Results of the Tau/Mu Alternate Ranging Demonstration

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On August 14, 1971, an experiment to determine the relative accuracies of the Tau ranging machine and the Mu ranging machine was performed at the Goldstone Deep Space Communications Complex. The results of this demonstration are described. The two ranging measurements agreed to 7.925 ns over the pass.

I. Introduction

On August 14, 1971, an experiment involving the Tau ranging machine at DSS 14, the Mu ranging machine at DSS 12, and the Mariner 9 spacecraft was performed to determine the relative accuracies of the two ranging machines. The result of this demonstration is summarized in Table 1.

II. Experiment Procedures

The experiment was performed by ranging the Mariner 9 spacecraft from DSS 12 for approximately 30 minutes. The spacecraft was then handed over to DSS 14

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where ranging data were taken for the next 30 minutes. The spacecraft was then returned to DSS 12 for the next range point. This procedure was repeated until six independent Mu range points were recorded by DSS 12. Groups of Tau range points clustered in five groups were recorded between the Mu data points.

The delay through both stations was measured before and after the test. Faraday rotation measurement of the ionosphere and radiosonde balloon measurements of the troposphere were obtained for the same period.

The ranging data obtained were processed by the DSN Tracking System. The data were fitted by the Tracking Data Editor (TRKED) Program (Ref. 1). Figure 1 shows the range residuals produced by TRKED after two iterations. The data were corrected as described below. The Mu points were averaged (nominally 20 minutes) and related to time of initial acquisition by

linear extrapolation. The Tau data for the last acquisition by DSS 14 were not usable for some unknown reason.

The equations for a differenced range observable are given in Ref. 2 along with a discussion of the errors for an intercontinental baseline. The error for this type of observable is given as

$$\epsilon_{\rho_{\text{DSS 12}}-\rho_{\text{DSS 14}}}(t) = [z_b \cos \delta_{s/c} - r_b \sin \delta_{s/c}$$
$$\times \cos (\alpha_{s/c} - \alpha_b)] \, \epsilon_{\delta_{s/c}}$$
$$- r_b \cos \delta_{s/c} \sin (\alpha - \alpha_B)$$
$$\times [\epsilon_{\alpha_{s/c}} - \epsilon_{\alpha_b}] + \sin \delta \, \epsilon_{z_b}$$
$$+ \cos \delta \cos (\alpha_{s/c} - \alpha_b) \, \epsilon_{r_b}$$
$$+ \epsilon_{\text{measurement system}}$$

where

z_b, r_b, α_b = baseline z-height, equatorial projection length and right ascension at time t. (These quantities are functions of polar motion and UT1)

$\delta_{s/c}, \alpha_{s/c}$ = declination and right ascension of the spacecraft at time, t

$\epsilon_{()}$ = error of subscripted term

$\epsilon_{\text{measurement system}}$ = includes uncertainties in calibrations applied for transmission media, ground link delays, clock synchronization and rate differences and spacecraft transponder delay. (For the work reported in this paper, signal-to-noise ratio (S/N) dependent errors are assumed negligible because of the relatively long averaging times)

For the short baseline case (as opposed to the intercontinental baseline case discussed in Ref. 2) the difference in transmission effects will also be negligible.

The other contributors to the error in range differences are discussed below and their effects are illustrated in Fig. 2.

The errors which can bias the data are:

(1) Differences in station height above the equatorial plane

(2) Spacecraft declination error

(3) Station clock offset

(4) Station frequency differences

(5) Station zero delay calibration difference

III. Difference in Station Height Above Equatorial Plane

DSSs 12 and 14 have been linked by ground surveys (Ref. 3) and very-long-baseline interferometry (VLBI). The largest uncertainty is in the difference in height for DSSs 12 and 14 which is inferred to better than 50 cm by comparing these survey measurements. The relative station equatorial height uncertainty of 50 cm would cause an error in range measurement between the two stations of 1.5 ns. This error is not negligible for the short baseline experiment, and will have to be measured by VLBI for long baseline alternate range experiments. Errors in polar motion and UT1 have a negligible effect due to the relatively short baseline between DSSs 12 and 14

IV. Spacecraft Declination Error

An error in spacecraft declination can cause a bias in measurement in range from two stations. If the spacecraft declination were in error by 0.1 arcsec, this would cause an error of 30 ps (3×10^{-2} ns) in round-trip time measurements for the two stations.

Consequently, since the spacecraft declination is known to much better than 0.1 arcsec, this is a negligible error.

V. Station Clock Offset

The error in station clocks—that is the offset between the two clocks—can produce an error in their relative measurement of range. This error is multiplied by the spacecraft velocity. The Mariner 9 has a geocentric velocity of 7 km/s on August 14, based on the Double Precision Trajectory Program, (DPTRAJ) calculations (Ref. 4). The clock offset between DSSs 12 and 14 amounted to Station 14 lagging Station 12 by 18.2 μs. This causes a measurement of range from Station 14 to be greater than the range measured at Station 12 by 0.9 ns. This error is not negligible and the Tau data were adjusted. For long baseline alternate range experiments, clock offsets should be measured to remove this bias. Uncertainties of less than 1 μs in the determination of the clock offset are negligible.

VI. Station Frequency Difference

The clock (Varian R20 Rubidium standard) at DSS 14 was running faster than the clock at DSS 12, which caused an error of 1.1 ns (DSS 14 range measurement was greater than DSS 12) and the Tau data were adjusted. The accuracy of this calibration leaves an uncertainty $\sigma_{\Delta f/f}$ of 2 to 6 $\times$ 10^{-12}. For the signal round-trip time of 173 s this causes an 0.1 to 0.3 m uncertainty in the differenced range.

VII. Station Ranging Calibration

The delay through the station as measured with the zero delay device for DSS 12 was 2140 ns. For DSS 14, the delay was 911 ns. The difference, 1229 ns, was removed from the data prior to the fitting by TRKED. Clearly, this quantity will always have to be measured for any future work. The calibration certainty σ_{delay} of 3 to 7 ns for each station results in a 1.3 to 3 m uncertainty in the differenced range.

VIII. Variations in Transponder Ranging Delays

There are two possible sources of different ranging delays through the spacecraft transponder. Namely, those due to the fact that the Mu and Tau systems have different side characteristics and those due to the difference in uplink S/N between DSS 12 and DSS 14. The total effect due to these two sources is assumed to be between 0.1 and 0.5 m.

IX. Conclusions and Recommendations

The remarkable consistency of the Tau and Mu ranging machines indicates that long baseline experiments, for example, California/Australia, are feasible and should be conducted. The relative accuracy of the two range measurements of one meter for the Mariner 9, which was 3 $\times$ 10^{10} meters from the Earth on August 14, amounts to better than one part in 10^{10}.

Acknowledgment

References

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Table 1. Mu/Tau alternate range residuals

Mu residuals, ns			Tau residuals, ns		
Mean	Std. Dev.	No. of points	Mean	Std. Dev.	No. of points
22.7	62	26	8.6	9	4
−35.6	50	26	0.1	11	35
−16.7	42	26	0.9	11	79
18.6	50	26	−2.3	15	24
−9.0	61	26	a	a	a
−16.6	57	26			

Summary over pass	Mean	Std. Dev.
Mu data	−6.10	22.5
Tau data	1.825	4.7
Difference	−7.925	

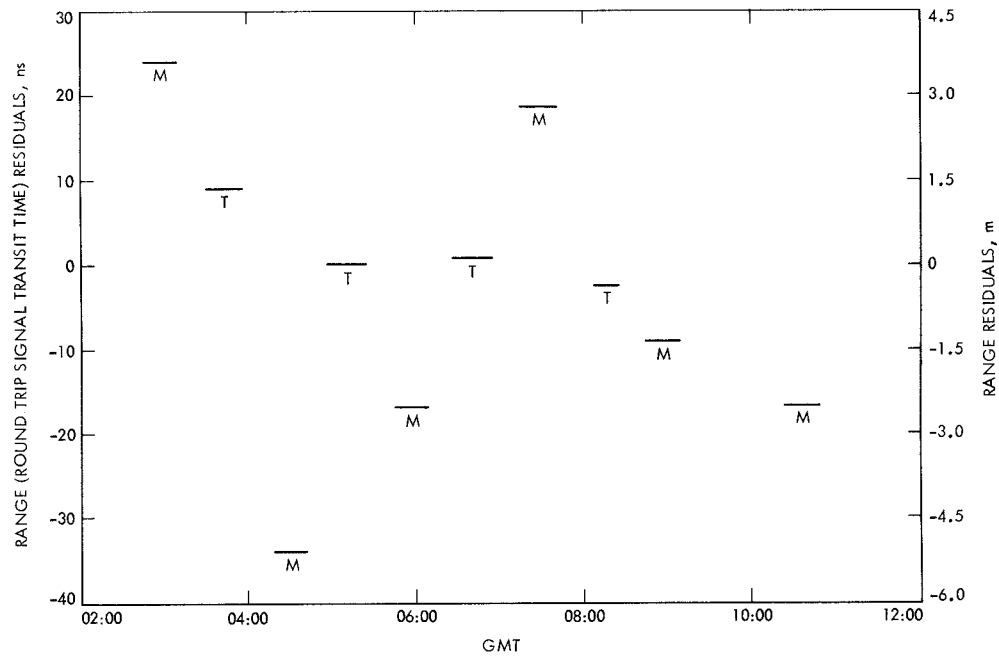[a]See text, Section II, paragraph 3.

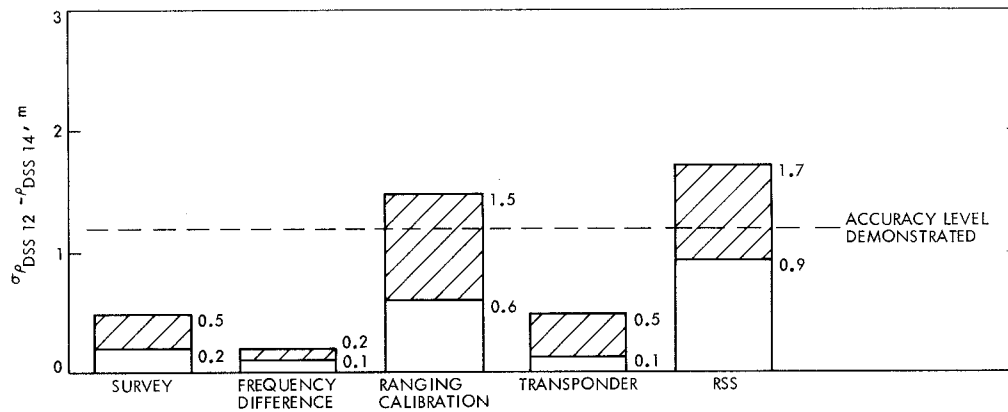Fig. 1. TRKED range residuals, Mu versus Tau range

Fig. 2. Limitations to differenced range measurements for Mariner 9 demonstration