On Improved Ranging – II

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This is the second in a series of articles intended to develop a road map for future developments in two-way range instrumentation. In the first article, we presented a rationale and experimental evidence for improvements to ranging which seem to be achievable through reasonably minor changes to the tracking station. In this article, we develop a heuristic overview of the principal systematic error sources for ranging, and some of the remedies for them. Our principal recommendations are for wider system and range-code bandwidths, and for simplification of the precision-defining form of the range code.

I. Introduction

This is the second in a series of articles intended to develop a road map for future developments in two-way range instrumentation. In the first article (Ref. 1), we presented a rationale and experimental evidence for improvements to ranging which seem to be achievable through reasonably minor changes to the tracking station. In this article, we develop a heuristic overview of the principal systematic error sources for ranging, and some of the remedies for them. As far as we can see now, it appears that both wider system bandwidth and real-time calibration are needed to achieve ranging accuracy at a few decimeters.

II. A Heuristic Review of Ranging Errors

Interpreting the influence of range code bandwidth on thermal noise errors can be done by analysis of simple problems with exact solutions. In the final analysis, systematic effects seem to almost always provide the limits for range system accuracy, and it seems painfully difficult to achieve more than a subjective understanding of these limiting errors. We are in the somewhat awkward position of developing approximate solutions for approximate problems, in order to compare the impact of various configuration options for future ranging machines. Only when a specific option is selected for detailed design, sensitivity analysis, and eventual testing, will some of this inexactness disappear.

Table 1 is a matrix description of the principal errors contributed to the ranging system by the ground instrumentation. The various ranging machines considered include the present configuration with the 0.5 MHz code with or without minor improvements, and alternative configurations with range codes of 1 MHz and 8 MHz, both with and without real-time calibration. All of these codes can be generated by the MU-II R&D ranging machine. The block diagram for real-time calibration of the range machine will be presented later.

Systematic errors which limit the current ranging system's accuracy appear to be dominated by harmonic distortion errors which may be 7-10 ns (or perhaps more) with the conventional 500 KHz code. Most other known error sources should be smaller, but should not be considered negligible. A part of the term we have labeled harmonic distortion is in fact due to mismatch between the algorithm used to compute range delay from the code correlations, and the waveform which we know is received. When taken through the transponder, the received waveform consists of a fundamental plus (somewhat attenuated) third harmonic. An algorithm which matches the true shape of this received waveform greatly reduces this error source, but is highly sensitive to minor changes in the relative amplitudes of the fundamental and its harmonic. This persistent error should be at the level of 3-7 ns when the algorithm is a good match to the median waveform.

We can further reduce the harmonic distortion error by filtering the waveform received at the tracking station to its fundamental component only. This eliminates the algorithm mismatch for the waveform, but leaves the harmonic interactions within the transponder's range code detector and mixer operative. The remnant error is estimated to be at the 2-3 ns level.

Leaving the transponder alone and increasing the range code to 1 MHz significantly reduces the harmonic distortion error because now only the fundamental term of the range code is present at the transponder modulator, the third harmonic being sheared away in the ranging channel filter. The distortion error is believed to be on the order of 0.5 ns or less. Further increases in the range code frequency must be accompanied by transponder bandwidth increases, as well as bandwidth increases in the tracking station transmitting equipment. With a code frequency of 8 MHz, the harmonic distortion term should be much less than 0.1 ns.

Multipath effects in the antenna have been found to contribute a 2-3 ns error for the 500 KHz code (Ref. 2). Due to the exact numerology of the bounce-lengths involved, this error will not be noticeably reduced by using the 1 MHz code, but is reduced to on the order of 0.3 ns by the 8 MHz code. Because of its position in the receiving system, attempting to calibrate the multipath effects could create more error through near-field effects in the antenna.

Multipath effects in cables combine with environmentally induced drifts in the cable electrical length to offer potential for significant errors. If the cable VSWR becomes as large as its specifications allow (VSWR = 1.5:1), the group delay error induced could be on the order of 30 ns, which would explain some of the larger errors encountered in the TDL tests (Ref. 1). On the other hand, the typical VSWR is believed to be far below the specified limit, making the typical error on the order of 1-2 ns for either the 500 KHz, or 1 MHz codes. The 8 MHz code is a large enough fraction of the center frequency of the modulated IF signal, so that the error is now dominated by direct electrical length changes of the cables. With both the direct cable length variation and the VSWR, induced errors are subject to measurement and calibration, and could reasonably be reduced to 0.1 ns by this means.

Sideband folding effects errors at the spacecraft transponder only when there is imbalance in both amplitude and phase shift in the ranging signal as transmitted. This imbalance results from filtering by the transmitter bandpass. It is an error only because the transponder coherently detects the signal, folding its sidebands together, while the zero-delay device and test translator do not. The estimates of its magnitude are based on a numerical example calculated for an assumed transmitter (Klystron) 4-pole 5-7 MHz passband (Ref. 3) and an assumed receiver 6-pole 30 MHz passband (Ref. 4). For the 500 KHz range code, the sideband folding induces a probable error of 0.2 ns. For the 1 MHz code this increases to 0.5 ns, because the sidebands are closer to the band-edges of the klystron. This error would increase to 5 ns with the 8 MHz code if enough of it would pass through the klystron filter to be measurable. As new uplink equipment is needed to use this wider code bandwidth, we assume that it will induce errors of 0.2 ns or less. Real-time calibration could determine the amplitude and phase of the uplink range modulation, and hence remove at least half of the error induced by the imbalance.

Realistic devices in a digital demodulator effect phase ripples of around 0.01 rn peak-peak in the ranging modulation (Ref. 5). For the 500 KHz code, such ripples correspond to induced errors of roughly 2 ns. This delay-estimate error is inversely proportional to the ranging frequency, so it is reduced to roughly 1 ns for the 1 MHz code and 0.1 ns for the 8 MHz code.

The code generator is one element of the group delay circuit for which drift in characteristics causes a strictly delay-like error independent of the code frequency used. We tentatively guesstimate this error at 0.2 ns, or 10% of a typical ECL gate delay. It could, in fact, be much larger, depending upon details of the implementation. Delays of this magnitude are of little or no concern with the 500 KHz or 1 MHz code frequencies. They become significant when higher code frequencies are considered, and must be carefully considered when the code generator is designed for a new higher accuracy range machine.

Taken together, these error sources aggregate to limit the precision of the present system to roughly 8-12 ns, but there is some potential of significantly larger errors due to cable drifts and VSWR. Nominal precision can be improved by 5-8 ns by changing the ranging software to model the waveform passed by the transponder. Inserting a narrowband filter into the IF ranging signal path, so that only the fundamental component of the range code is detected, will further improve nominal precision to around 5 ns. There is no degradation relative to SNR from this filtering (Ref. 6).

Further improvements require more extensive changes to the range machine. A 1 MHz code is filtered by the transponder itself to the fundamental term only. With further filtering on the ground to scrub off harmonic distortions, the resultant precision should be on the order of 3 ns or better. The 1 MHz code has also been shown to have substantial immunity to anomalous equipment-induced errors which may be substantially larger than those we have been able to rationalize with nominal instrument behavior (Ref. 1). Addition of the real-time calibration mechanism improves the apparent precision to 2.3 ns, which seems an inadequate return for a great deal of complexity.

Higher code frequencies require an extensive rebuild of the ranging instrumentation. To use an 8 MHz code, for example, the transponder (one-sided) bandwidth should increase to 12 MHz, and the ground transmitter klystron bandwidth must also be increased. We probably also require use of an X-Band uplink because of frequency-allocation limits at the DSN S-Band uplink frequency. For the wider bandwidth, we achieve a nominal 0.65 ns precision. For the X-Band uplink, in place of the S-Band, we obtain a factor-of-two reduction in the errors inherent in charged particle calibration of range. The dominant error source now is in position to be calibrated out, and a real-time calibration scheme, to be discussed in the next section, should hopefully be able to further improve the nominal instrument precision to 0.4 ns overall.

It should be realized that the precision estimated here for an instrument with higher code frequencies is still only an estimate, and the actual achievable precision will only be known through extensive laboratory measurement and testing. In addition, no allowance has been made for drifts in the transponder itself. Code-detection cleanup on the transponder may be necessary to achieve sub-ns delay stability of range, and a great deal of care in design will be required to restrict errors in the code generator, the demodulator(s), or even the calibrator itself, to a small part of a ns. Any range code in the 5-20 MHz region may be, in fact, wide enough that dominant errors are related to circuit delays, and are not subject to reduction by increased bandwidths. Effective use of such higher code frequencies and achievement of decimeter precision ranging may well require either real-time calibration or careful stabilization of the instrument delays.

III. Real-Time Calibration of Ranging

Figure 1 shows one concept for real-time calibration of the tracking station for ranging. It may not be the best scheme, and is certainly not the only scheme for such calibration.

A VLBI-type phase calibrator (Ref. 7) injects its pulse train into the front end of the DSN receivers to measure their transfer-function and delay. The pulse train is stable and known in time relative the tracking station primary frequency-and-time standard, e.g. an H-Maser. The one receiver carries signals as received from the spacecraft. The second receiver carries a sample of the signal being transmitted to the spacecraft. The output of the calibration detectors attached to these receivers are labeled τ_3 and τ_2, but should in fact be measures of the complex transfer functions for these two receivers. These transfer functions are then inputted to the range code detectors to map their calculations back to the calibrator injection point.

The design of the range code detectors and calibration detectors must permit such mapping to be done without introducing errors which exceed those calibrated out.

The principal worry in doing the real-time calibration as shown is that interaction between the phase-calibrator signals and the ranging signal could prevent adequate measurement of either.

IV. Experimental Corroboration

Our claims with respect to the 1 MHz range code were in large part experimentally confirmed by TDL tests which demonstrated up to an order of magnitude reduction in range instrument biases (Ref. 1). In order to extend this demonstration into the actual spacecraft tracking environment, the R&D MU-II ranging machine has recently been installed at the Australian conjoint stations DSS 42/43 (Ref. 8). This machine is normally being used with its 1 MHz range code, and band-limiting filters in its receive channels.

Preliminary recent results of ranging Voyager 1 spacecraft from DSS 43 with the MU-II show an RMS range residual scatter of 1.7 ns, or about one-quarter of that which typifies the standard DSN range machine at the same signal conditions (Ref. 9). The full results of testing at the Australian conjoint station will be published when available.

V. Recommendations

The recommendations which we can make now are primarily those made earlier (Ref. 1).

Firstly, increase the range code frequency to 1 MHz, processing the received signal for the fundamental component only. No changes to spacecraft transponder, or to uplink transmitter should be needed to achieve a factor of two-to-four improvement in range instrument precision.

For the overall ranging system, it is not the instrument, but charged particles in the signal path that induce the dominant errors. Replace the S-Band uplink with X-Band to reduce the after-calibration (S/X downlink) delay error by a factor-of-two, and to reduce the dynamic charged particle errors by an order-of-magnitude.

Finally, increase the bandwidth of the uplink, the transponder, and the range machine to accommodate the fundamental component of a 10-20 MHz range code. The X-Band uplink is needed to accommodate this bandwidth, and to avoid or lessen charged particle effects. Either real-time calibration or careful stabilization of the instrument delays seem to be needed to achieve the accuracy potential of this higher code frequency.

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Table 1. Ranging system errors contributed by ground instrumentation

	Harmonic Distortion	Antenna Multipath	Cable Drift & VSWR	Sideband Folding	Demod. Quantizer	Code Generator Delays	RSS	New Equipment Req'd.
Present System	7–10	~2	1–2	0.2	2	0.2	8–12	– – –
Model Distortion	3–7	~2	1–2	0.2	2	0.2	5–8	RS
Fundamental 1/2 MHz	2–3	~2	1–2	0.2	2	0.2	4–5	RS, RH
Fundamental 1 MHz	<0.5	~2	1–2	0.5	1	0.2	3	RS, RH
R/T Calibration at 1 MHz	<0.5	~2	~0.1	0.2?	1	0.2	~2.3	RS, RH, ϕ_c, CR
8 MHz Code New Klystron New Transponder	~0	~0.3	~0.5	~0.2	~0.1	0.2	0.65	RS, RH, XP, XM
R/T Calibration at 8 MHz	~0	~0.3	~0.1	0.1?	~0.1	0.2	0.4	RS, RH, XP, XM, ϕ_c, CR

Equipment Legend: RS = Range Software
RH = Range Hardware
ϕ_c = Phase Calibrator
CR = Calibration Receiver
XP = Transponder
XM = DSS Transmitter

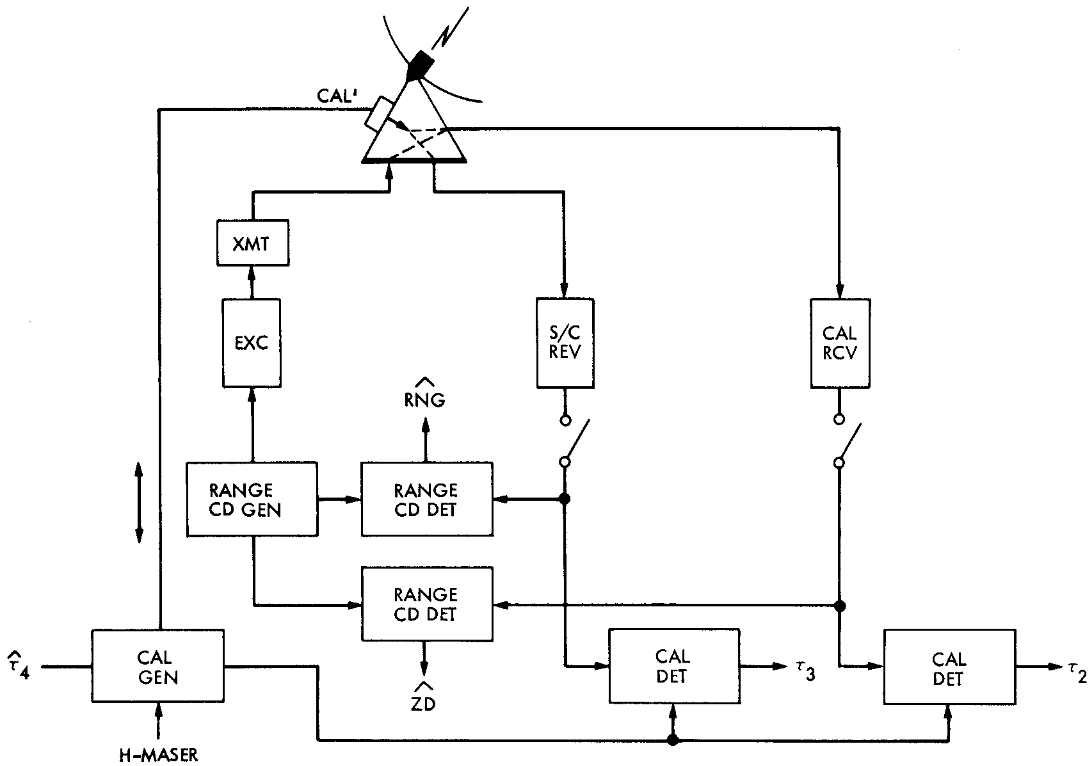

Fig. 1. Real-time calibration of ranging