Tracking Operations During the Pioneer 11 Jupiter Encounter

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Tracking operations during the Pioneer 11 Jupiter encounter proceeded quite smoothly and resulted in a highly successful encounter. Major features that distinguished this encounter from the previous Pioneer 10 Jupiter encounter were the much closer spacecraft approach to Jupiter, which induced far more dynamic excursions in the near encounter tracking parameters, and the Mars Deep Space Station two-way entry into occultation. This report details the preencounter planning and subsequent analysis of tracking operations during the Pioneer 11 Jupiter encounter phase.

I. Introduction

On December 3, 1974, at 05:21:38.9 GMT (spacecraft time), the Pioneer 11 spacecraft reached closest approach to the planet Jupiter. This encounter was simultaneously visible to both the Goldstone and the Australian Deep Space Complexes, thus allowing prime participation by two 64-m antenna Deep Space Stations--DSSs 14 and 43. Figure 1 presents an overview timeline of the near-encounter period and shows the significant tracking events in ground transmit time, spacecraft time, and ground receive time (all in GMT).

Almost exactly one year earlier, the Pioneer 10 spacecraft encountered the planet Jupiter on a similar mission and provided man with his first close-up examination of this massive planet. At that time, efforts to ensure the success of tracking operations were concentrated in the following three areas:

(1) The occultation of the spacecraft by the Jovian satellite Io shortly before occultation of the spacecraft by Jupiter itself.

(2) The operation of the then only recently implemented digital controlled oscillators (DCOs).

(3) The complications in occultation strategy caused by the (then novel) very long round-trip light time (RTLT) of approximately 90 min.

The Pioneer 11 encounter, however, was significantly different from the Pioneer 10 encounter in several areas. Foremost among these were the following:

(1) The absence of any Jovian satellite occultations of the Pioneer 11 spacecraft.

(2) The considerably closer approach of the Pioneer 11 spacecraft to Jupiter (as compared to Pioneer 10), resulting in far more dynamic excursions in near-encounter tracking parameters. For instance, one can compare the radius of closest approach (RCA) in kilometers, the near-encounter frequency excursion at DSS 14 (ΔXA, in hertz at voltage-controlled oscillator (VCO) level) and the maximum frequency rate at DSS 14 ($d(XA)/dt$, in hertz/minute, at VCO level) as follows:

	Pioneer 10	Pioneer 11
RCA, km	203,260	113,694
ΔXA, Hz at VCO	1500	3200
$d(XA)/\mathrm{dt}$, Hz/min	−10.3	−31.2

Figure 2 similarly illustrates the correspondingly large doppler shift (for the expected doppler modes) at enter occultation.

(3) The decision to enter Jupiter occultation in the two-way (coherent) tracking mode for the Pioneer 11 occultation, in contrast to the Pioneer 10 enter occultation, which was performed in the one-way (noncoherent) tracking mode.

In consideration of the above, the preplanning of Pioneer 11 near Jupiter encounter tracking operations was most intensively focused on properly accounting for the very large tracking parameter excursions and the special problems of entering Jupiter occultation in the two-way tracking mode.

In the following sections the near-encounter tracking operations planning to account for the large tracking parameter excursions and the two-way enter occultation will be detailed and analyzed as to degree of success achieved. Additionally, other areas of critical tracking operations, particularly rapid reacquisition of the uplink and downlink at exit occultation and quality of near real-time tracking predictions, will be analyzed.

II. Uplink Tuning Strategy

A. Maintenance of Two-Way Lock at DSS 14 During the Enter Occultation Period

As was previously mentioned, one of the prime differences with the Pioneer 10 Jupiter encounter was the decision to have the Pioneer 11 spacecraft enter Jupiter occultation in the two-way mode. This entails a far greater risk than entering occultation in the one-way mode in that if the spacecraft receiver loses lock shortly before enter occultation, the downlink will shift from two-way to one-way (a shift on the order of several thousand hertz at S-band), and precious radio metric data would be lost while the ground receivers attempted to reestablish lock. Even if the ground receivers were able to rapidly reestablish lock, the resultant one-way doppler data would be nearly useless (for radio science purposes) because 10 or more minutes of one-way doppler data are needed to establish the drift pattern of the spacecraft beacon frequency. Finally, a switch from two-way to one-way might very possibly drive the signal out of the open-loop receiver bandwidth, thus losing this radio metric data source also. This problem was particularly appropriate to the period immediately prior to enter occultation, since it was expected that as the signal began passing through the Jovian atmosphere, there would be momentary periods of signal attenuation which could cause the spacecraft to drop lock. To mitigate this possibility to the greatest extent possible, it was proposed by Dr. A. Kliore, the occultation experimenter, that during the period of ionospheric/atmospheric traversal by the signal, the DCO at DSS 14 be used to ramp the uplink so as to approximate XA (the spacecraft best lock with doppler accounted for). The general strategy would consist of approximating the ionospheric/atmospheric period of signal traversal by a single ramp. Further, it was decided that the scheme would be defined by the following specific conditions. Let

$TSF_{11}(t)$ = track synthesizer frequency—transmitted uplink frequency, at VCO level

$XA_{11}(t)$ = spacecraft best-lock uplink frequency (corrected for doppler)

Then it would be required that

$$TSF_{11}(t_0) = XA_{11}(t_0)$$

$$\left\{\frac{d}{dt}\,[TSF_{11}]\right\}_{t_0} = \left\{\frac{d}{dt}\,[XA_{11}]\right\}_{t_0}$$

t_0 = top of Jovian atmosphere

The rationale for the above ramping strategy would be that if there occurred momentary signal attenuation and subsequent loss of spacecraft receiver lock, the ground transmitted frequency would be at almost exactly best lock (and would continue at best lock, timewise), and hence the spacecraft receiver would be in a position to relock the uplink almost immediately.

Finally, the uplink strategy at DSS 14 was impacted by the extremely large change in the near-encounter doppler frequency, in particular, during the pre-occultation period of the pass. For instance, the total excursion of XA during this period was about 780 Hz at VCO level (75,000 Hz at S-band).

Since it was a Pioneer Project goal to keep the frequency stress at the spacecraft below approximately 250 Hz, considerable additional tuning somewhere in the pass would be required. It was proposed by the Network Operations Analysis Group (NOAG) that the same ramp necessary during the ionospheric/atmospheric traversal period be utilized by starting it at an earlier time so that the maximum stress at the spacecraft would be constrained to approximately 250 Hz, or, by starting the ramp approximately 9 min earlier. This suggestion would have the effect of simplifying overall tracking operations during the pre-occultation period since a single ramp would be easier to implement, and less risky. The suggestion was accepted by the Pioneer 11 Occultation Planning Group, and, the total uplink strategy at DSS 14 is shown in Figs. 3 and 4.

The final parameter values selected for use at DSS 14 were as follows:

Ramp start time	04:01:53	GMT
Ramp stop time	04:26:53	GMT
Starting frequency	21.988600	MHz (VCO)
Frequency rate	−0.5200	Hz/s (VCO)

B. Acquisition of the Uplink by DSS 43 After Exit Occultation

Although the spacecraft would (nominally) be commanded noncoherent for the first 10 to 15 min following exit occultation, it was concluded by the Pioneer Project that it would be expedient to acquire the uplink as soon as possible after exit occultation so as to gain command capability, if desired. To facilitate this decision, the following strategy was implemented:

(1) DSS 43 transmitter on before exit

(2) Uplink sweep to begin approximately 3 min following exit occultation

(3) Sweep parameters to be chosen to yield a total sweep of approximately $XA + 60$ Hz to $XA - 100$ Hz and a sweep rate relative to the spacecraft of approximately −30 Hz/min at VCO level

The acquisition parameters finally selected in accordance with the above guidelines are as follows:

Ramp start time	05:06:00	GMT
Ramp stop time	05:11:00	GMT
Starting frequency	21.986360	MHz (VCO)
Frequency rate	−1.0000	Hz/s (VCO)

This scheme contained three crossings of XA by the transmitter frequency, and hence three separate chances of uplink acquisition, the first to occur within a minute of exit. The above uplink strategy is shown in Fig. 5.

III. Ground Receiver Strategy

A. Maintenance of Ground Receiver Lock at DSSs 14 and 43 During the Enter Occultation Period

For the enter occultation period, it was concluded that ramping the ground receivers according to the same logic as the exciter (except, of course, increasing the times by one RTLT and adjusting the frequencies and frequency rates to account for the differences between the transmitter and receiver frequency levels) would accomplish the identical goal of having the ground receivers at their best-lock frequencies in case of momentary losses of lock.

The ground receiver ramp parameters selected were:

Ramp start time	05:23:16	GMT
Ramp stop time	05:48:16	GMT
DSS 14 starting frequency	49.052579	MHz (DCO)
DSS 43 starting frequency	49.053106	MHz (DCO)
Frequency (DSSs 14 and 43) Rate	+1.6941	Hz/s (DCO)

It was subsequently assessed in near real time that the relative rate between the ground receivers and the downlink frequency at the start of the above ramp would result in an uncomfortably large dynamic phase error ($\Delta\theta$)

of approximately 20 deg plus a static phase error (SPE) of approximately 4 deg, in the desired configuration of narrow (12 Hz) tracking loop filter. To correct this possible problem area, a second receiver ramp was added which partially replaced the original ramp (above), so that the final ground receiver ramp strategy was as follows:

First ramp start time	05:05:00	GMT
DSS 14 starting frequency	49.051763	MHz (DCO)
DSS 43 starting frequency	49.052290	MHz (DCO)
Frequency (DSSs 14 and 43) rate	+1.0000	Hz/sec (DCO)
Second ramp start time	05:30:00	GMT
Frequency (DSSs 14 and 43) rate	+1.6941	Hz/sec (DCO)
Ramp stop time	05:48:16	GMT

Figure 6 shows the predicted DSS 14 ground receiver best-lock frequency versus the above ramp strategy, while Fig. 7 shows the DSS 14 downlink frequency rate versus the above ramp (rate) strategy.

B. Acquisition of the Downlink at Exit Occultation

Over the past year, and in particular during several planetary exit occultations, the DCOs have proved themselves with increasingly excellent results as a new advance in the rapid acquisition of a signal whose frequency and time of appearance are both subject to large uncertainties. The applicable mode of operation for this type of acquisition is the acquisition mode (ACQ MODE), in which a triangular frequency sweep is initiated at a fixed sweep rate and between prestored upper and lower frequency limits. After testing to determine a reasonable sweep rate (i.e., the highest sweep rate possessing an extremely high probability of acquisition), and consideration of (Pioneer Project Navigation supplied) orbital uncertainties, the following DCO acquisition mode parameters for DSSs 14 and 43 ground receivers were selected:

DCO sweep rate	±1000 Hz/s (S-band)
DCO sweep excursion about the exit occultation point	±5000 Hz (S-band)

These sweep patterns can be seen in Figs. 8 and 9 for DSSs 14 and 43, respectively.

IV. Postencounter Analysis

The previous sections of this report dealt with the Jovian encounter planning as it pertained to tracking operations. Procedures such as uplink tuning for the minimization of spacecraft phase error, ground receiver tuning for minimization of ground station phase error, and DCO ACQ MODE usage for downlink acquisition(s) at exit occultation were discussed and the final plans for the various phases of the operations were outlined.

In the following sections, the degree of success of the various operations will be ascertained from the vantage point of postencounter analysis of the returned radio metric data.

A. Maintenance of the Uplink From DSS 14 During the Enter Occultation Period

As was previously mentioned, an uplink ramp of 25-min duration and at a rate of approximately 50 Hz/s at S-band was executed by DSS 14 so as to maintain the maximum spacecraft receiver static phase error below 25,000 Hz at S-band and to substantially eliminate both the dynamic and the static phase error at the time of traversal of the top of the Jovian atmosphere. The success of this effort can be judged only indirectly, as there is no way of knowing what might have occurred had not the uplink tuning been performed. However, considering that the uplink was maintained throughout the time up until the loss of lock by the closed-loop ground receivers, and in fact up until the time of loss of lock by the open-loop ground receivers, the uplink tuning must be gauged as a complete success.

B. Maintenance of the Downlink by the (Closed Loop) Receivers at DSS 14 and DSS 43 During the Enter Occultation Period

As previously described, both DSSs 14 and 43 executed two receiver ramps during the enter-occultation period with a similar purpose to the uplink ramp performed by DSS 14—to substantially eliminate the static and dynamic phase error for the ground receivers at the time of traversal of the top of the Jovian atmosphere. The closed-loop receivers at DSSs 14 and 43 dropped lock at the following times:

DSS 14	05:41:48 GMT
DSS 43	05:41:49 GMT

Both of the above times can be considered favorably when compared to the loss of lock by the DSS 43 open-loop receiver at 05:42:05 GMT (as supplied by Dr. Kliore), or only 16 to 17 seconds later. Figure 10 shows the closed-loop doppler data for both DSSs 14 and 43 immediately prior to and subsequent to the loss of lock. Although receiver ramps cannot be seen in the doppler data, the following observations, which tend to support both the accuracy of and the rationale for the ground receiver ramps, can be made:

(1) The closed-loop receivers maintained continuous lock throughout the high-frequency rate portion of the enter-occultation period, and the dropped lock times of 05:41:48 and 05:41:49 would indicate a substantial signal entry into the atmosphere before loss of lock.

(2) The large fluctuations seen in the closed-loop doppler data (Fig. 10) in the 30 s before loss of lock would seem to indicate that had the ground receivers not been close to the best-lock frequency and best-lock frequency rate, they might easily have been knocked out of lock.

(3) After loss of lock, the receiver frequency (which is then directly reflected in the doppler data) can be seen in Fig. 10 to agree very closely with the predicted receiver frequency—thus indicating the ramp was correctly computed and implemented by the DSS.

Finally, it should be noted that the various tuning schemes did not take into account refraction by the Jovian atmosphere, and had it been possible to accurately predict and factor into the tuning schemes the Jovian atmosphere refraction, even better results might possibly have been obtained.

C. Downlink Acquisition by DSSs 14 and 43 at Exit Occultation

As was earlier mentioned, the use of the DCOs in the acquisition mode has produced excellent results in recent planetary occultations; the Pioneer 11 exit occultation has proved to be no exception to these results. Figures 8 and 9 show the actual receiver sweep patterns executed by DSSs 14 and 43, respectively. Using the open-loop receiver lockup times (indicated in Figs. 8 and 9) as the time of signal appearance, it can be seen from Fig. 9 that DSS 43 locked to the emergent signal on the first crossing through the received frequency (at 06:24:21 GMT), while in Fig. 8 it can be seen that DSS 14 locked to the emergent signal on the second crossing through the received frequency (at 06:24:41 GMT).

D. Acquisition of the Uplink at DSS 43 After Exit Occultation

Since the uplink acquisition sweep was performed by DSS 43 at a time when the spacecraft had been previously commanded noncoherent, it was not possible to pinpoint the exact time of uplink acquisition by extrapolating backward from the time of downlink mode change (from one-way to two- or three-way) by one RTLT, as might normally be done. All that can be said is that the uplink acquisition was routinely successful, as evidenced by the fact that the subsequent command to the spacecraft to return to coherent operations some minutes later was successfully received and executed.

E. Acquisition of the Post Occultation Two-Way Downlink by DSSs 14 and 43

In response to the postoccultation command to the spacecraft to return to the coherent mode, both DSSs 43 and 14 dropped lock at 06:41:02 GMT, at which time the downlink had shifted from one-way to two-way and three-way, respectively. Within about two minutes DSS 43 reacquired the downlink and confirmed two-way. However, DSS 14 required several additional minutes to reacquire. A study of the DSS 14 doppler data, as seen in Fig. 11, discloses that the station was searching for a two-way downlink instead of the actual three-way downlink (with DSS 43). This error at the station might have been triggered by a request from the Network Operations Control Team (NOCT) for the stations to flag their data as two-way when the proper request should have been for the stations to flag their data as either two-way or three-way, as appropriate. This slight delay in downlink acquisition by DSS 14 did not impact either the return of scientific (telemetered) data or radio metric data, due to the rapid reacquisition by DSS 43.

V. Prediction Accuracy

In virtually all recent planetary encounters, the various navigation teams have indicated that their orbital solutions will continue to improve right up until the time of encounter. Actual recent experience with both small and large planet encounters, however, suggests that clear-cut orbital accuracy improvement ends somewhere in the time period from encounter minus two days to encounter minus one week. Table 1 presents a list of various tracking parameters of interest during the Pioneer 11 encounter, as a function of the various probe ephemeris tapes (PETs) supplied by the navigation team. Once again a small but steady improvement is noted up until the encounter-minus-two-day PET (Q635) but that the next and final preoccultation PET at E − 6 hours (Q639) represents a small net loss in prediction accuracy.

VI. Summary of Tracking Operations During the Pioneer 11 Jupiter Encounter

Tracking operations during the near-encounter period proceeded exactly as planned and resulted in a highly successful encounter. The most significant features of this encounter, which distinguished it from the previous Jupiter encounter, were:

(1) The very dynamic excursions in near encounter tracking parameters

(2) The two-way entry into enter occultation

The pre-occultation planning described at length in this report would appear to have very successfully incorporated and accounted for the above features.

Table 1. Values for DSS 14

PET	Date received	Enter Occultation			Exit Occultation	
		XA at 04:20	D2 at 05:40	Time	D1 at 06:30	Time
6544	N/A	8057.7	1567912	05:40:33	1377121	06:25:14
6548	11/13/74	8030.4	1562418	N/A	1369007	N/A
6549	N/A	8028.0	1561945	05:39:35	1368785	06:24:09
6550	11/28/74	8030.5	1562432	05:39:40	1369145	06:24:14
Q631	11/29/74	8033.7	1563055	05:39:46	1369638	06:24:22
Q634	11/30/74	8034.8	1563275	05:39:49	1369820	06:24:24
Q635	12/01/74	8035.2	1563350	05:39:50	1369882	06:24:25
Q639	12/03/74[a]	8033.8	1563072	05:39:47	1369647	06:24:22
From actual data		8036.4	1563590		1370590	

[a]E − 6 h PET

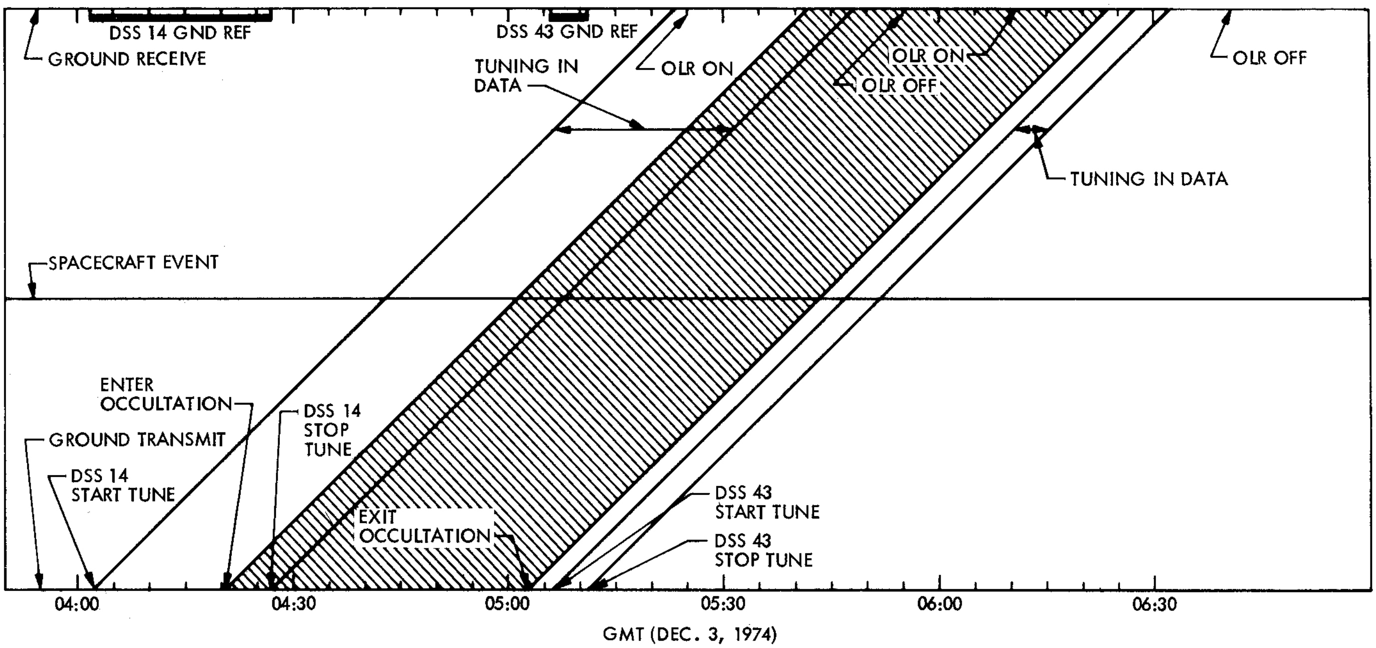

Fig. 1. Pioneer 11 Jupiter encounter

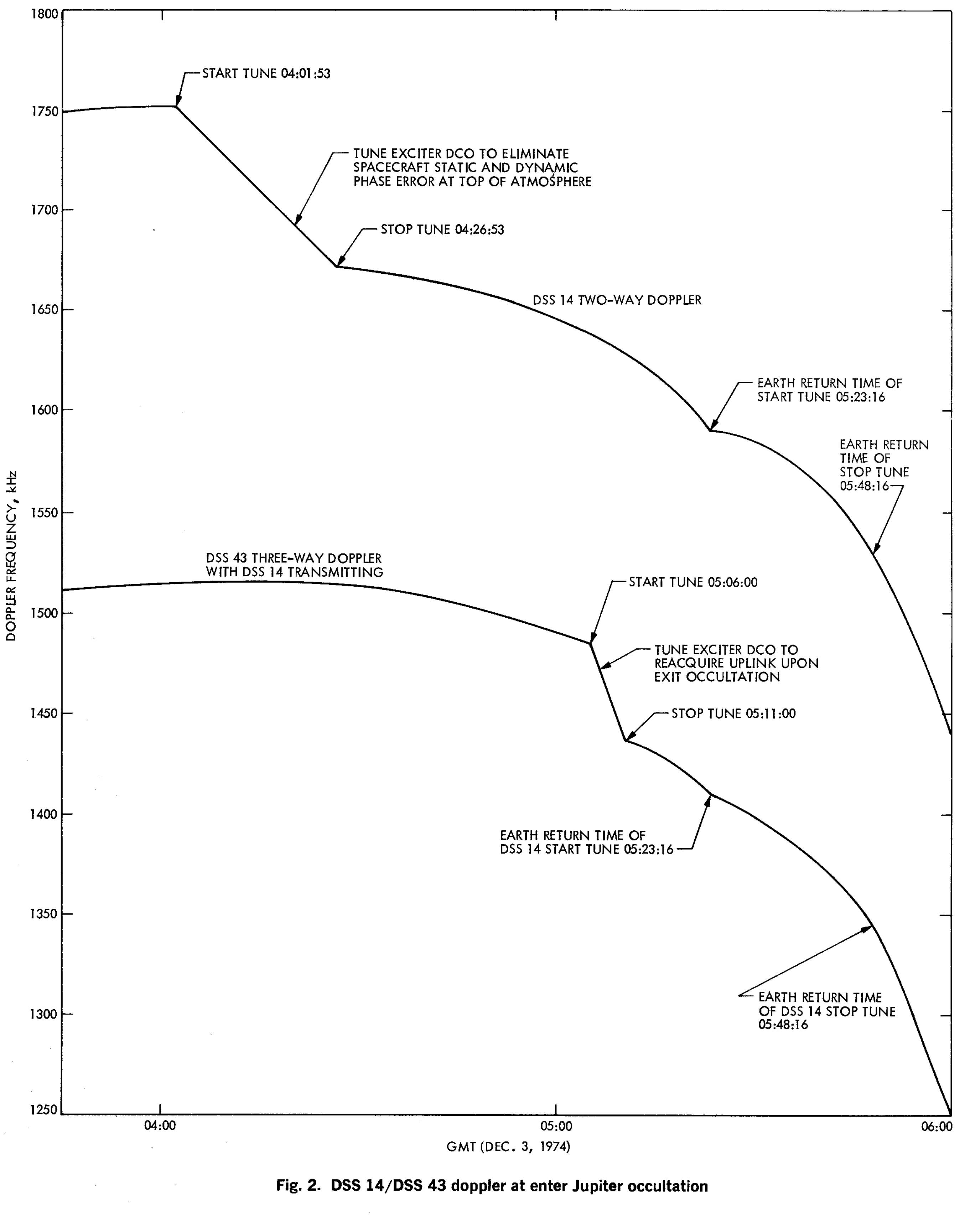

Fig. 2. DSS 14/DSS 43 doppler at enter Jupiter occultation

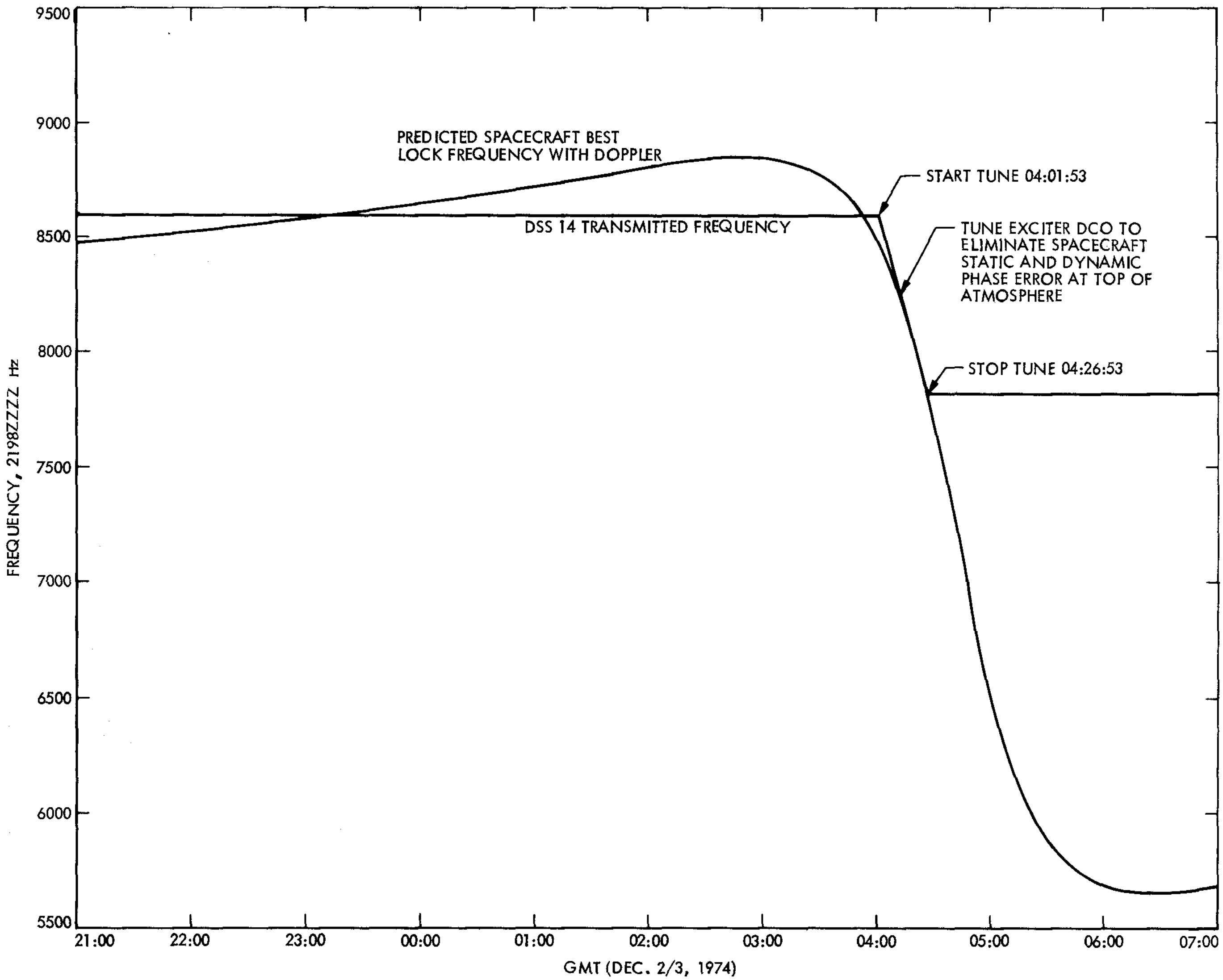

Fig. 3. DSS 14 transmitted frequency pattern

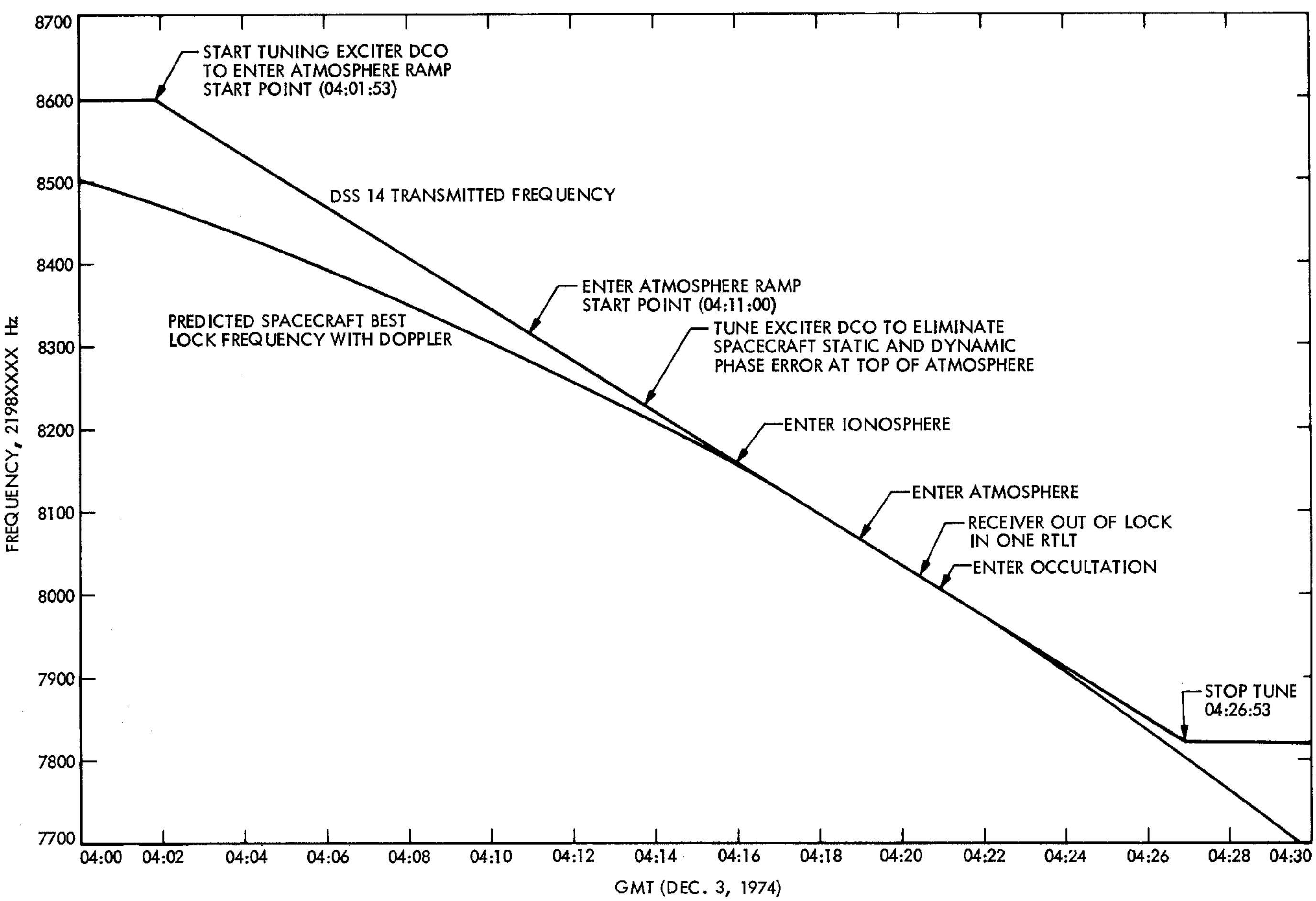

Fig. 4. DSS 14 transmitted frequency pattern at enter Jupiter occultation

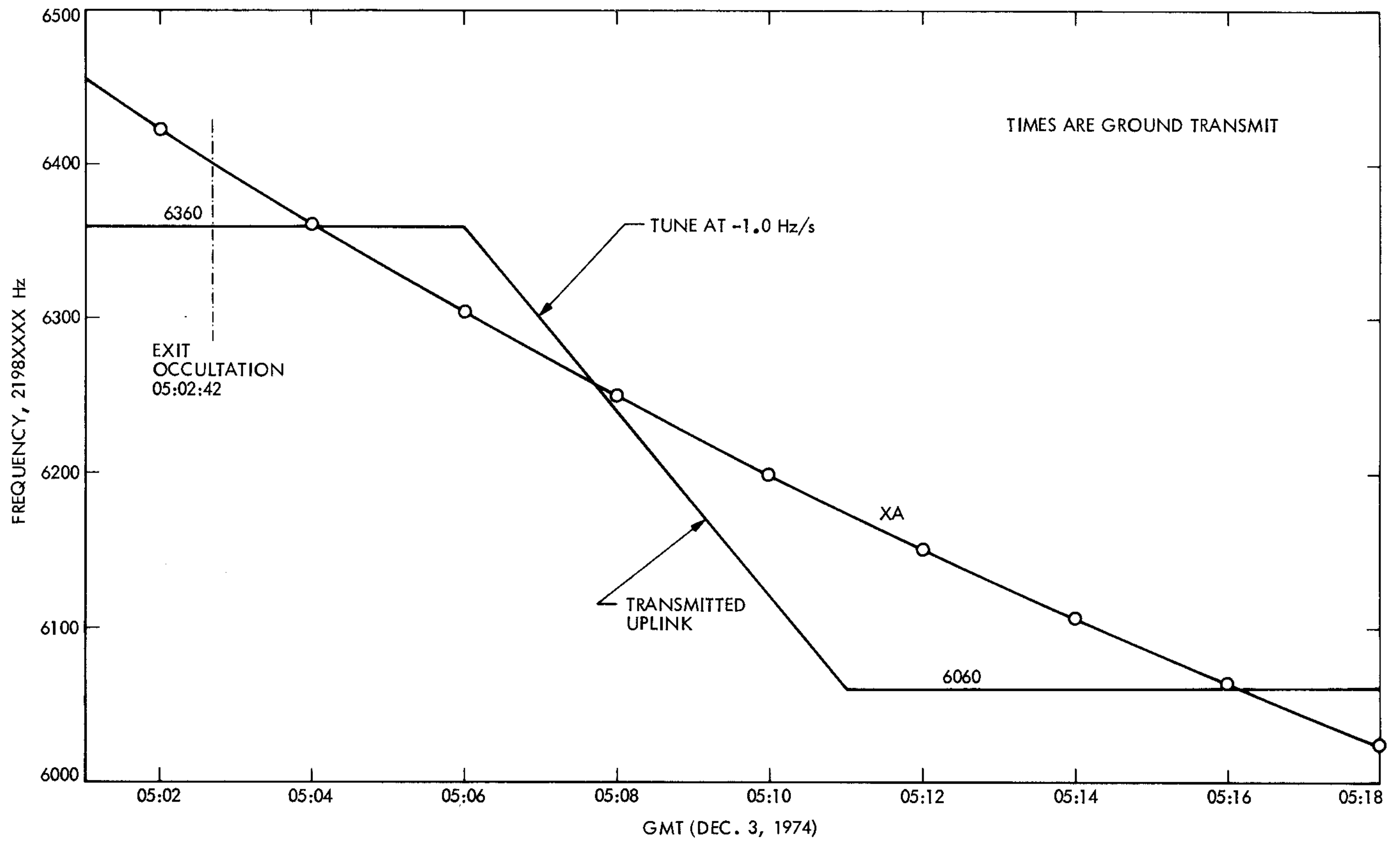

Fig. 5. Sweep pattern to acquire uplink after exit occultation at DSS 43

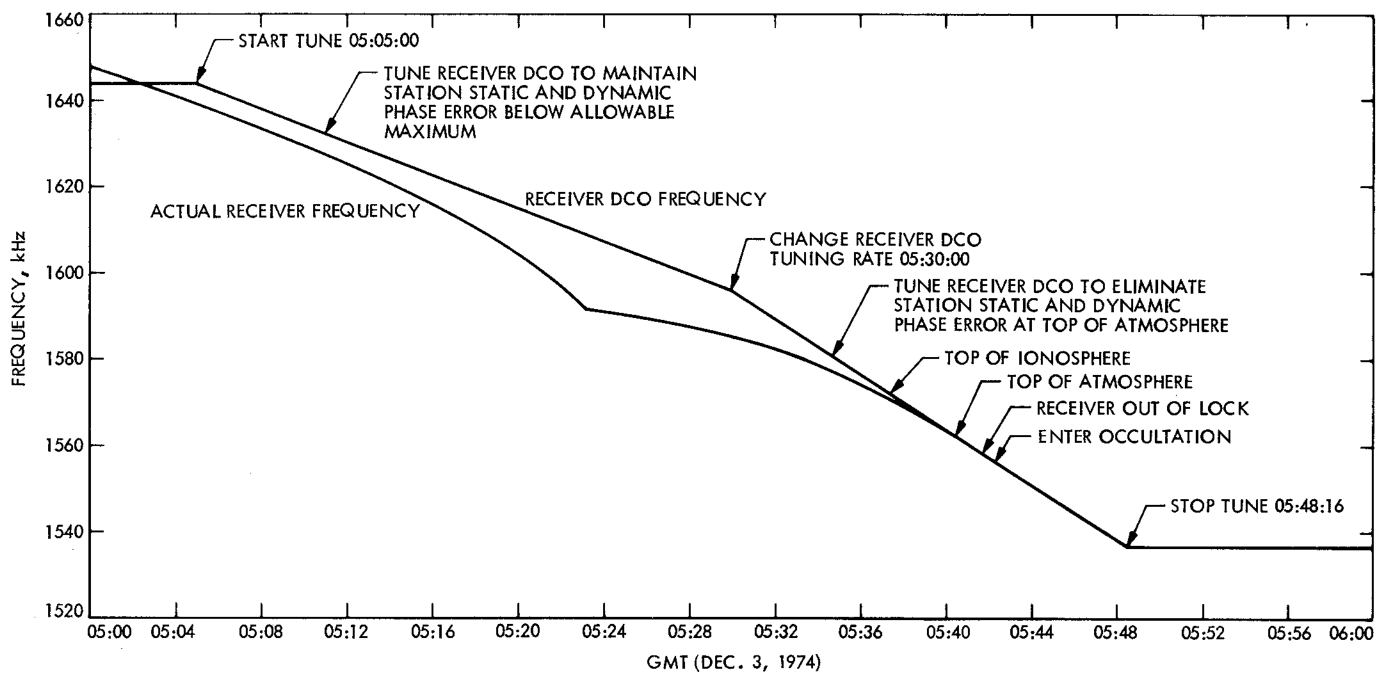

Fig. 6. DSS 14 two-way doppler at enter Jupiter occultation

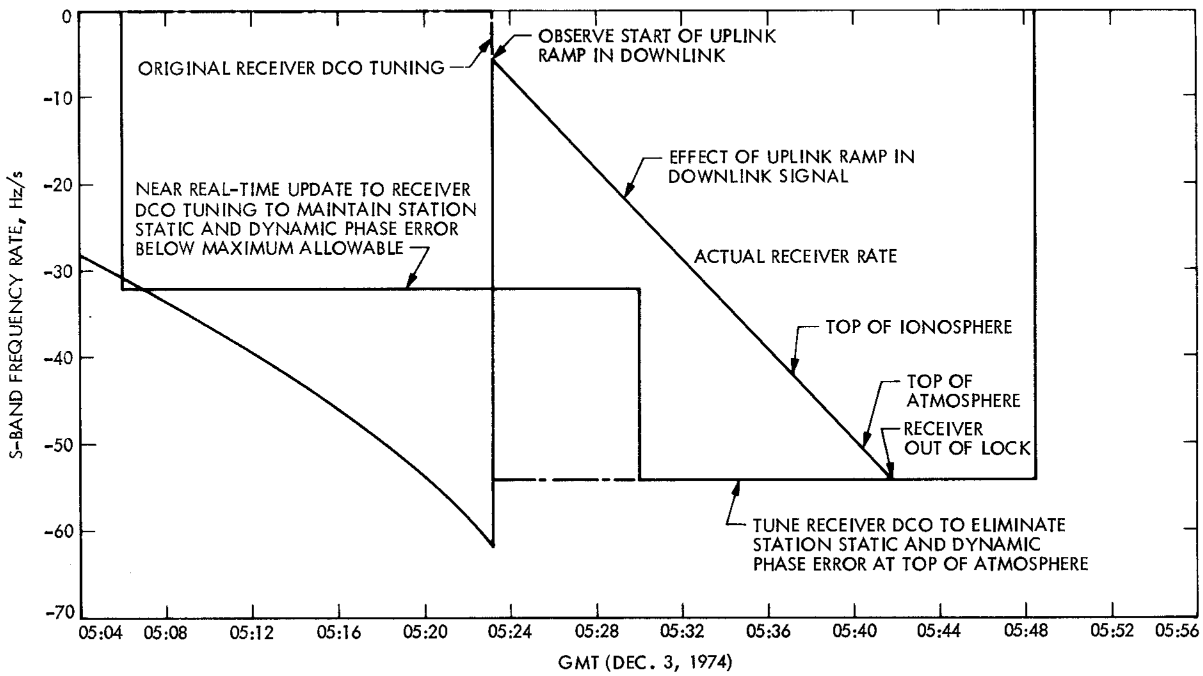

Fig. 7. DSS 14 receiver rate at enter Jupiter occultation

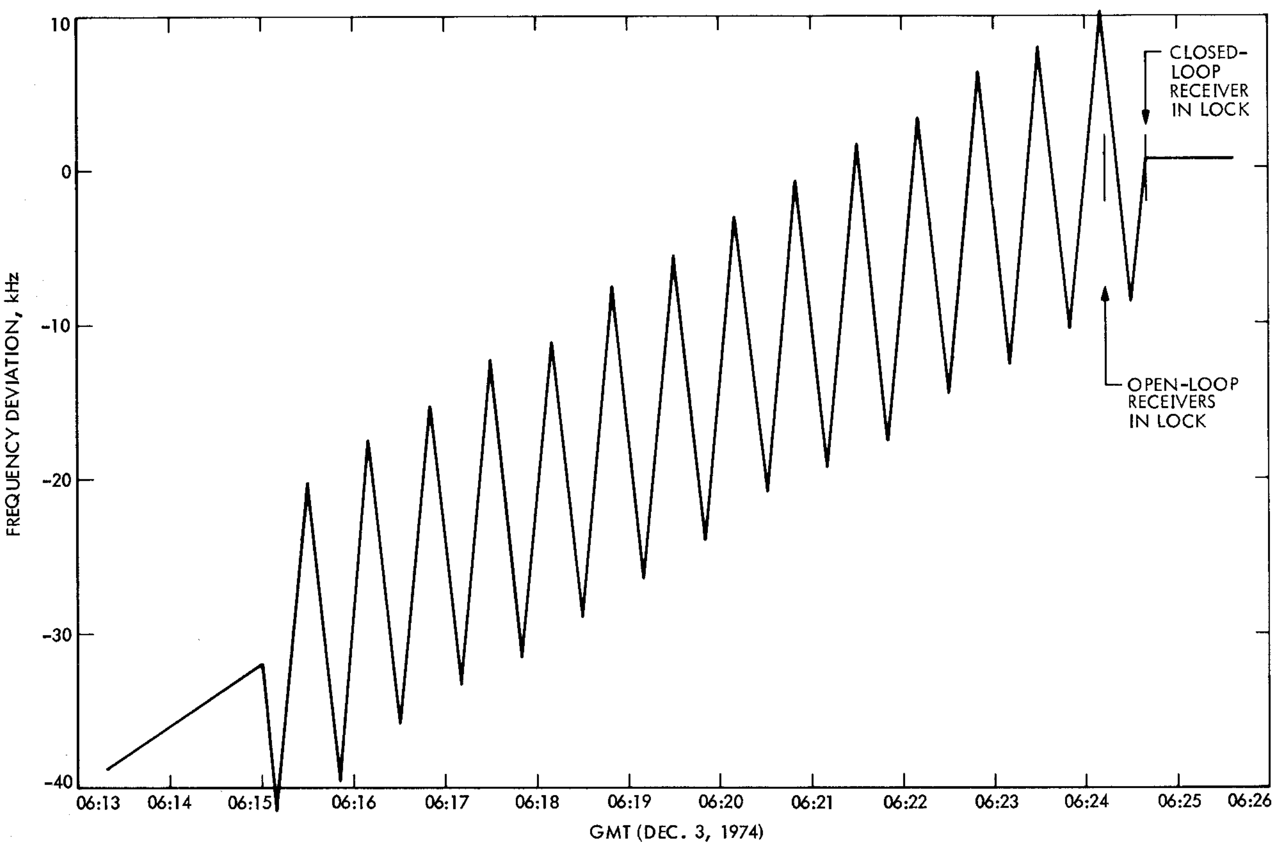

Fig. 8. DSS 14 actual minus predicted one-way doppler at exit Jupiter occultation

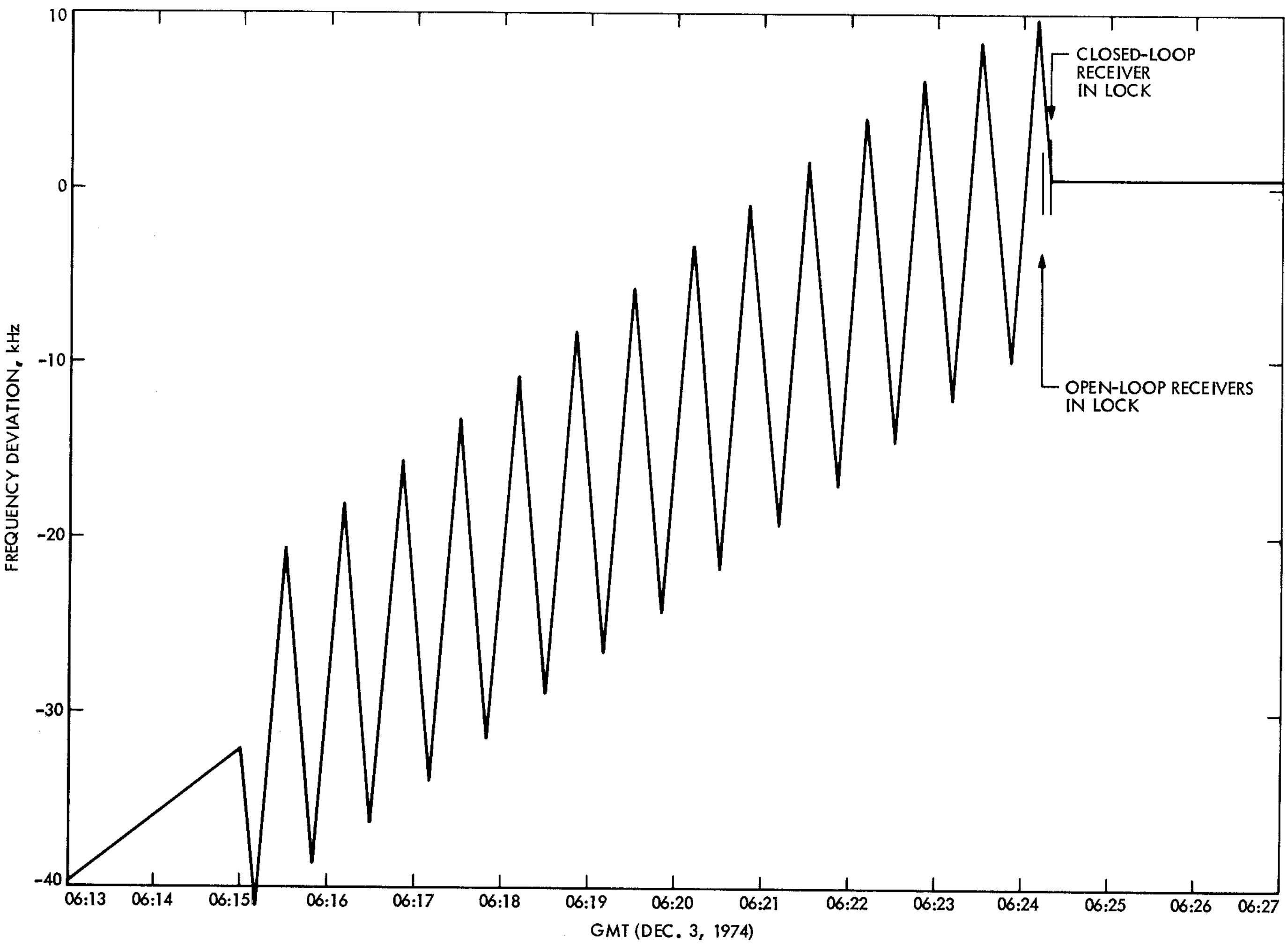

Fig. 9. DSS 43 actual minus predicted one-way doppler at exit Jupiter occultation

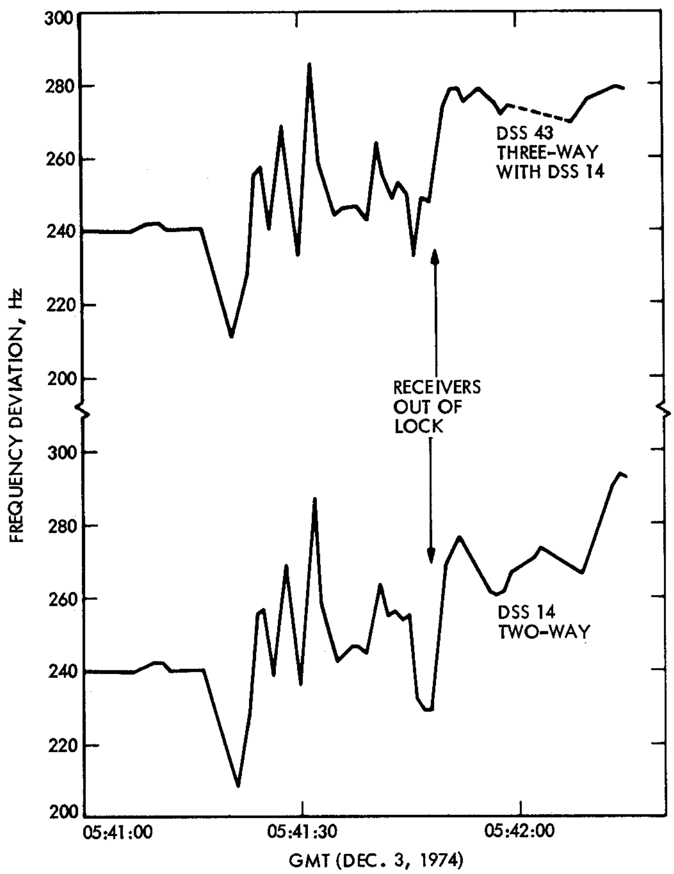

Fig. 10. DSSs 14 and 43 actual doppler minus predicted doppler at enter Jupiter occultation

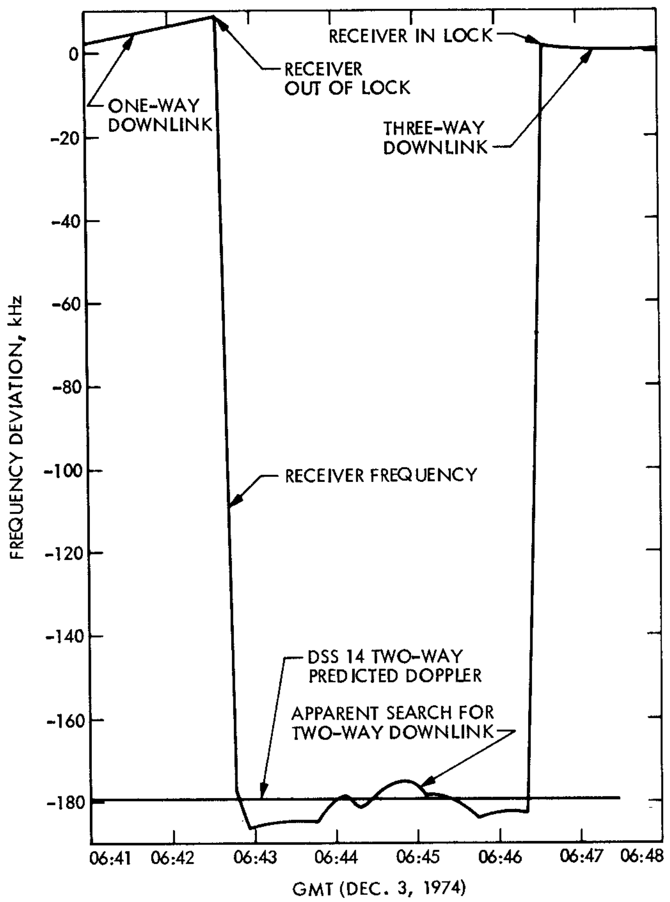

Fig. 11. DSS 14 actual minus predicted three-way doppler with DSS 43 at acquisition of coherent downlink