X-932-74-212
PREPRINT

NASA TM X- 70722

GEOS OBSERVATION SYSTEMS INTERCOMPARISON INVESTIGATION RESULTS

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(NASA-TM-X-70722) GEOS OBSERVATION SYSTEMS INTERCOMPARISON INVESTIGATION RESULTS (NASA) 45 p HC $5.25 CSCL 22A

N74-32293

Unclas
G3/31 46712

JULY 1974

GSFC

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GREENBELT, MARYLAND

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X-932-74-212

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ABSTRACT

This document is the result of an investigation designed to determine the relative accuracy and precision of the different types of geodetic observation systems used by NASA. A collocation technique was used to minimize the effects of uncertainties in the relative station locations and in the earth's gravity field model by installing accurate reference tracking systems close to the systems to be compared and precisely determining their relative survey. The Goddard laser and camera systems were shipped to selected sites, where they tracked the GEOS satellite simultaneously with other systems for an intercomparison observation.

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1. INTRODUCTION

One of the NGSP objectives was to intercompare the observations from the different types of geodetic observation systems used by NASA (MINITRACK, MOTS, GRARR, C-band radar, laser), Smithsonian Astrophysical Observatory (Baker-Nunn, laser), Air Force (PC-1000), Army (SECOR), Navy (TRANET), and Coast and Geodetic Survey (BC-4) to aid decisions on how to properly weight and combine the data from the different systems for the World Datum and Earth Gravity Field Model and to indicate which systems would be most useful for future geodetic research and applications. An investigation was designed to determine the relative accuracy and precision of these systems to better than 10 meters. This paper summarizes the results of this investigation.

2. METHODS USED

If reference orbits accurate to better than 10 meters were available, then these orbits could be used to determine the errors in the systems. However, because of survey and gravity field errors, the errors in the most accurate orbits at the time this investigation was initiated were estimated at 100 to 1000 meters.

Therefore, a collocation technique was used to minimize the effects of uncertainties in the relative station locations and in the earth's gravity field model by installing accurate reference tracking systems close to the systems to be compared and precisely determining their relative survey. This approach also allowed local synchronization of the system clocks. The laser and camera systems available at Goddard, which were thought to be accurate to 1 to 2 meters and 1 to 2 arc seconds, respectively. were chosen as the reference systems for the investigation. These systems are described elsewhere.

The Goddard laser and camera systems were shipped to selected sites, where they tracked the GEOS satellite simultaneously with the other systems. A reference orbit was determined by a least-squares fit of the reference data (R) on each pass and used to compute reference quantities (C) for the systems to be compared. The actual observations (O) from the systems being compared (called comparison systems) were first preprocessed to remove the known errors and to achieve compatibility with the reference quantities (C), then differenced with the reference quantities to form the residuals (O-C). Measurement biases (B) and timing biases (T), both relative to the reference systems, were then derived from the residuals (O-C) by means of the relationship

$$(O-C)_i = B - T\,\dot{C}_i + E_i$$

where $\dot{C}_i$ is the time rate of change of the quantity C_i and E_i is the noise component in the observations.

This procedure has the following characteristics:

1. The orbit program corrects for the parallax errors due to the different locations of the systems.

2. Errors in the reference trajectory due to errors in the gravity field model are held to within ±1 meter during the 15-min or less duration of a single pass (reference 1). These errors are not inherent in the observations (R), but are inherent in the quantities (C) computed for the comparison systems, owing to imperfect fitting of the observations (R) by the computed orbit due to unknowns in the gravity field model.

3. By local synchronization of the clocks of the reference and comparison systems, timing errors due to clock differences are held to ±0.1 msec or less. This is equivalent to ±0.5 meter or less in range measurement for the maximum range rates. The program corrects for known time differences between the observations (R) and the comparison system observations (O) when the quantities (C) for the comparison systems are generated.

4. Except for the small errors cited above, the reference orbits produce reference quantities (C) and residuals (O-C) for nearly collocated systems, which are as accurate as the data (R) to which these orbits are fitted. Thus the reference orbits produce quantities (C) which are accurate to the 1 to 2 meter accuracy of the data (R) within the laser data span. This level of derived range accuracy produces a derived range rate accuracy of 0.5 to 2.0 cm/sec. Likewise, the reference orbits produce angles (C) for nearby systems, which are accurate to the 1 to 2 seconds accuracy of the camera systems (R) within the camera data span. Thus, to the extent that measurement and timing biases, assumed constant over one pass, are adequate error

models, the bias differences are determined to at least the accuracy of the point-by-point accuracies quoted above for the reference systems.

3. TESTS PERFORMED

During this investigation, one intercomparison of cameras and a series of five intercomparisons of laser systems were performed to determine whether these reference systems were consistent to within their estimated accuracies of 1 to 2 seconds and 1 to 2 meters, respectively.

Other systems were compared against collocated reference laser systems and/or cameras in the following tests:

1. GRARR at Rosman, North Carolina.
2. Two C-band radars, SECOR, and TRANET, at Wallops Station, Virginia.
3. GRARR and C-band at Carnarvon, Australia.
4. MINITRACK at all sites.

3.1 CAMERA INTERCOMPARISON TEST

An intercomparison of some of the different camera types was conducted at Jupiter, Florida, where NASA/GSFC MOTS-40, MOTS-24, and PTH-100 cameras were located within 30 meters of each other and operated simultaneously with the SAO Baker-Nunn and K-50 cameras and with an Air Force PC-1000 and a NASA-Langley BC-4 (300-mm focal length) camera during the period November 1965 to May 1966. GEOS-1 was tracked. Details are given in reference 2.

3.1.1 Combined Data Orbits

The flashing lights on the GEOS-1 and -2 satellites were programmed to flash in sequences of seven flashes. The first flash fell on the even minute and subsequent flashes were spaced at 4.0-sec intervals for a total duration of 24-sec.

For each seven-flash sequence, observed simultaneously by two or more of the Jupiter cameras, an initial set of orbital elements was differentially corrected to obtain a least-squares fit over the 24-sec span of data to all the observations by these cameras. For each participating camera, an rms of the seven right ascension residuals and an rms of the seven declination residuals were calculated for each sequence. The mean rms, averaged over the indicated number of sequences, is given on the left side of Table 1 for each camera.

These results tend to verify the 1 to 2 seconds accuracy estimate for the NASA MOTS-40 and PTH-100 reference cameras, since data from these cameras are consistent with data reduced from different camera systems by independent organizations.

The larger rms values for the MOTS-24 and the BC-4 cameras are probably due to both the shorter focal length and the smaller aperture of these cameras. The shorter focal length makes the observations more sensitive to measuring errors, and the smaller aperture makes the flashing light and stellar images less distinct and more difficult to center on the measuring system crosshairs. Also, some of the BC-4 right ascension observations may have been affected by timing problems (reference 2).

3.1.2 Bias Relative to the MOTS-40

To determine whether there were any consistent angular biases, orbits computed with observations from MOTS-40 and with observations from at least one other camera were selected for further analysis. For each 24-sec orbit from MOTS-40 data the means of the seven right ascension residuals and of the seven declination residuals for the MOTS-40 were subtracted from those for the other participating cameras. The resulting differences in the means are a close approximation to the angular biases for the comparison cameras relative to the MOTS-40. These differences in means are averaged over the indicated number of sequences and the average (B) is given on the right side of Table 1 for each camera, along with the rms fluctuation (σ) of each set of differences about its average value (B). The total rms ($\sqrt{B^2 + \sigma^2}$) is also given. These results support the accuracy estimates for the cameras, since the average of the mean differences (B) is generally less than 1" and the rms fluctuation (σ) of these mean differences about their average is generally less than 2".

3.2 INTERCOMPARISON OF LASER SYSTEMS

Five tests were performed during the two years October 1968 through October 1970. Three of the tests were at the Goddard Optical Research Facility (GORF) between the prototype Goddard laser system (GODLAS) and the transportable Goddard laser system (MOBLAS, MOBLA-2, or MOBLA-3). The other two tests were at the Smithsonian Astrophysical Observatory (SAO) site at Mt. Hopkins, Arizona, between the SAO laser system (HOPLAS) and the MOBLAS (called HOMLAS or HOMLA-2 in these tests). Details on all five tests are given in reference 3.

In each test the range, azimuth, and elevation (RAE) [illegible] MOBLAS were used to form a reference orbit on each pass by adjusting a[illegible]itial se[illegible] orbital elements by least squares. The adjustment results in a zero mean for the residuals in range and azimuth. The mean of the residuals in elevation was us[illegible]y different from zero by a few seconds, owing to correlation with the ranges, which were more heavily weighted. The residuals appear random, with no systematic effects remaining except the nonzero mean of the residuals in elevation. Therefore the rms of the residuals in range and azimuth may be interpreted as noise.

The residuals obtained from the MOBLAS orbit for the other laser systems were then used to determine a measurement bias (B) and a time bias (T) for each pass, as was descr[illegible]ed earlier. After fitting this error model to the residuals, the remainders (E_i) appear random with zero mean and may therefore be interpreted as the noise in the observations from the comparison laser systems.

The results of all five tests are shown in Table 2 and Figure 1.

3.2.1 GORF-1 Test

GODLAS was compared with MOBLAS at the Goddard Optical Research Facility in the October through November 1968 period. The assembly of MOBLAS had been completed just before this experiment, and this test includes some of the first passes taken by MOBLAS. Five passes were observed simultaneously in this test.

The initial analysis of the GORF-1 data indicated that GODLAS and MOBLAS had an average rms error in range of 1.86 and 1.23 meters, respectively, after a reference orbit had been fitted to the ranges from MOBLAS on each pass and GODLAS range and time biases had been solved for on each pass. The average bias in range of GODLAS with respect to MOBLAS was 4.1 meters for the five passes, and the rms fluctuation of the five biases about this average was ±0.6 meter.

The GSFC Optical Systems Branch analyzed the calibration technique used with MOBLAS during this test. They established that MOBLAS was calibrated at a signal level that was two orders of magnitude larger than the level expected for the returned signal. It was later determined that MOBLAS reads short by 4.6 meters under these conditions.

If the MOBLAS data are corrected by adding 4.6 meters to each range measuremen[illegible] the bias of GODLAS (with respect to the orbit computed from MOBLAS data as shown in the second line of Table 2) is reduced from 4.1 ± 0.6 meters to -0.5 ± 0.6 meters. The noise remains the same.

In all tests conducted after the GORF-1 test, MOBLAS was calibrated for the level expected from the returned signal.

3.2.2 ARLACO Test

The Arizona Laser Collocation (ARLACO) test was conducted from October 1969 through January 1970. MOBLAS was collocated with the SAO laser system (HOPLAS) at the Mt. Hopkins Observatory in Arizona. Halfway through the test, MOBLAS was moved 10 meters to the west, thus breaking the experiment into two tests, ARLACO-1 and ARLACO-2.

An analysis of the data from the first two passes revealed a range bias of 5.5 meters and a time bias of 100 msec for HOPLAS with respect to the orbit computed from MOBLAS data. Of the 5.5 meters, 4.8 meters were traced to a change in the internal delay in the HOPLAS system since the last calibration. The 100 msec time bias was due to an intentional offset in the times of HOPLAS observations to avoid interference with observations by MOBLAS, but the offset was overlooked in the processing. After these discrepancies were corrected, the intercomparison continued.

For the 14 passes observed during the October-November 1969 period, the HOPLAS ranges had an average noise of 1.34 meters. The MOBLAS ranges had an average noise of 1.06 meters. The average bias of the HOPLAS ranges with respect to the orbit from the MOBLAS data was - 1.6 ± 1.5 meters.

During the second phase of ARLACO, December 1969 through January 1970, data were taken on 11 passes. The noises for HOPLAS and MOBLAS were 1.09 and 1.00 meters, respectively, and the average bias of the HOPLAS ranges with respect to the orbit computed from MOBLAS was 1.3 ± 1.7 meters.

3.2.3 GORF-2 Test

The GORF-2 test took place between March 1970 and May 1970. At that time MOBLAS was the same as it was during the CALACO experiment. Data were taken on 21 passes. GODLAS and MOBLAS had an average noise level of 1.00 and 1.06 meters, respectively, and an average bias of -1.2 ± 1.3 meters for the GODLAS ranges with respect to the orbit computed from the MOBLAS data.

3.2.4 GORF-3 Test

Between the GORF-2 and GORF-3 tests, both the MOBLAS and GODLAS systems were modified to incorporate a more sophisticated pulse detection scheme. Pulse height was measured and the pulse threshold detection level was set at one-half the measured pulse height. In addition, a quantitative measure of the MOBLAS pulse height was made, recorded, and was used in a software correction of the range measurements on the MOBLAS. This feature was present in the GODLAS during earlier tests.

The results of the GORF-3 tests, although not applicable to the earlier laser intercomparisons with GRARR, C-Band, SECOR, and TRANET, show significant reductions in the laser system noise and relative range bias, with all parameters at the submeter level.

3.2.5 Summary of Laser Results

The tests support the estimate of 1 to 2 meter single pass accuracy for the Goddard reference laser systems. The average of the biases derived on each pass for the GODLAS ranges with respect to the orbit computed from MOBLAS data lies between -1.2 ± 1.3 and 0.9 ± 0.3 meters for the three GORF tests. The average of the biases for the SAO HOPLAS with respect to the orbit computed from MOBLAS data lies between -1.6 ± 1.5 and 1.3 ± 1.7 meters for the two ARLACO tests.

3.3 INTERCOMPARISONS OF OTHER SYSTEMS WITH THE LASER AND CAMERA

Besides the tests described above, three other comparisons between a laser system and other systems were conducted during this investigation. These were the Rosman Laser Collocation (ROLACO) test to compare GRARR on GEOS-1 (reference 4), the Wallops Island Collocation Experiment (WICE) to compare the FPQ-6 and TPS-16 C-band radars, a SECOR system, and a TRANET system on GEOS-2 (references 5 and 6) and the Carnarvon Laser Collocation (CALACO) experiment to compare another GRARR and FPQ-6 radar on GEOS-2 (reference 7). The Goddard Laser System (GODLAS) was used as the reference laser for the ROLACO and WICE tests, and MOBLAS (called CRMLAS at Carnarvon) was used for the CALACO test.

The data were analyzed in these tests as in the laser/laser tests (section 3.2). The residuals in range, azimuth, and elevation (RAE) from laser systems were minimized in the least-squares sense by adjusting a set of orbital elements for each pass to form a reference (RAE) orbit. The mean and rms of the comparison system residuals about the RAE orbit were computed for each type of observation and for each pass. In the tables given here, the average mean and the average rms over the number of passes indicated are given. These are designated as "mean before" and "rms before," since they are determined from residuals before fitting an error model. In addition, the rms fluctuation of the means for each pass about the average mean for all passes and of the rms's for each pass about the average rms is given in the same columns.

On each pass, the residuals for the comparison systems were used to determine a measurement bias (B) and a station time bias (T) relative to the laser system. The term "station time bias" is used to indicate that each type of observation from a given comparison system contributes to the determination of the time bias of that system. In these tables, only the average B and T over the indicated number of passes is given, along with the rms fluctuation of the single pass B and T about the given average. Since T is usually small, the average bias B is almost the same as the mean before fitting the error model. The mean after fitting the error model is not given in the tables, since it is always zero. The column headed "rms after" is the rms of the average residual after fitting the error model, along with the rms fluctuation, in the rms's for each pass, about the average rms. These numbers represent the noise in the observations by the comparison system.

The RAE reference orbits closely fit the observations from the laser system within the laser data span and therefore produce reference ranges and angles for nearby systems with essentially the same accuracy or bias as the laser system data. From the previous (laser/laser) tests the range biases for the laser system are below 2 meters with respect to other laser systems. As will be shown later, in tests involving camera observations, the biases in the laser system angles with respect to camera observations are below 30". Error analyses indicate the range rate accuracies from the laser system RAE orbits are within 0.5 to 2.0 cm/sec.

To evaluate the observed angle, observations from a collocated camera are used instead of the laser system azimuth and elevation observations in forming reference orbits when camera data are available. These orbits are designated range, right ascension, and declination (RRD) orbits. The RRD orbits fit the laser system range and camera system angle observations closely and therefore produce reference ranges and range rates, for nearly collocated systems, with essentially the same accuracy as the RAE orbits and produce improved angles with the 1" to 2" accuracy of the camera data.

3.3.1 ROLACO Test

The results of the July through December 1966 GEOS-1 ROLACO test of the Rosman GRARR versus GODLAS are summarized in the statistics in Table 3 and in the plot of the derived GRARR relative range biases against date in Figure 2. After an orbit was fitted to the data from the laser system, the remaining rms noise was 1.8 meters for the laser.

An earlier evaluation of the Rosman GRARR by means of GEOS-1 short-arc reference orbits generated with data taken the first week of January 1966 from four eastern U. S. SECOR stations had indicated this GRARR had a range bias of -20.5 ± 4.9 meters (reference 8). Investigations into the cause of this bias led to the discovery of several small errors in the GRARR calibration and preprocessing procedures which accounted for -9.7 meters of the GRARR range bias (reference 9), leaving a net bias of -10.8 ± 4.9 meters for the Rosman GRARR at that time.

For the ROLACO test the GRARR calibration and preprocessing procedures were changed to add the above corrections, resulting in an average single-pass bias in the GRARR range data relative to the laser orbit of -5.3 meters with an rms fluctuation of 12.4 meters about this average value for the 10 bias values obtained. The average GRARR time bias relative to the laser was -2.1 ± 1.2 msec. All 10 passes were on GRARR channel A. More details are given in reference 4.

In an independent comparison of the Rosman GRARR observations with accurate orbits obtained from camera observations, Lerch, Marsh, and O'Neill (reference 10) reported average range and time biases on channel A of -10.0 ± 8.8 meters and -2.4 ± 2.4 msec on 12 passes relative to a 5-day orbit during the first week of January 1966, and -5.6 ± 11.6 meters and -1.9 ± 5.1 msec on 14 passes relative to another 5-day orbit a week later. These results included the -9.7 meter bias correction mentioned above. The -10.0 meter GRARR channel A bias obtained here is in remarkable agreement with the -10.8 meter GRARR channel A bias obtained with respect to the SECOR orbits during the same first week in January 1966. The long arc GRARR results obtained for the second week of January 1966 are consistent with the ROLACO test results for data taken 6 to 12 months later.

Lerch, et al also reported average biases on channel C of 18.1 meters and -1.4 msec on 3 passes during the first 5-day orbit.

3.3.2 WICE Test

The WICE statistics for the two C-band radars, the SECOR, TRANET, and laser systems and the camera systems are summarized in Tables 4 and 5. Table 4 gives the results for all the available passes, using GODLAS data to generate RAE reference orbits. Table 5 gives the results for those passes which had collocated data from the PTH-100 camera to combine with the laser system data to generate RRD reference orbits. Both the RAE and the RRD orbits provide reference ranges with essentially the accuracy of the laser system data. The accuracy of the angles from the RAE orbit is determined by the accuracy of the laser system angles (about 30"), whereas the accuracy of the reference angles from the RRD orbit is determined by the camera angles (1" to 2").

In Figures 3, 4, 5, and 6 the pass-to-pass variations in the derived biases in range, range rate, azimuth, and elevation are shown for the participating systems. (More details may be found in references 5 and 6).

Examination of the tables and figures reveals the characteristics of the participating systems as outlined below.

3.3.2.1 Rms and Bias in Range

The rms noise in data from GODLAS was reduced in this test from the earlier ROLACO value of 1.8 meters to 1.3 meters. After error modeling, the rms noise in the C-Band radar and SECOR ranges is also less than 2 meters. The FPQ-6 data are the smoothest, averaging 1.0 meter over the 34 RAE orbits and 0.8 meter over the 21 RRD orbits.

In the 34 simultaneous trackings by laser systems and by the FPQ-6 on beacon, there were 10 passes in which the radar tracked both beacon and satellite surface on the same pass; i.e., the beacon was tracked on the first third of the pass, the surface on the middle third of the pass, and the beacon again on the last third of the pass. For these passes the bandwidth of the FPQ-6 receiver was optimized to receive a 1.0-μsec-wide pulse rather than the 0.6-μsec-wide pulse used in tracking beacons. The pulse width mismatch resulted in the ranges from the beacon tracking being short by approximately 30 meters, and these ranges were corrected by adding 30 meters. If these 10 passes are ignored, the remaining 24 passes (beacon only) (shown in Figure 2) yield essentially the same results as all 34 passes, except the average bias in range is changed from -1.6 ± 2.6 to -2.0 ± 2.7 meters, as shown in Table 4.

In the 27 sets of data from FPS-16 on a beacon the average of the range biases is 5.7 ± 4.1 meters, resulting in a net difference between the biases of 7.3 meters in the two radars.

The radar calibration techniques used in WICE were analyzed by the Wallops Station personnel. The results of the analysis and tests verifying the analysis indicated that the FPQ-6 and FPS-16, were miscalibrated and their range data should be corrected by algebraically adding -0.6 meter to the FPQ-6 and -7.9 meters to the FPS-16 measurements. If this correction is made, the range bias on the FPQ-6 of -1.6 ± 2.6 meters shifts to -2.2 ± 2.6 meters, as shown in Table 4. The average FPQ-6 range noise of 1.0 ± 0.3 meters and time bias of 0.3 ± 0.3 msec remain unchanged. If the FPS-16 data are corrected for the -7.9 meter calibration error, the average range bias changes from 5.7 ± 4.1 to -2.2 ± 4.1 meters. The two collocated C-band beacon track average range biases then agree with each other to better than 0.1 meter. The results in Tables 4 and 5 were obtained before the post-test calibration analysis and hence do not include these corrections except where indicated.

FPQ-6 skin track data were successfully taken on 8 of the 10 passes where skin tracking was attempted. No FPS-16 skin tracks were attempted. The average range rms noise and average range bias for the skin track portion of the 8 FPQ-6 passes were 8.6 ± 2.0 meters and -5.2 ± 2.7 meters, respectively. The corresponding averages for the beacon track portion of the same 8 passes were 1.1 ± 0.4 meters for range noise and -1.8 ± 2.2 meters for range bias. Thus, the FPQ-6 skin track range bias is 3.4 meters more negative than the FPQ-6 beacon track range bias on the 8 common passes.

There were 16 passes that were common to the 24 FPQ-6 and 27 FPS-16 beacon-only passes. This breakdown is not shown in Table 4, however, if the derived biases for the two radars are differenced on each of the 16 common passes, the average range bias difference of the FPS-16 relative to the FPQ-6 is 6.3 ± 5.6 meters. If the calibration analysis corrections of -0.6 and -7.9 meters are applied, this average range bias difference is reduced to -1.0 ± 5.6 meters.

Note that the pass-to-pass variation in range bias in the radars (Table 4) was ±2.6 meters for the 34 FPQ-6 biases and ±4.1 meters for the 27 FPS-16 biases when taken relative to the laser system. The pass-to-pass variation in range bias increased to ±5.6 meters when the FPS-16 biases were taken relative to the FPQ-6 biases, indicating the uncorrelated nature of the range bias in the two radar systems.

The correlation coefficient between the FPQ-6 and FPS-16 range bias values for the common 16 passes is -0.22, indicating the pass-to-pass variations in bias are probably not due to the laser system.

The difference in FPQ-6 average range bias obtained with all 20 beacon-1 (0.750 microsec delay) tracks relative to that obtained with all 14 beacon-2 (4.935 microsec delay) tracks is -1.6 meters (see Table 4). A similar comparison with the FPS-16 for 14 beacon-1 and 13 beacon-2 tracks leads to a value of +2.6 meters. Thus, if a consistent range bias exists between beacon-1 and beacon-2 tracks for both radars, it is obscured by the pass-to-pass fluctuations in range bias for the two radars.

The average range bias of -17.5 ± 4.0 meters in SECOR appears realistic to within the estimated laser system accuracy of 1 to 2 meters, especially since the analysis of the radar calibration discovered the -7.9 meter error on the FPS-16 and reduced its bias relative to the laser system from 5.7 to -2.2 meters. An analysis of the SECOR calibration and preprocessing procedures by the Army Map Service led to the correction of several minor preprocessing errors, which changed the derived biases by 1 or 2 meters in earlier submissions of these data. However, the analysis failed to account for the large bias shown in Table 4 for the latest submission. The temporal variation in the biases shown in Figure 3 suggests that the delay characteristics of the satellite transponder may have been changing slowly with time. A linear extrapolation of the SECOR range bias values in Figure 3 intersects the zero bias about one month before the launch of GEOS-2 on 11 January 1968, when presumably the last calibration of the transponder could have been made.

3.3.2.2 Range Rate Rms and Bias

The FPQ-6 radar obtained range rate skin track observations on four of the laser passes. These data were relatively noisy because of the low signal levels involved in skin tracking GEOS-2. However, the average range rate bias of +2.4 cm/sec is not unreasonable, considering the laser orbit estimated accuracy of ±0.5 to ±2.0 cm/sec in range rate.

The WICE TRANET station could track on the two lower GEOS-2 Doppler beacon frequencies (162 and 324-MHz, designated by TRAN-59) or on the higher pair (324 and 972-MHz, designated by TRAN-35). In order to conserve spacecraft power, the 972-MHz beacon was turned off part way through these tests, so fewer passes were obtained by TRAN-35.

The initial analysis of the TRANET data yielded range rate positive biases of 21.2 ± 7.7 and 18.4 ± 5.5 cm/sec for TRAN-59 and TRAN-35, respectively. An analysis of the Naval Weapons Laboratory (NWL) editing and preprocessing procedures indicated that at least some of this bias was due to the NWL practice of omitting the satellite-to-station transit time correction and the tropospheric refraction correction prior to solving for a per-pass bias, which was then provided with the observations on each pass. This per-pass bias absorbs the bias component of the error due to neglecting the two corrections. When the user applies the provided per-pass bias as well as the two omitted corrections, he overcorrects for the neglected corrections by the amount of the bias component absorbed in the per-pass bias provided by NWL. Since the transit time correction is always a negative time correction, which adjusts the observation times back to when the signals left the satellite, the net result is always a positive range rate bias.

Agreen and Marsh (reference 11) compared observations from 5 TRANET stations against 13 optical 2-day reference orbits generated from worldwide camera data. They reported a positive average range rate bias for all 5 participating TRANET stations of 8.2 to 10.2 cm/sec ± 2.4 to 3.4 cm/sec relative to the optical orbits. It has not yet been explained why the TRANET positive range rate biases found in this analysis were only about half the magnitude of those found in the WICE test.

As a result of the WICE analysis, NWL again preprocessed the early WICE TRANET data. This time the two corrections mentioned were made before solving for the per-pass bias. These final results are also given in Table 4, where it can be seen that the biases with respect to the RAE orbits are now reduced to 1.4 ± 3.5 cm/sec for TRAN-59 and -3.2 ± 7.5 cm/sec for TRAN-35. The results with the fewer RRD orbits are slightly better.

The TRANET biases for a single pass are plotted against time in Figure 4 where the wider fluctuations in derived biases at the beginning of the test may reflect a learning period for the operators.

3.3.2.3 Angle Rms and Bias

The biases in azimuth and elevation from pass to pass, relative to the RRD orbits, (Table 5 and Figures 5 and 6) indicate that the angle biases of the laser system are substantially less than the angle biases of the radar. However, the rms values indicate the radar point-to-point angle data are smoother than the laser system data.

In the angle residuals statistics, the camera right ascension residuals are multiplied by cosine declination and the laser and radar azimuth residuals are multiplied by cosine elevation in order to compare these residuals on the same sky angle scale as the declination and elevation residuals. The sky angle scale is also more useful for interpreting the results as radar boresight error or for relating the angle observation errors to target position errors.

The average angle biases in the laser system and the radars derived from the RRD orbits differ from those derived from the RAE orbits by less than 6 seconds. The average angle rms's derived from the RRD orbits differ from those from the RAE orbits by less than 10 seconds. Thus, the RAE orbits based on data from the laser system appear adequate for determining average angle biases and rms's to 10 seconds or better in tests such as WICE.

The average azimuth and elevation biases in the laser system data changed respectively from 0 ± 0 seconds and -6 ± 13 seconds for the RAE orbits to 5 ± 21 seconds and 0 ± 15 seconds for the RRD orbits, indicating that the RAE orbits are adequate for determining pass-to-pass angle biases to about 22 seconds or better (in the 1-sigma sense) in sucn tests.

3.3.2.4 Station Time Bias

The FPQ-6 and FPS-16 beacon track derived average station time biases are both 0.3 ± 0.3 msec relative to the laser, indicating the laser might have a -0.3 msec timing error. However, the FPQ-6 derived time bias of 0.1 ± 0.7 msec on 8 range data skin tracks, and the SECOR derived time bias of -0.6 ± 0.5 msec are not consistent with this interpretation.

The larger derived Tranet time biases evident on the RRD range rate evaluations are due to the high correlation between the derived range rate and time biases, and to relaxing the a-priori constraint on time bias from 0.2 msec on the RAE orbits to 2.0 msec on the RRD orbits.

3.3.3 CALACO Test

The CALACO test results for the collocated GRARR, FPQ-6 C-band radar, MOBLAS laser, and PTH-100 camera are summarized in Tables 6 and 7 and Figures 7 through 11. The statistics derived from the laser RAE orbits are given in Table 6 and those from the RRD orbits in Table 7. The temporal variation in the derived C-band range and timing biases and in the GRARR range, range rate, and timing biases are given in Figures 7, 8, 9, 10, and 11. respectively.

After sending the preprocessed C-band observations, the radar coordinator at Wallops Station advised us of a hardware problem that caused a time error of an unknown integral multiple of 10 msec. This error was constant within a pass but varied from pass to pass. It had not been feasible to determine the unknown integers by comparison with the worldwide long-arc orbits. However, comparison of the radar observations with the laser system observations enabled us to determine these integers and to correct the radar observation times by the proper multiple of 10 msec before the normal intercomparison procedure.

3.3.3.1 Range Rms and Bias

The MOBLAS range average rms noise remaining after fitting the orbits is 1.3 ± 0.2 meters, which is similar to the rms noise of 1.2 meters observed in the prior GORF-1 test.

The FPQ-6 C-band range rms noise, after removing a measurement and timing bias, is 1.1 ± 0.4 meters, similar to the previous results for the two C-band radars at Wallops.

The Carnarvon GRARR range rms noise of 3.0 ± 0.2 meters on GEOS-2 is smoother than the 6.8 ± 2.1 meter value obtained for the Rosman GRARR on GEOS-1. The difference could be due to the setup of ground systems, the different transponders, or the greater height of GEOS-1.

An average range bias of -15.0 ± 6.5 meters was initially found for the FPQ-6 relative to the laser system. In attempting to explain this large bias, it was determined that the radar range calibrations were performed on a distant range target without correction for the delay introduced by the atmosphere. By using values of atmospheric pressure, temperature, and humidity collected for the laser system and camera passes, the actual delay through the atmosphere to the range calibration target was calculated to be 20.0 ± 0.7 meters larger than the assumed value. Thus the radar calibration preprocessing for this station produced ranges that were too short by 20.0 ± 0.7 meters on each pass. A post-test calibration correction for this refraction bias was computed for each pass and applied to the range bias previously derived for that pass. As can be seen in Table 6, this step improved the average range bias from -15.0 ± 6.5 meters to 5.0 ± 6.7 meters. Users of these radar data should make certain that this refraction bias correction is applied.

Correction by the user of the remaining radar average range bias of 5.0 meters relative to the laser system reduces the pass-to-pass total rms error of that radar at that time from ± 8.4 to ± 6.7 meters. This assumes the following definition of total rms error:

$$\text{total rms error} = \sqrt{B^2 + \sigma^2}$$

where σ is the pass-to-pass bias fluctuation about B (σ = ±6.7 meters in this case) and B is the average range bias (B = 5.0 meters in this case).

When the FPQ-6 average range biases for the two C-band beacons are compared, the beacon-1 bias minus the beacon-2 bias is -1.7 meters before the above refraction correction is made and -1.5 meters after it is made. This difference is similar in magnitude and consistent in sign with the -1.6 meter difference obtained between beacon-1 and beacon-2 for the Wallops FPQ-6 but is not consistent with the +2.6 meter difference obtained with the Wallops FPS-16.

Similarly, a 3.2 meter difference in average range bias was noted between channels A and C of GRARR. This range bias difference was significant at the 1% level in a statistical test on the probability of a chance occurrence of such a difference. Application of the derived range bias corrections of -1.7 meters for channel A and -4.9 meters for channel C reduces the total rms range error from ±4.0 to ±3.6 meters for channel A and from ±8.9 to ±7.4 meters for channel C.

3.3.3.2 Range Rate Rms and Bias

The Carnarvon GRARR range rate rms noise of 1.4 ± 0.7 cm/sec is smoother than the values obtained during the WICE test for the C-band skin track data or for the TRANET Doppler data.

The GRARR average range rate bias, without regard to channel, of 0.5 ± 2.4 cm/sec, and the values for the individual channels are all smaller than the values for the WICE range rate systems and are within the estimated accuracy of the orbits based on laser system data. Correction for the derived range rate biases for GRARR in this test or for the FPQ-6 or TRANET (after the preprocessing correction noted) in the WICE test is not justified, since this does not improve the accuracy of the pass-to-pass range rate data significantly, owing to the variability in the derived pass-to-pass biases.

3.3.3.3 Angle Rms and Bias

Results for the 14 CALACO passes, with camera angle data added to the laser data to form RRD reference orbits, are given in Table 7. The zero means and small rms's for the observation residuals in the laser ranges and camera angles indicate that the RRD orbits have adjusted closely to these observations (R). Then the RRD orbits produce observations (C) having essentially the same bias as the observations (R) for evaluation of observations (O) from nearly collocated systems.

For both the radar and the laser systems, the angle residual average rms in Table 7 lies between 31 seconds and 38 seconds. The average of the angle residual mean is within ±30 seconds for both systems and is smaller for the laser system than for the radar.

3.3.3.4 Station Time Bias

The Carnarvon FPQ-6 radar derived average station time bias of 0.3 to 0.5 msec relative to MOBLAS is consistent with the 0.3 msec value derived for both radars relative to GODLAS in WICE. This result might indicate that a systematic error, having the appearance of a time bias, exists in the laser systems, were it not for the -0.6 msec value obtained for SECOR in WICE and the 0.0 msec value obtained for the GRARR in the CALACO test.

3.3.4 Intercomparisons of Minitrack With Collocated MOTS-40 Cameras

The MOTS-40 MINITRACK calibration camera at the center of each MINITRACK site observed GEOS flash sequences within the MINITRACK beam. The 24-sec reference orbits from these camera observations were used to determine a per-pass bias for the simultaneous MINITRACK observations. The results indicated that the MINITRACK observation per-pass biases relative to the camera orbits were about 10 to 20 seconds (reference 12).

A long-arc comparison of MINITRACK observations relative to a 5-day camera orbit indicated an rms for the MINITRACK per-pass angle biases of about ±40 seconds (reference 13).

It was noted in these studies that the MINITRACK biases were smaller when the refraction corrections normally introduced in the orbit differential correction (DC) program were suppressed, or when only those observations near the base line bisecting plane, which are therefore nearly immune to refraction error, were used. This effect was traced to an overcorrection for refraction in the DC program resulting from use of a single-path refraction correction rather than a differential two-path refraction correction required for an interferometer (references 14, 15, 16, and 17).

4. SUMMARY AND CONCLUSIONS

In this investigation it has been assumed that for the purposes of the NGSP the most important indicator of accuracy in the observations is the per-pass measurement bias (B) and time bias (T) and the pass-to-pass fluctuations (σ) in these biases. The point-to-point noise within a pass has little effect on the NGSP results, since these solutions are determined by the orbit adjusted to the observations and this orbit smooths out the nearly random noise of the data points within a pass, provided there are enough data points.

If the pass-to-pass fluctuation (σ) in the measurement bias (B) is random, then this parameter also is averaged out to some extent in the NGSP results, provided enough passes are used in the solutions. The stable component of the pass-to-pass bias has the most damaging effect on the solutions.

A composite error indicator used to help summarize the intercomparison test results is the total rms error, which equals $\sqrt{B^2 + \sigma^2}$. This error probably best estimates the relative accuracy of the GEOS observation systems for NGSP applications.

The pass-to-pass biases (B) were determined relative to orbits determined from the reference laser systems and cameras. Estimates of the accuracy of the reference system observations were supported by a camera/camera collocation test and by five laser/laser collocation tests. Other GEOS observation systems were evaluated against collocated lasers and cameras in three major tests performed at Rosman, North Carolina, at Wallops Island, Virginia, and at Carnarvon, Australia. Summaries of the various tests are available in a single document in reference 18.

4.1 CAMERAS

The Jupiter camera intercomparison test results support the 1 to 2 seconds accuracy per seven-flash sequence for most of the cameras tested, since for all but the shorter focal length and smaller aperture MOTS-24 and BC-4 (300 mm) cameras, the mean rms's with respect to the combined data orbits were within 2 seconds (Table 1).

A few NASA sites had MOTS-24 cameras originally, but these were all replaced by MOTS-40 cameras prior to GEOS-1.

The C&GS world geometric survey project at first used the 300-mm-focal-length BC-4 cameras, but later converted to the 450-mm-focal-length version, thereby improving the BC-4 plate scale by 50%. Also, the C&GS observations were shutter chops of the relatively bright continuous trails of the ECHO and PAGEOS balloons rather than of the GEOS flashes, thereby increasing the number of observations available for averaging and improving the detectability and measurability of the images on the photographic plate.

4.2 LASER SYSTEMS

The results support the 1 to 2 meter accuracy estimate for the lasers over one pass, since, except for the initial few passes with the new systems in the GORF-1 and ARLACO-1 tests the total rms error of the comparison systems with respect to the reference systems was within 2.2 meters (Table 8).

After the calibration error on the first few passes for MOBLAS was corrected, the total rms error for the GODLAS ranges with respect to an orbit computed from MOBLAS data was only 0.8 meter for GORF-1. The total rms error for GODLAS with respect to MOBLAS for GORF-2 and GORF-3 was respectively 1.8 meters and 0.9 meter.

4.3 ACCURACIES OF RANGING SYSTEMS

Unsuspected systematic errors were discovered in the observations from most of the systems. The identified systematic errors were usually traced to the calibration or preprocessing procedures rather than faults in the systems.

Table 8 summarizes the average and standard deviation of the range biases for each test derived for the comparison systems with respect to the reference systems.

The total rms error, before applying corrections discovered as a result of the tests, represents typical system accuracy for a pass under normal operating conditions, for which, however, an extra effort was made to remove known errors from the calibration and preprocessing procedures.

The probable sources of the identified biases and their measured corrections are also given in Table 8, along with the improved average range biases and total rms errors after these corrections had been applied. These improved total rms errors represent potential system accuracies for one pass only if the effort is expended to detect and correct the small calibration and preprocessing errors, such as those discovered in these tests.

The normal error estimates are probably best for relative data weighting for the NGSP solutions. The potential error estimates are useful for simulations investigating what is possible with these systems if the extra effort is made.

4.4 ACCURACIES OF RANGE RATE SYSTEMS

The range rate observations by GRARR and -band radar are probably unbiased to within the ability of these tests to detect a b

The TRANET data originally submitted for W s well as all other TRANET data in the Geodetic Satellite Data Service (GSDS), are affected by per-pass negative Doppler frequency biases, equivalent to the positive range rate biases resulting from the NWL preprocessing procedures.

These biases could be removed by reprocessing all the TRANET data and applying the corrections to transit time and tropospheric refraction before solving for the per-pass base frequency bias provided by NWL. This was done for the WICE TRANET observations on all 26 passes, and the range rate average bias ($B \pm \sigma$) and the total rms error ($\sqrt{B^2 + \sigma^2}$) were reduced from 21.2 ± 7.7 cm/sec and 22.6 cm/sec to 1.4 ± 3.5 cm/sec and 3.8 cm/sec respectively, for TRAN-59 relative to the laser. Similarly, for TRAN-35, the total rms error was reduced from 19.2 cm/sec to 8.2 cm/sec.

Alternatively, the user could improve his use of the TRANET observations by recognizing the existence of an a priori positive range rate bias and solving for this bias, under an appropriate a priori constraint, along with the orbit, survey, and gravity field parameters.

A more exact procedure would be to determine, with the use of a nominal orbit, the transit time and tropospheric refraction Doppler frequency correction profile versus time in each pass. Then the mean positive frequency bias component in this profile should be solved for and the result used to remove the positive bias component from the base frequency (F_B) provided by NWL. This should remove the net negative Doppler frequency bias component, or the net positive range rate bias component, from the TRANET observations.

Range rate ($\dot{R}$) was related to the TRANET observations by means of the following equation:

$$\dot{R} = \frac{c\,(F_B - F_M)}{F_M}$$

where F_M is measured frequency provided by NWL, F_B is the base frequency provided by NWL, and C is the speed of light ($2.9?725 \times 10^8$ m/sec).

4.5 ACCURACIES OF ANGLE SYSTEMS

No obvious angle biases were detected in the Jupiter camera test. The camera angles appear to be accurate to 1 to 2 seconds whereas the laser angles appear accurate to better than 30 seconds and the C-band angles appear to be accurate in the region of 30 to 70 seconds.

The MINITRACK angles appear accurate to 10 to 20 seconds, provided the correct refraction theory is applied.

4.6 STATION TIME BIASES

The time bias in the Rosman GRARR of -2.1 ± 1.2 msec relative to the laser was not supported by the 0.0 ± 1.2 msec value found for the Carnarvon GRARR relative to the laser.

The time biases in the Wallops FPQ-6 and FPS-16 of 0.3 ± 0.3 msec relative to the laser were supported by the 0.4 ± 1.1 msec value found for the Carnarvon FPQ-6. As explained earlier, probably the C-bands or possibly the lasers have a systematic error, which behaves like a 0.3/msec time bias for the C-bands or like a -0.3 msec time bias for the lasers.

4.7 GENERAL REMARKS

The measurement biases discovered in these tests are recommended for correcting the observations only in those cases where the probable source of the bias has been identified and measured, and only for the specific laser and C-band observations affected, as indicated in Table 8.

All the TRANET and MINITRACK observations were affected by the biases discussed hence all these data should be corrected as indicated.

The sources of the GRARR and SECOR range biases on GEOS-2 were not identified, so it is not known whether these values apply only to the specific GRARR's and SECOR's tested at the collocation test times or to all GRARR's and SECOR's at all times.

The camera angle accuracies of 1 and 2 seconds are far more accurate than the laser or C-band angle accuracies of 30 to 70 seconds. However, at a satellite distance of, say, 1.5 million meters, an angle accuracy of 1 second is equivalent to only 7.3 meters in satellite position component normal to the line of sight.

The laser range accuracies of 1 to 2 meters during GEOS-1 and -2 were already better than the range accuracies of the C-band, GRARR, and SECOR electronic systems or the total rms errors of 3 to 18 meters, as summarized in Table 8. Improvements now being made to the lasers indicate an increase in accuracy of an order of magnitude should soon be achieved.

Results obtained with Doppler observations appear competitive with those obtained with laser observations so far. Improvements to the GRARR/USB S-band Doppler systems and the TRANET/GEOCEIVER Doppler systems enabling a readout of the Doppler cycle count without destroying the continuity of the count over longer intervals should increase the accuracy of results obtained with these Doppler observations.

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Table 1. Camera Intercomparisons at Jupiter

CAMERA	COMBINED DATA ORBITS MEAN RMS (ARC SEC)			MOTS-40 ORBITS MEAN DIFFERENCE (ARC SEC)				
	NO. OF SEQ'S	$\Delta\alpha \cos\delta$	$\Delta\delta$	NO. OF SEQ'S	$B \pm \sigma$ $\Delta\alpha \cos\delta$	$\sqrt{B^2+\sigma^2}$ TOT RMS	$B \pm \sigma$ $\Delta\delta$	$\sqrt{B^2+\sigma^2}$ TOT RMS
SAO BAKER-NUNN	35	1.39	1.38	31	-0.74 ± 1.25	1.45	0.08 ± 1.14	1.14
SAO K-50	12	1.41	1.57	10	-0.42 ± 2.07	2.11	-0.82 ± 1.26	1.50
Air Force PC-1000	28	1.62	1.42	19	-0.11 ± 1.69	1.69	-0.72 ± 1.50	1.66
NASA MOTS - 40	53	1.61	1.47	53	0 ± 0	0	0 ± 0	0
NASA MOTS - 24	20	2.30	1.96	18	-0.85 ± 1.95	2.13	0.60 ± 1.56	1.67
NASA Pth - 100	18	1.87	1.54	14	-1.03 ± 2.14	2.37	0.52 ± 1.57	1.65
NASA BC4 - 300	22	6.07	4.27	15	-3.95 ± 7.96	8.89	1.06 ± 2.95	3.13

Table 2. Comparison Laser vs. Moblas Laser Tests

TEST	DATE	# PASSES	COMP. LASER	RMS RANGE NOISE (METERS)		AVG. RANGE BIAS (B ± SIGMA) (METERS)
				COMP. LASER	MOBLAS	COMP. LASER—MOBLAS
GORF-1*	Oct—Nov 68	5	GODLAS	1.86	1.23	4.1 ± 0.6
GORF-1	Oct—Nov 68	5	GODLAS	1.86	1.23	-0.5 ± 0.6
ARLACO-1	Oct—Nov 69	14	HOPLAS	1.34	1.06	-1.6 ± 1.5
ARLACO-2	Dec 69—Jan 70	11	HOPLAS	1.09	1.00	1.3 ± 1.7
GORF-2	Mar—May 70	21	GODLAS	1.00	1.06	-1.2 ± 1.3
GORF-3	Oct 70	4	GODLAS	0.59	0.59	0.9 ± 0.3

*MOBLAS had a calibration error of 4.6 meters.

Table 3. ROLACO RAE Statistics

System	Name	Measurement	No. Passes	Mean Before	Rms Before	Rms After	Measurement Bias (B)	Station Time Bias (T) (Milliseconds)
Reference System								
Laser	GODLAS	Range (meters)	15	-	1.8 ± 0.8	-		-
		Azimuth (arc sec)	15	-	91 ± 62	-	-	-
		Elevation (arc sec)	15	-	37 ± 25	-	-	-
Comparison System								
GRARR	ROSMAN	Range (meters)	10	-	-	6.8 ± 2.1	-5.3 ± 12.4	-2.1 ± 1.2
		R. Rate (cm/sec)	9	-	6.9 ± 5.8	-	-	-

Table 4. WICE RAE Statistics

SYSTEM	NAME	MEASUREMENT	NO. PASSES	MEAN BEFORE	RMS BEFORE	RMS AFTER	MEASUREMENT BIAS (B)	STATION TIME BIAS (T) (MILLISECONDS)
Laser	GODLAS	Range (meters)	35	0.0 ± 0.6	1.3 ± 0.2	—	—	—
C-band	FPQ-6 (-0.6 m. added)	Range (meters)	34	—	—	1.0 ± 0.3	-2.2 ± 2.6	0.3 ± 0.3
C-band	FPQ-6	Range (meters)	34	-1.4 ± 2.5	2.5 ± 2.0	1.0 ± 0.3	-1.6 ± 2.6	0.3 ± 0.3
C-band	FPQ-6 (beacon only)	Range (meters)	24	—	—	1.0 ± 0.2	-2.0 ± 2.7	0.3 ± 0.3
C-band	FPQ-6 (beacon segment)	Range (meters)	8	—	—	1.1 ± 0.4	-1.8 ± 2.2	0.3 ± 0.2
C-band	FPQ-6 (skin track)	Range (meters)	8	—	—	8.6 ± 2.0	-5.2 ± 2.7	0.1 ± 0.7
C-band	FPQ-6 (beacon 1, all)	Range (meters)	20	-2.0 ± 2.2	2.6 ± 2.0	0.9 ± 0.2	-2.2 ± 2.4	0.3 ± 0.3
C-band	FPQ-6 (beacon 2, all)	Range (meters)	14	-0.5 ± 2.6	2.3 ± 1.9	1.2 ± 0.3	-0.6 ± 2.5	0.3 ± 0.3
C-band	FPS-16 (-7.9 m. added)	Range (meters)	27	—	—	1.4 ± 0.4	-2.2 ± 4.1	0.3 ± 0.3
C-band	FPS-16	Range (meters)	27	5.9 ± 4.1	6.7 ± 3.2	1.4 ± 0.4	5.7 ± 4.1	0.3 ± 0.3
C-band	FPS-16 (beacon 1)	Range (meters)	14	7.2 ± 3.3	7.6 ± 2.9	1.2 ± 0.2	7.0 ± 3.4	0.3 ± 0.3
C-band	FPS-16 (beacon 2)	Range (meters)	13	4.5 ± 4.2	5.7 ± 3.1	1.6 ± 0.[illegible]	4.4 ± 4.3	0.3 ± 0.3
SECOR	WSECOR	Range (meters)	32	-18.1 ± 3.7	18.4 ± 3.6	1.8 ± 0.4	-17.5 ± 4.0	-0.6 ± 0.5
C-band	FPQ-6	R. Rate (cm/sec)	4	—	—	9.8 ± 4.2	2.4 ± 2.9	0.2 ± 0.2
TRANET	TRAN59 (early)	R. Rate (cm/sec)	24	—	—	8.5 ± 5.1	21.2 ± 7.7	0.0 ± 0.0
TRANET	TRAN35 (early)	R. Rate (cm/sec)	15	—	—	12.1 ± 10.2	18.4 ± 5.5	0.0 ± 0.0
TRANET	TRAN59 (final)	R. Rate (cm/sec)	26	1.5 ± 3.7	5.6 ± 3.5	4.5 ± 2.0	1.4 ± 3.5	0.0 ± 0.1
TRANET	TRAN35 (final)	R. Rate (cm/sec)	16	-3.7 ± 7.9	9.3 ± 9.6	6.1 ± 7.0	-3.2 ± 7.5	0.0 ± 0.0
Laser	GODLAS	Azimuth x Cos El. (arc sec)	35	0 ± 0	53 ± 33	53 ± 53	0 ± 0	—
C-band	FPQ-6	Azimuth x Cos El. (arc sec)	34	38 ± 37	53 ± 44	21 ± 18	38 ± 37	—
C-band	FPS-16	Azimuth x Cos El. (arc sec)	27	-52 ± 57	78 ± 55	41 ± 33	-51 ± 56	—
Laser	GODLAS	Elevation (arc sec)	35	-6 ± 13	30 ± 11	27 ± 9	-6 ± 13	—
C-band	FPQ-6	Elevation (arc sec)	34	23 ± 15	27 ± 14	11 ± 4	23 ± 15	—
C-band	FPS-16	Elevation (arc sec)	27	24 ± 23	35 ± 19	19 ± 7	24 ± 23	—

Table 5. WICE RRD Statistics

SYSTEM	NAME	MEASUREMENT	NO. PASSES	MEAN BEFORE	RMS BEFORE	RMS AFTER	MEASUREMENT BIAS (B)	STATION TIME BIAS (T) (MILLISECONDS)
Laser	GODLAS	Range (meters)	22	0.0 ± 0.0	1.3 ± 0.2	1.5 ± 0.2	—	—
C-band	FPQ-6 (-0.6 m. added)	Range (meters)	21	—	—	0.8 ± 0.1	-2.2 ± 1.8	0.4 ± 0.3
C-band	FPQ-6	Range (meters)	21	-1.7 ± 1.8	2.4 ± 1.2	0.8 ± 0.1	-1.6 ± 1.8	0.4 ± 0.3
C-band	FPS-16 (-7.9 m. added)	Range (meters)	21	—	—	1.1 ± 0.3	-0.8 ± 3.5	0.3 ± 0.2
C-band	FPS-16	Range (meters)	16	7.1 ± 3.4	7.6 ± 2.9	1.1 ± 0.3	7.1 ± 3.5	0.3 ± 0.2
SECOR	WSECOR	Range (meters)	20	-17.5 ± 3.3	17.8 ± 3.2	1.7 ± 0.3	-16.8 ± 3.8	-0.7 ± 0.3
TRANET	TRAN59	R. Rate (cm/sec)	15	2.2 ± 4.1	5.7 ± 4.7	3.9 ± 1.9	0.3 ± 3.7	0.8 ± 1.5
TRANET	TRAN35	R. Rate (cm/sec)	10	-0.5 ± 3.2	5.0 ± 1.8	2.7 ± 0.7	-2.2 ± 4.7	0.6 ± 0.8
Laser	GODLAS	Azimuth x Cos El (arc sec)	22	11. ± 23.	64. ± 46.	57. ± 42.	5. ± 21.	—
C-band	FPQ-6	Azimuth x Cos El (arc sec)	21	46. ± 21.	51. ± 22.	17. ± 15.	38. ± 20.	—
C-band	FPS-16	Azimuth x Cos El (arc sec)	16	-43. ± 40.	62. ± 31.	31. ± 18.	-52. ± 50.	—
Laser	GODLAS	Elevation (arc sec)	22	1. ± 13.	30. ± 10.	27. ± 9.	0. ± 15.	—
C-band	FPQ-6	Elevation (arc sec)	21	26. ± 10.	28. ± 9.	10. ± 3.	25. ± 12.	—
C-band	FPS-16	Elevation (arc sec)	16	26. ± 19.	34. ± 16.	18. ± 6.	24. ± 19.	—
Camera	WALLOP	Rt. Asc. x Cos Dec. (arc sec)	22	0.4 ± 0.9	1.6 ± 0.8	—	—	—
Camera	WALLOP	Declin. (arc sec)	22	0.2 ± 1.5	1.7 ± 1.1	—	—	—

Table 6. CALACO RAE Statistics

SYSTEM	NAME	MEASUREMENT	NO. PASSES	MEAN BEFORE	RMS BEFORE	RMS AFTER	MEASUREMENT BIAS (B)	STATION TIME BIAS (T) (MILLISECONDS)
Laser	CRMLAS	Range (meters)	92	0.0 ± 0.0	1.3 ± 0.2	—	—	—
C-band	NCARVN (+20 ± 0.7 m added)	Range (meters)	23	—	—	1.1 ± 0.4	5.0 ± 6.7	0.4 ± 1.1
C-band	NCARVN	Range (meters)	23	-13.1 ± 4.4	13.3 ± 4.4	1.1 ± 0.4	-15.0 ± 6.5	0.4 ± 1.1
C-band	NCARVN (beacon 1)	Range (meters)	12	-13.3 ± 4.1	13.3 ± 4.1	1.0 ± 0.2	-15.8 ± 7.5	0.5 ± 1.4
C-band	NCARVN (beacon 2)	Range (meters)	11	-13.0 ± 4.5	13.2 ± 4.4	1.2 ± 0.5	-14.1 ± 4.6	0.3 ± 0.5
C-band	NCARVN (beacon 1 corrected)	Range (meters)	12	—	—	1.0 ± 0.2	4.1 ± 7.9	0.5 ± 1.4
C-band	NCARVN (beacon 2 corrected)	Range (meters)	11	—	—	1.2 ± 0.5	5.6 ± 4.9	0.3 ± 0.5
GRARR	CARVON (A+C)	Range (meters)	64	-4.1 ± 6.4	7.6 ± 4.0	3.0 ± 0.2	-4.0 ± 6.7	0.0 ± 1.2
GRARR	CARVON (A)	Range (meters)	17	-1.5 ± 3.7	4.8 ± 1.6	3.0 0.2	-1.7 ± 3.6	0.2 ± 0.5
GRARR	CARVON (C)	Range (meters)	47	-5.1 ± 6.9	8.6 ± 4.1	2.9 ± 0 2	-4.9 ± 7.4	-0.1 ± 1.4
GRARR	CARVON (A C)	R. Rate (cm/sec)	64	0.5 ± 0.9	1.7 ± 0.8	1.1 ± 0.7	0.5 ± 2.4	—
GRARR	CARVON (A)	R. Rate (cm/sec)	17	0.3 ± 0.1	1.6 ± 0.8	1.3 ± 0.4	-0.2 ± 0.7	—
GRARR	CARVON (C)	R. Rate (cm/sec)	47	0.6 ± 0.9	1.7 ± 0.8	1.5 ± 0.7	0.8 ± 2.7	—
Laser	CRMLAS	Azimuth x Cos El. (arc sec)	92	0. ± 0.	30. ± 17.	—	—	—
C-band	NCARVN	Azimuth x Cos El. (arc sec)	23	-17. ± 32.	54. ± 56.	42. ± 55.	-17. ± 32.	—
Laser	CRMLAS	Elevation (arc sec)	92	-8. ± 14.	22. ± 13.	—	—	—
C-band	NCARVN	Elevation (arc sec)	23	22. ± 28.	36. ± 23.	15. ± 18.	22. ± 28.	—

Table 7. CALACO RRD Statistics

SYSTEM	NAME	MEASUREMENT	NO. PASSES	MEAN BEFORE	RMS BEFORE	RMS AFTER	MEASUREMENT BIAS (B)	STATION TIME BIAS (T) (MILLISECONDS)
Laser	CRMLAS	Range (meters)	14	0.0 ± 0.0	1.3 ± 0.2	N.A.	N.A.	N.A.
C-band	NCARVN	Range (meters)	5	-9.3 ± 4.2	9.5 ± 4.1	N.A.	N.A.	N.A.
GRARR	CARVON	Range (meters)	12	-6.4 ± 7.0	8.9 ± 5.2	N.A.	N.A.	N.A.
GRARR	CARVON	R. Rate (cm/sec)	12	0.3 ± 1.3	1.7 ± 0.7	N.A.	N.A.	N.A.
Laser	CRMLAS	Azimuth x Cos El (arc sec)	14	10. ± 24.	35. ± 23.	N.A.	N.A.	N.A.
C-band	NCARVN	Azimuth x Cos El (arc sec)	5	-28. ± 8.	38. ± 10.	N.A.	N.A.	N.A.
Laser	CRMLAS	Elevation (arc sec)	14	-26. ± 11.	31. ± 9.	N.A.	N.A.	N.A.
C-band	NCARVN	Elevation (arc sec)	5	30. ± 6.	35. ± 5.	N.A.	N.A.	N.A.
Camera	1CARVN	Rt. Asc x Cos Dec (arc sec)	14	0.0 ± 0.0	0.9 ± 0.3	N.A.	N.A.	N.A.
Camera	1CARVN	Declin. (arc sec)	14	0.0 ± 0.8	1.4 ± 0.7	N.A.	N.A.	N.A.

Table 8. Range System Accuracies, Typical and Potential
(All Values in Meters)

TEST	RANGE SYSTEM	NORMAL BEFORE CORR.				POTENTIAL AFTER CORR.	
		AVG. BIAS $B \pm \sigma$	TOTAL RMS $\sqrt{B^2 + \sigma^2}$	BIAS SOURCE	ADDED CORRECTION	AVG. BIAS $B \pm \sigma$	TOTAL RMS $\sqrt{B^2 + \sigma^2}$
GORF-1	MOBLAS	-4.1 ± 0.6	4.1	CAL. SIG. LEV.	4.6	0.5 ± 0.6	0.8
ARLACO-1	HOPLAS	(2 passes) 5.5 ± 0.6	5.5	CAL. CHANGE	-4.8	(14 passes) -1.6 ± 1.5	2.2
ARLACO-2	HOPLAS	1.3 ± 1.7	2.1	UNKNOWN			
GORF-2	GODLAS	-1.2 ± 1.3	1.8	UNKNOWN			
GORF-3	GODLAS	0.9 ± 0.3	0.9	UNKNOWN			
ROLACO	GRARR (A)	-15.0 ± 12.4	19.5	CALIB	9.7	-5.3 ± 12.4	13.5
CALACO	GRARR (A)	-1.7 ± 3.6	4.0	UNKNOWN			
CALACO	GRARR (C)	-4.9 ± 7.4	8.9	UNKNOWN			
WICE	FPS-16	5.7 ± 4.1	7.0	CAL SURVEY	-7,9	-2.2 ± 4.1	4.7
WICE	FPQ-6	-1.6 ± 2.6	3.1	CALIB.	-0.6	-2.2 ± 2.6	3.4
CALACO	FPQ-6	-15.0 ± 6.5	16.3	CAL. REFR.	20.0 ± 0.7	5.0 ± 6.7	8.4
WICE	SECOR	-17.5 ± 4.0	18.0	UNKNOWN			

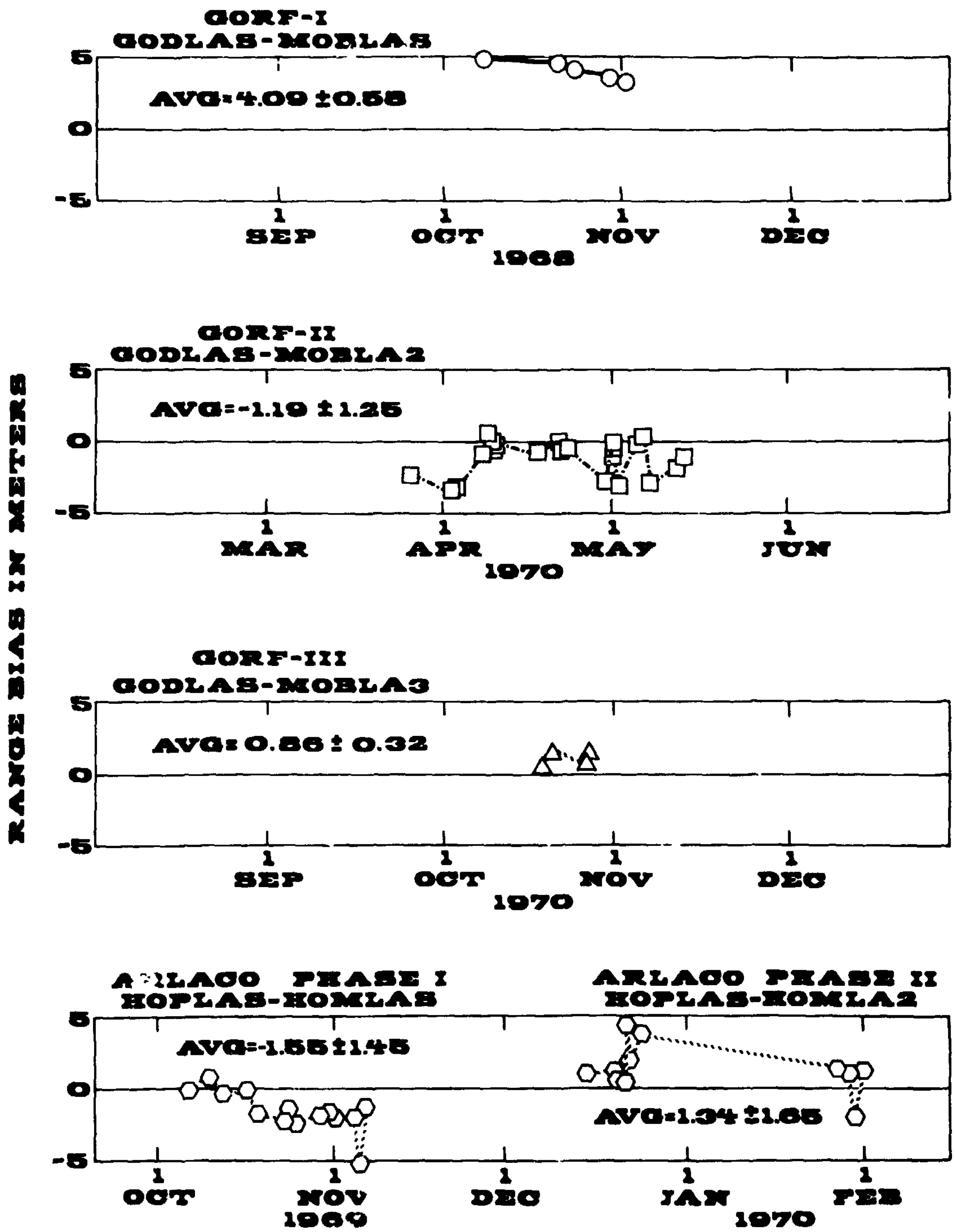

Figure 1. Summary of 4 Laser/Laser Intercomparison Tests
Relative Range Bias vs Date

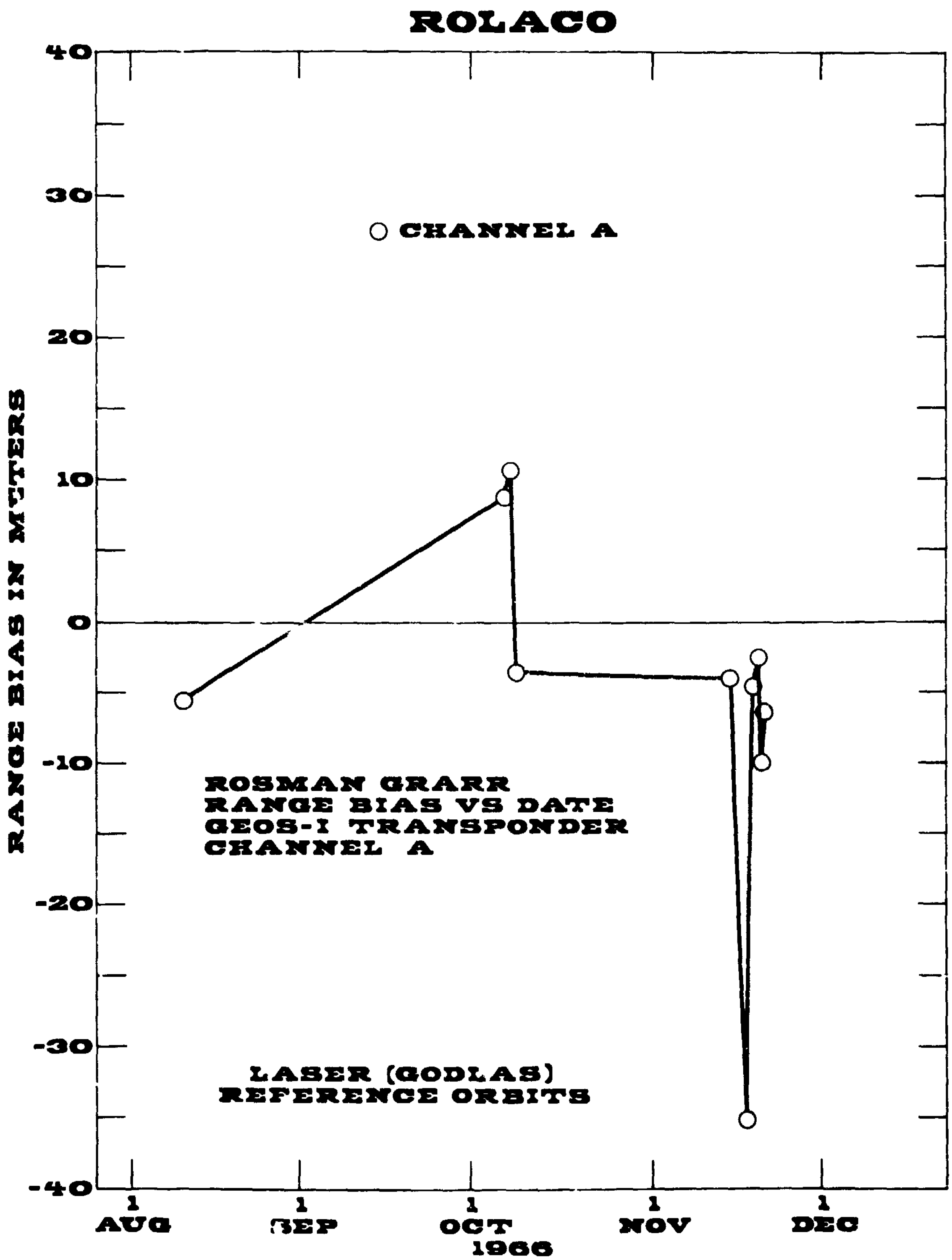

Figure 2. Rosman GRARR Range Bias vs Date GEOS-1 Transponder Channel A

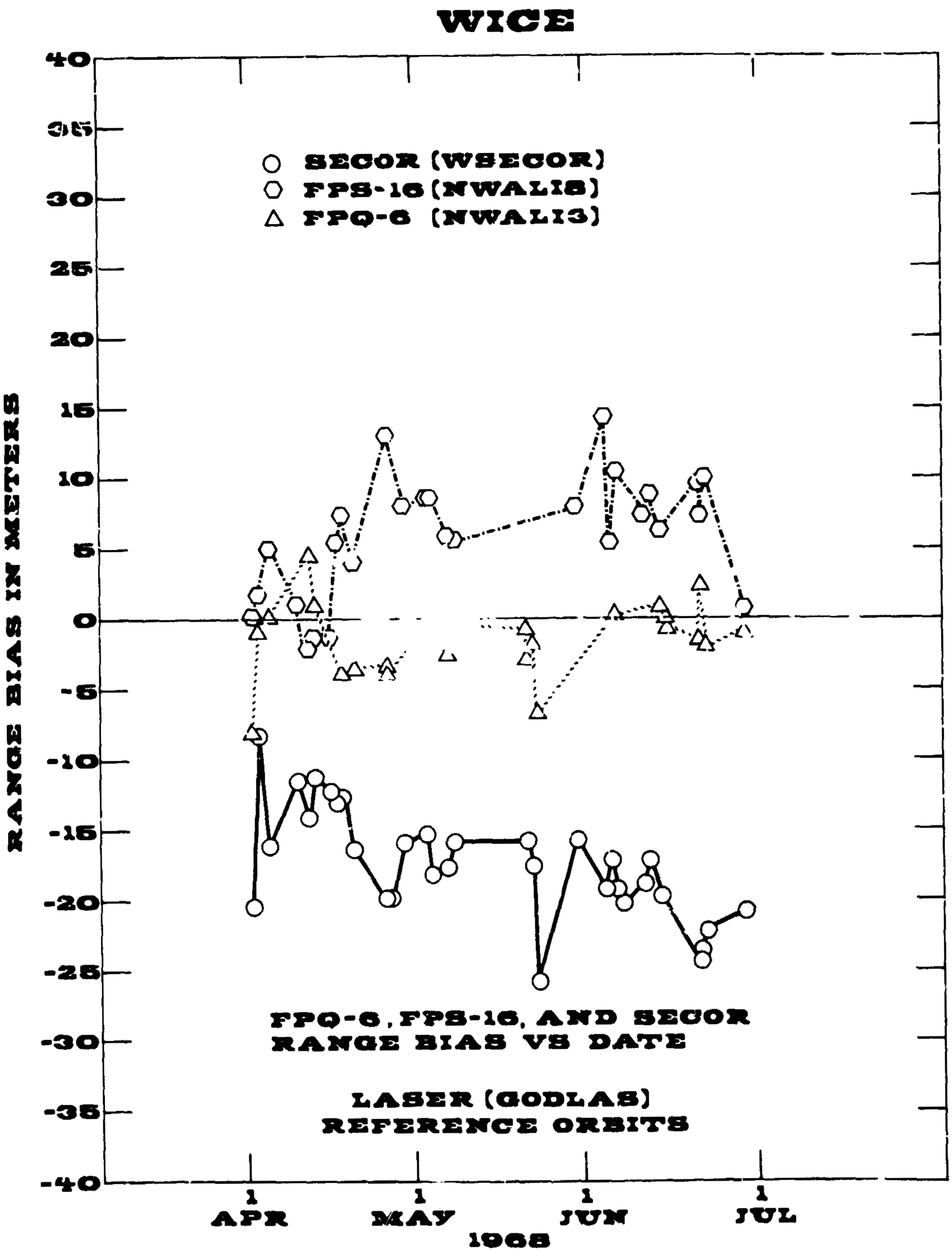

Figure 3. FPQ-6, FPS-16, and SECOR Range Bias vs Date

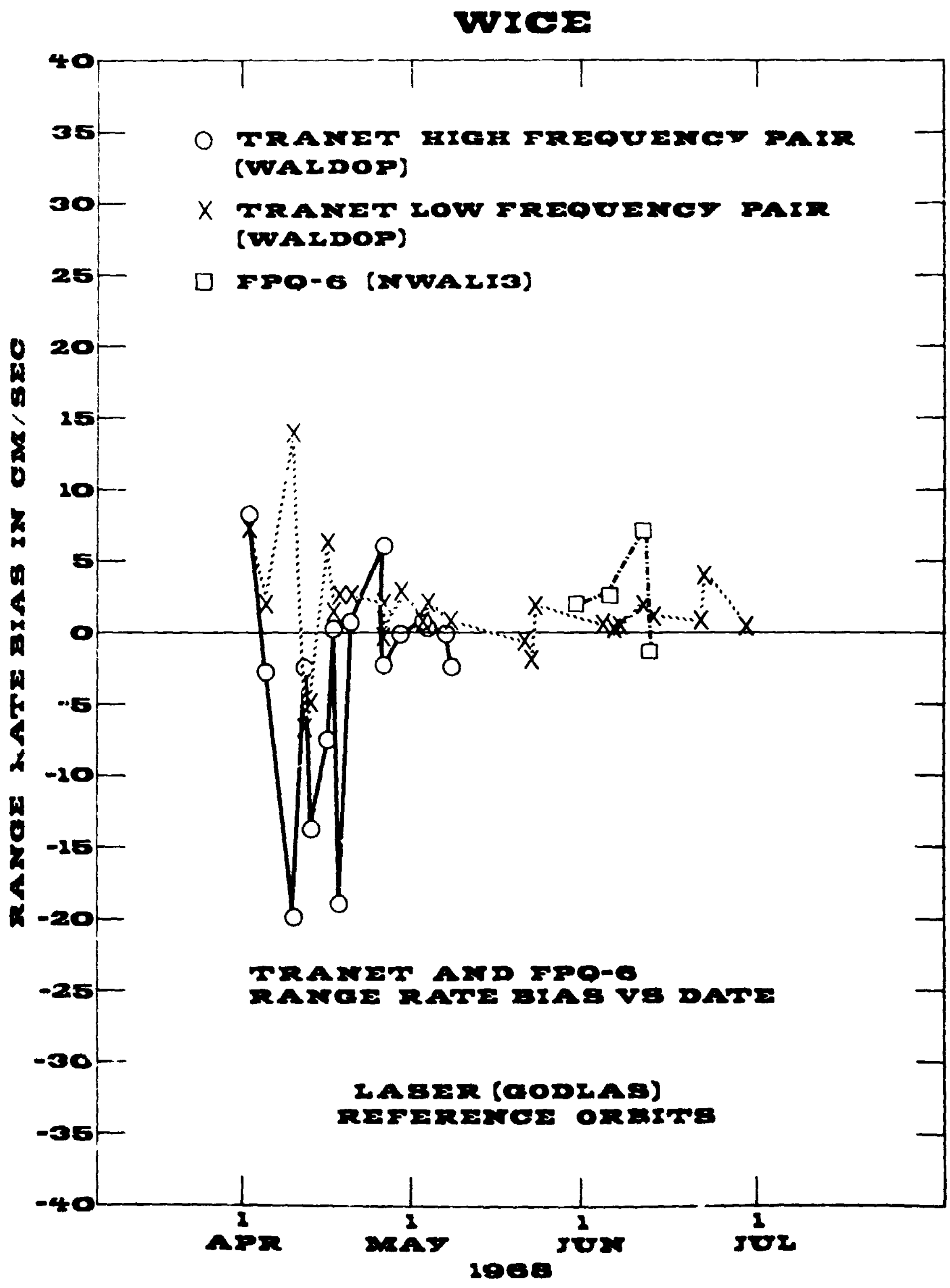

Figure 4. TRANET and FPQ-6 Range Rate Bias vs Date

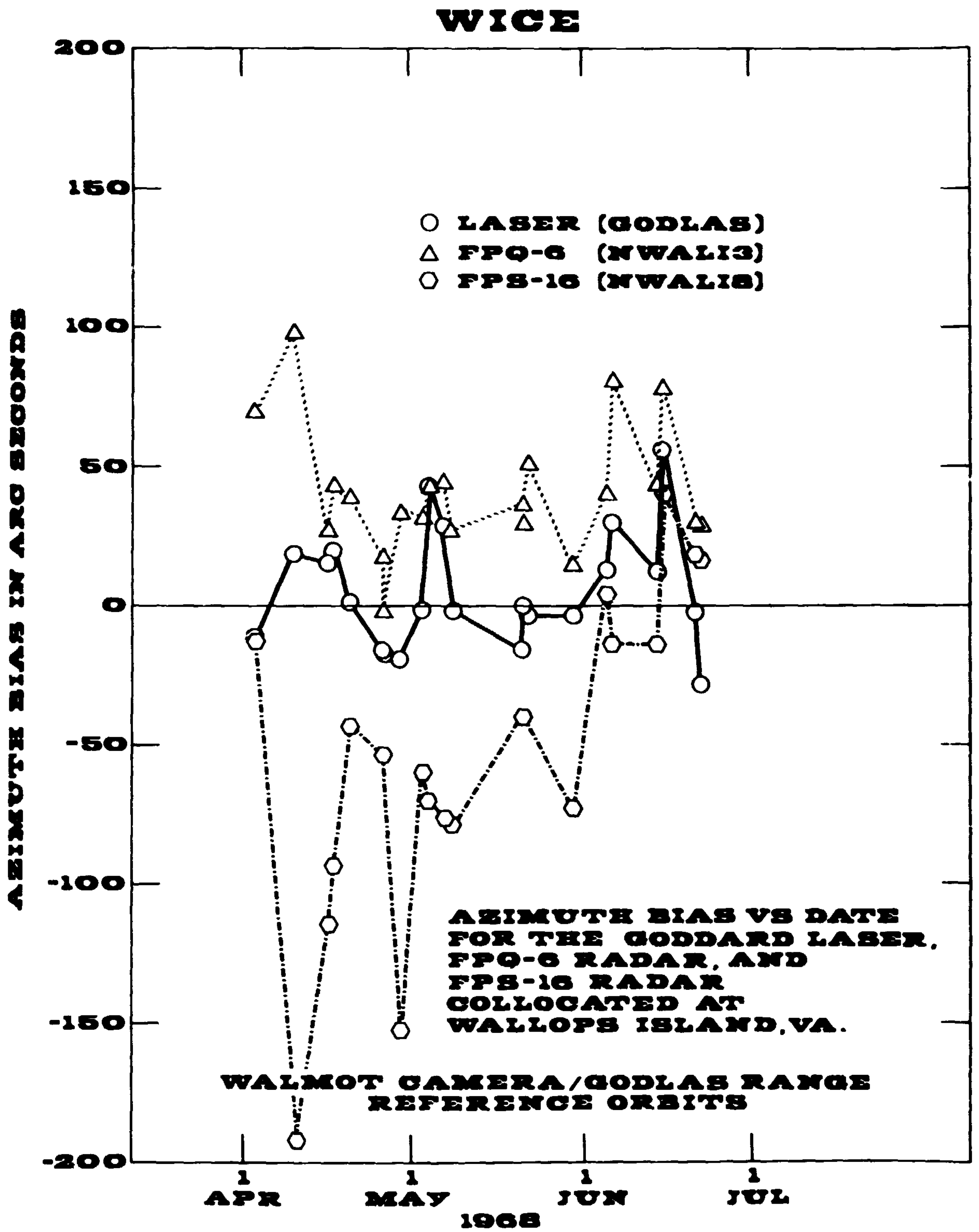

Figure 5. Azimuth Bias vs Date for the Goddard Laser, FPQ-6 Radar, and FPS-16 Radar Collocated at Wallops Island, Va.

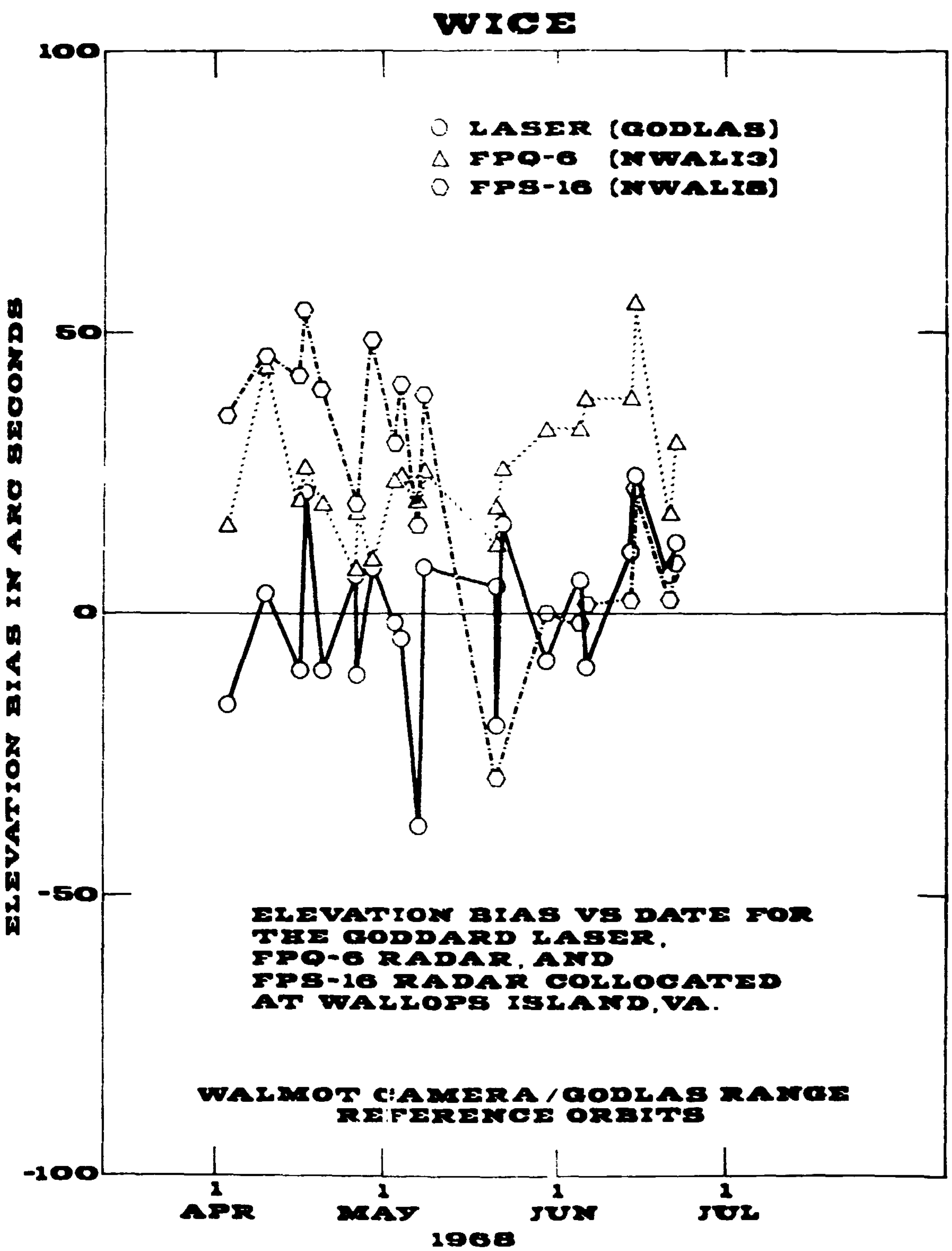

Figure 6. Elevation Bias vs Date for the Goddard Laser, FPQ-6 Radar, and FPS-16 Radar Collocated at Wallops Island, Va.

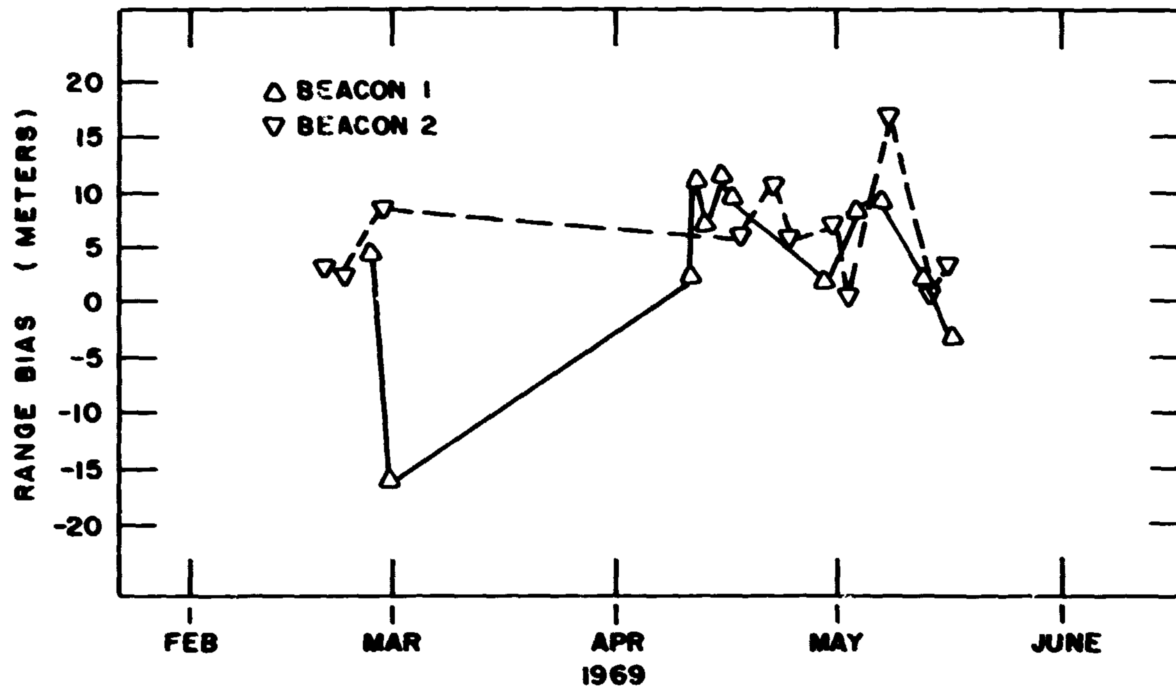

Figure 7. CALACO NCARVN C-band Range Bias vs Time

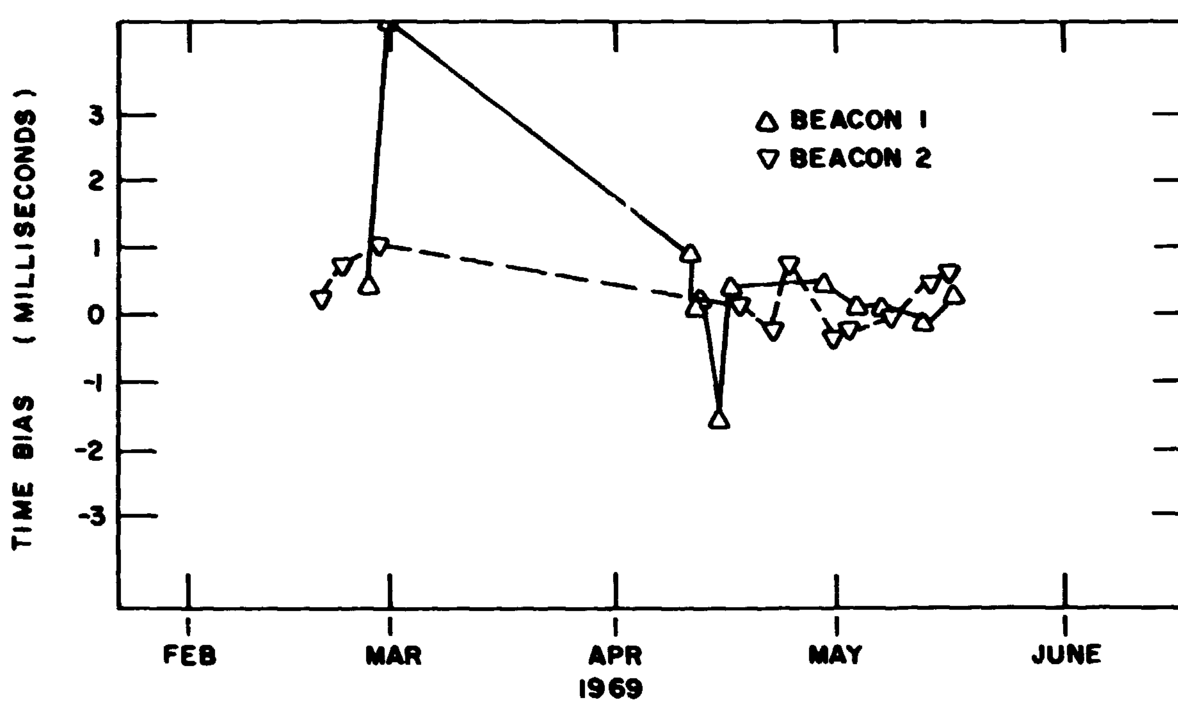

Figure 8. CALACO NCARVN C-band Timing vs Time

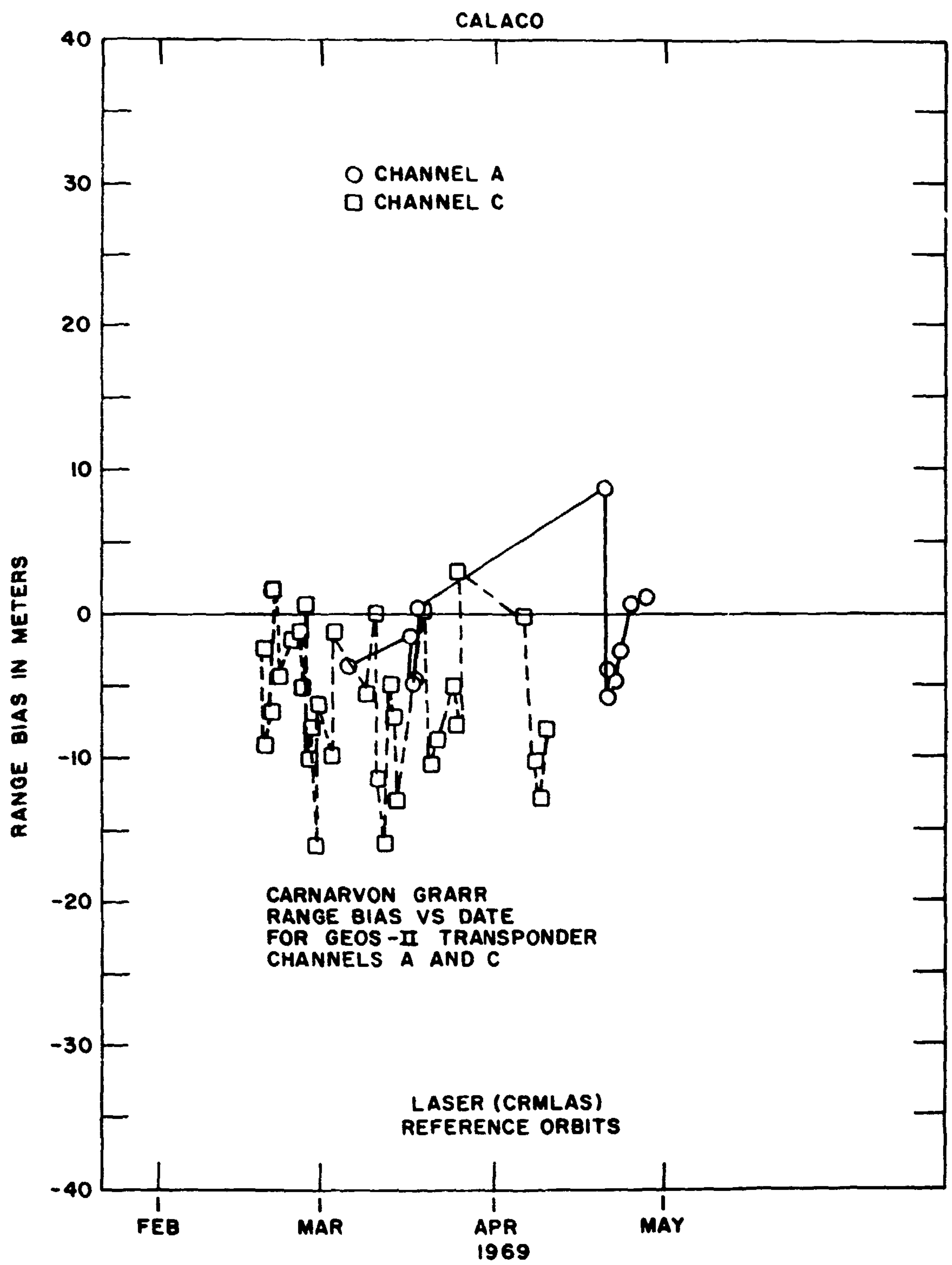

Figure 9. Carnarvon GRARR Range Bias vs Date for GEOS-2 Transponder Channels A and C

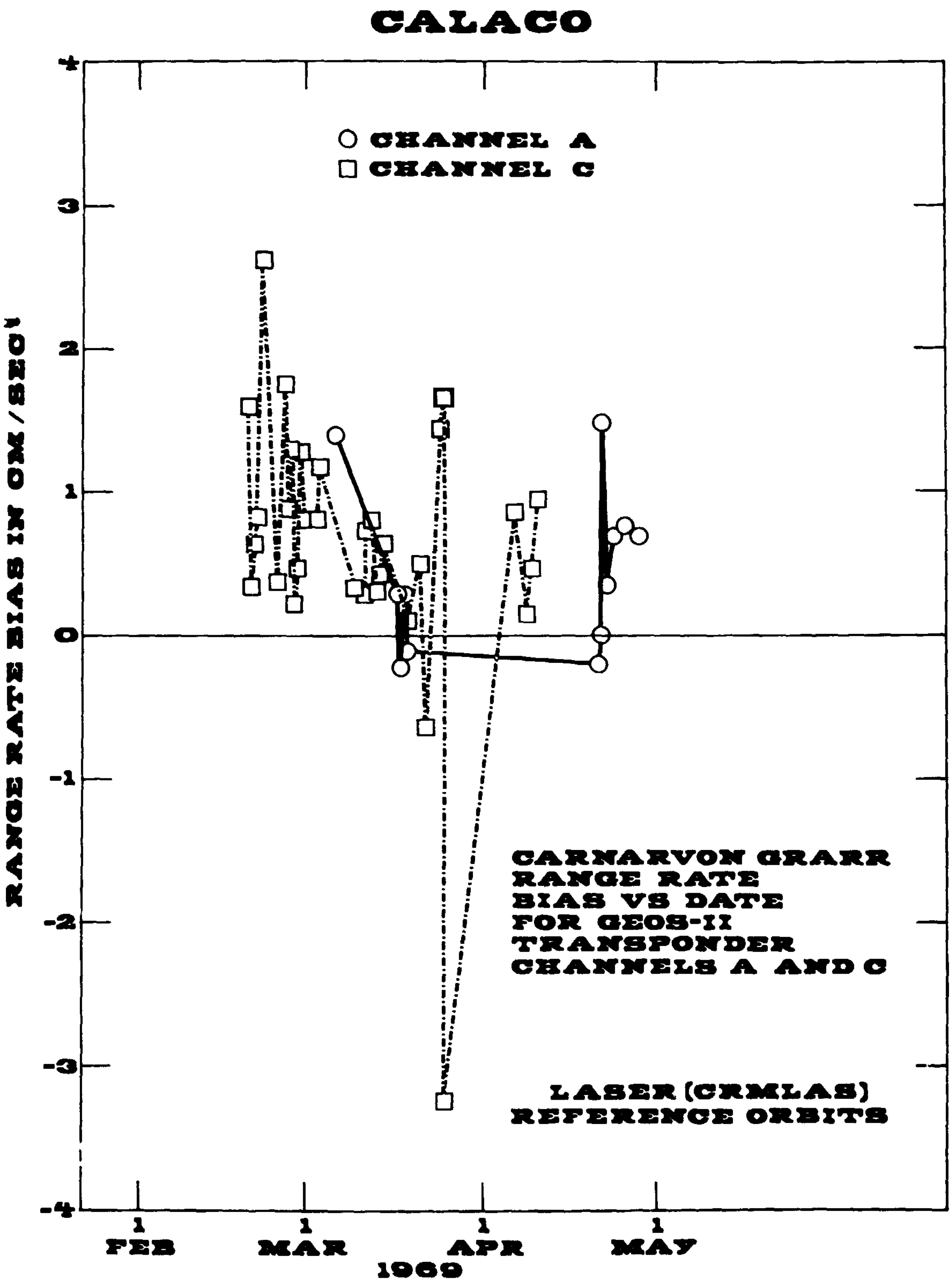

Figure 10. Carnarvon GRARR Range Rate Bias vs Date for GEOS-2 Transponder Channels A and C

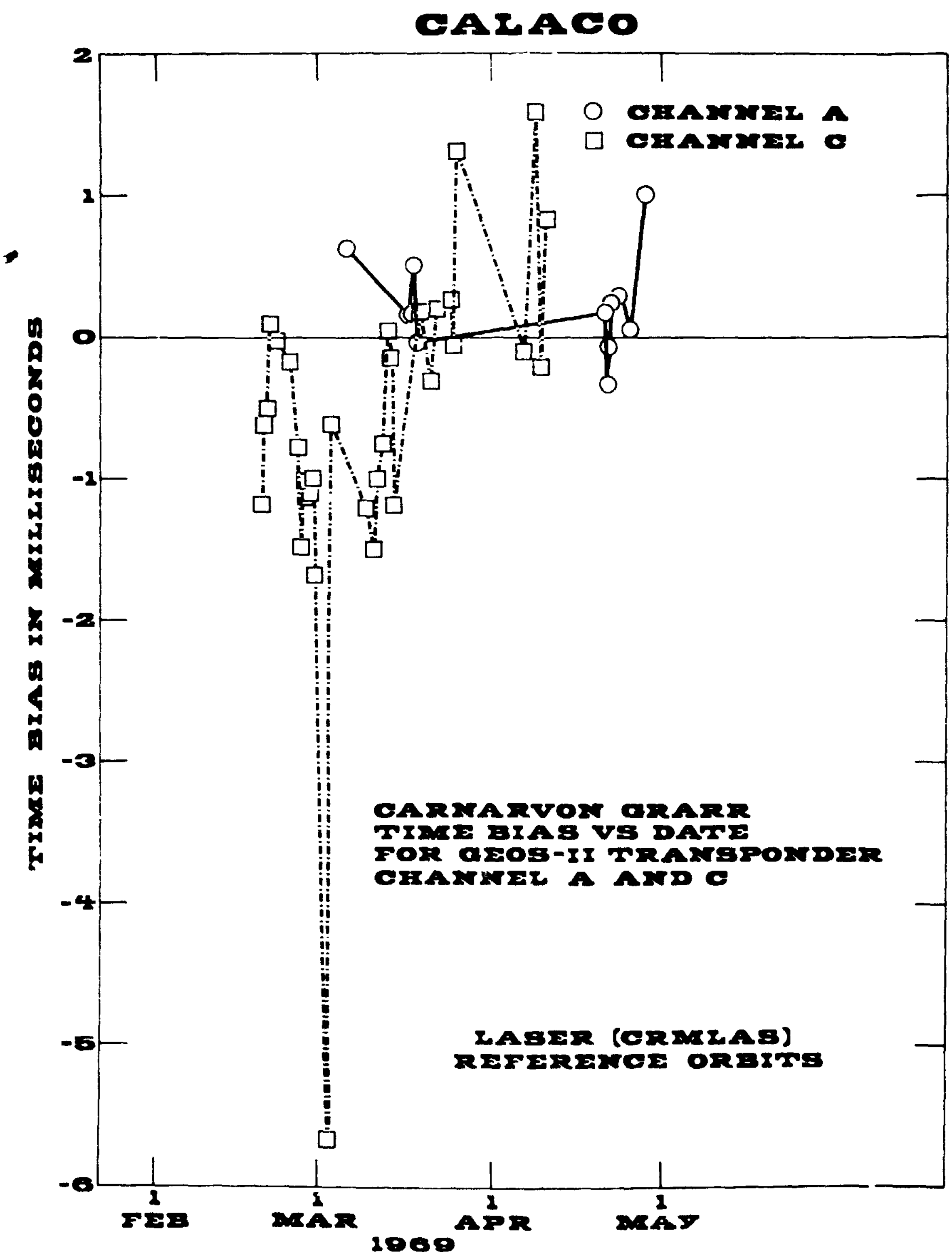

Figure 11. Carnarvon GRARR Time Bias vs Date for GEOS-2 Transponder Channel A and C

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