

VARIOUS USES OF THE GPS OPERATIONAL CONTROL SYSTEM (OCS) TRACKING DATA

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ABSTRACT

The GPS Operational Control System (OCS) has five monitor stations located world-wide. These stations continuously track all satellites in view, and this raw tracking data is transmitted to the master control station at the Consolidated Space Operations Center (CSOC) for further real time processing. The data is stored on tape and is available for post processing as well. This paper discusses a variety of ways the tracking data can be analyzed to obtain useful information regarding Navstar satellite performance as well as the performance of the OCS itself. Satellite tracking by the monitor stations is quite complete, with continuous tracking of the P-code modulation of both the L1 and L2 carrier frequencies, as well as continuous phase tracking of the carriers themselves. This allows for post processing in a variety of ways depending on the physical effect the analyst is trying to unravel.

Carrier tracking is very precise with the tracking noise down in the region of a few millimeters. This low noise characteristic makes it possible to separate out the short term stability of the satellite's atomic frequency standard. Over the past years this has proven to be a most valuable use of the tracking data.

Another use of the tracking data is to study the characteristics of the ionosphere at the monitor station. From both pseudo range (PR) and accumulated delta range (ADR) at both carrier frequencies, the fine grain structure of the total electron count (TEC) as the satellite passes over the monitor station can be obtained.

The code tracking noise in making the PR measurements can be studied in some detail. One recent new approach to these studies allows us to separate multipath effects at the monitor stations from other noise sources.

The OCS combines all the tracking data over 15 minutes to obtain a single value of pseudo range. To accomplish this it uses a technique called "ionospherically corrected, ADR smoothed pseudo range." By post processing the raw tracking data, it is possible to perform an accuracy evaluation of this technique.

1. THE GPS SIGNAL STRUCTURE

The navigation signal from the Navstar/GPS satellites is transmitted on two L-band frequencies, 1575.42 MHz called L1 and 1227.6 MHz called L2. Both the L1 and L2 frequencies are bi-phase modulated by a very long, precise, pseudo random sequence (P code) at a rate of 10.23 MHz. Actually the L1 carrier frequency is quadrature modulated, since it is also modulated by a coarse/acquisition (C/A) pseudo random sequence. The C/A code on L1 will not be discussed in this paper since the OCS monitor stations use the P code almost all the time. Data at a rate of 50 bits per second is also superimposed on the

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P and C/A code modulations. The data does not play a direct role in tracking and therefore is not discussed in this paper.

A GPS receiver operates by simultaneously tracking both the carrier frequency and the P-code modulation of the carrier. Internal to any GPS receiver is a replication of both the carrier frequency and the P-code sequence of random 1's and 0's. By lining up the internally generated P code with that being transmitted from the satellite, the time when the receiver receives the GPS signal can be obtained by measuring the time offset of the aligned P code with respect to a clock in the receiver. From this time of arrival measurement and the known speed of light, a measure of the range from the satellite to the monitor station is obtained.

By means of a phase lock loop circuit in the receiver, the internally generated carrier frequency can be synchronized to the signal received from the satellite. By keeping count of the cycles of the internally generated carrier frequency, the motion of the satellite toward or away from the monitor station can be observed. A summation of the cycles produces a measurement of the integrated Doppler effect. This measure is also referred to as accumulated delta range. It should be noted that to determine a very precise measure of the change in range of the satellite during a pass over the monitor station, the carrier tracking must be absolutely continuous. There can be no cycle slip of the phase lock loop.

2. OCS MONITOR STATIONS

Each monitor station consists of eight channels so that, in principle, it has the capability of continuously tracking eight satellites simultaneously. The channels consist of 16 demodulators, 8 for tracking the L1 carrier frequency and 8 for tracking L2. In tracking a satellite, each channel provides four basic measurements at each measurement time. These measurements are pseudo range and accumulated delta range as measured on the L1 and L2 frequencies. The measurements are taken every 1.5 sec, thus an OCS monitor station collects a great deal of data. For example, during a 6-hour pass of a satellite there would be 14,400 sets of tracking data or a total of 57,600 measurements.

The pseudo range measurements are obtained by tracking the P-code modulation of the carrier. This modulation is at a chipping rate of about 98 nanoseconds, which corresponds to 29.3 meters. The quantization in tracking the code is 1/128 of a p-code chip, which corresponds to 0.23 meters. Typically the total 1 sigma noise in obtaining the pseudo range measurement is about 0.3 meters. This applies to pseudo range measurements obtained from both L1 and L2.

The accumulated delta range measurements (ADR) are obtained by tracking the carrier frequencies. Compared to pseudo range, ADR is much more precise. At the L1 frequency of 1575.42 MHz, the carrier wave length is only 19 cm. The quantization in the carrier tracking is 1/256 of a wave length which is less than 1 mm. Similar precision is obtained in tracking the L2 frequency of 1227.6 MHz, which corresponds to a wave length of 24 cm.

The pseudo range measurements are a measure of the absolute range from the monitor station to the satellite. The accumulated delta range measurements provide only a precise measure of the change in range to the satellite during a pass over the monitor station. By appropriately combining pseudo range and accumulated delta range, it is possible to have the best of both worlds. From pseudo range, we obtain absolute information and from accumulated data range, we have measurements of extremely high precision. Furthermore, by combining both types of measurements from the L1 and L2 carrier frequencies, we also can combine these measurements so as to have ionospheric delays removed from these composite measurements.

3. IONOSPHERICALLY CORRECTED PSEUDO-RANGE AND ACCUMULATED DELTA RANGE (ADR)

Two frequencies are used on GPS to provide measurements for automatically correcting for the ionospheric delay. The delay at each frequency can be obtained by noting the difference in the measured pseudo range at L1 and L2. The ionospheric delay at the L1 and L2 frequencies is given by the following equations:

$$\Delta PR1 = \frac{f_2^2}{f_1^2 - f_2^2} \quad (PR2 - PR1) = 1.545728 (PR2 - PR1) \quad (1)$$

$$\Delta PR2 = \frac{f_1^2}{f_1^2 - f_2^2} \quad (PR2 - PR1) = 2.545728 (PR2 - PR1) \quad (2)$$

PR1 and PR2 are the pseudo range at L1 and L2 respectively, and $\Delta PR1$ and $\Delta PR2$ are the ionospheric delay at these two carrier frequencies f_1 and f_2 . The ionosphericly corrected pseudo range PRC is obtained as a function of the two uncorrected pseudo range measurements as follows:

$$PRC = 2.545728 PR1 - 1.545728 PR2 \quad (3)$$

Similarly, the ionosphericly corrected accumulated delta range ADRC is obtained by combining the accumulated delta range measurements at L1 and L2 as follows:

$$ADRC = 2.545728 ADR1 - 1.545728 ADR2 \quad (4)$$

Utilization of the above relations to combine the two pseudo range measurements to obtain a single ionosphericly corrected pseudo range is done for each pair of pseudo range measurements taken every 1.5 seconds during a pass of the satellite over the monitor station. Likewise, all the pairs of accumulated delta range measurements are also combined for each of the measurement times during a satellite pass.

4. OBTAINING ADR SMOOTHED PSEUDO-RANGE

Over a 15-minute time interval, where the end points roughly correspond to the Kalman filter K points, a smooth representation of pseudo range is obtained during this time interval. This is obtained from a total of 600 pairs of

ionospherically corrected pseudo range and accumulated delta range. The procedure for obtaining ADR smoothed pseudo range is as follows:

For all 600 1.5 second data points the average value of all the pseudo range measurements is obtained. Likewise the average value of all the accumulated delta range measurements is also obtained. The difference of these average values is added to each and every accumulated delta range measurement. In this way the average of the ADR measurements is made to be the same as the average of the pseudo range measurements. Now the pseudo range measurements are much more noisy than accumulated delta range. However, when the average of 600 such measurements is obtained, the noise in the resultant average value will statistically be reduced by a factor of 24.5. Having adjusted the average value of accumulated delta range to match the average of the pseudo range measurements, we have obtained a very smooth representation of pseudo range in these adjusted ADR measurements. This way the best of both worlds has been obtained: an absolute value of range from the code tracking and a very low noise representation of this range by virtue of the high resolution inherent in tracking the carrier frequencies.

5. AN EXAMPLE OF OCS TRACKING DATA

To illustrate the various uses of the OCS raw tracking data, only one set of data has been selected for this purpose. This is from a pass of Navstar 3 over the Hawaii monitor station during August 2, 1985. The data is continuous over almost 6-1/2 hours and is representative of a better quality set of raw tracking data. There is a total of 15,528 1.5-second data points.

6. NOISE IN THE PSEUDO RANGE MEASUREMENTS

Successive pseudo range and accumulated delta range measurements change in a gradual systematic fashion, mainly because of satellite motion and earth rotation. To evaluate the short-term fluctuations in the data, it is necessary to remove these longer term systematic effects. A straightforward technique for accomplishing this is to fit, in a least squares sense, a polynomial function of time to the tracking data. The residuals of the tracking data to the polynomial fit are computed from the polynomial expression. These residuals represent the noise in the data and, for the pseudo range data, are generally similar to uncorrelated white noise and are not sensitive to the degree of the polynomial used in the fitting process. For this example, a 17th degree polynomial was used.

A plot of the residuals of the pseudo range data taken from L1 tracking is shown on Figure 1. The rms value of the noise is 0.403 meters. Likewise, the residuals from L2 tracking are shown on Figure 2 where the rms noise is 0.274 meters. To remove the ionosphere, the L1 and L2 pseudo ranges are combined as given in Equation (3). A plot of the residuals of this combined pseudo range data is shown on Figure 3, and the rms value of the noise is 1.10 meters.

As shown on Figures 1, 2 and 3, the noise in the L1 pseudo range data is somewhat greater than the L2 data, and the noise in the combined pseudo range data is much greater than either. This is because of the multiplicative factors in Equation (3) for combining the L1 and L2 pseudo range data.

7. NOISE IN THE ACCUMULATED DELTA RANGE DATA

Unlike pseudo range, there is very little noise in the carrier tracking of the GPS signal. In fact, almost all the noise observed in the accumulated delta range (ADR) data is really the short term variation in the atomic frequency standards, both the satellite and monitor station clocks. Using the same polynomial fitting technique that is done for the pseudo range data, the residuals for the ADR from tracking the L1 carrier are given on Figure 4 and from tracking L2 on Figure 5. Using Equation (4) to remove the effect of the ionosphere from the ADR data, the residuals for the combined ADR data are given on Figure 6.

As shown on Figures 4, 5 and 6, the residuals for the L1 and L2 ADR data, as well as the combined ADR data, are virtually identical. This is because almost all of the noise is contributed by the satellite and monitor station atomic clocks which have the same effect on L1 and L2 tracking. Overall, the ADR noise is an order of magnitude less than the noise in the pseudo range data. There is some structure in the ADR noise, whereas the pseudo range noise is almost entirely white noise.

The data on Figures 4, 5 or 6 allows one to determine the short-term stability of the combination of the Navstar 3/Hawaii monitor station pair of atomic clocks. The resulting Allan variance (or sigma-tau) plot is shown on Figure 7.

8. DIFFERENTIAL IONOSPHERIC DELAY

The GPS signal structure provides a unique means for studying the ionosphere. Taking the difference between pseudo range measurements at the L2 frequency and at L1 provides the differential ionospheric delay and is a direct measure of the total electron count between the satellite and monitor station. A plot of this difference is shown on Figure 8. Two difficulties are apparent upon examination of the data. Part of the plot indicates a negative differential delay between L2 and L1; this is quite impossible, L1 being at the higher frequency. There is clearly a bias between the L1 and L2 demodulators used for tracking Navstar 3 at the Hawaii monitor station. This bias is a matter of proper calibration of the monitor station receiver. It should be noted that the data used as the example in this paper was taken on August 2, 1985 at which time the OCS had been operating for a short time and calibration and other procedures had not been fully ironed out.

The second difficulty shown on Figure 8 is the pseudo range tracking noise which also shows up as the quantization of the L1 and L2 code tracking loops. At both carrier frequencies, this quantization is one 128th of a chip which, at the P-code modulation, is 29.3 meters; thus the quantization level is 0.23 meters. This noise and quantization can be eliminated by the use of the accumulated delta range data. Taking the difference of the L1 and L2 data, we again have a measure of the differential ionospheric delay, except for its absolute value. This is corrected by the following: The average of all the pseudo range differences is computed and, likewise, the average of all the accumulated delta range differences is also obtained. The difference of the two averages is added to the ADR difference data. In this way we obtain the best of both worlds, absolute ionospheric delay from the pseudo ranges (aside

from the calibration problem) and very fine grain detail from the ADRs. The results are shown on Figure 9. To further illustrate the fine grain nature of GPS carrier tracking, a blowup of Figure 9 between 100 and 200 minutes is shown on Figure 10. The spread of the data points shows that the carrier tracking noise is just a few millimeters.

9. ANOTHER METHOD FOR OBSERVING PSEUDO RANGE NOISE

Conceptually, the alternative method is to first subtract the accumulated delta range data from the corresponding pseudo range. All that remains in this difference are the pseudo range noise, twice the ionospheric delay (since the effect of the ionosphere is opposite in sign for code and carrier tracking) and an overall bias. The ionosphere is then removed by using the difference of L1 and L2 ADRs, scaled up to the appropriate level by the factors given in Equations (1) and (2). Using this approach, the expression for obtaining only the noise in the L1 pseudo range is given by:

$$PRN1 = PR1 - 4.091456 \times ADR1 + 3.091456 \times ADR2 \quad (5)$$

Likewise, the equation for the noise in the L2 pseudo range data is given by:

$$PRN2 = PR2 - 5.091456 \times ADR1 + 4.091456 \times ADR2 \quad (6)$$

Finally, the bias is removed by subtracting the average of all the data points as computed either from Equation (5) or (6), as the case may be. The results of this alternative method are shown on Figures 11 and 12. Note that these plots are quite similar to Figures 1 and 2.

10. IS IT MULTIPATH?

A matter of some concern has been the possible effect of multipath at the monitor stations. The initial part of the L2 pseudo range noise plot on Figure 12 is suggestive of some small effect as indicated by the oscillatory behavior of the noise. This is even more clearly illustrated on Figure 13 where a 40 point running average (1-minute average) of the data on Figure 12 is plotted. Whether or not this is multipath could be determined by plotting the data for successive days. If the oscillatory pattern repeats, that is a rather clear indication there is multipath. This has not been done for this example of raw tracking data since, in any case, the effect is negligibly small. In fact, studies of data from other monitor stations show that, while some small multipath effect probably does exist, the overall effect on GPS is not significant.

11. EVALUATING THE ACCURACY OF ADR SMOOTHED PSEUDO RANGE

As discussed previously, using Equations (3) and (4) to remove the ionosphere, all of the L1 and L2 pseudo range and accumulated delta range data can be combined into a single set of pseudo range and ADR data. To obtain ADR smoothed pseudo range every 15 minutes, take the first 15,000 data points, taken over 6-1/4 hours, and divide them into 25 groups of 600 points. For each group, the average of the differences between pseudo range and ADR are computed and added to the ADRs. The result is the ADR smoothed pseudo range.

Throughout the pass, the ADR measurements are completely contiguous. Ideally, except for a bias, pseudo range and ADR should track each other continuously, varying only because of the noise in the pseudo range measurements. Consequently, the 25 average differences should all be the same. Since, as has been shown, the rms combined pseudo range noise is about 1.10 meters, one might expect the noise in the 600 point average differences to be reduced by a factor of the square root of this number or down to about 0.045 meters. This of course assumes a pure white noise process. Not so.

If we now compute the overall average of the 25 average differences and subtract this overall average from the individual averages, the resulting residuals of the 25 average differences would be as shown on Table I. The standard deviation of these residuals is 0.24 meters, about five times what might be predicted based on white noise. It indicates that the actual uncertainty of the ADR smoothed pseudo range might be of the order of 1/4 meter, one sigma. This is still very good and well within the requirements of GPS.

12. SUMMARY

By fitting a polynomial function of time to the raw code tracking data, the noise in the pseudo range data can be determined.

Likewise, noise in the accumulated delta range data can also be determined. From this the short term stability of the satellite/monitor station atomic clocks can be obtained.

The ionospheric delay between the satellite and monitor station can be evaluated in fine detail because of the low noise in carrier tracking.

By appropriate combining of pseudo range and accumulated delta range, an alternate method for observing pseudo range noise is made available. Taking running averages of this noise data enhances the detection of possible multipath effects.

The use of "ADR smoothed, ionospherically corrected pseudo range," by the OCS can be evaluated by post processing of the raw tracking data.

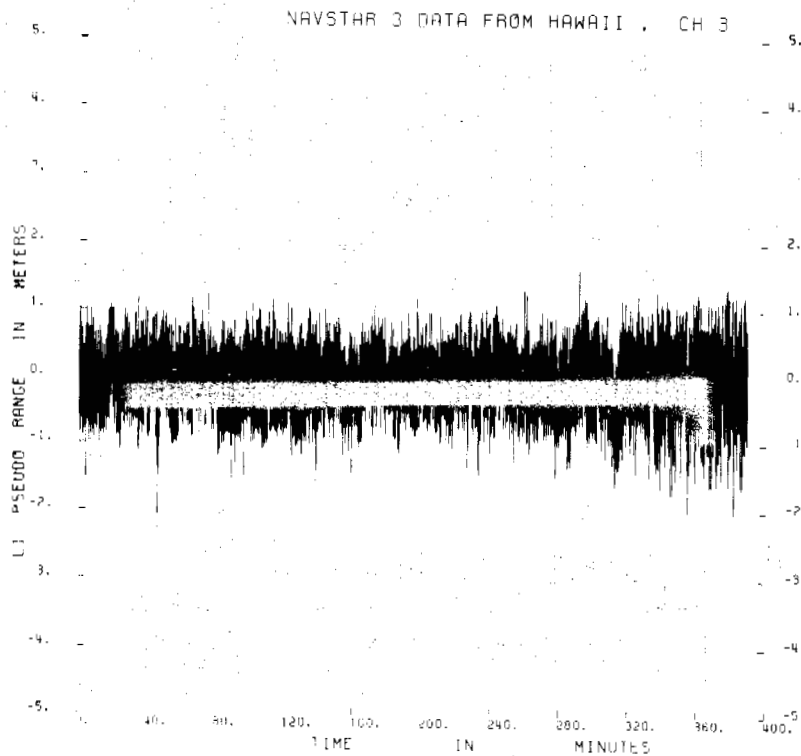


Figure 1. L1 Pseudo Range Residuals

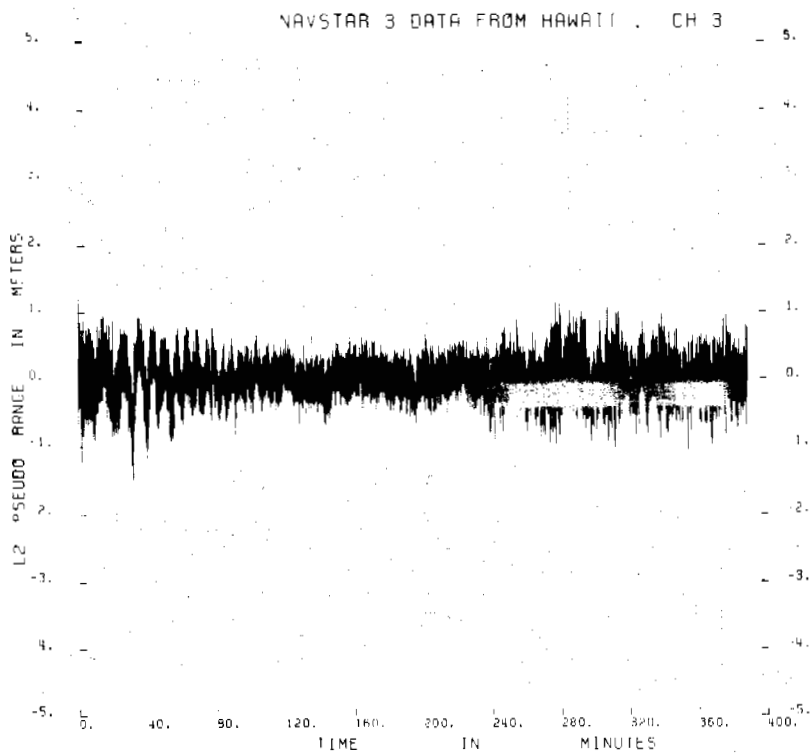


Figure 2. L2 Pseudo Range Residuals

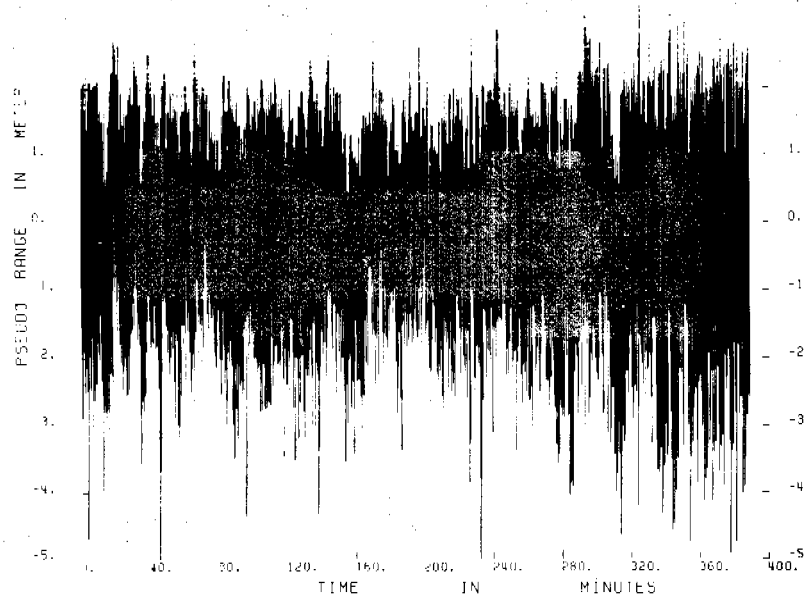


Figure 3. Combined Pseudo Range Residuals

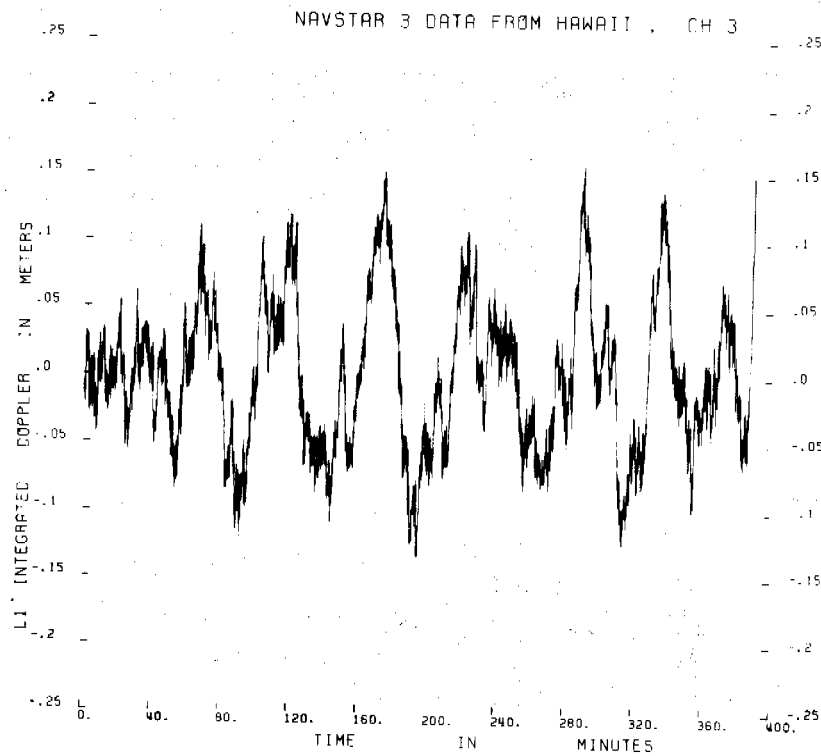


Figure 4. L1 Accumulated Delta Range Residuals

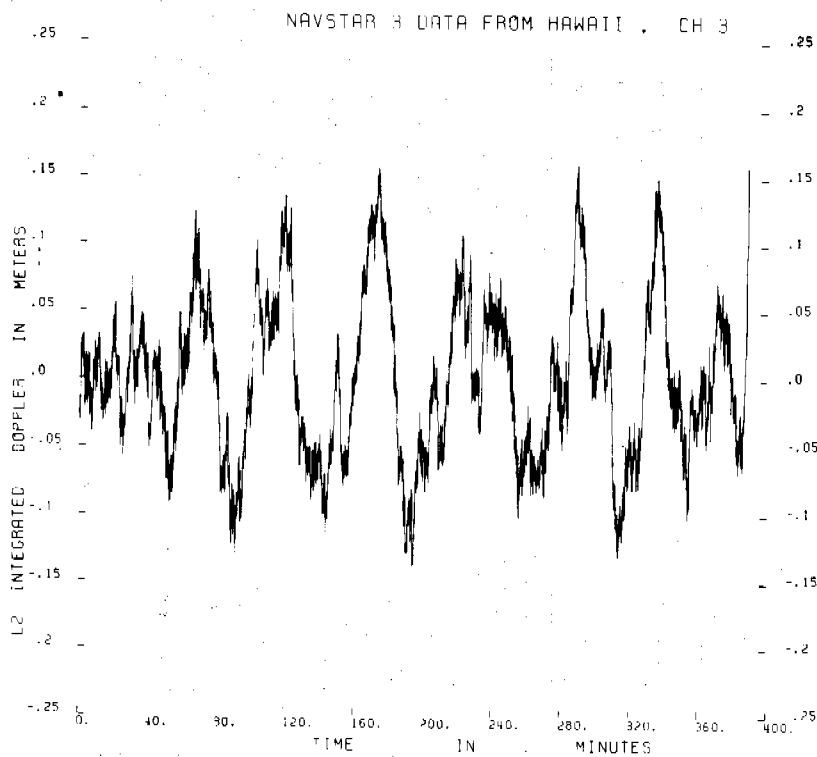


Figure 5. L2 Accumulated Delta Range Residuals

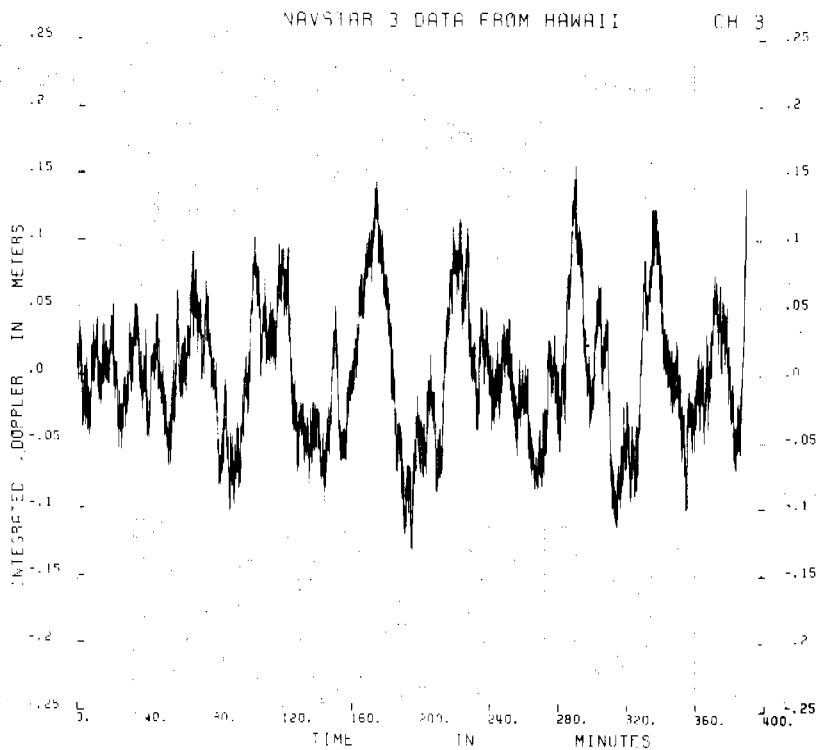


Figure 6. Combined Accumulated Delta Range Residuals

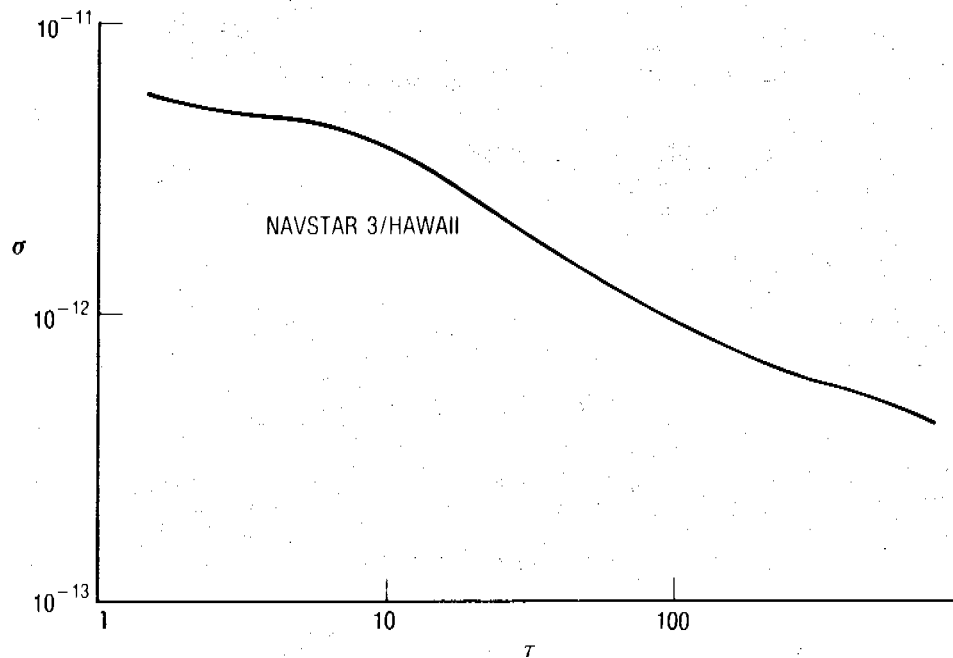


Figure 7. Short Term Allan Variance

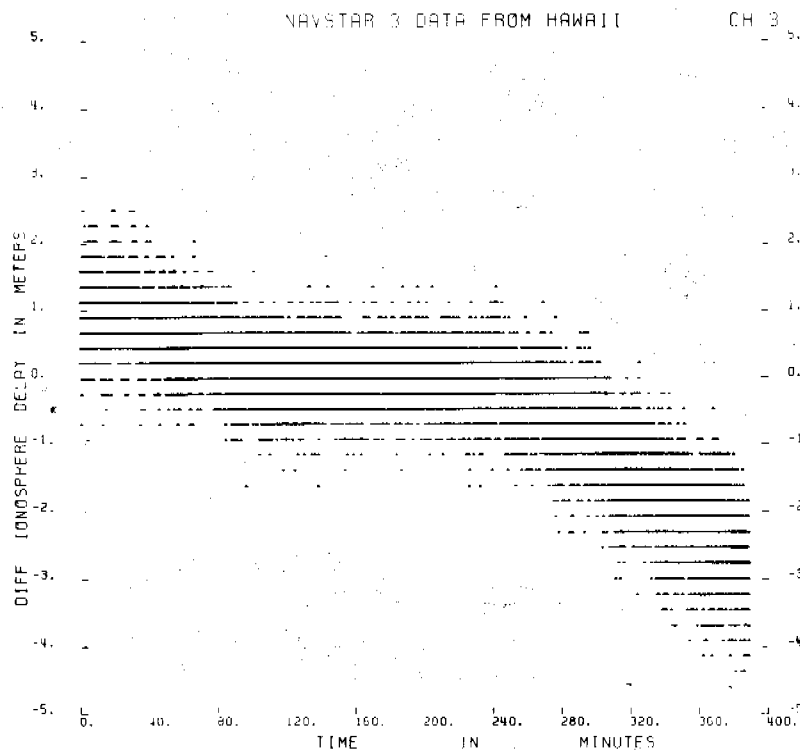


Figure 8. Difference Between L2 and L1 Pseudo Range

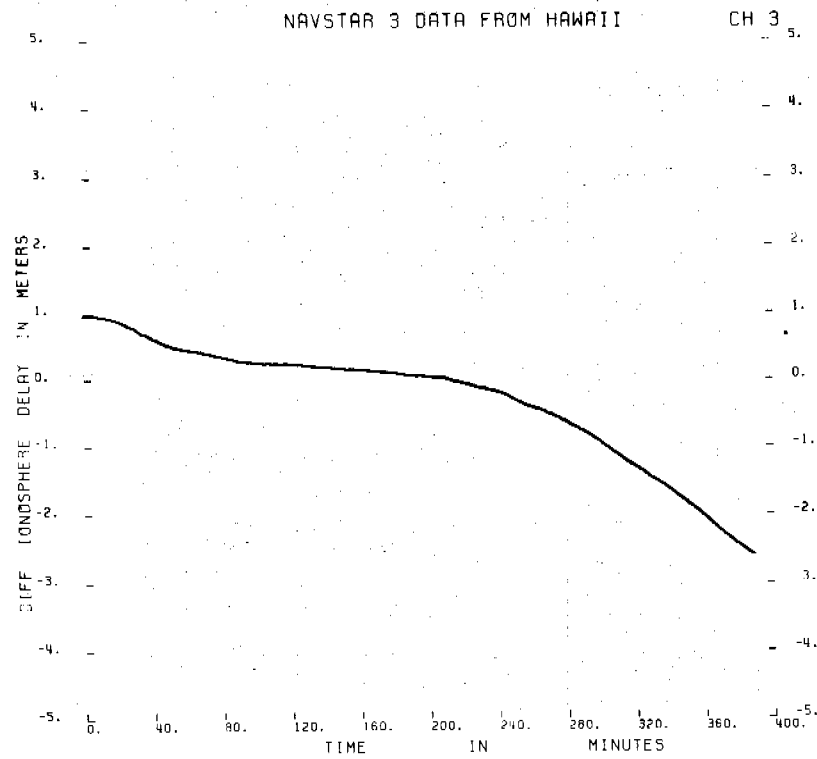


Figure 9. Difference Between L2 and L1 ADR

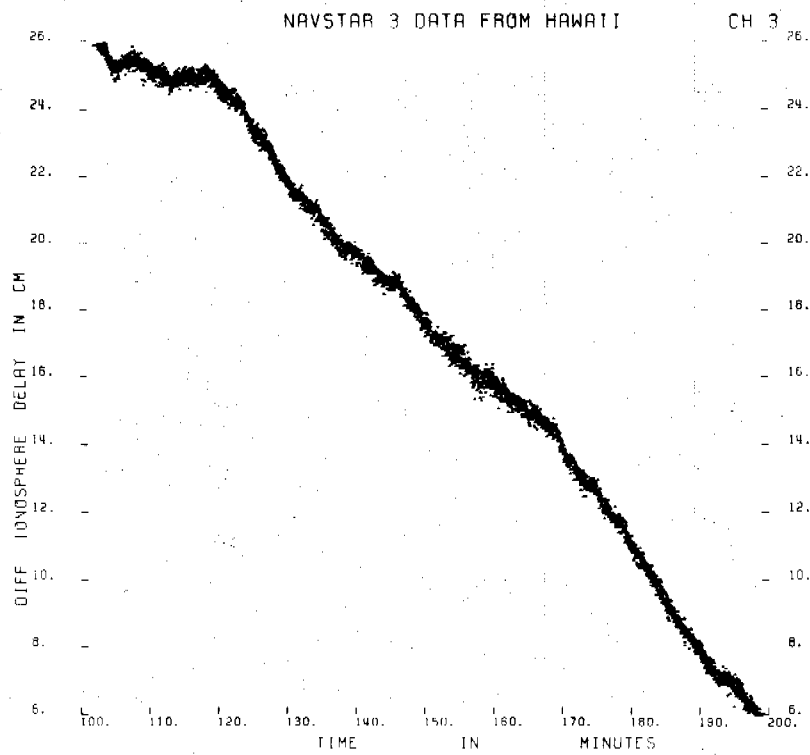


Figure 10. Amplification of 100-200 min Segment of Figure 9

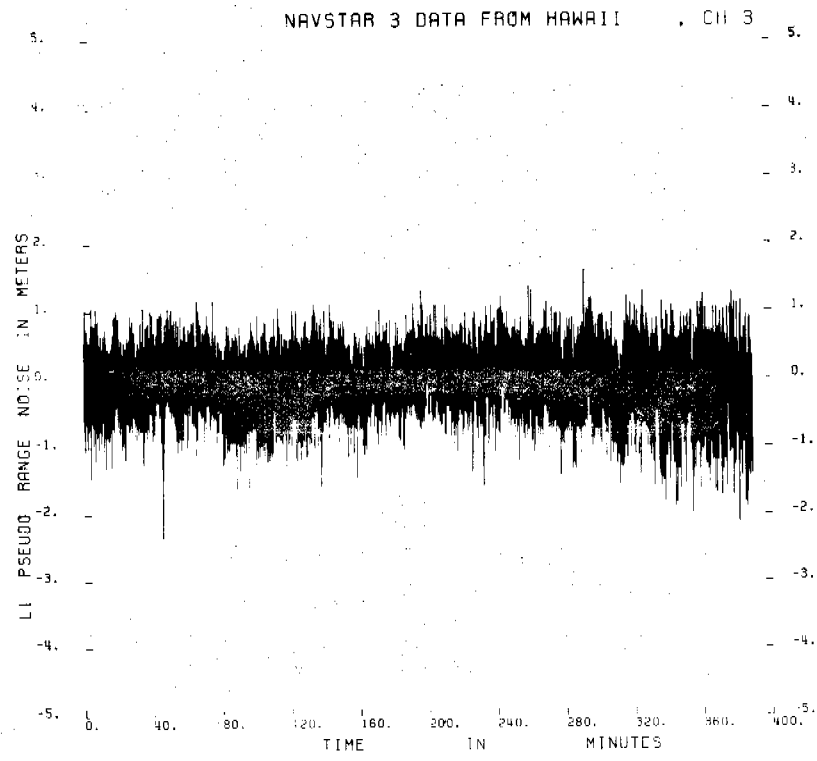


Figure 11. L1 Pseudo Range Noise

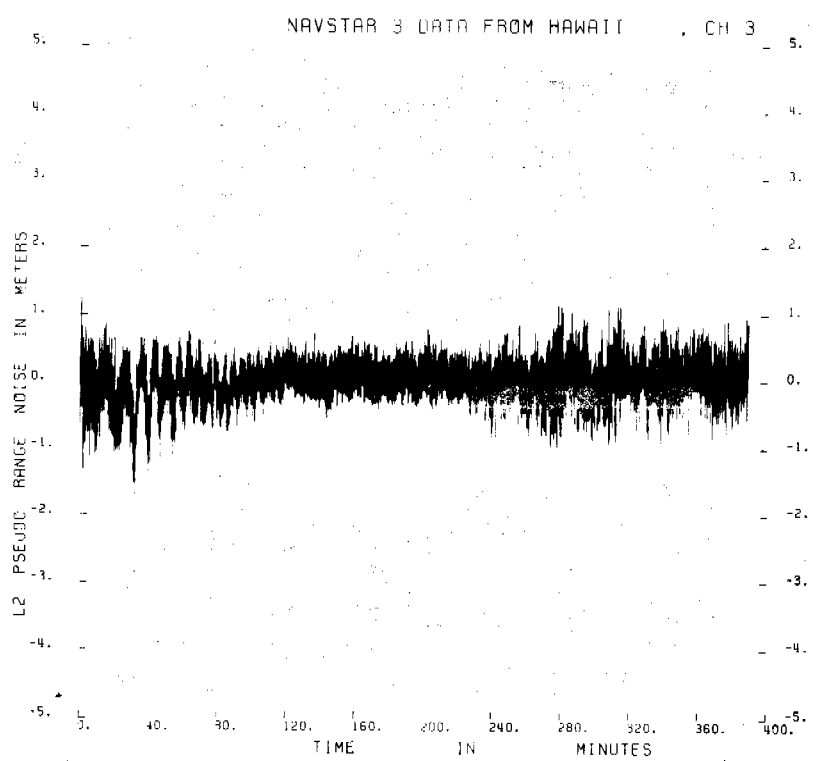


Figure 12. L2 Pseudo Range Noise

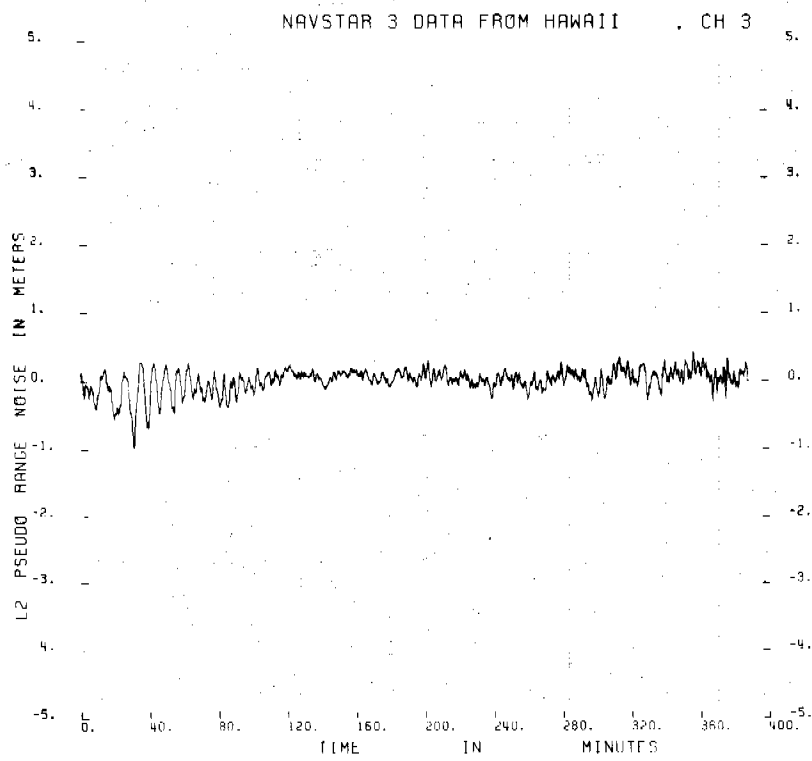


Figure 13. 40-Point Running Average of Data on Figure 12

Table I. Residuals of the 600-Point Average Differences in Meters.

1	.073	14	.152
2	.159	15	.082
3	.269	16	.076
4	.193	17	.316
5	.312	18	.336
6	-.025	19	-.048
7	-.262	20	.252
8	-.313	21	-.274
9	-.065	22	.073
10	.063	23	-.463
11	-.365	24	-.290
12	.031	25	-.358
13	.075		