Radio Science Requirements and the End-to-End Ranging System

A. L. Berman
TDA Engineering Office

Radio science ranging requirements negotiated between past and present flight projects and the DSN have generally focused on just the DSS and spacecraft hardware. All elements in the end-to-end ranging system must be analyzed and considered in terms of an error hierarchy before reasonable and cost-effective requirements can be levied upon any individual element. This article defines and examines the end-to-end ranging system as it applies to the generation of radio science ranging requirements. Particularly emphasized is the variability of the performance levels of certain of the system elements with respect to the type of radio science experiment being performed and the DSN-spacecraft frequency band configuration.

I. Introduction

To date, negotiations between flight projects and the Deep Space Network (DSN) have assumed that ranging system[1] "errors" occur primarily in the Deep Space Station (DSS) and spacecraft (S/C) hardware, and, therefore, radio science ranging[2] requirements were generally levied solely on these elements. Conversely, the radio science experimenter is typically most concerned with the total data "noise" and "accuracy" of the final *processed* radio science ranging data. It would thus seem immediately apparent that an end-to-end systems approach to radio science ranging requirements would be more appropriate; this article further suggests that without such an approach, requirements levied on a partial subset of elements (i.e., DSS and S/C hardware) as per the current practice will not produce the data quality desired by radio science experimenters, nor will it produce the cost-effective employment of resources.

To illustrate the problem, consider the ranging accuracy level of 2 to 10 centimeters being projected for the Mark IV DSN (1980s). Preliminary calculations (see the appendix), assuming the "ultimate" DSN configuration of S- and X-band simultaneously on uplink and downlink, suggest that for conditions of very dense plasma (i.e., as will apply during relativity experiments), the plasma error *after calibration* will be

[1]The expression "ranging system" is being used generically in this article, and is specifically not meant to imply the more formal DSN "System."

[2]Although this article deals solely with the *radio science* applications of ranging data, it is considered entirely likely that the methodology being here proposed is equally valid in the case of the *navigational* applications of ranging data.

significantly larger than 10 centimeters! Should this prove true, further consideration of a 2- to 10-centimeter ranging system (at least for relativity experiments) would have to be considered as unrealistic.

In the following sections, this article will attempt to define the "end-to-end radio science ranging system," and will explore how such a system description and analysis provides the proper framework for the levying of cost effective and justifiable requirements on both the flight projects and the DSN.

II. The End-to-End Radio Science Ranging System

The end-to-end radio science ranging system is schematically illustrated in Fig. 1. Ranging signals which have been modulated onto a carrier are transmitted from the DSS to the spacecraft, are transponded and retransmitted by the spacecraft, and are received by the DSS, where the range delay information is extracted. During this operation, the ranging signals pass through various interactive media, including the troposphere, ionosphere, and solar wind, which all induce additional and either partially or wholly unknown range delays in the signals. The ranging data are passed from the DSS to the Orbit Determination Program (ODP), along with DSS calibrations consisting of antenna structure measurements and ranging system internal (electrical) delay measurements. In the ODP, both the DSS and spacecraft calibrations (made prior to launch) are applied to the data. In the case of relativity and celestial mechanical experiments, the data are directly referenced to the spacecraft ephemeris, the accuracy of which is determined by the various ODP internal models. An additional error source is the spacecraft unmodeled (or nongravitational) forces. One is now in a position to identify the major elements of the end-to-end radio science ranging system, as follows:

(1) DSS ranging system hardware

(2) Spacecraft Radio Subsystem hardware

(3) Unmodeled spacecraft forces

(4) Interactive media, including

  (a) Troposphere

  (b) Ionosphere

  (c) Solar Wind

(5) DSS antenna structure measurements

(6) DSS internal range delay calibrations

(7) Spacecraft calibrations

(8) Orbit Determination Program, including

  (a) Heliocentric Cruise Models

  (b) Planetary Orbiter Models

  (c) Planetary Lander Models

III. Development of a Radio Science Ranging Error Hierarchy

With the identification of the major elements of the end-to-end radio science ranging system, one wishes to assess the current or projected performance of each element, with the goal being the ranking of the error contributions from largest to smallest. Obviously, it would hardly be cost-effective to levy a performance requirement on a given element which is more stringent than an "inherent" limitation of one or more of the other system elements (unless such a requirement can be levied with little attendant impact on resources). To illustrate with the example of Section I, if there exists an "inherent" plasma limitation of approximately 1 meter, it surely makes little sense to levy the exceedingly difficult requirement of 10-centimeter accuracy on the DSS ranging (hardware) system. What is not generally recognized is that certain of the ranging system elements are variable with regard to:

(1) The *type* of radio science experiment being considered

(2) The DSN and spacecraft *configuration*

and that these elements are in no way directly related to the DSS and spacecraft hardware performance! Further, it is here suggested that these "other" elements are frequently the dominant error sources in radio science ranging experiments.

One can first consider the case of (uncalibrated) plasma errors. Although both single- and dual-frequency plasma range measurements themselves constitute a prime radio science experiment (solar corona/solar wind), plasma becomes a difficult "error" for all other radio science ranging experiments. Although some celestial mechanics experiments may be fortunate in that they are capable of being performed at large Sun-Earth-probe (SEP) angles (i.e., minimum plasma conditions), radio science *relativity* ranging experiments must always be performed under conditions of very dense plasma. For instance, a very preliminary estimate of the plasma "error" during the 1976 Viking ranging relativity experiment is a ranging data noise of about $1\sigma \approx 15$ meters (Ref. 1), over a time scale of several months. The important point here is that this error contribution is a direct function of the (frequency band) configuration of the DSN and spacecraft. Should the S-band uplink be replaced with X-band, one would expect this error source to immediately drop from the 15-meter level to about 1 meter, due simply to the inverse frequency squared plasma dependence. If simultaneous dual-frequency (uplink and downlink) capability is achieved, this improvement could be expected to be even better.

The Orbit Determination Program (ODP) provides a good example as to how the type (or phase) of a mission directly influences the total end-to-end radio science ranging system performance. It is considered that the ODP modeling of planetary landers has the smallest error, followed by planetary orbiters, and, finally, the worst case, heliocentric cruise. Unfortunately, ODP performance numbers for the three mission phases over the several month time scales of interest are not well known. At any rate, one could generate a *hypothetical* ranging system error hierarchy by making some guesses as to the relative size of the ranging error contribution of plasma, ODP, unmodeled forces, etc. The point of the exercise is to underscore the need to consider the type of the radio science experiment, the DSN and spacecraft frequency band configuration, and spacecraft unmodeled forces, long before one attempts to levy the appropriate requirements on the DSN and spacecraft ranging system hardware performance. Let one *assume* the following error sources (time scales of several months):

(1) Plasma	
(a) S-Band Uplink	15 meters
(b) X-Band Uplink	1 meter
(2) Orbit Determination Program	
(a) Heliocentric Cruise	30 meters
(b) Planetary Orbiter	10 meters
(c) Planetary Lander	3 meters
(3) Unmodeled S/C forces	
(a) Heliocentric Cruise	20 meters
(b) Planetary Orbiter	20 meters
(4) DSS ranging hardware	5 meters
(5) Spacecraft ranging hardware	0.5 meters

The error hierarchy for these assumptions is presented as a function of mission type and frequency band configuration in Fig. 2. The important point of Fig. 2 is that the dominant ranging system errors vary greatly as a function of the mission type or phase and the DSN-spacecraft frequency band configuration, and these are parameters not generally addressed in the generation of radio science ranging requirements.

As an example of the type of decision which might emerge after an end-to-end system error hierarchy is constructed, consider the case of the hypothetical planetary lander of Fig. 2. Normally, if one wanted to achieve a substantial increase in ranging accuracy, one would straightforwardly consider implementing a new generation of DSS ranging hardware. In this particular case, however, it would appear far more cost-effective to stay with the current DSS ranging hardware and implement X-band uplink capability instead.

Celestial mechanics ranging experiments would require a similarly complex error hierarchy. On the other hand, (dual-frequency) plasma experiments are much simpler in that they do not depend on the ODP (models), the uplink frequency band, or spacecraft unmodeled forces. Obviously, the end-to-end ranging system for this type of radio science ranging experiment is vastly simpler, and the appropriate requirements are expected to be generated with far less difficulty.

IV. Performance Validation

As was already mentioned, the only performance of vital interest to the radio science experimenter is the total data accuracy and noise of the final (ODP) processed data. This is the end-to-end system product, and examination and evaluation of such (actual in-flight) data can represent the only true measure of how well radio science ranging requirements are being met. It is true, of course, that individual elements can be tested in stand-alone (DSS hardware) or laboratory (spacecraft hardware) environments, or possibly via simulation (ODP software); however, final processed in-flight data over time scales of several months must be considered the final standard by which the success in meeting radio science ranging requirements for relativity and celestial mechanics experiments is gauged.

Dual-frequency downlink plasma experiments are an entirely different case, however; here the major determinant of accuracy is the DSS hardware and calibrations, and these can be routinely validated for time scales under 12 hours via the dual-frequency equivalent of the "pseudo-DRVID" scheme (Ref. 2). In this approach differenced dual-frequency range measurements are compared to (integrated) dual-frequency doppler measurements. Also, single-frequency range measurements can be used in the same fashion to check a subset of the end-to-end radio science ranging system elements (DSS and spacecraft hardware, DSS calibrations) over time scales of less than 12 hours.

One finally concludes that the only pertinent tests of the end-to-end ranging system for the relativity and celestial mechanics experiments are:

evaluation of processed in-flight data

and for dual-frequency downlink plasma experiments:

dual-frequency pseudo-DRVID

V. Summary

Radio science ranging requirements negotiated between past and present flight projects and the DSN have generally focused on just the DSS and spacecraft hardware. All elements in the end-to-end system must be analyzed and considered in terms of the error hierarchy before reasonable and cost-effective requirements can be levied upon any individual element. Quite important to this process are plasma and ODP software considerations, which are shown to be especially complex in that their performance level depends on the type of radio science experiment to be performed and the DSN-spacecraft configuration. Finally, it is noted that while laboratory or stand-alone type tests of individual elements may be possible and useful in an interim sense, the final validation of radio science ranging system performance can only be achieved via evaluation of the final processed in-flight radio science ranging data themselves.

References

1. Anderson, J. D., private communication (meeting, June 7, 1978).
2. Berman, A. L., "Pseudo-DRVID: A New Technique for Near-Real-Time Validation of Ranging System Data," in *The Deep Space Network Progress Report 42-29,* pp. 180-187, Jet Propulsion Laboratory, Pasadena, Calif., Oct. 15, 1975.
3. Berman, A. L., "Phase Fluctuation Spectra: New Radio Science Information to Become Available in the DSN Tracking System Mark III-77," in *The Deep Space Network Progress Report 42-40,* pp. 134-140, Jet Propulsion Laboratory, Pasadena, Calif., Aug. 15, 1977.
4. Berman, A. L., "A Telecommunications 'Design Table' for The Solar Corona," IOM ALB-77-63, Sept. 21, 1977 (JPL internal document).

Appendix

Inherent Ranging Accuracy Limitations Under Conditions of Dense Plasma

One would like to know what the residual (i.e., uncalibrated) plasma errors might be when X-band uplink capability is achieved. Two very preliminary methods of calculating the expected error for near sun ranging both yield errors at about the 1-meter level. The calculations are described below.

A. X-Band Uplink; S- and X-Band Downlink

The simplest method of producing plasma corrections when dual-frequency downlink is available is to "double" the downlink dual-frequency (differenced) range. Assuming that the range delay is induced at the signal path closest approach point and given a signal Round-Trip-Light-Time (RTLT) and closest approach distance, one can use the Solar Wind Phase Fluctuation Spectrum (Ref. 3) to deduce the expected range error. Assuming an RTLT of 4000 seconds (which yields approximately 3000 seconds as the time between uplink and downlink closest approach) and a closest approach distance of 10 solar radii, one expects a range error of about 20 meters at S-band. To translate this error to X-band uplink, one simply scales by the square of the ratio of S-band to X-band (3/11), which immediately yields an "inherent" plasma limitation for near sun ranging with X-band uplink of approximately 1.5 meters.

B. Simultaneous S- and X-Band Uplink and Downlink

Theoretically, round-trip dual-frequency range measurements should provide "perfect" plasma calibrations. Unfortunately, the X-band uplink being implemented is in a slightly different ratio to the S-band uplink than is the X-band downlink as compared to S-band downlink (i.e., the spacecraft S- and X-band turnaround ratios will be slightly different). This effect will cause an error in the *round trip* plasma measurement of perhaps 1 to 10 percent. Again assuming a closest approach distance of 10 solar radii, one has (Ref. 4) an S-band plasma delay of 1200 meters, or, scaling to X-band, 90 meters. If one optimistically assumes that the round-trip plasma measurement is good to 1 percent, one is still left with an error of approximately 0.9 meter for near sun ranging with simultaneous S- and X-band on both uplink and downlink.

In conclusion, even assuming the 1980s implementation of X-band uplink, it is difficult to see that near Sun ranging (as is required by relativity experiments) can be achieved beyond about the 1-meter accuracy level.

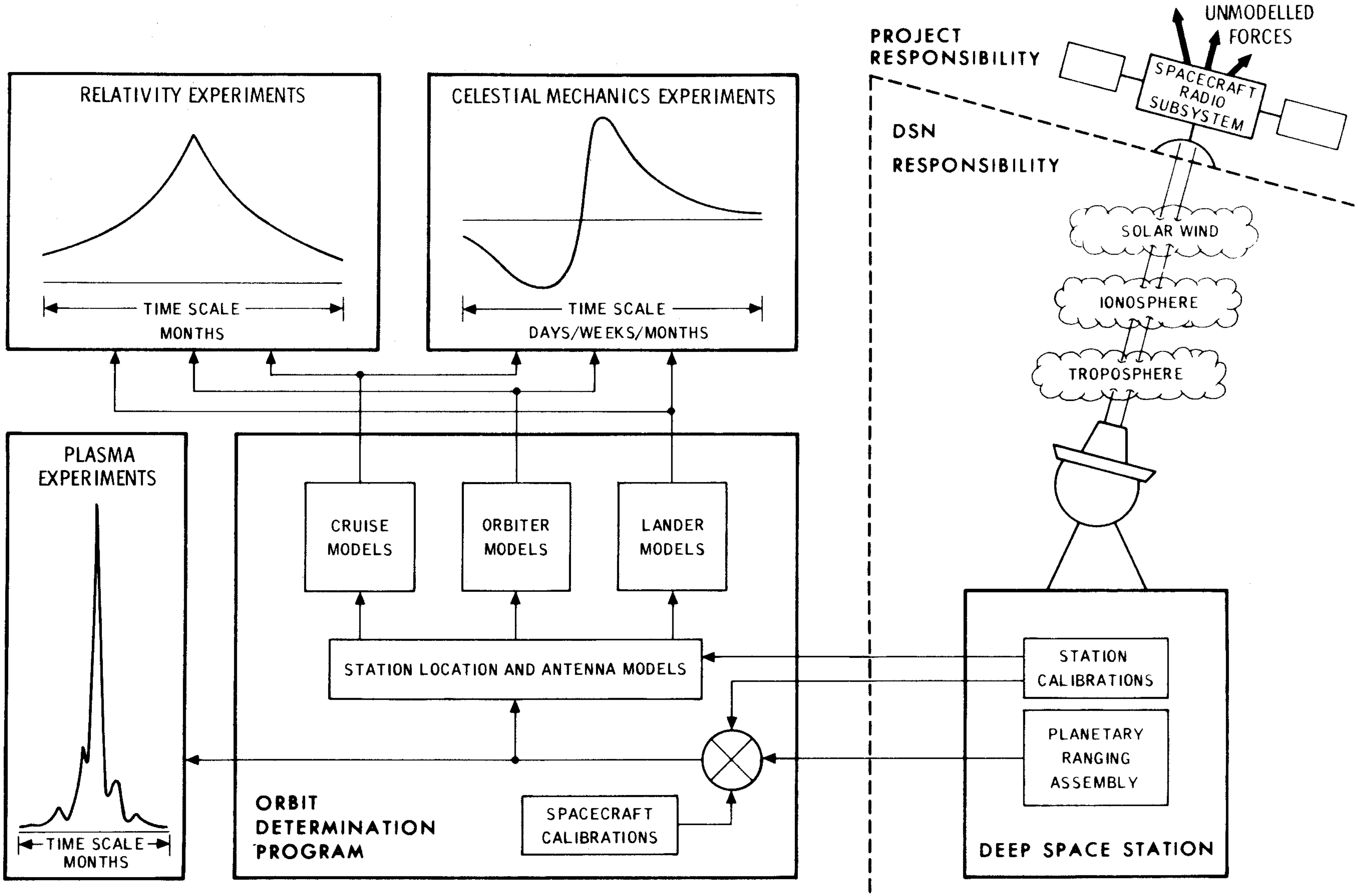

Fig. 1. The end-to-end radio science ranging system

MISSION PHASE OR TYPE

FREQUENCY BAND CAPABILITY (TWO-WAY)	HELIOCENTRIC CRUISE	PLANETARY ORBITER	PLANETARY LANDER
S-BAND	• ODP (30M) • UNMODELLED FORCES (20M) • PLASMA (15M) • DSN H/W (5M) • S/C H/W (.5M) TOTAL RSS ERROR = 39M	• UNMODELLED FORCES (20M) • PLASMA (15M) • ODP (10M) • DSN H/W (5M) • S/C H/W (.5M) TOTAL RSS ERROR = 27M	• PLASMA (15M) • DSN H/W (5M) • ODP (3M) • S/C H/W (.5M) TOTAL RSS ERROR = 16M
X-BAND	• ODP (30M) • UNMODELLED FORCES (20M) • DSN H/W (5M) • PLASMA (1M) • S/C H/W (.5M) TOTAL RSS ERROR = 36M	• UNMODELLED FORCES (20M) • ODP (10M) • DSN H/W (5M) • PLASMA (1M) • S/C H/W (.5M) TOTAL RSS ERROR = 23M	• DSN H/W (5M) • ODP (3M) • PLASMA (1M) • S/C H/W (.5M) TOTAL RSS ERROR = 6 M

Fig. 2. Hypothetical error matrix for a radio science relativity experiment