DSS Range Delay Calibrations: Current Performance Level

G. L. Spradlin
DSN Network Operations Section

It is the intent of this report to describe a task undertaken approximately 18 months ago, under the auspices of the Ranging Accuracy Team, to develop a means for evaluating Deep Space Station (DSS) range delay calibration performance, and through which inconsistencies frequently noted in these data could be resolved. Development of the DSS range delay data base is described. The data base is presented with comments regarding apparent discontinuities. Data regarding the exciter frequency dependence of the delay values are presented, and the report concludes by noting the improvement observed in the consistency of current DSS range delay calibration data over the performance previously observed.

I. Introduction

The measurement of the distance, or range, to a spacecraft, as accomplished by the DSN Ranging Subsystem, is essentially a precision measurement of the time interval between transmission and receipt of a binary-coded signal called the range code. Unfortunately, the time interval (from transmission to receipt of the range code) measured by the Ranging Subsystem is not the desired measurement. For the purposes of orbit determination, the measurement needed must be from the defined station location to a reference point on the spacecraft and back, and therefore, the delay actually measured by the Ranging Subsystem must be modified (corrected) to account for delays of the range code that are not part of this reference-point-to-reference-point measurement. Among other correction factors that must be applied to the measured value to obtain the desired value is the delay experienced by the range code as it passes through the station equipment, or the station range delay.

Historically, the station range delay has been considered one of the largest contributors to inaccuracies in spacecraft range measurements despite the measurement (calibration) of the station's range delay prior to and immediately after each spacecraft track during which range data were taken. Inconsistencies and apparent errors in the station range delay calibration could be expected to contribute at least several meters of uncertainty to the spacecraft range measurement. The inconsistencies of station range delay calibrations were recognized by the Ranging Accuracy Team as being incompatible with the stringent range accuracy requirements of future missions, and hence, one of the initial tasks undertaken by the team was to develop a data base from which current performance could be ascertained, and improvement monitored. This report describes this effort, and delineates the current station range delay calibration performance.

II. Establishing The Data Base

It was decided in early June 1975 that the data base would not include any currently available data, nor would it include station range delay calibrations as reported via the station posttrack reports. Instead, each station capable of ranging was requested to perform special range delay calibration measurements.

To provide control over the conditions under which the measurements were to be made, each station was requested to use a specific set of parameters including specifications of range code component integration times, level of carrier suppression, downlink signal level, antenna pointing angles, and uplink power level. The report from the station was to include, in addition to the range delay calibration, five postrange acquisition Differenced Range Versus Integrated Doppler (DRVID) values so that the range delay calibration could be corrected for waveform distortion, exciter frequency, the number of the receiver used, and which maser was used.

It was originally thought that a one-month period of data collection would provide a sufficient data base; however, due to a lack of available time at the stations to perform unscheduled activities, far too few measurements were made available to constitute a data base. Time for the stations to take the needed measurements was then made available through the Deep Space Network (DSN) Scheduling Office. The measurements were to be made on a noninterference basis during or immediately after normal station posttrack countdown procedures. One-half hour was added to the allotted time for the normal posttrack procedures to help alleviate any time bind that might be caused by making the additional measurements. Measurements were scheduled to be made at each station as frequently as once per day with no more than seven days between measurements, depending upon station time availability. Also, the time span over which data would be collected was extended from the original one-month period to a six-month period.

Coincident with the effort to establish a data base, a task was undertaken to reevaluate and update the standard pre- and posttrack range delay calibration procedures, including the reporting format (Post Track Report). Provisions were made in the new procedures to incorporate the controlled range delay calibration into the standard station procedures. The Post Track Report format was redesigned to provide detailed information regarding configuration, and to provide the needed data to ascertain the health of the ranging subsystem. The obvious advantage of the aforementioned incorporation is that the data base would now receive almost continuous inputs as a product of normal station operations, and station range delay calibration performance could be more closely monitored.

After a confidence-building period of approximately one month, the specially scheduled calibrations were discontinued, and the new Post Track Report was adopted as the data source for the data base. A copy of the portion of the new Post Track Report format containing range calibration information is shown as Fig. 1. Item A.3 contains the station range delay calibration data, and the necessary configuration information. The information used as input to the data base is found in items 3.(a).1 and .2, and 3.(b).1 and .2. The numbers reported here by the stations are converted from the frequency dependent unit of measurement (Range Unit, RU) output by the ranging subsystem, after adjustment by the DRVID correction, to meters (one-way) for ease of comparison with flight project navigation and radio science requirements, and for entry into the data base.

III. The Data Base

Station range delay calibration data extracted from the data base and plotted in meters (one-way) versus day of year are presented in Figs. 2 through 10. Specific station performance will not be detailed at this point. Instead, it is intended simply to present the data base, and to explain peculiarities, events, and characteristics that can be seen in the plotted data. A more detailed analysis of the data will be presented in a subsequent section of this report.

A. Goldstone, Pioneer, DSS 11

DSS 11 is the station to have most recently acquired a ranging capability, this event occurring approximately sixty days after data collection began from other stations. Early data from DSS 11 indicated that, for whatever reason, this station did not reflect the inconsistency of range calibrations noted in the early data from other stations. In fact, it became an interim goal to try to improve the performance of other stations to that level already being achieved at DSS 11. As indicated on this station's plot, an Engineering Change Order (ECO) that altered the station range delay calibration path was installed temporarily, day 63 through day 70, and permanently on day 158. All calibrations indicated on this plot were made using Maser 1 and Receiver 1.

B. Goldstone, Mars, DSS 14

Figure 3 is a plot of DSS 14 S-band calibrations. All data were taken using the S-Band Polarization Diversity (SPD) maser and primarily Receiver 3 of the Block IV Receiver-Exciter Subsystem, although there is a scattering of points taken using Receiver 4. Also, all calibrations were made using the Block IV doppler translator instead of a dish-mounted Zero Delay Device (ZDD); both devices perform the function of simulating a spacecraft by converting a transmit-level frequency to a receive-level frequency.

Prior to day 90, DSS 14, like other stations in the Network, utilized the Planetary Ranging Assembly (PRA) to conduct spacecraft ranging. On day 90 an R&D ranging machine, the MU II, was installed to provide range data enhancement for the Helios project at superior conjunction. The MU II has been retained at DSS 14, and is currently used for both Viking and Helios ranging operations.

Figure 4 presents DSS 14 X-band range calibrations. The family of points seven to eight meters below the major point grouping represents a periodically occurring anomaly that recently has been determined to be the result of a procedural error (incorrect switch position) during the range delay measurement.

C. Australia, Weemala, DSS 42

DSS 42 range calibrations presented in Fig. 5 were taken using Receiver 5, Maser 1, and a dish-mounted ZDD.

As mentioned earlier, DSS 11 did not indicate the inconsistency in range calibrations noted elsewhere in the Network. As data collection progressed, it became quite clear that DSS 42 was unable to provide consistent calibrations, and that the problem was not due to an equipment failure, nor was it procedural in nature. It also became clear that DSS 42 range calibrations were highly exciter reference frequency dependent, and that the calibrations at DSS 11 were not. Further, it was found that the locations of the dish-mounted ZDDs at these two stations were radically different, and that a poor location of the ZDD could result in the calibration inconsistency being observed, the apparent result of signal multipath effects. A pragmatic decision was made to relocate the DSS 42 ZDD to a position on the antenna identical to that where the ZDD was located on the DSS 11 antenna. This was done on day 114 with an obvious and dramatic reduction in range calibration inconsistency. An additional small step in the plotted calibrations can be seen to occur on day 140 coincident with a klystron change.

D. Australia, Ballima, DSS 43

DSS 43 calibrations presented in Fig. 6 reflect a multiplicity of configurations. The majority of data collected prior to day 30 of 1976 were taken using the Block III Receiver-Exciter Subsystem, Receiver 1, the SPD Maser, and a dish-mounted ZDD. After day 30, the Block IV Receiver-Exciter Subsystem became the prime data source, and data from Receivers 3 and 4 in conjunction with the SPD maser are represented. As with DSS 14, all Block IV measurements utilized the Block IV doppler translator.

Calibrations made at DSS 43, while using the dish-mounted ZDD, again indicate a strong exciter-frequency dependence. The apparent increase in the calibration measurement after day 260 of 1975 resulted from work done in the tricone area of the antenna, but did not appear to significantly alter the apparent frequency dependence of the dish-mounted ZDD calibrations.

The cause of the dramatic improvement indicated after day 140 is not clearly understood, but it is felt to be the result of possibly two things: (1) stringent configuration control exercised per Viking project requirements, and (2) a significant decrease in the frequency dependence of range calibrations made using the doppler translator (possibly due to an inadvertent but fortunate elimination of a multipath or leakage problem).

Figure 7 presents DSS 43 X-band range calibration data. Again a distinct change in the plot occurs at day 140. With the exception of the anomalous calibrations reported on day 142 and day 162, all calibrations after day 140 fall into one of two distinct families of points. Tests conducted at DSS 43 indicate that while there is only a minor change in the S-band range calibration value as exciter frequency is changed, the change in the X-band calibration value is quite significant. Thus the two families are not unexpected, as the upper grouping of points represents calibrations extracted from Viking Orbiter 1 Post Track Reports (i.e., the calibrations were made in the region of frequency channel nine), and the lower point grouping from Viking Orbiter 2 Post Track Reports (calibrations made in the region of frequency channel 20).

E. Spain, Robledo, DSS 61

DSS 61 range delay calibrations shown in Fig. 8 were made using Receiver 5, Maser 1, and a dish-mounted ZDD.

The small grouping of points between days 261 and 282 of 1975 at approximately the 360-meter level reflects the temporary insertion of an additional cable in the range delay calibration path during station troubleshooting of a ranging subsystem problem. There is no available explanation for a similar family of points between days 43 and 76 of 1976.

Although it is not obvious by inspection of DSS 61 range delay calibrations presented on Fig. 8, tests conducted at DSS 61 indicated that this station's range calibration value was also exciter-frequency dependent and, like DSS 42, the DSS 61 ZDD was relocated to a position similar to the DSS 11 ZDD location on that antenna. The ZDD relocation occurred on day 77 of 1976, after which a clear improvement was observed in the range calibration consistency. An additional discontinuity and noted increase in frequency dependence is observed on day 139, coincident with an S-band mixer change.

F. Spain, Robledo, DSS 63

Like DSS 43, DSS 63 range calibrations presented in Fig. 9 indicate that a number of configurations were used for calibrations at this station through day 125 of 1976. Data prior to day 300 of 1975 reflect use of the Block III Receiver 1, the SPD maser, and a dish-mounted ZDD. Measurements after day 4 and before day 112 reflect mixed use of Block IV Receivers 3 and 4, the SPD maser, and the Block IV doppler translator. With the exception of four points, all measurements after day 112 were made using Receiver 3, the SPD maser, and the Block IV doppler translator.

Use of the high-power klystron at DSS 14 and DSS 43 has not been mentioned, as use of this device has not had a significant impact on the reported range delay calibration. This statement cannot be made of calibrations reported at DSS 63. For an unknown reason the use of the high-power klystron at DSS 63 does result in a significantly different range delay. The family of points between 648 and 651 meters reflects its use.

The increased point-to-point consistency of calibrations after day 135 is again attributed to tight station configuration control, a result of Viking Project support.

Figure 10 presents DSS 63 X-band range calibration data. The data were taken using primarily Receiver 4; however, a scattering of points representing Receiver 3 is also present.

The family of points between roughly 624 meters and 628 meters is representative of use of the high-power klystron (denoted by the "H," above the plotted point), and an anomaly recently traced to a faulty relay in the Block IV X-band doppler translator.

Again there is a general reduction in the scatter of the calibrations after day 130, and as with the S-band calibrations, it is felt this phenomenon is attributable to configuration control.

IV. Calibration Performance Analysis

The frequency dependence of the station range delay calibrations has been mentioned numerous times in the preceding section of this report. The cause of the frequency dependence of the range delay is not clearly understood as of this writing. In fact, the extent to which it is a problem is also not clear. In an effort to understand how the range delay varies as a function of frequency, each station capable of ranging has been requested to conduct a "Range Delay Versus Frequency Test." Essentially, the test simply provides calibration data at channel center frequencies, channels 5 through 26.

It was previously mentioned that DSS 11 did not reflect the frequency dependence noted in data from DSS 42 and DSS 61, and that the ZDDs at DSS 42 and DSS 61 were relocated to agree positionally with the DSS 11 ZDD location, in an apparently successful attempt to reduce the DSS 42 and 61 frequency dependencies. Figure 11 presents the results of a range delay versus frequency test conducted at DSS 11 on day 252 of 1975. Clearly, there is a variation of the range delay with change in frequency; however, the peak-to-peak change is only about 1.5 meters. Compared to the approximate 8-meter and 7-meter changes seen on Figs. 12 and 13 (DSS 42 and DSS 61, respectively) DSS 11 appears relatively insensitive to changes of frequency.

Figures 14 and 15 present DSS 42 and DSS 61 range delay versus frequency data after relocation of their ZDDs. The reduction in frequency dependence is noticeably significant with both stations showing a range delay variation with frequency change of roughly 2 to 3 meters peak-to-peak.

Tests run at DSS 14 and DSS 43 also indicate a range delay variation with frequency change. The results of the DSS 14 test are shown in Fig. 16 (S-band) and Fig. 17 (X-band) with indicated peak-to-peak changes of approximately 6 meters and 3 meters respectively. The DSS 43 results shown in Fig. 18 (S-band) and Fig. 19 (X-band) indicate an S-band peak-to-peak change of about 3 meters, and an X-band peak-to-peak change of roughly 6 meters, and for an unknown reason, a significantly different profile.

Test data from DSS 63 are not yet available; however, inspection of range delay information in the data base indicates that neither the S-band nor X-band range delay calibrations vary significantly as a function of frequency.

Each spacecraft tracked by the DSN is assigned and communicates within a particular frequency channel. All station range delay calibrations made and reported via the Post Track Report are measured at a frequency within the frequency channel assignment of the spacecraft whose track is being reported upon. With the information presented above (a station's range delay calibration is frequency dependent), the consistency or repeatability of a station's range delay calibration cannot clearly be ascertained without consideration of the spacecraft (or spacecraft frequency channel assignment) as an independent variable. That is, the determination of the consistency of a station's range delay calibration should be based upon a consistent spacecraft (i.e., consistent frequency), as much as it would upon use of a consistent station hardware configuration (same receiver, same maser, etc.).

The data presented in the data base consist primarily of range delay calibrations extracted from Post Track Reports for Viking Orbiter 1 (VO-1) and Viking Orbiter 2 (VO-2). The information presented in Table 1 describing station range delay calibration performance was constructed considering the spacecraft as an independent variable. The mean and standard deviation ($1\ \sigma$) were computed using the last N range delay calibrations (excluding known anomalous points mentioned earlier) reported from each station. The mean for each configuration has been indicated on the data base plots (Figs. 2 through 10). Only those station hardware configurations recently and frequently used have been considered.

It was mentioned at the beginning of this report that station range delay calibrations have historically been considered a major source of inaccuracies in the measurement of spacecraft range, and that the inconsistencies in the station calibrations were suspected to have contributed up to several meters of uncertainty to the range measurement.

Data presented in Figs. 2 through 10 clearly indicate that unexplained point-to-point inconsistencies of from 5 to 10 meters were commonplace in the calibrations recorded during the first several months of data collection. The data base also delineates that by relocation of the ZDDs at DSS 42 and DSS 61, stringent configuration control at all stations, an increasing knowledge of the sensitivity of the range delay to many variables, and continuous monitoring and feedback regarding calibration performance to the stations, the consistency of the calibrations has been greatly increased, and point-to-point consistency of less than one meter ($1\ \sigma$) is the current level of performance.

V. Summary

Station range delay calibrations have long been considered one of the major contributors to inconsistencies observed in spacecraft range measurements. Recognition of this plus knowledge of future mission needs for highly accurate range data led to an effort undertaken by the Ranging Accuracy Team, to acquire knowledge regarding the current ability of the Network to provide consistent range delay calibrations, and to develop a data base through which improvements in calibration performance could be monitored.

It has been the intent of this report to describe the data base development, graphically present the data base, and to provide some explanation of trends or characteristics that are observed in the graphical presentation. A substantial amount of data is presented regarding one easily discernible characteristic—the frequency dependence of the range delay.

Table 1 is presented at the conclusion of the analysis section, and provides a summary of station range delay calibration performance. The mean and standard deviations for each frequently used station configuration (receiver, maser, and spacecraft) are presented. It can be seen that station calibrations are now quite consistent, with the standard deviations being generally less than one meter. This represents a significant improvement over the 5- to 10-meter variations observed early during the data base development.

Table 1. Station range delay calibration performance

DSS	Configuration	N	MEAN, m	σ, m
11	RCVR1/TWM1/VO-1	33	307.0	0.4
	RCVR1/TWM1/VO-2	62	306.2	0.4
14	RCVR3/SPD/VO-1	57	493.5	0.5
	RCVR3/SPD/VO-2	30	495.6	0.4
	RCVR4/XRO/VO-1	53	481.7	0.6
	RCVR4/XRO/VO-2	23	482.5	0.3
42	RCVR5/TWM1/VO-1	8	381.7	0.6
	RCVR5/TWM1/VO-2	33	382.1	0.5
43	RCVR3/SPD/VO-1	43	509.1	0.3
	RCVR3/SPD/VO-2	22	508.7	0.3
	RCVR4/XRO/VO-1	41	498.0	0.7
	RCVR4/XRO/VO-2	20	494.7	0.6
61	RCVR5/TWM1/VO-1	12	353.5	0.9
	RCVR5/TWM1/VO-2	35	350.9	0.7
63	RCVR3/SPD/VO-1	36	656.7	0.5
	RCVR3/SPD/VO-2	29	657.3	0.5
	RCVR4/XRO/VO-1	31	634.1	0.5
	RCVR4/XRO/VO-2	29	635.0	0.5

A. MISSION INDEPENDENT.

1. DSS______; DAY______; PASS______: MISSION______; S/C ID______.

2. ACQUISITION______Z; END OF TRACK______Z.

3. RANGE DELAY:

(a) S-BAND PRETRACK MEASUREMENTS AT -150 DBM (1, 2) AND AT EXPECTED SIGNAL LEVEL (3, 4):

1. RANGE ______ RU; DRVID ____ RU; S/L -150 DBM; RDA ATTR______ DB
2. RANGE ______ RU; DRVID ____ RU
3. RANGE ______ RU; DRVID ____ RU; S/L______DBM; RDA ATTR______ DB
4. RANGE ______ RU; DRVID ____ RU

XMTR PWR___KW; EXC NO. _____; TWM ________ ; RCVR NO. ______
EXC FREQ __________ HZ; CARRIER SUPPRESSION (3 and 4) _______ DB

(b) X-BAND PRETRACK MEASUREMENTS AT -150 DBM (1, 2) AND AT EXPECTED SIGNAL LEVEL (3, 4):

1. RANGE ______ RU; DRVID ____ RU; S/L -150 DBM; RDA ATTR______ DB
2. RANGE ______ RU; DRVID ____ RU
3. RANGE ______ RU; DRVID ____ RU; S/L______DBM; RDA ATTR______ DB
4. RANGE ______ RU; DRVID ____ RU

TWM ________ ; RCVR NO. ______

(c) S-BAND POST TRACK MEASUREMENTS AT ACTUAL SIGNAL LEVEL OF THE PASS:

RANGE ______ RU; DRVID ____ RU; S/L______DBM; RDA ATTR______
RANGE ______ RU; DRVID ____ RU
XMTR PWR___KW; EXC NO. _____; TWM ________ ; RCVR NO. _____
EXC FREQ ___________HZ; CARRIER SUPPRESSION _______________ DB
XMTR PWR DURING PASS_____ KW; KLYS NO. _________

(d) X-BAND POST TRACK MEASUREMENTS AT ACTUAL SIGNAL LEVEL OF THE PASS:

RANGE ______ RU; DRVID ____ RU; S/L______ DBM; RDA ATTR______
RANGE ______ RU; DRVID ____ RU
TWM__________ ; RCVR NO. ______

(e) REMARKS: *

4. STATION TIME OFFSET WITH RESPECT TO DSN MASTER:

(a) OFFSET_________, UNCERTAINTY ___________REFERENCED TO____**_____.

(b) TIMING SYSTEM RESET SINCE LAST POST TRACK REPORT: MAGNITUDE _________, DIRECTION ____________.

5. SYSTEM NOISE TEMPERATURE _____________ DEG. K

6. EQUIPMENT FAILURES OR ANOMALIES (indicate start and end times or start and estimated time for return to operation. Reference TFR(s) and DR(s).)

Fig. 1. Post Track Report format

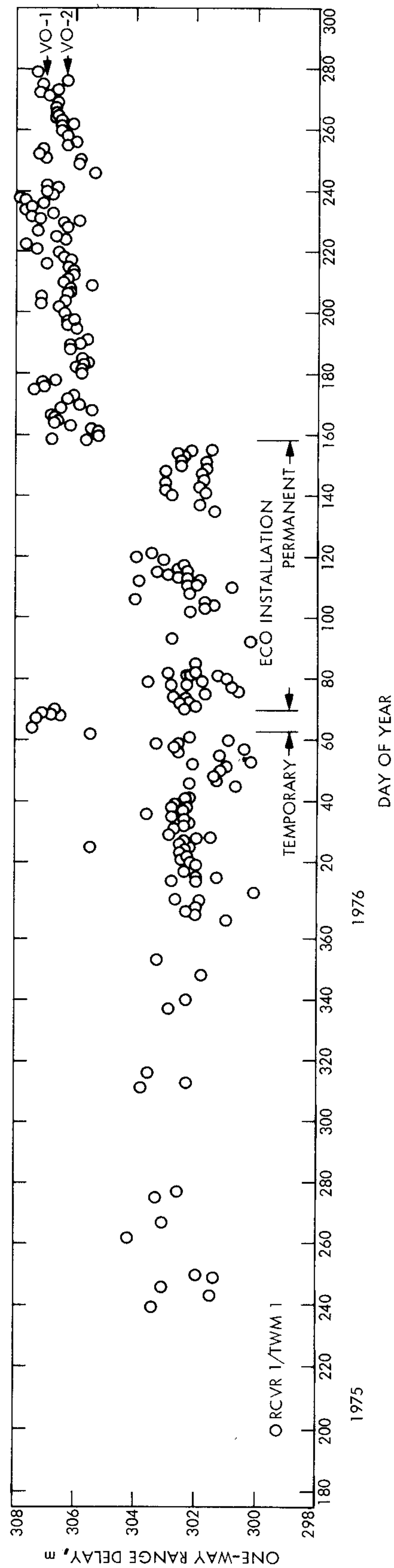

Fig. 2. Station range delay calibration data, DSS 11

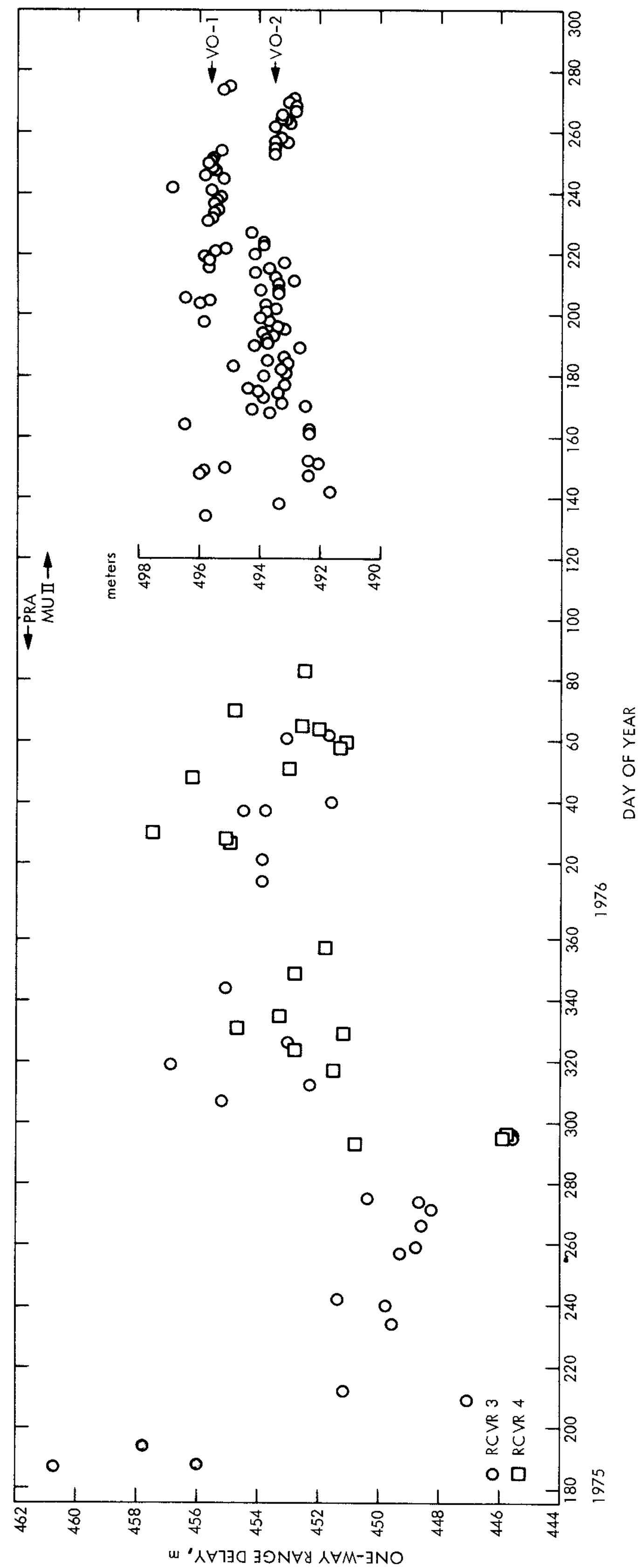

Fig. 3. Station range delay calibration data, DSS 14 S-band

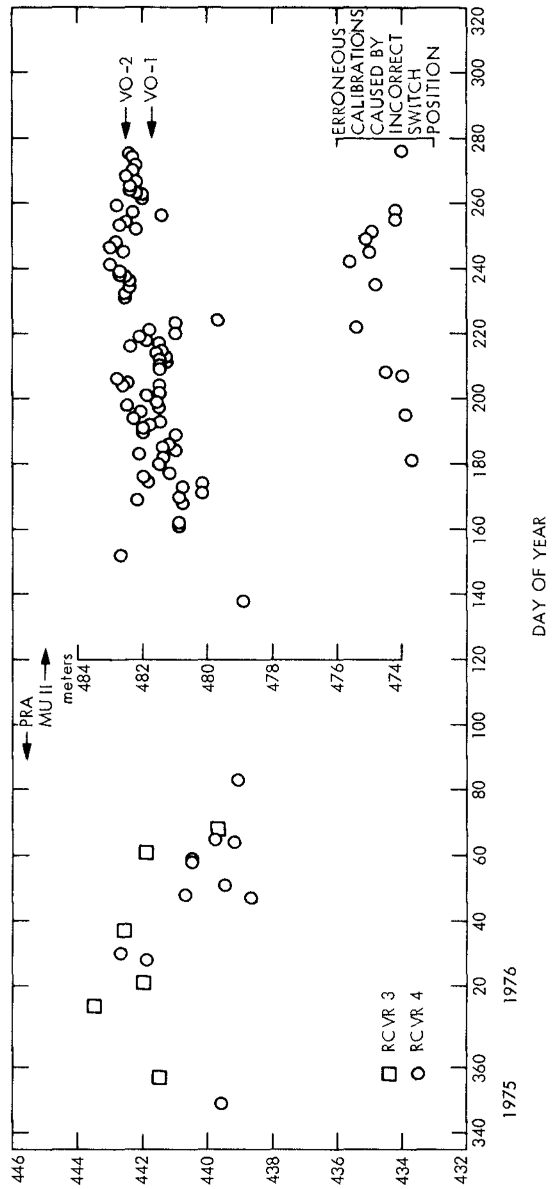

Fig. 4. Station range delay calibration data, DSS 14 X-band

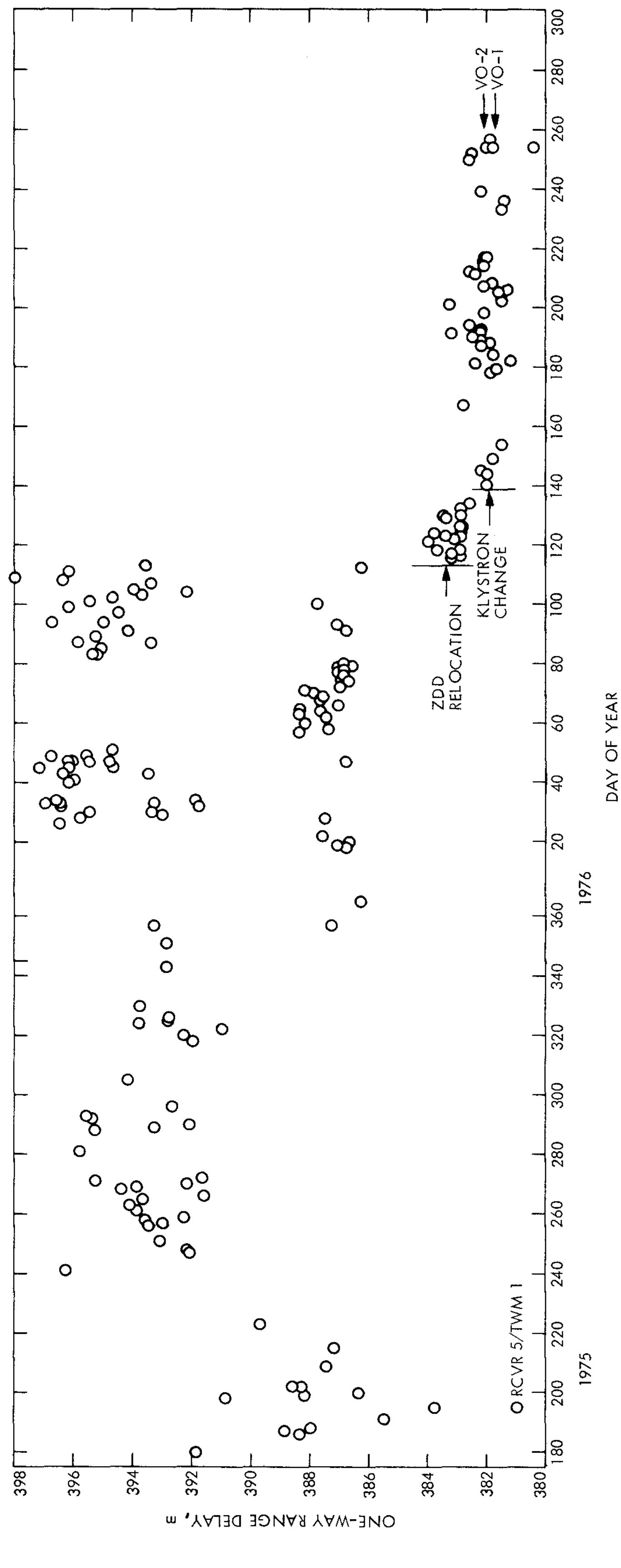

Fig. 5. Station range delay calibration data, DSS 42

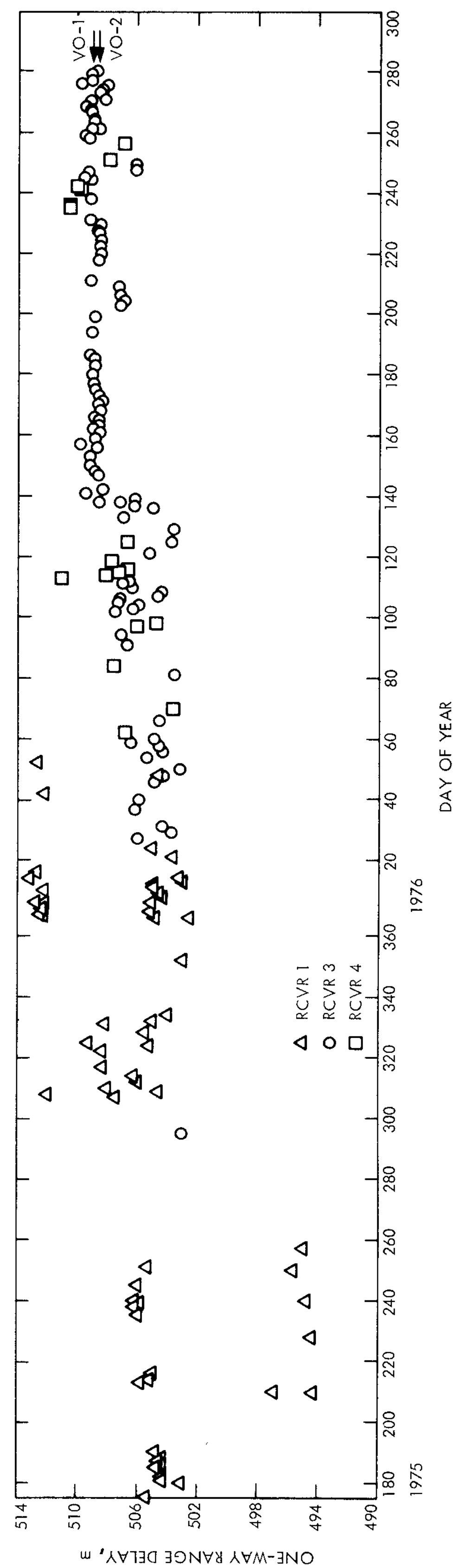

Fig. 6. Station range delay calibration data, DSS 43 S-band

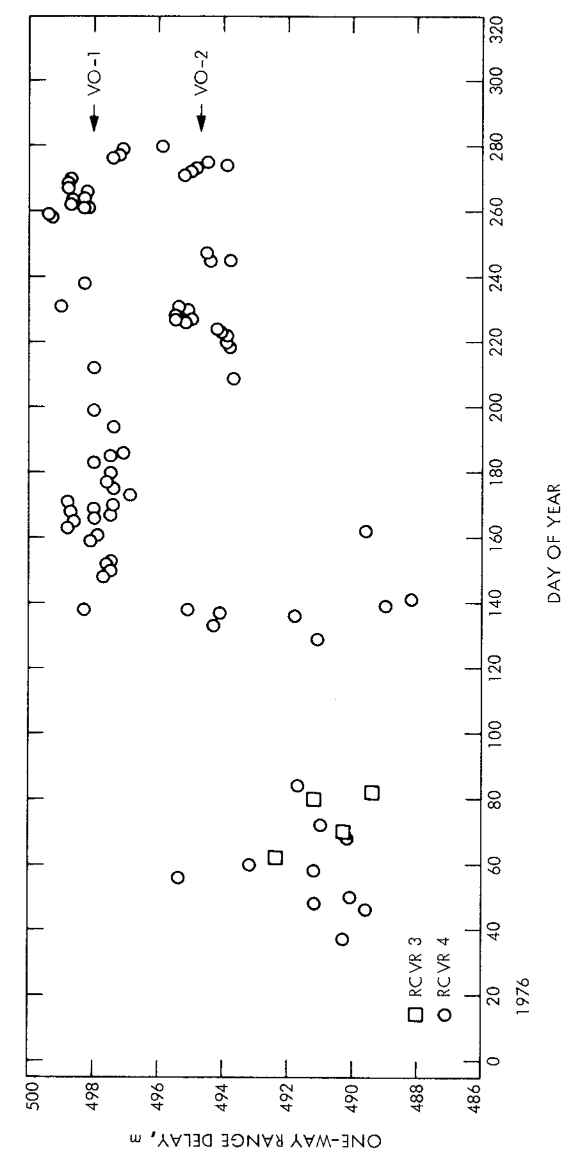

Fig. 7. Station range delay calibration data, DSS 43, X-band

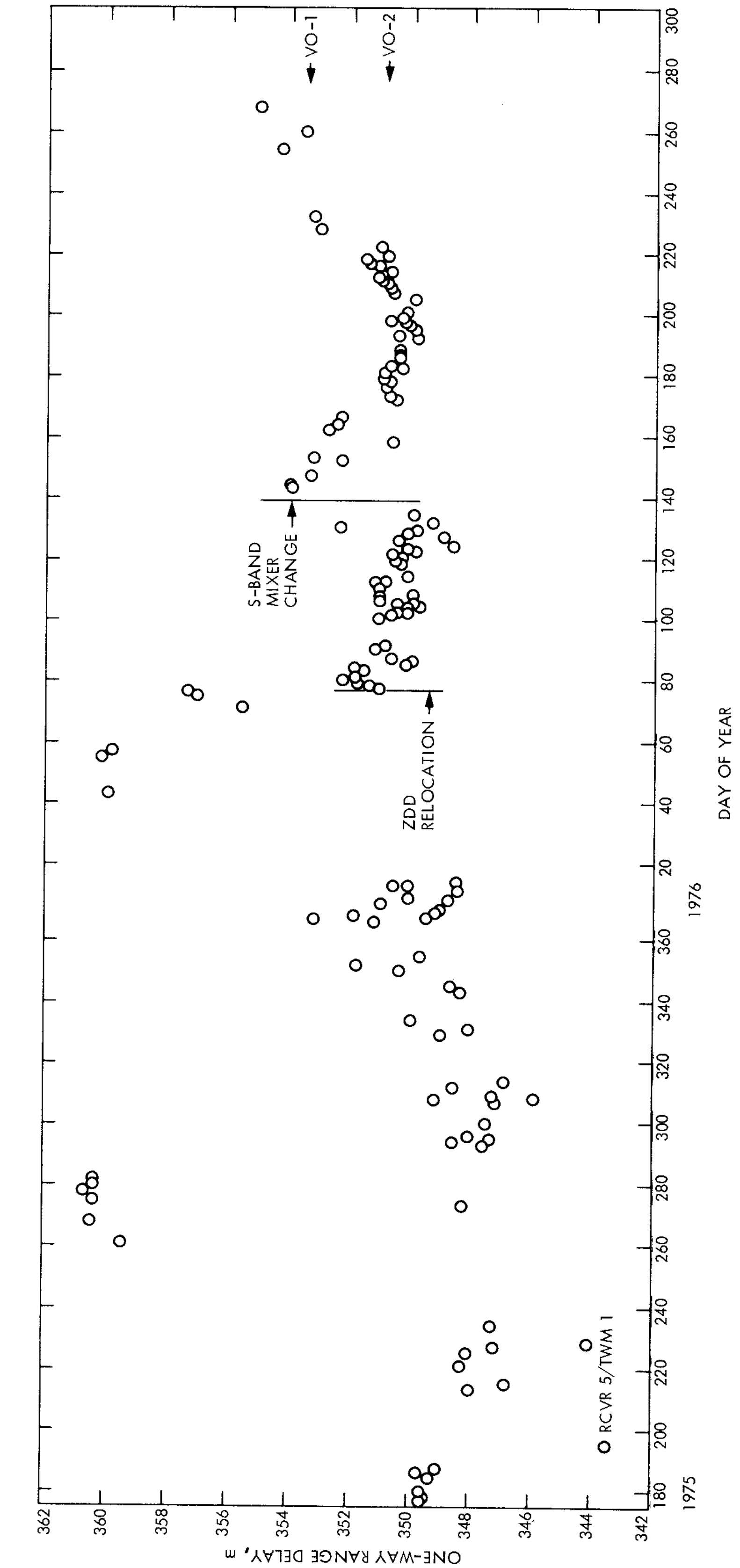

Fig. 8. Station range delay calibration data, DSS 61

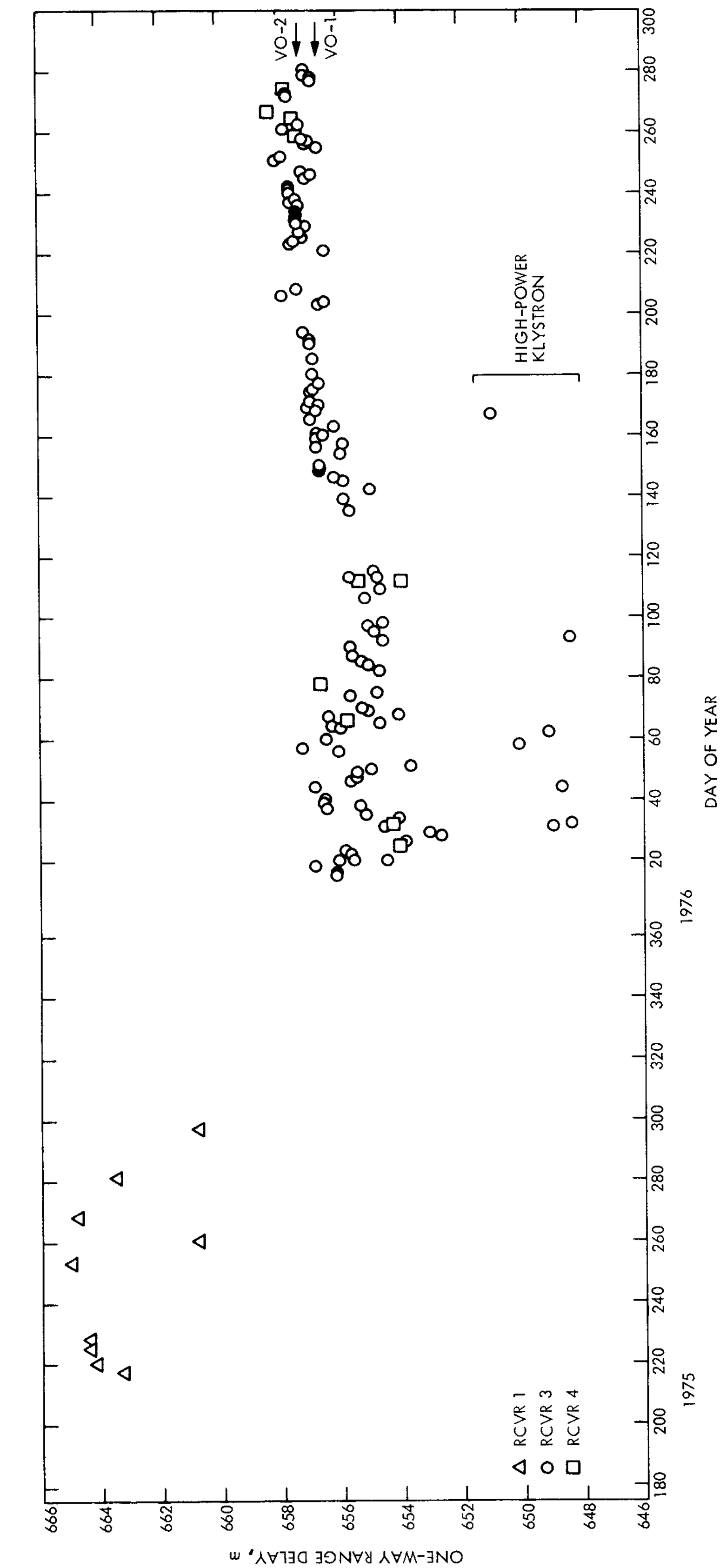

Fig. 9. Station range delay calibration data, DSS 63 S-band

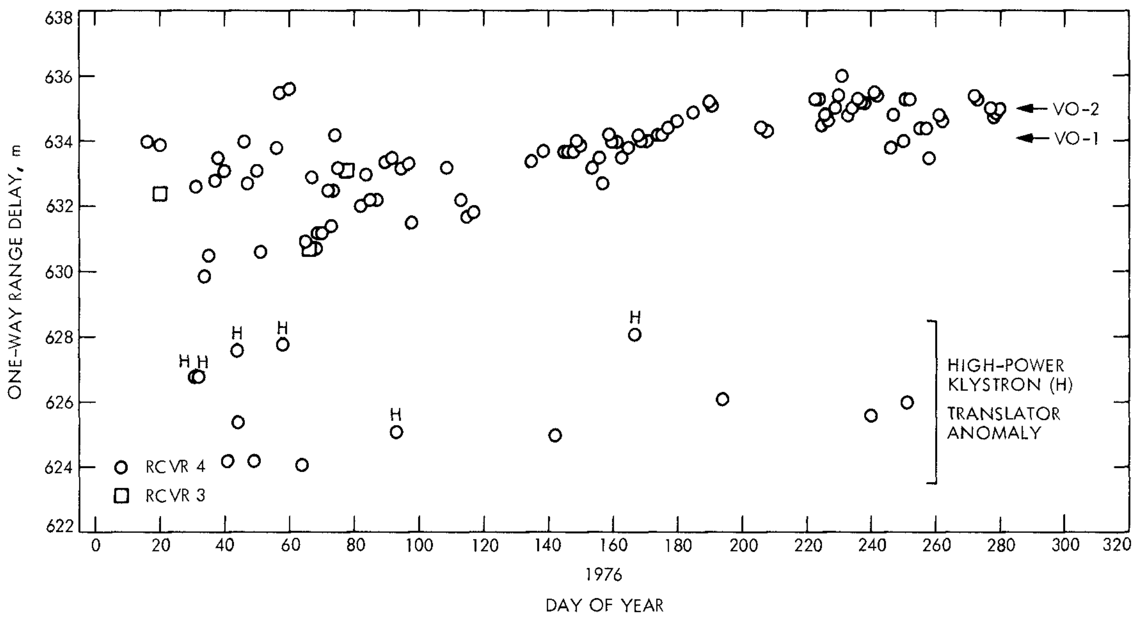

Fig. 10. Station range delay calibration data, DSS 63 X-band

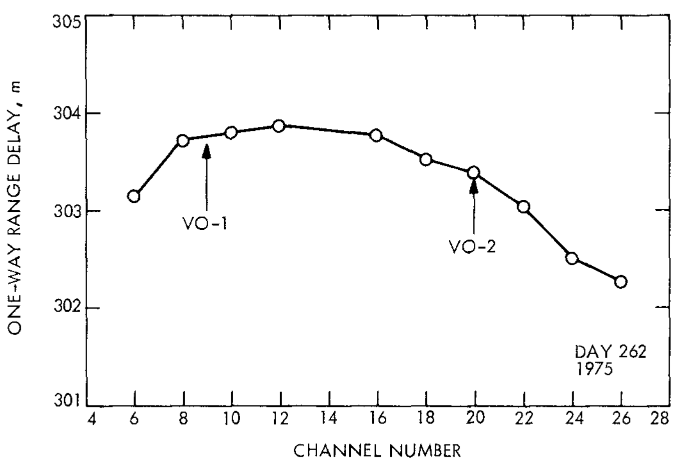

Fig. 11. DSS 11 station range delay versus frequency

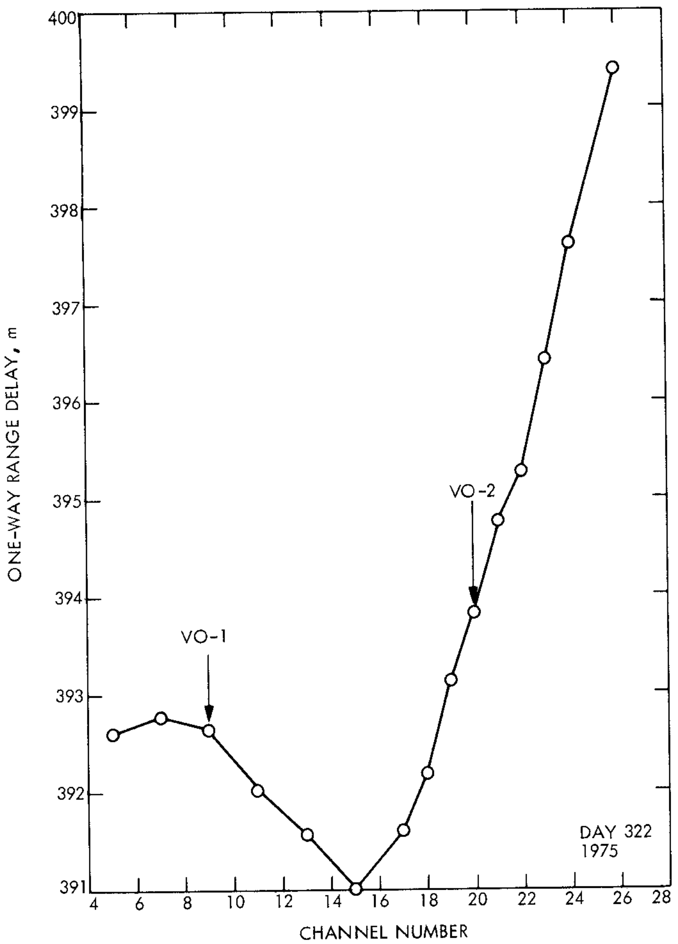

Fig. 12. DSS 42 station range delay versus frequency prior to ZDD relocation

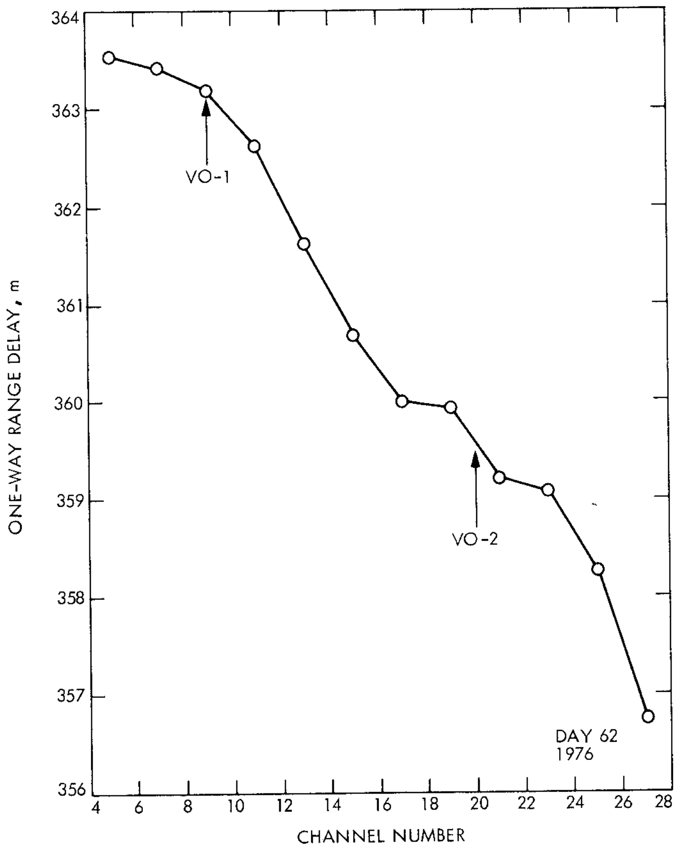

Fig. 13. DSS 61 station range delay versus frequency prior to ZDD relocation

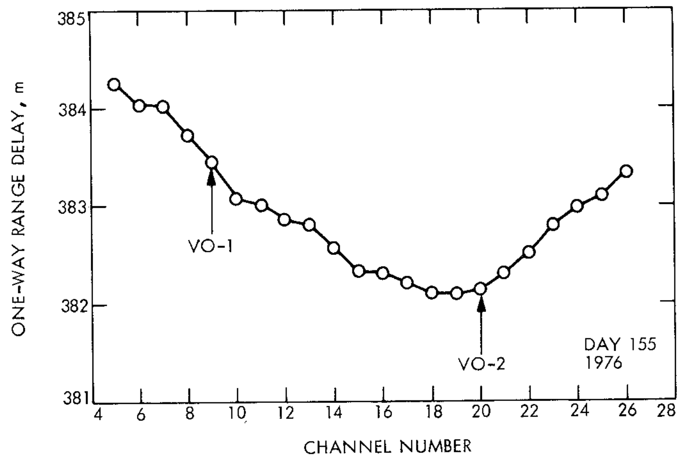

Fig. 14. DSS 42 station range delay versus frequency after ZDD relocation

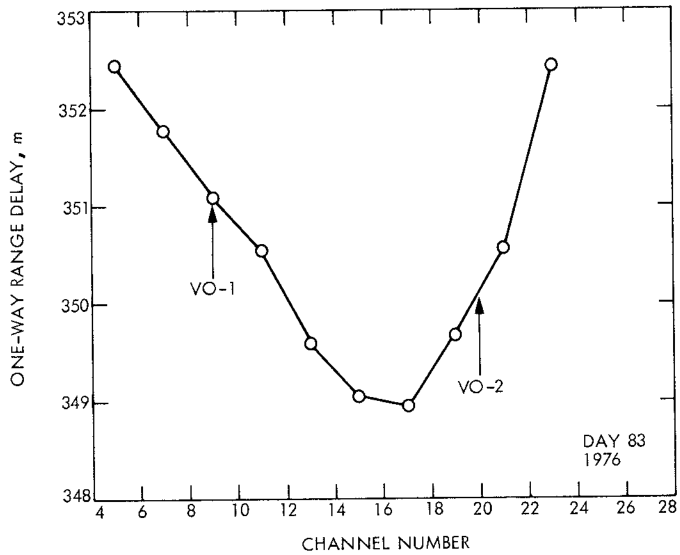

Fig. 15. DSS 61 station range delay versus frequency after ZDD relocation

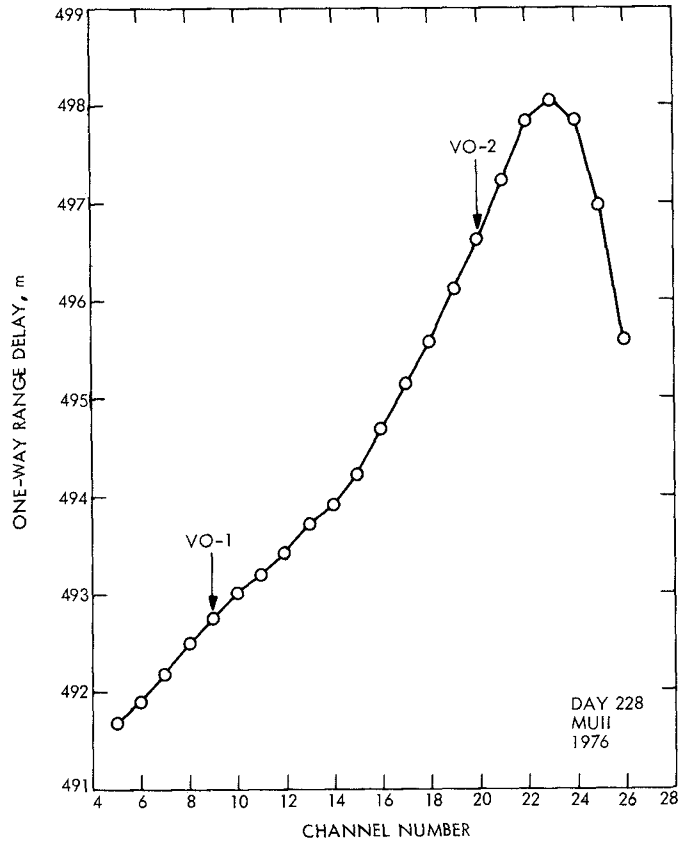

Fig. 16. S-band range delay versus frequency

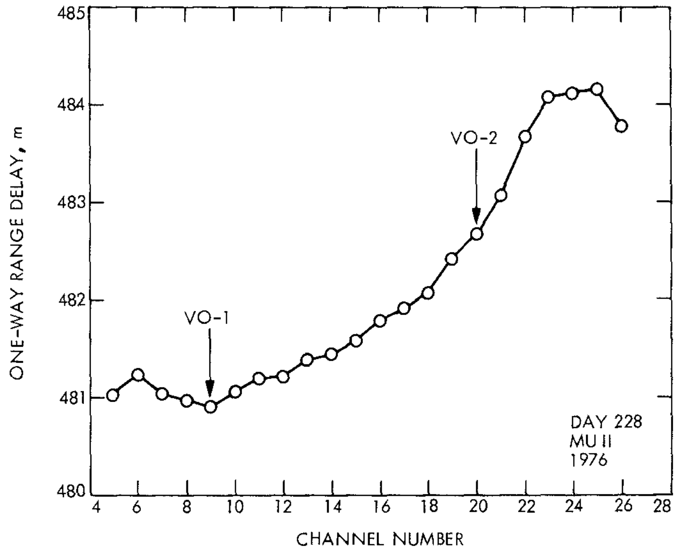

Fig. 17. DSS 14 X-band range delay versus frequency

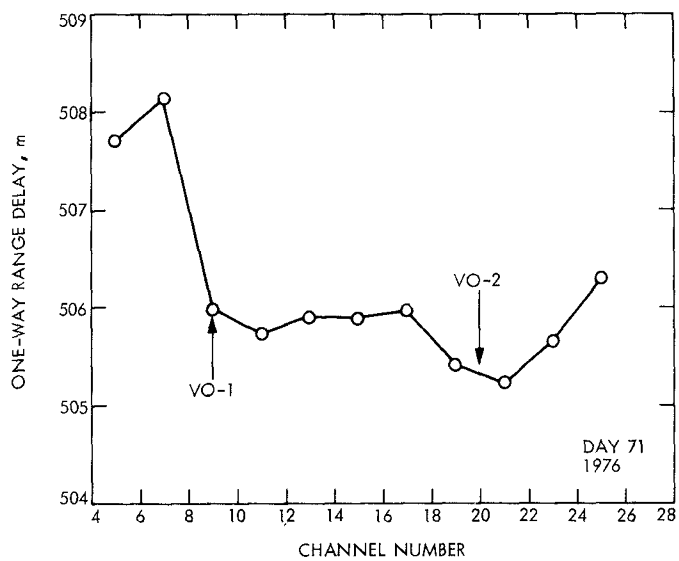

Fig. 18. DSS 43 S-band range delay versus frequency

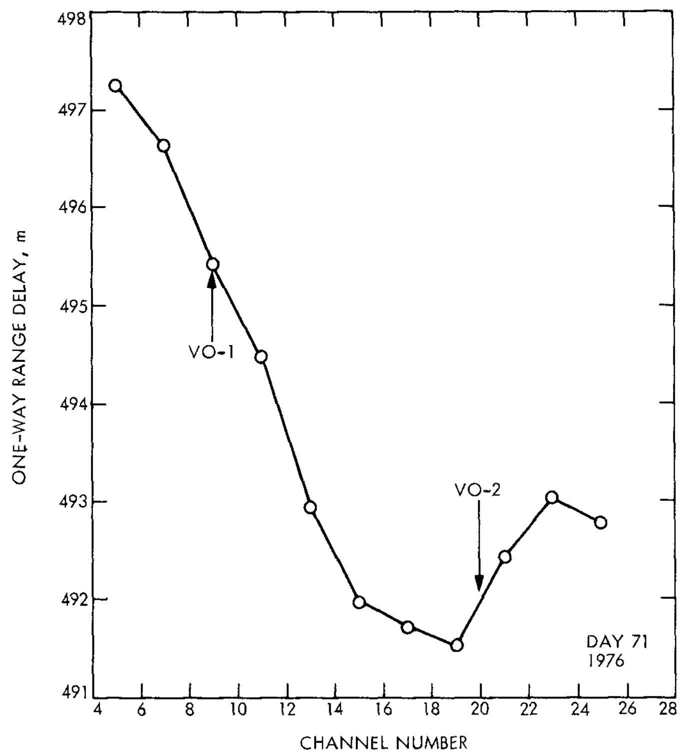

Fig. 19. DSS 43 X-band range delay versus frequency