COMBINATION OF DATA FROM DIFFERENT SPACE GEODETIC SYSTEMS FOR THE DETERMINATION OF EARTH ROTATION PARAMETERS

Brent A. Archinal
Department of Geodetic Science and Surveying
The Ohio State University
Columbus, Ohio 43210-1247
U.S.A.

ABSTRACT. Simulation experiments have been performed in order to compare the Earth Rotation Parameter (ERP) results obtained from a) individual observational systems, b) the weighted mean of the results from a), and c) all of the observational data, via the combination of the normal equations obtained in a). These experiments included the use of 15 days of simulated Lunar Laser Ranging (LLR), Satellite Laser Ranging (SLR) to Lageos, and Very Long Baseline Interferometry (VLBI) data using realistic station positions and accuracies. Under the assumptions chosen, the normal equation combination solutions usually provide the best ERP over recovery periods of 6 and 12 hours, and 1, 2, and 5 days. However, solutions by the weighted mean (and even by VLBI alone) provide results that are nearly as good, i.e., within a factor of one to two in accuracy. Complete details are presented in [Archinal, 1987].

1. INTRODUCTION

In the past, Earth Rotation Parameters (ERP) have been determined using data from only one observational system at a time, or by the combination of parameters previously obtained in such determinations. The question arises as to whether combining observations from several systems in one adjustment would provide better ERP results than combining the ERP time series determined by the individual systems or than the ERP determined from any single system. One would expect there to be some improvement, but the question is one of how much improvement.

To look at this problem, it was decided to perform a simulation study, using realistic networks of Lunar Laser Ranging (LLR), Satellite Laser Ranging (SLR) to Lageos, and Very Long Baseline Interferometry (VLBI) stations. A simulation approach was taken so that "true" ERP values would be available as a standard of reference, and to allow looking at very high observational data rates. Only these three observational systems were considered, since it is clear that most other methods provide ERP results of at least several times lower accuracy.

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In addition, it was decided to look at several short ERP recovery periods, as these periods are currently of the highest interest. The overall length of the simulated data period was kept to 15 days, in order to minimize the computer resources used and ignore long period model effects.

The models used to simulate and recover the ERP have been kept fairly simple, reflecting the overall geometry of the situation only, and ignoring (modeled or unmodeled) systematic errors or system weighting differences. Since various methods of ERP determination and not the observational systems themselves are being compared, and the interest is only in the increase in relative accuracy, this assumption seems reasonable. For example, if observational data of one system were degraded by systematic errors, it is assumed that all of the ERP series being compared would be degraded by the same amount (these series being a) the ERP recovered from that system's data, b) the ERP recovered by taking the weighted means of the individual systems' ERP series, and c) the ERP recovered from all data). If the observational systems themselves were to be compared, complete modeling of systematic errors would be needed, and investigations done into the relative weighting of the systems.

2. SIMULATION ASSUMPTIONS

In any simulation experiment, the results are entirely dependent on the set of assumptions made. These are discussed here in regard to the modeling of the geometry, station networks, and the simulated ERP values used to create the simulated data.

2.1 Geometric Models

For the LLR observations, a satellite in a Keplerian orbit about the Earth with the same elements as the Moon is assumed. For SLR, a satellite is assumed with the same Keplerian orbit as Lageos, but affected by the central mass and J_2 of the Earth (the latter so that the node of Lageos' orbit realistically regresses). Both of these orbits are solved for with six parameters weighted at the 1 meter level. For VLBI, a real IRIS radio source catalog was assumed. The positions of those sources were essentially fixed, with weights of 50 μs in right ascension and 50 μas in declination, and with the right ascension of one source completely fixed. Fixed values for the Earth's angular velocity, precession, and nutation were assumed, except for the variations in the angular velocity supplied by the simulated ERP (see 2.3 below). Stations are assumed to be observing continuously (when the targets are above a 15° elevation angle) in order to compare ERP determination at the highest possible levels of accuracy of the individual systems.

2.2 Station Networks

The stations chosen are stations which were realistically expected to

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operate at high data rates as of the 1986-1987 period, and are listed in Table I. The instruments available at or near each location are also shown in that table. Of all the stations only two are not in operation at the present time, i.e., the Simeiz and Richmond LLR/SLR instruments. Random noise has been added to all of the observations, with standard deviations for the lasers as shown (agreeing with [Schutz, et al., 1985; Coates, 1985]), and for the VLBI delays as 0.1 ns. Normal point observations are assumed every 10 minutes for LLR and every 2 minutes for SLR when possible. For the VLBI observations an actual IRIS schedule [W. Carter, 1984, personal communication] was shifted in time as needed. No correlations between any observations were assumed.

TABLE I STATION POSITIONS AND ACCURACIES

Location	Latitude °	Latitude '	Longitude °	Longitude '	Laser Accuracy	System Type
Grasse, France	43	45	6	55	5.0	L-S
Wettzell, F.R.G.	49	09	12	53	7.1	S-V
Graz, Austria	47	07	15	30	3.8	S
Matera, Italy	40	42	16	37	13.9	S
Simeiz, U.S.S.R.	44	32	34	01	10.0	L-S
Yargadee, Australia	-29	03	115	21	2.3	S
Simosato, Japan	33	34	135	56	9.7	S
Orroral, Australia	-35	38	148	57	5.0	L-S
Maui, HI, U.S.A.	20	43	203	44	4.2	L-S
Huahine, French Polynesia	-16	44	208	58	9.7	S
Quincy, CA, U.S.A.	39	59	239	03	2.8	S
Ft. Davis, TX, U.S.A.	30	41	255	59	8.4	L-S-V
Richmond, FL, U.S.A.	25	40	279	37	10.0	L-S-V
Greenbelt, MD, U.S.A.	39	01	283	10	3.4	S
Arequipa, Peru	-16	28	288	30	14.5	S
Westford, MA, U.S.A.	42	37	288	30	-	V
Herstmonceux, U.K.	50	52	359	39	4.7	S

Notes: Laser accuracy is in cm. VLBI delay accuracy is 0.1 ns.
System Type: L-LLR, S-SLR, V-VLBI.

2.3 Simulation of ERP

To create the simulated data, ERP were themselves simulated by superimposing sine curves with amplitudes and periods derived from variations seen in real ERP data [Robertson and Carter, 1985]. Adding real trends (from 5-day IRIS data) to these values, a 6-hour step function was generated for all three ERP components over the 15-day period. These values were used to generate the simulated observations, and as a standard of reference for 6 hour ERP recovery. For longer periods, the step functions were averaged over time to obtain reference values.

3. SIMULATION AND SOLUTION METHODS

The data are simulated using the geometric models, station and target definitions, simulated ERP, and observational accuracies just described. The primary software used for simulation of the data was the program GEODYN [Putney, 1977] (provided via NASA/GSFC).

Individual system solutions were also performed with the same software, using a Bayesian least squares technique. The solutions involving all of the systems' data were performed by adding the normal equations generated in the individual solutions and solving the combined set of equations (via the SOLVE program, also provided by GSFC). The technique was iterated in some test experiments to verify that convergence does occur with the first such iteration. Weighted means of the individual systems' ERP series were also taken (in locally written software).

4. RESULTS

Simulations were carried out using the same simulated data, but recovery of ERP over various periods. Presented here are some of the results for 1 day ERP recovery and a summary of the results for all the periods.

Table II shows statistics of the recovered 1 day ERP series. For each of the three ERP components and all five of the recovery methods, the RMS difference and (absolute value) bias is shown from the reference values. As well as the absolute difference statistics, in parenthesis a measure of relative accuracy is given. The values are the multiples of the lowest values in each row. A value of 1 indicates the "best" method, values slightly higher indicate fairly good results, and high numbers much worse results. For polar motion, we see confirmation that all of the methods give fairly good results except for LLR. It is also clear that the data combination solution gives the best results for X and VLBI the best for Y, with the weighted mean results also good in both cases. The VLBI X and SLR results are 2 to 4 times worse than the best results. For UT1-UTC, all of the methods provide good results (with the data combination solution giving the best), except SLR which has a 2 ms bias.

TABLE II STATISTICAL DIFFERENCES, 1-DAY ERP RECOVERY

Method	LLR	SLR	VLBI	Wt.Mean	Combined
X pm, RMS, mas	7.7 (4.9)	3.6 (2.2)	3.4 (2.2)	3.0 (1.9)	1.6 (1.0)
X pm, bias, mas	3.7 (133)	0.5 (16.)	0.6 (22.)	0.9 (32.)	0.03 (1.)
Y pm, RMS, mas	14. (15.)	2.8 (3.0)	0.9 (1.0)	2.6 (2.7)	1.1 (1.2)
Y pm, bias, mas	4.2 (29.)	0.4 (3.0)	0.3 (2.1)	0.6 (3.8)	0.1 (1.0)
UT1-UTC, RMS, ms	0.3 (1.0)	2.0 (7.9)	0.4 (1.4)	0.3 (1.0)	0.3 (1.0)
UT1-UTC,bias,ms	0.01 (1.)	2.0 (44.)	0.04 (3.)	0.02 (2.)	0.1 (5.9)

Notes: Values in parentheses show "relative accuracy" (multiple of lowest value in line). Absolute value of biases shown.

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This bias exists in the SLR results due to the well known inseparability of the satellite orbit orientation (line of nodes) with respect to UT1-UTC.

Similar relative RMS statistics for each of the ERP recovery periods are summarized in Table III. This shows for each period the relative results symbolically, with an "*" designating the best method, a "+" methods with a factor of 1 to 2 difference, a "-" a factor of 2 to 3, and a blank greater difference. It is easily seen that: a) the data combination solution always gives the best or nearly the best results, b) the weighted mean (or perhaps the VLBI) solution alone is nearly as good, c) that VLBI generally gives the best Y polar motion (due to the strong geometry of the IRIS network for determining Y), and d) that LLR gives the best long period UT1-UTC, but poor polar motion values.

TABLE III RELATIVE ACCURACIES FOR ALL METHODS AND ERP RECOVERY PERIODS

Recovery Period	LLR			SLR			VLBI			Weighted Mean			Data Comb.		
	X	Y	U	X	Y	U	X	Y	U	X	Y	U	X	Y	U
6 hours				+	+		-	-	-	+	+	-	*	*	*
12 hours			-	-	+	+	+	*	+	+	+	+	*	+	*
1 day			+	-	-		-	*	+	+	-	*	*	+	+
2 days			*	-			-	*	+	+	-	+	*	+	+
5 days			*	-	+		-	+	+	+	+	+	*	*	+
all				-			-	-	-	+	-	-	*	+	+

Notes: X - X polar motion; Y - Y polar motion; U - UT1-UTC
* best method (smallest RMS difference)
+ RMS difference multiple is between 1 and 2.
- RMS difference multiple is between 2 and 3.
(blank) RMS difference multiple is greater than 3.

5. CONCLUSIONS

The main conclusion must rest on the question of how significant a factor of 1 to 2 improvement in ERP is. Under the assumptions made, for 6-hour to 5-day ERP recovery, the data combination solution generally gives the most accurate results, and (although not completely shown here) the smallest biases. However, the weighted mean (and perhaps the VLBI) results alone are nearly as good, at least within a factor of 2. Those who determine and use ERP series must decide if this magnitude of improvement is important or whether other advantages of the data combination solution make it a worthwhile method to continue investigating.

It should also be cautioned again that the individual systems cannot be realistically compared here since complete models, systematic errors, and relative weighting has not been considered. As one example, it is quite possible that better LLR and SLR solutions could be obtained if stronger weights were applied to the orbits. [Larden, 1982] shows much better polar motion and slightly better UT1-UTC results for LLR when the lunar orbit is assumed perfectly known.

For further work, some simulation experiments will be attempted in order to verify that the relative accuracies found here are realistic under various conditions. Specifically, more normal observing schedules and different orbital and observational weighting will be considered.

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DISCUSSION

Robertson: Since you are doing a simulated solution to evaluate the effectiveness of different techniques, shouldn't your simulations involve comparable numbers of observing stations for each technique rather than having vastly more SLR stations than VLBI?

Reply by Archinal: Only stations which were realistically expected to be in operation over the next few years were used. Since this is for a comparison of combination techniques and not observing techniques, any imbalance in the number of stations should have little effect.

Robertson: Did your simulation include effects of laser data loss from cloud cover or lunar phase angle?

Reply by Archinal: No.

Dickey: I would like to voice some concerns about your analysis and recommend that further study is required. Your paper is a study that includes no data and does not include many "real world" effects such as weather. Stolz and Larden include more realistic assumptions and conclude that $\sim$ milliarcsecond accuracy or less in polar motion and 0.1 milliseconds accuracy or less in Universal Time can be achieved.

Reply by Archinal: The conclusions made do indeed suggest that further research be done to consider systematic and other effects. The results here are less optimistic than those of Stolz and Larden, since they apparently assumed the lunar orbit was perfectly known, and we did not.

Dickey: You comment that all techniques have the same systematic errors. This is not true.

Reply by Archinal: I did not say that all the (observational) techniques contained the same systematic errors, but rather that each of the combination solutions done was derived from the same set of simulated data. For example, if the SLR data was simulated using too high or low a precision, it still affects equally the individual, weighted mean, and "data combination" solutions, and thus a relative comparison of these reduction methods should not be affected.

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