Planetary Ranging Operational Software

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The Planetary Ranging Operational Program is now in use at DSSs 12, 43, and 63. It provides ranging capability to several AU. The program also monitors changes in the charged particle density due to diurnal variations in Earth's ionosphere and solar outbursts. The charged particle measurement is used to correct the doppler data. Both outputs contribute to the more precise orbit determination required for multiple encounter and orbiter missions.

I. Introduction

The Planetary Ranging Assembly is operational at DSSs 12, 43, 63, and 71, and CTA 21. It was used in support of MVM'73.

Discrete frequency ranging is presently implemented in the software. The algorithms are essentially the same as those used in the research and development (R & D) discrete spectrum (mu) machine, which was used for MM'71 (Refs. 1 and 2). Continuous spectrum (PN code) ranging will be available for Helios using algorithms similar to those in the R & D continuous spectrum (tau) machine (Refs. 3 and 4). Only discrete spectrum ranging is discussed here.

The program produces two data types, range and differenced range versus integrated doppler (DRVID). The range is measured in light time units with a resolution of about 15 centimeters. The maximum range which can be measured without ambiguity varies with the number of components specified, being about 0.5 light second when all 20 components are used.

DRVID, which is monitored throughout the pass, is used for charged particle calibrations. Diurnal variations in Earth's ionosphere cause a variation in indicated spacecraft range of several meters during a pass. While the range error itself is insignificant, its diurnal variation introduces a systematic bias in apparent spacecraft angular position as derived from the doppler, causing significant navigation errors.

The program runs in a dedicated Interdata ID-4 minicomputer. The assembly language program uses most of the 16-kilobyte memory.

Program control is from a hexadecimal keyboard and a 256-character (8 × 32) display panel. The panel displays eight variables, and a short description of each. During initialization the variables displayed include the code type, the integration times, and the acquisition time. The operator updates the list and starts the acquisition.

The initialization parameters are used to build a schedule table containing the time and subroutine address for each event in the acquisition sequence. Events are timed to integer seconds. The time each component is transmitted, reception time (one round-trip light time later), and the time the range number is computed are typical events. The program then counts down to acquisition time. No further manual intervention is necessary.

II. Acquisition Sequence

The discrete frequency coders consist of chains of 20 flip-flops, producing 20 square waves having frequencies between approximately 1 Hz and 500 kHz. All but the highest frequency is used to bi-phase modulate the 500-kHz signal. Each component is then a 500-kHz square wave which is periodically inverted. This process keeps most of the ranging power at high frequencies, minimizing interference with the telemetry and command channels.

Since the received waveform is the same as that transmitted, the ranging phase detector output as a function of phase is the autocorrelation function. The autocorrelation function for the first four components is shown in Fig. 1. Only one of the phase detector outputs (the "in-phase") is shown. The other (quadrature) output is similar, except that it has zero crossings where the in-phase output has peaks.

The general form of the C_3 and higher autocorrelation functions is a triangular wave modulated by a lower-frequency triangular wave. The phase of the high-frequency component is sensitive to small displacements, and is used for DRVID during acquisition. The polarity of the low-frequency component is used for range measurement. The components are transmitted sequentially, starting with the highest frequency, C_1 (the clock).

Before the start of clock reception, both coders are driven by the exciter voltage-controlled oscillator (VCO), and run at the same frequency and phase. Doppler rate aiding is applied to the receiver coder at the start of the next second after predicted clock reception. The range number will be valid for the spacecraft position that existed at the instant the rate aiding was applied.

For a receding spacecraft the receiver coder thereafter runs at a lower frequency, the new frequency exactly matching that of the doppler-shifted ranging signal. The phase relationships between the receiver coder and the received signal remain indefinitely as they were at the instant the doppler rate aiding was switched in, and can be measured leisurely.

The phase detector outputs are integrated over 0.25-second intervals by the hardware. The integrator outputs are digitized with two 8-bit analog-to-digital converters, and an interrupt is generated to the computer.

In order to cancel dc offsets in the analog circuitry, the reference signals to the phase detectors are inverted or exchanged each quarter second. The software decommutates the two inputs, and inverts the previously inverted samples. The resulting A and B outputs, when summed over one second, are free of gain and offset errors. These one-second samples are integrated for the time specified during initialization.

The clock phase is computed from the integrated phase detector outputs using the equation

$$\tau = 512\left(1 - \frac{B}{|A| + |B|}\right)\frac{B}{|B|} \tag{1}$$

where A is the in-phase detector output and B is the quadrature output. The equation produces a number in the range -1024 to 1023 range units, corresponding to -180 to nearly $+180$ degrees in phase.

The clock phase measurement constitutes the low order 11 bits of the range number. The remaining bits depend on the polarity of the other components.

For the C_2 integration, the receiver coder is shifted to place the clock over a positive peak. Figure 1 shows that if the clock is shifted to a positive peak, the C_{2A} component will be at a positive or a negative peak rather than a null, and only channel A polarity need be measured for range acquisition.

The C_2 integration in the example (Fig. 1) produces a negative result. In this case, 2048 or 2^{n+9}, where n is the component number, is subtracted from the range number. Further, in order that the C_3 integration also be on a peak, the receiver coder is shifted by 180 degrees of C_2. This is accomplished by inverting the flip-flop in the divider chain which produces C_2, which advances the receiver coder.

The process is repeated for each additional component C_n: if the channel A output is negative, then 2^{n+9} is subtracted from the range number and that component is inverted in the receiver coder.

This algorithm usually produces a negative range number, which is then evaluated modulo 2^{m+10}, where m is the last component number.

III. DRVID

The doppler rate aiding is only exact for a dispersionless transmission path. Doppler rate aiding is derived from the carrier phase delay, while the phase of the ranging signal depends on the group delay. Changes in the columnar charged-particle density therefore cause a small phase error, which is measured for DRVID.

The program measures DRVID both during and after acquisition. It is apparent that Eq. (1) could be used during acquisition to compute the phase of C_2, as was the case for C_1. Since the period of C_2 is twice that of C_1, the result would have to be doubled to provide DRVID in range units. Different correction factors apply to each component.

A simple numerical calculation shows that the slope of C_2 near 0 deg is ½ that of C_1; C_3 is ¾ that of C_1, and in general

$$M_{c_1} = \frac{2^{n-1}}{2^{n-1}-1} M_{c_n} \tag{2}$$

The channel B output is by definition zero at 0 deg. It is therefore only necessary to multiply by the slope correction factor from Eq. (2) to obtain the corrected B:

$$B' = \frac{2^{n-1}}{2^{n-1}-1} B = B + \frac{B}{2^{n-1}-1}$$

The magnitude of the channel A slope is identical to that of channel B. A geometrical argument leads to:

$$A' = A - \left| \frac{B}{2^{n-1}-1} \right|$$

The resulting A' and B' values are averaged over several components and used with Eq. (1) to compute DRVID during acquisition. The system returns to the clock for DRVID after acquisition, where no correction is required.

The receiver coder is shifted back to the peak whenever it drifts more than 16 range units away, permitting arbitrarily large DRVID excursions to be tracked.

IV. Signal-to-Noise Ratio Estimator

The program provides an estimate of P_r/N_0, the ratio of ranging power to noise power density. The quantity is computed from

$$\frac{P_r}{N_0} = 10 \log_{10} \frac{(|A| + |B|)^2}{\sigma_A^2 + \sigma_B^2} BW$$

The equation is of a different form from that which would be used for sinusoidal signals. The problem is that the total detected power, which is proportional to $A^2 + B^2$, is, for square waves, a function of phase angle. The quantity $(|A| + |B|)^2$ indicates what the detected power would be if the received signal were in phase with the reference, and can be used to estimate P_r/N_0 regardless of phase angle.

BW is the total noise bandwidth. The detection process folds the signal about zero, so the noise bandwidth of the post-detection low-pass filter is doubled to get the RF bandwidth.

The low-pass filtering is mostly due to a single-pole RC network having a time constant of 0.36 second. The digital sampling technique used further reduces the noise bandwidth. The baseband noise bandwidth, considering both analog and digital effects, is 0.51 Hz.

V. Program Outputs

The range number is transmitted to the Mission Control and Computing Center (MCCC) when it becomes available. DRVID and estimated P_r/N_0 are sent periodically throughout the pass. These parameters are also displayed at the DSS Tracking Subsystem (DTS) control panel, along with relative time, correlator outputs, and the component being processed. The displayed parameters can go simultaneously to a teletype if local hard copy is needed.

VI. Summary

Planetary ranging has existed as an R&D effort for several years. New hardware and software have now been installed at selected sites, making ranging to planetary distances a routine operational capability of the DSN.

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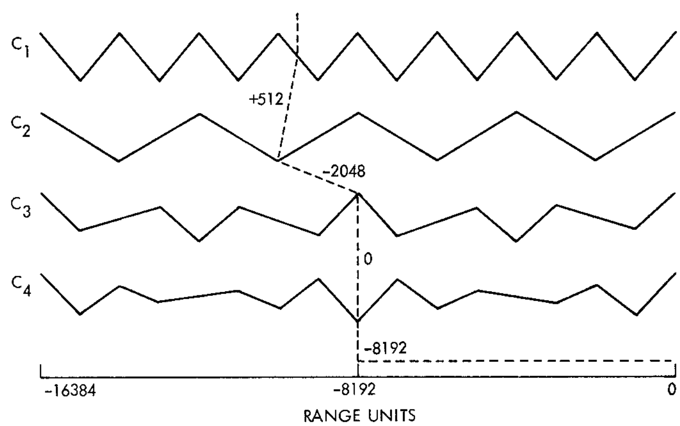

Fig. 1. Acquisition sequence