FIXING THE GPS BAD ATTITUDE: MODELING GPS SATELLITE YAW DURING ECLIPSE SEASONS

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BIOGRAPHIES

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ABSTRACT

It is well known that high-precision GPS navigation degrades during GPS eclipse seasons. We have determined that a major source of this degradation is the mismodeling of the yaw attitude of those GPS satellites that are in eclipsing orbits. The yaw attitude of GPS satellites is essentially random during an eclipse and for up to 30 minutes past exiting from shadow. Furthermore, commonly used models of the noon turn can be inaccurate for a period of up to 30 minutes. This leads to both measurement and dynamic errors. Errors in the radio metric measurements are introduced due to mismodeling of the carrier phase wind-up and the position of the GPS antenna phase center with respect to the spacecraft center of gravity. This measurement error can be larger than 10 centimeters. Errors in the satellite dynamics are introduced because the direction of the solar pressure force is mismodeled during the 30-minute recovery period after exiting the shadow and during the noon turn,

We present an analysis of the effects of attitude mismodeling on precise positioning with GPS. A remedy was proposed for the GPS attitude control subsystem that will make yaw attitude modelable. In June 1994, the US Air Force has implemented the proposed modification to the attitude control subsystem. Details of the new model for the GPS satellite attitude during shadow events and noon turns are presented as well as the necessary modifications to navigation software packages. Early results using GPS under the new attitude control system are also presented.

EVIDENCE OF A PROBLEM

It has been evident for quite some time that the accuracy of orbit determination of GPS satellites degrades significantly during eclipse seasons (Schutz et. al. 1990, Fliegel & Gallini 1992). One of the most useful measures of orbit solution quality is the difference between two overlapping orbits. Daily GPS orbits are produced routinely at JPL such that a 6-hour overlap exists between consecutive days. Figure 1 shows clearly a significant improvement in overlap difference when no GPS satellites are eclipsing. Any precise application of the GPS also suffers degradation as, for example, the positioning of the Topex/Poseidon satellite (Bertiger et. al. 1995). A 10-day (1 cycle) average of Topex orbit overlaps (Figure 2) also shows a significant improvement when all the GPS satellites are in the clear.

A closer look at an eclipsing satellite is required to reveal more about the nature of the problem. Figure 3 is a plot of the post-fit residuals of SVN 24 with 14 receivers observing its signal. Large outlying residuals are seen to be strongly correlated with the events of the satellite

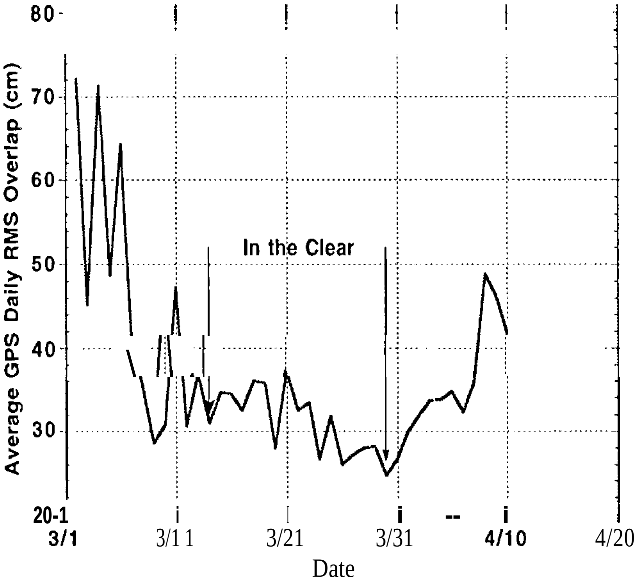

Figure 1. Average daily overlap of the J]']. routine solution for GPS (the Flinn process).

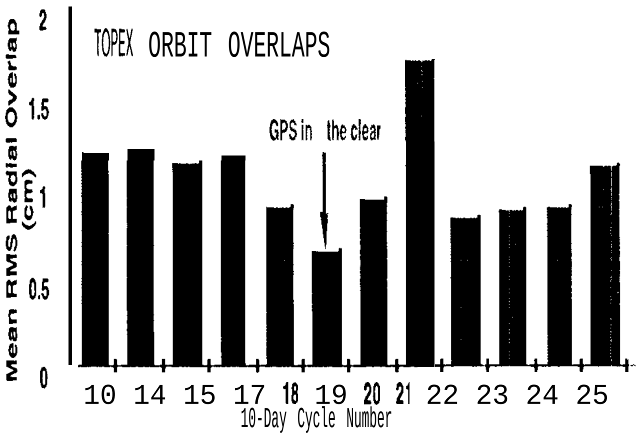

Figure 2. 1 0-day averages of Topex mbit overlaps.

going into shadow. This correlation is not as strong for every eclipsing satellite as can bc inferred from Figure *4* which shows the post-fit residuals of SVN 17 with all observing receivers.

Speculations as to the nature and origin of the problem abound, most notably, those suggested by Fliegel (1992). In that paper Fliegel mentions that the GPS satellite performs its midnight turn AFTER shadow exit. This statement motivated the work reported here, To our knowledge, all existing models for the GPS satellites perform the "midnight turn" at midnight, that is, at the middle of the shadow period. Mistiming the midnight turn is a gross error and it raises the following questions: Is it really true that the midnight turn is performed after

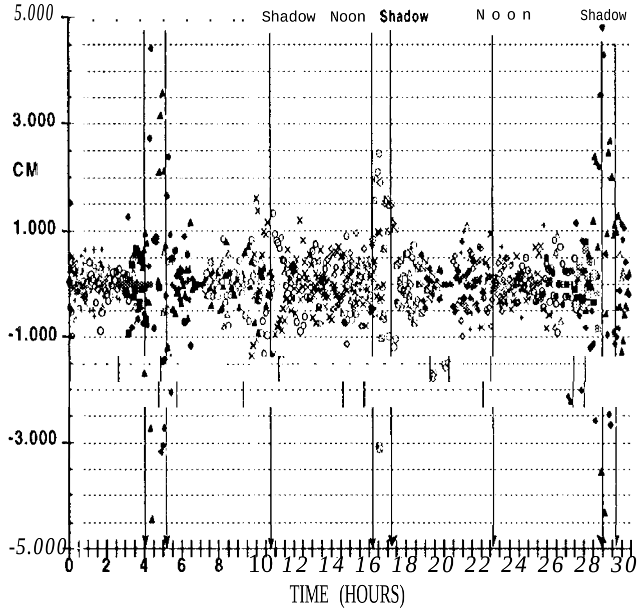

Figure 3. Post-fit residuals of the eclipsing GPS 24 with all observing receivers. July 12, 1993.

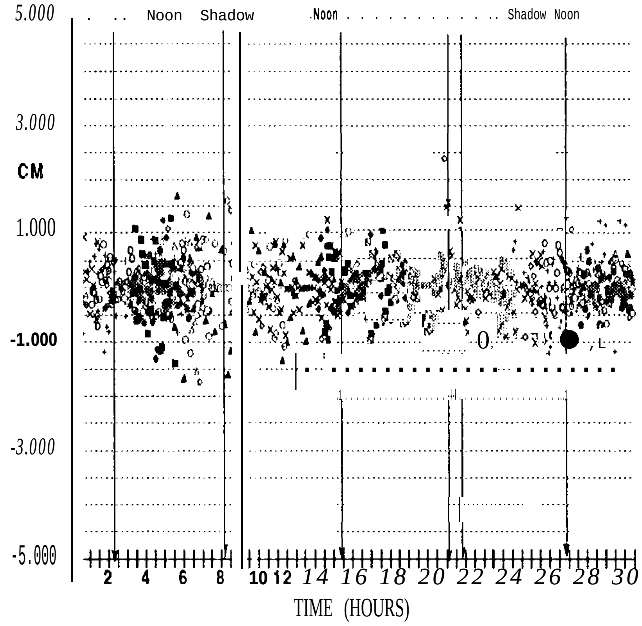

Figure 4. Post-fit residuals of the eclipsing GPS 17 with all observing receivers. July 11, 1993.

shadow exit, if so, why, and how can it be modeled correct I y?

In order to answer these questions wc needed some satellite telemetry. This was supplied to us courtesy of the US Air Force, 2SOPS at Falcon AFB. Figure 5 depicts the yaw momentum of the eclipsing SVN 31 as it goes in anti out

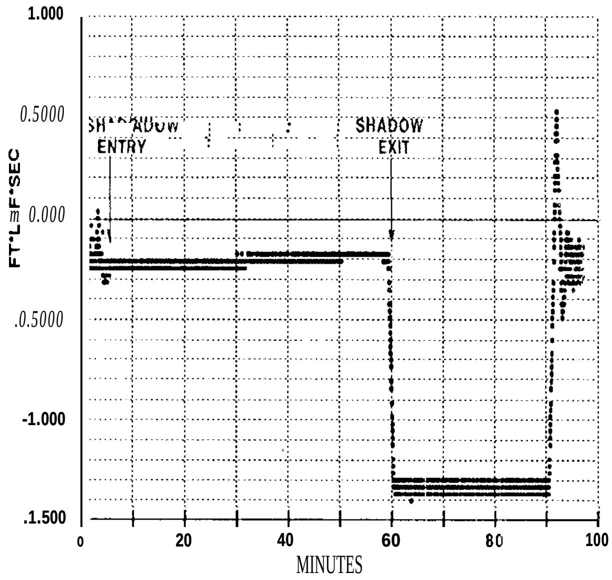

Figure 5. Yaw momentum telemetered from GPS 31 during shadow crossing on November 2, 1993.

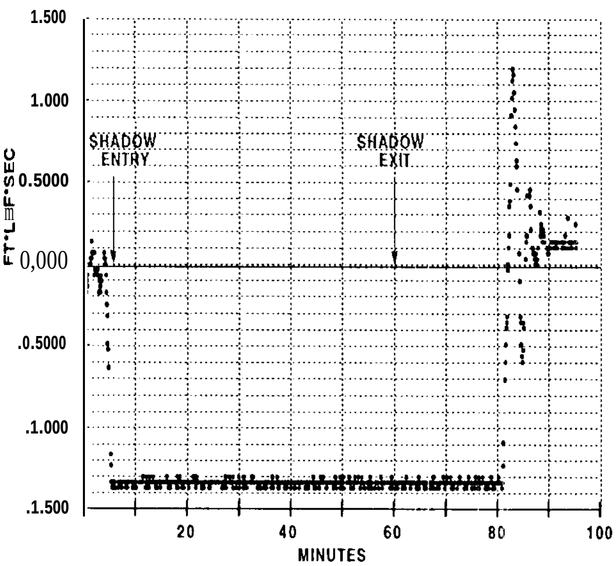

Figure 6. Yaw momentum telemetered from GPS 24 during shadow crossing on July 9, 1993.

of shadow. As evident from the figure this satellite yaws at a small rate during shadow anti then at full rate until it reaches its nominal attitude. Another eclipsing satellite, SVN 24 (Figure 6), yaws at full rate from shadow entry until about 20 minutes after shadow exit. Other telemetry data have shown GPS satellites behavior that spans the spectrum from full yaw rate in one direction throughout shadow crossing, to reversing yaw rate direction during shadow, (o periodic freezing and yawing at various rates. in short, the attitude of the GPS satellites during shadow was observed to be essentially random and hence unmodelable.

THE PROBLEM

An analysis of the Attitude Control System (ACS) on the Block II GPS satellite reveals the reason for the random behavior during shadow. 'l'he ACS determines the yaw attitude of the satellite by using a pair of solar sensors set on the solar panels. As long as the Sun is visible, the signal from the solar sensors is a true representation of the yaw error. During shadow, in the absence of the Sun, the output from the sensors is essentially zero and the ACS is driven in an open loop mode by the noise in the system. It turns out that even a small amount of noise can be enough to trigger a yaw maneuver at maximum rate.

The randomness of the yaw attitude of GPS satellites during shadow reduces the quality of a high precision navigation solution since it implies two major modeling errors - dynamic anti kinematic. Dynamically, the solar pressure and beat radiation forces on the satellite are mismodeled, both in magnitude and direction, since they depend strongly on the satellite's attitude. Indeed, the stronger solar pressure force is active only outside shadow but then, for as long as 30 minutes, the satellite is maneuvering to regain its nominal attitude in an unmodelable way (since we don't know its attitude upon shadow exit). Kinematically, the mismodeling of the radiometric measurement is two-fold. Because the GPS satellite's antenna phase center is about 20 cm off the satellite's rotation axis its mismodeling can give rise to a ranging error of up to 10 cm for some receivers (see Figure 7). The other kinematic effect is the mismodeling of the wind-up effect, The phase wind-up is a little-known but important element in the modeling of the radiometric measurement. It relates to the relative orientation of a transmitter-receiver pair. In a nutshell, since the GPS signal is right-hand-circularly-polarized, any rotation of the transmitter will be interpreted by a phase-tracking receiver as a phase change. Thus, without proper modeling a change in range will be concluded. Errors of this nature are proportional to the carrier wave length and the number of unmodeled rotations of the transmitter. For a more detailed description of the wind-up effect refer to Wu et. al. (1 993). Luckily, this wind-up mismodeling cancels out when double differencing is performed since two receivers observing the same GPS satellite wiii sense the same phase shift upon rotation of the satellite. It is mainly the phase-center mismodeling that is manifested in Figure 3. But it is the combination of the dynamic and kinematic mismodeling that is responsible for the overall reduction in solution quality.

The mismodeling during the shadow crossing and recovery period is most damaging for precise orbit determination because it can last up to 90 minutes - more than 10% of the orbit period, Another common mismodeling, although less severe, is taking place at the other side of the orbit, during the "noon turn". Most models do not realize the

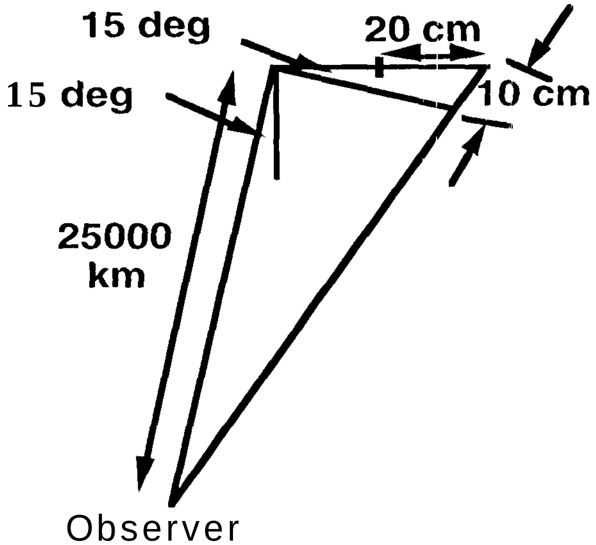

Figure 7. 10 cm range error can be observed by a receiver 15° off the transmitter boresight (e.g. Topex) as a result of a 40 cm lateral error in modeling the transmitter phase center.

physical limit on the satellite's yaw rate and yaw the satellite at the arbitrarily high rates that are required to keep its nominal orientation. In reality the satellite reaches its yaw rate-litnit about 5° from orbit noon. This will extend the duration of the noon turn for up to 30 minutes. Naturally, this problem appears only for beta (prime) angles smaller than 5° and it grows in significance as the beta angle approaches zero. (The beta angle is defined as 90° minus the angle between the s/c angular momentum vector and the Sun-Earth line.)

THE REMEDY

To make the yaw attitude of the G1'S satellites modelable, it was suggested by J, Anselmi that the ACS be biased by a small but fixed amount. The ACS has provisions to allow such a bias. Biasing the ACS means that the Sun sensor's signal is superposed with another signal (the bias) equivalent to an observed yaw error of 0.5° (the smallest bias possible). As a result, during periods when the Sun is observed, the satellite yaw attitude will be about 0.5° in error with respect to the nominal orientation - a negligible error. During shadow, this bias dominates the open loop noise and will yaw tbc satellite at full rate in a known direction. Upon shadow exit, the yaw attitude of the satellite can then be calculated and the Sun recovery maneuver upon shadow exit can also be modeled.

The US Air Force implemented this suggestion on June 6, 1994. It went into effect on all Block 11 satellites (except for **SVNS 14,** 18 and 20). It also turned out that three satellites (SVNs 13, 23 and 2.4) have already bad 0.5° yaw bias for unrelated reasons, The sign of the bias is changed by ground command twice a year such that it is opposite the sign of the satellite's beta

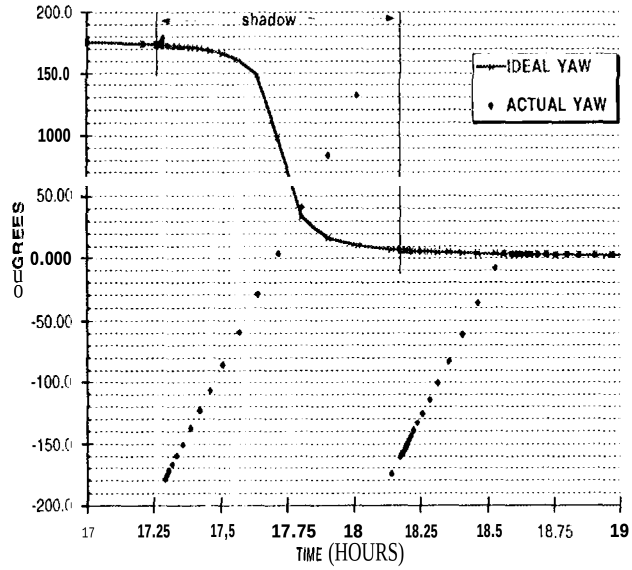

Figure 8. Ideal (nominal) yaw attitude vs. actual yaw. No ya-w reversal upon shadow exit

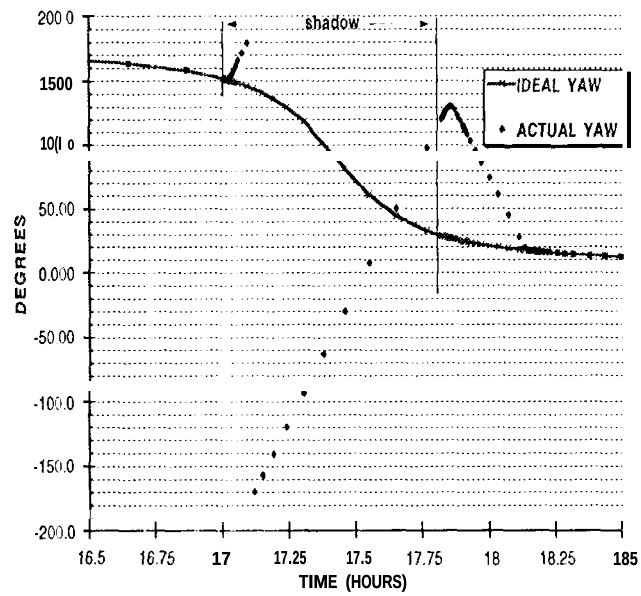

Figure 9. Ideal (nominal) yaw attitude vs. actual yaw. Yaw reversal upon shadow exit.

(prime) angle. This was found to shorten the Sun recovery time upon shadow exit.

NEW YAW-ATTITUDE BEHAVIOR AND MODELS

A satellite with a biased ACS behaves as follows. Upon shadow entry it reverses it natural yaw direction (because of the sign of the bias) and spins up to its maximal yaw rate. Upon shadow exit the satellite performs the optimal maneuver necessary to recover its nominal orientation. This means that it either maintains its spin rate (Figure 8) or reverses its spin rate (Figure 9), whichever is quicker to achieve its nominal attitude. This behavior can be easily modeled.

We have developed two models for the yaw attitude. of a GPS satellite. One is crude and fast and tbc other one is more precise but rather slow. The results in this paper where obtained using the precise model but all indications are that the crude model is sufficiently accurate.

The crude model has two parameters: the maximal yaw rate of the satellite and tbc maximal yaw rate rate, that is, the spin-up rate. The logic is as follows. Upon shadow entry the satellite reverses its yaw and spins-up as fast as possible subject to the constraining parameters above. Outside shadow the satellite yaws to minimize the difference between the actual yaw angle and the nominal (desired) yaw angle as fast as possible, subject to the constraining parameters above. This model is implemented as a finite difference scheme where the yaw rate and yaw-rate rate are represented by backward differences. The scheme is very stable and there are no practical limits on the step size. This model is accurate enough for representing the satellite's yaw attitude during shadow crossing but it is less accurate outside shadow and especially around the noon turn because the yaw bias is not present in this model explicitly. (A fixed yaw bias causes a varying yaw error depending on the relative geometry of the Sun, the satellite and the satellite's orbit. The actual yaw error will grow as the satellite. approaches the noon turn).

To handle accurately the yaw attitude outside shadow, the noon turn in particular, as well as inside shadow, we developed a model that is a simulation of the satellite's ACS. A block diagram of the model is shown in Figure 10. To maintain numerical stability this model requires a small step size.

The implementation of both these models as FORTRAN subroutines, as well as a host of other utilities to deal with the yaw attitude of GPS satellites are available to the public. They reside in directory pub/GPS_yaw_attitude on internet node 128.149.70.41 where they arc accessible through anonymous FTP.

One problem remains though. It turns out that no set of rate parameters fits all satellites. Furthermore, the value of the. maximal yaw rate can change for a given satellite from one shadow crossing to tbc next and from shadow crossing to noon turn. The reason for that is that the angular momentum stored in the reaction wheels upon shadow entry or at any other point in time cannot be predicted with sufficient accuracy. It depends on the instantaneous moments applied on the satellite as well as their history and is also dependent on momentum dumping that is taking place occasionally. Also, every satellite has a different yaw moment of inertia which changes slowly in time as the mass properties of the satellite change. Unavoidable errors in modeling the yaw attitude and the shadow boundaries contribute additional uncertainty. As a result, for precise applications, there is a need to estimate the maximal yaw rate for each shadow event and for each noon turn. Indeed, variations of up to 30% were observed

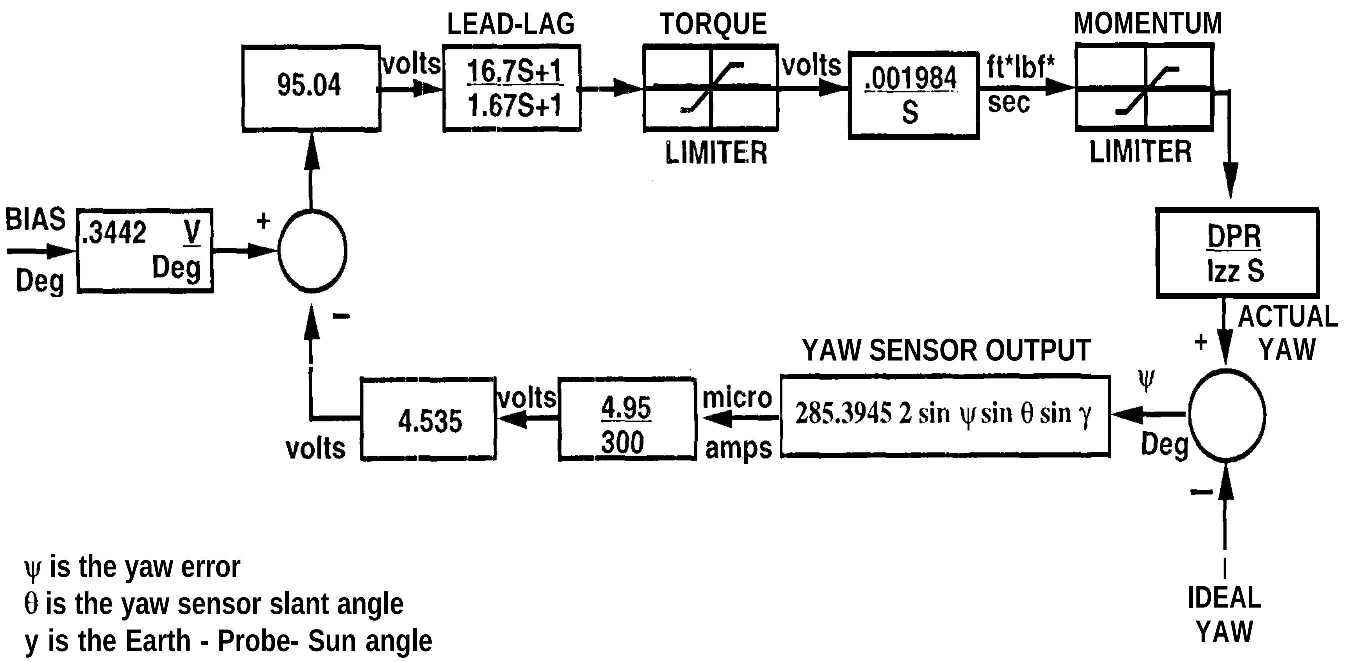

Figure 10. Block diagram of the precise yaw attitude model which is a simulation of the on-board system. Izz is the yaw moment of inertia of the relevant satellite.

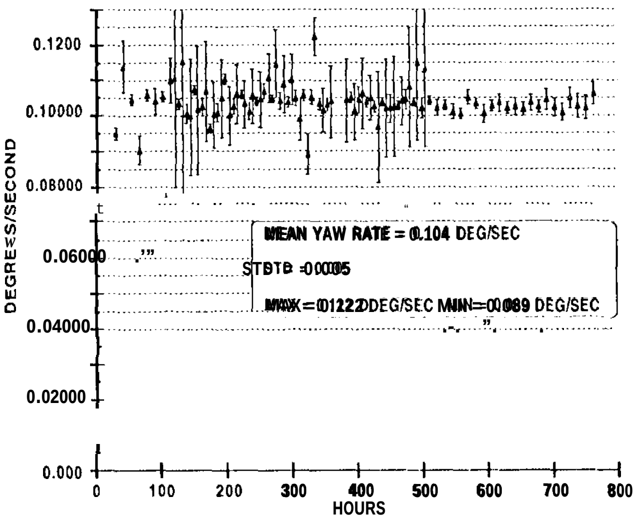

Figure 11. Estimated yaw rates together with their formal errors for **SVN** 37 during October 1994, The points with the large error bars correspond to noon turns. maximal yaw rate during noon turns is achieved and solved-for only for about 15 clays when tbc beta angle is less than 5°.

in the estimated values of the maximal yaw rate (Figure 11). This estimation requires high quality data in sufficient quantity. If this is not available then the following numbers should be used: for Block 11 satellites - 0.1 I 3 degrees/second, for Block 11A satellites - 0.103 degrees/seconci.

The estimation problem is further complicated by the apparent non-linear dependence of the. satellite's attitude on the yaw rate, There is always a yaw rate value such that if the satellite yaws faster, a yaw rate reversal will occur upon shadow exit and if the satellite yaws slower a yaw rate reversal will not occur. In the vicinity of such a value a small estimation error will result in large modeling errors. One way to overcome this problem is to reject data from shadow exit until 30 minutes thereafter - the ambiguous period. Other techniques exist, like iterating on the solution or preprocessing the data to determine the direction of the yaw rate after shadow exit.

RESULTS

At this point in time the new attitude model can be applied only toward correcting the kinematic mismodeling. To correct the dynamic mismodeling, the new model has to be coupled with a new solar pressure model, one which allows non-nominal spacecraft orientation. This is currently under development. The following results were obtained with the attitude model used only to improve the kinematic modeling of the radiometric measurements. The dynamic part still contains a modeling error.

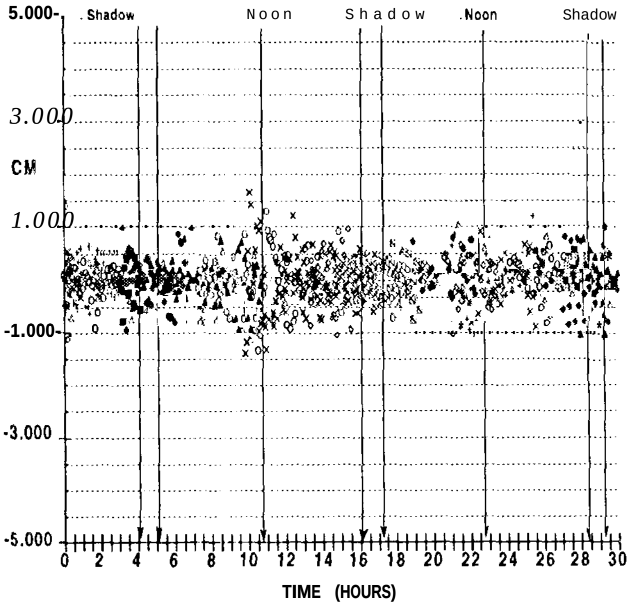

Figure 12. Post-fit residuals of the eclipsing GPS 24 with all observing receivers. New yaw attitude model is on and yaw rates are solved-for. July 12, 1993.

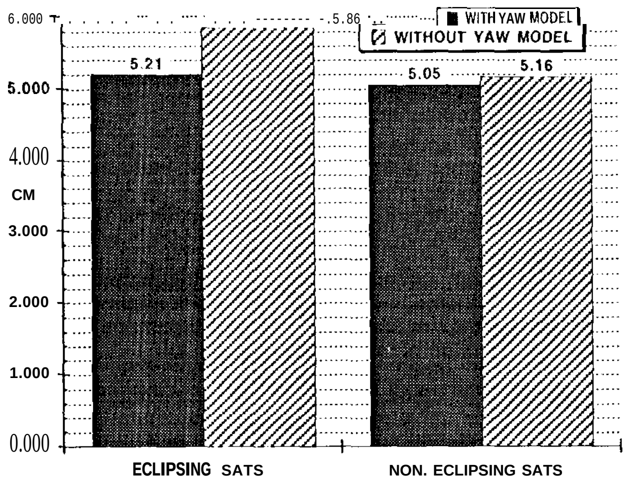

Figure 13. Weekly averages of post-fit residuals. June 19 - 25, 1994.

It is not easy to demonstrate improvement in precise orbit determination as a result of the changes to the GPS ACS. The reason is that the two states of the system cannot exist simultaneously and thus cannot be directly compared. Still, confidence in the new system and the accompanying models can be built through a series of experiments focusing on long-term trends as well as on some special cases. One such special case is SVN 24. The ACS on this satellite was biased at least a year prior to June 6, 1994. Figure 3 demonstrates the consequences of ignoring the actual attitude of the satellite and

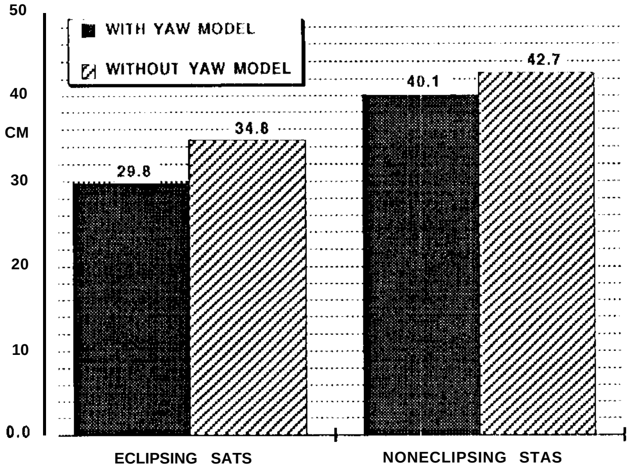

Figure 14. Weekly averages of GPS overlaps. June 19-25, 1994.

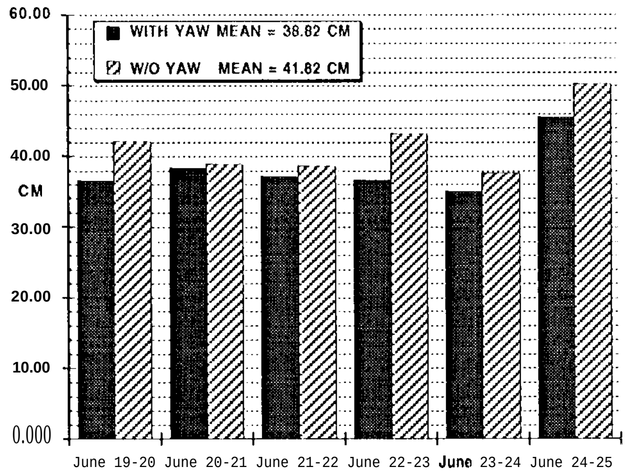

Figure 15. GPS daily overlaps with and without the new yaw model.

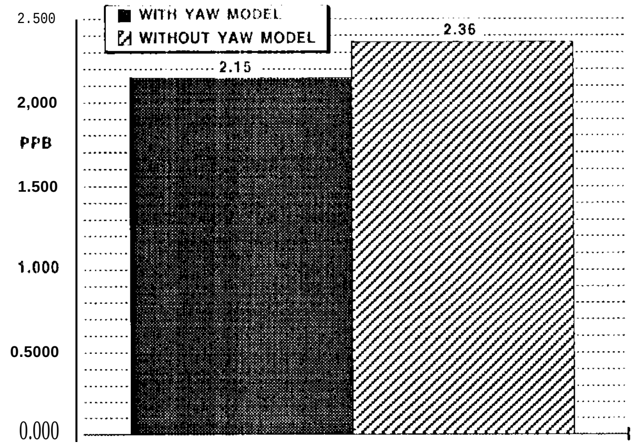

Figure 16. Baseline repeatabilities. In parts-per-billion. June 19-25, 1994.

(mis)modeling the midnight turn as though it takes place at "midnight". Once the new model is applied to this satellite, the post-fit residuals improve dramatically and the correlation between post-fit residuals and shadow events disappears (Figure 12). In addition to post-fit residuals, improvement was observed in just about every measure of solution quality - in this case, in the Topex orbit solution, ground stations solution, wet zenith delay etc.

Another experiment is to model the GPS constellation after June 6 1994 with and without the new attitude model and compare the results. Figures 13 - 16 detail the results of such an experiment, conducted over the week of June 19-25 with the JPL Flinn process (Zumberge & Bertiger 1995). During that week there were 4 satellites in eclipse.

Naturally, the solution accuracy of the eclipsing satellite improves more than that of the non-eclipsing satellite but, nevertheless, the improvement is universal. Improvements are observed every day of the week (Figure 15) and also in

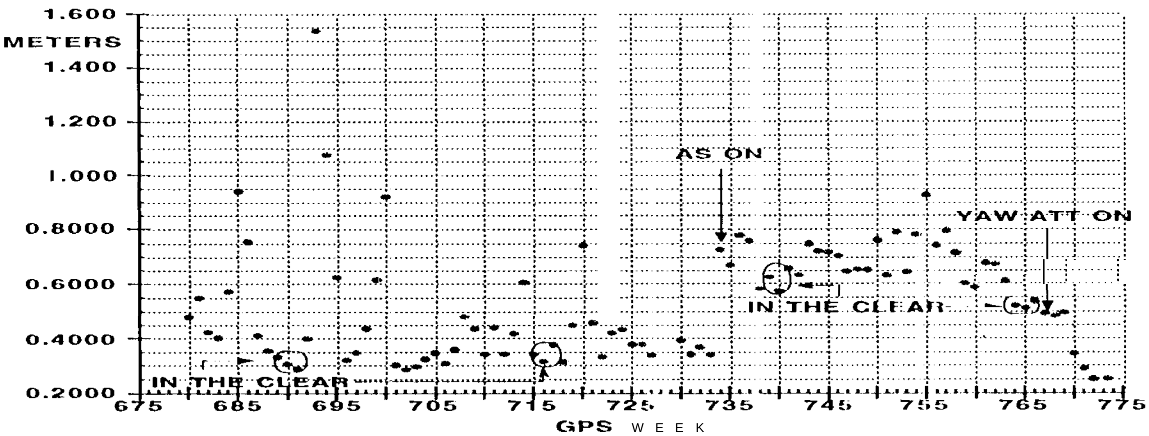

Figure 17. GPS weekly overlaps from the Flinn process, 1993-1994.

derivable qualities like baseline repeatabilities of the ground receivers (Figure 16).

Finally, we compare trends in solution quality before and after the biasing of the ACS. Figure 17 shows the weekly averages of the GPS overlaps in the JPL Flinn process over the last two years. Weeks in which no satellites were eclipsing are surrounded by small frames. Prior to June 6, 1994 (GPS week 752) those non-eclipsing weeks can be seen as a local minima (some unrelated improvements in solution strategy occasionally bring down the overlap to a

level of a non-eclipsing period). Scc also Figure 1, A clear exception is the last non-eclipsing period (GPS weeks 764 - 766). Immediately after it wc implemented the new attitude models and the trend of overlap degradation stops, as can be seen from the next 3 weeks (when another improvement to the Flinn solution strategy was implemented).

As a result of the success of the new attitude model the JPL Flinn process is routinely producing tables containing the solved-for yaw rate values for each eclipsing satellite and for each midnight and noon turn. These tables are publicly available, together with precise GPS orbits, on interact node sideshow (1 28. 149.70.41) under directory pub/jpligsac.

ACKNOWLEDGMENTS

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