Spacecraft Ranging from a Ground Digitally Controlled Oscillator

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Range measurements to the Pioneer 10 and Mariner 10 spacecraft were made, without the use of a ranging system per se, by using the Jet Propulsion Laboratory Deep Space Network's new digitally controlled oscillator (DCO) device. These measurements were accomplished by controlling the linear ramps of the transmitted carrier frequency with a recently installed DCO instrument at the Goldstone facility and analyzing the received linearly ramped Doppler data with a computer program. The accuracy of these range measurements is on the order of 1.5. km.

I. Introduction

THE tuned oscillator range (TOR) data utilize the new programed oscillator device of the Deep Space Network (DSN). The addition of this new equipment at DSSs 14 and 43, Goldstone, Calif., and Canberra, Australia, was for the purpose of tracking Pioneer 10 during Jupiter flyby. Ranging information can be obtained when the reference frequency is ramped by means of a digitally controlled oscillator (DCO). The reflected signal shows a pattern that is dependent upon the round-trip light time, enabling measurements to be made of the topocentric distance from the station to the spacecraft.

Since the primary purpose of the installation of the DCOs was to support Pioneer 10 during Jupiter encounter, training exercises were scheduled to permit station operators to become familiar with the new equipment and to establish working procedures for the Jupiter flyby. Data taken from DSSs 14 and 43 during several of these training exercises were utilized, and processing of the data was begun to see if range information could be extracted. The data were successfully analyzed and several round-trip range estimates of the Pioneer 10 and Mariner 10 spacecrafts were made.

Additionally, we were concerned about the accuracy and orbital sensitivity of this data. A direct estimate of its accuracy and sensitivity was obtained by observing the difference between the TOR data and DSN range data of the Mariner 10 spacecraft. This provided a confirmation of our theoretically determined TOR accuracy, which was based upon the following errors: 1) phase errors (short term); 2) phase drift (long term); 3) phase errors caused by the troposphere; and 4) ramp initiation time quantization error. The limiting or the largest errors were caused by the instability or drift of the frequency standard. This error is about 1.5 kms (one-way), and is larger than errors due to the troposphere or to ramp-on time errors.

The magnitude of this error corresponds with the observed accuracy of 3 km (2-way) from the Mariner 10 data.

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II. Analysis

The received observable ϕ is the difference between the accumulated (integrated) cycles at time t of received signal and a locally accumulated reference. Assume that at time t, $C(t_1)$ cycles were transmitted to the spacecraft. At a later time t_3, $C(t_1)$ is received again at the ground. The ground reference cycle is $C(t_3)$. Assume further that there were no cycles "lost" between transmission and reception due to troposphere, ionosphere, etc. The observable $\phi(t_3)$ is then:

$$\phi(t_3) = C(t_3) - C(t_1) + \phi_0 \tag{1}$$

where ϕ is an arbitrary number of cycles or phase and

$$C(t) = \int_{t0}^{t} \omega(\tau)\,\mathrm{d}\tau \tag{2}$$

$$C(t) = \int_{t0}^{t} [\omega_0 + \dot{\omega}(\tau - t_0)]\,\mathrm{d}\tau = \omega_0(t - t_0) + [\dot{\omega}(t - t_0)^2/2]$$

where $\omega =$ frequency at time t, τ = station time, $t_0 =$ ramp initiation time, ω_0 = some reference frequency, and $\dot{\omega} =$ frequency ramp. Thus, at reception time t_3, the observable is

$$\phi(t_3) = \omega_0(t_3 - t_1) + (\dot{\omega}/2)[(t_3 - t_0)^2 - (t_1 - t_0)^2] + \phi_0 = \omega_0(t_3 - t_1) + (\dot{\omega}/2)[t_3 - t_1)^2 + 2(t_3 - t_1)(t_1 - t_0)] + \phi_0 \tag{3}$$

We recognize $(t_3 - t_1)$ to be the round-trip time of the signal.

Let c = speed of light and $R = c(t_3 - t_1)$ = two-way range. The observable is:

$$\phi(t_3) = (\omega_0 R/c) + (\dot{\omega}/2c^2)R^2 + (\dot{\omega}/c)R(t_1 - t_0) + \phi_0 \tag{4}$$

At a later or subsequent reception time t_3', the observable is:

$$\phi(t_3') = (\omega_0 R'/c) + (\dot{\omega}/2c^2)R'^2 + (\dot{\omega}/c) \times R'(t_1' - t_0) + \phi_0 \tag{5}$$

To eliminate the unknown arbitrary constant ϕ_0, the phase counts at t' and t_3 are differenced to produce the differential phase $\Delta\phi$:

$$\Delta\phi(T) = \phi(t_3') - \phi(t_3) = [\omega_0(R' - R)/c] + (\dot{\omega}/c)[R'(t_1' - t_0) - R(t_1 - t_0)] + (\dot{\omega}/2c^2)(R'^2 - R^2) \tag{6}$$

The differenced cycle or phase count $\Delta\phi$ can be associated with any time between t_3 and t_3'. Customarily, the observable is time tagged halfway between t_3' and t_3:

$$T = t_3 + \tfrac{1}{2}(t_3' - t_3) \tag{7}$$

Notice from Eq. (6) that the conventional differential phase ($\dot{\omega}=0$) will tell us the range change from time t_3 to t_3'. With the DCO data ($\dot{\omega}\neq 0$), we can also determine range. To see this, assume a static case where the transmitter, spacecraft, and receiver are stationary (such as might be the situation for a geostationary satellite). Then $R' = R$ and $t_1' - t_1 = t_3' - t_3 = \tau$, where τ is the Doppler averaging time. Differential phase, $\Delta\phi$, and range, R, are related by

$$\Delta\phi(T) = (\dot{\omega}/c)R\tau \tag{8}$$

Whereas conventional data with a zero frequency rate have zero differential phase, the DCO or ramped frequency data (differential phase between two successive data readouts) have values which are proportional to the round-trip distances.

III. Data Analysis

Two sets of data from Pioneer 10 and one from Mariner 10 were analyzed from DSS 14. The ramp patterns for the first 2 sets are tabulated in Tables 1 and 2. The first pass of data (PASS I) was taken on June 19, 1973 and the second pass (PASS II) on July 10, 1973. An additional set of data including DSN operational range from Mariner 10 was received Nov. 12, 1973 (PASS III) and was also analyzed.

Pioneer 10 Data on June 19, 1973 (PASS I)

Figure 1 shows the Doppler residuals resulting from a time-delay difference between the ground reference tuning pattern and the returned signal. The received signal was time delayed about 1 hr, which was the time required for the signal to reach the spacecraft and return to the ground. As can be seen, the difference between the received signal and the ground reference produced the Doppler residuals, which were on the order of 200 kilocycles. Doppler caused by a relative motion between the spacecraft and the transmitter on both the up and down links were removed by a computer program. Next, the initial conditions of Pioneer 10 were supplied to us by the Pioneer Project Navigation and based upon this orbit, round-trip light times for each data point were computed. The extra cycles were removed from the data according to the required light time transit. Only the first part of the pass was analyzed because the later data had an error in reported ramp initiation time. The error was approximately 13 sec, and rather than correct for this error (for the sake of demonstration), this later data was eliminated. A 40 μsec delay was noted as well, which resulted in a small, but distinct bias of 6×10^{-3} Hz. An additional delay of one sec which always occurs was also taken into account by our computer program. The reported Program Oscillator Control Assembly (POCA) rate is also subject to possible errors. The POCA rate can only be controlled to 10^{-4} Hz. In other words the electronic control unit will accept a rate entry to four digits after the decimal point. The rates reported to us were at S-band, whereas the actual control rates were 1/32 smaller. Rates not divisible by 32 to 4 decimal places were truncated by the POCA operator. Figure 2 is the result of the foregoing corrections. Step residuals appeared due to the misplacement of Pioneer 10 in this assumed trajectory by approximately 250 km. The ramped Doppler data gives us an additional measurement dimension not readily or directly available from conventional Doppler. The unramped Doppler yields a solution of the orbit by inference through the acceleration dynamics after sufficient spatial motion has occurred (about 6 weeks or longer).

The step biases are due to a trajectory error times a ramp rate. Since over one pass we may regard the orbit error to be a constant, the offsets are due to differing ramp rates. Thus the largest offset is due to a ramp rate of 150 Hz/sec. Halfway between, a bias of half that is due to a ramp rate of 74.9984 Hz/sec is realized. Centered about zero are the two offsets caused by a ramp rate ± 30 Hz/sec.

Table 1 Ramp test pattern for June 19, 1973[a]

Ramp no.	(T_0+T) Ramp-on time hr	min	sec	Ramp rate (S-band) Hz/sec at excitor
1	0	0	0	150
2	0	3	20	75
3	0	10	00	30
4	1	27	47	0
5	1	32	47	−30
6	2	50	34	−75[b]
7	2	57	14	−150
8	3	00	34	0
9	3	05	47	−150
10	3	09	07	−75[b]
11	3	15	47	−30
12	4	33	34	0
13	4	38	34	30
14	5	56	21	75[b]
15	6	03	01	150
16	6	06	21	0

[a] Begin time T_0 = 9:40:00 (GMT). [b] Actual S-band rate ± 74.9984 Hz/sec. (Test information from E. Cloonan.)

Table 2 Ramp test pattern for July 10, 1973[a]

Ramp no.	Ramp on time (GMT) hr	min	sec	Ramp rate (excitor) (DCO rate)[a] Hz/sec
1	06	30	00	3.125
2	06	46	40	0
3	07	09	43	−3.125
4	07	26	23	0
5	07	47	03	−3.125
6	08	03	43	0
7	08	26	46	+3.125
8	08	43	26	0
9	09	04	06	+3.125
10	09	20	46	0
11	09	43	59	−3.125
12	10	00	39[b]	0
13	10	21	19	−3.125
14	10	37	59	0
15	11	01	02	+3.125
16	11	17	42	0
17	11	38	22	+3.125
18	11	55	02	0
19	12	18	04	−3.125
20	12	34	44	0

[a] S-band rate = 32 × (DCO) rate = 100 Hz/sec. [b] Suspect time error of −5 sec. (Test information from S. Schlaifer.)

Pioneer 10 Data on July 10, 1973 (PASS II)

A second set of data taken on July 10, 1973, was analyzed. In the intervening period, a trim maneuver had taken place. This necessitated a solution for the new orbit. Additions were made to the code in the program, which included the new data partial derivatives required for an automatic least-square differential-correction process. This batch of data from July 10, 1973, was sent through the computer and automatic iterations for the solution of the new orbit were begun. After the first iteration, the Doppler data were centered about zero, but the range was still in error by an amount equivalent to 0.5 Hz (see Fig. 3). Since the ramp rates for this pass were always 100 Hz/sec at S-band, the offsets were always the same size and centered about zero. After the second iteration, all of the

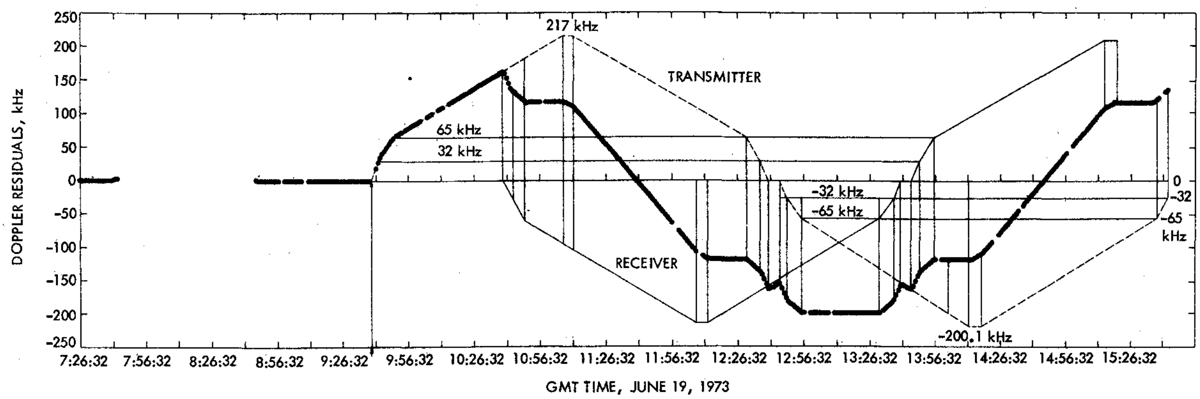

Fig. 1 Tora experiment, June 19, 1973. DSS 14 Pioneer 10 Doppler residuals before ramp adjustments.

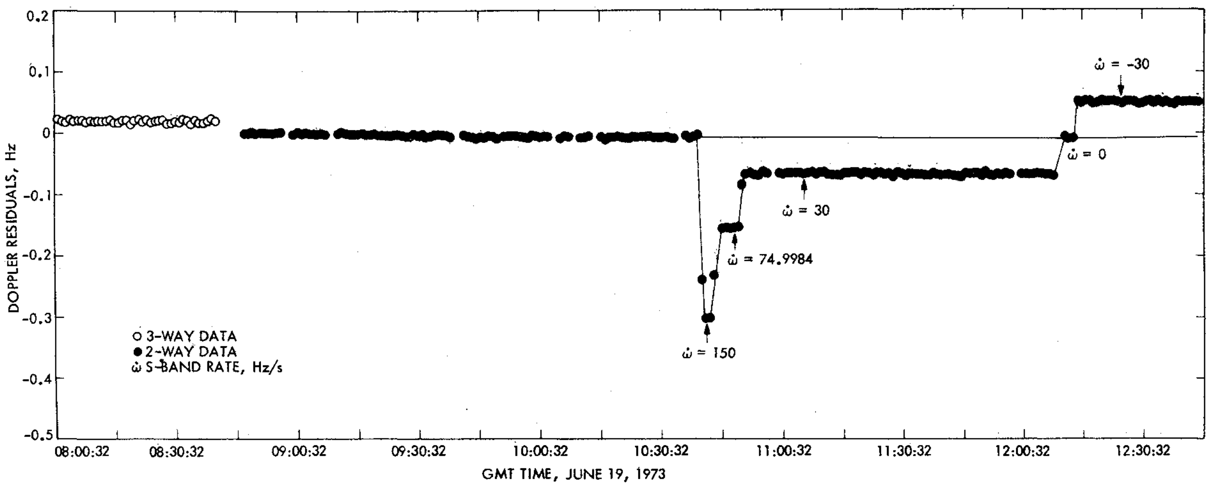

Fig. 2 Tora experiment, June 19, 1973. DDS 14 Pioneer 10 residuals after ramp adjustments with no orbit corrections.

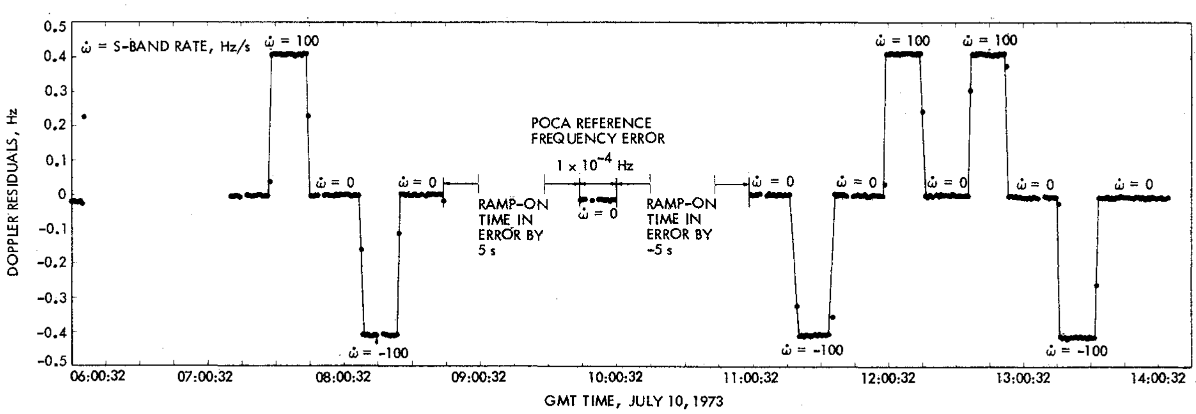

Fig. 3 Tora experiment, July 10, 1973. DSS 14 Pioneer 10 data with orbit and ramp corrections, second iteration.

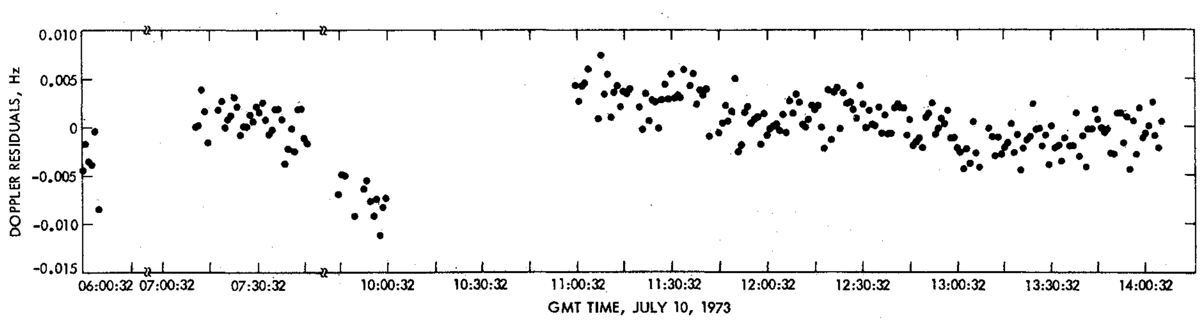

Fig. 4 Tora experiment, July 10, 1973. DSS 14 Pioneer data and ramp corrections, final iteration.

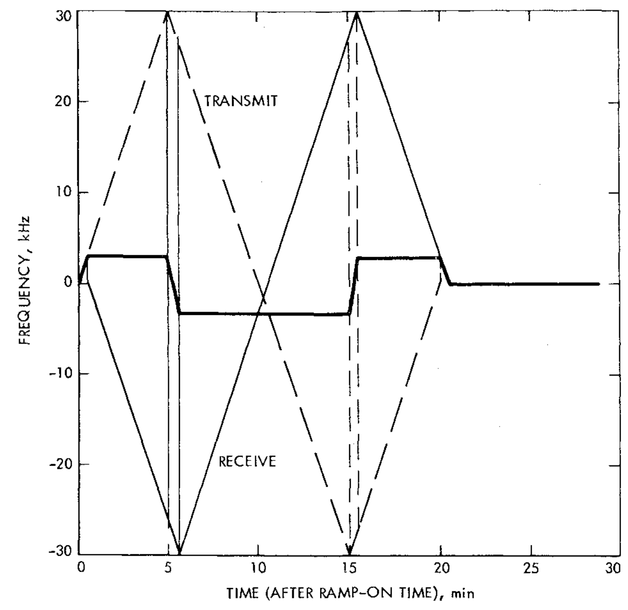

Fig. 5 Mariner 10 ramp profile from DSS 14.

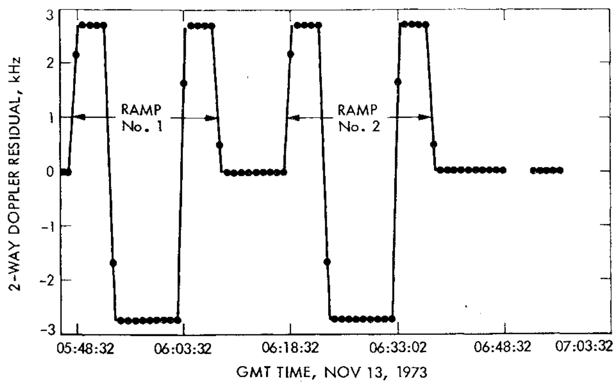

Fig. 6 Mariner 10 Doppler residuals from DSS 14 before ramp adjustments on Nov. 13, 1973.

biases disappeared, indicating the data derivative formulation and program coding to be correct and thus causing the solution to converge. There was a POCA initiation time error of 5 sec, causing residuals of 500 Hz to appear in the middle of this pass. Again, rather than correcting our time inputs to the program, for the sake of this demonstration, these data were eliminated from the data set used for the orbit solution.

Since spacecraft range errors appear in the TOR Doppler data as step biases, these step biases disappear when the spacecraft orbital parameters have been corrected and the TOR data residuals appear only as normal noise. As a measure and demonstration of how well the orbit has been corrected for range errors, we examine the TOR Doppler residuals for remaining systematic errors.

When the blunder points were removed, we were able to adjust the orbit so that the data residuals were on the order of 1/1000 Hz. Figure 4 shows the result of this solution. An attempt was made to correct the 5-sec ramp initiation time, but resulted in rejecting this portion of the data due to a computer input error.

Figure 4 shows the level to which we can fit the ramp frequency data when all the large blunder points have been removed. It is evident that the only noise component remaining is the high frequency component, and when the ramp pattern is included in the data analysis, the new TOR Doppler data residuals look the same as the conventional unramped data residuals.

Mariner 10 Data on November 12, 1973 (PASS III)

Since Pioneer 10 does not have a spacecraft ranging transponder, no direct ranging is possible, thus range accuracy

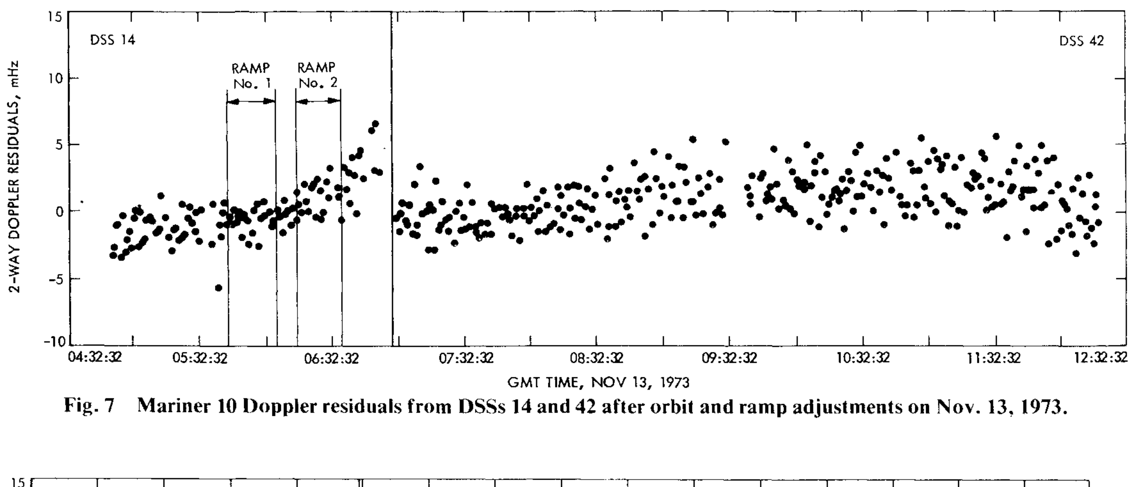

Fig. 7 Mariner 10 Doppler residuals from DSSs 14 and 42 after orbit and ramp adjustments on Nov. 13, 1973.

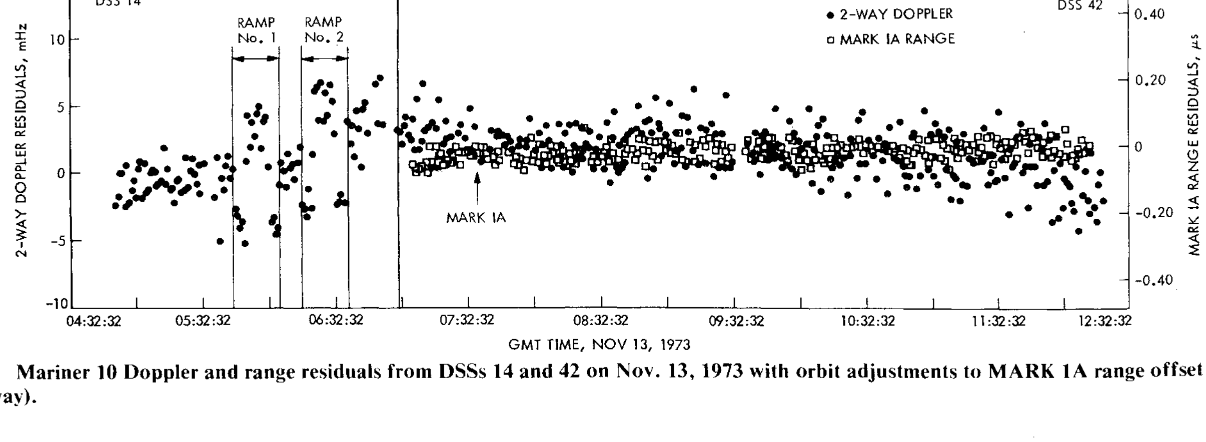

Fig. 8 Mariner 10 Doppler and range residuals from DSSs 14 and 42 on Nov. 13, 1973 with orbit adjustments to MARK 1A range offset of 5 km (one way).

from the TOR data was inferred from analyzing the TOR Doppler data residuals alone. For Mariner 10, direct ranging was available and we were able to compare TOR data with this other data source.

The Mariner 10 ramp test was performed on November 12, 1973, utilizing the 64 antenna at Goldstone, Calif. Direct range measurements were also made using the spacecraft ranging transponder and the MARK 1A ranging systems at JPL DSS 42 near Canberra, Australia, and DSS 62 near Madrid, Spain. In this test, the ramped Doppler range estimates could be directly checked by actual ranging measurements.

The ramp profile consisted of a positive 100 Hz/sec *S*-band rate for five minutes, followed by a -100 Hz/sec rate for 10 min and then another positive 100 Hz/sec for 5 min. This profile was repeated after 10 min of nonramped Doppler. Figure 5 shows the ramp pattern. The signal is received one round-trip light time later (about 25 sec) as a mirror image of the transmitted ramp.

The data signature produced by the difference between the transmitted and received ramps is seen near the center of Fig. 5. Figure 6 is a plot of the actual ramped Doppler residuals referenced to the Mariner 10 orbit. The ramp pattern of Fig. 5 (solid dark line) has not been modeled, and is observed in Fig. 6 as it was received and repeated a second time. The amplitude of this plot divided by the 100 Hz/sec ramp rate and by the spacecraft 240/221 multiplier yields the round-trip light time of about 25 sec.

When the ramps are modeled by the Planetary Orbiter Error Analysis System (POEAS), a least-squares orbit determination program, the ramped observed minus computed (O-C) Doppler residuals cannot be distinguished from normal Doppler residuals (see Fig. 7). The 8 mHz upturn in the residuals beginning at the initiation of ramp No. 2 is a consequence of imperfect tropospheric refraction modeling at the low elevation angles encountered near the end of the Goldstone pass. It was also noted (although not shown in Fig. 7) that when the ramped Doppler data are fitted and compared to the range data, the O-C range residuals are consistently biased less than one microsecond in round-trip time (150 m in one-way range).

To determine the sensitivity of the ramped Doppler to range error, the MARK 1A ranging data from DSSs 42 and 62 were deliberately computer-biased by five kilometers in one-way range. A range-only solution was performed on this artificially biased range data. An examination of the O-C Doppler residuals after the biased range-only least-squares fit clearly shows the ramp signature resulting from the biased range (see Fig. 8), whereas ordinary Doppler data is virtually unaffected. The MARK 1A range residuals after the fit are indicated by white squares on Fig. 8. The Doppler residuals (black dots) are seen to be unchanged from Fig. 7 except for the ramped data, exhibiting the normal insensitivity of Doppler data to range bias. The ramped data are offset ± 5.0 mHz, or 1.0 mHz per kilometer of one-way range. This indicates a sensitivity of the ramped Doppler to one-way range errors of the order of 1.5 km.

Conclusions

Three sets of ramped Doppler data from DSS 14 of Pioneer 10 and Mariner 10 spacecrafts were analyzed. The method used shows exciting promise for providing a new measurement dimension, range, from Doppler data. Interpretation of the data seems sound, and the incorporation of our understanding into computer programs yielded reasonable results. Finally, in the process of analyzing this new TOR data from Pioneer and Mariner 10, we have: 1) obtained a direct estimate of its accuracy and sensitivity; 2) confirmed our theoretical estimates of its accuracy; and 3) interpreted our results in terms of a new data type corresponding to topocentric range to the spacecraft.