GPS DATA ANALYSIS FOR EARTH ORIENTATION AT THE JET PROPULSION LABORATORY

J. ZUMBERGE, F. WEBB, U. LINDQWISTER, S. LICHTEN, D. JEFFERSON, R. IBANEZ-MEIER, M. HEFLIN, A. FREEDMAN, G. BLEWITT
Jet Propulsion Laboratory,
California Institute of Technology
Pasadena, California 91109

ABSTRACT. Beginning in June 1992 and continuing indefinitely as part of our contribution to FLINN (Fiducial Laboratories for an International Natural Science Network), DOSE (NASA'S Dynamics of the Solid Earth Program), and the IGS (International GPS Geodynamics Service), analysts at the Jet Propulsion Laboratory (JPL) have routinely been reducing data from a globally-distributed network of Rogue Global Positioning System (GPS) receivers. Three products are produced and distributed weekly: (i) precise GPS satellite ephemerides, (ii) estimates of daily polar motion and length-of-day, and (iii) a descriptive narrative of the analysis for the week. These are typically made available to the public approximately two weeks following the data recording. In addition, more sophisticated data reduction techniques have been developed for non-routine, research-oriented GPS data analysis. These have been successfully utilized to measure sub-daily Earth orientation fluctuations. Based on comparisons of our earth orientation parameters with independent techniques, we estimate daily pole position accuracies (1σ) of ±0.6 milliarcseconds and length-of-day accuracies of ±0.13 msec. Ongoing work at JPL is aimed at continuing the trend of producing more and higher-quality results at lower cost.

1. Introduction

The first GPS geodynamics experiment for the IERS (GIG '91), a two-week campaign in early 1991, saw the first globally-distributed deployment of precise Global Positioning System receivers, and demonstrated few-parts-per-billion precision [1] in estimates of terrestrial site locations. Largely as a result of the success of GIG '91, the International GPS Geodynamics Service (IGS) began informal operation in June 1992 and formal operation in January 1994, JPL has contributed to the IGS since it began and, in conjunction with its ongoing support of NASA's Dynamics of the Solid Earth (DOSE) program, will continue to contribute. JPL has also contributed in a research capacity to the analysis of the GPS data and resulting scientific products.

Shown in Figure 1 is the distribution of terrestrial GPS P-code receiver's as of February 1993. Global coverage is very good, with only a few noticeable "holes". Within the next two years, it is anticipated that these holes will be plugged with new receivers at strategic locations, Figure 2 summarizes the steadily increasing number of stations and satellites beginning in early 1992 and continuing to the present. One can speculate on whether the trend will continue, but currently the data volume, as measured by (# stations x # satellites), doubles in just over a year!

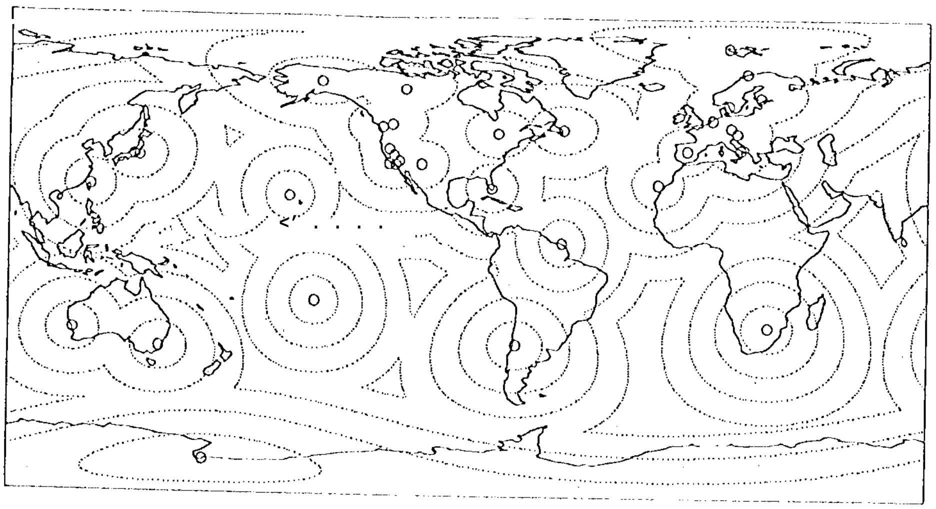

Figure 1. Distribution of terrestrial GPS receivers used in the daily analyses. The dotted lines represent contours of the distance-to-nearest-site function. The contour interval is 1000 km.

Described in this paper are the routine analysis procedures used at JPL, the resulting Earth orientation data products, and their estimated accuracies. Also described are more sophisticated and CPU-intensive analysis procures being used for the non-routine, research-orielltcci tasks. Wc conclude with a brief look at JPL's plans for improving the efficiency and quality of its analyses,

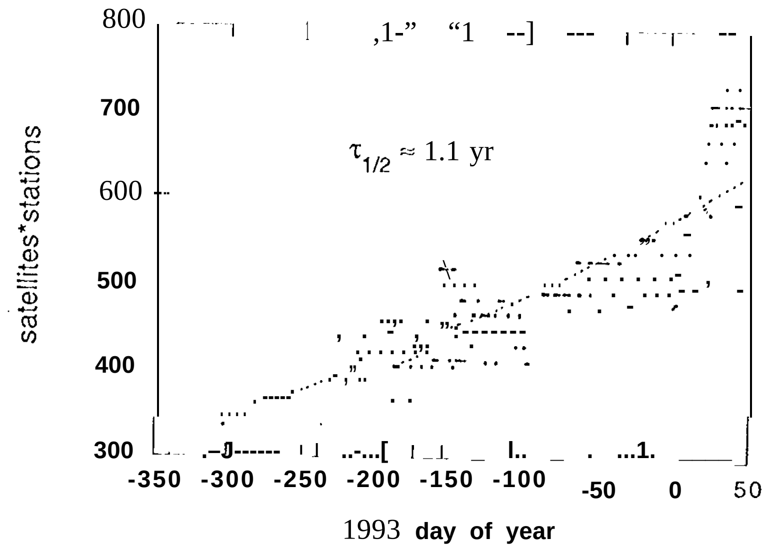

Figure 2. The number of satellites times the number of stations used in daily analyses beginning early 1992. At the current rate, tile data volume doubles in a little over 1 year.

2. Procedure and Products

Figure 3 gives a simplified overview of the routine procedure. JPL's GPS Networks Operations (GNO) Group retrieves data from the global network, organizes them by time and site, converts them to the Rinex format, and makes them available for analysts, Once it is determined that sufficient data arc available for a given day, a file is created which specifies what data are to be used in that day's analysis, as well as specific sites or GPS satellites from which data should be deleted or deweighted due to known problems.

Based on input from this file, a daily script that runs several programs is launched, requiring a total of approximately 19 hours of cpu time on a 17-Mflop Unix workstation when data from 30 stations and *20* satellites are included. When completed, the daily analysis results in estimates for Earth orientation, GPS satellite ephemerides, and locations of terrestrial sites.

The operational cycle is one week, during which seven daily analyses arc completed. Together with the result from Saturday of the previous Week and Sunday of the following week, these are used in quality control. Four files are produced anti distributed weekly, wi(h naming convention `jpl0www7`, where www is the GPS week and '/ indicates the results are for the entire week. The files are distinguished by their extensions: . sum for a narrative summary, `.sp1` or . sp3 for GPS ephemerides [2,3], anti `.erp` for Earth orientation. The orbit product and orbit accuracy comparisons arc discussed further in [4].

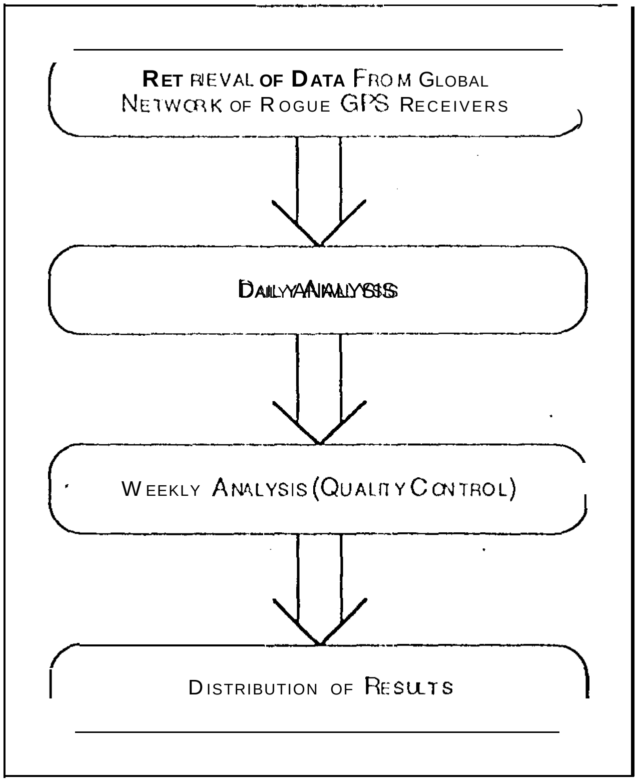

Figure 3. Simplified Flow Chart of FLINN Analysis

The analysis software used is the JPL-developed GIPSY-OASIS 11. This software, which incorporates Kalman filtering, and various standard JPL GPS estimation strategies are described in detail in [5,6,7].

in normal operation, each day is processed separately using the 24 hours of the UTC day plus the last 3 hours of the previous day and first 3 hours of the following day. Norma] points are formed every 10 minutes, 'he data types we use are the undifferenced ionosphere-free phase and pseudorange, with assumed noise of 5 mm and 50 cm, respectively.

The GPS satellite motion is modeled as a 9-parameter epoch state vector which includes three-dimensional position, velocity, and solar radiation pressure. Additional parameters allow the solar radiation pressure to vary in a stochastic way about its average value. The noise model for this variation is first-order Gauss-Markov with a 4-hour time constant and 10% standard deviation. Especially during periods when a satellite is in the Earth's shadow, the extra variation allows significantly better modeling of its motion.

The nominal value for the Earth's pole position (x Andy) is obtained from the IERS Bulletin B predicts, ant] its deviation from that nominal is modeled as a linear function of time. The deviation Of UT1R – UTC from the nominal (again, IERS Bulletin B predicts) is also assumed to be linear with time, but in this case only the rate is estimated. This rate is the negative of length of day (I .01)1<).

The terrestrial sites include eight which are assume.ci to be at known locations. These are Algonquin Park, Ontario, Canada; Fairbanks, Alaska, U. S.; Hartebeesthoek, South Africa; Kokee Park, Hawaii, U.S.; Madrid, Spain; Santiago, Chile; Tromso, Norway, anti Yaragadee, Australia, The fixed values are updated at the beginning of each month to account for site velocities from ITRF91 (IGS mail message 90) [8]. Location of all other terrestrial sites arc solved for every ciay starting from ITRF91 nominal positions.

GPS carrier phase biases arc estimated as real-valued parameters. Clock biases for transmitters anti receivers arc estimated as white noise processes, except for one reference station clock. The zenith troposphere delay at each receiver site is modeled as a random waik process. The 19S0 International Astronomical Union (IAU) nutation model, the Yoder et al. [9] Earth and ocean tide model, and the GEMT3 (more recently, JGM2) gravity field model arc assumed.

3. Results

3.1. DAILY EARTH ORIENTATION

Shown in Figure 4 arc tile Earth orientation results. A discontinuity at days 200-201 (July 18-19, 1992) is a consequence of the change in fiducial strategy which went from three (Fairbanks, Algonquin, and Madrid) fixed sites to the eight described earlier. From July 19 through the end of 1992, excluding some days during which anti-spoofing was in effect, the average difference between JPL's pole position measurements anti those from the IERS Bulletin B Final values is about 0.8 mas for x and 1.2 mas for y, with standard deviations of about 0.6 mas for both x and y.

Although GPS measurements are almost completely insensitive to UT1R – UTC, they are sensitive to its time derivative, essentially the Earth's spin rate. With $T \equiv 1$ day, the quantity

$$\mathrm{LODR} \equiv -T \frac{d}{dt}(\mathrm{UT1R} - \mathrm{UTC}) \qquad [1]$$

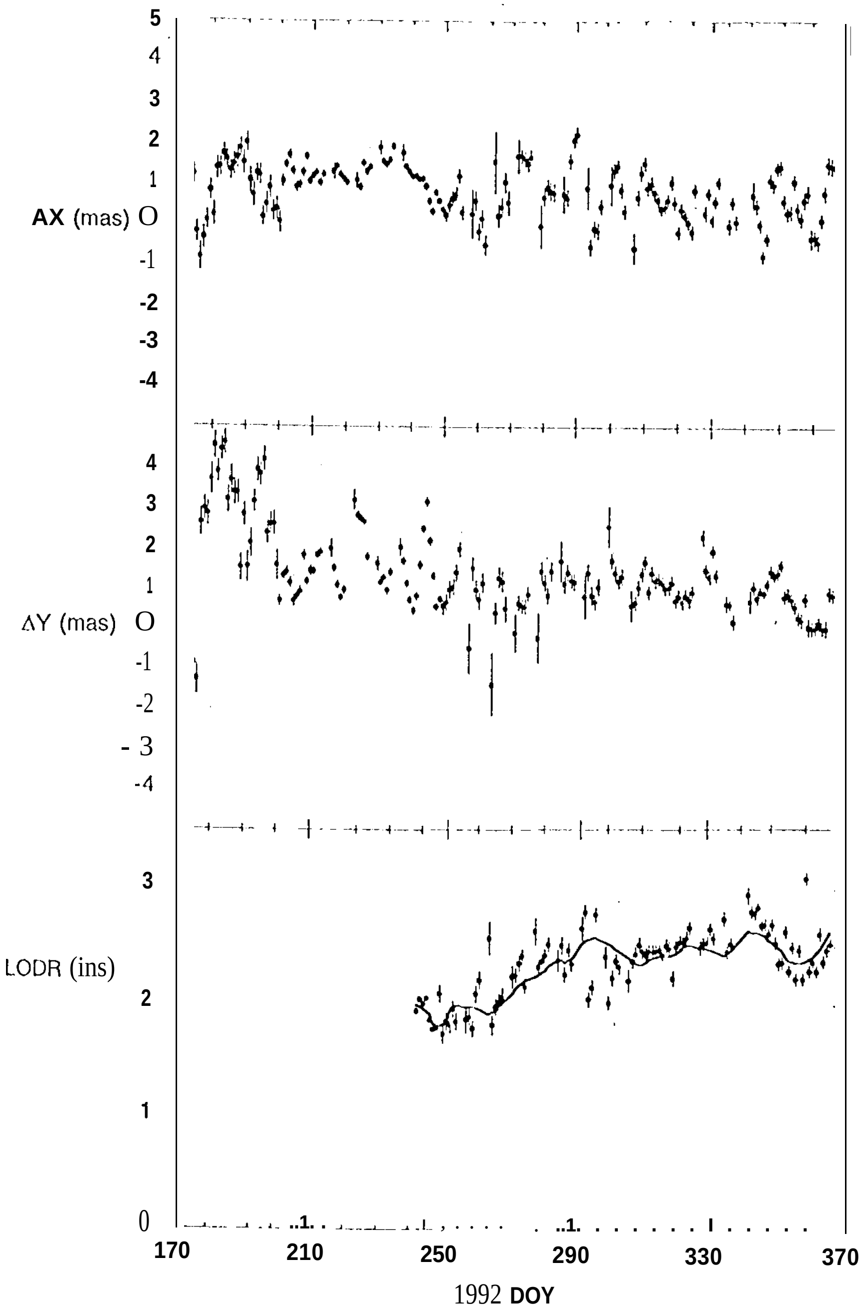

Figure 4. GPS estimates of Earth orientation parameters compared with IERS Bulletin B Final Values. For pole position, the values show (ΔX and ΔY) are the GPS measurements minus the IERS values, and the error bars reflect the formal uncertainty in tile GPS measurements. For LODR, the solid line indicates the negative time derivative of the IERS value of UT1R - UTC, and the points indicate the GPS measu rements and formal uncertainties.

is the conventional measure of this spin rate. We began including daily estimates of LODR beginning with GPS week *660* (August 30, 1 992). Shown at the bottom of Figure *4* are our daily estimates of LODR and a smooth curve which represents the negative derivative of the IERS Bulletin B Final values of UT1R -- UTC. Excluding a few 3σ outliers, the agreement is approximately 0.13 msec (1σ) with a negligible bias.

Because the daily estimates of LODR arc for the most part independent, an integration of them to recover UT1 R -- UTC (given some initial starting value) would exhibit random walk behavior. Thus, some method is required to prevent the walk from wandering too far away. We are currently investigating the forward-running filter

$$UT1R - UTC(t+1) = \alpha A + (1 - (Y,) [UT1 R -- UTC(t) + LODR(t + '172)], \qquad [2]$$

where A is a separate estimate of UT1R – UTC(t + 'J') and α is a free parameter. (WC continue to use T = 1 day.) The parameter α should be small enough so that the resulting UT1 R -- UTC series will exhibit a time variation consistent with the daily GPS-measured LODR values, and only just large enough to suppress large random-walk excursions. A reasonable choice for A is the most-recent IERS Bulletin B *Final* value of UT1R - UTC (typically 30- to 60-days old), incremented to the present by the daily GPS measurements of LODR. In the near future wc intend to include the results of such a procedure in our . erp files.

The Epoch '92 campaign, running from July '26- August 8 1992, was a particularly intensive period of observation for other geodetic techniques. It occurred when our estimation strategy had not matured to its current state. Therefore, these days were reprocessed in early 1993 with the current estimation strategy. The results arc on JPL's bodh i distribution compute]", and arc also available on the Crystal Dynamics Data information System (CDDIS) at Goddard Space Flight Center. The reprocessed data show marked improvement over the original analyses in both orbit quality and Earth orientation accuracy.

3.2. SUB-DAILY EARTH ORIENTATION

The analysis strategy for obtaining estimates of sub-daily Earth orientation fluctuations has much in common with the operational procedure described above. Differences in strategy are discussed here; the Earth orientation results, however, are discussed in detail in Freedman et al. [this volume] and Ibanez-Meier et al. [this volume].

The principle changes made to the daily FLINN strategy deal with the use of multiple day data arcs in place of the 30-hour data arcs of FLINN. To utilize multi-clay arcs, the dynamic orbit models for the GPS satellites must be modified. This may involve modifying the solar radiation pressure models or giving up the goal of a single epoch state for each satellite over the entire data arc, In addition, the estimation strategies for both UT1 and polar motion x and y arc different from those of the daily analyses. Finally, two minor changes include the usc of 6-minute normal point spacing and assumed data noise levels twice as large as those assumed by FLINN.

Variations in UT1 -- UTC starting from an initial fixed value were estimated every 30 minutes by using a first-order Gauss-Markov process update with a correlation time of 4 hours and a steady-state process noise 1-σ constraint of 0.06 ms. Polar motion variations were modeled as a white noise process with weak (120 mas) constraints. For both UT1 and polar motion, a a variety of estimation intervals were tried, ranging from the normal point interval of 6 minutes up to 3 hours. Figure 5 illustrates the UT1 values that result from various estimation intervals. All curves have been difference with a reference series [Freedman et al., this volume] and are offset for clarity.

Curves A and B represent two sets of 30-minute estimates (whose differences are explained below), curve C shows UT1 estimated every 6 minutes, and curves D and E show two sets of 3-hour estimates. D and E differ in that an apriori diurnal and semidiurnal tide model was explicitly used in the estimation of time series E, whereas no such model was used in D. The optima] estimation interval, in the sense of yielding the best signal to noise ratio without undue attenuation of the expected diurnal signal, was 30 minutes.

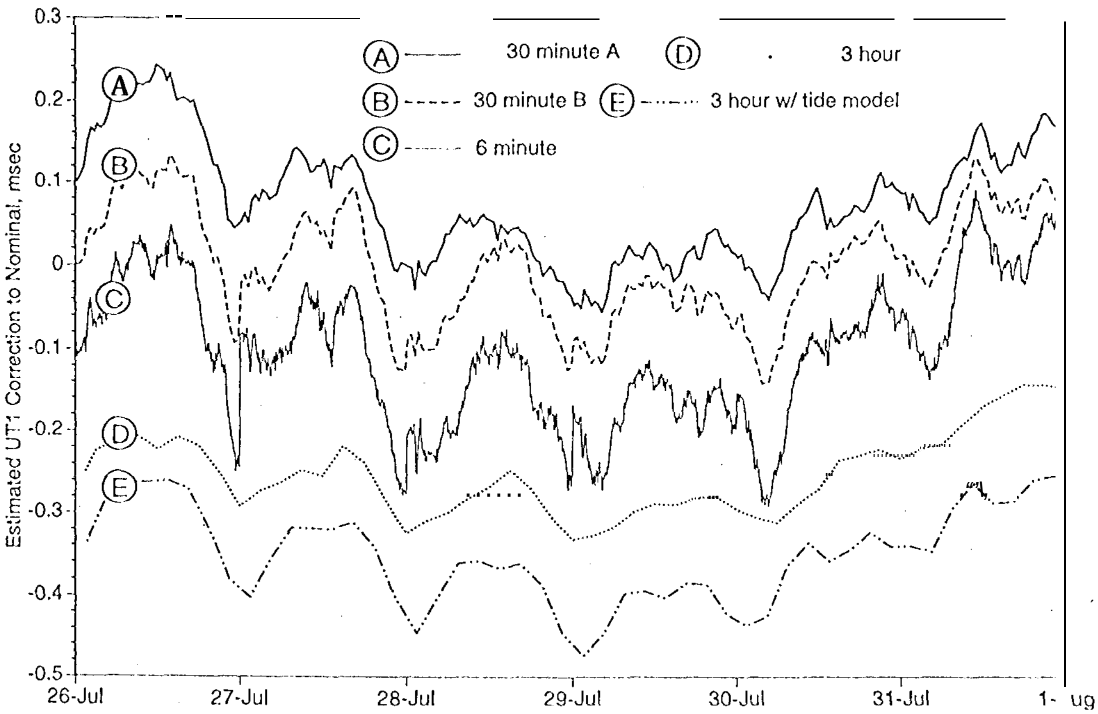

Figure 5. Comparison of sub-daily UT1 time series estimated with various strategies. Time series are offset vertically for ease of comparison. See text for explanation of curves and labels.

Two different estimation strategies for the satellite orbits were employed. In the earlier strategy [5,10], one set of satellite states (positions and velocities) was estimated for each satellite over the course of the multi-clay arc. The solar radiation pressure coefficients Gx, Gy, and Gz were esti- 'mated as constants with 10 percent colored noise added and updated every hour. The biases for the Gx and Gz parameters were constrained to be 100% correlated. The stochastic portion of the solar radiation model consisted of a first-order Gauss-Markov process with a correlation time of 4 hours. We found that this strategy, although adequate for estimating UT1 -- UTC variations, tended to attenuate much of the polar motion signal, presumably absorbing it within the satellite orbit and solar pressure force models, Curve A in Fig. 5 shows the 30-minute UT1 series resulting with this strategy.

A second strategy [1 1] consisted of re-estimating each satellite state (position, velocity and solar radiation pressure coefficients) every 24 hours. In this case, the solar radiation parameters were modeled as constants over 24 hours. The white noise restarts for each GPS satellite were staggered over a 5-hour interval around noon to maintain continuity in the UT1 series. Figure 5 curve B shows the 30-minute UT1 series obtained with this strategy, and all other curves in Fig. 5

use this latter strategy. Typical postfit rms residuals were close to 6 mm for carrier phase and 35 cm for pseudo-range data.

4. Conclusions and Future Prospects

Since the first half of 1992, JPL has made regular contributions to the IGS, consisting of precise GPS orbits and daily Earth orientation results. We expect to continue these contributions. Accuracies are currently estimated to be a few tens of centimeters for GPS orbits, about half a milliarcsec for pole position, and a bit over 0,1 msec for LODR.

Additional strategies for multi-day tires, for routine as well as research use, are being tested. These may be utilized routinely as cpu speeds increase, and are sure to be used in future sub-daily Earth orientat ion research.

Accuracies of all quantifies may improve significantly once we start resolving carrier phase bias ambiguities [1 2], which should begin sometime this calendar year (the current limitation comes from our computing resources). Quality control will be enhanced by daily monitoring of several regional baselines.

A number of weekends during 1992 saw implementation of anti-spoofing (AS). Only recently has the Rogue receiver software been upgraded to handle AS data. Since the upgrade, AS has been processed successfully, although with somewhat degraded accuracies. Analysts at JPL will be investigating modifications of the nominal strategy to better accommodate AS data,

As was shown in Figure *2, the* quantity of data has steadily increased, and will probably continue to increase in the near future owing to both more satellites and more receivers. So that the computational burden remains tractable, we may need to process a select number of stations to fix orbits, anti then use fixed orbits for the remaining stations.

In addition to the current offerings, new products that may be distributed soon are satellite and station clock solutions. If a demand exists, troposphere estimates and stochastic solar radiation pressure estimates could also be made available.

Finally, additional automation in routine processing may reduce the manpower required to keep up to date with the analyses. The current turnaround time of approximately two weeks could conceivably be reduced to a few days, or even less.

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