PERFORMANCE 1VALUATION OF THE GPS YAW BIAS IMPLEMENTATION

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On June 6, 1994, the US Air force implemented a yaw bias on most GPS satellites. By January 1995 the implementation was extended to all Block 11 satellites. The yaw bias was introduced as a way to make the yaw attitude of the GPS satellites modelable during shadow crossings. A yaw attitude model was written to simulate the new satellite attitude during eclipse seasons. This model was made freely available to the GPS community. Proper utilization of the yaw attitude model significantly improves the overall accuracy of precise positioning with GPS. Failure to account for the new attitude model could result in large positioning errors due to the mismodeling of the antenna phase center of the GPS satellite and of the carrier phase wind-up. After 6 months experience with the biased constellation a new yaw attitude model was written that is more efficient and accurate than the first model.

In this paper we discuss the implementation of the new attitude model in JPL's IGS process which produces daily GPS orbits of the highest quality . The design of the new model will be outlined, as well as guidelines for its implementation in POD schemes. The experience gained after a year of operations with the yaw-biased GPS constellation will be analyzed to evaluate the performance of (he attitude models and assess optimal estimation strategies based on the observed variability of the relevant parameters. Finally, we will discuss operational aspects of implementing the new model.

INTRODUCTION

On June 6, 1994, the US Air Force implemented a yaw bias on most GPS satellites. By January 1995 the implementation was extended to all the satellites except SVN 10. The yaw bias was introduced as a way to make the yaw attitude of the GPS satellites modelable during shadow crossings (Bar-Sever et al., 1995). The yaw attitude of a biased GPS satellite during eclipse seasons is markedly different from the yaw attitude of a non-eclipsing satellite, or from that of an unbiased satellite. The yaw attitude of the GPS satellite has a profound effect on precise geodetic and space applications. This required the development of a special attitude model for biased GPS satellites. In addition to the yaw bias effects, that model also corrected other mismodeling that existed in the old model, namely, that of the “noon turn”.

The first attitude model written for the biased constellation, named GYM94 (for “GPS Yaw attitude Model - 94”), was made freely available to the GPS community in the form of a collection of FORTRAN routines (Bar-Sever, 1994). GYM94 was implemented in JPL's GIPSY software and, in various forms, in other high-precision geodetic packages. A second generation model, GYM95, replaced GYM94 in GIPSY in early 1995.

More than a year after the implementation of the yaw bias, it is time to evaluate the success of this endeavor and to review its operational aspects. This is not an easy task since the biased and the unbiased constellations do not exist side by side and cannot be compared directly. Some preliminary results have already indicated significant improvement in precise geodetic and space applications (Bar-Sever et al., 1995) but only now we possess enough data to have meaningful statistical comparisons between the performance of the biased and the unbiased constellations. Some of these statistical comparisons are reported in this paper. Also demonstrated here is the critical dependence of the yaw attitude model on the yaw rate parameter and the need either to estimate this parameter or to use a good a-priori value. This will lead us to a discussion of the operational aspects of the biased constellation and to propose a simplification of these operations.

THE NEW YAW ATTITUDE MODEL (GYM95)

The analysis that led to the implementation of the yaw bias on GPS satellites is described in Bar-Sever et al. (1995). A general description of the first yaw attitude model (GYM94) can also be found there. GYM94 computed the satellite yaw angle through numerical integration of a control law. Its output was a large file containing the yaw attitude history and, optionally, partial derivatives of the yaw attitude with respect to the yaw rate parameter. This file could later be interpolated to retrieve a yaw angle at the requested time. This process required relatively large amounts of computer memory and CPU time. In addition, the model's complex control law - a simulation of the on-board attitude determination algorithm did not allow much physical insight into the problem and was hard to tune. To overcome all these deficiencies the GYM95 model was created. GYM95 is simple enough to be described by a small set of formulas, allowing easy implementation in different computing environments. Its analytic nature, as opposed to the numerical nature of GYM94, allows queries at arbitrary time points with great savings in computer resources, Finally, it allows more flexibility in tuning and adapting it to the changing conditions of the GPS constellation.

The yaw attitude of a GPS satellite can be divided into four regimes: nominal attitude, shadow crossing, post-shadow maneuver and noon turn. Shadow crossing, together with the post-shadow maneuver comprise the "midnight turn". Most of the time (and for non-eclipsing satellites all the time) the satellite is in the nominal attitude regime. The post-shadow maneuver begins immediately after emerging from the Earth's shadow and lasts until the satellite has regained it nominal attitude. This phase can last from zero to 40 minutes. The noon turn maneuver does not occur until the beta angle goes below about 5° and can last between zero and 40 minutes. During each regime the satellite yaw attitude is given by a simple formula with the main parameters being the time of entry to the appropriate regime and the yaw rate. For example, during shadow crossing the yaw attitude, Ψ, is given by:

$$\Psi = \begin{cases} \Psi_i + \dot{\Psi}_i*(t - t_i) + 0.5*|RR|*SIGN(b)*(t - t_i)^2 & t < t_i + t_1 \\ \Psi_i + \dot{\Psi}_i*t_1 + 0.5*|RR|*SIGN(b)*t_1^2 + |R|*SIGN(b)*(t - t_i - t_1) & \text{Else} \end{cases}$$

where b is the yaw hips, R is the maximal yaw rate, RR is the yaw rate rate, Ψ_i is the yaw angle upon shadow entry, $\dot{\Psi}_i$ is the yaw rate upon shadow entry and t_i is the time of shadow entry. t_1 is the spin-up/down time and is given by:

$$t_1 = (|R|*SIGN(b) - \dot{\Psi}_i)/(|RR|*SIGN(b)).$$

This formula expresses the simple fact that during shadow crossing the satellite is yawing at the maximum rate, R. It also takes into account the transition period, t_1, from nominal yaw just before shadow entry to maximal yaw. This transition depends on the sign of the yaw bias and on the maximal yaw rate rate, RR. As discussed below, the Air Force is maintaining the yaw bias such that the sign of the bias is opposite to that of the orbit's beta angle. This requires changing the sign of the bias twice a year when the orbit's beta angle crosses zero. The effect of having the beta angle and the bias of opposite sign is to reverse the yaw direction of the satellite as soon as it crosses into shadow. The satellite, then, spins down and then spins up again in the other direction until it reaches its maximum yaw rate. It keeps yawing at that rate until it crosses into clear again and reaquires the Sun in its sensors. It then performs the quickest maneuver needed to resume nominal attitude. This may result in another yaw rate reversal. The satellite usually resumes nominal attitude within 30 minutes after shadow exit. Figures 1 and 2 illustrate the two types of yaw maneuvers of a conventionally biased satellite during shadow crossing. A satellite having a bias with the same sign as that of the beta angle will spin up as 'it enters into shadow instead of reversing its sense of rotation.

THE YAW RATE PARAMETER

The central parameter in the GPS yaw attitude model is the satellite maximal yaw rate (Bar-Sever et al., 1995), 10% Error in the yaw rate value will lead to a significant 35° error in yaw attitude during long shadow events. In order to minimize yaw rate errors they are being routinely estimated at JPL for each satellite and for each shadow event. The estimated yaw rate is treated as a piece-wise constant parameter for each satellite, The parameter value is allowed to change twice per revolution, mid-way between noon and midnight. Since a small error in the yaw rate can cause a large yaw error over time and since our a-priori knowledge of the yaw rate is not sufficiently accurate, we found it necessary to iterate on the yaw rate value. JPL routinely publish the final estimates for the yaw rates. They are available as daily text file via anonymous ftp to 128.149.70.41, directory "pub/jpligsac". Due to a software bug, yaw rates prior to February 16, 1995, are not available. The yaw rates were observed to be, indeed, both satellite-dependent and time-dependent. Most users of the new yaw attitude model are currently not estimating the yaw rates and, instead, treat them as constants with three possible values that were supplied early on by JPL. These values are: 0.11 30/see for Block II satellites, O. 103°/sec for Block 11A satellites and 0,087 °/see for those Block 11 satellites with a reaction wheel failure (SVNS 14, 16, 18, 19 and 20). A review of the estimated midnight yaw rate values over the last six months (Figure 3) reveals that the three a-priori values need to be corrected, but the current behavior displayed by the estimated yaw rates preclude any constant value from being a good approximation over the whole eclipse season.

The most striking feature in Figure 3 is the discontinuity of the estimated yaw rates in the middle of eclipse season. This, as yet unexplained behavior, is exactly correlated with the time of the upload of a new yaw bias to the satellite attitude control system. This upload occurs twice per year at the middle of eclipse season for each satellite. Only SVNS 22, 25 and 29 do not seem to suffer from a yaw rate jump, but only SVNS 22 and 25 should be considered an exception, though, because SVN 29 does not undergo a bias switch.

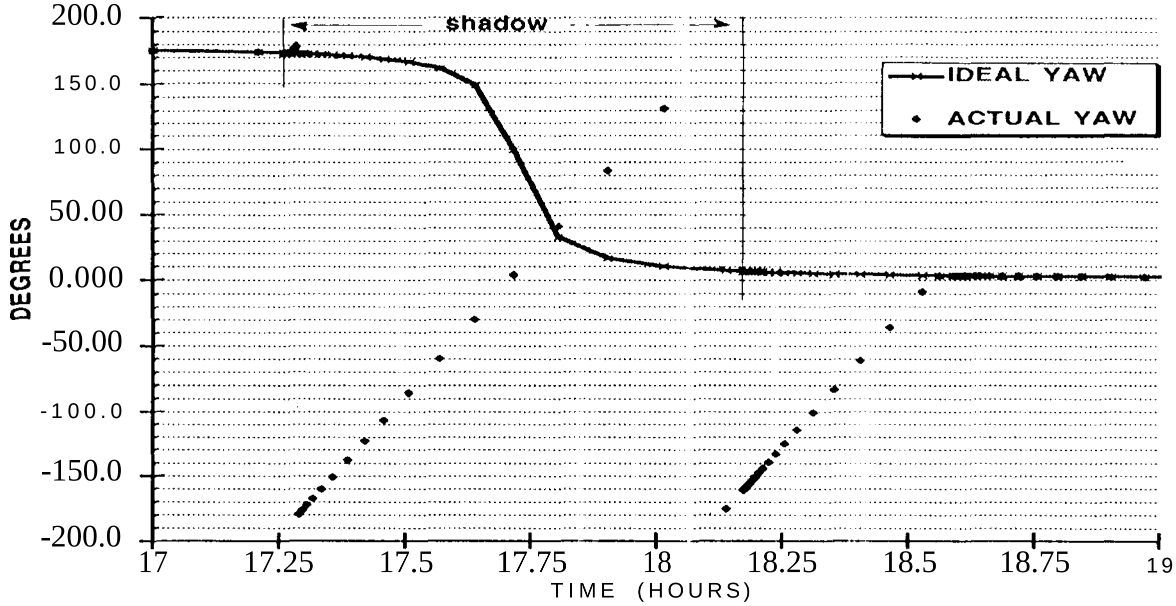

Figure 1. An illustration of a typical yaw maneuver during shadow crossing when no yaw rate reversal is needed upon shadow exit. The "ideal" yaw is what the satellite would have done if it could see the Sun and it is the way the old yaw attitude was modeled,

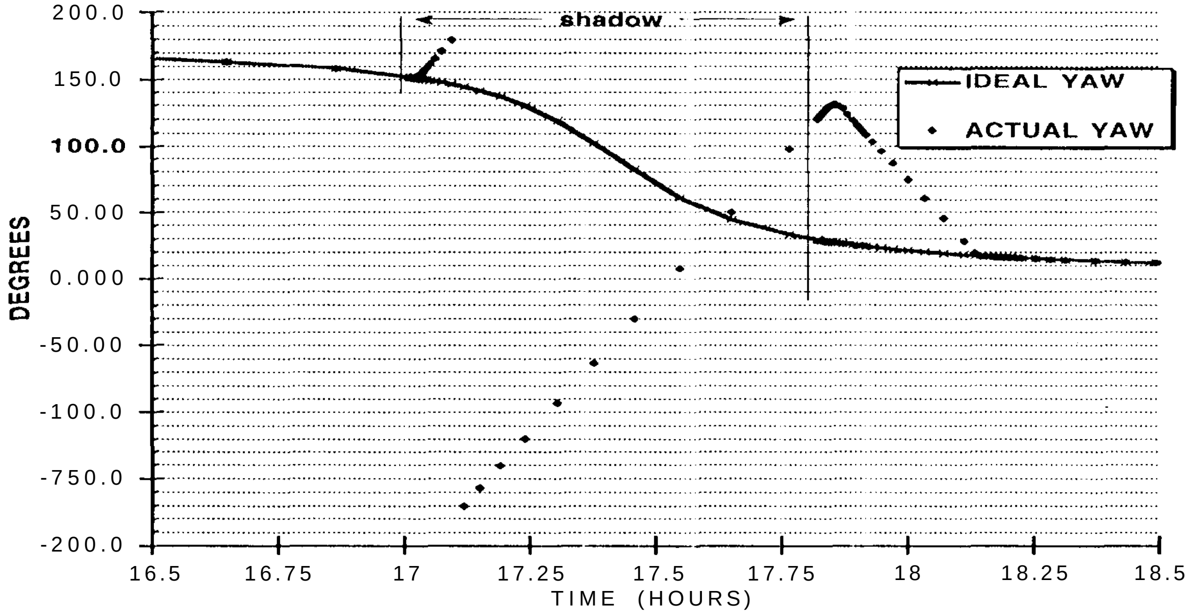

Figure 2. Same as Figure 1 but with yaw rate reversal upon shadow exit.

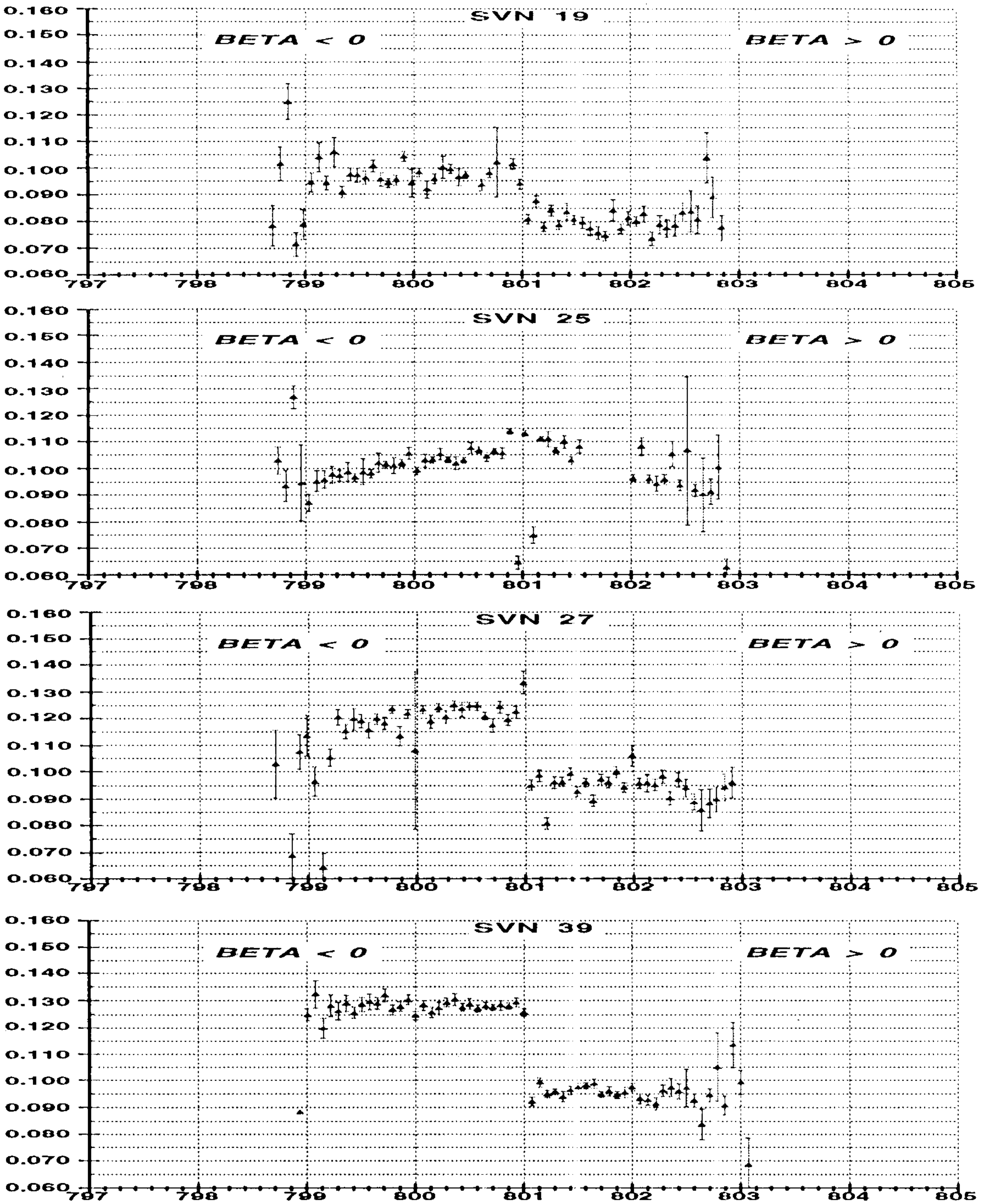

Figure 3a. Estimated midnight turn yaw rates for plane A satellites between March and August, 1995, along with their formal errors. The abscissa scale is in GPS week and the ordinate scale is in degrees/seconds.

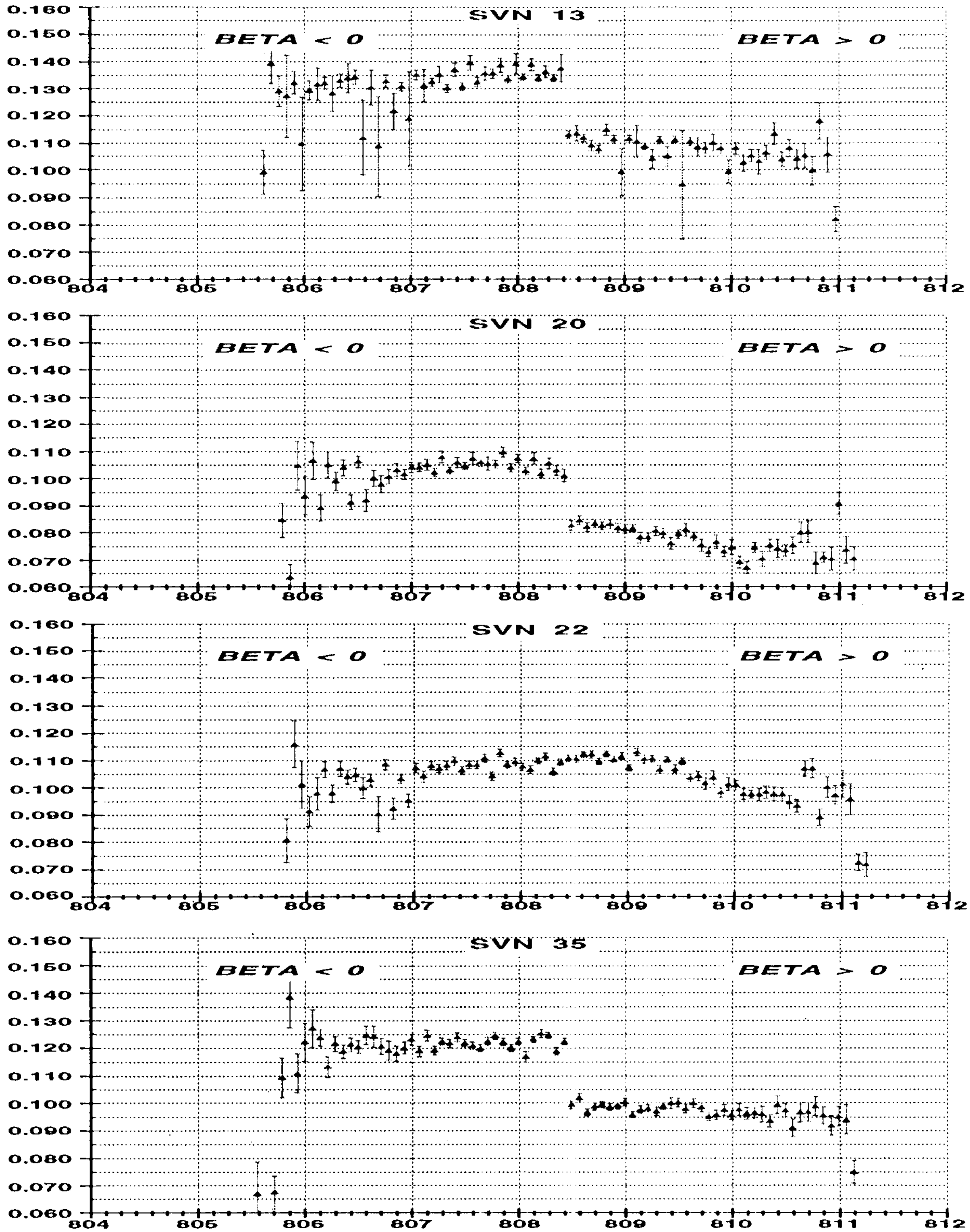

Figure 3b. Same as Figure 3a but for plane C satellites.

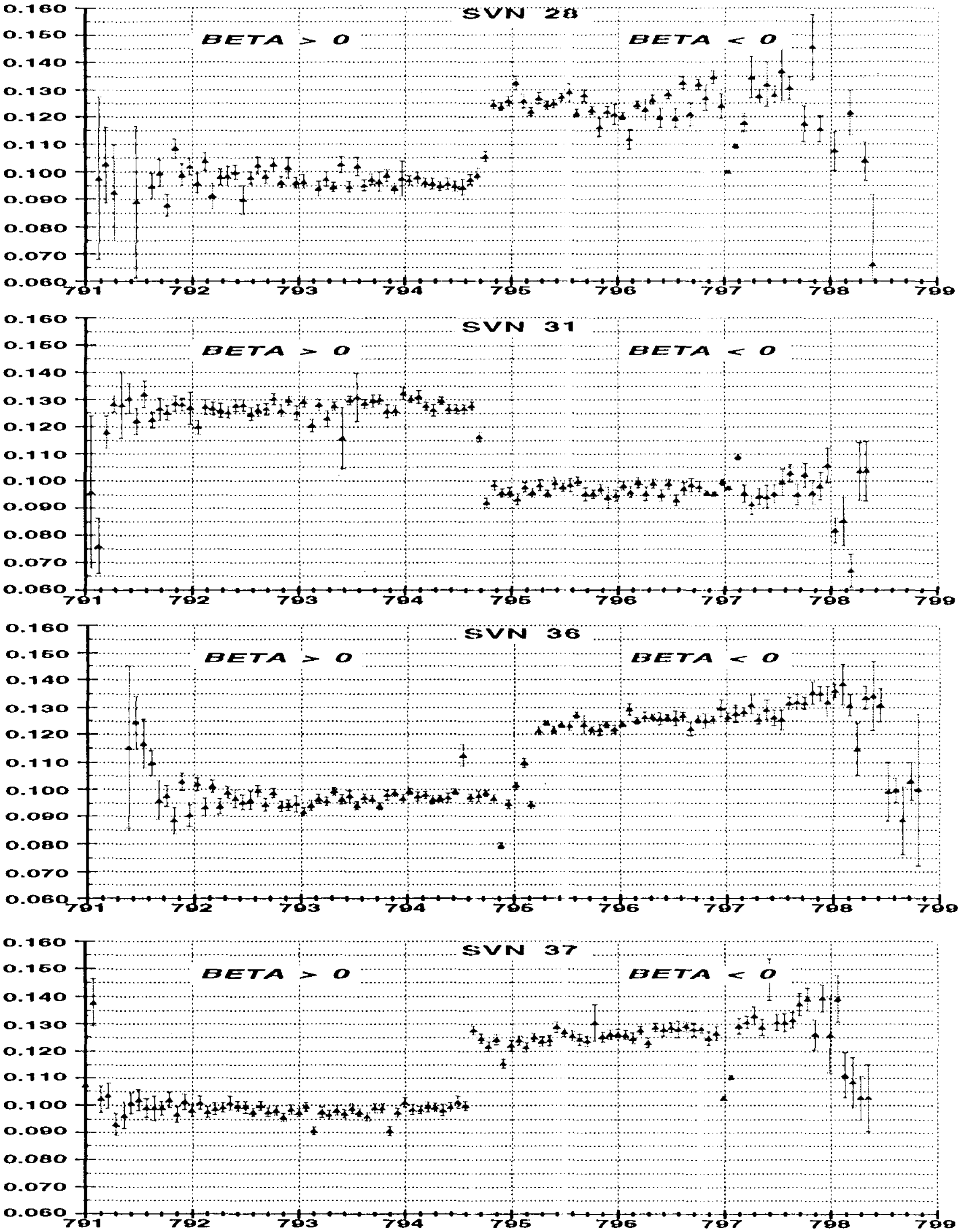

Figure 3c. Same as Figure 3a but for plane D satellites.

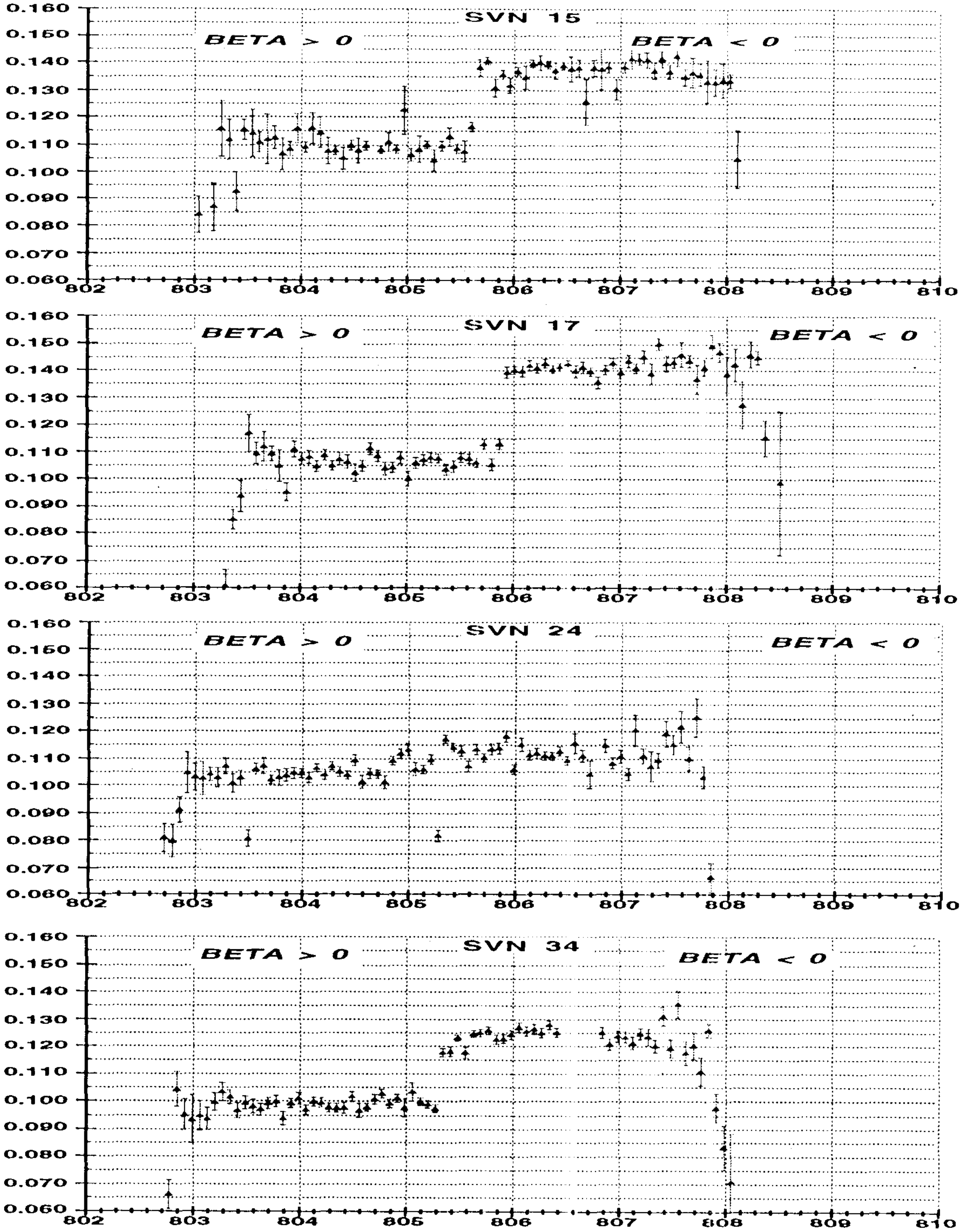

Figure 3d. Same as Figure 3a but for plane E satellites,

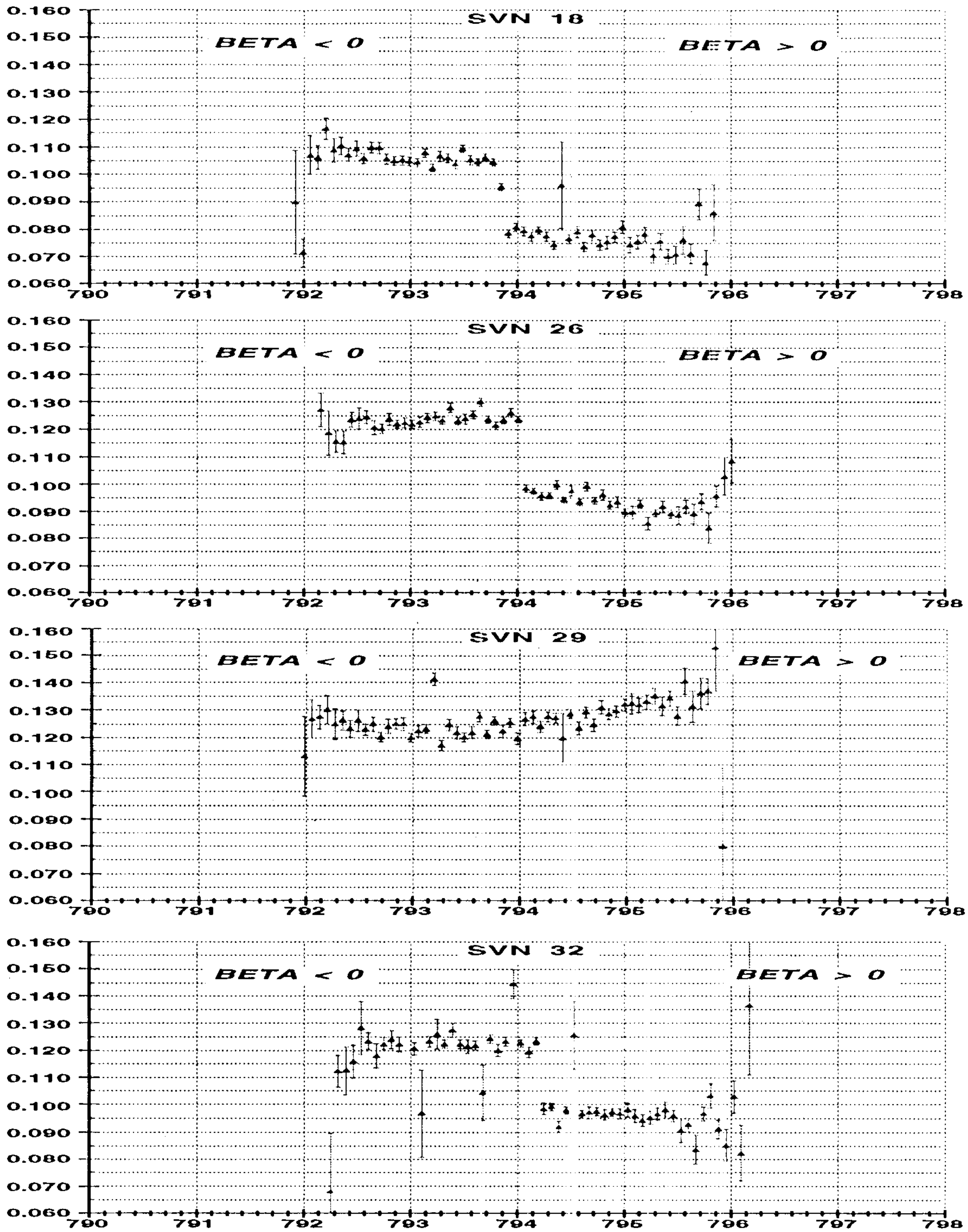

Figure 3e. Same as Figure 3a but for plane F satellites.

PERFORMANCE EVALUATION OF THE BIASED CONS'J'EI.LATION

Great care needs to be exercised when comparing the performance of the GPS prior to June 6, 1994- the unbiased constellation, to that of the current, biased, constellation, This is because there arc constant improvements in GPS data processing and it is hard to isolate the effects of the yaw bias on observed improvements in the quality of GPS-based products. Nevertheless, some judgment can be made as to the success of yaw-biasing the constellation by comparing carefully - selected statistics from before and after the yaw bias implementation.

One useful comparison is that of the post-fit residuals. This measure of solution quality is most sensitive to the quality of the modeling and to the number of degrees of freedom in the estimation scheme. The most important improvement in the IGS processing at JPL in the past year has been in the global distribution of the ground network. Assuming everything else is kept constant, this should have little effect on the post-fit residuals. But, we are not going to compare post-fit residuals from before and after the yaw bias implementation. What wc are going to compare is the ratio of post-fit residuals of eclipsing satellites to that of non-eclipsing satellites. Theoretically, the only difference between eclipsing and non-eclipsing sate] lites is in the modeling of their navigation signal. Figure 4 demonstrates that we are now doing a much better job in modeling eclipsing satellites than before the yaw bias was implemented. In fact, there is no evidence for any mismodeling of eclipsing satellites now.

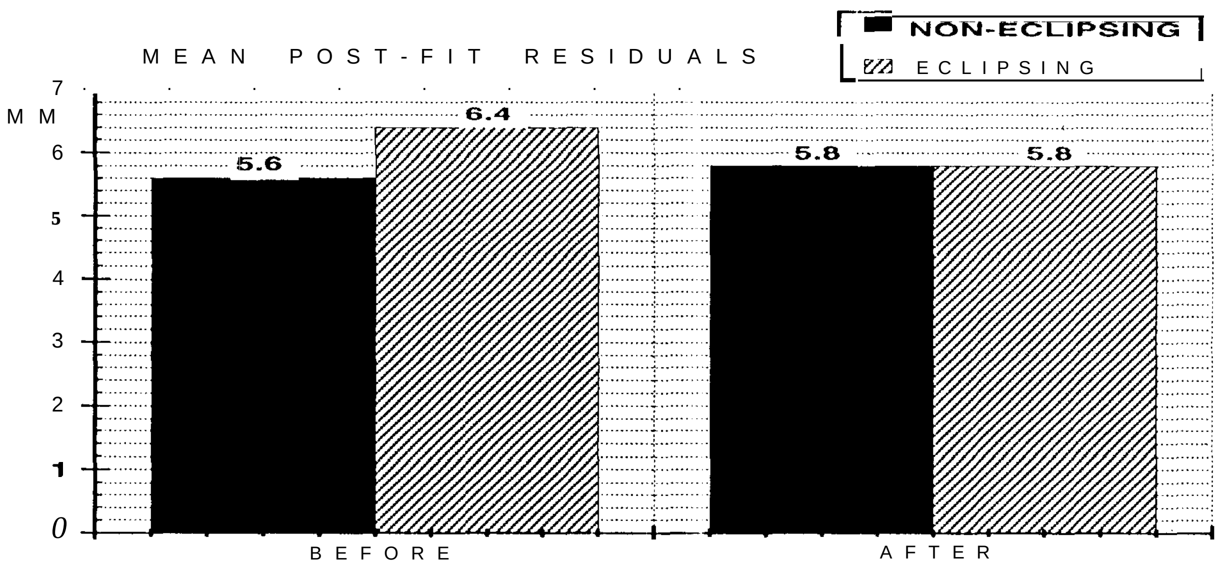

Figure 4. Comparison of post-fit residuals of eclipsing and non-eclipsing satellites, The "after" results are based on the JPL IGS products from June 18 to July 27, 1995 (Zumberge & Bertiger, 1995). The "before" results are based on reprocessing data from January 8 to February 27, 1994 with the current estimation technique, Roughly the same satellites are eclipsing in both periods,

It is not clear, though, how much of the additional data strength suggested by the improved level of post-fit residuals is going toward improving the actual products. The GPS orbits themselves are one such product. In fact, observations about GPS orbits were the motivation that led to the study of the yaw attitude problem and to the implementation of the yaw bias. A good measure for the quality of orbit solutions is overlap repeatabilities. JPL's daily solutions span 30 hours, centered on noon of each day, resulting in a six-hour overlap between consecutive days. The RMS difference between the two daily solutions during this overlap period is indicative of the quality of the orbit. Figure 5, from 1993, shows the mean of the orbit overlap of all GPS satellites as the constellation was in transition to a period when there are no eclipsing satellites. A consistent improvement in overlap repeatabilities during such a transition was typical before the bias was implemented, suggesting the existence of a problem in modeling eclipsing satellites.

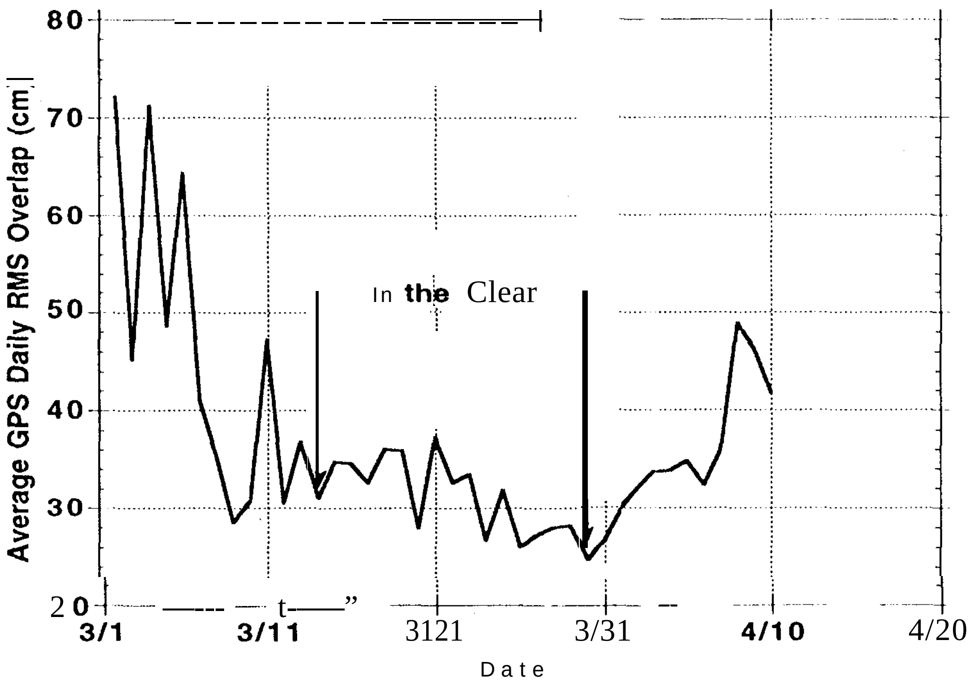

Figure 5 Mean daily overlap repeatability of all GPS satellites during March and April, 1993, when the GPS constellation transitioned in and out of a period when no satellites were eclipsing.

A long-term comparison of overlap repeatabilities clearly demonstrates that this pattern ceased to exist immediately after the implementation of the yaw bias. Figure 6 depicts weekly averages of overlap repeatabilities of all GPS satellites from January, 1994, to August, 1995. The GYM94 mode] was implemented in JPL's GIPSY software in September 1994 as the GPS constellation was emerging out of a period when all satellites were in the clear. It is evident from Figure 5 that from then on, periods when all satellites were in the clear are no longer local minima for the mean orbit repeatabilities, suggesting that the mismodeling of satellites during eclipse seasons no longer exist.

A more direct measure of the improvement to orbits of eclipsing satellites can be seen from Figure 7 which shows that after the yaw bias was implemented the quality of the orbits of eclipsing satellites is essentially the same as that of non-eclipsing satellites, in marked contrast to the situation before the implementation, where *eclipsing* orbit were 18% worse off than non-eclipsing satellites.

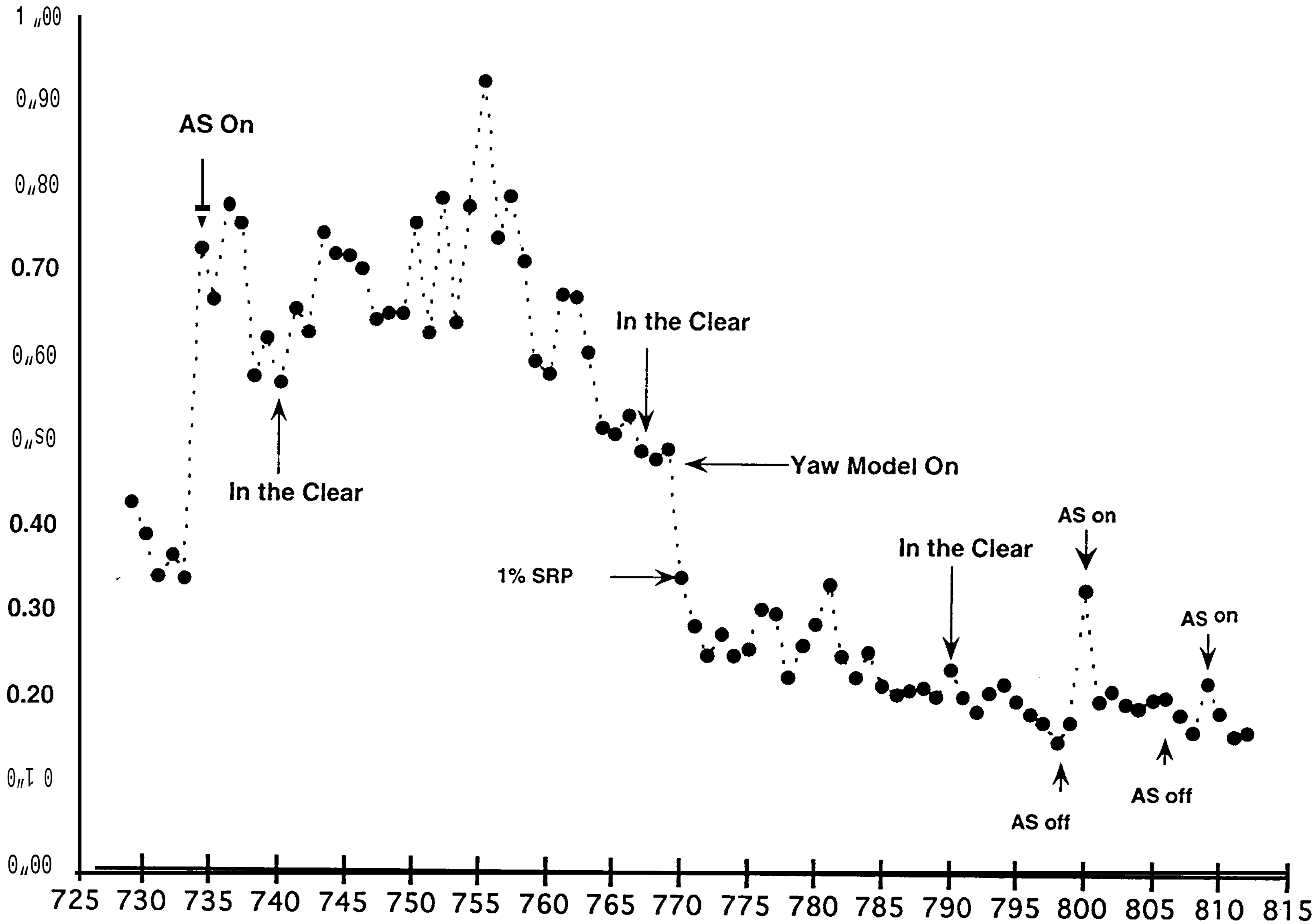

Figure 6. Weakly mean GPS orbit repeatablities of the JPL solutions for the IGS. The mean is taken over all satellites and over a full week. The yaw model was implemented at JPL on September 20, 1994 (GPS week 767). The abscissa scale is in GPS week. The ordinate scale is in meters. (From David Jefferson, JPLIGSAC)

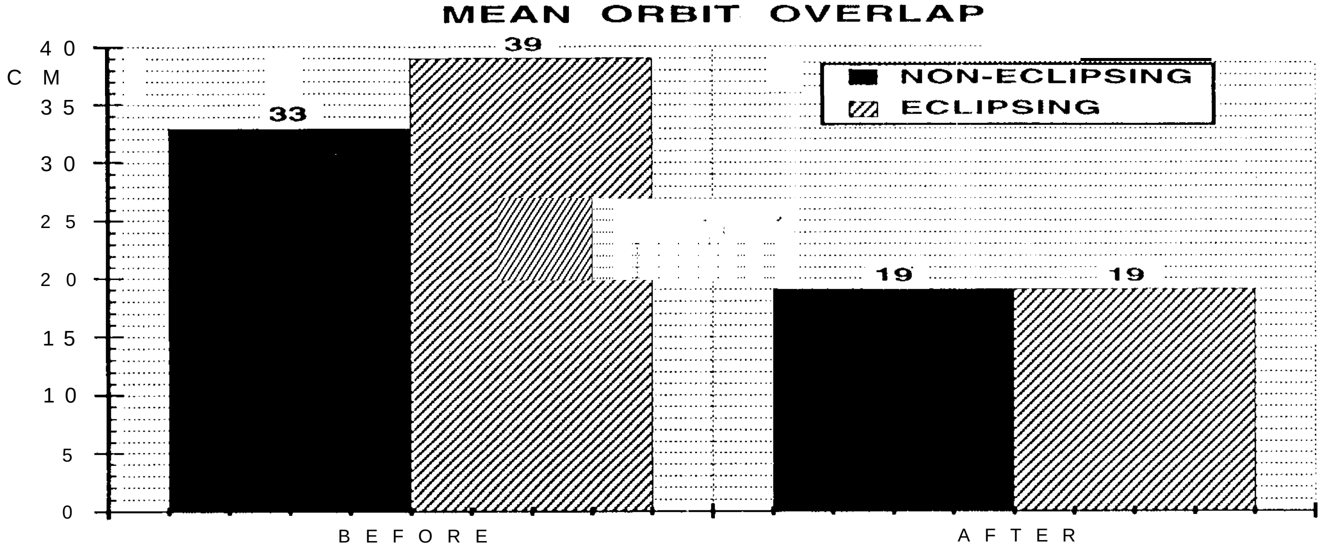

Figure 7. Comparison of orbit repeatabilities of eclipsing, and non-eclipsing satellites. The "after" results are based on the JPL IGS products from June 18 to July 27, 1995 (Zumberge & Bertiger, 1995). The "before" results are based on reprocessing data from January 8 to February 27, 1994 with the current estimation technique. Roughly the same satellites are eclipsing in both periods.

OPERATIONAL ASPECTS OF THE BIASED CONSTELLATION

Except for SVN 29, which suffers from a problem that precludes its yaw bias from being changed, The Air Force is maintaining the yaw bias on all satellites such that the sign of the bias is opposite the sign of the orbit's beta angle. This requires the upload of a new yaw bias twice a year for every satellite. This upload is done roughly when the orbit's beta angle crosses zero. As was demonstrated earlier, knowledge of the sign of the yaw bias is critical for proper modeling of the satellite attitude. Because of operational constraints the exact upload time is not known sufficiently in advance. This, and the lack of formal communications channel between the GPS operators and the GPS-user community causes delay in the dissemination of the bias switch timing information. As a result, the radiometric signal from the eclipsing satellites is often mismodeled during a few-day period around the time beta angle crosses zero (when the eclipse period is maximal).

The reason behind the yaw bias switching is to minimize the time it takes for the spacecraft to recover nominal attitude after shadow exit, As is shown bellow, keeping the sign of the yaw bias opposite to that of the beta angle does imply faster recovery of the nominal attitude on average - but only by a very small margin. Furthermore, it will be argued here that there are no clear benefits to bc gained from a quicker recovery of the nominal attitude.

A simulation was performed to asses the time needed to recover the nominal attitude after shadow exit. The recovery time is equal to the yaw error upon shadow exit, time the maximal yaw rate, after adjustment is made to account for possible reversing of the yaw rate direction and the resulting spin down and spin up time. The yaw error upon shadow exit was computed as a function of the shadow length, where account has been taken of the spin down and spin up time after shadow entry if the sign of the bias is opposite that of the beta angle. The recovery time was computed for a variety of realistic yaw rates and for all possible shadow duration. Two cases where compared: one with the yaw bias and beta angle having opposite signs (the current situation), and the second one is with the yaw bias and beta angle having the same sign. The difference in recovery time between these two cases is termed here "the recovery gain". The results of this comparison are presented in Figure 8. The recovery gain is seen to change during eclipse season and it attains both positive and negative values for every choice of the yaw rate. This suggests that the figure of merit should be the seasonal average of the recovery gains, These averages are presented in Table 1, below. It can be seen that under the most favorable conditions, that is, satellites with yaw rate of about 1.1 deg/see, the gain in recovery time is just 4.1 minutes. For the more commonly observed yaw rate values of 0.95 deg/sec and 1.3 deg/sec the gain is about 3 and 2 minutes, respectively. For the five slowly-spinning reaction-wheel "cripples" there is actually a negative gain of about two minutes. Note that if the yaw bias remains unchanged during the whole year then half the time it will have a sign opposite to that of the beta angle and, consequently, half the time the recovery rate will be optimal and averaging over a full year will yield recovery gains that are smaller than 2 minutes in the most extreme case.

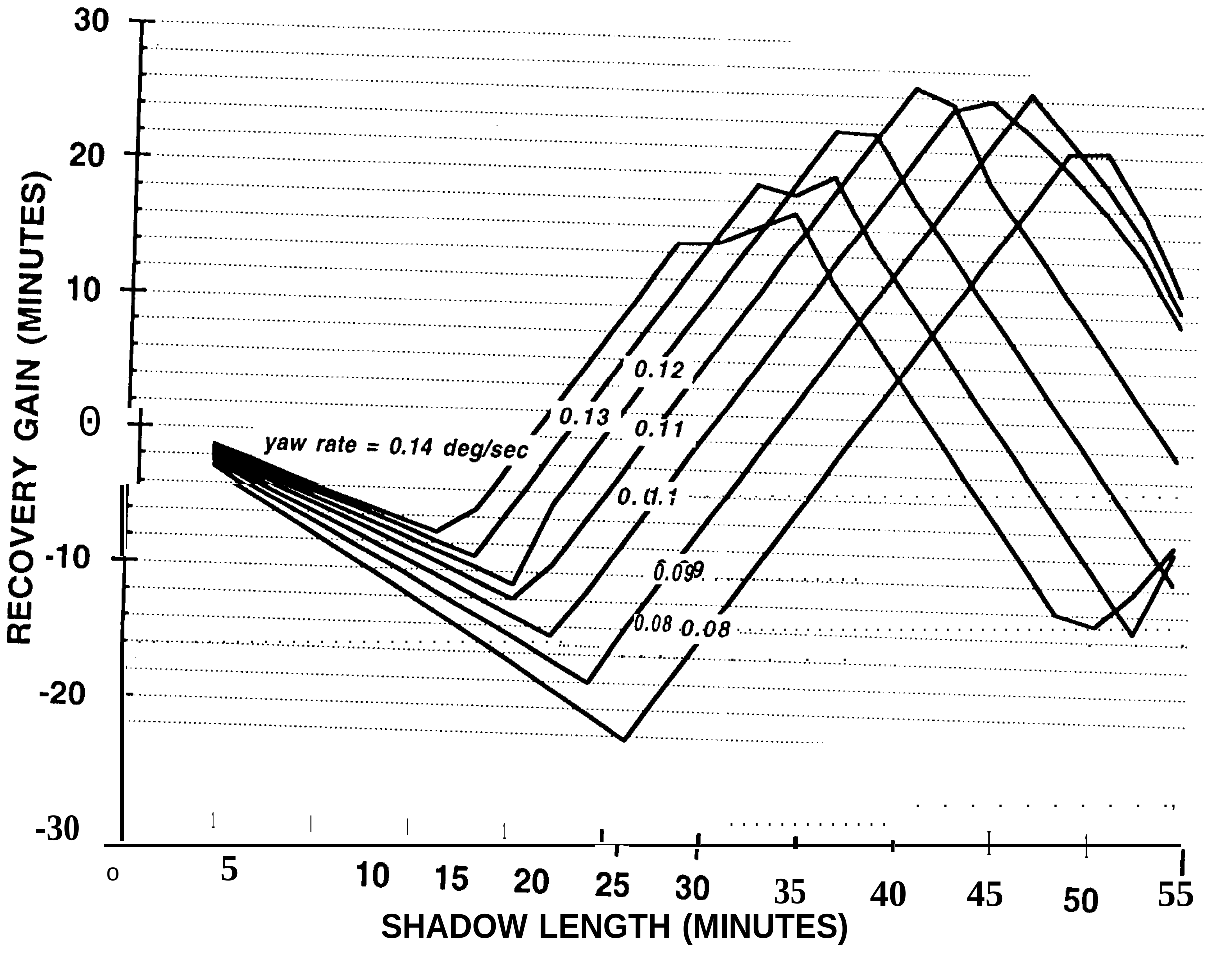

Figure 8. Given a positive beta angle, the recovery gain is the difference between the recover-y time with yaw bias equal to -0.5° and the recovery time with yaw bias equal to +0.5°. The recovery time is defined as the time from shadow exit until the nominal yaw attitude is recovered.

Table 1, Seasonal and yearly mean values of the recovery gains for seven realistic yaw rate values.

yaw rate (deg/see)	0.8	0.9	1.0	1.1	1.2	1.3	1.4
Average gain over half a year (rein)	-2,7	1.1	3.8	4.1	2.9	].7	0.5
Average gain over a year (rein)	-1.4	0.5	1.9	2,()	1.4	0.9	0.3

But recovering nominal attitude a bit sooner or later has really no effect on the functionality of the spacecraft. The only concern might be to avoid delay in the resumption of power supply from the solar panels, but this has no relation to the duration of the attitude recovery time. The reason is that the solar panels are never more than 28 degrees in error upon shadow exit and the average error is probably much smaller. This guarantees sufficient power supply immediately upon shadow exit. Since the array pitch rate is about 0.1 deg/see, optimal power supply will resume in less than 5 minutes, regardless of any yaw maneuver the satellite is undergoing. These facts are evident in Figure 9 which was constructed from SVN 24 telemetry during maximum eclipse - a worst case scenario. The pitch error is corrected within 5 minutes after shadow exit and full power supply is available 1 minute after shadow exit.

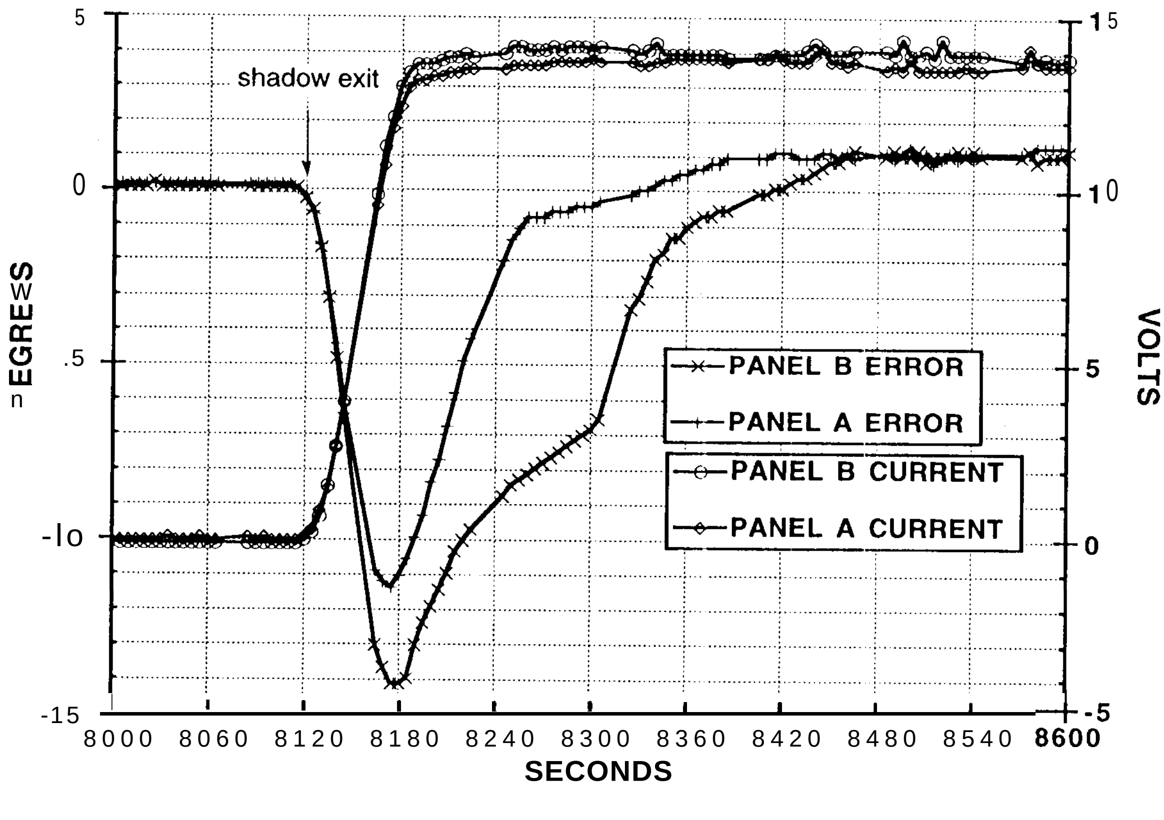

Figure 9. Solar panel pitch error (left ordinate) and current supply (right ordinate) immediately after shadow exit, during eclipse season in 1993, The origin of the abscissa scale is arbitrary. This satellite was yaw biased,

In conclusion, there seem to be no good reason for maintaining the current procedure of yaw bias switching twice a year. Instead, it is recommended that the yaw bias on all GPS satellites will be permanently set to +0.5 (the unchangeable value on SVN 29), JPL will continue to estimate and monitor the yaw rates of all GPS satellite in an effort to publish a set of values that will always be accurate enough to be used as a-priori for precise GPS applications,

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