Tracking Operations During the Pioneer 10 Encounter

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Tracking operations during critical mission phases have become increasingly complex due to more sophisticated mission objectives and expanded tracking capability within the DSN. This article describes tracking operations during the Pioneer 10 Jupiter encounter phase with special attention paid to the role of the newly-installed digital controlled oscillator.

I. Introduction

On December 4, 1973, at 02:25:28 GMT (spacecraft time), the Pioneer 10 Spacecraft reached closest approach to the planet Jupiter. During the near encounter period, which bracketed the closest approach time by several hours, the spacecraft was occulted in turn by the Jovian moon Io and by Jupiter itself. Complicating this encounter was a round-trip light time (RTLT) of approximately 92 min, which was a considerably longer RTLT than had been experienced during any of the previous planetary encounters conducted by the Jet Propulsion Laboratory. At the same time, the Deep Space Network (DSN) tracking system had entered a period of rapid expansion; for instance, new capabilities recently or shortly to be committed for support are: high speed data (HSD) transmission, Block IV receivers, X-band capability, planetary discrete ranging, 10/s data sample rate and the digitally controlled oscillator (DCO). To varying degrees, implementation of each of the above complicates tracking operations, and, in the case of Pioneer 10 encounter, just the use of the DCO added greatly to the complexity of critical phase tracking operations.

At this point, a brief description of the DCO is in order (greater detail is available in Refs. 1, 2, and 3). Basically, the DCO consists of a Dana Model 7010-S-241 digiphase synthesizer and a control assembly. The control assembly contains manual programming capability to generate frequency sweeps that can be manually programmed in advance to occur at specified station times in hours: minutes: seconds. A total of four rates can be stored with corresponding start times to generate a sequence of up to four linear ramps without further adjustment during a given period. As each ramp is executed, an additional ramp can be manually programmed to bring the stored total back to four. Two other sweep control features are included to aid acquisition and station handovers. Primarily for use in the receiver is the acquisition (acq) mode, which generates a triangular frequency sweep at a fixed sweep rate between prestored upper and lower limits, and primarily for use in the exciter is the track (trk) mode, which provides the capability to start a frequency sweep at a precise time and at a fixed sweep rate and to sweep to another fixed frequency.

The most obvious advantages of the DCO are apparent in its use in the exciter. Sweeps to acquire the uplink can now be set up well in advance of the actual time, and can be effected with an exact start time, an exact tuning rate, and an exact end time. Furthermore, the precision of the DCO is so great that doppler data during tuning is of the same order of quality as doppler data at a constant track synthesizer frequency (TSF). The more obvious complications posed by the DCO appear in conjunction with its use in the receiver. Previous to the DCO, tuning to acquire the downlink was done manually by an operator who swept the receiver against page print predicts and waited to detect an audio beat—the flexibility of this system residing in the fact that the operator could easily reverse the direction of the sweep if he felt that he was not sweeping in the right direction or was in the wrong frequency region. The DCO in the receiver, on the other hand, must be exactly preprogrammed as to sweep rates and sweep limits, and if for some reason these do not result in an acquisition, new receiver sweep limits must be calculated by hand or electronic calculator (DCO receiver predicts are not included in regular JPL tracking prediction output), and manually entered into the DCO registers—both functions being time consuming and prone to error.

In the following sections, the frequency management strategy for the Io and Jupiter occultations and the ground receiver reacquisition strategy at Io and Jupiter exit occultations are discussed, with special attention paid to the role of the DCO in both events.

II. Io Occultation

The original intent for the Io occultation was to have DSS 14 enter Io occultation in the two-way mode, with DSS 43 acquiring the uplink shortly after exit Io occultation. After the initial meeting of the Pioneer 10 Occultation Planning Committee, it became evident that something far more desirable might be attainable—exit Io occultation in the two-way mode. This would be of considerable importance to the occultation experimenters and would provide as a bonus additional two-way data for the celestial mechanics experimenters. The fortuitous combination of circumstances that allowed this enhanced goal were:

(1) The spacecraft best lock corrected for doppler (XA) during the time period surrounding Io occultation was very nearly linear.

(2) The newly installed DCOs at DSS 14 and DSS 43 could follow the XA curve during the Io occultation period almost exactly with just one linear ramp.

The general plan to attempt an exit Io occultation in the two-way mode follows: DSS 14 would begin ramping with the DCO at exactly the predicted XA and with a rate equal to the XA rate sometime prior to predicted enter Io occultation (this to account for the sizable uncertainties in the enter and exit times), and would continue until some time after the predicted Io exit time. This would cause the spacecraft receiver to be left at exactly the predicted XA and subsequently would hit the spacecraft with the predicted XA at exactly the moment of exit occultation. Although the spacecraft would be left at the predicted XA at enter occultation, it would immediately begin to drift to whatever the actual XA was. However, the amount of drift would be quite small. Weeks prior to the occultation, the following 3-σ uncertainties were assumed:

$$\text{one-way doppler } (3\,\sigma) = 15 \text{ Hz (at voltage-controlled oscillator (VCO) level)}$$

$$\text{spacecraft best lock } (3\,\sigma) = 25 \text{ Hz (at VCO level)}$$

These result in a combined XA 3-σ uncertainty of approximately 30 Hz. The length of Io occultation was approximately 90 s and the spacecraft receiver relaxation constant was 1320 s, so that one could calculate a total drift away from predicted XA in the 3-σ case as:

XA_A = actual best lock with doppler

XA_P = predicted best lock with doppler

XA_S = spacecraft receiver at a given time

so that at enter:

$$XA_A - XA_P \cong 30 \text{ Hz}$$

and at exit:

$$\begin{aligned}\Delta XA &= XA_S - XA_P \\ &= 30 \text{ Hz } (1 - e^{\Delta t/t_0}) \\ &= 30 \text{ Hz } (1 - e^{-90/1320}) \\ &\approx 2 \text{ Hz}\end{aligned}$$

Considering a more reasonable 1-σ case, one would have a total drift of only ⅔ Hz (at VCO level) away from the transmitted signal (XA_P) at exit, so that one would expect to lock up at the spacecraft almost immediately.

After exit, DSS 14 would be presumed to have the uplink, and a transfer to DSS 43 would be effected. Finally, in the event that DSS 14 did not reacquire the uplink, DSS 43 would sweep the uplink with its exciter DCO as a backup to insure acquisition of uplink. Using the following definitions:

let

T_1 = time of 3-σ earliest enter Io occultation at DSS 14

T_2 = time of 3-σ latest exit Io occultation at DSS 14

T_E = nominal time of enter occultation at DSS 14

T_X = nominal time of exit occultation at DSS 14 so that:

$$T_1 = T_E - 3\sigma$$

$$T_2 = T_X + 3\sigma$$

with 3σ defined as 45 s, the finalized strategy was as follows:

(1) Prior to enter, DSS 14 transmits a constant uplink DCO frequency equal to predicted XA at $T_1 - 30$ s.

(2) At time $= T_1 - 30$ s, DSS 14 begins tuning at a DCO rate equal to the predicted XA rate and continues until time $= T_2 + 32$ s, at which time the transmitter is turned off.

(3) At time $= T_2 + 30$ s, DSS 43 turns on its transmitter at a DCO frequency equal to its predicted XA at $T_2 + 30$ s, and begins tuning at a DCO frequency rate equal to its predicted XA rate until time $= T_2 + 60$ s is reached.

(4) At time $= T_2 + 60$ s, DSS 43 sweeps its DCO frequency up to predicted $XA + 40$ Hz, down to $XA - 20$ Hz, and then remains at that DCO frequency until Jupiter occultation.

The above strategy is shown in Fig. 1. This graph was prepared from predictions based on an orbit determination (OD) solution (actually Probe Ephemeris Tape (PET) Number 6526), which was available approximately five days prior to encounter. However, one problem remained—how to recompute and transmit to the stations in a timely fashion all the new frequencies, rates, and times based on each new OD solution as it might become available. This problem turned out to be amenable to a very simple procedure. The key to this procedure was the fact that XA (upon which the ramps were based) was essentially linear during this period, and the degree of linearity was essentially independent of OD solution (whereas event times and doppler were definitely not):

$$\frac{d(XA)}{dt} \approx C_0$$

where C_0 is relatively insensitive to differing OD solutions.

Since the above was true, none of the ramp rates need change, regardless of the OD solution. Choosing the center of Io occultation (time of, XA of) as a reference point, one only need plot this one event point from each new solution to update the strategy—the horizontal displacement between the new solution and reference point gives the time bias to be applied to all times and the vertical displacement between the reference point and the new solution similarly gives the frequency bias to be added to all frequencies. Center of Io points from solutions (PETs) 6527 through 6530 can be seen plotted on Fig. 1. Solution (PET) 6529 was that actually used during the encounter (it was available approximately 48 h prior to encounter) and biases from the reference OD solution (6526) were:

$$\Delta\,\text{frequency} = -4\ \text{Hz}$$

$$\Delta\,\text{time} = +80\ \text{s}$$

The results of this effort were not immediately known, as the closed loop ground receivers failed to acquire the downlink immediately following exit Io occultation, however, subsequent investigation of the open loop receiver data taken during exit Io occultation shows that the downlink was indeed two-way at exit.

III. Tuning to Acquire the Uplink After Exit Jupiter Occultation

A simple sweep of predicted XA ± 50 Hz (at VCO level) was planned to acquire the uplink after exit Jupiter occultation (note: this sweep takes place before ground observed *enter* occultation); this sweep can be seen in Fig. 2, based on solution 6526. It was planned to keep both the ramp times and rate fixed and only adjust the start and end frequencies based on each solution; thus, the doppler at 04:12:00 GMT from each new solution was plotted on Fig. 2. A conflict within the sequence of events (SOE) necessitated a last minute change to the times of the sweep also so that the final biases applied to the sweep were:

$$\Delta\,\text{frequency} = +33\ \text{Hz}$$

$$\Delta\,\text{time} = -4\ \text{min}$$

The frequency bias was composed of the XA change between solutions 6526 and 6529, plus the XA change caused by a time shift of 4 min. This uplink sweep successfully acquired the spacecraft.

IV. Fast Ground Receiver Acquisitions

As was mentioned in Section I, use of the ground receivers in time-critical reacquisitions of the downlink is somewhat complicated by the DCO, as compared to the previous manual timing performed by the receiver operator; the Pioneer 10 encounter marked the first use of the

DCO during a critical phase. The three events when rapid reacquisition of the downlink was of considerable importance, were (in order of importance):

(1) Jupiter exit occultation.

(2) Io exit occultation.

(3) One-way out of lock condition at transmitter off time prior to Jupiter enter occultation.

It was decided that the DCO acq mode would provide the best chance for a fast reacquisition in the above events. In the acq mode, the DCO drives the receiver back and forth over a fixed frequency range with a fixed sweep rate. This has one obvious drawback in that for the most optimum case of a ground receiver search, one wishes to sweep back and forth about a doppler profile that is not a fixed frequency but more usually a strongly varying function of time. The trade-off with the acq mode is that one must increase the sweep range to encompass the amount of doppler change as well as doppler and other uncertainties during the period in which one expects to lock up. As mentioned previously, the most important fast reacquisition was that upon exit Jupiter occultation; Fig. 3 shows the one-way doppler and the one-way doppler with expected atmospheric corrections as of solution 6526 approximately 5 days before encounter. Successive solutions 6527 through 6530 are also plotted as exit occultation points (time of, *D1* of). In this particular case it was felt that a sweep of ±3000 Hz (S band) about both *D1* and *D1* plus atmospheric corrections would suffice to include both uncertainties due to doppler and the spacecraft auxilliary oscillator; however, since there was also a large uncertainty in time of exit occultation, it was decided to increase the sweep to ±4500 Hz to account for change of doppler with time. This allowed both the doppler and atmospherically corrected doppler to be swept ±3000 Hz from a time of nominal exit −135 s to a time of nominal exit +135 s. A sweep rate of 300 Hz/s (S band) was selected (based upon pre-encounter test results) which meant that with both station receivers being swept asynchronously, one could expect a lock up of the downlink no later than 60 s after exit. The receivers were started at exit occultation −12:00 min and the center point of the sweep corresponded to the doppler at exactly exit occultation. The time and doppler were chosen from solution 6529; see Fig. 3. Two changes were made to this procedure in near real time: (1) the center doppler value was adjusted for a +2200-Hz frequency change in the auxilliary oscillator, which was noted just prior to enter occultation, and (2) because of slow ground receiver lock up times at Io exit occultation and at the transmitter off time (one-way out of lock), one of the two receivers was swept at 100 Hz/s (S band) instead of 300 Hz/s. As it turned out, the receiver sweeping at 300 Hz/s locked first at approximately 05:30:24 GMT, which was 33 s after the best estimate of exit Jupiter occultation at 5:29:51. This falls within the expectation of ground receiver lock no later than 60 s after exit occultation.

The results of downlink reacquisition at Io exit and especially at the transmitter off time are less satisfactory. In both cases the doppler at exit Io occultation and at the one-way out of lock condition (an RTLT after transmitter off) were swept ±4500 Hz at 300 Hz/s. The best estimate of exit Io occultation was 03:29:18 GMT and DSS 43 locked up receiver 1 at 03:29:40 GMT or 22 s later. However, the doppler extractor was connected to receiver 2 and it did not lock up until 03:31:06 GMT or 108 s after Io exit. DSS 14 was not able to reacquire the downlink until 03:35:35 or 6 min 17 s after exit. Finally, reacquisition of the one-way downlink after transmitter off, which should have been the easiest of the three reacquisitions, turned out to be the most difficult. The ground received time of transmitter off was 04:03:56 GMT, and the first station to reacquire lock was DSS 14 at 04:05:33 GMT or 97 s later. DSS 43 was not able to confirm good one-way downlink until 04:10:40 GMT or 6 min 44 s after transmitter off. The unexpectedly long downlink reacquisition time at Io exit and at transmitter off time are under continuing investigation, but to date this analysis has yielded contradictory results (at the same time it should be noted that open loop predicts were provided for both Io and Jupiter occultations, and open loop data were successfully acquired in each case).

References

1. Wick, M. R., *Operational Procedure–Block III High Rate Doppler Receiver/Exciter Subsystem.* Specification OP 509255 A. Jet Propulsion Laboratory, Pasadena, Calif., Aug. 15, 1973 (JPL internal document).

2. Donnelly, H., and Wicks, M. R., "Programmed Oscillator Development," in *The Deep Space Network Progress Report*, Vol. X, pp. 180–185. Technical Report 32-1526. Jet Propulsion Laboratory, Pasadena, Calif., Aug. 15, 1973.

3. Wick, M. R., "DSN Programmed Oscillator Development," in *The Deep Space Network Progress Report*, Vol. VII, pp. 111–124. Technical Report 32-1526. Jet Propulsion Laboratory, Pasadena, Calif., Apr. 15, 1972.

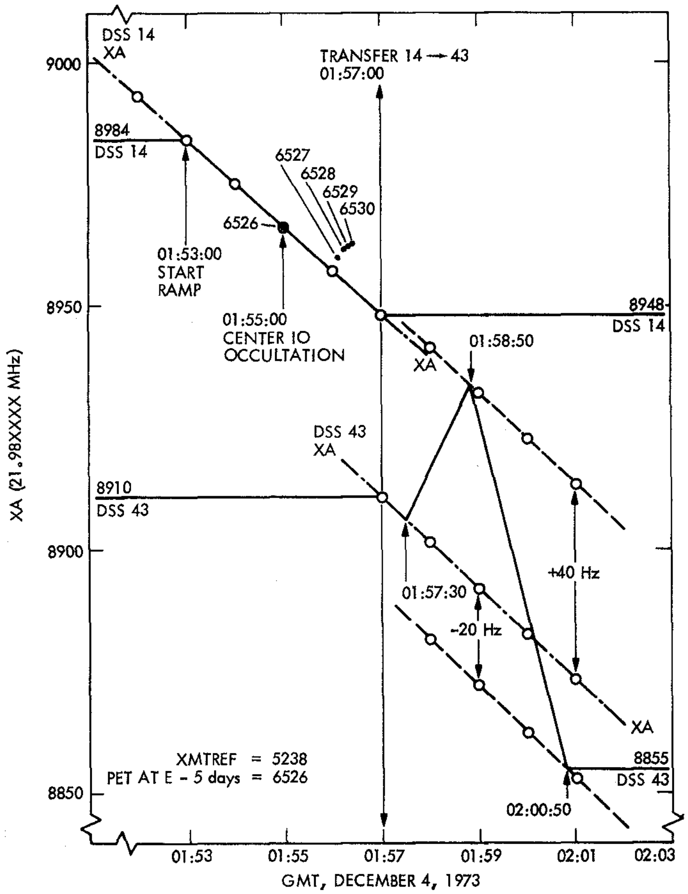

Fig. 1. Frequency strategy Pioneer 10 Io occultation

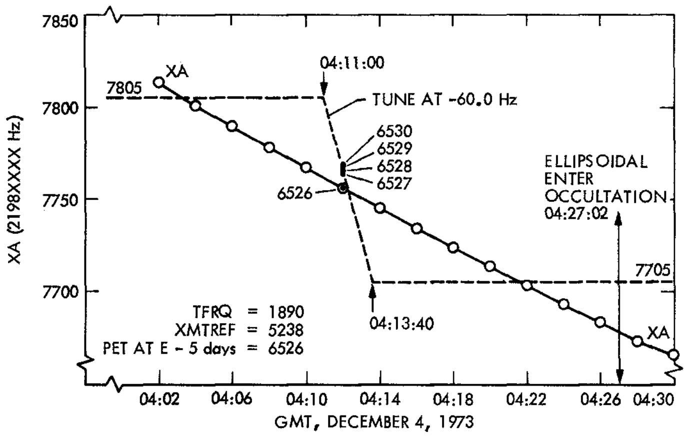

Fig. 2. DSS 43 tuning patter prior to observed Jupiter enter occultation

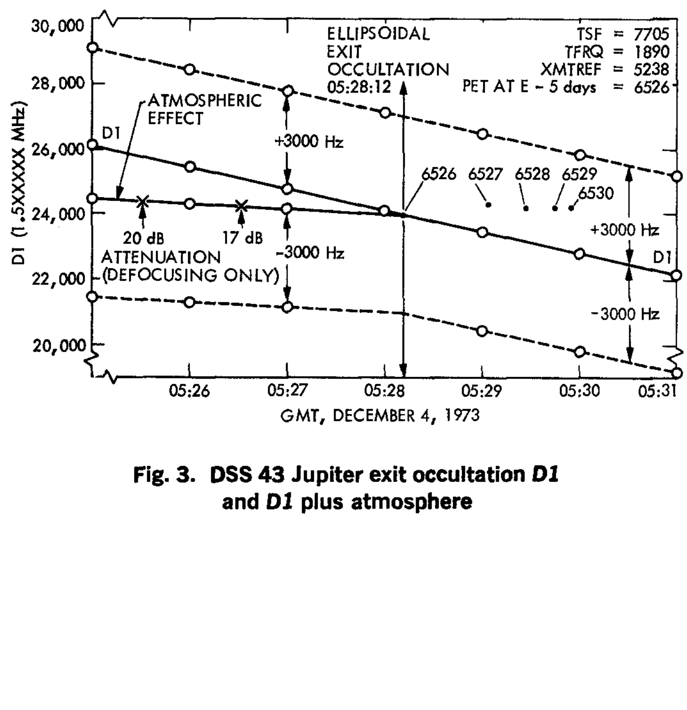

Fig. 3. DSS 43 Jupiter exit occultation *D1* and *D1* plus atmosphere

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