On Improved Ranging

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The currently deployed ranging systems are subject to a variety of waveform distortion errors and equipment vagaries which limit the accuracy of the range data used for Navigation and Radio Science. In light of this fact, this article presents arguments, both subjective and experimental, for increasing the accuracy of the currently deployed ranging system by the adoption of an approximately 1 MHz sine wave for the precision-defining signal for ranging. Inferences are also drawn for the design of more precise and wider bandwidth ranging systems in the future.

I. Introduction

We have, in recent months, reviewed the instrumental limitations to range measurement accuracy. Two specific objectives were sought: devising cost-effective improvements to the current generation of ranging systems, and establishing guidelines for future ranging system development. Our analysis and supporting experimentation indicate that within the bandwidth constraints of the current, or NASA Standard Transponder, a 1 MHz range code plus appropriate filtering in the ground systems should improve the accuracy achievable to the order of 1 meter (6 ns). In the long term, further improvements to range accuracy can be achieved only by increasing the bandwidth of the entire end-to-end ranging system. Since many elements of a two-way ranging instrument are common with three-way or differential one-way instruments, the information we have obtained should also provide useful guidance to the design of these related systems.

One unexpected result of our work was confirmation of the previously suspected sensitivity of the ranging system to errors caused by changes in Tracking Station equipment configuration. In our current test series, errors induced by changes in the uplink modulator were as large as 11 meters (70 ns). This type of error may be a prime contributor to the ranging system problems currently under investigation by both Viking and Voyager projects.

II. Near-Term Improvements

In the design of precise measurement systems, it is virtually imperative to utilize the entire available bandwidth with signals that are readily detected and processed in a way which directly contributes to improving the accuracy of the measurements. This is not done in the current ranging systems, in which both the fundamental and third harmonic of the precision-defining range code fall within the passband of current transponders. While the third harmonic *could* be processed to enhance ranging accuracy, this processing is not done, nor is it readily implemented. With the current range-code detection schemes, the third harmonic contributes nothing to measurement precision, and could be removed by filtering (Ref. 1). Its principal function in the current system has been to allow a numerically simple conversion from range-code correlations to estimated range. In actuality, the presence of the third harmonic creates the opportunity for severe distortion errors to arise, so that its removal would improve accuracy, though not precision. Phase-shift and filter effects vary between stations and between transponders, to cause configuration-dependent bias errors and waveform distortion effects which are the limiting error sources of the current system.

Let us suppose that the received ranging waveform consists of the fundamental and third harmonic from a square-wave. As noted above, we have previously shown that simply throwing away the third harmonic does not degrade the precision of the range delay estimate with respect to thermal noise. However, aside from ambiguities, it is easy to show that a range delay estimate can be constructed using this third harmonic alone which has exactly the same precision as the delay estimate derived from the fundamental component. Since the fundamental can resolve the three-fold ambiguities of the third harmonic, and since their thermal noise errors are independent, the two delay estimates could be combined to effect a $\sqrt{2}$ improvement in precision over either one alone.

If, however, the transponder in question can pass the third harmonic of the conventional 500 KHz range code with little attenuation, it can also pass the fundamental of a 1 MHz range code with little or no attenuation. Doubling the range-code frequency provides a direct factor-of-two improvement in delay-estimate precision with respect to the conventional 500 kHz range code as conventionally processed. It also provides a $\sqrt{2}$ improvement in delay-estimate precision over the best processing for the conventional range code. As the third harmonic of the 1 MHz code now does not pass through the transponder, further improvements require first increased transponder bandwidths, and subsequently increased bandwidth throughout the system.

There is an additional advantage to the 1 MHz code which results because none of the code harmonics pass through the transponder. Professor L. Rauch has recently pointed out (Ref. 2) that nonlinear elements such as exist in the transponder's modulator and power amplifiers can induce phase-shifts in the fundamental component of a waveform which depend upon the phase of the harmonics entering the nonlinear element. With all harmonics removed from the range code prior to such nonlinearities, delay errors induced by the harmonics should be minimized. We anticipate that use of the 1 MHz range code, coupled with filters in the ground receiving system which pass only the fundamental of this code, will greatly reduce sensitivity to DSN equipment variations which manifest themselves in changes in the harmonic structure of the waveform.

Knowing that the third harmonic of the conventional 500 kHz range code is passed by the transponders, it has been suggested that a range code of that frequency be used to gain an additional factor-of-1.5 increase in range precision. This gain is unlikely to be achieved for two reasons: First, the third harmonic is attenuated by 3 dB in several of the present physical transponders, and second the 1.5 MHz signal is now close to the transponder filter band-edge and thus more subject to phase-shifts due to environmental changes in the transponder.

It is worth noting here that if a PN range code were used instead of square-wave, only those spectral lines below the first zero of the spectrum are at a phase which helps improve signal delay resolution, while those between the first and second spectral null (may) degrade resolution. This is exactly analogous to the behavior of a square-wave as discussed above, where the third harmonic, falling between the first and second spectral nulls, is nonbeneficial in resolving range delay with a correlation-type estimator. When we earlier asked (Ref. 3) for the best unit-power waveform to be tracked by a delay-locked loop in terms of residual phase jitter, the answer was almost identical to a PN which had been filtered to include only the frequency region below the first spectral null. The length of that PN depended upon the SNR that was to be achieved by the delay-lock tracker, which effected the band-limit constraint for that system.

The PN, however, is a waveform with many spectral components within the main lobe of its spectrum. Any nonlinearities in the ranging circuit will generate cross-modulation terms between these components which coincide with some other component. This creates the potential for waveform distortion effects similar to those we have now, albeit at a lower magnitude. If we keep the waveform spectrally simple, i.e., a sine-wave which occupies nearly the full bandwidth available, the distortion effects induced by nonlinearities can be scrubbed off by filtering at appropriate places within the system.

The conclusion we wish to draw from this can be summarized as follows: To get the best possible results for ranging, the available bandwidth should be completely utilized by those signal components which are most useful. For the near term, a 1 MHz range code will substantially improve the accuracy achievable with current transponders. Our recent test results, to be described next, reinforce this opinion. A future article will discuss other currently limiting error sources, and the anticipated effect of increasing the available ranging bandwidth.

III. Experimental Results

Several experiments were recently conducted to measure the so-called ranging "waveform-distortion" error and test the concepts previously proposed (Ref. 1) as a cure. These experiments utilized the Mu-II Ranging System (Ref. 4) installed at the Telecommunications Development Laboratory (TDL). The first of four groups of experiments determined the precision of the current ranging system. The remaining three experiments measured the improvement in precision gained by (1) filtering all but the fundamental frequency of the 500 kHz range code prior to demodulation, (2) utilizing a 1 MHz range code, and (3) using a 1 MHz range code filtered as in (1).

The results of our investigations indicate that a filtered 1 MHz code (3 above) reduces the waveform distortion to below 1 ns of error. This also increases the ranging system immunity to errors induced by equipment variation in receivers, exciters, and transmitters.

A. The Setup

Figure 1 illustrates the various experiment configurations. The Mu-II Ranging System range code modulated a carrier which was echoed either by a wideband zero-delay device or the proof test model of the MVM'73 transponder. Mu-II Channels 1 and 2 were respectively connected to 10 MHz IF signals from the Block IV and Block III receivers. One of a pair of passband filters was inserted into either the Block IV or Block III to Mu-II IF cable to provide a band-limited received range code. The filter characteristics are shown in Fig. 2 for the "500 kHz" filter and Fig. 3 for the "1 MHz" filter.

B. Experiments and Results

The general test plan consisted of utilizing both the zero delay device and the MVM'73 transponder in conjunction with each of the following four test conditions:

(1) 500 kHz code, unfiltered

(2) 500 kHz code, with filtered IF signal

(3) 1 MHz code, unfiltered

(4) 1 MHz code, with filtered IF signal

The data from tests (1) and (2) or test (3) and (4) were obtained simultaneously by connecting one channel of the Mu-II directly to the Block III (IV) IF signal and inserting a filter in the Block IV (III) IF signal attached to the other channel. Comparison of Block III and Block IV data showed error differences on the order of tenths of nanoseconds. Because differences between the two Mu-II channels were of the same magnitude, the taking of data simultaneously is reasonable and justified by minimizing the test time. It must be noted that Mu-II channel 1 exhibited an unexpected periodic error, which appears as periodic hash on the data graphs displayed below. From extensive testing we infer that this error is due to hysteresis in the channel 1 A/D converter and interaction between the three Mu-II coders. The hysteresis was predicted by Layland (Ref. 5). Coder interaction was discovered experimentally. Because these inseparable errors are small (<1 ns), they will be ignored in this article.

Each of the tests described below involved stepping the local model of the received range code in 7 ns steps over a span of one quarter of the period of the highest frequency code (clock). At each step, the code phase measurement $\hat{\theta}$ is compared to the actual phase θ. The graphs are the error function $\theta - \hat{\theta}$ and are in units of nanoseconds. This is a direct display of the so-called "waveform-distortion" error.

1. 500 kHz code, zero delay device. This configuration is identical to current DSN ranging (Planetary Ranging Assembly – PRA) zero-delay calibrations. Figure 4a is the error function without filtering. The peak-to-peak error is 18.5 ns. A dramatic improvement is shown in Fig. 4b. By adding the "500 kHz filter," the error is reduced to 1.5 ns.

2. 500 kHz code, transponder. The peak-to-peak error in Fig. 5a is about 7.4 ns. This is the error of the unfiltered ranging system. Adding the "500 kHz filter" (Fig. 5b) reduces the error to about 2.1 ns. This is a substantial improvement over the current ranging system.

3. 1 MHz code, zero-delay device. Tests with a 1 MHz range code confirmed the expected improvements. Using the zero-delay device, a peak-to-peak error of 3.9 ns (Fig. 6a). Using the "1 MHz filter" reduced this error to 1.0 ns (Fig. 6b).

4. 1 MHz code, transponder. This final test set further justifies the use of a 1 MHz code and filter. Without the filter (Fig. 7a), the error is 14.2 ns. When the "1 MHz" filter is used, the error (Fig. 7b) is only 0.6 ns.

C. End-To-End Distortion Immunity

The "end-to-end ranging system" includes the ranging machine, exciter, transmitter, receiver, spacecraft transponder, zero delay devices, and all cables, switches, connectors, etc., in the ranging path. Each component in this path is capable of inducing, to varying degrees, range code distortions in both the frequency and time domains. Jumps in DSN station range calibrations and spacecraft range residuals evidence the relative susceptibility of the range system to equipment vagaries.

The exciter modulator is one major source of waveform distortion. Two standard DSN modulators were compared in terms of relative spacecraft delay versus modulation index.

The left side of Fig. 8 shows an almost 70 ns worst-case disparity between modulators. Use of the 1 MHz code and filter reduced this to about 10 ns. A similar modulator measurement was made earlier (Ref. 1) using only the 500 kHz code and "500 kHz filter." The worst-case difference was 10 ns without the filter and 3 ns with it. During the current series of tests, using the 500 kHz code with no filter produced the 70 ns disparity noted earlier. A 30 ns worst-case difference resulted when the "500 kHz filter" was used. These current numbers were easily repeatable to within 1–2 ns during the six-month period while we sought to explain the differences between the 500 kHz results now and in 1975. We now believe that these discrepancies are due to the extensive modification to TDL which occurred between the two test series.

In addition, we strongly suspect that the numbers previously seen correspond only with the behavior of a superbly tended calibration laboratory which TDL was in 1975. Our current measurements follow a period when TDL has been "mothballed" without continuous expert attention, and may in fact be more representative of the ranging system behavior to be expected in the operational DSN tracking stations. The delicate nature of the current range system is obvious. Utilizing a 1 MHz range code and IF filter increases system immunity to equipment variation.

IV. Comments

We have demonstrated that use of a 1 MHz range code and a narrow-passband IF filter can reduce waveform distortion error by a factor of as much as 20. Along with this improvement in ranging precision, ranging accuracy is enhanced by nullifying many errors caused by equipment vagaries. In our opinion, the IF filter and concomitant modification of ranging system software (and in the case of the Planetary Ranging Assembly, hardware) are the most cost-effective way of improving the current generation ranging system.

The lessons we have learned here are also important for the development of the next generation ranging system. Clearly we need to increase the available bandwidth, and as we do, we should occupy that bandwidth almost completely with a sinusoidal ranging tone for precise definition of range.

Acknowledgements

We would like to thank J. Weese for his extraordinary efforts in making and keeping TDL operational for our experiments.

References

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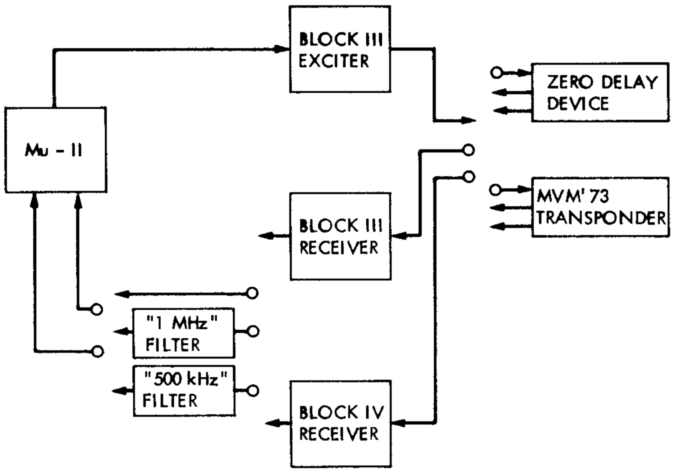

Fig. 1. TDL configuration

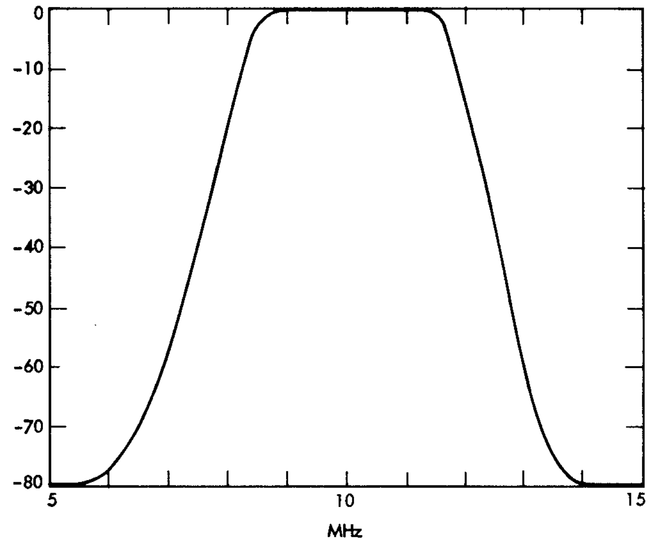

Fig. 3. "1 MHz filter" bandpass

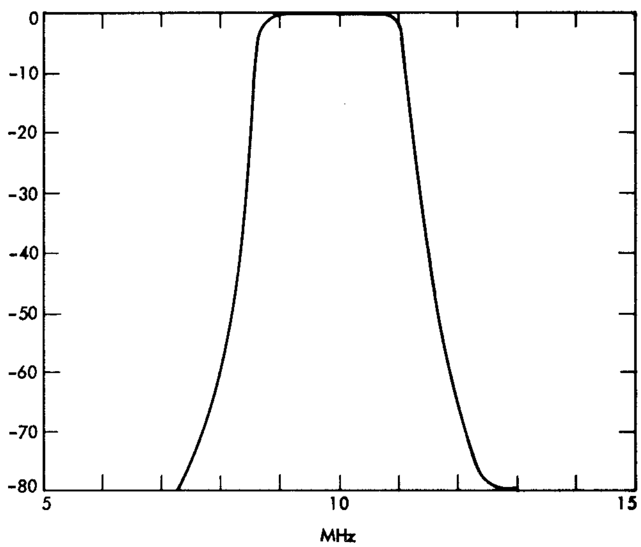

Fig. 2. "500 kHz filter" bandpass

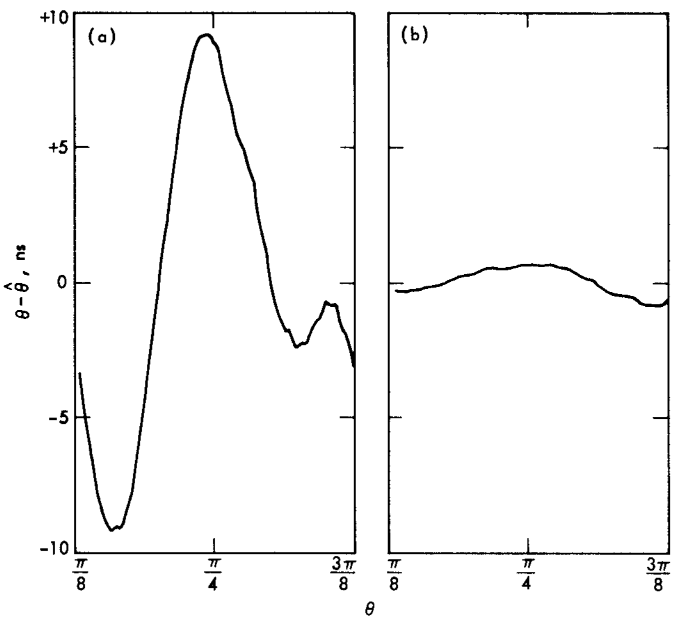

Fig. 4. Phase error—500 kHz code, zero delay device: (a) Unfiltered, (b) 400 kHz filter

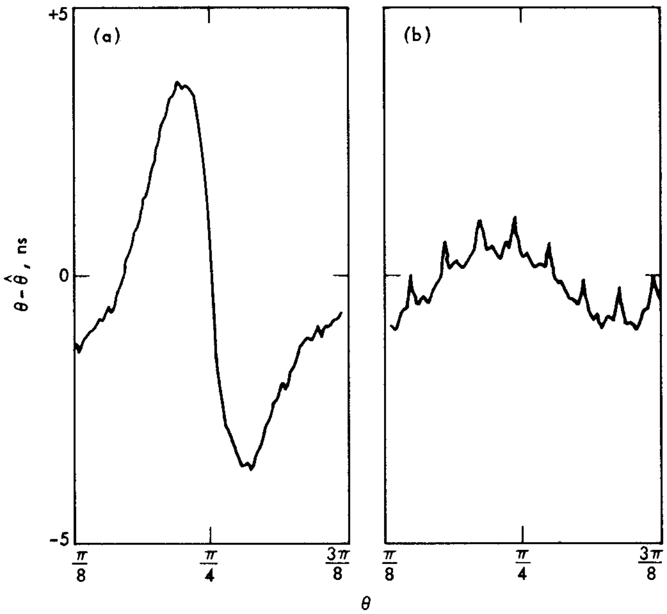

Fig. 5. Phase error—500 kHz code, transponder: (a) Unfiltered, (b) 500 kHz filter

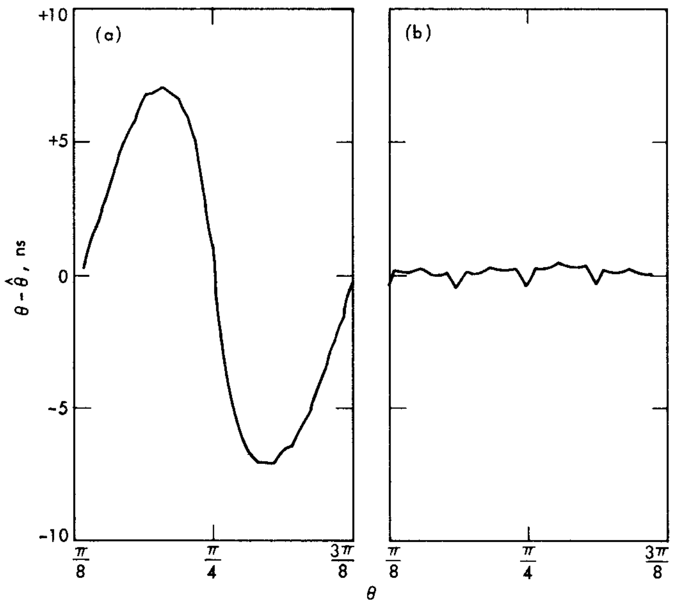

Fig. 7. Phase error—1 MHz code, transponder: (a) Unfiltered, (b) 1 MHz filter

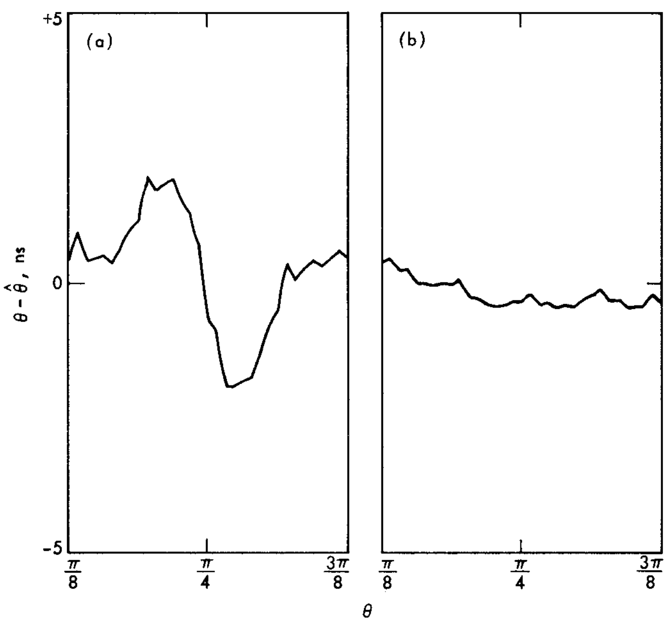

Fig. 6. Phase error—1 MHz code, zero delay device: (a) Unfiltered, (b) 1 MHz filter

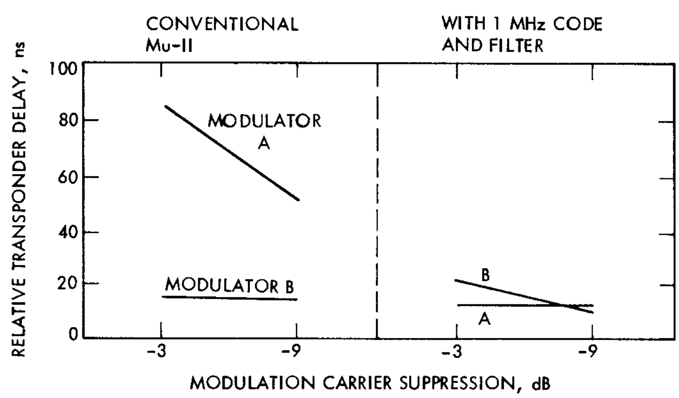

Fig. 8. Range variation caused by modulator change