. For the purpose of this study, the values for Earth Orientation Parameters (EOP) were not estimated – the daily values determined from the IGS combined solutions were used and held fixed. However, EOPs were estimated for the October 1997 data; which also formed the Asia Pacific Regional Geodetic Project (APRGP) of the Geodesy Working Group under the auspices of the Permanent Committee for GIS Infrastructure for Asia and the Pacific, United Nations Cartographic Conference. In addition, in the case of short arc (few days) solutions of the KSP network (described below), it was attempted to closely simulated an operational system, and hence EOPs were estimated.

The JGM3 geopotential model to degree and order 70 (18 for Etalon-2) was used; with the modification that the values for the normalized C(2,1) and S(2,1) coefficients as recommended in IERS Conventions 1996 were adopted. Third body perturbations due to the Sun, Moon and Planets, Earth and Ocean Tide effects on the gravitational potential and on site position deformations were all incorporated in the computations. The complete descriptions of the physical models used are found in Van Martin (1996) and Govind (1994).

The trajectories generated from the estimated satellite orbit parameters from these solutions were used to simulate “model perfect” data for the four Keystone sites. Measurement uncertainty of 10 mm. and 5 mm. of noise was added to this data. These values are consistent with the post-fit residuals of the current best operating SLR systems in North America, Europe, and Australia which were included in the initial global solutions for January, March and May 1997; and later for the APRGP of October 1997. Figure 2.1 shows the data production (number of normal points) for a small sample of the best currently operating global SLR stations. Table 2.1 shows the observation quality (weighted rms of postfit residuals of one-way ranges). In order to further demonstrate the state-of-the-art SLR data quality, Figures 2.2, 2.3 and 2.4 are examples of pass-by-pass post-fit residuals of two-way-ranges, two-way range biases and time biases for station Greenbelt observing Lageos-2 during October 1997.



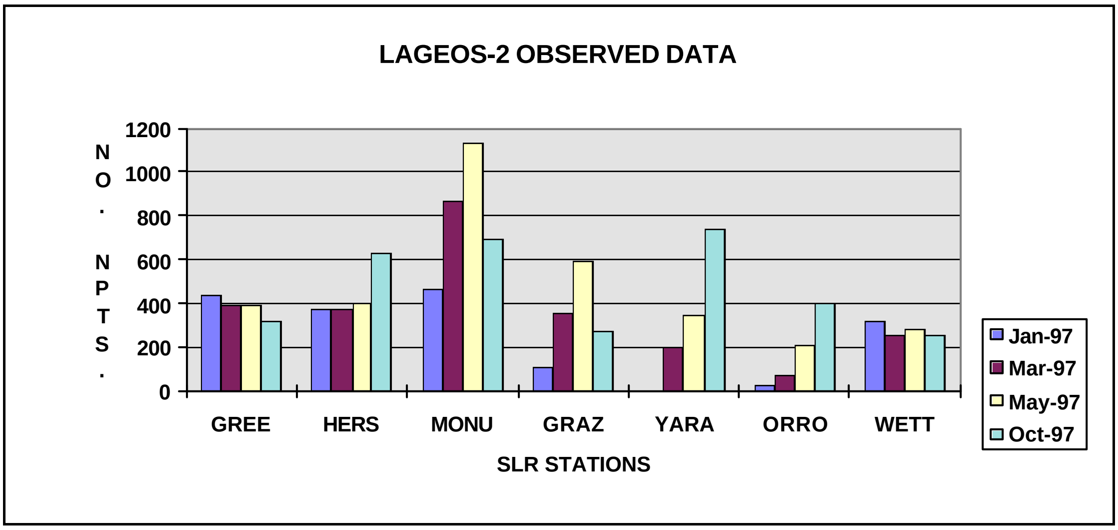


Figure 2.1 Examples of Current SLR Station Performance – Data Production

Table 2.1 Examples of Current SLR Station Performance - RMS of Postfit Residuals (mm.)

	Lageos-1				Lageos-2			
	JAN97	MAR97	MAY97	OCT97	JAN97	MAR97	MAY97	OCT97
MONU	5.8	6.1	6.1	6.0		4.6	5.1	5.2
GREE	5.4	5.8	6.2	4.0	4.4	3.9	4.8	3.8
HERS	4.4	4.7	5.8	11.2	4.3	5.5	5.6	8.3
WETT	7.4	7.0	6.9	8.3	7.5	7.2	8.2	7.9
GRAZ	3.2	5.5	4.6	6.9	3.0	4.6	5.3	5.7
YARA		5.1	3.5	4.7		7.1	5.4	3.7
ORRO			7.8	7.4	8.1	7.2	6.8	5.7

The quantity of simulated data generated for the Keystone stations and the rationale for the observing strategy is discussed in the section 3.0.

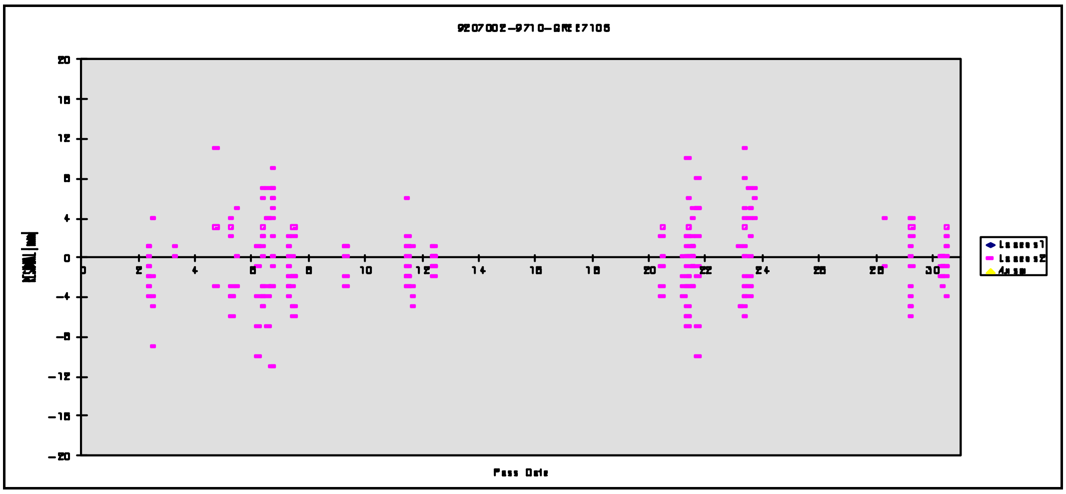


Figure 2.1: Pass-by-Pass Post-fit Residuals – Greenbelt – Lageos-2 – October 1997

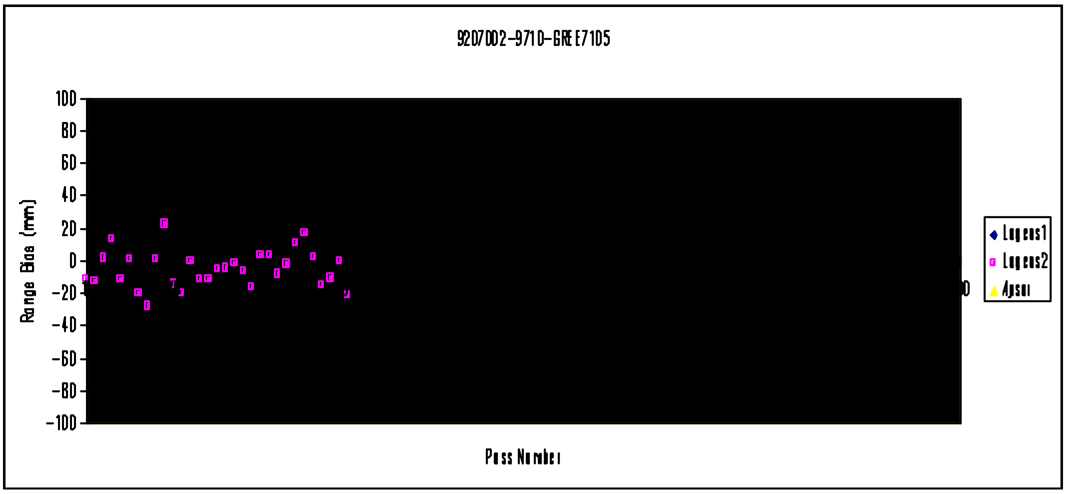


Figure 2.2: Pass-by-Pass Range Bias – Greenbelt – Lageos-2 – October 1997

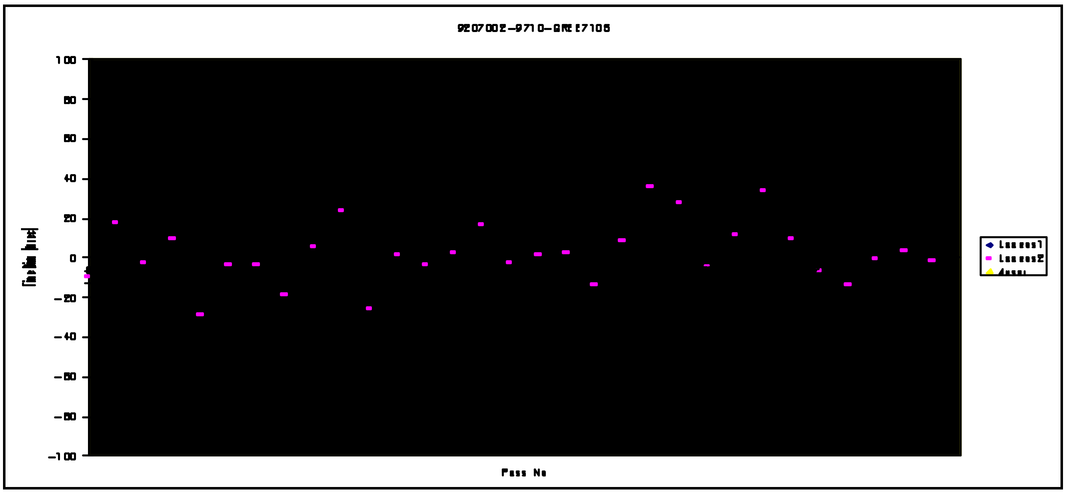


Figure 2.3: Pass-by-Pass Time Bias – Greenbelt – Lageos-2 – October 1997

The simulated Koganei data was merged with the observed global data set and the POD computations repeated. The number of normal points of simulated range data that was augmented into the respective global solutions were:

Satellite	Jan97	May97
Lageos-1	435	371
Lageos-2	194	371

The precisions of the estimated orbit parameters were examined – to establish any significant improvement as a result of including data from this station.

Several small network solutions for the four Keystone stations were performed, using the simulated data, and apriori orbit parameters from the "real" solution which were initially used to generate the simulated data set as follows:

Solution Type	Arc Length	Month
Lageos-1	one month arc	Jan97
Lageos-2	one month arc	Jan97
Lageos-1+Lageos-2 Combined	one month arc	Jan97
Lageos-1	one month arc	May97
Lageos-2	one month arc	May97
Ajisai	one month arc	May97
Lageos-1+Lageos-2 Combined	one month arc	May97
Lageos-1+Lageos-2+Ajisai Combined	one month arc	May97
Etalon-2	one month arc	May97

Subsequently the computations for the global observed data sets (May97 only) were repeated for 15-day arc lengths. Using the trajectories generated from the estimated satellite orbit parameters for the second 15-day arc solutions, model perfect data for the second 15 days were simulated. This simulated data, together with the estimated orbit parameters from the first 15-day solution (as apriori) were then used to compute short-arc solutions for the Keystone network – comparing the estimated orbit parameters and their precisions with the original second 15-day arc that produced the simulated data and the precisions of the estimated station coordinates. In order that the exercise closely simulates practice (no EOPs are generally known for the second 15-day arc), EOP are estimated as well.

The short-arc KSP network solutions were done as follows:

Solution Type	Arc Length	Period
Lageos-1	5 day arc	May9702
Lageos-2	5 day arc	May9702
Lageos-1+Lageos-2 Combined	5 day arc	May9702
Lageos-1+Lageos-2 Combined	8 day arc	May9702
Lageos-1+Lageos-2 Combined	10 day arc	May9702
Lageos-1+Lageos-2+Etalon-2 Combined	5 day arc	May9702
Lageos-1+Lageos-2+Etalon-2 Combined	10 day arc	May9702

3.0 Data:

Figure 3.1 shows the distribution of global SLR stations for which data (of varying standards of performance), acquired through the CDDIS at NASA/GSFC, was available and incorporated into the original POD solutions for January, March, May and October 1997.

Table 3.1 shows some of the typical orbit properties of the satellites used in this study and their related observation outcomes. The quantity of simulated data "the observation budget" for the Keystone stations (which forms the major aim of this study) were determined as follows; both in terms of typical working hours and generally compared to the quantity of data produced by some of the currently best performing stations. A realistic representation of a possible observation budget was attempted. The data was simulated using an elevation cutoff angle of 20 degrees with a measurement uncertainty of 10 mm and added noise of 5 mm. (to concur with the expected 8 mm. measurement uncertainty of the KSP stations) The January, March and May global solutions showed that the typical noise level of the best currently operating SLR stations is at the 3 to 9 mm level (as seen from Table 2.1).

Table 3.1: Orbit Properties and Data Outcomes --Normal Points -- (NP) for KSP Stations.

Satellite	**Period (minutes)**	**Pass Duration (minutes)**	**NP rate (seconds)**	**Typical # of NP/per pass**	**max # of NP/month**
Lageos	222	50	120	25	2900
Ajisai	115	13	30	25	3100
Etalon-2	675	270	300	55	2000

The simulated data was produced as follows:

- Night Observations only for all satellites that were tracked.
- There were no weekend operations.
- The data span – observation days – for each satellite during the months of January and May 1997 are shown below/

Table 3.2 Simulated Data Station Operations

Satellite Tracked	Dates	Length of Shift
Lageos-1	1-31 January 1997	7 p.m. - 7 a.m.
Lageos-2	1-31 January 1997	7 p.m. - 7 a.m.
Lageos-1	1-23 May 1997	9 p.m. - 5 a.m.
Lageos-2	1-31 May 1997	9 p.m. - 5 a.m.
Ajisai	1-25 May 1997	9 p.m. - 5 a.m.
Etalon-2	1-31 May 1997	9 p.m. - 5 a.m.

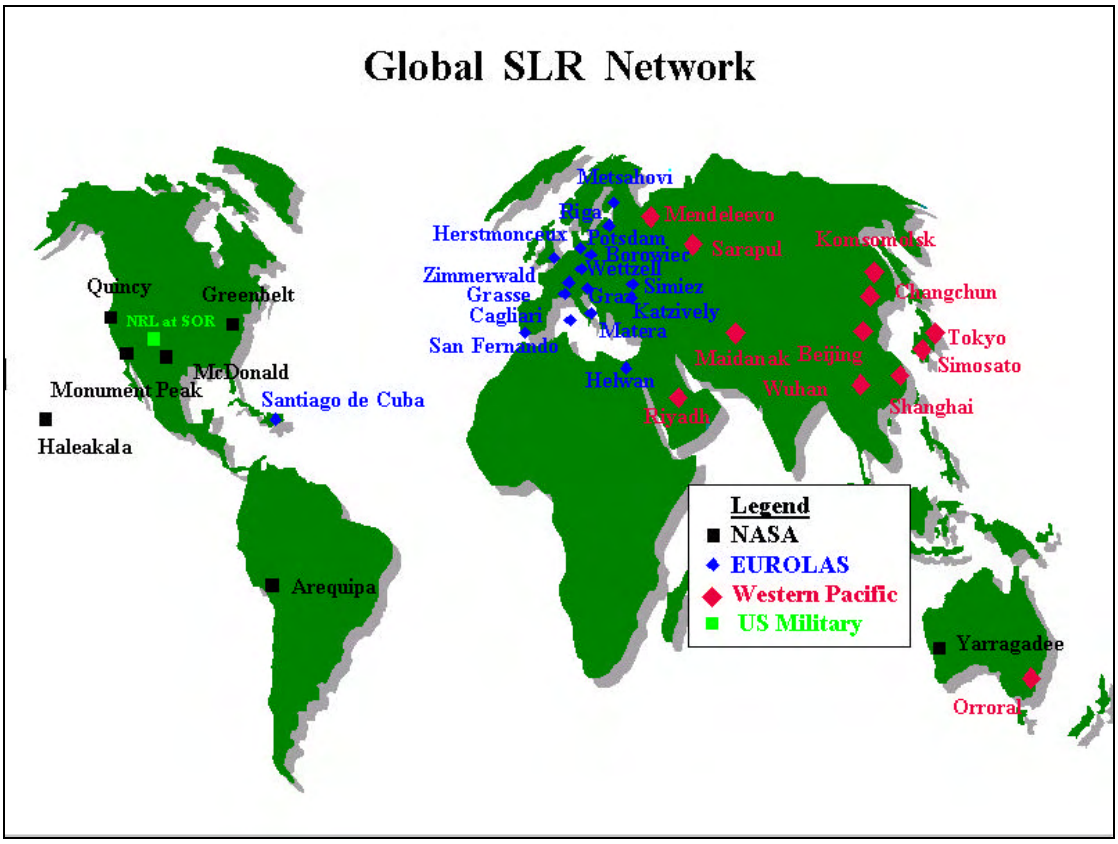


Figure 3.1 Map of Global SLR Stations observing during January, March, May and October 1997.

4.0 Results and Analysis:

A sample of the results obtained from the January, March, May and October 1997 global solution were shown in Section 2.0 in terms of post-fit residuals, two-way range biases and time biases.

The inclusion of the Koganei simulated data in the POD showed significant improvement (50%) in the precision of the estimated satellite position for Lageos-1 in January 1997; and very marginal improvement in the precision of the satellite position estimates (<5%) for both Lageos-1 and Lageos-2 solutions for March and May, 1997. This is attributed to the fact that no SLR data for Yaragadee was available and the Orroral data set was significantly small (17 normal points) for January 1997 which resulted in a very weak POD solution being determined from the available observed data.

Tables 4.1, 4.2 and 4.3 list the results of KSP small network simulation studies. From the solutions, it is seen that height precision is correlated with the number of data points that were observed / entered the solution. For single satellite one month solutions, the height precisions approach the 1.0 mm. specifications for Lageos-1 (January 1997) and Lageos-2 (May 1997) – the months that recorded the highest number of normal points.

However, further improvement in the precision of the estimated station heights is evident from the multi-satellite one-month arc solutions. The combination of Lageos-1 and Lageos-2 and Lageos-1, Lageos-2 and Ajisai data satisfies the geodetic precision specifications for station height estimates. Small network, long-arc (one month) multi-satellite computation strategies has significant potential for determining high precision station heights from SLR normal point data; if the combined total (all satellite) of normal point data exceeds 1100 observations per station per month. This number of data points was achieved through the observation schedule / station operations discussed in Section 3.0

The small network short arc (several days) solutions is best at the 1.5 to 2.0 mm level for an 8 to 10 day arc for a two satellite computation. Eight-day arcs over a small network may approach the 1.0 mm. level of precision for height estimates when data from more than two satellites are combined. It is noted that in this case, EOPs were also estimated which would generally weaken (intentionally) the estimated precisions (at some level) of the geodetic parameters.

4.1 KSP Results -- October 1997 Data:

The number of observed and edited normal points and the rms of the post-fit residuals for the Kashima and Koganei KSP stations are given below:

KSP Station	Satellite	#Observations input	#Observations after editing	rms post-fit residual (mm.)
Kashima	Lageos-1	142	140	8.7
Kashima	Lageos-2	73	73	6.0
Koganei	Lageos-1	57	50	9.7

This is compared to the performance of the Greenbelt SLR station for the same observing period; which had produced 422 and 315 normal points for Lageos-1 and Lageos-2 having a rms of the post-fit residuals of 4.0 and 3.8 mm. For the purposes of further comparisons, Figures 4.1 to 4.9 showing the pass-by-pass post-fit residuals, two-way range bias and time biases for Kashima and Koganei are provided.

The station height estimates, precisions and differences from the latest VLBI + Terrestrial Survey (Kunimori 1997 – personal communication) are given below for the three solution types.

Station	Solution Type	Height Estimate (meters)	Precision Estimate (mm)	Solution minus VLBI+Survey
Kashima	Lageos-1	70.883	3.4	0.045
Kashima	Lageos-2	70.873	2.5	0.035
Kashima	Lag-1+ Lag-2	70.882	2.5	0.044
Kaganei	Lageos-1	124.118	5.2	

The combined Lag-1 + Lag-2 solution minus the VLBI + Survey coordinates in the east and north components were determined as -0.036 and -0.009 meters respectively.

KSP Small Network Solutions:

Table 4.1: Single Satellite Solutions.

Solution Type	Lageos-1	Lageos-2	Lageos-1	Lageos-2	Ajisai	Etalon-2
Arc Length	one month	one month	one month	one month	one month	one month
Month	Jan97	Jan97	May97	May97	May97	May97
Number of Data Points/station	670	340	250	880	480	260
Cart. Station Coords Sigma(mm)	2.0-2.6	2.2 - 3.5	2.3 - 3.7	1.8 - 2.3	2.4 - 3.8	1.2 - 1.7
Station Ht. Sigma (mm)	1.4	2.3	3.0	1.2	1.9	1.3

Table 4.2: Multi-Satellite Solutions.

Solution Type	Lag-1+Lag-2	Lag-1+Lag-2	Lag-1+Lag-2+Ajisai
Arc Length	one month	one month	one month
Month	Jan97	May97	May97
Number of Data Points/station	1000	1100	1610
Cart. Station Coords Sigma(mm)	1.7	1.7 - 2.0	1.5 - 1.7
Station Ht. Sigma (mm)	1.2	1.1	0.9

Table 4.3: Small Network / Short Arc Experiments: (* data simulated for second half of the month from 15-day arc solution)

Solution Type	Lageos-1	Lageos-2	Lag-1+Lag-2	Lag-1+Lag-2	Lag-1+Lag-2
Arc Length	five days	five days	five days	Eight days	Ten days
Month	May9702*	May9702*	May9702*	May9702*	May9702*
Number of Data Points	90	265	355	560	695
Note: The rms of the radial, along track, and cross track differences should be examined to ascertain the magnitudes of errors in the short-arc orbit.					
Cart. Station Coords Sigma(mm)	3.6 - 5.2	2.9 - 3.5	2.7 - 3.3	2.3 - 2.7	2.3 - 2.5
Station Ht. Sigma (mm)	4.2	2.1	1.9	1.5	1.4

5.0 Conclusions and Recommendations

Meeting observation precision specifications of 8 mm. or better, the observation strategies and station operations, and computation procedure must be considered as a single package or process – the adoption of a strategy for the one component – must be consistent with the other components of this process.

Several experiments consisting of a number of computation strategies using a combination of single or multiple satellites with arc lengths of several days to one-month were performed over the KSP network. The data was simulated using the estimated satellite state vectors from one-month arc solutions using globally observed data during the months of January (Lageos-1, Lageos-2), March (Lageos-1, Lageos-2) and May (Lageos-1, Lageos-2, and Ajisai) 1997. The precisons of the estimated heights in each case was examined. The quantity of simulated data was generated for each KSP station on the basis that there were night observations only, eight or twelve hour shifts and no weekend observations. It was assumed that for some days in the month there were no observations due to weather, maintenance etc.

The determination of station heights from the KSP network (maximum line length of 135 km.) at the precision of 1.0 mm.can be achieved as follows:

- Normal point range data is at a precision of 8 mm. or better. The analysis of the global SLR data for January, March, May and October 1997 showed that the precision of normal points from current state-of-the-art SLR stations is at the 3 to 5 mm. level in most cases. The precision of the October 1997 range normal points from Kashima was 8.7 mm. for Lageos-1 and 6.0 mm. Lageos-2. For the same period, the precision of the observations at Koganei to Lageos-1 was 9.7 mm.

- At least 1100 data points are required over a one month arc. This can comprise multiple satellites. For a single satellite solution, the Lageos-2 solution for May 1997 produced height estimates at the precision of 1.2 mm with 880 data points per station. The combination of Lageos-1 and Lageos-2 (1100 data points per station) was marginally better – approaching the 1.0 mm specification. However, the combination of Lageos-1, Lageos-2 and Ajisai (1600 data points per station) produced heights with a precision of 0.9 mm. The optimum "observation budget" of 1600 range normal points per station per month translates into a combined total of 45 complete Lageos-1 and Lageos-2 passes together with 20 complete Ajisai or 10 Etalon passes.

- The KSP network short arc solutions showed that the height estimates can only be achieved at the 1.5 mm level for a 10 day arc of Lageos-1 and Lageos-2 combined. Since this is considered to be a close simulation of the KSP operations, EOPs will not be available and therefore had to be estimated. This weakens the solution. Also, for this type of quick turn-around of results, including Ajisai is considered not be appropriate – since Ajisai POD requires that atmospheric drag parameters to be estimated which in turn requires magnetic and solar flux data. There is generally a one month delay in obtaining this data.

- However, Etalon-1 and Etalon-2 satellites would be most appropriate for KSP applications. The one month arc solution for Etalon-2 gave a precision of the estimated station height at 1.3 mm. A combined short-arc solution for Lageos-1, Lageos-2, Etalon-1 and Etalon-2 has the potential to provide station height estimates at the 1.0 mm level with just several days (8 to 10) days data. The Etalon satellites can contribute significantly to high precision geodesy but the current low data volume and sparse observations globally makes its use very limited. It is suggested that for KSP applications and observing strategy, an equally high priority for Lageos-1, Lageos-2, Etalon-1 and Etalon-2 be considered; and process the data as a small network short arc (8 - 10 days). This should satisfy both the geodetic specifications and the "near real time" requirements of a solution for the station positions. It is recommended that a simulation study comprising the above combination solution be undertaken.

- The October 1997 results showed that the observations at the Kashima and Koganei were reasonably good with this limited data set; and these being an initial set of observations from new stations. The rms of the post-fit residuals at Kashima were 8.7 and 6.0 mm for Lageos-1 and Lageos-2 respectively. The rms of the post-fit residuals at Koganei was 9.7 mm for Lageos-1. The precisons of the estimated heights at Kashima from a combined Lageos-1 and Lageos-2 was 2.5 mm and that of Koganei was 5.2 mm. (Lageos-1 only). However, a there is a discrepancy 4.4 cm. in the height component from the supplied VLBI + Terrestrial Survey value. The source of this difference (SLR or Survey) could be located with continued computations of the SLR data.

6.0 References:

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7.0 Acknowledgements:

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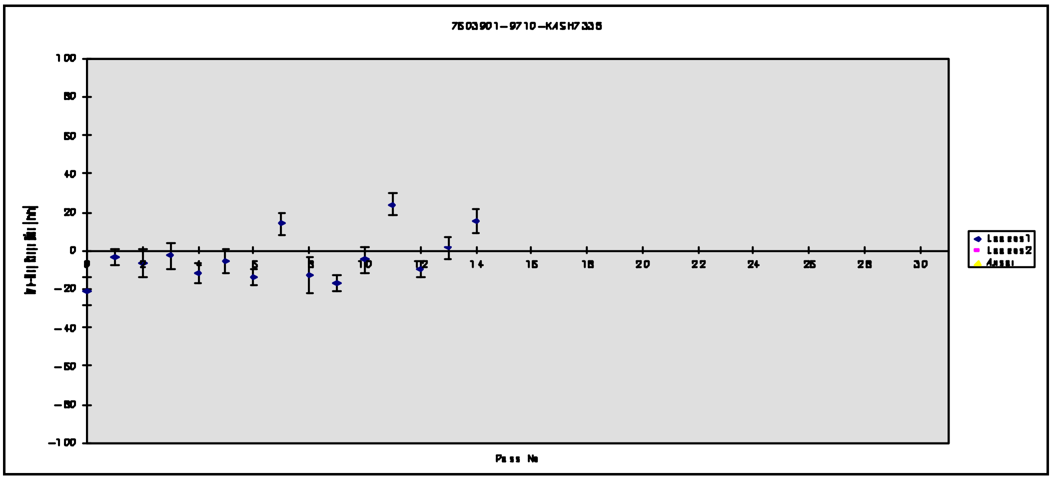

Figure 4.1: Pass-by-Pass Post-fit Residuals – Kashima– Lageos-1– October 1997

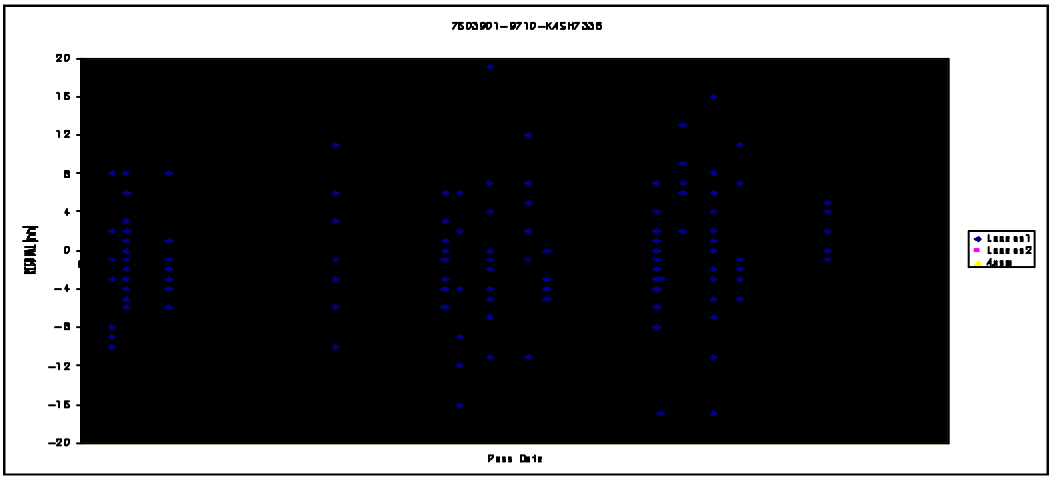

Figure 4.2: Pass-by-Pass Range Bias – Kashima – Lageos-1– October 1997

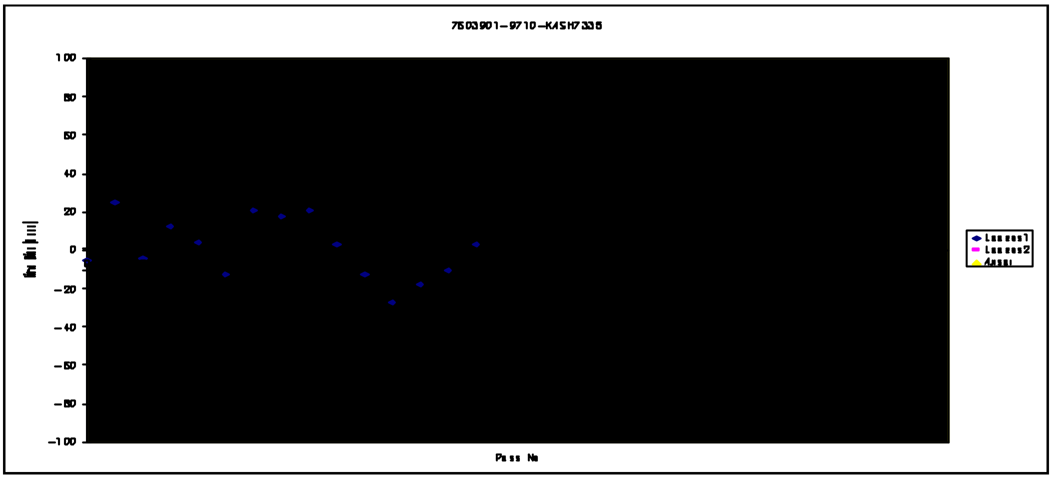

Figure 4.3: Pass-by-Pass Time Bias – Kashima – Lageos-1– October 1997

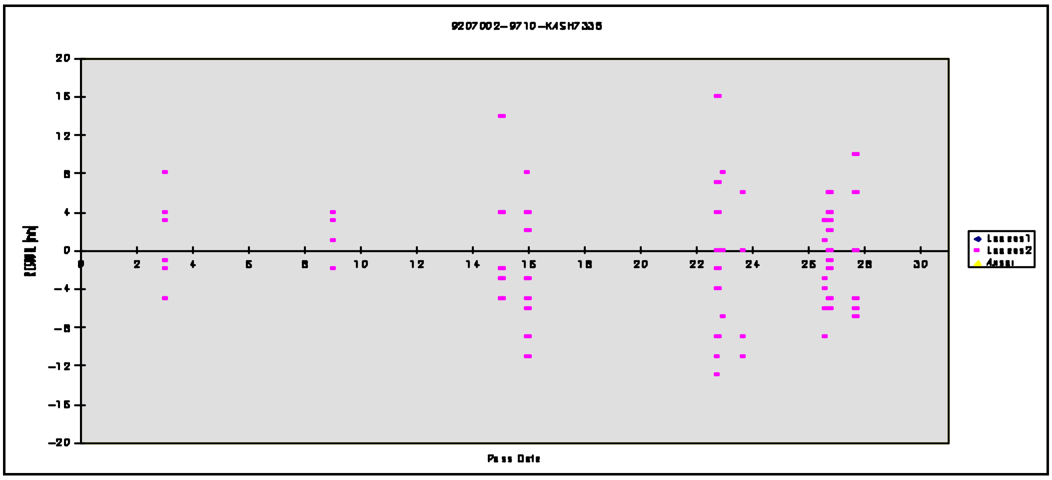

Figure 4.4: Pass-by-Pass Post-fit Residuals – Kashima– Lageos-2 – October 1997

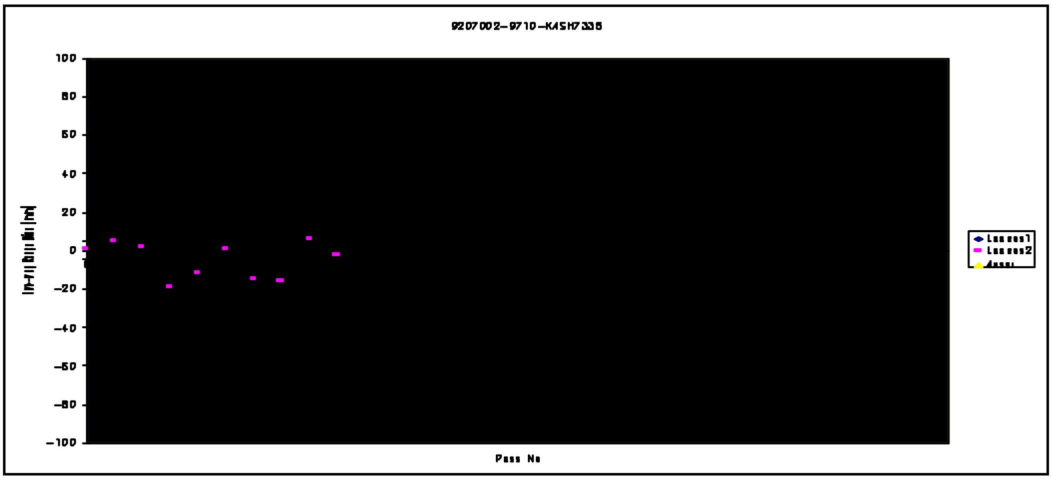

Figure 4.5: Pass-by-Pass Range Bias – Kashima – Lageos-2 – October 1997

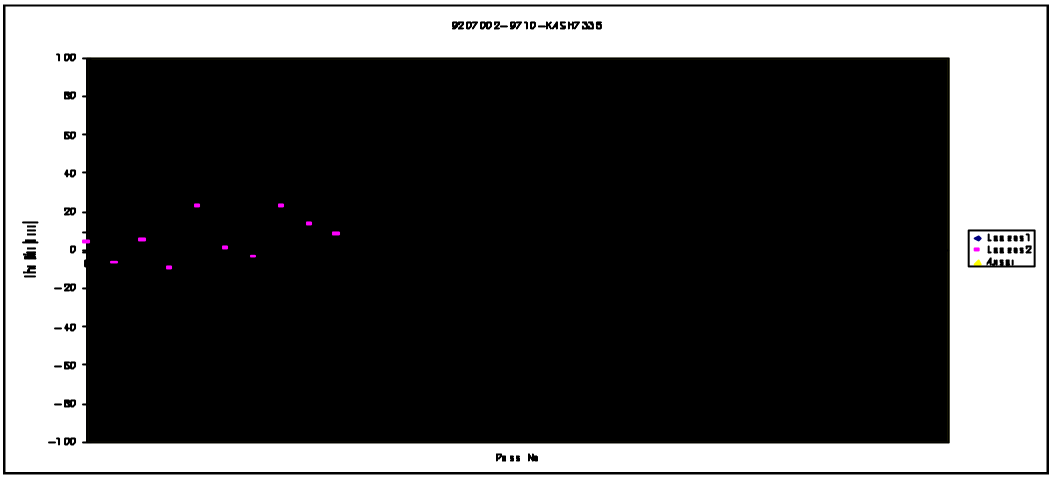

Figure4.6: Pass-by-Pass Time Bias – Kashima – Lageos-2 – October 1997

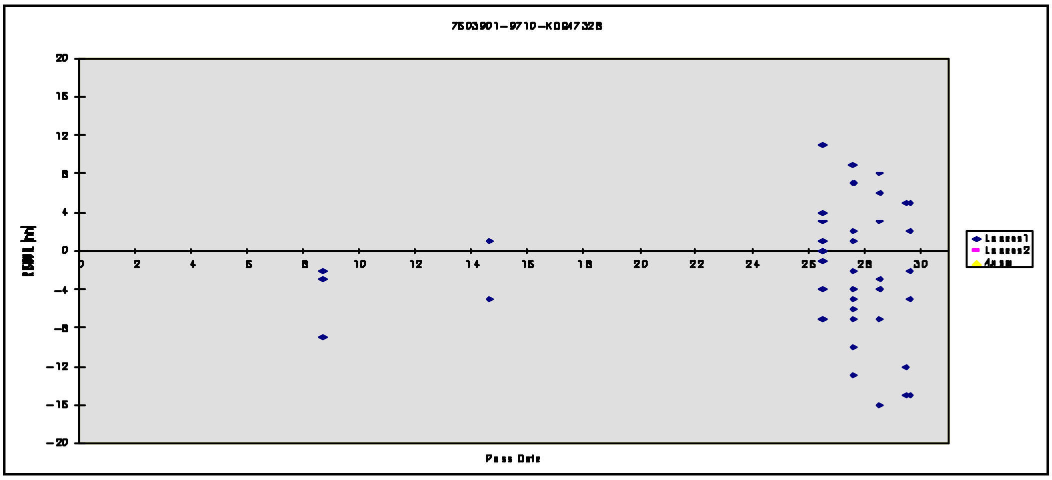

Figure 4.7: Pass-by-Pass Post-fit Residuals – Koganei– Lageos-1– October 1997

Figure 4.8: Pass-by-Pass Range Bias – Koganei – Lageos-1– October 1997

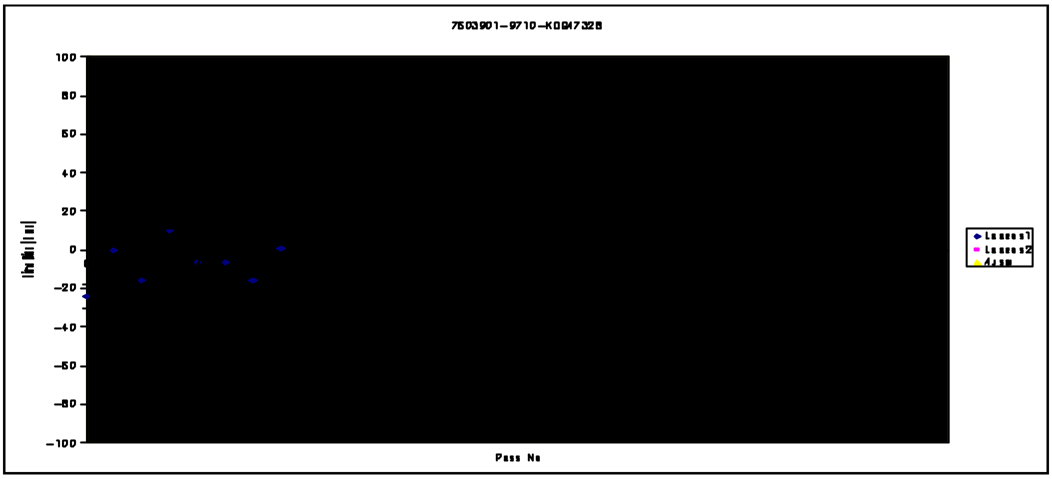

Figure4.9: Pass-by-Pass Time Bias – Koganei – Lageos-1– October 1997