Tracking Operations During the Mariner 10 Venus Encounter

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Tracking operations during the Mariner 10 Venus encounter phase were strongly impacted by the first critical phase usage of the Block IV S- and X-band receivers, the relatively new digitally controlled oscillators, and the large uncertainties associated with the Venusian atmosphere. This report describes the pre-encounter planning and subsequent analysis of tracking operations during the Mariner 10 Venus Encounter phase.

I. Introduction

On February 5, 1974, at 17:01:04 GMT (spacecraft time), the Mariner 10 spacecraft reached closest approach to the planet Venus. The encounter was visible only to the Goldstone complex, thus limiting participation to DSS 14 (the prime station) and DSS 12 (the backup station), and was noteworthy from a tracking system standpoint in that it marked the first use of the Block IV S- and X-band receivers (at DSS 14) during a critical phase, planetary encounter. Briefly described (for greater detail, refer to Ref. 1), the Block IV receiver is a quadruple conversion, superheterodyne, phase-locked receiver capable of either S- and/or X-band operation. Increased capabilities of the Block IV receiver over the Block III receiver are as follows:

(1) Improved single pass phase and modulation delay stability.

(2) Increased receiver sensitivity.

(3) Increased modulation bandwidth.

(4) Programmable oscillators (DCOs).

(5) S- and X-band operation.

(6) Automatic control capability.

(7) More efficient packaging.

(8) Increased reliability.

For the Venus encounter, the mode used at DSS 14 consisted of the Block III exciter as the transmitter, with one Block IV receiver at S-band, with a coherent ratio of 240/221, and the other Block IV receiver at X-band, with a coherent ratio of 880/221. Combined with the two Block III receivers, this made a total of four receivers at DSS 14. Each of these receivers was equipped with a digitally controlled oscillator (DCO), which had to be programmed separately. The DCOs were still relatively new, having been used only once previously in a critical encounter phase (Pioneer 10 Jupiter encounter, December 5, 1973) and so remained a vital area of concern. Besides the burden of supplying DCO level predictions manually from JPL to DSS 14 for four separate receivers, the Block IV receivers posed an additional difficulty in that both the S- band and X-band doppler data are interleaved into the same pseudo-residual stream. Since the doppler residuals for S-band and X-band data are radically different (by a factor of 11/3), near real-time interpretation of doppler residuals at the Network Operations Control Area (NOCA) during periods of rapidly changing residuals, such as those occurring at planetary encounters, is made extremely difficult. Finally, a very important facet of the Venus encounter was the extremely large refractive effect of the Venusian atmosphere during the period between geometric enter and exit occultation (at its peak, this refraction amounted to approximately 13,000 Hz, two-way S-band). This large refractive effect evidenced itself very strongly during the pre-encounter tracking operations planning phase in three areas:

(1) As the signal became increasingly refracted, it also became increasingly attenuated, and, as no information existed regarding the accuracy of what little attenuation information was available, there was a large uncertainty as to when one would drop and subsequently acquire both spacecraft uplink and downlink.

(2) No information was available regarding the accuracy of the atmospheric doppler predictions, impacting the selection of an acquisition sweep range.

(3) The IBM-360 Prediction Program does not model planetary atmospheric refraction, so the refraction predictions had to be manually factored into otherwise computerized prediction data for the various encounter strategy studies.

II. Uplink Tuning Strategy

The original strategy called for both enter and exit occultation to occur in the one-way mode. However, some days before encounter, additional testing of the spacecraft auxiliary oscillator disclosed an unacceptable short-term instability, so the decision was made to enter occultation in the two-way mode. This decision immediately introduced a complication with the usage of the open-loop receivers. It was quite conceivable that the uplink could be lost one round-trip light time (RTLT) or more before loss of the downlink, such that part of the open-loop data would be two-way and part one-way (this in fact happened, and will be amplified in a later section). To avoid possibly losing the one-way segment of data (since the bandwidth of the open-loop receivers is limited), it was desirable to see if the one-way and two-way downlinks could be forced to be the same frequency at the time of expected two-way/one-way transition. This was accomplished as follows:

Define: D1 = one-way downlink

D2 = two-way downlink

TSF = Track Synthesizer Frequency (transmitted frequency)

XMTREF = spacecraft best lock

TFREQ = spacecraft auxiliary oscillator

XA = spacecraft best lock including doppler

$\dot{r}$ = spacecraft range rate

c = velocity of light

R = received time

T = transmitted time

Now:

$$\mathrm{D1}_R = 96\,\frac{240}{221}\,\mathrm{TSF}_R - \mathrm{TFREQ}\left(1 - \frac{\dot{r}}{c}\right) + 10^6$$

$$\mathrm{D2}_R = 96\,\frac{240}{221}\,\mathrm{TSF}_R - 96\,\frac{240}{221}\,\mathrm{TSF}_T\left(1 - \frac{2\dot{r}}{c}\right) + 10^6$$

By requiring $\mathrm{D1}_R = \mathrm{D2}_R$, one has:

$$-\mathrm{TFREQ}\left(1 - \frac{\dot{r}}{c}\right) = -96\,\frac{240}{221}\,\mathrm{TSF}_T\left(1 - \frac{2\dot{r}}{c}\right)$$

or

$$\mathrm{TSF}_T = \frac{221}{96\,(240)}\,\mathrm{TFREQ}\,\frac{1 - \dfrac{\dot{r}}{c}}{1 - \dfrac{2\dot{r}}{c}}$$

Now for $1 \gg \dot{r}/c$

$$\frac{1 - \dfrac{\dot{r}}{c}}{1 - \dfrac{2\dot{r}}{c}} \approx 1 + \frac{\dot{r}}{c}$$

so that:

$$\mathrm{TSF}_T \approx \frac{221}{96\,(240)}\,\mathrm{TFREQ}\left(1 + \frac{\dot{r}}{c}\right)$$

Furthermore:

$$\mathrm{XA}_T = \mathrm{XMTREF}\left(1 + \frac{\dot{r}}{c}\right)$$

so that one finally arrives at the necessary condition upon the transmitted frequency:

$$\mathrm{TSF}_T \approx \frac{221}{96\,(240)}\,\mathrm{TFREQ}\left\{\frac{\mathrm{XA}_T}{\mathrm{XMTREF}}\right\}$$

Whether this condition is feasible for any given spacecraft depends on the values of TFREQ and XMTREF; in this case it was feasible, but would cause the spacecraft to be left approximately 80 Hz (at voltage-controlled oscillator (VCO) level) above XA at approximately the time of loss of uplink at enter occultation. However, this immediately impacted the uplink acquisition strategy at exit. In general, the spacecraft is left at XA at enter occultation (because one has the best chance of knowing where the spacecraft is at exit) and then a simple sweep around XA at exit is performed to reacquire the uplink. Since the spacecraft was being left quite far from XA, one would have to calculate (rather imprecisely) where the spacecraft had drifted to, and then perform a much wider sweep because of the uncertainties introduced by the spacecraft drift. The calculations were as follows:

TSF − XA (at approximately drop lock)

$\cong$ 80 Hz

Δt (from drop lock to reacquisition)

$\approx$ 1200 seconds

Mariner 10 receiver relaxation constant

$= t_0 \approx$ 3600 seconds

so that the drift back to best lock would be:

$$\begin{aligned}\Delta &= \Delta_0\, e^{-\Delta t/t_0} \\ &\cong (80\ \mathrm{Hz})\, e^{-1200/3600} \\ &\cong 57\ \mathrm{Hz}\end{aligned}$$

It was therefore decided to execute a two-way acquisition sweep of (XA + 60 Hz) ±60 Hz. This sweep successfully acquired the spacecraft and will be dealt with in greater detail later in this report. The uplink frequency strategy is detailed in Fig. 1, while Fig. 2 describes the one-way and two-way doppler during the occultation period.

III. DSS 14 Reacquisition Strategy at Exit Occultation

A fast reacquisition of the downlink by the closed-loop receivers at exit occultation was a prime goal, and it was here that the heaviest impact of the large Venusian atmospheric refraction was felt. Given the large uncertainties in signal strength and doppler as a function of time, the DCO Automatic Acquisition Mode was an obvious choice. The selection of sweep rate and sweep range, however, was a far more difficult problem. The situation one was faced with was a signal emerging at threshold (~ −175 dBm) and slowly, over a period of minutes, increasing to its full unrefracted value (~ −130 dBm). To acquire at very low signal strength, one must greatly lower the sweep rate, but in so doing, it takes much longer to sweep out the uncertainty band, thus lowering the chances of rapid acquisition. The Radio Science Occultation Team finally decided on choosing a sweep rate which would be conservative for a signal strength of −150 dBm, and after considerable testing at DSS 14, the value of ±1000 Hz/s was chosen, in conjunction with a tracking loop filter setting of 100 Hz (wide). A sweep range of D1 − 3000 Hz to D1 + 5000 Hz was selected, where D1 was the predicted one-way doppler (with atmospheric refraction included) at the time of predicted −150 dBm downlink signal strength. This sweep range was selected as it covered the expected uncertainties from all sources as well as allowing for the increasing doppler if the reacquisition of the downlink was not as rapid as had been expected.

IV. Analysis of Tracking Operations at DSS 14 During Venus Occultation

A. Accuracy of Atmospherically Refracted Doppler Predictions

Information regarding atmospheric refraction of doppler was provided by Dr. G. Fjeldbo of the Tracking and Orbit Determination Section (391). These data were made available as a plot of the expected X-band doppler shift due to atmospheric refraction superimposed upon the nominal transparent planet X-band doppler curve. Post-encounter analysis of the doppler residuals as computed by the IBM-360 Pseudo-Residual Program reveals that these atmospheric corrections were quite accurate. The

Pseudo-Residual Program computes doppler residuals by subtracting from a received actual doppler data point a value obtained from the IBM-360 Predicts Program. Since these predicts do not contain atmospherically refracted doppler corrections, the doppler residuals directly reflect the magnitude of the doppler shift due to the atmosphere of Venus, as well as trajectory and frequency inaccuracies. A plot of the doppler residuals computed by the Pseudo-Residual Program on data received from the Block IV S-band receiver during the enter occultation period can be seen in Fig. 3. Superimposed on the plot of these data is a plot of predicted atmospheric effect. As can be seen from Fig. 3, biases due to trajectory and/or frequency inaccuracies were very small (note the period prior to encountering the atmosphere), and the computed doppler residual compares very favorably with the predicted doppler shift due to the atmospheric refraction.

B. Loss of the Uplink and the Downlink at Enter Occultation

Referring to Fig. 3, it can be seen that two-way lock with the spacecraft was maintained for approximately 6 min beyond geometric occultation. At that time, the spacecraft, being unable to maintain lock on the uplink, began transmitting using the on-board auxiliary oscillator. With the out-of-lock condition, the Block IV S-band receiver began to drift, unexpectedly resulting in the receiver locking to the auxiliary oscillator-generated downlink. The Block IV S-band receiver maintained one-way lock for approximately 40 s before the signal became too weak to sustain receiver lock. The offset that can be seen between the predicted one-way doppler residuals and the actual values indicated on the plot is the result of inaccuracy in predicting the spacecraft auxiliary oscillator frequency, this difference being approximately 580 Hz.

Following the loss of receiver lock one-way, the Block IV S-band receiver again began to drift as a result of the receiver VCO being stressed off nominal rest frequency. Figure 4 is a plot of the observed doppler during the period of receiver drift. By fitting a curve through these points, it was determined that the receiver time constant was approximately 675 s. This compares reasonably with a theoretical (assuming the narrow (30 Hz) tracking loop filter) receiver time constant of approximately 650 s. The exponential drift of the receiver and the relatively long time constant indicate that the Block IV receiver loop was not shorted (which would have immediately removed the stress) and that the tracking loop filter in use was 30 Hz (resulting in the relatively long time constant). It should be noted that it had been planned to switch to the wide (100 Hz) tracking loop filter following loss of lock, but that apparently during the excitement and confusion resulting from the unexpectedly lengthy ground receiver lock at enter, this sequence of events (SOE) item was not executed. Had the switch to the wide (100 Hz) tracking loop filter taken place, the receiver time constant would have been reduced to approximately 35 s. At loss of one-way lock the receiver VCO was stressed approximately 15.7 kHz (S-band) off nominal rest frequency. During the approximate 465 s the receiver was allowed to drift, this stress had decayed to approximately 7.9 kHz off receiver VCO rest frequency. During this interval the receiver DCO was being set up for re-acquisition of the spacecraft as it emerged at exit occultation.

C. Acquisition of the One-Way Downlink at Exit Occultation

The receiver tuning pattern executed by DSS 14 can be seen in Fig. 5. The data points plotted are the doppler residuals as computed by the Pseudo-Residual Program, but modified such that zero represents the predicted one-way doppler. The acquisition search can plainly be seen to be in the wrong frequency region (due to failure to short the VCO). However, even if the search had been in the correct frequency region, acquisition would have been precluded by the incorrect tracking loop filter setting.

After several minutes of sweeping, the data indicate that DSS 14 altered the sweep pattern and did cross the expected lock up frequency. However, since the tracking loop bandwidth had not been changed to the prescribed wide (100 Hz) tracking loop filter, the sweeps were too fast for the receivers to acquire the downlink. After several minutes of searching in the widened sweep pattern, DSS 14 did acquire the downlink. This occurred at approximately 17:28:58 GMT and, as is apparent from the plot, only after the sweep rate had been reduced (to approximately ⅓) to a rate compatible with the still-in-use narrow-band (30 Hz) tracking loop filter. It should be noted at this point that the Block III prime and backup receivers using the correct tracking loop filter, an identical sweep region, and with the receiver VCO stress removed acquired at approximately 17:26:00 GMT.

The Block IV X-band receiver acquired the two-way downlink at approximately 17:40:58 GMT. Due to the intensified effort to lock the Block IV S-band receiver and the complications introduced due to the differences between the S-band and X-band receivers, the lock up of the X-band receiver was delayed until some time after lock of the S-band receiver had been achieved.

The doppler residuals seen in Fig. 6 are of the exit occultation period. Again it can be seen that the predicted residuals and the actual residuals reflect the effects of atmospheric refraction, with the offset being due to the previously mentioned inaccuracy in the predicted auxiliary oscillator frequency.

D. Acquisition of the Uplink at Exit Occultation

At approximately 17:32:50 GMT, the downlink switched from the one-way to the two-way doppler mode. This switch occurred without loss of lock as the one-way doppler and two-way doppler were nearly equal at this time. As mentioned in an earlier section, the uplink frequency at the expected loss of signal time at enter occultation was chosen to cause the one-way doppler and the two-way doppler frequencies to be as close together as possible to optimize the open-loop receivers. To demonstrate that the one-way and the two-way doppler frequencies were also nearly equal at the time of the two-way acquisition, it is necessary to determine how far off the spacecraft nominal rest frequency (XA) the spacecraft receiver was when loss of two-way lock occurred at enter occultation. From Fig. 3 it is apparent that the spacecraft dropped the uplink at approximately 17:15:28 GMT ground received time or about 17:10:34 GMT ground transmit time. The value of XA at this time, corrected for atmospheric refraction, was 22014595.6 Hz. The transmitted frequency (TSF) at the time the spacecraft dropped the uplink was 22014680.0 Hz. Therefore, at loss of two-way lock, the spacecraft receiver was stressed off XA by +84.4 Hz.

During the out-of-two-way lock period, the spacecraft receiver drifted back toward XA. Using the equation that describes this relaxation, the spacecraft rest frequency at two-way reacquisition time can be determined as follows:

$$\Delta = \Delta_0 \text{ (at start of drift) } e^{-\Delta t/t_0}$$

where

Δt = period of drift

t_0 = spacecraft receiver time constant

Δ = (actual spacecraft receiver) − XA

Since the spacecraft dropped lock at 17:10:34 GMT and reacquisition occurred at 17:27:56 GMT (ground transmit times), Δt = 1042 s. From spacecraft measurements:

$$t_0 \approx 3600 \text{ seconds}$$

Therefore,

$$\Delta \approx (84.4 \text{ Hz})\, e^{-(1042/3600)}$$

$$\Delta \approx 63.2 \text{ Hz}$$

Since the predicted XA at this time was:

$$\text{XA} = 22014448.8 \text{ Hz}$$

the expected spacecraft best lock (XA_A) at this time would be:

$$\begin{aligned} \text{XA}_A &\approx \text{XA} + \Delta \\ &\approx 22014448.8 \text{ Hz} + 63.2 \text{ Hz} \\ &\approx 22014512.0 \text{ Hz} \end{aligned}$$

The actual transmit frequency (TSF_A) at the spacecraft reacquisition time is found as follows:

$$\text{TSF}_A = \text{TSF}_1 - \text{(ramp rate)} \times \text{(time)}$$

where

$$\begin{aligned} \text{TSF}_1 &= \text{pre-ramp TSF} = 22014450.0 \text{ Hz} \\ \text{ramp rate} &= 2 \text{ Hz/s} \\ \text{time} &= 32.8 \text{ s} \end{aligned}$$

Thus

$$\text{TSF}_A = 22014515.6 \text{ Hz}$$

The difference between the expected lock-up frequency and the actual lock-up frequency is:

$$\begin{aligned} \text{TSF}_A - \text{XA}_A &= 22014515.6 \text{ Hz} - 22014512.0 \text{ Hz} \\ &= 3.6 \text{ Hz (at VCO level)} \end{aligned}$$

thereby indicating good agreement between expected and actual. Finally, using the equation developed earlier to determine the transmitted frequency (TSF_B) that forces the one-way doppler frequency and the two-way doppler frequency to be equal, we have as follows:

$$\text{TSF}_B = \frac{221}{96\,(240)}\, \text{TFREQ} \left\{ \frac{\text{XA}}{\text{XMTREF}} \right\}$$

where

$$\begin{aligned} \text{TFREQ} &= 2294999220.0 \text{ Hz} \\ \text{XA} &= 22014448.8 \text{ Hz} \\ \text{XMTREF} &= 22013600.0 \text{ Hz} \end{aligned}$$

Thus,

$$\mathrm{TSF}_B = 22014513.2 \text{ Hz}$$

The difference between the one-way and the two-way doppler frequencies at two-way reacquisition time is found to be:

$$96\frac{240}{221}\{\mathrm{TSF}_A - \mathrm{TSF}_B\} = 96\frac{240}{221}\{22014515.6 - 22014513.2\} \text{ Hz}$$

$$= 251 \text{ Hz (S-band)}$$

With so small a difference between the one-way and the two-way doppler frequencies, the switch from the one-way mode to the two-way mode occurred without loss of lock. Within 60 s the station had been informed of this condition and had thrown the two-way data mode switch. This can be seen in Fig. 6 at approximately 17:34:20 GMT, at which point the two-way residuals reflect only biases due to prediction inaccuracies.

E. Summary of DSS 14 Lock Status During Venus Occultation

Table 1 provides a summary of the receiver lock status for the DSS 14 Block III prime and backup and Block IV S-band and X-band receivers. The in/out of lock times are derived from the monitor automatic gain control (AGC) data.

V. Accuracy of Orbital Solutions as Encounter Is Approached

Table 2 presents the accuracies of (as compared to the actual data at encounter) the last four Orbital Determination Solutions as provided for encounter planning. Probe Ephemeris Tapes (PETs) M778 and M774 were provided several weeks prior to encounter, while PETs M781 and M780 were provided in the last days before encounter. In all cases the residuals provided represent the Δ between the referenced PET and the final observed doppler and time. Two generalizations (at least for this encounter) can be formulated here:

(1) The 3-σ uncertainties provided by the Navigation Team for encounter planning were approximately 1500 Hz (S-band, two-way) for doppler and 40 s for time events. Using the four referenced solutions, the navigation-provided uncertainties would have to be considered quite conservative, which is as it should be.

(2) There is a noticeable improvement between the PETs (M778 and M774) provided weeks ahead of the encounter versus those (M781 and M780) provided in the last days before encounter. However, there is, for instance, no clear cut improvement in going from M780 to M781 (the final PET provided). Therefore, the idea of changing many tracking parameters in the last hours before an encounter might be considered more of a possible, but unlikely contingency, rather than a planned for and totally expected procedure.

VI. Summary of Tracking Operations During the Venus Encounter Phase

Tracking operations during the Venus encounter phase were extremely successful on balance, especially in light of the considerable difficulties posed by the confluence of radically new equipment at DSS 14 (the Block IV receivers) and the large uncertainties associated with the Venusian atmospheric effects on telecommunications. The one minor problem during this phase was the late acquisition by the Block IV receivers at exit occultation, which is explained in large part by the unexpectedly lengthy lock at enter occultation and a degree of unfamiliarity with the new equipment. Furthermore, the late acquisition entailed no loss of data since:

(1) The DSS 14 Block III receivers locked up extremely early in the exit occultation, successfully receiving all spacecraft data.

(2) The DSS 14 open-loop receivers successfully acquired data during both enter and exit occultations, thus satisfying radio science requirements.

Reference

1. Donnelly, H., Shallbetter, A. C., and Weller, R. E., "Block IV Receiver–Exciter Development," in *The Deep Space Network*, Space Programs Summary 37-66, Vol. II, pp. 115–124, Jet Propulsion Laboratory, Pasadena, Calif., Nov. 30, 1970.

Table 1. Summary of DSS receiver events

Event	Ground received time (Feb. 5, 1974), GMT
Enter atmosphere[a]	17:09:10
Enter geometric occultation[a]	17:09:23
Block IV X-band out of lock	17:10:45
Block III prime and backup out of lock	17:14:58
Block IV S-band out of lock (two-way)	17:15:35
Block IV S-band out of lock (one-way)	17:16:30
Block III backup in lock	17:25:48
Block III prime in lock	17:26:03
Block IV S-band in lock	17:28:58
Exit geometric occultation[a]	17:30:17
Exit atmosphere[a]	17:30:28
Two-way[a]	17:32:50
Block IV X-band in lock	17:40:58

[a]These are best estimates from actual encounter data.

Table 2. Accuracy of orbit determination solutions generated prior to Venus encounter

Time	Observed doppler, Hz	Δ from observed, Hz			
		M781	M780	M778[a]	M774[a]
16:00 GMT	1214895.35	−2.5	−3.65	−11.52	−11.07
Closest approach	1214073.47	+3.1	+74.42	+72.55	+88.16
Enter occultation	1204820.21	−4.1	−10.38	−45.23	+58.56
Exit occultation	1191292.72	−33.8	−13.61	+7.37	+63.79
18:00 GMT	1167523.96	−41.2	−11.93	+33.94	+88.00

[a]PETs M778 and M774 were based upon pre-gas leak solutions.

Event	Ground observed, GMT	Δ from observed, s			
		M781	M780	M778	M774
Closest approach	17:03:31.344	+3.656	+1.126	+3.226	+3.816
Enter occultation	17:09:22.585	−0.585	+0.415	+4.415	+6.415
Exit occultation	17:30:16.842	+1.158	+2.158	+6.158	+6.158

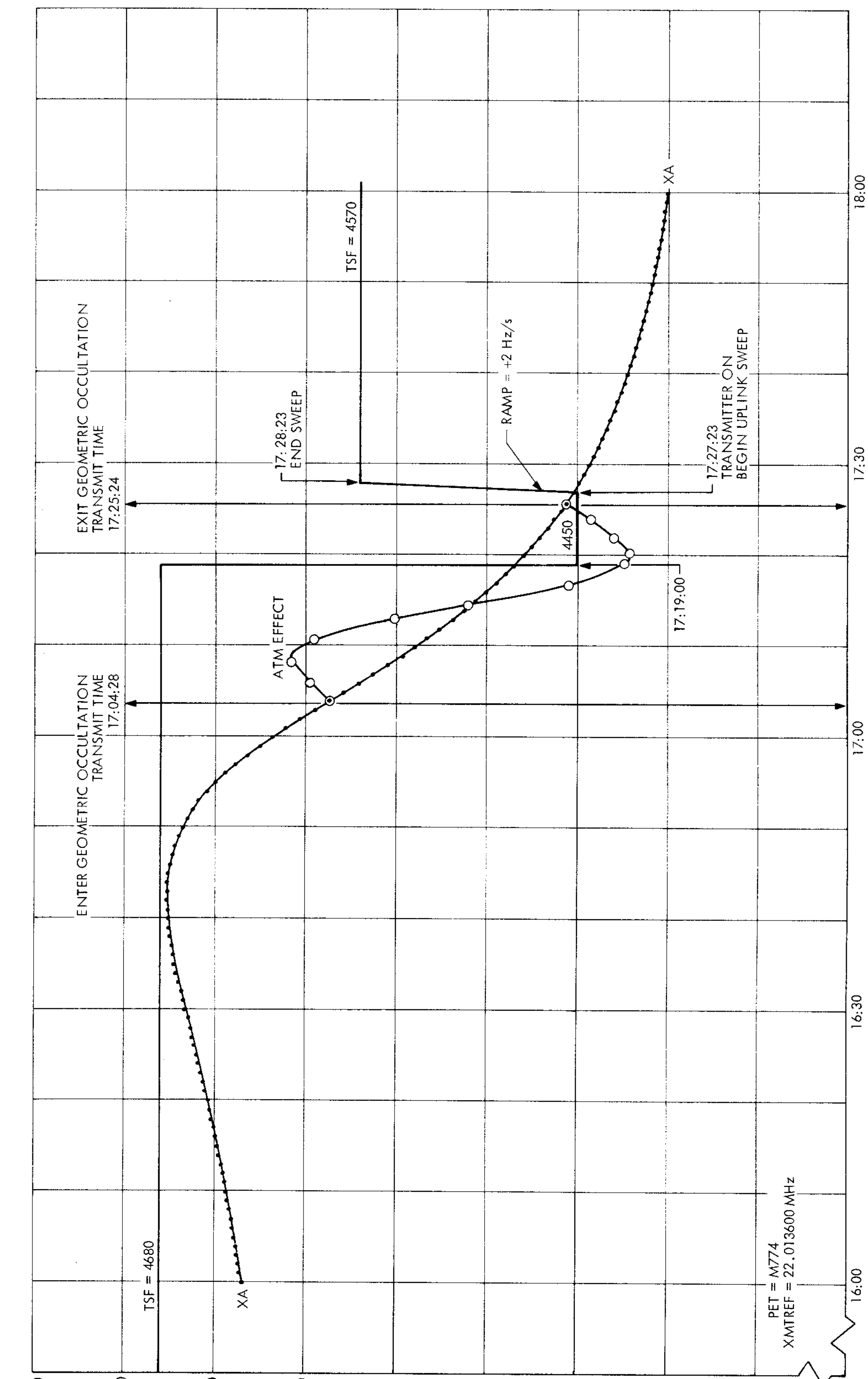

Fig. 1. XA and tuning pattern for Venus encounter (DSS 14)

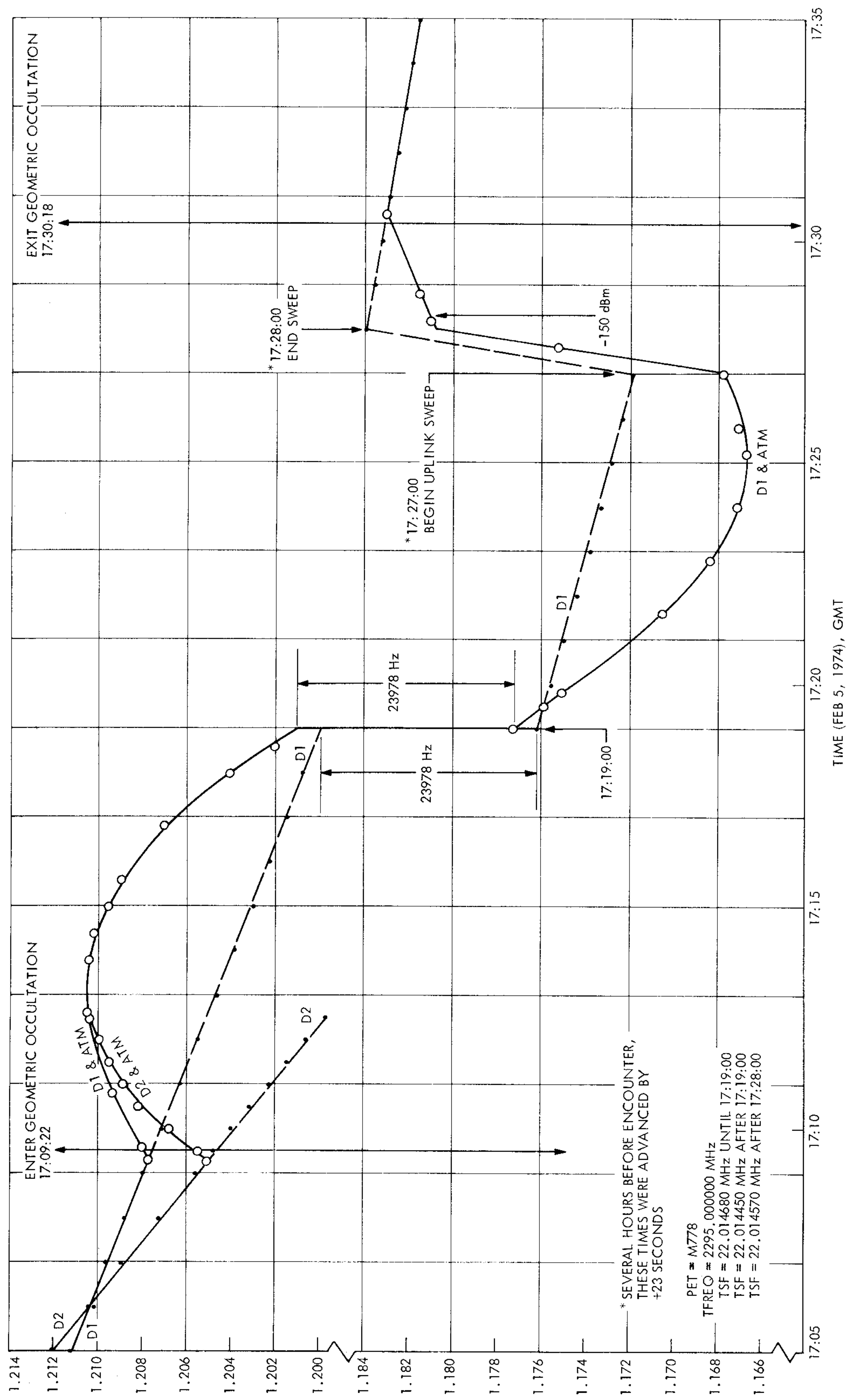

Fig. 2. D1 and D2 plus atmospheric correction for Venus encounter (DSS 14)

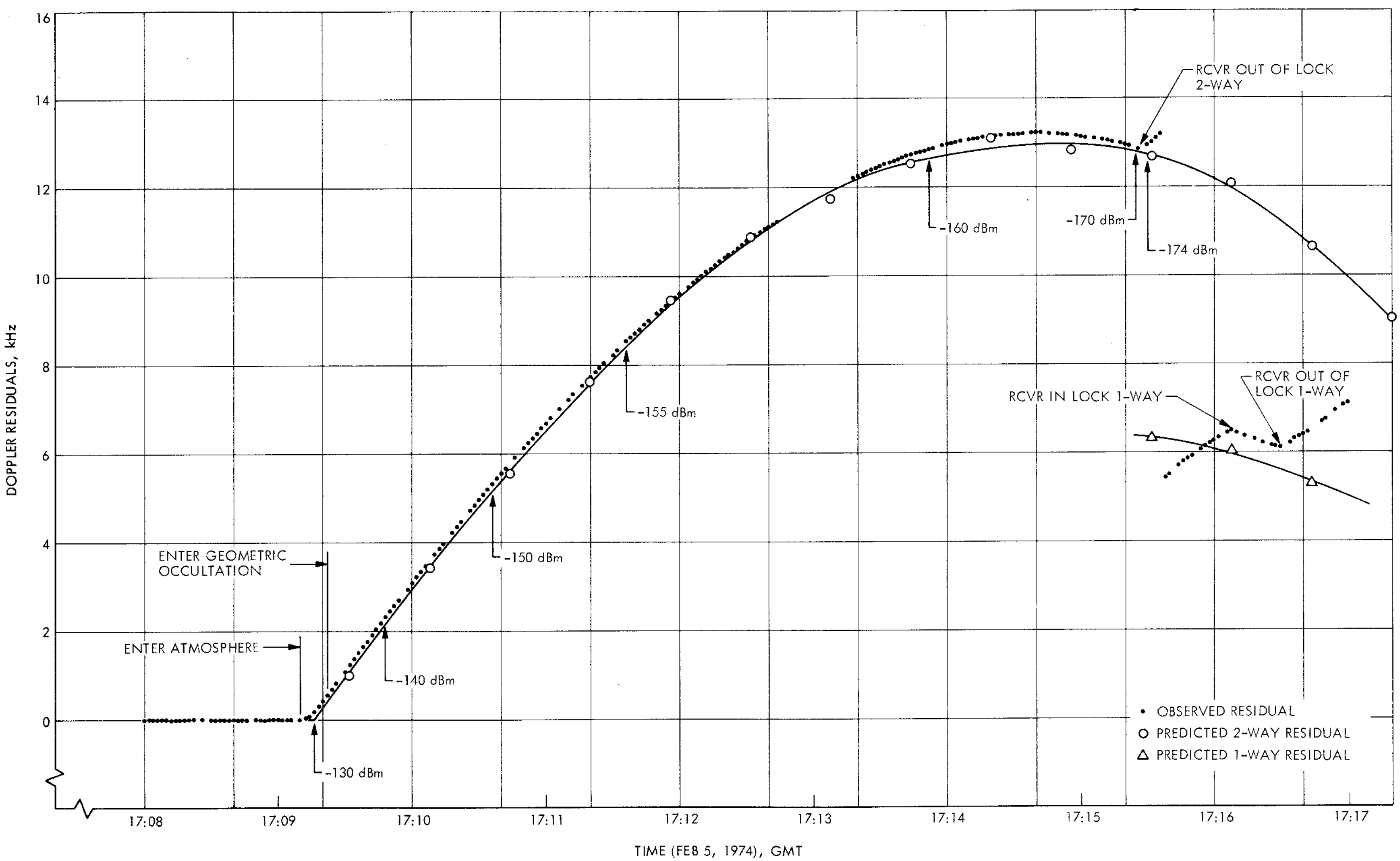

Fig. 3. Enter occultation doppler residuals for Venus encounter (DSS 14 Block IV S-band)

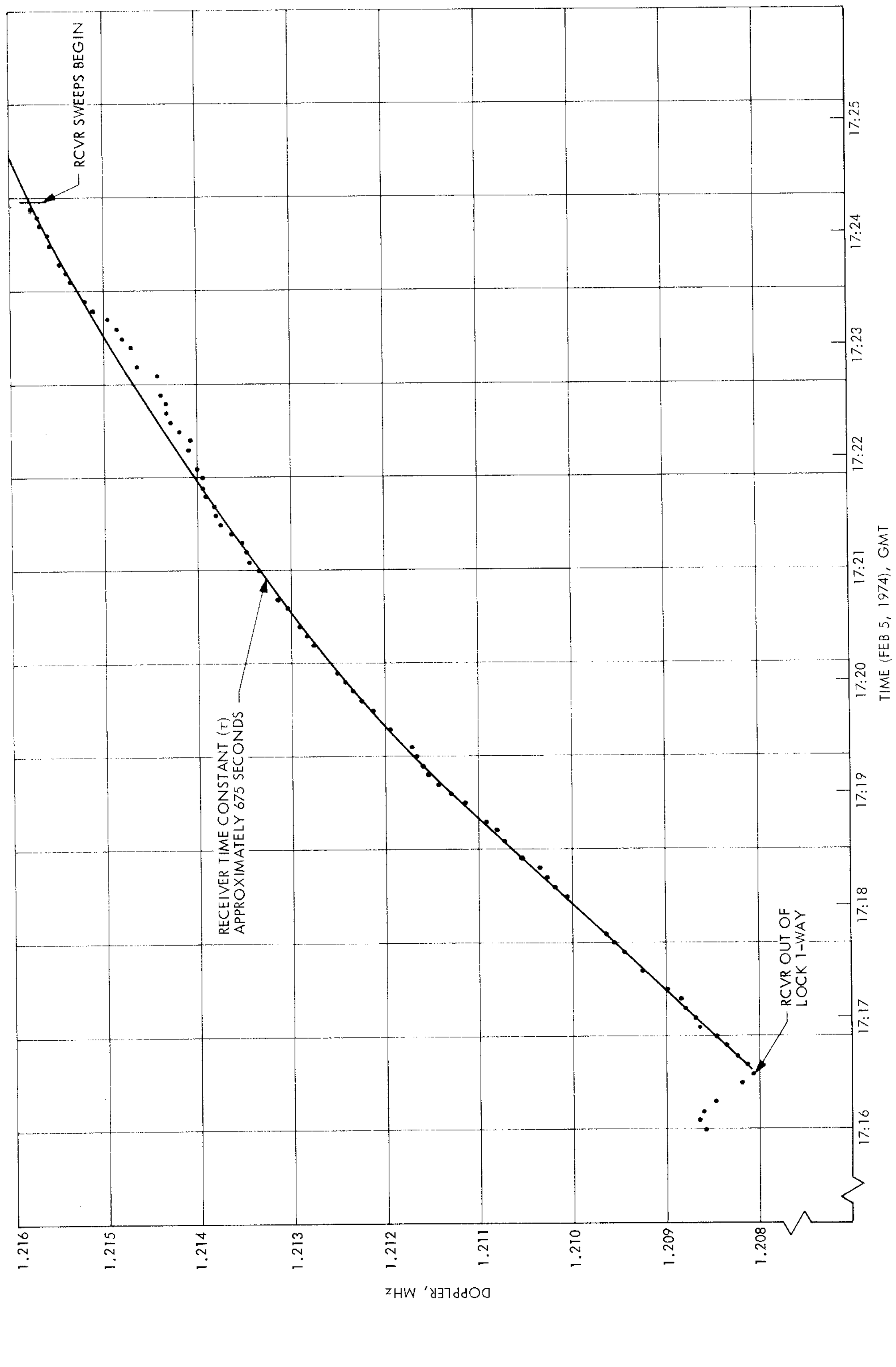

Fig. 4. Receiver stress relaxation DSS 14 Block IV S-band for Venus occultation

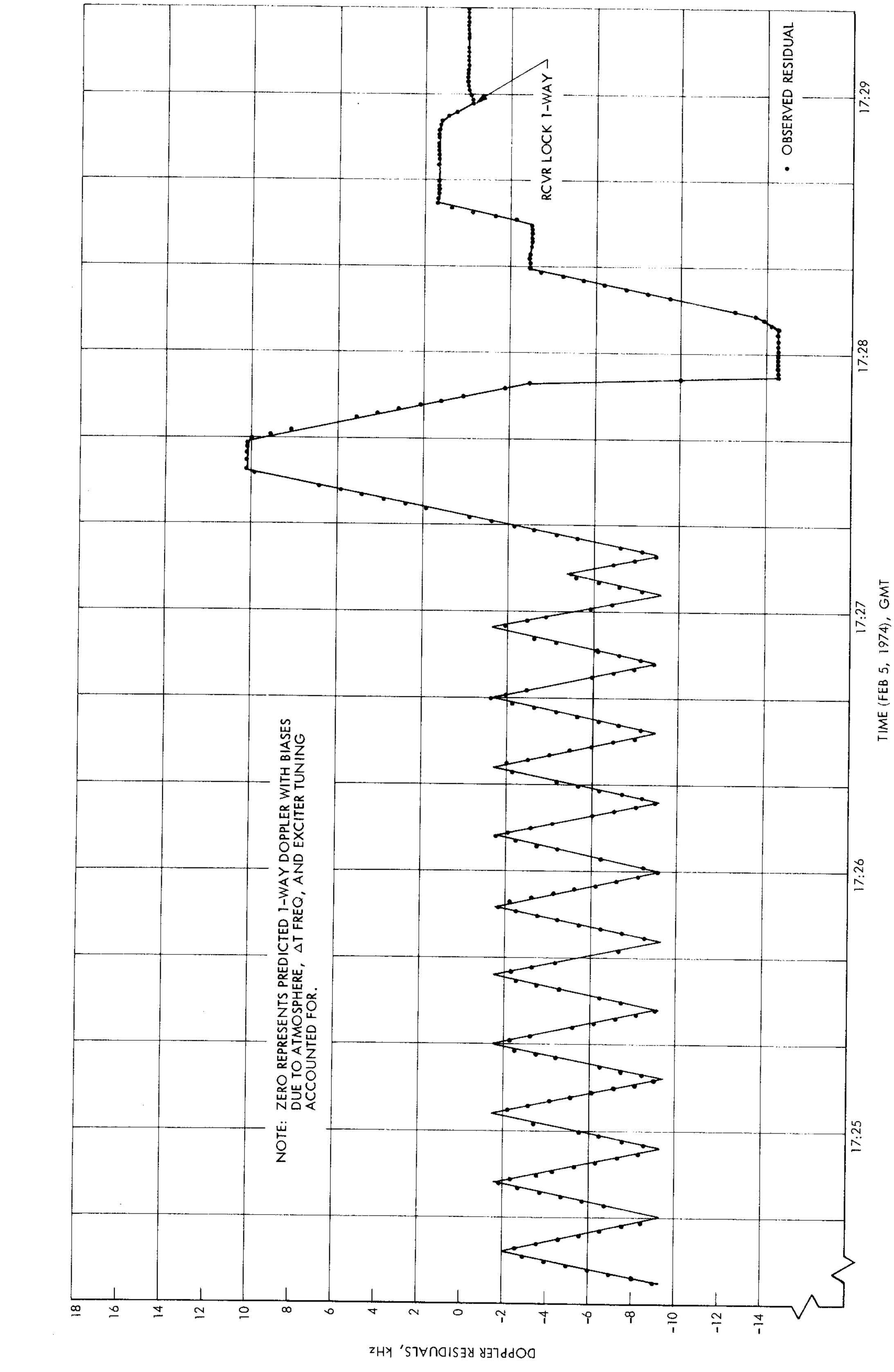

Fig. 5. DSS 14 Block IV S-band receiver turning pattern for Venus exit occultation

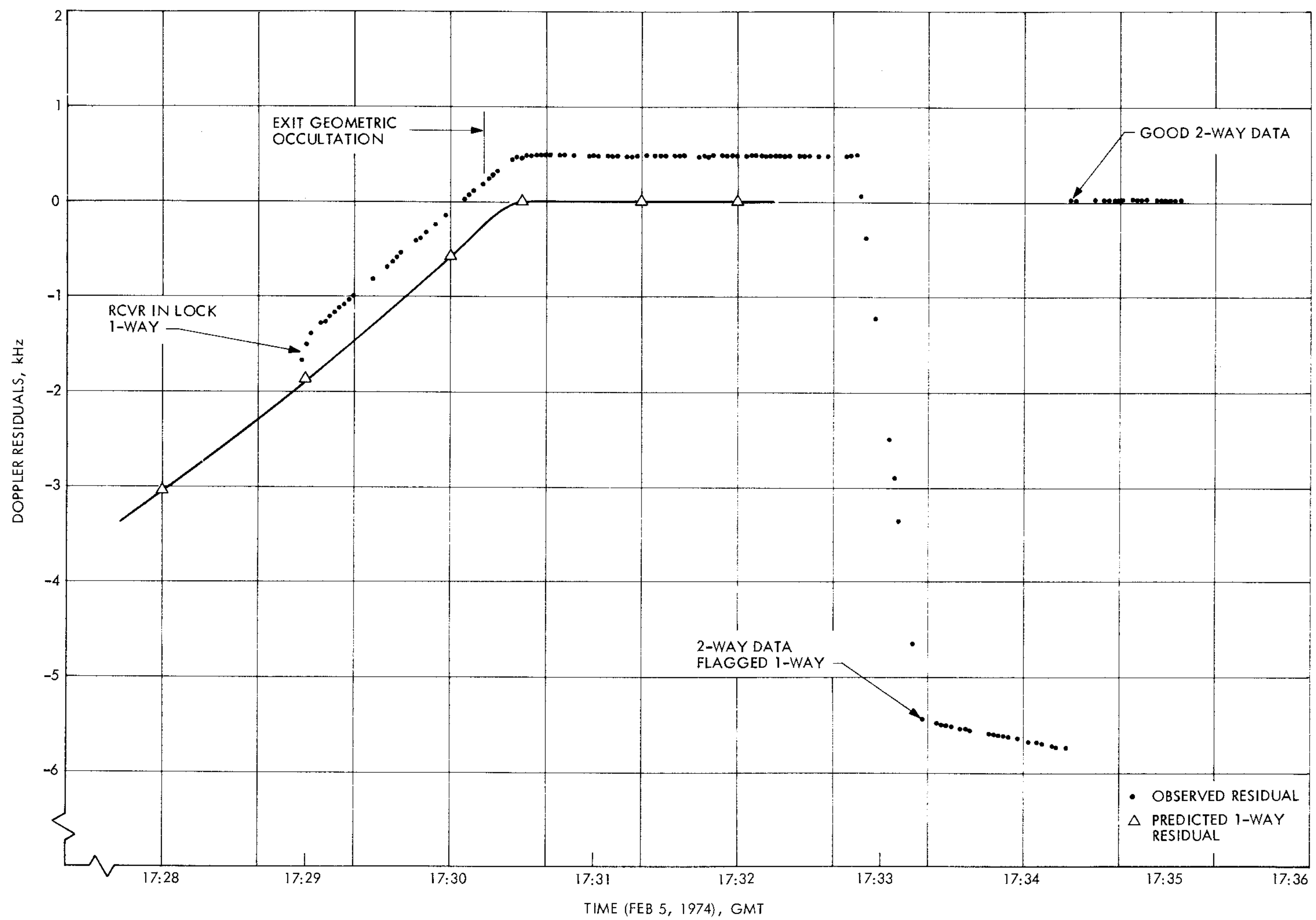

Fig. 6. Exit occultation dopper residuals for Venus encounter (DSS 14 Block IV S-band)