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TOWARD 10^9 GPS GEODESY: VECTOR BASELINES, EARTH ROTATION AND REFERENCE FRAMES

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INTRODUCTION

The University of Texas Center for Space Research research efforts under NASA Grant No. NAG-1936 during the period January 1, 1992, through December 31, 1992, were in the following areas:

- GPS orbit accuracy assessments and efforts to improve the accuracy
- Analysis of global GPS data collected during the first three months of the IGS campaign
- Analysis of regional data

A brief summary of each of the above activities is presented in the following.

DISCUSSION

The commonly used force models and the associated adjustable parameters for the GPS satellites do not adequately represent the actual forces experienced by the satellites. This seems to be particularly true so far as the nongravitational forces are concerned. Significant evidence indicates that the commonly used ROCK4 model is inadequate. As a result, long-arc fits as well as predictions are inaccurate at the level of being of limited use for geodetic applications. For example, typical rms of fit for a one-day arc is around 15 mm, whereas that for a one-week arc is at a few-decimeter level when a minimal set of parameters are estimated. The level of rms differences between overlappng short arcs is another indication of the force model error.

Experimentation with a variety of empirical force model parameters shows improvement in the rms of observation residual for long (>1 day) arcs. For example, estimation of once-per-revolution, drag-like parameters and components of once/revolution periodic acceleration in the radial and normal directions, along with the ambiguity and troposphere parameters, using the IGS campaign data for the GPS week of 651 resulted in an rms fit of about 1.5 cm for a 7-day arc. This one-week solution trajectory was compared to the one-day arc solution trajectories in order to assess the orbit quality. Results were presented at the Sixth International Geodetic Symposium on Satellite Positioning.

During the summer of 1992, from June 21 to September 21, data from about 20 to 25 ground stations collected for the IGS campaign were routinely processed, and the GPS ephemerides and polar motion solutions were submitted to the IERS every week. Evaluation of the polar motion solutions obtained using GPS data was routinely made against the Lageos-determined quick-look solution of the Earth orientation parameters, and the GPS determinations were found to be satisfactory. At the end of the three-month period, using a major portion of the data, coordinates of all but three sites were estimated in an effort to define a reference frame, and the associated polar motion series for the three-month period was recomputed. This series has been assessed by the USNO to be at the 0.8 mas (rms) level in x and 0.65 mas (rms) level in y. Results of IGS data analyses were presented at the Fall Meeting of the American Geophysical Union and will appear in the Proceedings of the 1993 Bern IGS Workshop. A preliminary version of the summary is given in the attachments. The results obtained during the IGS campaign indicate that precisions of a few parts per billion in vector baselines has been achieved.

FUTURE WORK

- Improving the nongravitational force model, especially the thermal imbalance force modeling.
- Estimation of carrier phase ambiguities show correlation with orbit, especially the vertical component of the orbit. Techniques of bias fixing and/or decoupling the effect of biases are being investigated.
- Regional campaign data analysis and reference frame determinations/comparisons will be performed to further assess improvements in vector baselines, particularly those obtained in areas remote from fiducial stations.

MEETING PRESENTATIONS AND PUBLICATIONS

- GPS Reference Frames and Earth Rotation, *Proc. Sixth International Geodetic Symposium on Satellite Positioning*, Columbus, Ohio, March 17–20, 1992 (B. E. Schutz, P.A.M. Abusali, H. J. Rim, M. M. Watkins, D. Kuang, and B. D. Tapley).
- GPS Orbit Accuracy, *Proc. Sixth International Geodetic Symposium on Satellite Positioning*, Columbus, Ohio, March 17–20, 1992 (P.A.M. Abusali, B. E. Schutz, D. Kuang, and H. J. Rim). B. D. Tapley).
- GPS Reference Frames and Orbit Accuracy, AGU Spring Meeting, Montreal, Canada, May 12–16, 1992 (B. E. Schutz, P.A.M. Abusali, M. M. Watkins, H. J. Rim, and D. Kuang).

- GPS Reference Frames and Orbit Accuracy, 8th International Workshop on Laser Ranging Instrumentation, Annapolis, Maryland, May 18–22, 1992 (B. E. Schutz).
- GPS Orbit Accuracy for Geodynamic Applications, World Space Congress COSPAR Meeting, Washington, D.C., August 28–September 5, 1992 (B. E. Schutz, P.A.M. Abusali, and M. M. Watkins).
- Terrestrial Reference Frame Determination and Comparison of Long- and Short-Arc Solutions From IGS Campaign 92, AGU Fall Meeting, San Francisco, California, December 7–11, 1992 (P.A.M. Abusali, B. E. Schutz, M. M. Watkins, D. Kuang, Y. S. Nam, S. H. Byun, C. F. Lo, and R. Gutierrez).

REPORTS

- Thesis completed: Y. C. Chao, Precise Baseline Determination Using GPS.

ATTACHMENTS

CSR RESULTS FROM IGS AND EPOCH-92

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ABSTRACT

This paper summarizes the participation of the University of Texas/Center for Space Research (UT/CSR) in the IGS campaign of June 21 to September 21, 1992. The models and parameters used in the regular operations during the IGS are documented. An adjustment to the reference frame and a new polar motion series were derived in a post-campaign analysis mode and preliminary investigations into orbit effects have been conducted. The IGS data and orbits were used to support network solutions during EPOCH-92.

OPERATIONS DURING IGS

The solution approach used explicit double difference ionospherically corrected phase measurements. One-day arcs were used throughout the campaign in which the GPS position and velocity vectors at 00:00 GPS time of each day were estimated, along with daily pole position, selected stations, GPS y-bias and scale parameter for ROCK4, 2.5 hour zenith delays for each station and double difference ambiguity parameters.

The reference frame used for operations during the campaign was based on the VLBI reference frame (GSFC GLB-718; Ma et al., 1991) translated, rotated and scaled into the SLR reference frame (UT/CSR 91 L 03; Eanes et al., 1991). The local ties between SLR, VLBI and GPS were taken from Boucher and Altamimi (1992). In the regular solutions, the following Rogue sites were held fixed: Algonquin, Goldstone, Pinyon, Fairbanks, Kauai, Hartebeestoek, Onsala, Wettzell and Yaragadee. The following Rogue sites were adjusted: Kootwijk, Kourou, Madrid, Mas Palomas, McMurdo, Ny Alesund, Santiago, St. Johns, Tahiti, Taiwan, Tidbinbilla, Usuda, and Yellowknife. The following codeless receivers were used regularly after Anti-Spoofing was activated on August 1: Hobart, Mojave, Townsville and Wellington.

Solutions were performed for Day 173 (Week 650) through Day 259 (Week 662), except for some AS days. Solutions were performed on the following days when AS was activated: Days 214-216 and Day 221. The solutions generally used all Block-I and Block-II satellites; furthermore, PRN 26 was included for the first time in Week 659. Apparent thrusts or other anomalies occurred from time to time and these satellites were excluded from the solution on the day of occurrence.

The IERS Standards (McCarthy, 1992) were generally followed. UT1 was not estimated and the Lageos-SLR series was used in the GPS solutions. The software used was the TEXGAP set of programs.

ADJUSTED REFERENCE FRAME AND POLAR MOTION

A 54-day subset from Weeks 650-662 was used to determine the site positions of all sites, except Wettzell, Kauai and Fairbanks, which were held fixed. In addition, daily GPS position and velocity vectors, force model y-bias and ROCK4 scale, x and y pole position, 2.5 hour zenith delay and ambiguity parameters were estimated. The resulting solution was reported by Watkins et al. in IGS Electronic Report No. 16. A comparison of ITRF91 to the resulting coordinates shows an RMS difference in the adjusted stations of 13 mm in x, 29 mm in y and 43 mm in z. After removing a bias in the x and y polar motion series, the weighted RMS of the new GPS series with respect to the Lageos-SLR series was 0.71 milliarcseconds in x and 0.59 milliarcseconds in y.

Experiments with estimating diurnal and semi-diurnal polar motion and dUT1 were performed using one day arcs. The resulting series for dUT1 shows good agreement with Lageos-derived series (results to be presented at Spring 1993 AGU by M. Watkins).

ORBIT ANALYSIS

Although one-day arcs were used for the operational activities, longer arcs were used to investigate the fidelity of the force and kinematic models. These longer arcs included a 7-day continuous orbital arc with estimation of sub-arc daily polar motion. With a 7-day arc spanning Week 651, each day contained 19-20 of the previously identified station set and contributed about 17,000 to 19,000 double difference measurements at a 2-min interval. For comparison with the 7-day arc, the operational one-day arcs produced double difference RMS values of approximately 12 mm to 18 mm.

Several 7-day arcs were studied, each of which used a different set of estimated parameters. Two cases are presented here:

Case 1) 7-day arc with 12-hr sub-arc parameters of ROCK4 scale and y-bias, daily sub-arc polar motion

Case 2) 7-day arc with empirical once per orbital revolution along track and cross track forces in which amplitude and phase were estimated as daily sub-arc parameters; daily sub-arc polar motion estimated

Approximately 5000 parameters were simultaneously estimated for each case. The double difference RMS of fit for Case 1 was 34 mm and the fit for Case 2 was 14 mm, approximately equivalent to the one-day arc fits. The higher RMS for Case 1 is one indicator of problems with the modeling, presumably errors in the nongravitational modeling are the major contributor. Evidence to support this presumption can be drawn from SLR analyses of the Etalon satellites which have an altitude similar to GPS (except they are not in deep resonance like GPS). The Etalon satellites are spherical with low area-to-mass ratios. The ability of the empirical models to absorb model errors is indicated by the RMS of Case 2.

EPOCH-92

The data and the orbits for Weeks 653-654 were used to support analyses of a Trimble SST network operated in the Southwest Pacific by M. Bevis et al. This network spans the Tonga Trench and extends to the New Hebrides and includes baselines ranging in length from a few hundred kilometers to 3500 km. The daily repeatability in baseline length (L) for Days 196-203 (just prior to EPOCH-92), represented by a + b L, was a = 9.7 mm and b = 1.3 ppb. Preliminary solutions during EPOCH-92, which included several AS days, tended to produce higher noise in the double differences by a factor of two. These preliminary solutions suggest some degradation in the network solutions caused by AS effects on the global network, however, the analysis is incomplete and a definitive statement cannot yet be made.

ACKNOWLEDGEMENTS

Without the dedicated work of the field operators and the data collection centers, none of the results given in this paper would have been possible. Furthermore, the contributions of Da Kuang, Y. S.-Nam, K. Byun, M. Lo, H. Rim and Dr. Roberto Gutierrez in data preprocessing are acknowledged. This study was supported, in part, by NASA/DOSE. Some computing resources were provided by the University of Texas System Center for High Performance Computing.

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GPS ORBIT ACCURACY

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ABSTRACT

Previous analysis of GPS data collected by special campaigns (e.g., CASA UNO, GIG-91, etc.) has shown that the satellites exhibit somewhat different characteristics, especially between the eclipsing and non-eclipsing satellites. Using the GIG-91 data which provided a reasonable global distribution of stations, the influence of unmodeled orbital effects has been examined using double differenced carrier phase data. While there is evidence that suggests the unmodeled orbital effects are not a limiting factor in achieving a part in 10^8 level in baseline results, these components may be factors in reaching a part in 10^9. Experiments with the GIG data set include comparison with other ephemerides and the estimation of empirical parameters for the purpose of improving the model error characterization.

1. INTRODUCTION

Previous results have shown that unmodeled forces exist when the GPS satellites are in eclipse season, i.e., the period during which the satellite experiences the umbra/penumbra of either the Earth or the Moon [Schutz et al., 1991; Fliegel et al., 1992; Gouldman et al., 1989]. Possible contributors to the observed effects include the proper representation of the discontinuity associated with the shadow boundary and the implementation of appropriate adjustments in the numerical integration algorithm [Lundberg et al., 1991]. However, studies of this effect by Feulner et al.[1990] demonstrate that, while the effect can be significant, it does not account for most of the observed effect. Another effect that is associated with thermal radiation imbalance was examined by Vigue et al.[1991] who demonstrated that the effect should be observable.

The objective of this investigation was to assess the GPS orbit accuracy and to examine possible parameterization to account for observed mismodeling of the measurements. Such an examination cannot be accomplished with a regional network, and is best suited for a global tracking network. The global data set of the GIG-91 Campaign [Melbourne, 1992] offers an opportunity to examine a variety of aspects concerning the fidelity of the GPS force, kinematic and measurement models. The campaign used about 20 Rogue P-code receivers plus several TI-4100 P-code receivers and numerous codeless receivers.

2. DATA AND MODELS

The software used for the data analysis was the set of programs know collectively as TEXGAP, described by Schutz et al.[1992]. For the results of this paper, ionospherically corrected phase measurements were used in a double difference mode.

The specific receivers used in the analysis were 17 Rogue receivers plus TI-4100 receivers in the Pacific to provide improved global coverage, as given in Table 1. The GPS force models followed the current IERS Standards [McCarthy, 1989] and scale factors on the ROCK4 [Fliegel, 1992] and y-bias parameters were estimated. The Chao [1974] troposphere model was used. Lageos-derived polar motion and UT1 were used as a priori. Pseudo-range measurements were used to verify and/or correct the respective receiver clocks. The reference frame is given by Schutz et al.[1992].

For this study, data from GPS Weeks 578 and 579 (days 34 to day 41, inclusive) were used. All available satellites (5 Block I and 10 Block II) were included in the analysis.

3. ESTIMATION STRATEGIES

All results were obtained using multi-satellite versions of UTOPIA, known as MSODP. The estimation process is based on a batch algorithm, using Givens rotations to solve the least squares problem. For the results, three sites were fixed (Goldstone, Wettzell, and Hobart) and the remaining 17 sites were adjusted. For each arc, satellite position and velocity were estimated at the initial time point of the arc, a solar radiation pressure scale factor and a y-bias were estimated. Zenith delay parameters were estimated at 2.5 hour intervals and phase ambiguities were estimated on each pass. In all cases, the a priori covariance was assumed to be infinite, thus allowing all parameters to freely adjust.

Alternate empirical forces were introduced for some cases. These forces include radial, along-track and cross-track components represented by a periodic function. The period of this function was adopted to be the orbital period, thus the empirical force accommodated once/revolution effects. The estimated parameters were amplitude and phase of the function.

The arc lengths included a series of "short arcs" of one-day duration, each of which was independent of the other arcs. For this study, a "long arc" consisted of a 5-day arc in which a single set of orbital parameters for each satellite were estimated. For the one-day arcs, three cases have been examined:

- Case 1: estimate ROCK4 scale parameter and y-bias for each satellite
- Case 2: estimate coefficients of once/revolution radial, transverse and normal perturbations instead of radiation pressure and y-bias
- Case 3: same as Case 2 except a constant along-track perturbation was estimated instead of the once/revolution transverse force

For the 5-day arc, a strategy similar to Case 1 was followed except that two y-bias parameters for each satellite were estimated.

4. RESULTS

The statistics of the Case 1 results are shown in Table 2. In general, the RMS of the double difference residuals from the one-day arcs were in the range of 1.2 to 1.6 cm. Examination of the raw phase measurements suggests that the ionosphere corrected phase measurement has a precision of about 0.3 to 0.4 cm, thus leading to the conclusion that the precision of the double difference (DD) measurement should be about 0.6 to 0.8 cm. The discrepancy between the DD precision estimate and the values in Table 2 is indicative of one aspect of mismodeling. However, it cannot be concluded that the discrepancy is caused completely by orbit mismodeling and the possibility that measurement systematics, such as multi-path, are a contributor must be considered.

The increased DD RMS from the 5-day arc, however, is indicative of a level of orbit model error since the measurement systematics are not dependent on the arc length, but force models are significantly dependent on the arc. Nevertheless, although the 5-day arc should use daily sub-arc values of SRP and y-bias to more nearly match the one-day arcs, past experience has shown that such representations do not substantially reduce the RMS on the long arc [Schutz et al., 1990].

There are possible sources of orbital mismodeling: gravitational and nongravitational. Experience with satellite laser range (SLR) measurements to the Etalon satellites, however, suggests that no significant gravitational mismodeling exists [Eanes, et al., 1991]. The two Etalon satellites were launched into GLONASS-like orbits by the USSR in 1989. Both are spherical, with a reasonably low area to mass ratio. The dominant model error on the Etalon satellites is nongravitational in origin, however, the nature of the nongravitational effects on Etalon is quite different than GPS and the Etalon experience cannot be extrapolated to GPS (or GLONASS). Concerning the gravitational contributions, the fact that the GPS satellites are in "deep resonance" distinguishes them from the Etalon satellites which are not; thus, there is still the possibility of a gravitational effect, but it is most likely of very long period and would not be evident in arcs with a duration of several days.

The mismodeling is further evidenced by discontinuities in the common time point between the one-day arcs. For PRN-3, the differences between the Case 1 one-day arcs and the 5-day arcs is shown in Fig. 1 for the radial, along-track and cross-track components. As shown, the discontinuities at the common time point are several meters in some cases, while others are at the level of 2 meters. The discontinuities are associated with mismodeling on the one-day arcs, however, the magnitude of the discontinuity is, in part, determined by the mismodeling on the 5-day arc. Note that the magnitudes of discontinuities in the radial and cross-track directions are much smaller than those in the along-track direction.

For PRN-3, the 5-day arc was compared with the ephemeris produced by Defense Mapping Agency. The differences are shown in Fig. 2. This comparison was accomplished without any adjustment to either the DMA or the UT ephemerides, and was formed by directly differencing the two ephemerides in the Earth-fixed system and transforming the difference into radial, along-track and cross-track components. Because of the difference in GM used in the ephemerides (DMA: 398600.5; UT: 398600.441 km^3/s^2), a radial bias exists at the meter level. The periodic differences probably reflect model differences, including reference frame differences. Since the two cases were generated by independent software and different global tracking networks as well as different data types, the differences can be regarded as an indication of the level of GPS orbit accuracy. The RMS of differences are 1.6 m radial, 2.3 m along-track and 2.6 m cross-track. The size of the cross-track in comparison to the along-track is an indication of reference frame differences.

Additional experiments using the once/revolution force model characterizations were conducted. The Case 3 result for PRN-3 is shown in Fig. 3 for the coefficients of the radial and cross-track components and the constant (over one day) along-track component is shown in Fig. 4, including the formal error of the respective daily estimates. Although the trends exhibited by these parameters appear to be systematic, it should be noted that the effect on the RMS of the one-day arcs has been small. Further experiments will be conducted using these parameterizations in long arcs.

5. CONCLUSIONS

Based on analysis of the GIG-91 data set, double difference phase residual RMS at the 1.2 to 1.6 cm level have been obtained for one-day arcs, while a 5-day arc shows 3.8 cm. The one-day arcs are probably influenced by both unmodeled forces on the GPS satellites and by systematic measurement model errors, while the 5-day arc is expected to be dominated by force model errors. Experience with other satellites at similar altitudes suggests the dominant force model error has a nongravitational origin. Comparison of the one-day arcs with the five-day arc shows discontinuities at the common time point of the one-day arcs with differences of several meters. Direct comparisons with DMA ephemerides show differences at the 2 to 3 meter level (RMS), thus providing an indication of the orbit accuracy over days 34-38. Use of empirical force models as a means of investigating the nature of possible model errors was applied to one-day arcs, with results that exhibit systematic characteristics. Future studies will investigate these parameterizations.

6. ACKNOWLEDGEMENTS

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TABLE 1. GIG-91 SITES

Rogue Receivers:

- Yaragadee, Australia
- Canberra, Australia
- Santiago, Chile
- Hartebeesthoek, S. Africa
- Kokee Park, Hawaii,
- Usuda, Japan
- Goldstone, CA
- Victoria, BC
- Fairbanks, Alaska
- Wettzell, Germany
- Madrid, Spain
- Matera, Italy
- Kootwijk, Netherlands
- Ny Alesund, Norway
- Tromso, Norway
- Algonquin, Ontario
- Yellowknife, NWT

Minimac 2816AT Receiver:

- Hobart, Tasmania, Australia

TI-4100 Receivers:

- W. Samoa
- Easter Island

TABLE 2. ARC STATISTICS

One-Day Arcs			
Day	Passes	DD Observations	RMS (cm)
34	221	11545	1.550
35	224	11421	1.511
36	291	15035	1.516
37	287	14823	1.396
38	280	13792	1.377
39	289	12397	1.378
40	304	13383	1.265
41	312	13742	1.204
Five-Day Arc			
34-38	1300	66629	3.857

DD denotes Double Difference

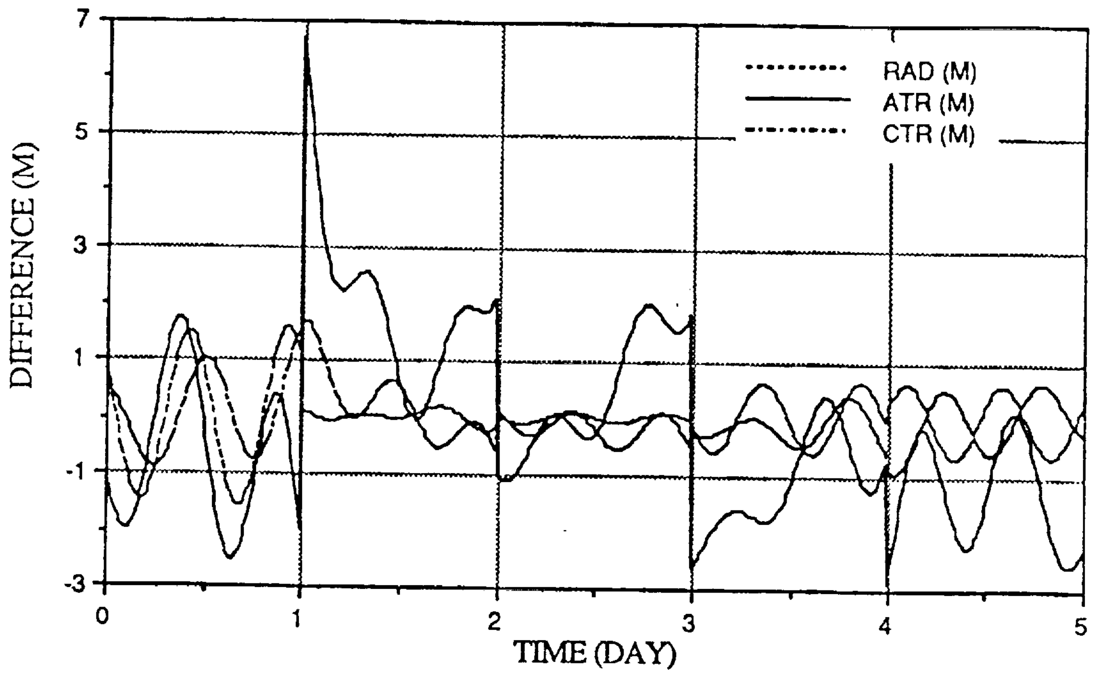

Figure 1. Difference between 5-day and 1-day arcs of PRN03 for Case 1; Epoch: Feb.3, 1991.

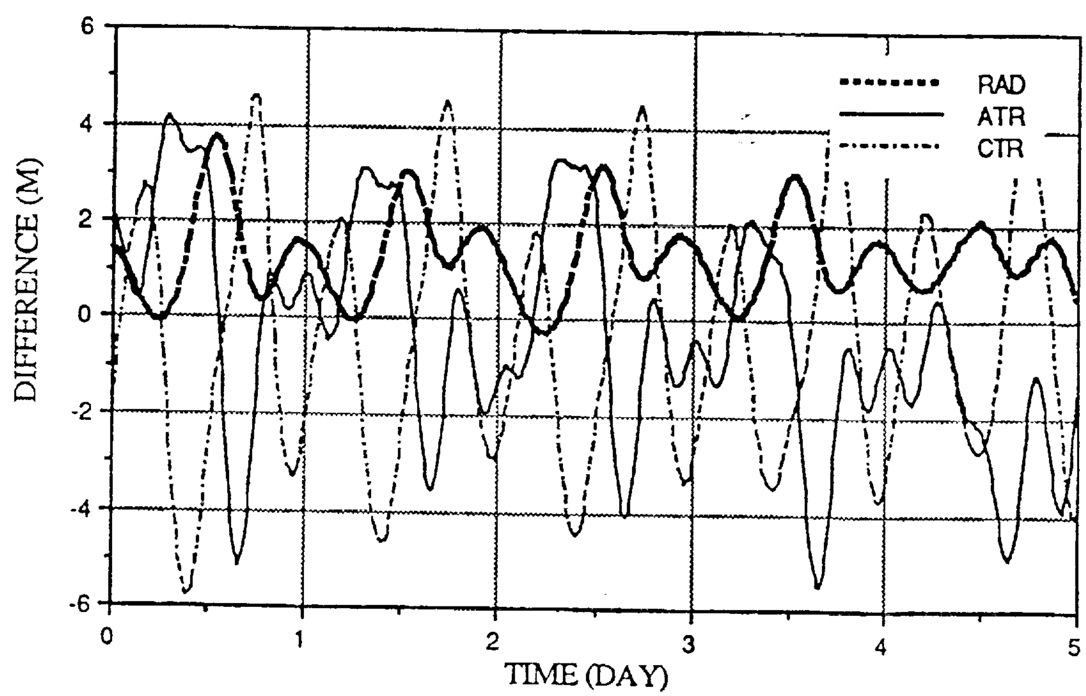

Figure 2. Difference between UT/CSR 5-day arc and DMA ephemeris of PRN03; Epoch: Feb.3, 1991.

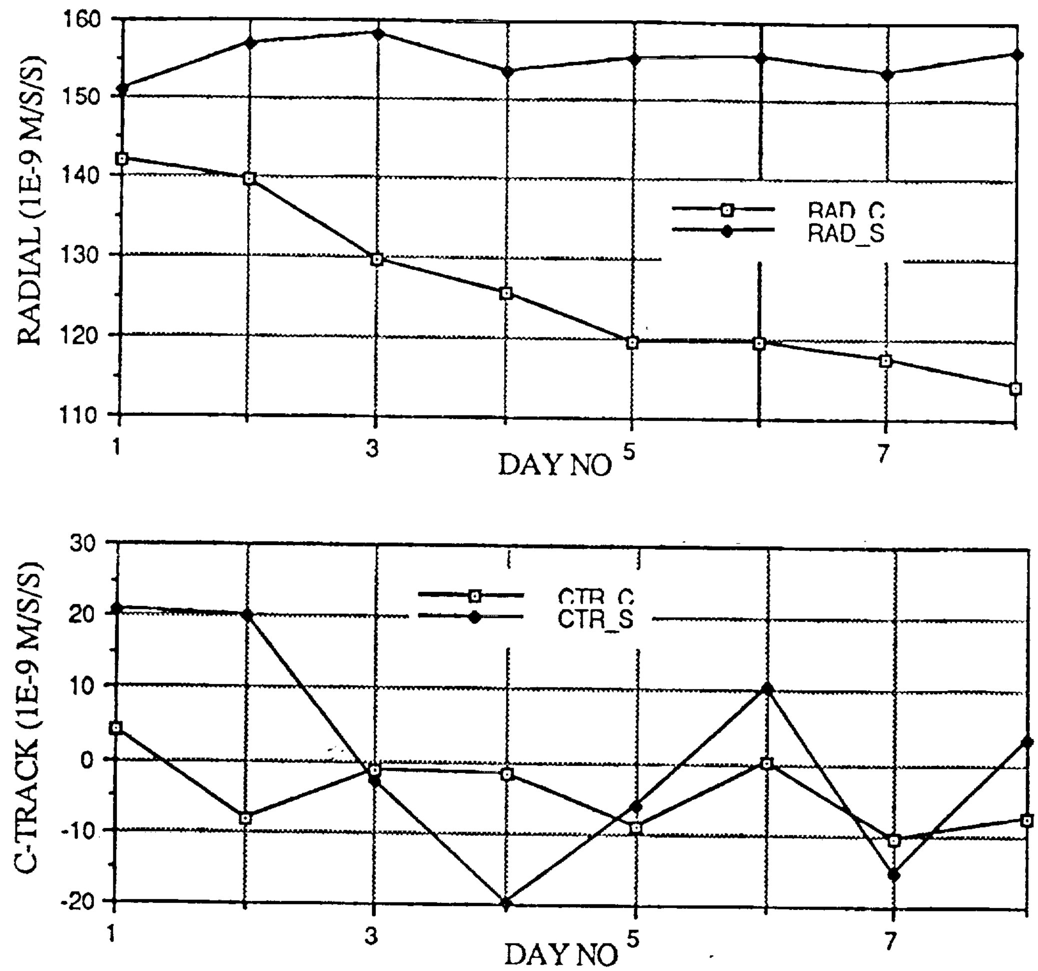

Figure 3. Estimated coefficients of once/rev radial and cross-track empirical acceleration for eight daily arcs of PRN03. Day No.1 is Feb.3, 1991.

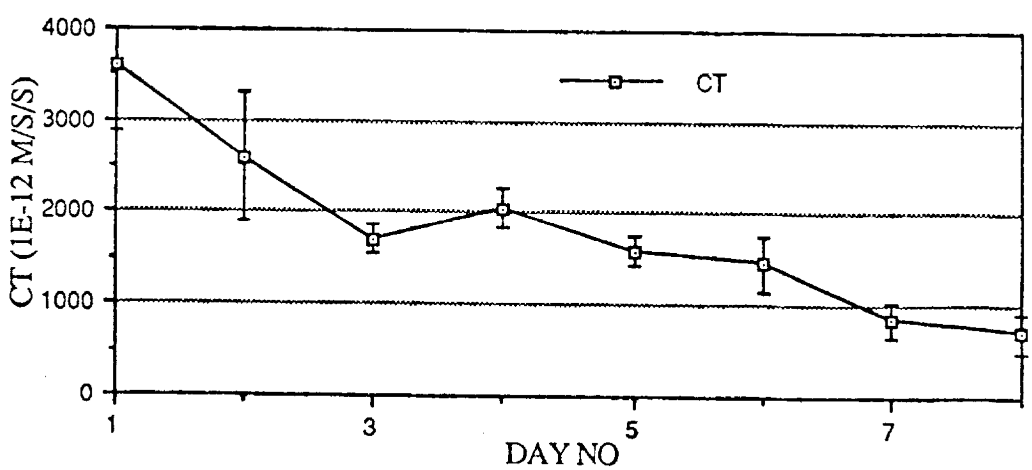

Figure 4. Estimated constant along-track empirical acceleration (Case 3) for eight daily arcs of PRN03. Day No.1 is Feb.3, 1991.

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GPS REFERENCE FRAMES AND EARTH ROTATION

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ABSTRACT

With the forthcoming International GPS Service (IGS) campaign scheduled for June 21, 1992 to September 21, 1992, and with the expectation that Analysis Centers will provide products within two weeks of the collected data, an examination of strategies for the generation of potential products is appropriate. The primary products of the IGS are GPS ephemerides, Earth rotation, baselines and reference frame information. This paper describes an analysis of GIG-91 data for the purpose of examining strategies for the generation of IGS products. Preliminary results from the studies has shown agreement with Lageos Earth rotation results at the 0.8 mas and 1.0 mas levels in pole position (x,y), respectively. Other strategies have produced results at the 1.5 mas level. Comparison of selected baselines with those obtained in other campaigns has shown agreement at the level of 10 ppb, and agreement with baselines determined by VLBI at the several ppb level.

1. INTRODUCTION

In January and February, 1991, one of the most ambitious global GPS campaigns to date was undertaken, known as GIG-91. This campaign [Melbourne, 1992] included a variety of receivers in most areas of the world. For the first time, almost 20 high quality Rogue P-code receivers were used at global sites. In some sense, the GIG-91 was a precursor for the 1992 IGS Campaign, which will commence on June 21 and end on September 21. An additional campaign, known as EPOCH '92, centered on August 1, will provide an opportunity for a variety of regional activities. The IGS concept is described by Mueller and Beutler[1992].

Potential products of the IGS have been extensively discussed and the report of a panel charged to identify those products and the timely availability is given by Schutz et al. [1991]. In summary, the panel noted that Earth rotation, GPS ephemerides and reference frame/baselines would be products with the widest utility. Timeliness of the products was deemed important and the expectation that some products could be available within a few days to a few weeks was noted.

With this background, the primary purpose of this paper was to conduct experiments using the GIG-91 data set to evaluate estimation strategies that could be used in the IGS. An additional purpose was the comparison of baseline results with those obtained by other techniques and from other GPS campaigns as a means of assessing the accuracy.

2. ANALYSIS SOFTWARE

All software used in the analysis of the SWP-90 data has been developed at the Center for Space Research (CSR) and is known collectively as TEXGAP (TEXas Gps Analysis Programs). The analysis process is divided into a preprocessing component and a geodetic component. In the preprocessing component, the data were reviewed and corrected for cycle slips, erroneous points and general data anomalies. In this process, the time tags of the phase measurements were validated and/or corrected using the L_1 C/A pseudo-range, or L_1/L_2 if the receiver operates with the P-code. Finally, explicit double difference ionospherically-corrected measurements were formed for the geodetic processing stage.

The geodetic processing was performed using MSODP1(Multi-Satellite Orbit Determination Program). In the general application of MSODP1, the GPS epoch orbit elements and selected force model parameters were simultaneously estimated with three-dimensional coordinates of the GPS. This software has undergone comparison with programs used for precision orbit determination of geodetic satellites, such as Lageos, Starlette and Etalon, all of which are targets for precision satellite laser ranging instrumentation [Tapley et al., 1985].

3. DATA AND MODELS

As previously noted, the GIG-91 data were used for the study as shown in Table 1. Although the network is dominated by Rogue receivers, TI-4100 receivers at W. Samoa and Easter Island were included to improve the southern hemisphere and Pacific coverage. In addition, a Minimac 2816 at Hobart was included because of the availability of a survey tie to VLBI at the time the investigation began; however, the local surveys have recently become available for Yaragadee and Tidbinbilla/Canberra.

The GPS force models followed the current IERS Standards [McCarthy, 1989] and scale factors on the ROCK4 [Fliegel, 1992] and y-bias parameters were estimated. The Chao [1973] troposphere model was used, and zenith delay parameters were estimated at 2.5 hour intervals from all sites. Lageos-derived polar motion and UT1 were used as a priori. For all cases, dual frequency double differenced phase measurements were used in the analysis. Pseudo-range measurements were used to verify and/or correct the respective receiver clocks.

The reference frame was based on Lageos satellite laser ranging (SLR) analysis, CSR91L03 [Eanes et al., 1991] and Very Long Baseline Interferometry (VLBI) analysis GLB718 [Ma et al., 1991]. The VLBI sites were transformed into the SLR reference frame using transformation parameters derived from 18 common sites. The technique has been described by Ray et al.[1991].

4. ESTIMATION STRATEGIES

For this study, two primary estimation strategies have been used and a third strategy was partially examined. The first strategy was based on independent one-day arcs in which orbit parameters (including y-bias and solar radiation pressure parameters), Earth rotation parameters (x,y) and station coordinates were estimated without a priori constraints (i.e., the a priori covariance was essentially infinite). The second strategy was based on a multi-day estimation of station coordinates, but daily determinations of orbit, force model and Earth rotation parameters. For some cases that used this strategy, a priori covariance constraints were used. The third strategy was based on a multi-day orbital arc, but daily solutions for station coordinates and Earth rotation parameters were obtained.

It is well-known that the models used to describe the dynamics of the GPS satellites are incomplete or contain errors (or both). These model deficiencies will lead to a discontinuity at the common time point between successive one-day arcs and will produce higher RMS measurement residuals on multi-day arcs unless the model deficiency is accommodated by estimated parameters. The latter accommodation of errors may not produce improved model parameters as the unmodeled effect may have a signature similar to the other effects, thus allowing the model error to be absorbed in other parameters.

In the multi-day station coordinate strategy, all stations were allowed to adjust, also referred to as a "free fiducial" case by Blewitt et al.[1992] and others. This strategy leads to a very ill-conditioned, or nearly singular, problem when Earth rotation parameters are estimated also and requires the introduction of some a priori constraints. The constraint commonly used is an a priori covariance with coordinate uncertainties chosen to be a specified value, e.g., 100 meters. Other ways of avoiding the singularity are to fix the coordinates of some stations or a combination of coordinates at more than one station. The minimal number of constraints required depends on the parameters being estimated.

5. EARTH ROTATION RESULTS

Using the first strategy of independent one-day arcs and fixing the coordinates of Hobart, Goldstone and Wettzell to the values given in Table 2, the GPS orbit parameters, other station coordinates and (x,y) Earth rotation were estimated. Although all of the fixed sites were at VLBI locations, Hobart is a Minimac receiver and the other two sites use Rogue receivers. In any case, the RMS differences of the estimated rotation pole position, compared to Lageos values [Eanes et al., 1991] produced RMS differences of 1.5 mas in x and 1.4 mas in y after removal of a 5 mas bias.

In an alternative case, Yaragadee, Goldstone and Wettzell were fixed and all non-Rogue sites were eliminated. The RMS differences in pole position were 2.6 mas in x and 3.3 mas in y. Further investigation is required to determine whether the cause of the change is associated with the fixed coordinates of Yaragadee or with the exclusion of the non-Rogue receivers.

Using the strategy in which a multi-day solution was obtained for the stations in a "free fiducial" mode with 100 m a priori on the station coordinate covariance elements, 1 day solutions for pole position (x,y) were obtained using 10 mas a priori. The RMS differences of the pole position, compared to Lageos, were 0.8 mas in x and 1.0 mas in y. In all comparisons, the RMS differences will change slightly if the GPS results are compared against other Earth rotation series.

6. BASELINES

From the three fixed site strategy, the daily repeatability for baseline length on selected baselines is shown in Table 3. The selected cases are all cases in which double differences were directly formed for the solution process. It can be noted that the repeatability for all cases involving the TI-4100 receivers exhibit worse repeatability than the other cases. It should be noted that for both W. Samoa and Easter I. the preprocessing identified some significant systematic features that could be related to multi-path problems.

An additional case was examined in which Trimble receivers at Wellington, New Zealand, and Townsville, Australia were included for the purpose of estimating the coordinates of these sites. In the case of Wellington, a result obtained during a 1990 campaign afforded an additional comparison. Data collected during July 1990 and processed as part of the Southwest Pacific Project (SWP) provided a set of coordinates for Wellington. The SWP results [Schutz et al., 1992] used a global network that differed from the GIG-91 in two primary ways. First, the SWP global network was dominated by "codeless" receivers and, second, Selective Availability (SA) was activated. As noted previously, the GIG-91 global network was dominated by Rogue P-code receivers and SA was not implemented. The comparison of the Hobart to Wellington baseline is given in Table 4 and the coordinates of the Australia/New Zealand sites derived from GIG-91 are given in Table 5.

7. CONCLUSIONS

Based on the preliminary results given in this paper, it has been shown that Earth rotation components (x,y) were obtained that agree with other determinations at the 1 mas level (RMS). Two strategies were examined: a multi-day case and cases using independent one-day arcs. Baselines from the three fixed site case show repeatability at the several ppb level, except for cases using the TI receivers in the Pacific which are at the level of 10-20 ppb. Further examination of the influence of mixing Rogue and TI data will be conducted and other estimation strategies are under examination.

Results for Wellington that were obtained from two campaigns show agreement at the 10 ppb level. In one case, the campaign was dominated by global codeless receivers, whereas the GIG-91 was dominated by Rogue receivers. An additional difference was the fact that SA was activated during the earlier campaign, but not during GIG-91.

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TABLE 1. GIG-91 SITES

Rogue Receivers:

- Yaragadee, Australia
- Canberra, Australia
- Santiago, Chile
- Hartesbeestoek, S. Africa
- Kokee Park, Hawaii,
- Usuda, Japan
- Goldstone, CA
- Victoria, BC
- Fairbanks, Alaska
- Wettzell, Germany
- Madrid, Spain
- Matera, Italy
- Kootwijk, Netherlands
- Ny Alesund, Norway
- Tromso, Norway
- Algonquin, Ontario
- Yellowknife, NWT

Minimac 2816AT Receiver:

- Hobart, Tasmania, Australia

TI-4100 Receivers:

- W. Samoa
- Easter Island

TABLE 2. COORDINATES USED FOR FIXED SITES (m)

Site	x	y	z
Goldstone (Rogue	-2353613.9840	-4641385.4730	3676976.4990
Hobart (Minimac L1)	-3950184.0724	2522364.5271	-4311588.6675
Wettzell (Rogue)	4075579.3868	931807.2475	4801570.9395

Note: The Rogue coordinates refer to the top of the antenna

TABLE 3. SELECTED BASELINES

Sites	Baseline Length (km)	Daily RMS Scatter (ppb of baseline length)
Algonquin - Wettzell	6154	5.6
Goldstone - Yellowknife	2986	8.8
Goldstone - Fairbanks	3807	6.3
Goldstone - Algonquin	3402	12.4
Yaragadee - Tidbinbilla	3197	8.9
Tidbinbilla - W. Samoa	4474	17.7
Kokee Park - W. Samoa	4124	22.2
Kokee Park - Usuda	5894	8.4

TABLE 4. COMPARISON OF HOBART-WELLINGTON BASELINE (m)

Case	x	y	z	L
SWP-90	-830464.717	-2085857.511	126148.175	2248641.049
GIG-91	-830464.699	-2085857.541	126148.187	2248641.070
Difference (xyz, L)	0.018	-0.030	0.012	0.021
Difference (NEU)	0.005	0.028	0.023	

(NEU: North, East, Up)

TABLE 5. COORDINATES OF SELECTED AUSTRALIA/ NEW ZEALAND SITES (m)

Data: GIG-91

Site	x	y	z	
Hobart	-3950184.072	2522364.527	-4311588.668	Minimac L_1
Wellington	-4780648.771	436506.986	-4185440.481	Trimble L_3
RMS	0.051	0.017	0.032	
Tidbinbilla	-4460987.995	2682362.260	-3674626.550	Rogue L_3
RMS	0.025	0.013	0.033	
Townsville*	-5041024.956	3296980.304	-2090553.463	Trimble L_3
RMS	0.020	0.039	0.009	

RMS refers to the daily scatter in the solutions
* denotes that some solutions were edited