In Search of the 'BEST' SLR Coordinates

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Abstract: *Analyst centers from each geodetic observing technique (i.e. SLR, GPS, DORIS, and VLBI) submitted their own individual station coordinate solutions to the IERS. The IERS combined these into a single product (e.g. ITRF 1997, ITRF 2000). Over the past several years, the sub-commissions of these geodetic techniques were re-organized into formal services (i.e. ILRS, IGS, IDS, IVS) to better serve its customers. The IERS has been re-structured recently and it will only accept a single coordinate set from each service. Within the ILRS, the Analysis Working Group (AWG) is required to produce the single ILRS coordinate solution.*

As of result of this task, the AWG has formed 4 pilot projects (i.e. Positioning and Earth Orientation Parameters; Software Benchmarking; Orbits; and Harmonization of Quality Control Results). These projects have one common goal - to develop a quality controlled SLR coordinate solution that ***'BEST'*** *represents the accuracy of the ILRS normal point data.*

During the rest of this paper, we will explore two complimentary analysis techniques that can assess the ***'BEST'*** *coordinate set and examine some modeling challenges. One technique involves comparing baseline lengths and the other involves range and time bias time series analyses. Station performance will be discussed first, since station performance is the limiting factor in coordinate accuracy.*

1. INTRODUCTION

This paper addresses the analysis of coordinate solutions from the 3rd iteration of the Analysis Working Group (AWG) POSitioning (POS) Pilot Project. The input data set was the LAGEOS-1,2 normal points from September 5th through October 4th, 1999, inclusive.

Note: Though the ILRS network tracks a diversity of satellites, ILRS station positions have been almost exclusively based on LAGEOS data. Future iterations of this Pilot Project will use an expanded data set and will incorporate other satellites.

2. STATION PERFORMANCE

The sites were evaluated based on their September 1999 LAGEOS data quantity and quality (see Table 1). The data ***quantity*** metrics are normal points (NP), number of passes, percentage of daytime data, and ratio of LAGEOS 1 passes to LAGEOS 2 passes.

The data ***quality*** metrics are percentage of good NPs, single shot RMS, and range bias stability.

High performance sites meet the following conditions:

- more than 30 LAGEOS passes/month,
- at least 10% of LAGEOS passes are in the daytime,
- LAGEOS Range Bias (RB) stability ≤ 10 millimeters (mm) and
- LAGEOS 1 to LAGEOS 2 pass ratio is between 0.8 and 1.2

Table 1, sorted by NP volume, contains the following 9 columns:

1 - Four-digit Site Identifier
2 - Location Name
3 - Number of Normal Points
4 - Number of Passes
5 - Percentage of Good NPs (based on CSR Analysis)
6 - Single Shot RMS(mm)
7 - Range Bias Stability(mm), based on MCC/CSR results
8 - Ratio of LAGEOS 1 to LAGEOS 2 Passes
9 - Percentage of Daytime LAGEOS Passes

Table 1: Performance of Best Sites

1	2	3	4	5	6	7	8	9
Site Id	Location	NPs	Pass	Good NP %	RMS (mm)	Stab (mm)	Ratio L1/L2	Day %
7110	Monument Peak	1699	140	98	8	8	0.95	26
7839	Graz	1066	71	100	9	6	1.21	16
7090	Yarragadee	999	84	98	10	8	0.79	66
7840	Herstmonceux	889	75	99	18	6	1.07	27
7105	Greenbelt	827	73	99	11	7	1.00	31
7849	Mt. Stromlo	717	80	100	11	8	0.91	61
7835	Grasse	471	40	100	12	8	1.01	25
7080	McDonald	329	37	100	14	8	1.03	45

3. BASELINE ANALYSIS

Baseline analysis was chosen as a coordinate evaluation tool, because baselines are easy to compute and are invariant to coordinate rotational (not scale) transformations. In this project phase, the Analyst Centers (ACs) were required to submit a coordinate solution based on the combination of LAGEOS-1 and LAGEOS-2 data, and had the option to submit 2 other coordinate solutions based solely on either LAGEOS-1 or LAGEOS-2 (i.e. no combination of LAGEOS).

3.1 LAGEOS-1 and LAGEOS-2 Combined Baseline Solution

Baselines were computed for each site pair and analysis center's combined LAGEOS-1 and LAGEOS-2 solution (see Table 2). For comparison purposes, baselines were derived using ITRF 1997, ITRF 2000, Mission Control Center (MCC) 2000, MCC 1999 and Center for Space Research (CSR) 1995 coordinate sets. (advanced to the coordinate solution epoch, day 263 year 1999). The MCC and CSR solutions are currently used in their respective weekly LAGEOS quality control reports. There are a total of 728 baseline combinations (8 sites * 7 sites * 13 solutions).

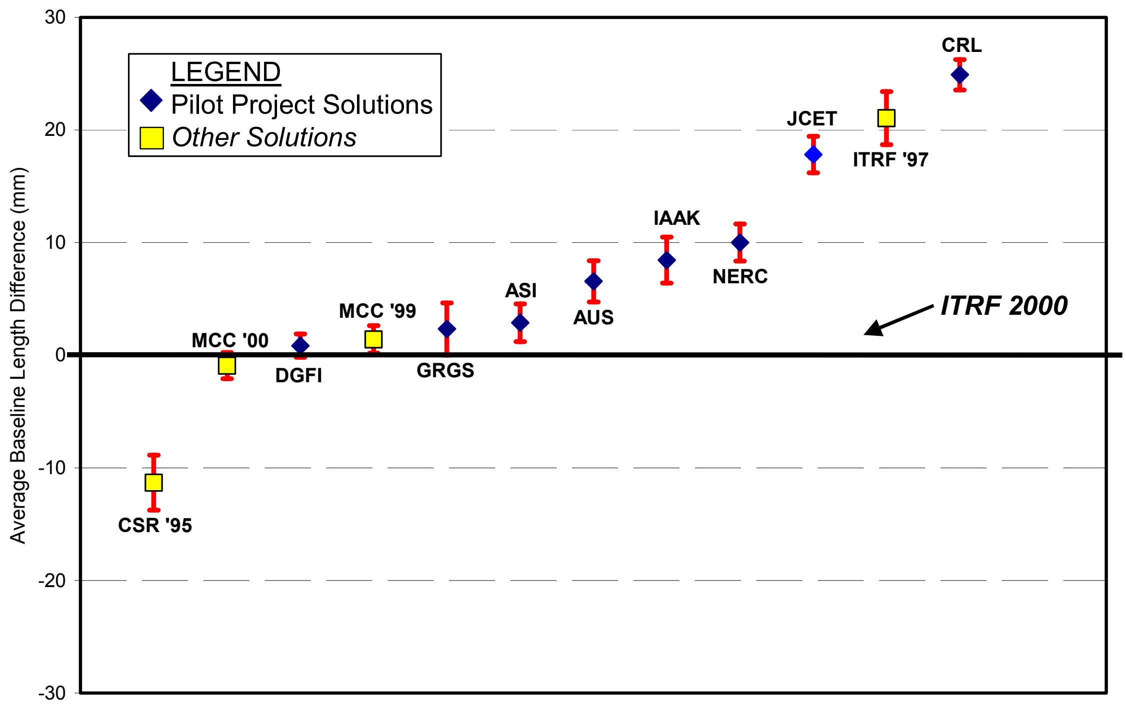
Table 2. Analysis Centers

Abbreviation	Name	Country
ASI	Agenzia Spaziale Italiana	Italia
AUS	Australian Land and Information Group	Australia
JCET	Joint Center for Earth Systems Technology, University of Maryland	United States
DGFI	Deutsches Geodatisches Forschungsinstitut	Germany
NERC	Natural Environment Research Council	United Kingdom
IAAK	Institute of Applied Astronomy	Russia
GRGS	Groupe de Recherche de Geodesie Spatiale	France
CRL	Communication Research Laboratory	Japan

ITRF 2000 baselines were used as the benchmark. Figure 1 displays the mean baseline length differences from each solution versus ITRF 2000. A positive difference implies the mean baseline length is longer than ITRF 2000 baselines. Conversely, a negative difference implies the mean baseline length is shorter than ITRF 2000 baselines.

Figure 1. Baseline Benchmark Results

Baseline Variations of High Performance Sites versus ITRF 2000



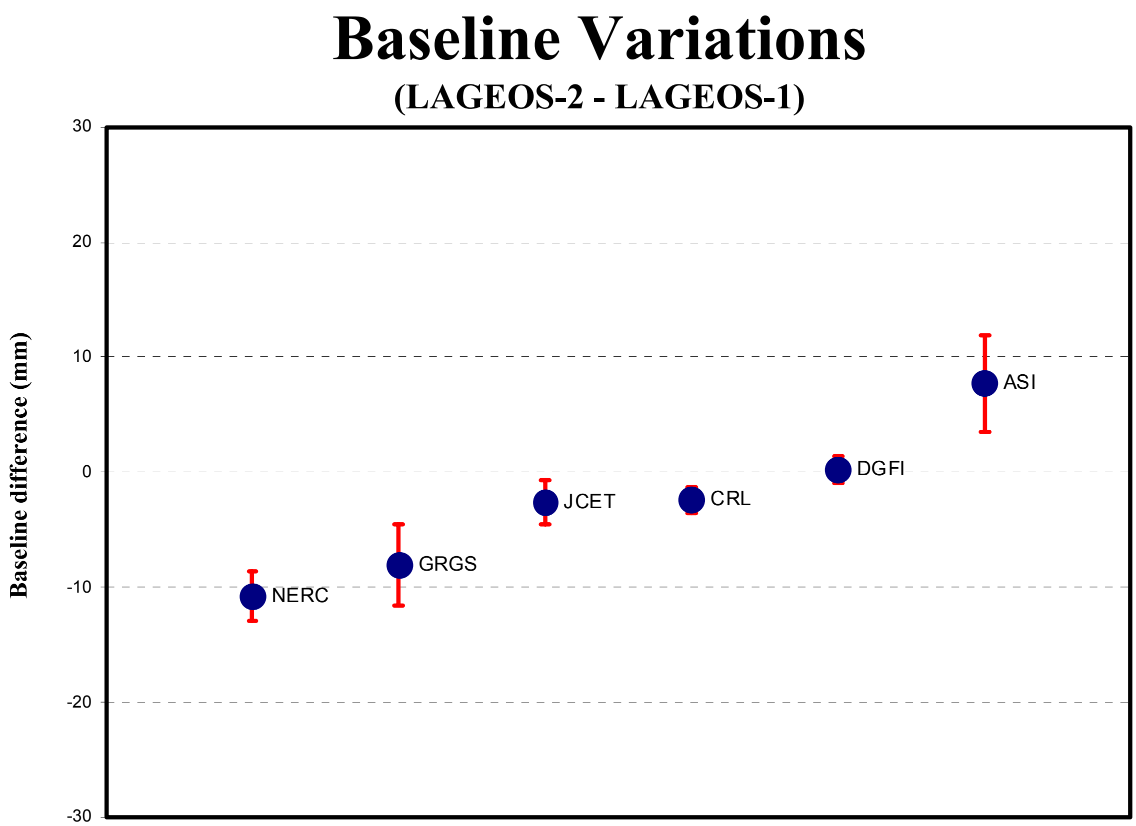
Centimeter (cm) baseline length deviations must be attributed to the modeling, because the data accuracy of these selected sites is sub-centimeter.

3.2 LAGEOS-1 and LAGEOS-2 Individual Baseline Solutions

Six of the eight analysis centers (ASI, CRL, DGFI, GRGS, JCET, NERC) submitted individual LAGEOS-1 and LAGEOS-2 solutions. Baselines were computed for each site pair (high performance sites only) and analysis center. Instead of analyzing baseline lengths between the twelve different solutions versus ITRF 2000, baselines were compared from each analyst center's LAGEOS-1 solution relative to its corresponding LAGEOS-2 solution. This is a benchmark of each analyst center against itself. Figure 2, below, is a graph of the benchmark results.

The modeling of LAGEOS-1 and LAGEOS-2 orbits are different due to their different orbital inclinations and spin rates, but site coordinates estimated from either satellite should be identical, in theory. Therefore, baseline lengths estimated from either satellite should be the same. In reality, coordinates/baselines derived from either LAGEOS satellite will not be identical, but they should agree to the 1-2 mm level for these selected sites. Figure 2 illustrates some apparent modeling issues in the ASI, GRGS and NERC solutions, because of their approximate 1cm baseline differences

Figure 2. Benchmark Results of each Analysis Center versus itself



4. MODELLING

In precision orbit determination (POD) and station coordinates estimation, an apriori set of coordinates and an initial state vector are an input requirement. ITRF 1997 coordinates and velocities were used as apriori positions and velocities for these coordinate solutions. ITRF 2000 was published after these solutions were submitted, but will be used as apriori site positions and velocities in future phases of this project.

Complex algorithms are needed to generate cm level (i.e. precise) orbits. IERS 1996 conventions (i.e. models) were recommended, but not required, for the use in these coordinate solutions, but the ACs were free to use their own data weighting, data editing, and bias estimation scheme.

4.1 Bias Estimation

Bias assessment for the best sites did vary considerably between ACs. DGFI, CRL, IAAK, and NERC did not estimate biases. AUS solved for site pass-by-pass range and time biases, but with tight constraints. ASI and JCET estimated fixed site range biases for LAGEOS-1 and LAGEOS-2 every 28 days and 7 days; respectively. GRGS solved for biases, but failed to provide their estimations.

ASI and JCET mean bias estimates of the best sites were -3.7 ± 1.2mm and $+15.0 \pm 0.6$mm, respectively. This is a difference of 18.7mm, which is well above the inherent accuracy of these systems. This demonstrates that Range Bias (RB) can be used as a '*nuisance*' parameter to absorb (i.e. sponge) any mis-modeling errors. When this occurs, site coordinates are compromised, mostly station heights. A height error will alter baseline lengths. The magnitude of the change will depend upon the height change and the location and separation of the sites. If a positive RB is estimated, and if in reality the RB is 0, then station height must increase more than the RB estimate to compensate for the modeling error. The ASI and JCET bias variations can explain 60% (i.e. 9 of the 15mm) of their mean baseline difference.

Range bias estimation can not explain the 24mm difference between DGFI and CRL baselines, because both groups assumed no biases. As a result, other modeling differences or errors must be inducing these variations. If mean baseline lengths vary, then perhaps there is a mean network height difference (i.e. scale difference) between the solutions. To test this hypothesis, height differences were simulated for these high performance sites. Simulation results revealed that a fixed 20mm change in station heights can explain the 24mm mean baseline difference between DGFI and CRL solutions (see Figure 3).

Range bias, the gravitational constant (GM), the speed of light, LAGEOS center of mass correction(s), and solid earth tides are the models that exert the most influence on the determination of station height [Dunn, 2000].

4.2 GM

All ACs, except NERC and CRL, used a GM value of 398600.4415 km^3/s^2. NERC and CRL used 398600.4418 km^3/s^2. NERC submitted a revised solution using the adopted GM standard while keeping all other modeling the same. The resultant impact on their baselines was a +1.7mm change (i.e. the baseline lengths increased). Based on the NERC results, it is assumed that the CRL baseline lengths would increase by a similar magnitude and thus produce a greater disparity from the DGFI results.

4.3 Other Models

All the ACs used 299792458 meters/second for the speed of light. All ACs used a LAGEOS center of mass correction of 251mm, except JCET and ASI, which used 252mm and 250mm; respectively. All ACs used the same EGM 1996 earth tide model.

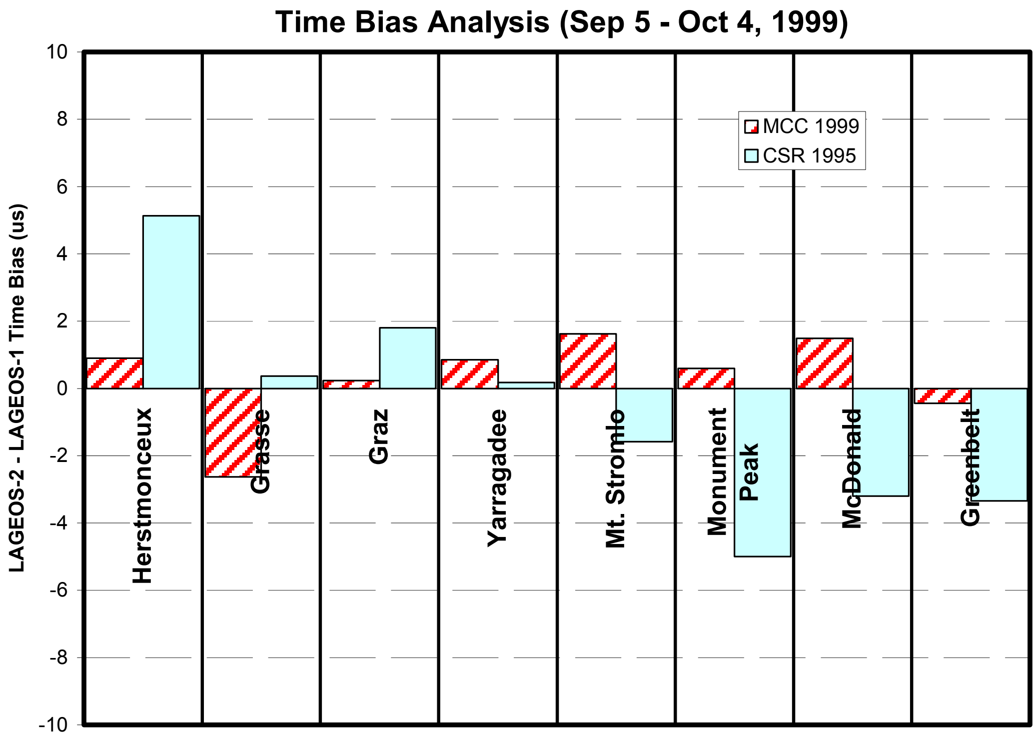
The Analysis Working Group Software Benchmarking Pilot Project will be addressing the source of these baseline variations.

5. AGGREGATE BIAS ANALYSIS

The accuracy of SLR is its greatest strength and is why SLR was used in the scale definition of the International Terrestrial Reference Frame (ITRF).

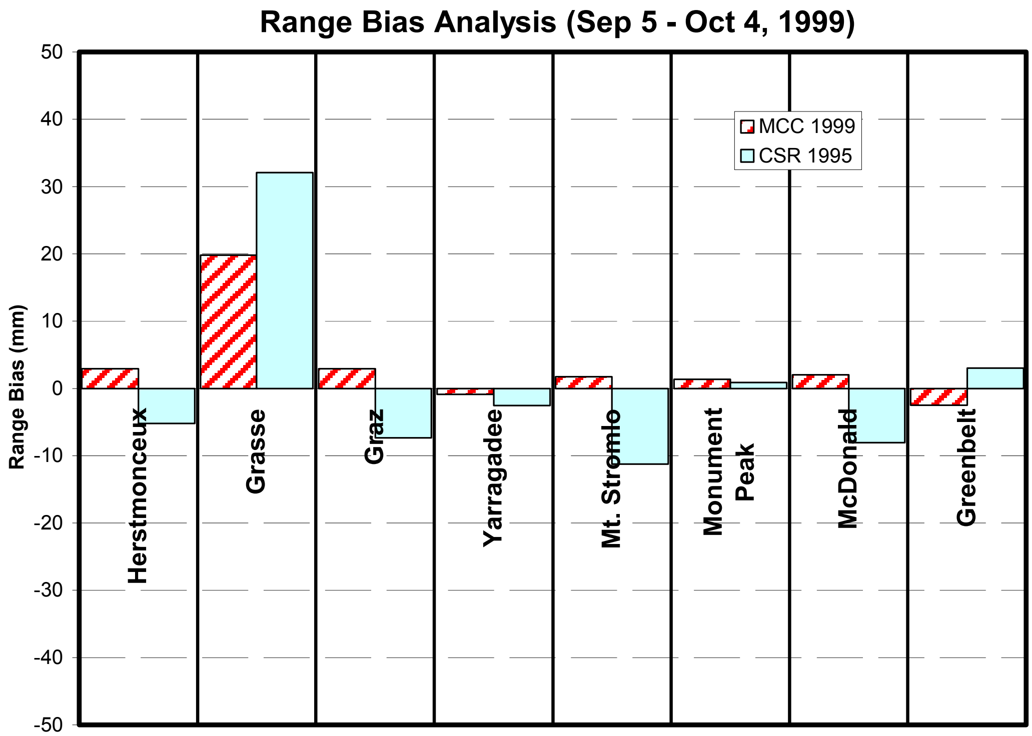
SLR normal point data can be used to verify the precision of site coordinates through aggregate range and time bias analyses, another unique capability of SLR. A horizontal site positioning error (i.e. latitude or longitude) will induce a time bias signature to its residuals [Husson et al, 2000]. The 'apparent' time bias depends on the magnitude and direction of the coordinate error and the pass geometry. Since LAGEOS−1 and LAGEOS−2 have different pass geometries, a good indicator of positioning accuracy is the mean time bias variations between these satellites. For most sites, MCC LAGEOS time bias differences are smaller relative to CSR (i.e. MCC's horizontal positions are more precise than CSR's). See Figure 3.

Figure 3: LAGEOS Time Bias Analysis



Another indicator of positioning accuracy is aggregate mean range biases (see Figure 4) since a station vertical (i.e. height) positioning error will induce an elevation dependent range bias. MCC range bias estimates are smaller relative to CSR (i.e. MCC's heights are more precise than CSR's).

Figure 4: LAGEOS Range Bias Analysis



6. CONCLUSIONS/RECOMMENDATIONS

DGFI coordinate solution is deemed the **'BEST'** from this 3rd iteration of the pilot project because:

1) Their baseline lengths are consistent between LAGEOS-1 and LAGEOS-2,
2) Their baselines are in closer agreement to ITRF 2000 than any other submitted solution,
3) Their baselines are in close agreement with MCC 1999 and MCC 2000 baselines and
4) The small deviations of range and time biases from the MCC 1999 solution.

Most of the baseline variations seem to be related to scale, the exact reason(s) for this is unknown, but will continue to be pursued. To obtain the best scale results requires modeling improvements to GM, the LAGEOS center of mass correction, and the tropospheric mapping correction.

7. ACKNOWLEDEMENTS:

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8. REFERENCES:

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