EVALUATION OF RANGE ACCURACY

FOR THE

GODDARD RANGE AND RANGE RATE SYSTEM

AT ROSMAN

Principal Contributors:

John H. Berbert (GSFC)
GEOS Principal Investigator

Robert Reich
RCA Service Company

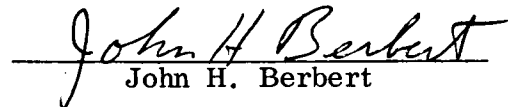J. Stephenson
D. Brown Associates

October 1966

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REVIEW AND CONCURRENCE SHEET

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ABSTRACT

This report presents the evaluation of the range accuracy of the GRARR Tracking System at Rosman, North Carolina, when compared with the SECOR system. Sample range data were obtained from the Rosman and the SECOR stations. The GEOS Data Adjustment Program (GDAP) is used to determine the values of state variables which affect the range accuracy. Credence of the state variables is given, and then the data are summarized and analyzed. Conclusions and recommendations for future operation are then made.

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INTRODUCTION

A series of tests were conducted in January, 1966, as part of the GEOS A Tracking Systems Intercomparison Investigation. Some of the data from these tests were analyzed to obtain a preliminary evaluation of the accuracy of the Goddard Range and Range Rate system (GRARR). These tests utilized the GEOS A satellite, four Sequential Collation of Range systems (SECOR), and one GRARR system. The station locations and types of equipment are listed in Table 1, and Table 2 lists the satellite passes and the stations participating per pass.

Table 1

Table of Stations and Equipment Used

STATION	ABBREVIATION	EQUIPMENT	
Homestead, Florida	(HST)	AMS	SECOR
Savannah, Georgia	(SAV)	AMS	SECOR
Greenville, Mississippi	(GRN)	AMS	SECOR
Herndon, Virginia	(HRN)	AMS	SECOR
Rosman, North Carolina	(ROS)	GRARR	

Table 2

Stations Participating for Test Data

PASS NO.	DATE	TIME	HST	SAV	GRN	HRN	ROS
665	1/1/66	0800Z	Yes	No	Yes	Yes	Yes
676	1/2/66	0600Z	Yes	Yes	Yes	Yes	Yes
677	1/2/66	0800Z	Yes	Yes	Yes	Yes	Yes
700	1/4/66	0620Z	No	Yes	Yes	Yes	Yes

The SECOR and GRARR stations tracked the GEOS satellite to provide a reference trajectory. The accuracy of the GRARR is determined by comparing the GRARR measured range with the range prediction taken from the reference trajectory data. The GEOS Data Adjustment Program (GDAP)[1], using the measured data, estimates the following state variables:

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[1]D. Brown Associates, Geodetic Data Analysis for GEOS A, NASA Contract NAS 5-9860.

- Orbital Elements
- Radar Error Model Coefficients
    Zero-set Bias (range)
    Timing (delay)
    Frequency Offset
- Propagation Anomaly
- Station Location

Optical data were not yet available for comparison during these tests. Since the GEOS satellite has only an S-band transponder, the GRARR VHF system could not be evaluated. Furthermore, the accuracy of range rate measurements of the GRARR system could not be determined, because the range rate analysis section of the GDAP was not complete.

SECOR SYSTEM

The SECOR system, which is operated by the Army Map Service (AMS), operates on a principle of "trilateration". Three or four ground stations make range observations, which are effectively simultaneous, by means of a transponder in a satellite. One station is designated as the master station and transmits a special pulse every 50 milliseconds. This pulse is then retransmitted by the satellite and received by all the stations. At each station, the pulse enables the contents of the digital servo to be recorded on magnetic tape. Therefore, after correction for propagation times from satellite to stations, all range readings correspond to the same satellite time. The a priori estimate of standard error in a single range measurement has been estimated, by those associated with AMS[2], and is presented in Table 3.

SECOR SYSTEM PREPROCESSING

The normal SECOR preprocessing by AMS was bypassed for this evaluation, and instead, a special edit program was implemented by D. Brown Associates (DBA) for use in the GDAP Program. For these passes, the following items were tabulated on computer printouts by AMS and were then formatted and key-punched for the computer. Considerable difficulty was experienced in resolving the range ambiguities (Least significant error is 256 Meters).

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[2] Prescott, Major N.J.D., Experiences with "SECOR" Planning and Data Reduction, pages 4 and 5.

- Range

- Dual-frequency Correction For Ionospheric Propagation Delay (assumes group velocity)

High frequency	449 Mcps
Low frequency	224.5 Mcps

- Propagation Delay (transit delay to satellite)

- Ambiguity Resolution (multiples of 256 meters)

- Pre- and Post-calibration Corrections From Each Site.

- Nominal or Station Time

Table 3

SECOR Standard Error of a Single Range Measurement

SOURCE OF ERROR	ELEVATION ANGLE	
	$60^{o} - 90^{0}$	15°
(a) Calibration-Satellite Transponder	1 Meter	1 Meter
(b) Calibration-Station	2 Meter	2 Meter
(c) Tropospheric Correction	0.25 Meter	2 Meter
(d) Dual-frequency Ionospheric Correction		
Night	0.25 Meter	1 Meter
Day	1.5 Meter	6 Meter
(e) Random Electronic Noise	1 Meter	1 Meter
(f) Frequency and Velocity of Light Propagation Errors	1 Meter	2 Meter
Combined (day) Error (RMS)	3.0 Meters	6.9 Meters
Combined (night) Error (RMS)	2.7 Meters	3.5 Meters

GRARR SYSTEM

The GRARR system is a high-precision spacecraft-tracking system capable of accurately determining the range and radial velocity of a spacecraft by measurement of the phase shift and doppler, respectively. Each GRARR station uses an S-band

system and a VHF system. Only the S-band system is used for this evaluation. The a priori estimates of random errors are presented in Table 4.

GRARR PREPROCESSING

The GRARR outputs are preprocessed at Goddard prior to final analysis by the GDAP. Range and time corrections are implemented by consideration of the calibrated transponder delay and WWV to station time errors. During this preprocessing, the data are put into a format that is useable in the GDAP.

Table 4

GRARR Estimated Random Errors[3]

NAME	HIGH FREQ (in meters)	LOW FREQ (in meters)
Oscillator Noise	0.2	0.0
Thermal Noise	0.7	0.0
Quantization	0.6	0.0
Digital Timing	4.5	2.8
Receiver Delay Variations	0.0	2.0
Oscillator Calibrations	0.0	0.5
Transponder Temperature +S/N Variation Delays	0.7	0.7
Transponder Group Delay Variations (doppler)	0.0	7.5
Sub-total (RMS)	4.6	8.3
Combined Total (RMS)	9.5	

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[3]Kronmiller, G.C., Jr., and Baghdady, E. J., The Goddard Range and Range Rate Tracking System: Concept, Design and Performance, Table III A and B.

GEOS DATA ADJUSTMENT PROGRAM (GDAP)[4]

After preprocessing is completed, the GDAP performs a least-square-fit adjustment utilizing a priori (input) estimates and preprocessed data to determine a posteriori (output) estimates. Both input and output estimates are of the state variables and standard errors of those variables. The state variables are the following:

- Orbital Elements

- Radar Error Model Coefficients

    Zero-set Bias (range)

    Timing (delay)

    Frequency Offset

- Propagation Anomaly

- Station Locations

In addition, the standard error estimate of the observations is used. The GDAP linearly estimates corrections to the current state variables. If the corrections to the state variables are greater than one-tenth of the a posteriori standard error estimated, the program iterates through another solution cycle (see Figure 1). This process is repeated until the correction is equal to or less than one-tenth of the a posteriori standard error estimate, at which time the solution is complete.

STANDARD ERROR ESTIMATES FOR RANDOM COMPONENTS OF RANGE DATA

The a priori standard error estimates are from the results of previous studies. Those for SECOR observations are given in Table 3, and those for GRARR observations are listed in Table 4. In Table 4, the random errors are delineated as high and low frequency. High frequency is defined as errors from 30 seconds of smoothing, and low frequency is defined as errors from several minutes of smoothing, where high frequency components are excluded. Thermal noise range error in Table 4 is a function of S/N and has been computed for GEOS at 3000 Km (maximum range). A more-detailed study of time serial behavior of errors will be done in the future. These estimates are used to determine the applied weighting and convergence in GDAP.

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[4] D. Brown Associates, Geodetic Data Analysis for GEOS A, NASA Contract NAS 5-9860.
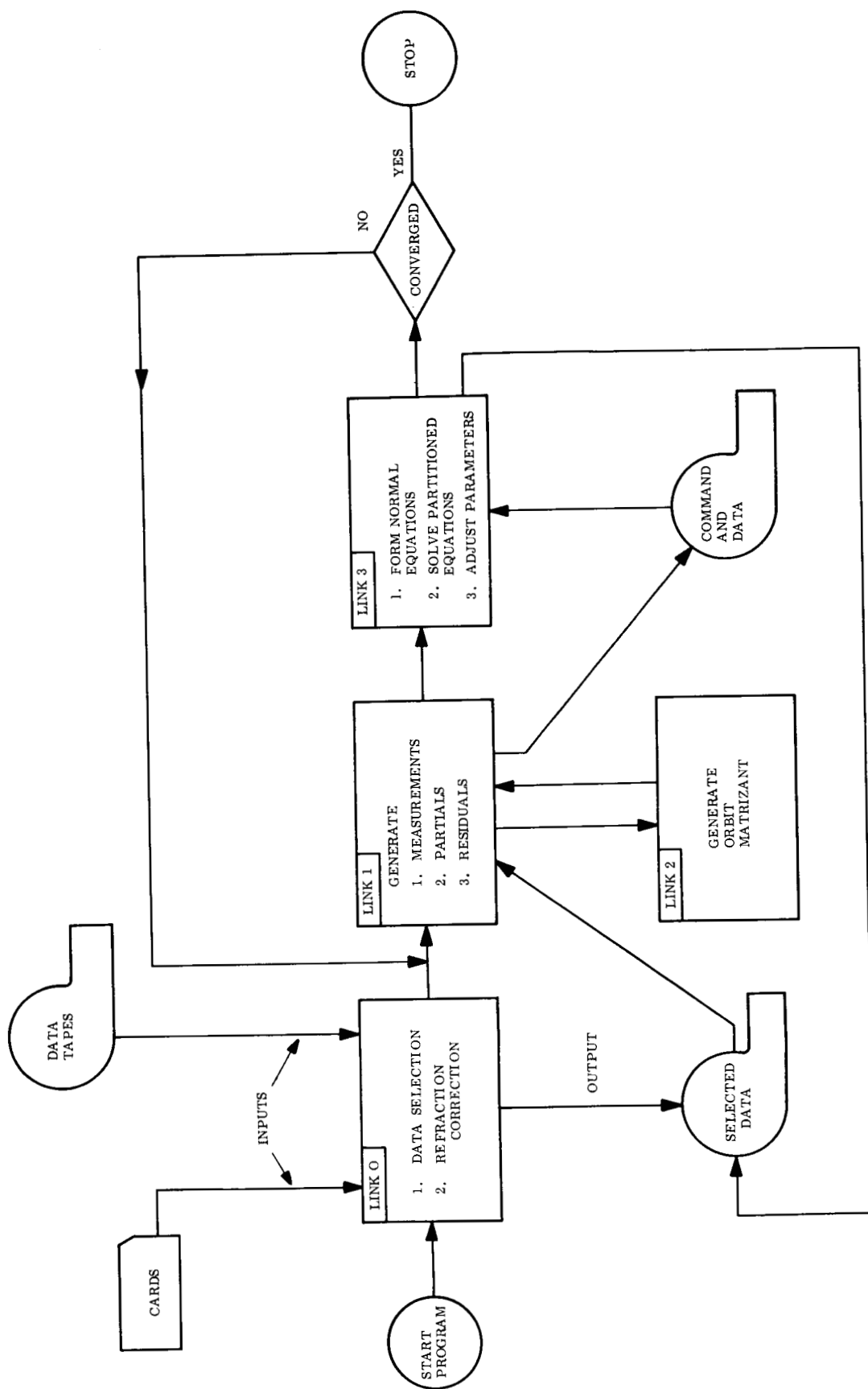
Figure 1. GDAP Program Cycle

STATE VARIABLES

Orbital Elements

The orbital elements are described by the position and velocity, which are designated by X, Y, Z, $\dot{X}$, $\dot{Y}$, and $\dot{Z}$ in cartesian coordinates, at epoch time, during each pass.

Radar Error Model Coefficients

The station radar errors evaluated are zero-set bias, timing or servo delay, and the velocity of light or oscillator frequency error. Timing or servo delay is represented by a coefficient proportional to range rate while the velocity of light or oscillator frequency is proportional to the range (parts per million). The radar error equation is

$$\Delta R = \Delta B + \Delta T \ \overline{(\text{Range Rate})} + \Delta K \ \overline{(\text{Range})},$$

where:

- ΔB is the error in the zero-set value of range

- ΔT is an error in timing which may be due to a clock error, a doppler sensitive delay in the transponder, or the inverse of the velocity coefficient of the range tracking servo.

- ΔK is the fractional error in the value used for the speed of light or in the up-down link frequencies to the satellite.

Propagation Anomaly

An approximation of the propagation delay uncertainty in both the ionosphere and troposphere is obtained from the formula $\dfrac{\Delta P}{\cos Z}$, where Z is the zenith angle of the tracker, Therefore, ΔP represents the range error due to uncertainties in propagation when the tracker is at zenith. The GDAP is used to solve for ΔP.

Station Location

Station location errors cause characteristic errors in the position and velocity data for a satellite. From the observed orbital errors, the GDAP is used to solve for the following station location errors:

- latitude of the station (in meters)

- longitude of the station (in meters)

- height of the station (in meters)

CREDENCE OF STATE VARIABLES

The a priori standard error estimates for the state variables and the range observations must be entered into the GDAP. The weight assigned to each observation is inversely proportional to the variance estimate, while a priori standard error estimates of the state variables constrain those variables about the initial estimates. The credence for each of the preselected values for standard errors is explained in the following paragraphs, and summarized in Table 5.

Table 5

Credence Values per Station for a priori Estimates of Standard Error
of State Variables and Random Error of Observations

Station	Radar Error Model Coefficients			Propagation Anomaly (Meters)	Station Location (Meters)	Range Data Random Error (Meters)
	Zero-Set Bias (Meters)	Timing (Milli-Seconds)	Frequency Offset (X 10^{-6})			
HST	10	0	5	5	2	8
SAV	10	0	5	5	2	8
GRN	10	0	5	5	2	8
HRN	10	0	5	5	10	8
ROS	30	100	5	5	5	12

Orbital Elements

The orbital elements were unconstrained in this analysis.

Radar Error Model Coefficients

Zero-Set Bias Errors

The zero-set bias error used for the SECOR stations in this evaluation is 10 meters; this is more than three times the published error. The estimated zero-set bias error used for Rosman is 30 meters (see Table 5), again three times the estimated errors.

Timing Differences

The SECOR timing, which was synchronized to the master station at Herndon, was used as a standard, and Rosman was compared to it. The a priori standard error estimate for Rosman was set at 100 milliseconds. This procedure was merely a convenience. It could have been reversed, and the answer obtained would have been identical. Thus, the timing error estimates must be treated as relative.

Frequency Offset

The frequency standard error, a priori, was set at 5 parts per million.

Propagation Anomaly

With the system at zenith, the a priori propagation standard error was estimated to be 5 meters.

Station Location Errors

The standard error selected for the site locations is the tolerance of the geodetic survey (see Table 5). Credences for various surveys are:

- direct supersurvey - 2 meters (Coast and Geodetic sites; one part per million accuracy)

- spur of supersurvey - 5 meters (Letter from Coast and Geodetic survey to J. H. Berbert quoted 2.5 meters for Rosman relative to SECOR sites.) The larger value of 5 meters was chosen to allow for the known ± 1.2 meter error due to offset of the GRARR antenna X and Y axes.

- first-order survey- 10 meters (from Simmons Formula for first order survey[5]) Later Herndon will also be tied to supersurvey.

Range Data Random Errors

After GDAP orbital smoothing of the data obtained from observations, spaced five seconds apart, the SECOR observation random error was initially estimated to be 2 meters. This is somewhat less than the standard error quoted in Table 3 because Table 3 includes systematic as well as random error contributions.

GODDARD DIRECTORY OF TRACKING STATION LOCATIONS, X-554-64-176, July 1, 1964.

Survey and bias adjustments were then found to be beyond the estimated errors listed in Table 5. The bias adjustment was also inconsistent for successive passes. A correlation analysis of successive five-second observations indicated the normalized correlation coefficient varied from approximately 0.3 to 0.7. This can be taken into account, approximately, by increasing the estimate of the standard error of the observations. A conservative value of 8 meters was selected for the SECOR stations. A correlation analysis of observations at Rosman indicated negligible correlation between successive five-second observations. Therefore, the 12 meter random error in the Rosman range data observed from GDAP orbital smoothing of the five-second observations (see Table 8) was used as the Rosman range data standard error estimate (see Table 5). This value agrees reasonably well with the theoretical estimate of 9.5 meters (see Table 4).

SUMMARY OF DATA

Data were obtained from four SECOR stations and one GRARR system for four passes. Tables 1 and 2 list the stations, equipment, and participation in passes. A least-squares-fit analysis (GDAP) was performed on these four passes. The site location errors per station were considered equal for all passes, but all other state variables were adjusted separately for each pass. A summary of bias, timing, and random errors is presented in Tables 6, 7, and 8, respectively.

The bias error for Rosman is found to be -20.5 ± 4.9 meters. The random noise is 12 meters.

The measured error for propagation frequency or velocity of light was 2 parts per million. However, since the uncertainty in the estimate was 5 parts per million, no significance was attached to this parameter. In addition, the propagation anomaly for the Rosman S-band system, and the various site location differences from survey were within the uncertainty of the estimate, and, therefore, the site location difference from survey could not be established with sufficient precision to be reported.

The average time difference between the SECOR master system at Herndon and Rosman was 0.3 milliseconds. It should be noted that, at the time that these data were obtained, the AMS was referring their range data to a station clock which was not carefully synchronized to WWV, since this is not necessary for their normal operation. Later in February, 1966, for purposes of the GEOS A Tracking System Intercomparison Investigation, the AMS modified their system so their data is now synchronized with WWV.

Table 6

Summary of Range Bias Error in Meters

PASS NO.	HST	SAV	GRN	HRN	ROS
665	-4	N/A	17	-13	-27
676	8	-11	- 2	9	-18
677	5	- 5	10	- 3	-23
700	N/A	2	- 3	2	-14
Combined	3.0	-4.7	5.5	-1.2	-20.5 $\pm$ 4.9

Table 7

Summary of Timing Differences for Rosman
Relative to SECOR Master Station at Herndon

PASS NO.	TIMING DIFFERENCE (milliseconds)	STANDARD DEVIATION OF ESTIMATE
665	+0.4	0.9
676	+1.0	1.0
677	-1.6	1.0
700	+0.9	1.5

Table 8

Summary of Range Data Random Errors in Meters

PASS NO.	HST	SAV	GRN	HRN	ROS
665	3.2	N/A	3.5	2.1	11.3
676	1.7	2.7	3.4	1.8	11.9
677	2.4	1.9	2.7	2.3	10.9
700	N/A	1.7	4.6	2.4	14.1
Combined	2.4	2.1	3.5	2.2	12.0

ANALYSIS OF ERRORS

GRARR RANDOM ERRORS

The random errors evaluated in this study and their high- or low-frequency value are given in Table 4. Polynomial fits of thirty seconds duration were constructed from GRARR data obtained during aircraft acceptance tests in August, 1964,

and from GEOS data. Standard deviation about the fitted curve varied from 4 to 8 meters. Error estimates after fitting a GDAP orbital trajectory from several minutes of data varied from 11 to 14 meters. This compares with the theoretically expected values of 4.6 meters for 30 seconds of smoothing and 9.5 meters for several minutes of smoothing. In future analyses, the power spectrum response of each theoretical random error will be synthesized into composite data and compared with measured data for a more realistic appraisal.

TEMPERATURE VARIATION OF GRARR TRANSPONDER

Temperature and S/N variables in transponder delay were measured before installation in the satellite (reference 3). Table 9 summarizes these errors which may be removed by a look-up table as a function of temperature and up-link signal strength.

Table 9

Transponder Variations with Temperature and Signal Level

PASS NO.	TEMPERATURE	POWER UP-LINK 1500/300 KM	RANGE VARIATION
665	Not Recorded	Not Recorded	Not Recorded
676	12.4°C	-64/-70 dbm	+ 1.5 meters
677	14.1°C	-64/-70 dbm	+ 1.5 meters
700	14.1°C	-64/-70 dbm	+ 1.5 meters

Test specifications require that the maximum tolerance for transponder delay shall not exceed 32 nanoseconds or 4.8 meters over a signal level of -15 dbm to -85 dbm with the temperature between -10°C and $+45^{\circ}$C.

TRANSPONDER DELAY VS DOPPLER

The up-link receiver contains a filter which produces a phase delay according to the doppler of the input. A preprocessor program will be used to compensate for this delay. Figure 2 shows a graph of the range error vs range rate (doppler). For this evaluation, only range rate from -5K m/sec to +5K m/sec were observed. The range measurement error caused by this transponder delay can be converted by application of the formula $\Delta T = \Delta R / \dot{R}$, to an equivalent satellite time error (lag) of approximately 0.8 milliseconds. The 0.8 milliseconds can be included in the solution for ΔT in the Radar Error Model. Test specifications require that the transponder
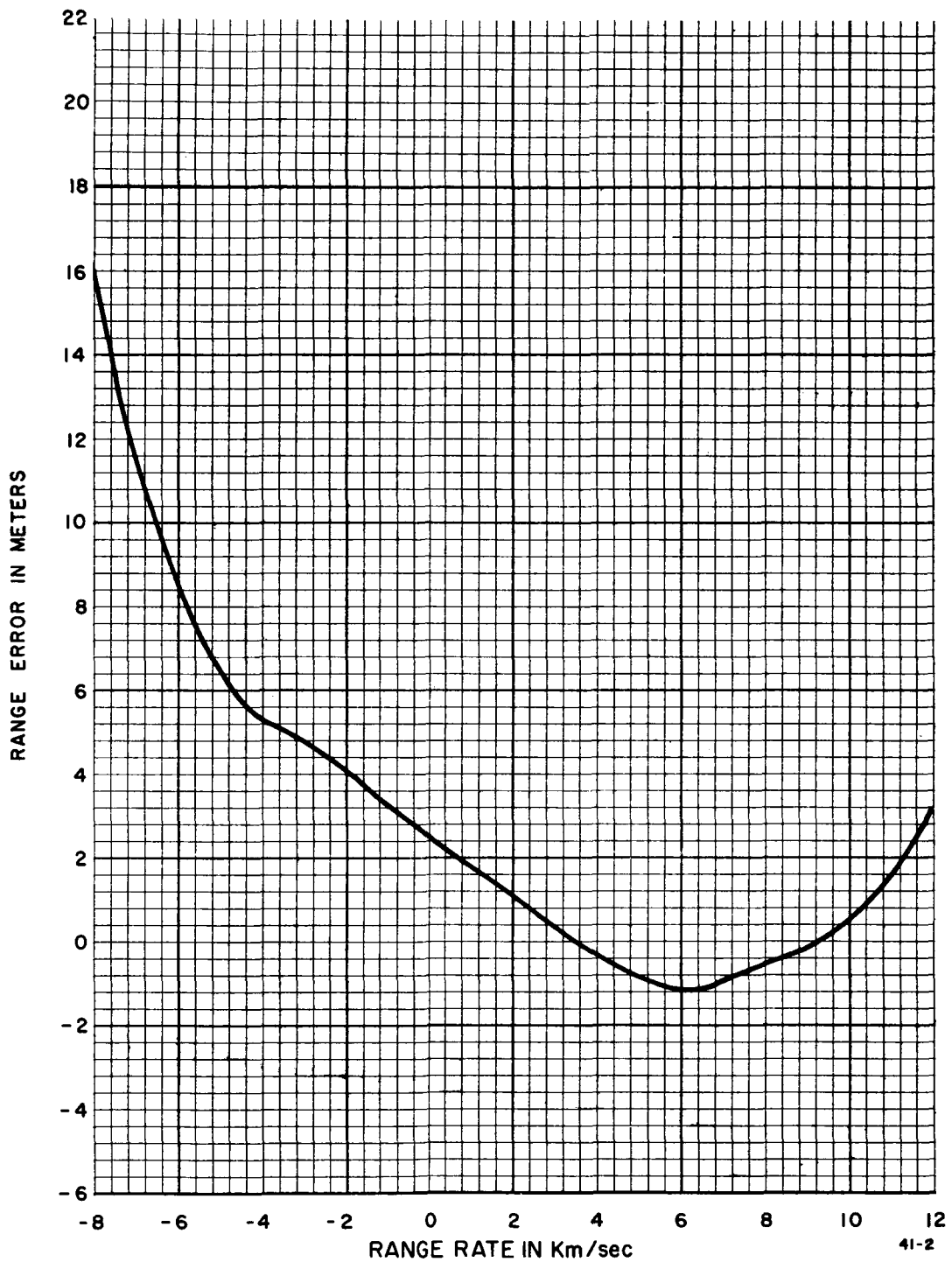
-12-

Figure 2. Range Error (Transponder Delay) vs Range Rate (Doppler)

delay shall not exceed 75 nanoseconds (11.25 meters) over a doppler frequency range from -85K cps to +85K cps. By application of $\Delta T = \Delta R/\dot{R}$, the specification may tolerate equivalent timing errors of 1.1 milliseconds.

ANTENNA POSITION BIAS

The Rosman S-band GRARR parabolic antennas are mounted on an X-Y system. The X-axis is oriented north-south and is fixed in position. The Y-axis, however, is oriented east-west, but it is mounted 1.2 meters above the X-axis. This causes the position of the Y-axis to vary sinusoidally in respect to the Geodetic location of the site. Although the discrepancy is within ± 1.2 meters, the preprocessing program will correct the Y-axis to the Geodetic location (center of X-axis). The correction is made by using the formula

Δ Range = d (cos Y), where Y is the Y-angle of the pedestal and
d is the offset above the X-axis = 1.2 meters.

ROSMAN ZERO SET BIAS

The average zero set bias for this experiment was -20 meters with a standard error of the bias estimate at 4 meters based on these four passes. The 14 foot RE-142 cable used in precalibration adjustments (at the collimation tower) accounts for -6.3 meters. The collimation tower transponder and cable delay from the horn to the collimation tower transponder should be measured together and this value used in future calibration efforts. Also, the displacement of the horn aperture on the collimation tower reflector, considering reflections within the cassegranian feed system, is one meter greater than that previously used. These errors of the GRARR system at Rosman, N. C., are listed in Table 10.

Table 10

GRARR System Ranging Errors for Rosman, N.C.

NAME	RANGE ERROR
Zero-set Bias (already corrected at Rosman prior to transmission)	156 meters
Aperture of Transponder Horn	-1.0 meters
Transponder and Cabling Delays from Aperture to Transponder	-6.3 meters
Collimation Tower Delay (specification)	0 to -15.0 meters
Total Error	-7.3 to -22.3 meters

TIMING ERRORS

Comparison of Rosman and SECOR timing showed that Rosman was apparently 0.3 milliseconds behind SECOR. This includes the lag of 0.8 milliseconds in the GRARR transponder, since this effect was not removed from the GRARR data. If the 0.8-millisecond delay due to doppler variation within the GRARR transponder is removed, the total difference in timing would be -.5 milliseconds. This evaluation was performed in January; however, the SECOR system was not able to monitor and adjust time discrepancies with WWV until February. This error is statistically insignificant.

AMBIGUITY ERRORS

An error of 1500 meters was detected for pass 665 at Rosman. This corresponds to an ambiguity error of one wavelength of the highest frequency sidetone. The sidetone alignment procedures were executed between 0200 and 0300 hours, Rosman local time, on January 1, 1966. Such ambiguity errors are relatively rare with the GRARR system and, in lieu of a better reason, is attributed to a "New Years Eve" effect in this case.

CONCLUSIONS

The values of the system errors at Rosman was determined to be the following:

- Radar Error Model Coefficients

Zero-Set Bias (range)	-20 ± 5 meters
Timing (Delay)	-0.5 milliseconds (with respect to Herndon SECOR)
Frequency Offset	Undetermined

- Propagation Anomaly   Undetermined

- Station Location Errors   Undetermined

- Random Errors   11 to 14 meters

FUTURE ACTION

As a result of the evaluation of the GRARR, using SECOR as a reference, and as a continuation of the GEOS Intercomparison Investigation, the following actions are planned:

1. Compensate for calibrated transponder errors and the relative motion of the dish X-Y axes in a computer program.

2. The error due to the collimation tower transponder and cable delay should be measured together and this value used in future calibrations.

3. Evaluate the accuracy of the range rate data as soon as the GDAP has been completed.

4. Evaluate the GRARR with other, more accurate sensors, namely, with optical data and with a laser located at Rosman, as outlined in the initial GEOS Investigation Plan.

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