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Donald J. Dempsey

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NASA
National Aeronautics and
Space Administration

Wallops Flight Center
Wallops Island, Virginia 23337
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GEOS-3 C-Band Radar Investigations

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Prepared Under Contract No. NAS6-2637

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1.0 INTRODUCTION

This report provides a detailed discussion of work performed by RCA under Contract NAS6-2637 in support of NASA Wallops Flight Center's GEOS-3 C-Band Radar Investigations.

The objectives and goals of the GEOS-3 C-Band Radar Experiment are delineated in reference (1). Reference (2) restates these program objectives and provides a discussion of the standardized C-Band radar operations and calibration procedures to be followed in achieving the objectives.

The overall experiment had a wide ranging set of objectives and goals. The primary objective was, however, "to better determine the absolute accuracy of instrumentation radar systems, develop refined methods of calibrating these systems, and improve the techniques employed in processing the associated data." All other objectives and goals were dependent upon the availability of accurate radar tracking data and were therefore necessarily of a subsidiary nature.

A world-wide network of C-Band Instrumentation Radars augmented by lasers and other tracking instrumentation systems were used in accomplishing the objectives and goals of the experiment. The work described in this report is, however, mainly associated with efforts expended using the NASA WFC AN/FPQ-6 Instrumentation Radar. This WFC radar together with the AN/FPS-16 Instrumentation Radar also located at NASA WFC were the primary instruments used in the accuracy, and calibration evaluations. The results achieved at WFC were then disseminated to other Ranges where they were verified, augmented and used as a part of routine operations. C-Band Working Group meetings were held periodically throughout the duration of the program with active participation by representatives of all the major U.S. Ranges. The dates and locations of the meetings were as follows:

(1) March 5-7, 1974; at VAFC, Calif.
(2) June 16-18, 1974; at PMTC, Pt. Mugu, Calif.
(3) October 22-23, 1974; at KMRD, Huntsville, Ala.
(4) January 21-22, 1975; at VAFB, Calif.
(5) July 14-15, 1975; at WSMR, N.M.
(6) December 1-2, 1976; at PAFB, Fla.
(7) September 21-23, 1976; at NASA-WFC, Va.
(8) July 27-28, 1977; at PMTC, Pt. Mugu, Calif.

These meetings served as forums for the interchange of information between experiment participants. Minutes of these meetings, particularly those after April 10, 1975, provide a fairly detailed chronological record of activities carried out throughout the duration of the experiment.

This report summarizes the activities and accomplishments of RCA during the experiment and is in large measure an overview of results previously presented at the C-Band Working Group Meetings. However, since representatives of RCA, Wolf Research and Development Corp. (WRDC) and NASA-WFC formed a closely knit interactive working group at WFC it is impossible to report soley upon RCA efforts without incorporating and acknowledging the contributions of both WRDC and NASA-WFC. In particular, the contributions of Messers W. B. Krabill (Principal Investigator, GEOS-3 C-Band Radar Experiment, NASA-WFC), K. L. Borman (WRDC) and Dr. C. A. Martin (WRDC) are gratefully acknowledged, as is the support of Mr. C. Davis and his NASA-WFC AN/FPQ-6 Radar operating crew.

2.0 RADAR ACCURACY INVESTIGATIONS

Based upon experience gained during the previously conducted GEOS-2 C-Band Radar System Project, a detailed set of radar operating and calibration procedures were generated for use during the GEOS-3 C-Band Radar Experiment. These procedures were disseminated to all experiment participants and were, as far as is known, carefully followed during all GEOS-3 tracking missions. These procedures and the data processing techniques used in correcting the resulting tracking data for refraction, transit time, and calibration determined bias errors are well documented in reference (2) and formed the basis for discussions at the prelaunch C-Band Working Group meetings.

The initial efforts for the GEOS-3 experiment consisted of conducting tracks of the then still active GEOS-2 satellite. These pre-GEOS-3 launch efforts were used to insure that all procedures were understood and that the data reduction programs were operating satisfactorily. Thus all aspects of the GEOS-3 data gathering and reduction procedures were verified and found to be completely operational prior to actual GEOS-3 launch.

The RCA efforts during this time span consisted of preparation of final radar operating and calibration procedures; analysis of radar calibration data to verify adequacy of the test calibrations; and assistance to NASA/WRDC in developing and checking data preprocessing procedures. This phase of the contract was successfully completed prior to the launch of the GEOS-3 satellite on April 10, 1975.

The remainder of RCA's efforts under the contract were associated with investigations into specific radar tracking or calibration problem areas. These post-launch efforts have , for discussion purposes, been organized by radar tracking functions (i.e., Range, Azimuth, Elevation, and Range Rate) and are discussed below.

2.1 Range Rate Investigations

The GEOS-3 Satellite carried both a coherent and a non-coherent C-Band transponder as a part of its space borne instrumentation. The non-coherent transponder was identical to units previously used during the GEOS-2 program. The coherent transponder, however, represented the first time such a C-Band coherent source was available in orbit. Therefore, a large part of the C-Band Investigations effort was based upon tracking this coherent transponder and evaluating the resulting data. Primary items of interest were evaluation of the accuracy of the range rate measurements; determination of error models for any unexpected but observed measurement errors; development of calibration techniques for bias error elimination; and investigation of methods for optimally using the range rate data.

As discussed in the following sections, the evaluation of the C-Band radial range rate measurements led to the discovery and eventual elimination of both systematic and bias errors. Once corrected data became available, it was determined that the range rate data were accurate to within approximately 1 cm/sec with a precision on the order of 5 mm/sec. Both of these evaluation results are well within the design specifications for the radar's pulse doppler tracking equipments.

A considerable amount of effort was expended in generating and evaluating an integrated form of the range rate data (i.e., range data developed from range rate measurements). This integration approach proved of great value as an evaluation tool for better understanding the range rate measurements themselves. Error terms which were unrecognizable in the raw velocity data were magnified and became glaringly apparent once the integration process was carried out. Also, the integration results proved to be extremely sensitive to system timing errors and to both systematic and bias errors in the basic radar ranging data. Finally, the integrated range rate data showed promise as an extremely precise (millimeter noise levels) and accurate (ranges accurate to within a few centimeters at orbital ranges) source of target slant range data.

2.1.1 Systematic ($\frac{PRI}{2}$) Doppler Error Discovery and Elimination

Reference 3 contains a detailed discussion of a sampling rate dependent error which was found to exist in the radar range rate measurements. The availability of a coherent transponder in an orbiting reference target was of primary importance in this discovery.

Coherent tracks of the GEOS-3 satellite during its post-launch check-out and calibration phase resulted in range rate residual errors which displayed a definite dependence upon radial range acceleration (see Fig. 1). Since a type 2 doppler tracking servo loop is used, the observed error could not be attributed to dynamic lag effects. The essentially infinite K_v of the loop precludes such a lag error dependence upon the first derivative ($\ddot{R}$) of the tracked parameter ($\dot{R}$).

During subsequent investigations into this error it was noted that the error was inversely proportional to the operating PRF of the radar. Figure 2 shows the error residuals resulting from a satellite track where the radar's PRF was changed by a factor of 4:1 (160 pps to 640 pps) during the track. It is easily seen that the residual error dropped by approximately 4:1.

This PRF dependence discovery was the key to isolating the source of this systematic range rate tracking error.

An analysis of the C-Band pulse doppler tracking loop was conducted and it was determined that the error was being introduced as a result of the finite sampling rate being used to update the doppler tracking local oscillator.

The form and magnitude of the error was evaluated for the case of a constantly accelerating target. In this particular case it was found that the error was equivalent to a timing error having a magnitude equal to 1/2 the local oscillator update interval. The sign was such that the doppler loop was providing measurements which led the true doppler.

Once the error source had been identified and its effect modeled, it became apparent that its effect could be eliminated by a simple time shifting of the doppler measurement data. The time shift required is simply:

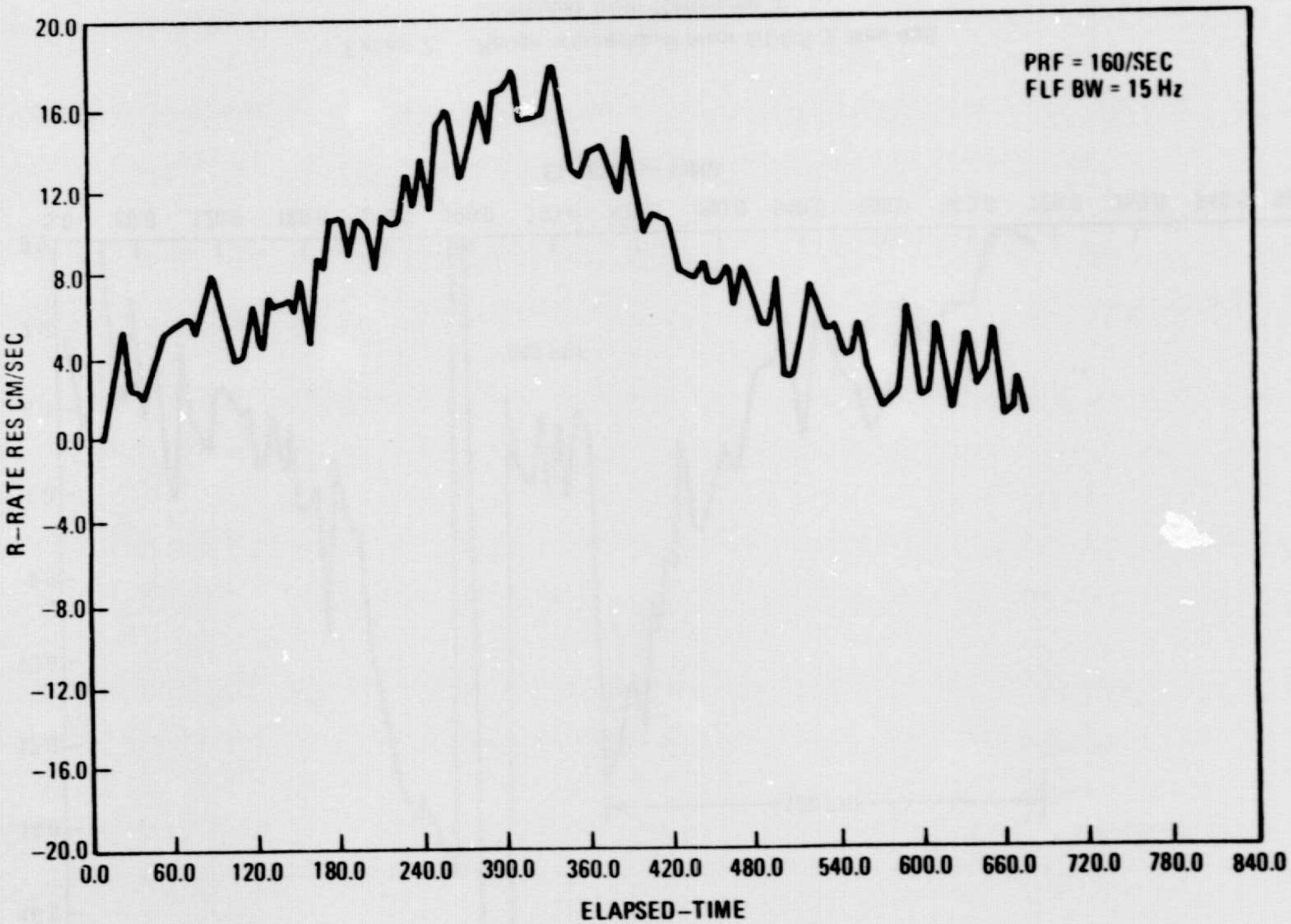

Figure 1. - Range rate residual error GEOS-3, Rev 212
(extracted from Reference 3)

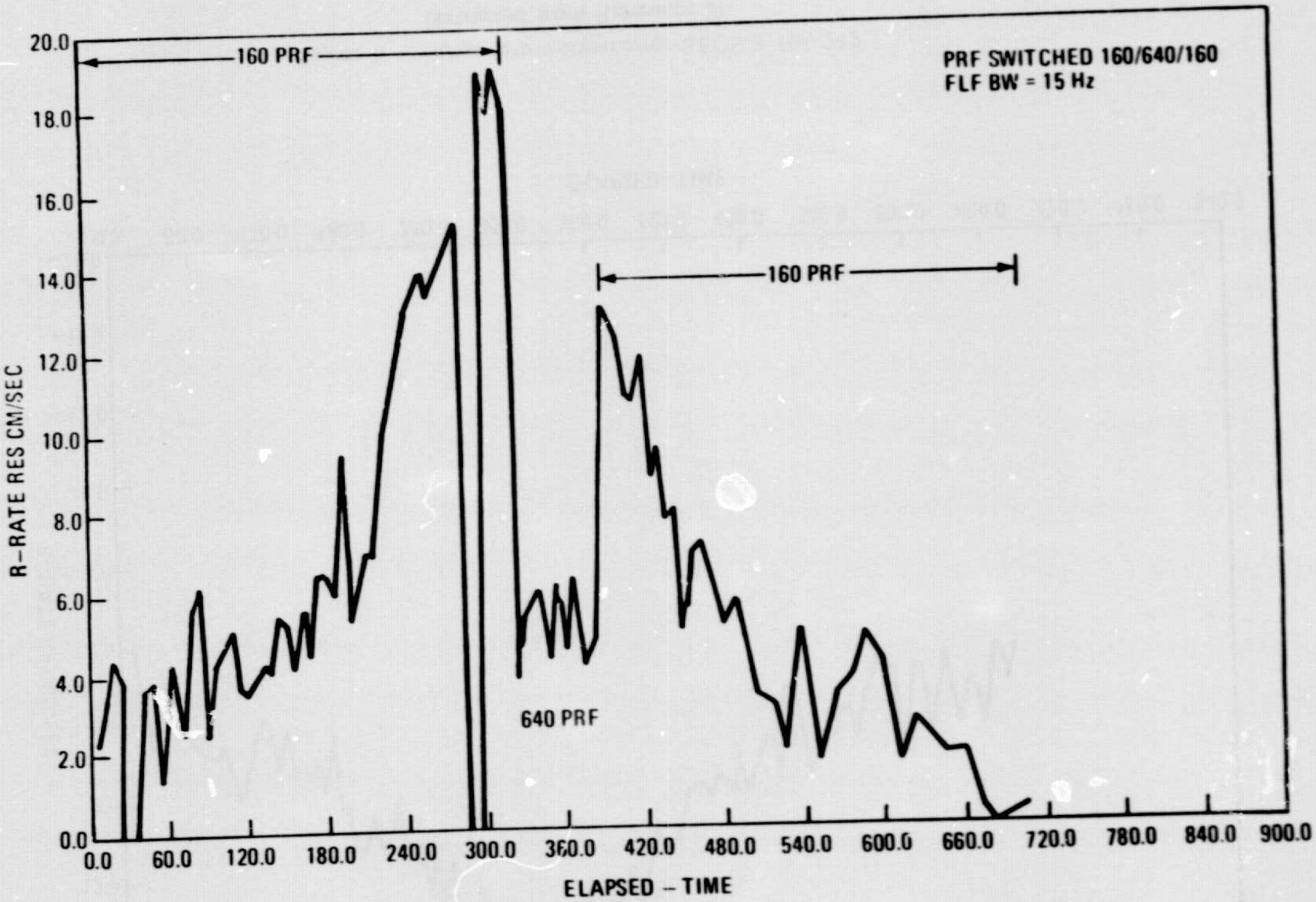

Figure 2. - Range rate residual error GEOS-3, Rev 498
(extracted from Reference 3)

Correct doppler time = measurement time + T/2

where T = L.O. sampling interval = PRI for unmodified radars.

This time shift correction of the doppler data was performed in the post-mission pre-processor data correction/formatting program for all GEOS-3 C-Band radar data reductions. Evaluation of resulting doppler error residuals verified that the correction was effective and satisfactory.

Since the time shift doppler error compensation technique was a post-mission correction, an investigation was carried out to determine if a simple and effective real-time correction could be implemented. It was found that the local oscillator update rate could readily be increased to 2560 Hz (rather than the previously used PRF) by the simple movement of a few wires within the system timing circuitry.

This real-time correction technique was implemented, tested, and evaluated on the WFC AN/FPQ-6 radar and the results were found to be fully satisfactory. The residual error remaining after the update rate modification was, as predicted, found to be negligibily small.

A description of the necessary hardware modification is contained in Reference 3.

2.1.2 Range-Rate Calibration

The C-Band pulse doppler systems were designed to provide essentially bias free measurements of target range rate. Such error free performance required, however, that the operators perform periodic alignments of the equipment. It was recognized that any uncorrected loop unbalance could result in a doppler bias error. Further, the loop was susceptible to long-term drift effects. The elimination of these drift effects also required that the loop balancing and alignment procedures be periodically performed. Due to the existence of these potential sources of doppler bias errors, the evaluation and elimination of C-Band range rate bias error was established as one of the goals for the GEOS-3 C-Band Investigations.

2.1.2.1 Theoretical Basis for Doppler Calibrations

A recommended technique for range rate calibration already existed at the outset of the GEOS-3 program. This technique utilizes the known characteristics of the pulse doppler frequency spectrum to obtain the necessary calibration measurements.

A train of RF pulses whose carrier maintains pulse-pulse phase coherence in the time domain is equivalently represented by a spectral line distribution in the frequency domain. The spectrum is mathematically defined as follows for a train of perfectly rectangular pulses of width τ in the absence of extraneous modulation:

$$F(\omega) = \tau \frac{\sin(\omega-\omega_o)\ \tau/2)}{(\omega-\omega_o)\ \tau/2} \cdot \frac{\sin[N(\omega-\omega_o)\ T/2]}{\sin[(\omega-\omega_o)\ T/2]} \quad .$$

The first term on the right side of this equation is associated with the type of carrier modulation. For the assumed rectangular pulse train, this term takes the form of the well known sin(x)/x spectrum. The second term on the right side of the equation defines an infinite sequence of frequency lines on either side of a center (peak of the sin(x)/x spectrum) line. These line spectra are separated from each other in frequency by an amount equal to 1/T. For the assumed pulse train 1/T is equal to the radar's operating pulse repetition frequency (PRF). In summary, the pulse doppler frequency spectrum consists of a center line and an infinite number of discrete $\pm$ sidelines each of which is separated from the center line by an amount N·PRF. This periodic line spectra is then enclosed by an amplitude determining envelope which has the form of sin(x)/x.

The important feature of this spectrum for calibration purposes is the occurrence of discrete sidelines which are separated in frequency by an amount equal to the PRF. Since these lines occur at both plus and minus frequencies, measurements made sequentially locked onto both the $\pm$ Nth sidelines should result in range rate readings which are equal in magnitude and of opposite algebraic sign. Note that accurate knowledge of the actual PRF is not necessary. It is necessary, however, that the PRF remain unchanged during any sideline measurements.

Based upon the spectral characteristics discussed above, it was proposed that the C-Band radars perform pre and post mission range rate calibrations by sequentially locking up on known $\pm$ sidelines. A static target was to be used during these calibrations and 100 samples of range rate data were to be recorded at each lock-on.

Based upon the theoretical aspects of the frequency line spectrum, adding measurements obtained at $\pm$ sidelines should result in a zero sum if there is no bias error in the system. A non-zero result is indicative of a range rate bias error. Thus the calibration measurements can be used to obtain a measure of the bias error as follows:

$$\epsilon_{\dot{R}}(\text{bias}) = \frac{\bar{R}(+\dot{N}) + \bar{R}(-\dot{N})}{2}$$

where: N indicates the location of the sideline used (Usually the first (N=1) sidelines are selected.

R = average of data samples recorded.

Once the bias error is known it can, of course, be easily corrected.

The $\pm$ 1 line lock-on doppler calibration procedure was implemented at the WFC FPQ-6 radar and the GEOS-3 satellite with its coherent transponder was used as a dynamic reference target to evaluate the validity and effectiveness of the calibration technique.

2.1.2.2 Doppler Calibration Results

Before discussing the GEOS-3 range rate evaluation results, it may be useful to list the pertinent doppler tracker's design specifications. The Coherent Signal Processor modification for the AN/FPQ-6 and AN/FPS-16 radars was designed to meet a 0.04 yd/sec (3.66 cm/sec) accuracy specification when presented with a single hit IF S/N of 20 dB or greater.

Similar specifications for the AN/MPS-36 Velocity Extraction Subsystem (VESS) call for a measurement accuracy of 0.1 ft/sec (3.05 cm/sec).

Keeping the above given design requirements in mind, it will be seen that the GEOS-3 results indicate that these C-Band pulse-doppler systems are capable of providing range rate data which not only meets but usually exceeds the design specifications.

During the course of the GEOS-3 program the C-Band range rate data were, at various times, used directly without calculating or applying the bias error corrections based upon the $\pm$ 1 line calibrations. Table 1 provides a listing of the recovered range rate bias estimates resulting from orbital analysis of these uncorrected data.

Table 1

RANGE RATE BIAS ESTIMATES WITH NO CALIBRATIONS

WFC AN/FPQ-6

GEOS-3 Rev. #	$\epsilon_{\dot{R}}$(Bias) cm/sec
1448	+1.0
1449	+1.0
1581	+0.9
1789-90	+0.9
1795-96	+0.9
4078-79	+1.4
4135-36	+1.3
4880-81	+1.1
4922-23	+1.2
5064-65	+1.2
5121-22	+1.3
5164-65	+1.2
5263-64	+1.4
5320-21	+1.5
5463-64	+1.6
5542-43	+1.2
5755-56	+1.3

mean = 1.20 cm/sec

RMS = 1.22 cm/sec

It is readily seen from the data of Table 1 that the C-Band Range Rate systems when properly maintained and operated are fully capable of surpassing their design requirements even without a range rate calibration. Unfortunately, analysis of data from other radar sites indicates that proper maintenance is not always achieved.

Figure 3 (extracted from reference 4) shows the results of an error analysis performed on data from various C-Band pulse doppler radars. As can be seen from this figure, both the mean and standard deviation of the range rate errors for these other radars are considerably worse than the WFC-FPQ-6. The variability of these results supports the need for a reliable range rate calibration technique.

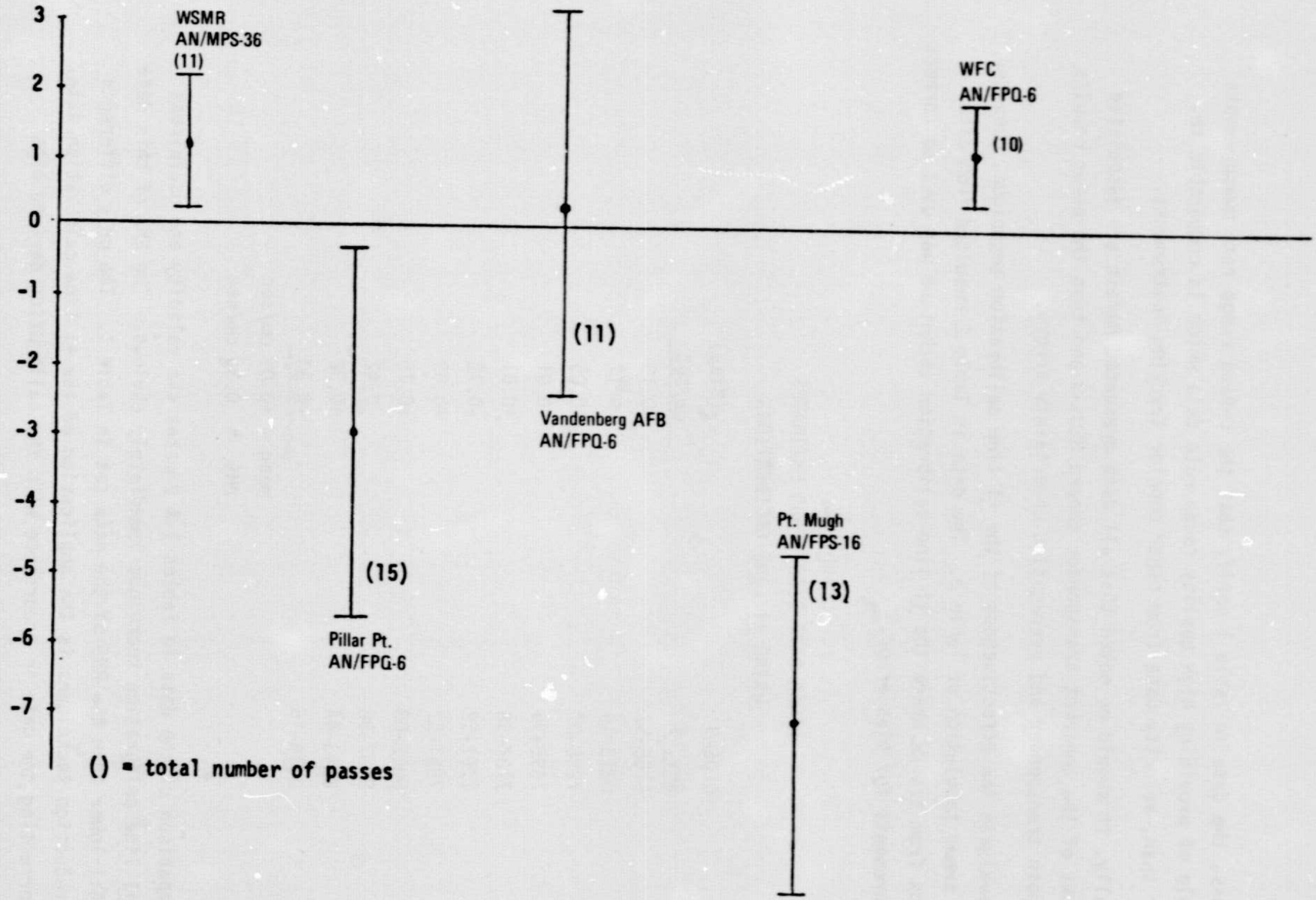

Figure 3. - Summary of Range-Rate Bias Recoveries from One Day Arcs
(extracted from Reference 4)

Nonetheless, the data in Table 1 verify that the C-Band range rate measurements are capable of providing high quality range rate data which is comparable to, or better than, velocity data from other doppler tracking instruments.

Finally, it should be noted that all data presented herein are associated with tracks of the coherent transponder aboard GEOS-3 and thus the error results include both transponder and propagation uncertainty errors.

To evaluate the effectiveness of the ± 1 line calibration technique, consider the bias error tabulation of Table 2. The data in Table 2 resulted from data reductions from tracks where the ± 1 line calibration technique was used to correct the measurements for bias error.

Table 2

RANGE RATE BIAS ERROR ESTIMATES

USING ± 1 LINE CALIBRATIONS

GEOS-3 Rev. #	$\epsilon_{\dot{R}}$(Bias) cm/sec
6756-57	-0.10
6813-14	-0.17
7206-07	-0.05
7695-96	-0.01
7737-38	+0.01
7751-52	-0.12
7851-52	+0.03
8002-03	+0.76
8187-88	-0.42
8343-44	+0.32
8414-15	+0.30
	mean = +0.05 cm/sec
	RMS = 0.30 cm/sec

Comparison of the data in Tables 1 & 2 makes the validity and usefulness of the ± 1 line calibration technique immediately obvious. The RMS of this data set is 4:1 lower than the RMS of the data set in Table 1. The only difference in the reduction techniques is the application of the ± 1 line calibration data. After correcting the data in accordance with the calibration derived bias error, the residuals are consistantly found to have a bias error of less than 1.0 cm/sec. These results are significantly better than the expected accuracy as given by the original design specifications and certainly demonstrate that the C-Band pulse dopplers are capable of providing the user community with an accurate source of range rate data.

2.1.3 Integrated Range Rate Investigations

The C-Band radars having a pulse doppler tracking capability provide a unique set of tracking data in that statiscally independent measurements of target range and range rate are available in a collocated instrument. The availability of the orbiting GEOS-3 satellite with its coherent transponder provided a dynamic reference target for investigating techniques to optimally process these collocated and independent measurement data sets.

Reference 5 contains a detailed discussion of the range rate processing techniques investigated as a part of the GEOS-3 C-Band Radar Investigations. The basic approach taken was to integrate the range rate data, compare these data to a range-only (essentially) derived reference orbit, and to evaluate the resulting residuals for consistency with known or suspected range rate error terms.

The principal result achieved from these range rate investigations was the conclusion that integrated range rate data provides an extremely sensitive analytical tool for evaluating the behavior of both the range rate and range data.

The sensitivity of the integrated range rate data to range rate measurement errors was, of course, expected and modeling of the data for known error terms was carried out from the onset of the investigations. The integration process tended to magnify the effects of these errors and the existence of any range rate bias, lag or timing errors became immediately obvious in plots of the residuals.

The sensitivity of the integrated range rate data to range errors was found to be greater than originally expected. Range bias errors of one meter or more were found to result in easily recognized integrated range rate residual patterns. This range bias sensitivity presents the user with the possibility of using this technique to correct range measurements for faulty range zero-set calibrations. Post-mission calculation of other non-radar dependent ranging errors such as beacon delay and pulsewidth mismatch errors may also be possible for missions where range rate data are collected (i.e., skin or coherent beacon tracking missions).

The integrated range rate data also showed noticeable sensitivity to systematic range tracking errors such as range servo lag and beacon delay variations with signal strength. Modeling the range data for, and removal of, these range systematic error terms resulted in significant improvements in the integrated range rate residual data.

Based upon theoretical predictions of an equal and opposite effect, it had been hoped that comparison of the integrated range rate data to a range derived orbit would result in a set of residuals which would contain a measure of ionospheric propagation effects. This did not materialize, however, primarily because presently unknown systematic range and/or range rate errors were perturbing the residuals to the extent that the predicted ionospheric propagation effects were masked.

The interested reader is referred to reference 5 for a detailed discussion of these investigations and their results.

2.1.4 Full CSP Tracking Tests

Several of the C-Band radars have the capability of closing the position loops (R,A,&E) through the doppler tracker and thus can develop fully coherent operation in all measurement coordinates. The principal advantage of this mode of operation is to obtain a S/N enhancement in these position loops due to coherent integration effects. However, the S/N enhancement effect only applies to targets already in track mode (i.e., no improvement is achieved during the target acquisition/mode) and the enhancement is only fully achieved in an otherwise low S/N environment. The S/N from a strong target such as the return from the GEOS-3 coherent transponder will be affected very little by switching to full coherent track. The GEOS-3 transponder normally provides strong signal return with a receive S/N well in excess of 25 dB. Thus, the noise is greatly suppressed through normal AGC action and coherent integration has little or no effect upon the resulting essentially noise free target return.

Since the Fine Line Position Track mode exists in the NASA WFC radar, it was decided that the mode should at least be checked out using GEOS-3. Therefore, a test was scheduled calling for full CSP tracking in all coordinates. This test was performed on 4/5/77 (GEOS-3 Orbit No. 10283).

As expected, very little of consequence resulted from this test and mention of it is being made only for completeness. The range tracking data from the test had a bias relative to the FPS-16 of +6 meters and an rms of 1.3 meters. Both Az and El data residuals had an rms of fit to the orbit of approximately 35 $\widehat{\text{sec}}$ and means of -11 $\widehat{\text{sec}}$ and +34.4 $\widehat{\text{sec}}$ respectively. These results are reasonably consistent with other position measurement results obtained in the non-coherent track modes. The rms of fit errors are somewhat larger than previous solutions (see reference 6) which indicate that rms errors of +5-25 $\widehat{\text{sec}}$ in Az and 10-20 $\widehat{\text{sec}}$ in El would be more typical for this radar. There was no apparent reason for the increased noise level in the angle data for the Fine Line Position Track mode. No repeats of the test were performed to verify and/or explain these results.

Probably the most significant result of this test was the confirmation that the Fine Line Position Track mode is still a fully functional operating mode for this radar. This is not a trivial result since this mode of operation had been unused for a number of years with no particular care being taken to keep it maintained or aligned.

2.1.5 Other CSP Tests

The WFC AN/FPQ-6 radar's Coherent Signal Processor was normally operated in the 15 Hz Fine Line Filter bandwidth at a radar PRF of 160 pps. Since difficulty was encountered in obtaining realistic estimates of the doppler servo lag error coefficients from the integrated range rate data, a few tests were performed where the system was operated at a PRF of 640 pps and a Fine Line Filter bandwidth of 40 Hz.

As expected, the doppler noise error increased in this wider bandwidth operating mode by a factor of approximately 3:1. This noise increase was predictable and the availability of post-mission digital filtering techniques made this effect of no particular consequence. The higher K_a (servo lag error acceleration coefficient) obtained in this wider bandwidth mode (225 versus 27 in 15 Hz mode) was expected to reduce the doppler servo lag error to a negligible magnitude and thus facilitate the investigations into why the solved for lag coefficients varied so widely from predictions. The expected results were in fact obtained. Being able to discount doppler servo lag effects led to the determination that range tracker servo lag effects were perturbing the orbit and appearing as an apparent inverted lag characteristic in the integrated range rate data.

The realization that relatively small (1 to 2 meters) range systematic errors could be sensed by the integrated range rate data was a significant factor in the success of the ongoing integrated range rate studies. Following this discovery, the range data were preprocessed for both servo lag and transponder delay variations with signal strength prior to orbit generation. This correction of range data removed many of the previously unexplainable "wiggles" in the integrated range rate residuals and allowed these residuals to be treated in a much more systematic fashion.

2.2 Range Error Investigations

The range tracking performance of C-Band radars was extensively investigated and evaluated during the GEOS-2 C-Band Radar Experiment. The final report for this previously conducted NASA program were thoroughly documented in the form of a project final report. Reference 7 is particularly pertinent to the present discussion since it contains an error model of the radar and provides a thorough discussion of the various radar range error sources and effects.

The GEOS-3 program thus started with a considerable background of information concerning the operational/calibration techniques required for reliable, accurate radar ranging data. Predictions on the expected performance of the C-Band radars could thus be made with a high level of confidence.

Very little experimentation was specifically planned for range data evaluation purposes but due to the widespread use of the data (primarily for altimeter calibration purposes) there was a constant awareness of, and interest in, the performance of the radar ranging systems. The report by Krabill and Martin (Reference 6) provides a good overview of the radar position measurement results achieved during the GEOS-3 program. The present report will not duplicate these already reported results except to note that:

a) Radar ranging data exhibited widely varying bias errors between sites in spite of the utilization of a consistent set of calibration and operating procedures at all sites. The measurement data were in general found to be accurate to within 10 meters (Transponder Track mode).

b) The radar ranging data from each site was found to be stable on a mission to mission basis to within an uncertainty of approximately 1 meter. Thus, while a particular site might exhibit a large bias error this error was generally time invariant on a pass to pass basis. This stability allowed the bias errors to be solved for and eliminated by means of orbital analysis techniques.

c) Following application of the orbital bias error correction techniques, the C-Band radar network provided ranging data of the necessary quality for supporting the GEOS-3 altimeter experiment (reference orbits with an uncertainty of 3 meters or less).

In addition to the above listed results, several problems or inconsistencies in the radar ranging data were observed and investigated during the course of the GEOS-3 C-Band Radar Investigations. These investigations are discussed in the subparagraphs which follow.

2.2.1 Long Term Radar Range Bias Investigations

The GEOS-3 Satellite was continuously and intensively tracked by various C-Band radars throughout the period from launch (April 1975) to March of 1976. In fact, tracking has continued on a reduced schedule up to the time of this report (May 1978). Thus, data are available from a large number of radars on a single target over an extended period of time. Such an extended set of data afforded the unique opportunity to investigate the long term ranging performance of these instruments.

The present discussion will be primarily oriented towards a discussion of observed long term drifts in the range data from several radars. However, before proceeding with this main topic, it is of interest to note that isolated cases of erratic short-term radar ranging errors were also observed. In these cases, it was generally possible to isolate the cause of large changes in radar bias errors at a particular site to a change in site operations and/or calibration techniques. An example of this type of error was the determination that large and erratic range bias errors in the Bermuda AN/FPQ-6 data were due to site adjustments of the radar's transmitted pulsewidth. Pulsewidth adjustments were compensated for during mission calibrations and no adverse effects would have been noted had the radar been used in a skin track mode. However, the GEOS-3 Satellite was actually tracked in the beacon track mode and, therefore, the change in transmitted pulsewidth resulted in a varying pulsewidth mismatch error. Once the erroneous transmitter adjustments ceased the Bermuda range data became quite stable and predictable from a short-term point of view.

Another example of an observed short-term range error effect occurred in the Wallops Island AN/FPQ-6 radar's data. In this case an apparent 1 to 3 meter range bias change occurred in January or February 1976. It was found that the site had changed reference range targets at this time and a subsequent investigation indicated that ground clutter effects were producing erroneous range calibrations from one of the two targets. While the target dependent nature of this error could be identified by comparing calibration data from the two targets, no reliable third reference target was available to identify which of the two reference targets was introducing the error. Approximately fifty sets of calibration data from the two targets were analyzed to establish that a difference of 2.1 meters was present in the data sets. This particular error will be mentioned again in discussing the apparent long-term drift error observed in the Wallops Flight Center's AN/FPQ-6 radar.

In Reference 6 Krabill and Martin discuss the existence of an apparent long-term radar range drift error in both the WFC and the Bermuda AN/FPQ-6 radars. This drift seemed to be cumulative and linear as a function of time. The drift attributed to the WFC AN/FPQ-6 was +4.14 cm/day as observed over a one year period. The Bermuda AN/FPQ-6 drift was computed to be +2.7 cm/day from a six month set of data. The Bermuda Island data from Reference 6 are reproduced in Figure 4.

Figure 5 presents a plot of Wallops Flight Center AN/FPQ-6 range error data which was accumulated over approximately a 600 day interval of time. Table A-1 in the appendix contains the data used in generating this figure. It should be noted that the data for the time period from launch to 1/22/76 have been adjusted by -2.1 meters to account for the change in reference range targets as discussed above. No justification is given for adjusting the pre 1/22/76 data. A +2.1 meter adjustment could have ben arbitrarily made to the post 1/22/76 data. But an adjustment must be made to one of the two data sets to account for the change in reference range calibration targets on 1/22/76.

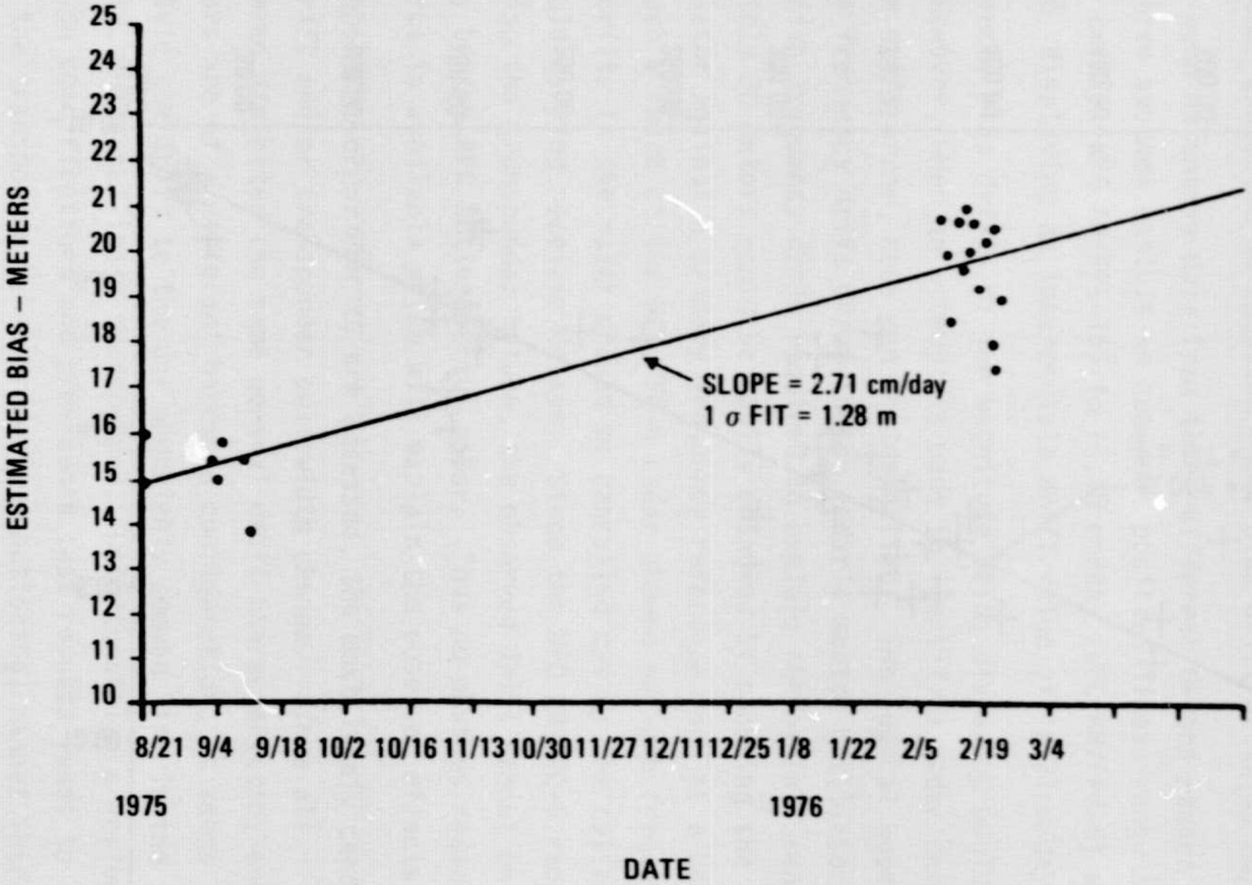

Figure 4. - Bermuda FPQ-6 biases estimated from two revolution single station orbital solutions (extracted from Reference 6)

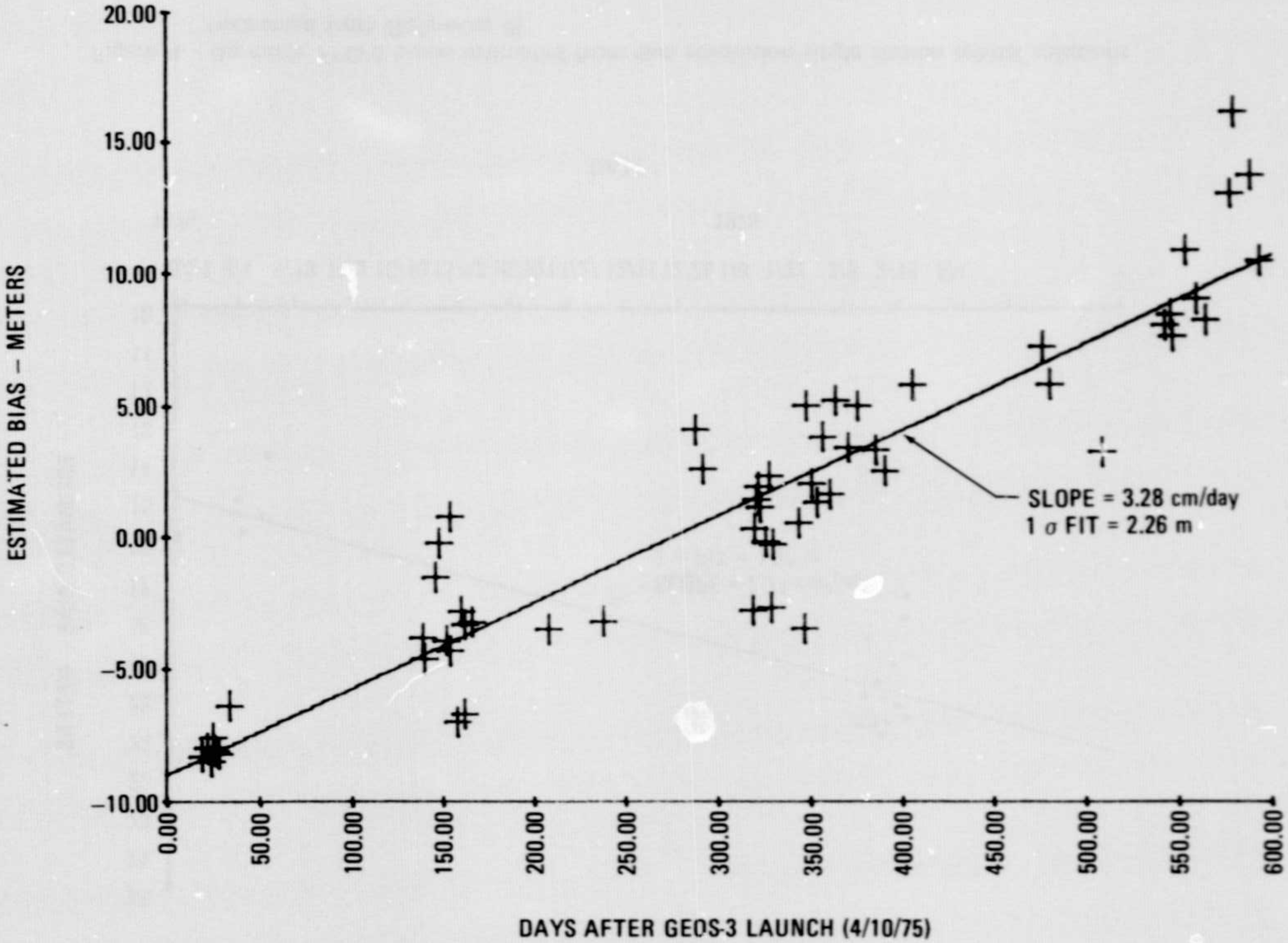

Figure 5. - NASA WFC AN/FPQ-6 biases estimated from two revolution GEOS-3 orbital solutions

Having made the arbitrary -2.1 meter range adjustment, the data presented in Figure 5 display an apparent long-term range drift of +3.28 cm/day as indicated by the slope of the straight line fitted to the data. The rms of the original data set is 6.05 meters while the rms of fit about the line is 2.26 meters.

Data from the WFC AN/FPS-16 radar were also analyzed and, over a one year period, this radar exhibited an apparent range bias drift of +2.49 cm/day.

Thus, based upon extensive data from three different C-Band radars it is found that all three systems exhibit an apparent positive linear range bias drift of from +2.49 cm/day (WFC AN/FPS-16) to +3.28 cm/day (WFC AN/FPQ-6) with the Bermuda AN/FPQ-6 displaying an intermediate drift value of +2.71cm/day.

At first glance, bias drifts of the magnitude being discussed would seem quite acceptable. However, when an attempt is made to identify a radar dependent source of such a drift error, none can be identified. The logical source would be a long-term frequency drift error in the radar's master oscillator. However, the cumulative frequency drift required to explain the overall range change of approximately 20 meters would be easily observed by checking the radar's master oscillator against a primary frequency reference such as a Caesium Beam oscillator. Such a check at the WFC FPQ-6 radar showed no such frequency error. Delay line drifts in the radar should be cancelled out by the calibration process as should varying receiver delays. Since the WFC AN/FPQ-6 radar is coherently tracking the transponder return, the observed drift cannot be attributed to faulty beacon AFC action in the radar. Thus no obvious radar dependent error source is available which will explain the observed effects.

If non-radar dependent error sources are assessed, the most likely candidates are transponder delay drift and/or transponder pulsewidth change. Since all three radars considered exhibited the same general drift characteristic, and since all three radars are of a different hardware configuration, it seems reasonable to attribute the drift to the one undeniably common link in the measurements - namely, the Satellite's transponder. Unfortunately, a review of the transponder design specifications and pre-launch test results leads to the conclusion that the transponder, when properly functioning, cannot introduce errors of the magnitude under discussion.

Therefore, one is faced with the dilemma of choosing one of two unlikely alternatives to explain the observed data:

a) All three radars have a common design deficiency or malfunction; or

b) The transponder has a design deficiency or is malfunctioning.

Since tests on the radars has failed to identify a radar dependent source of the error, this report will conveniently choose to select (b) as the more likely cause of the observed drift. A hypothetical explanation for the source of the drift error is presented in the next section where Bandwidth/Pulsewidth mismatch effects are discussed.

2.2.2 Bandwidth/Pulsewidth Mismatch Investigations

During the course of the previously conducted GEOS-2 C-Band Radar Experiment, a Bandwidth/Pulsewidth Mismatch error model was postulated (see Reference 7). It was hoped that this model could be verified as a part of the GEOS-3 C-Band Radar Investigations. Further, since it was recognized that accurate measurements of receiver bandwidth and transmitter/transponder pulsewidths would be extremely difficult to obtain in practice, it was decided that a possible self-calibration technique should be tried. This technique required that the change in radar range be measured as the radar receiver bandwidth was varied both during calibration (ΔR_C) and track (ΔR_T). The theory predicted that the mismatch error could then be computed as:

$$\varepsilon_{mm} = 2(\Delta R_T - \Delta R_C)$$

The validity of this approach was tested using the WFC AN/FPQ-6 radar as a test instrument. A tabulation of the measurements is presented in Table A-2 of the Appendix. Table A-3 in the Appendix shows the results of the mismatch calculations for those cases where both calibration and track bandwidth changes were available. This latter table also lists the computed radar bias error based upon a linear fit to the orbital reduction error estimates. Assuming that the orbital estimation results are correct, a cursory glance at the predicted versus true columns leads to the conclusion that the bandwidth switching technique is far from satisfactory. Not only does it fail to predict the observed errors (assuming they are in fact due to a mismatch effect), but it produces errors of the wrong algebraic sign. Therefore, applying corrections based upon the bandwidth switching data would tend to increase the observed error rather than reduce it. This was a disappointing and discouraging result. Figure 6 depicts the mismatch errors

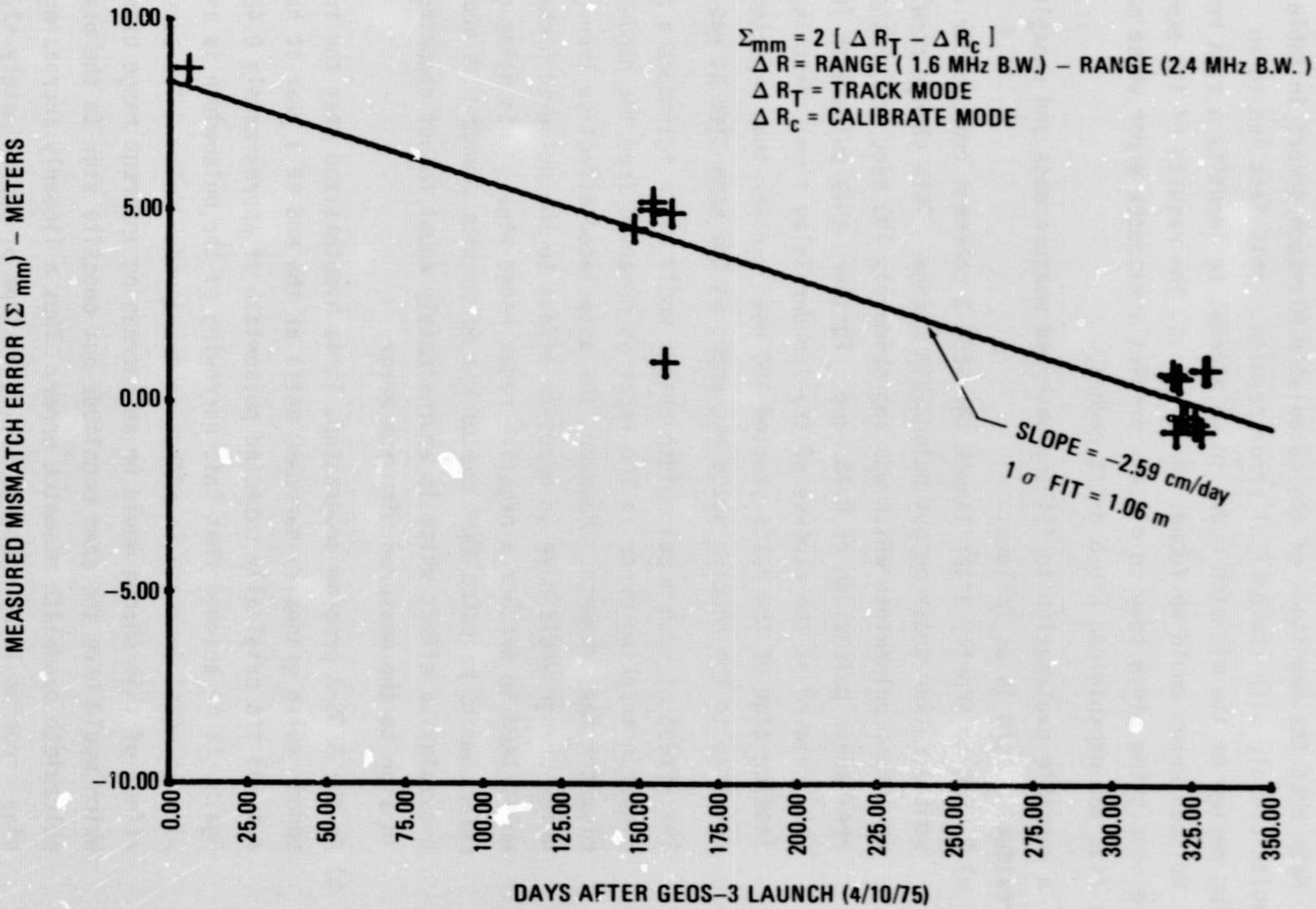

Figure 6. - Measured NASA WFC AN/FPQ-6 Mismatch Error

as computed from the bandwidth switching data together with a best fit line. It is noted that the slope of the linear fit is -2.59 cm/day.

Note that the magnitude of the calculated mismatch errors in Table A-3 agree quite closely with the orbital error results. This fact led to an agonizing review of the mismatch model in an attempt to identify a sign reversal error. No such error could be found. Nonetheless, the results of the experiment are intriguing since they so closely predict a mismatch error whose magnitude closely fits the unexplained FPQ-6 drift errors.

A possible explanation to fit the observed measurements and unexplained range residual errors is as follows:

a) During or shortly after launch the GEOS-3 coherent transponder underwent a rather gross output pulsewidth change. This change resulted in an output pulsewidth which was approximately 100 nsec longer than the pre-launch pulsewidth of 0.48 μsec. Further, this pulsewidth increase was achieved at the expense of transponder delay time. That is, the leading edge of the pulse started 100 nsec earlier than expected relative to the receive pulse and ended at the same time as was expected.

   The effect of such a pulsewidth change would be to introduce a positive mismatch tracking error in the radar as observed from the bandwidth mismatch measurements. However, the associated effective transponder delay change would have an opposite effect to the pulsewidth change and would tend to produce a negative radar range bias. This delay change effect would be twice that due to the pulsewidth change thus producing a cumulative effect which is approximately equal to but opposite in sign to the measured mismatch error.

b) As the GEOS-3 program progressed, it is hypothesized that the transponder pulse gradually narrowed until at the end of a year it had assumed its originally expected pulsewidth of approximately 0.48 μsec. Again, it is assumed that this narrowing of the pulsewidth is associated with an equal increase in effective transponder delay. The cumulative effect of this change would be an increasing apparent range bias error which would have the same magnitude but opposite sign to the measured pulsewidth bandwidth mismatch error. Thus a linearly increasing range bias error would be measured having a slope of approximately +2.5 cm/day. This error would be noted by all interrogating C-Band radars.

c) Individual radars would display a range bias slope of +2.5 cm/day only if their transmitted pulsewidth remained invariant over the time interval of interest. If an individual radar had an increasing transmit pulsewidth it would exhibit an overall bias slope in excess of +2.5 cm/day, while a decreasing transmit pulsewidth would be indicated by a lower bias slope. Thus, the WFC AN/FPS-16 with its magnetron transmitter tube remained fairly stable in its pulsewidth and data from this radar show only the transponder induced effects. The WFC AN/FPQ-6 radar with its linear, coherent amplifiers (TWT's and Klystron) exhibited a widening pulsewidth and thus its data showed a bias slope greater than +2.5 cm/day. Bermuda's AN/FPQ-6 also had a widening pulse but less than that which occurred at the WFC AN/FPQ-6.

While the above explanation is pure conjecture, it is partially supported by two observations. First, the pulsewidth from the GEOS-3 transponder as observed by the WFC AN/FPQ-6 radar shortly after launch appeared to be erratic with a leading edge which seemed to "jump" about 100 nsec. Further, at this time the dominant pulsewidth (as indicated by the trace intensity on the CRT) was associated with the wider of the two observed widths. Similar observations in February of 1977 showed only a well behaved pulse. Unfortunately, no attempt was made to determine whether the stabilized pulse had taken on the wider or narrower pulsewidth condition.

Also, at the time of the WFC AN/FPQ-6 overhaul (9 Sept. 1976) it was noted that its measured output pulsewidth was wider than nominal. Since pre-GEOS-3 measurements had shown a nominal pulsewidth, it can be reasonably assumed that the width increased during the course of the GEOS-3 tracking. However, no data are available to indicate when the pulse broadening occurred or whether the broadening was a gradual or an abrupt phenomenon.

In summary, the GEOS-3 radar mismatch experiment was at first glance a failure. However, if the above described hypothetical transponder pulsewidth variation is true, then the pulsewidth mismatch experiment was exceptionally successful. In truth, the answer probably falls somewhere between these extremes and additional experiments should be conducted to establish the final answer.

2.2.3 Range Systematic Errors

As noted in the previous discussions dealing with integrated range rate experiments, two known radar range systematic errors were found to be discernable in the C-Band radar range data.

First, the transponder delay versus receive signal strength was found to be significant both as a general function of track range and as a function of transponder antenna lobing effects. Future satellite programs using radar tracking should, as a minimum, apply a range data correction for this effect using radar AGC voltage as a measure of transponder receive signal strength. This approach, of course, assumes reciprocity applies and that noted radar AGC changes are a reflection of transponder slant range and antenna lobing effects. Due to the bandwidth limitations of the radar AGC loop, only reasonably long term transponder antenna effects will be taken into account. Downlink telemetering of the transponder's receive signal strength would be a better indication of signal strength dependent delay variation effects but such an approach is necessarily compromised when multiple radars are interrogating the transponder. The final determination of which approach is most applicable to a future program will have to be made based upon each individual program's tracking requirements. Some compensation for this transponder delay variation must, however, be routinely applied.

The second effect noted was the lag error introduced by the radar's range tracking system. This range acceleration dependent error was for GEOS-3 quite small (1-2 meter peak error at PCA) but it did have a noticeable effect upon the orbit as determined by the integrated range rate experiment. For most applications the magnitude of this error is probably negligible. However, when highly accurate orbits are desired, this range servo lag error should be taken into account and corrections should be made to the radar ranging data. The lag effects are deterministic in nature and corrections can be readily applied during post-mission data reductions.

2.3 Angle Error Investigations

The GEOS-3 C-Band Radar Investigations program incorporated no plans for a detailed investigation of C-Band radar angle errors. In its normal orbital generation routines, NASA weighs the radar angle data such that essentially range only solutions are obtained. Therefore, the behavior of the radar angle tracking loops was not of primary concern to NASA. However, the availability of high accuracy range only orbits provides a ready reference for evaluating angle tracking data. Some limited use of the orbital data for angle tracking assessment was therefore conducted based upon tracking data accumulated during the two week intensive tracking interval of GEOS-3 (late February, early March 1976).

Krabill and Martin present tabular results of the angle tracking evaluations performed at NASA WFC (see Reference 6). Discussion of the results of these evaluations is also included in the reference. No additional discussion will be included in this report except to note that the angle tracking data were, in general, remarkably accurate. A somewhat surprising result was that data from sites using extensive angle calibration equipments/techniques did not appear to be significantly more accurate than data from sites such as NASA-WFC where angle calibrations are considered to be of only secondary importance. Another surprising result as noted by Krabill and Martin was:

> "Although on-axis radars showed generally much lower noise levels than non-on-axis radars, there was no comparable lack of systematic patterns, particularly for lags."

The above quote is surprising in its content since it was expected that on-axis radars with their computer aided angle tracking would exhibit noticeably smaller lag error effects. Such did not prove to be the case at least for the limited data set analyzed.

3.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

3.1 Radar Range Rate Investigations

(1) A systematic hardware dependent error was identified in the C-Band Radar pulse doppler systems. The cause of the error was isolated and correction techniques were formulated, tested and found to be valid.

(2) A technique for range rate bias calibration was formulated, tested and found to be valid. Residual range rate bias errors after calibration were unresovable using the orbital generators available. The residual error is probably on the order of 1 cm/sec or less.

(3) Investigations were made into the use of integrated range rate data. These investigations proved most useful in using the resulting doppler derived ranges as an evaluation tool for analyzing the performance of both the radar's range rate and ranging subsystems. Noise levels of the integrated range rate range data were at the 2-3 cm level.

In conclusion, the C-Band Radar range rate investigations were extremely successful. This measurement system was found to be both highly precise and highly accuracte. Additional efforts might be warranted in developing filtering techniques for optimal combining of range and range rate data so as to obtain a best estimate of target range from the two independent sets of data.

3.2 Radar Range Data Investigations

(1) C-Band Radar range measurements were found to be sufficiently stable to permit bias error estimation and elimination to be performed. Corrected data were found to be adequately accurate to meet the GEOS-3 Altimeter Calibration requirements.

(2) Short term range bias changes were observed from time-to-time and, after investigation, could generally be attributed to changes in site operating/calibration techniques.

(3) Long term range bias drifts were noted in at least three of the NASA radars. While quite small (~+2.5 cm/day), the source of this drift error could not be isolated as being radar dependent. The possibility exists that transponder effects are at least partially responsible for the observed error trend.

(4) Pulsewidth Bandwidth - Mismatch error investigations were conducted which appeared to provide less than satisfactory prediction of this mismatch range tracking error. Due to the unresolvable nature of the range drift error however, it is conjectured that the mismatch error experiment may have in fact yielded useful results. A combination of the observed mismatch error with a hypothetical transponder delay error could be used to account for the observed long term drift in the range residual errors from several radars.

(5) Analysis of integrated range rate residual errors led to the identification of transponder receive signal strength dependent delay variations as a significant source of orbital error. Use was made of the radar's AGC voltage to correct the raw radar range measurements for this transponder delay variation error.

Radar range tracker lag error effects were also noticeable in the integrated range rate residuals. It was found that this error could be removed to a satisfactory level by applying corrections based upon the theoretical models for the lag error effect.

In conclusion, the C-Band radar range data were found to be fully adequate to meet the goals of the overall GEOS-3 program. Corrected range data were found to be accurate within the 1 to 5 meter level. It is recommended that additional investigations/experiments be conducted to further test the validity of the mismatch error measurement technique. If found to be valid, this technique could be of widespread interest to the C-Band radar (and all other pulsed radars) community.

3.3 Radar Angle Error Investigations

(1) Radar angle tracking errors were found to be in agreement with predictions as long as reasonable care was taken in performing angle calibrations. Results also indicated that recourse to more sophisticated angle error calibration techniques and equipments, while useful, did not yield commensurate improvements in tracking accuracy. The cost effectiveness of these newer calibration techniques thus becomes questionable. The data user community must be the final arbiter of the need for such techniques.

(2) The usefulness of satellite calibration techniques (range and angle) was vividly demonstrated during the GEOS-3 C-Band Radar Experiment. Both single station multi-arc and multi-station single/multi-arc solutions showed sensitivities which are more than adequate for radar calibration purposes.

It is concluded that satellite calibration techniques are the most effective method for calibration of tracking radars. It is recommended that the C-Band Radar community give serious consideration to the development and launch of dedicated Radar Calibration Satellites.

REFERENCES

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(3) Krabill, W.B. and D.J. Dempsey; "C-Band Radar Pulse Doppler Error, Its Discovery, Modeling and Elimination"; NASA WFC Technical Memorandum 69366; February 1978.

(4) Krabill, W.B.; "Range and Range Rate Bias Solutions for Various C-Band Radars"; Minutes of C-Band Working Group Meeting held at NASA WFC; September 21-23, 1976.

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(6) Krabill, W.B. and C.F. Martin; "C-Band Radar Calibration Using GEOS-3"; NASA WFC Technical Memorandum 73275; March 1978.

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Table A-1(a)

ESTIMATED WFC AN/FPQ-6 RANGE BIAS

- FSR USED AS REF. RNG. TGT -

- PRE DLM -

Days After Launch	GEOS-3 Orbit No.	Date (1975)	Range Bias (meters)*
19	202-03	4/23	-8.3
22	240	4/26	-8.0
24	267-68	4/28	-8.5
25	274-75	4/29	-7.6
26	288-89	4/30	-8.1
28	324-25	5/2	-8.2
34	410-411	5/8	-6.4
139	1975	8/27	-3.8**
140	1994-95	8/28	-4.6**
146	2073-74	9/3	-1.5
148	2107-08	9/5	-0.2
152	2159	9/19	-3.9
154	2187-88	9/11	+0.8
154	2193-94	9/11	-4.3**
158	2244-45	9/15	-7.0
160	2273-74	9/17	-2.8
162	2301-02	9/19	-6.7
162	2306	9/19	-3.3
166	2349-50	9/23	-3.2
208	2955-56	11/4	-3.5
238	3381-82	12/4	-3.2

* Bias errors adjusted by -2.1 m to account for reference range target effects.

** Denotes bias relative to laser generated orbit.

Table A-1(b)

ESTIMATED WFC AN/FPQ-6 RANGE BIAS

- MET TWR. USED AS REF. RNG. TGT. -

- PRE DLM -

Days After Launch	GEOS-3 Orbit No.	Date (1976)	Range Bias (meters)
288	4078-79	1/23	+4.1
292	4135-36	1/27	+2.6
---------------DELAY LINE ADJUSTMENTS ---------------			
319	4524-25	2/23	-2.8
---------------DELAY LINE ADJUSTMENTS ---------------			
320	4538-39	2/24	+0.3
321	4547-48	2/25	+1.4
322	4561-62	2/26	+1.9
---------------DELAY LINE ADJUSTMENTS ---------------			
323	4581-82	2/27	+1.1
---------------DELAY LINE ADJUSTMENTS ---------------			
326	4624-25	3/01	-0.2
328	4652-53	3/03	+2.3
---------------DELAY LINE ADJUST & TR TUBE REPLACED ---------------			
329	4666-67	3/04	-2.7
330	4681-82	3/05	-0.3
344	4880-81	3/19	+0.5
---------------DELAY LINE ADJUSTMENTS ---------------			
347	4922-23	3/22	-3.5
348	4936-37	3/23	+5.0
--------------- DELAY LINE ADJUSTMENT ---------------			
351	4979-80	3/26	+2.0
354	5022-23	3/29	+1.3
357	5064-65	4/1	+3.8
---------------DELAY LINE ADJUSTMENTS ---------------			
361	5121-22	4/05	+1.6
364	5164-65	4/08	+5.2
---------------DELAY LINE ADJUSTMENTS ---------------			
371	5263-64	4/15	+3.4
376	5320-21	4/20	+5.0
386	5463-64	4/30	+3.3
391	5542-43	5/05	+2.5
406	57755-56	5/20	+5.8

TABLE A-1(b) (continued)

Days After Launch	GEOS-3 Orbit No.	Date (1976)	Range Bias (meters)
477	6756-57	7/30	+7.2
481	6813-14	8/03	+5.8
---------------- TR TUBE REPLACED ----------------			
509	7206	8/31	+3.2

Table A-1(c)

ESTIMATED WFC AN/FPQ-6 RANGE BIAS

- MET TWR. USED AS REF. RNG. TGT. -

- POST DLM -

Days After Launch	GEOS-3 Oribit No.	Date (1976)	Range Bias (meters)
543	7695-96	10/4	+8.0
546	7737-38	10/7	+8.4
547	7751-52	10/8	+7.6
554	7851-52	10/15	+10.8
560	7931-32	10/21	+9.0
565	8002-03	10/26	+8.2
578	8187-77	11/8	+13.0
580	8215-16	11/10	+16.1
589	8343-44	11/19	+13.7
594	8414-15	11/24	+10.4

Table A-2

NASA WFC AN/FPQ-6 BANDWIDTH SWITCHING

TEST RESULTS (No Radar Adjustments)

Days After Launch	GEOS-3 Orbit No.	Date (1975)	ΔR_T (meters)	ΔR_C (meters)
6	Unknown	4/16	15.9	11.6
126	1790	8/14	-	14.0
126	1795	8/14	-	14.9
126	1796	8/14	-	14.6
130	1846	8/18	-	14.0
130	1853	8/18	-	15.2
138	1961	8/26	-	14.9
138	1965	8/26	-	16.2
138	1966	8/26	-	16.8
144	2045	9/01	-	14.6
147	2103	9/04	13.2	-
148	2107	9/05	16.5	15.6
148	2108	9/05	17.8	14.2
152	2159	9/09	15.6	-
154	2187	9/11	16.7	15.6
154	2188	9/11	18.0	14.1
154	2193	9/11	17.7	15.1
158	2244	9/15	16.3	16.8
158	2245	9/15	18.2	16.7
160	2273	9/17	19.1	16.3
160	2274	9/17	17.2	15.1
162	2302	9/19	18.3	15.5
162	2306	9/19	16.1	-
166	2349	9/23	17.8	-
166	2350	9/23	16.7	-
166	2358	9/23	19.4	-
173	2449	9/30	18.3	-
173	2450	9/30	19.7	-
176	2492	10/3	17.8	-
208	2955	11/4	17.0	-

Table A-3

NASA WFC MEASURED AN/FPQ-6 PULSEWIDTH/

BANDWIDTH MISMATCH ERROR

Days After Launch	GEOS-3 Orbit No.	Date	$\epsilon_{mm} = 2(\Delta R_T - \Delta R_C)$ (meters)	Estimated Bias (meters)*
6	Unknown	4/16/75	+8.7	-8.8
148	2107-08	9/05	+4.5	-4.2
154	2187-88	9/11	+5.0	-4.0
154	2193	9/11	+5.2	-4.0
158	2244-45	9/15	+1.0	-3.8
160	2273-74	9/17	+4.9	-3.8
319	4524-25	2/23/76	+0.7	+1.5
320	4538-39	2/24	-0.8	+1.5
321	4547-48	2/25	+0.6	+1.5
322	4561-62	2/26	-0.4	+1.6
323	4581-82	2/27	-0.4	+1.6
326	4624-25	3/01	-0.6	+1.7
328	4652-53	3/03	-0.8	+1.8
329	4666-67	3/04	+0.8	+1.8
330	4681-82	3/05	+0.8	+1.8

* Note - Estimated true Bias obtained from best Linear Fit to Orbital Bias Solutions.