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IMPROVED RANGING SYSTEMS

LARRY E. YOUNG
Jet Propulsion Laboratory

JJ574450

I. INTRODUCTION

Spacecraft range measurements have provided the most accurate tests, to date, of some relativistic gravitational parameters, even though the measurements were made with ranging systems having error budgets of about 10 meters (in *Relativistic Gravitation*). The thesis of this paper is that technology is now available to allow an improvement of two orders of magnitude in the accuracy of spacecraft ranging. The largest gains in accuracy result from the replacement of unstable analog components with high-speed digital circuits having precisely known delays and phase shifts.

II. ERROR SOURCES

Ranging instrumentation consists of a ground site transmitter, a spacecraft transponder (which receives the uplink ranging signal and coherently transmits a downlink), and a ground receiver which determines the time interval between uplink transmission and downlink reception. The time interval consists of the round trip, (vacuum) light travel time plus instrumental and media delays. The estimated magnitudes of some important error sources for the current ranging system, as well as for the proposed future system, are shown in the table below.

TABLE 1

ESTIMATED MAGNITUDES OF ERROR SOURCES

ERROR SOURCE	TODAY (TYPICAL)	FUTURE (+10 YEAR)
S/C Transponder Delay Change	500 cm	3 cm
Interplanetary Plasma	100 cm (X Up, S/X Down)	1 cm (Dual Up/Down)
Ionosphere	100 cm (4 cm IF GPS ION CAL)	1 cm (Dual Freq)
Tropospheric Delay	12 cm	0.5 cm
Antenna Multipath (SC and Ground)	50 cm	1 cm
Antenna Microwave Delay	30 cm	3 cm
GND Ranging Instrument (Random + Systematic)	100 cm	1 cm
Ground Frequency Standard	3 cm (5×10^{-15} Over 6 Hr)	<1 cm
Sta. Loc. & Earth Orient.	30 cm	3 cm
RSS of 2 Way Range Errors	533 cm	6 cm

III. REDUCTIONS OF ERROR IN FUTURE SYSTEMS

The above errors result from measuring and mapping media delays and from instrumental errors. The plasma mapping errors can be greatly reduced through the use of dual frequency transmissions for both uplink and downlink signals. Techniques have been suggested to reduce the tropospheric delay errors to the sub-cm level (Treuhaft 1988). Adequate improvements in the calibration accuracy for effects such as antenna delay and multipath, station coordinates, and earth orientation, are being developed to satisfy the requirements of VLBI and GPS measurements.

The dominant error sources in today's systems are instrumental. The largest contribution is the spacecraft transponder, which is difficult to calibrate after launch. Transponders have delay variations due to aging, temperature changes, radiation, signal amplitude changes, etc., that are a few per cent of the total analog delays. For the delay of 1 microsecond typical of a 1 MHz bandpass, delay variations of tens of nanoseconds result.

It would be possible to devise methods for in-flight calibration of the transponder delay, but the preferred solution is to directly reduce the error by developing a new digital transponder with a total analog delay of only a few nanoseconds. The key to this approach is high rate sampling of the broad band (~500 MHz) received signal, after minimal broad band analog processing (pre-amplification and bandpass filtering). All subsequent operations performed on the ranging and Doppler signals are digital, i.e., the outputs are uniquely determined by the inputs. The time delay of the digital operations depends only on the stability of the local frequency standard, and varies by less than 1 cm for typical spacecraft frequency standards.

Several advantages are obtained by using a digital design for transponders and for ground site transmitter/receivers. Some of these are listed below.

(1) The responses of digital circuit elements, such as filters, are exactly known, and not dependant on temperature, etc., (assumes the circuit remains purely "digital").

(2) Greater system design flexibility is allowed. For example, if two planetary landers are in the beam of the same earth antenna, their transponders could individually track the uplink range code (and carrier), and generate downlinks with orthogonal (between landers) "reconstructed" range codes coherent with the uplink signal received at each lander. The digital ground receiver would simultaneously track the two downlink signals to provide accurate differential Doppler and range measurements.

(3) Digital implementations allow improvements in power consumption, size, and reliability.

(4) Greater algorithmic flexibility is possible, as more operations and functions are available to the digital designer.

IV. CONCLUSION

It is now possible to design a spacecraft ranging system with anticipated measurement errors under 10 cm. The digital technology to track multiple ranging signals with cm-level accuracy has been demonstrated in the ROGUE GPS receiver. Development of custom GaAs chips to allow direct sampling of RF signals with 500 MHz bandwidth, followed by digital signal processing, is in process at JPL. The implementation of a 10 cm ranging system will probably not occur, however, until required for navigation. The utility of 10 cm range measurements for navigation is currently being studied at JPL. Potentially attractive navigation applications of accurate range include synergistic combinations of range and VLBI measurements. This combined data type could be applied, for example, to the relative navigation needed between a Mars rover and ascent vehicle, or to the determination of pre-encounter trajectory perturbations which would be used to pin down the target planet's ephemeris (grav-nav). Should the results of these studies indicate that 10 cm range data are valuable to navigation, components of improved range measurement systems could be installed on future spacecraft and at tracking sites, enabling more precise measurements of parameters used to test predictions of relativistic gravitational theories.

REFERENCES

September 1987, *Relativistic Gravitation: NASA's Present and Future Programs.*
Treuhaft, R. 1988, *"Tropospheric Monitoring Technology,"* these Proceedings.

DISCUSSION

SHAPIRO: Are there any firm plans (i.e., funds allocated and people assigned) for implementation of a 10 cm ranging system?

YOUNG: There is no current plan to implement 10 cm range measurements. A highly digital receiver will, however, be implemented by the mid 1990's. If studies on the navigation utility of 10 cm ranging have a positive result, that capability could be included in the revised receiver.