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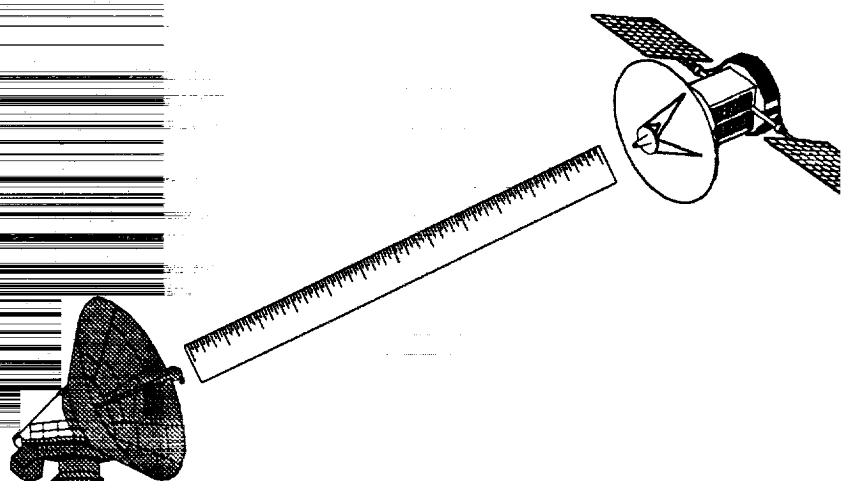
Sequential Ranging — How It Works

Harold W. Baugh



June 15, 1993

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16. Abstract

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The publication also includes an appendix that gives a brief discussion of PN ranging, a capability now under development.

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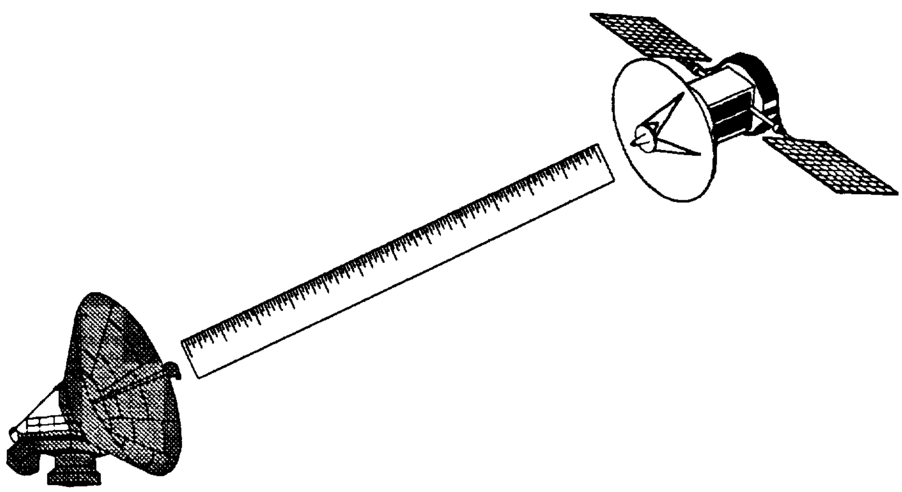

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SEQUENTIAL RANGING -- HOW IT WORKS

ABSTRACT

This publication is directed to the users of data from the Sequential Ranging Assembly (SRA), and to others who have a general interest in range measurements. It covers the hardware, the software, and the processes used in acquiring range data; it does not cover analytical aspects such as the theory of modulation, detection, noise spectral density, and other highly technical subjects. In other words, it covers ***HOW*** ranging is done, but not the details of ***WHY*** it works.

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I. INTRODUCTION.

This paper is directed to the users of data from the Sequential Ranging Assembly (SRA), and to others who have a general interest in ranging. It will cover the processes used in acquiring range data; it will not cover the theory of modulation, detection, noise spectral density, etc. In other words, it will cover the HOW but not the WHY of ranging.

II. GENERAL.

A. **Data**. The Deep Space Net (DSN) handles several types of data during a Spacecraft Track, as shown in Figure 1. The principal types are Command, Telemetry, Doppler, and ranging.

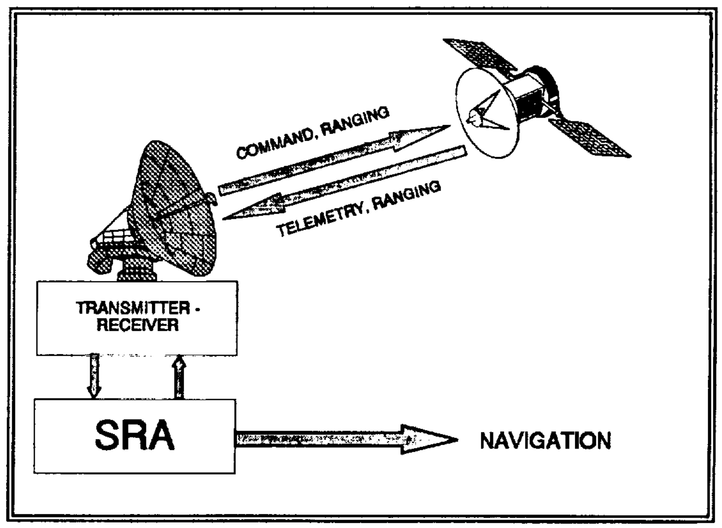

Figure 1 DSN TRACKING

1. Commands. The station sends Commands to a Spacecraft (S/C).

2. Telemetry. Telemetry originates in the S/C; the station demodulates and decodes the information.

3. Doppler. A DSN station derives Doppler data as a byproduct of receiving and tracking a carrier. Doppler data may be 1-way, if the downlink carrier frequency is controlled solely by the S/C, or 2-way, if the downlink carrier is derived from the uplink.

4. Range. The station acquires range data by modulating the uplink carrier with a known digital code, and measuring the time for the code to make the round trip from the station to the S/C and back to the station.

B. **Uses**. The DSN uses commands to control S/C configuration and performance. Telemetry provides engineering and scientific data. S/C projects use Doppler and range data to navigate the S/C, so it can reach a desired target to collect scientific data. The DSN is also used as a science instrument for charged particles in the intervening space.

C. **Requirements**. Ranging can be used when tracking a Spacecraft (S/C) with a ranging channel -- the Voyagers, Galileo, Ulysses, and Mars Observer have them; Magellan and the Pioneers do not. The S/C transponder must use coherent turn-around.[1*] The channel must be commanded ON by mission Operations before the start of the ranging operation. The Metric Data Assembly (MDA)[2] controls the SRA and reports its results.

D. **Signals**. The exciter uses the ranging signal to modulate the uplink carrier. The S/C then demodulates the signal and uses it to modulate the downlink carrier. The ground receiver tracks the downlink, and delivers a 10-Mhz intermediate frequency (IF) signal to the SRA. This signal carries the ranging modulation, delayed by the round trip light time (RTLT).

The job of the SRA is to recover the modulation from the IF and measure the range. The unit of the measurement is called the Range Unit (RU), whose exact value depends on the exciter reference frequency; for conversational purposes the RU can be considered to be a nanosecond.

E. **Equipment**. The SRA performs its tasks with a central processing unit (CPU, an Intel 286), and other special assemblies, as indicated in Figure 2. These include coders, digitizers, digital filters, and correlators. The equipment is organized into two channels so that it can process signals from two receivers at once, for example, the S-band and X-band receivers in a Block-III assembly.

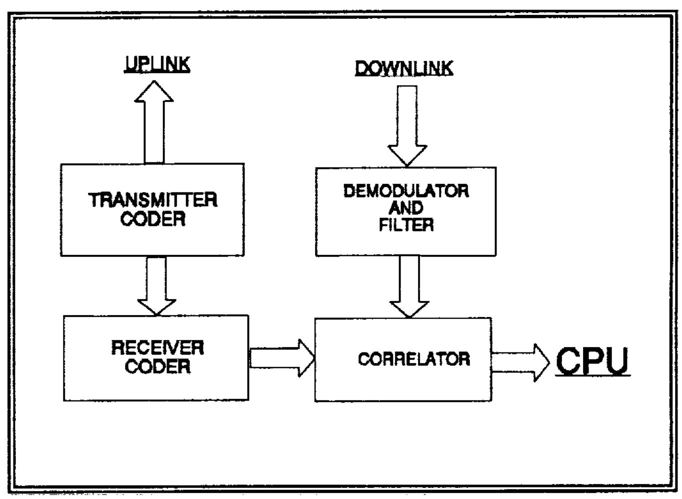

Figure 2 SRA (PARTIAL)

1. Coders. There are three coder assemblies -- one transmitter coder (XCODER) and two receiver coders (RCODERs), one for each of two channels. Each coder is a binary counter with associated code-combining logic.

* All notes appear at end of document.

The code combiners select squarewave signals (***components****) and combine them to form the required composite codes. XCODER produces the code to be transmitted; RCODERs create local models of the expected receiver code. Since the two receiving channels are separate but identical, the discussion to follow will cover only one.

a. XCODER. A signal extracted from the exciter multiplier chain at about 66 Mhz drives XCODER. The exact value of the 66 Mhz varies with carrier frequency, but is always 1/32 of the S-Band carrier. The CPU initializes (sets to all 0's) the XCODER to start a ranging operation; it runs freely, without interruption from then on.

b. RCODER. The 66 same Mhz also drives the RCODERs via logic that adjusts the frequency to keep the coders in step with the code in the received signal. [See ***Doppler Rate-Aiding***, later.] The logic also lets the CPU insert or delete pulses to advance or retard the RCODER to account for the RTLT as needed in the acquisition process.

2. <u>A/D</u>. An analog-to-digital (A/D) converter running at 40 Mhz samples the 10-Mhz IF, providing four samples (8-bit bytes) per cycle of IF. This lets the SRA demodulate the IF into a stream of baseband Data[3] at 10 megabytes per second.

3. <u>Filter</u>. Base-band bytes go through a digital filter made of large-scale integrated (LSI) circuits. The CPU programs it as a low-pass filter for the fundamental frequency of the highest square wave in the ranging code, so that it discards all harmonics and hence reduces any wave-form distortion in the radio system. (The CPU may also configure it as an all-pass filter.) [See 1. and 2. under ***Correlation Process***.]

4. <u>Correlator</u>. Filter output goes to the correlator, where data samples are multiplied by ± 1, depending on the current state of the RCODER bit, and the products are summed for 0.1 second. Every tenth of a second, the CPU reads the accumulated values into the computer for further accumulation.

F. **Clocks**. The ranging signal consists of a sequence of square waves varying from 2 Mhz to as low as 1 Hz. (The 2-Mhz clock, C3, is not used at present because all current S/C ranging channels have a bandwidth of less than 2 Mhz.) For any mission, the sequence consists of a highest frequency, known

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** Placing items in *Italics* is the same as having them in "Quotes," and indicates that they are being used in (perhaps) non-standard form; they are *Jargon* peculiar to this discipline.

as the clock, to provide the required resolution, and additional frequencies that decrease by powers of 2, called components, until the period of the last component is longer than the navigators' uncertainty as to the range to the S/C.

The highest clock in current use, C4, is actually about 1.03 Mhz, but is called 1 Mhz for convenience. SRA software divides the clock period into 1024 parts, so the resolution provided by C4 is roughly 1 nanosecond (1 RU). The accuracy with any clock is approximately the same percentage of the clock period, if the same integration time (T1) is used.

Lower frequencies are available as clocks, providing nominal frequencies and accuracies as given in the table to follow. The ***Potential Accuracy*** given in the table represents the value that corresponds to 1/1024 of a cycle of the clock. This value will be approached if the signal is sufficiently strong and the clock integration time (T1) is long enough, and no blunders occur during acquisition. (In the example to follow, the clock is assumed to be C4.)

COMPO-NENT	FREQUENCY (approx)	POTENTIAL ACCURACY
C4	1 Mhz	1 ns
C5	500 Khz	2 ns
C6	250 kHz	4 ns
C7	125 kHz	8 ns
C8	64 kHz	16 ns
C9	32 kHz	32 ns
C10	16 kHz	64 ns

III. PROCEDURE.

A. **Uplink**.

1. Clock. Transmission starts with a pure clock signal, C4, a 1-MHz square-wave modulating the transmitter. The SRA transmits this for a time ***T1***, the time needed to evaluate the phase of the received clock to a resolution of one part in 1024.

2. Components. Next, the SRA transmits the C5, 500 kHz (2-µsec period) square-wave for ***T2*** seconds. Since the receiving process needs only to decide if this component is upright or inverted, which is a 1-bit decision,

T2 is smaller than T1, usually about one tenth as long. C5 is followed by C6, C7, etc., until ***C-last*** is reached.

3. DRVID. (Differenced Range versus Integrated-Doppler.) At this point, if DRVIDs are required (more about this, later), the transmission schedule reverts to ***Clock***, sending this for as many T3 intervals as ***DRVN***, the requested number of DRVIDs.

4. Next cycle. Now the process returns to Step 1, sending the whole sequence over again, until the specified number of cycles has been sent, or until the end of the track.

B. **Downlink.**

1. Wait. At the start of the transmission sequence, the SRA schedules a delay equal to the predicted RTLT. The prediction need only be correct to the nearest second, and the SRA truncates any fractional part. After that delay, the SRA defines ***T0***, the time for which this range value will apply, and synchronizes RCODER to the current state of XCODER.

2. Clock Phase. The offset between the received clock and the local clock derived from the XCODER clock and rate-aiding, Φ in Figure 3, is called the ***phase*** of the clock. The SRA software divides the task of measuring the phase of the received clock into two parts, ***First-Cut*** and ***Final*** measurement. The SRA expresses Φ as a fraction of a clock cycle, and multiplies it by the number of RU in a cycle.

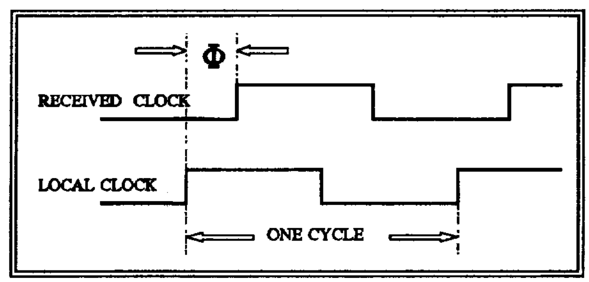

Figure 3 CLOCK PHASE

   a. First Cut. SRA integrates the output of the correlator for 1/8 of T1 to estimate IC & QC (see Figure 4), from which it calculates a rough value for Φ, accurately enough to approach within a few shifts[4] of 45°. IC is the accumulated sum of ***correlation*** values obtained by multiplying the received data by an ***in-phase*** local model. Similarly, QC results from multiplying the signal by a ***quadrature*** model (that is, the model shifted by 90°).

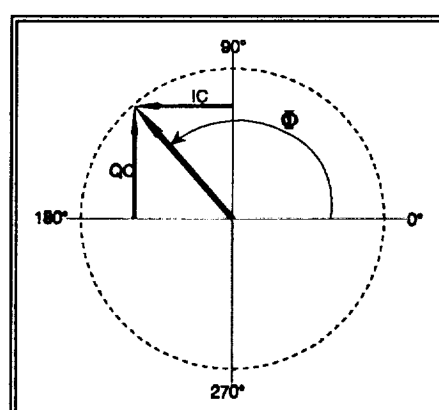

Figure 4 FIRST CUT

b. Shifting. Using the estimate, we shift the clock by -Φ to a place near 0°, and then by +1/8 of a cycle to reach a point near 45°, which is optimum location for making the Final determination.

c. Final. Final clock phase measurement correlates the remaining 7/8 of T1 to measure in-phase and quadrature correlation values (IC & QC in Figure 5), compute the exact value of the phase at T0, and then move the clock to a phase of 0°.

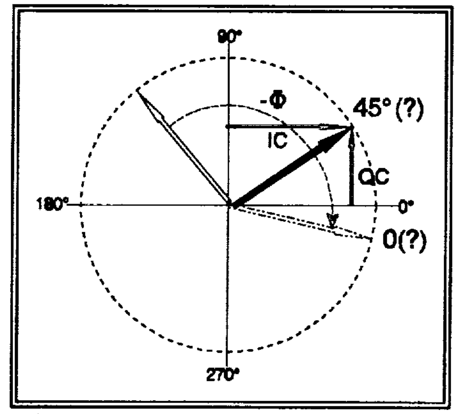

Figure 5 FINAL CUT

3. Data. The phase at T0 defines the fractional part of the data field reported to Navigation via the MDA under the name of Range Number. The SRA computes phase as a signed number scaled to a fraction of a clock period, and stores the number as the initial value of the Range Number. The rest of the number (its higher-order bits) depend on study of the remaining components.

4. First Component. With the clock at 0°, all the edges of the local model line up with the edges of the received code. The only unknown is whether an RCODER component is upright or inverted with respect to its mate in the received code.

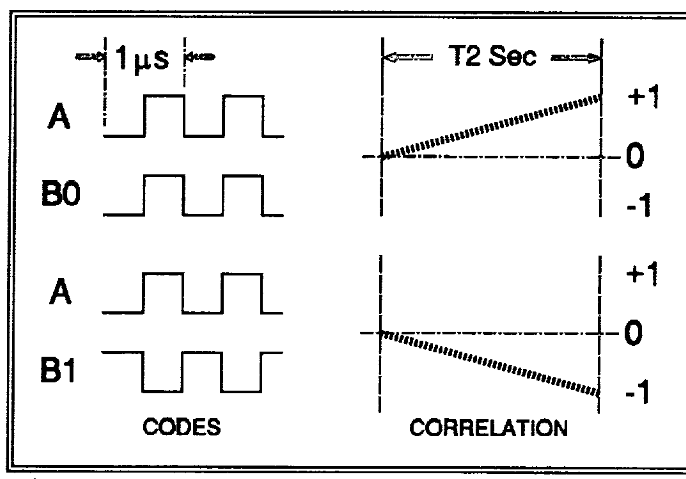

Figure 6 COMPONENT INTEGRATION

At the left in Figure 6, A is the received code component (C5 in this example), while B0 and B1 are two possibilities for the coder output. The right side shows the integration process.

The CPU integrates correlations for T2 seconds. If the correlation is positive (B0), the CPU adds a binary ***0*** into the Range Number as the next bit of the number. If the sign is negative (B1), the CPU adds a binary ***1***, and sends a pulse into RCODER to invert that component.

Positive case	
Before Integration	uuuuuuuuuuuuuuuuuuuuubbbbbbbbbb
After Integration	uuuuuuuuuuuuuuuuuuuu0bbbbbbbbbb
Negative case	
Before integration	uuuuuuuuuuuuuuuuuuuuubbbbbbbbbb
After integration	uuuuuuuuuuuuuuuuuuuu1bbbbbbbbbb

where uuu...= unknown bits; bbb...= bits already determined

(Clock measurement determines the first ten low-order bits, which correspond approximately to the low-order µsec of range.)

Note that for the 500-kHz (C5) component this process is similar to determining whether the number of µsec in the range is odd or even.

5. Other Components. This process continues for each of the lower-frequency components, with each binary ***1*** or ***0*** inserted one bit position to the left of the bit for the previous component. Thus, the 125-kHz (C7) component tells whether range contains an odd or even number of 4-µsec groups, and so on.

6. DRVID. This type of data is a function of charged-particle density along the signal path, and is mainly of interest to Radio Science researchers.[5] Since it also depends on S/C spin rate, it provides an optional method of assessing S/C attitude.

   If DRVID measurements are wanted, (continuing with the 1-MHz example) the CPU selects C4 as the local model, moves the clock to 45°, and correlates for T3 seconds. T3 is usually about 7/8 of T1, since it is measuring phase to one part in 1024, but starting with a known phase. The in-phase and quadrature correlations will be equal if the phase is really 45°; a difference between the measured angle and 45° tells how much the clock has drifted during acquisition, and is called DRVID. The SRA reports DRVID measurements in RU.

IV. OTHER TOPICS.

A. **Doppler Rate-Aiding**. The S/C is generally moving with respect to the tracking station, so the received signal will have a Doppler shift. This means that the frequency of the local clock will not match that of the received code. The Receiver-Exciter Subsystem contains a Doppler Extractor that generates a frequency that varies with the relative velocity of the S/C. The SRA uses this signal to adjust the RCODER digital clock to keep it synchronized with the clock in the received code.

1. Bias. The extractor adds a constant frequency to the Doppler, to prevent it from changing sign during a track. The bias normally used for Ranging is 5 MHz.

2. Sense. Because of peculiarities in early implementations,[6] the sign convention for the Doppler signal extracted by the DSN does not follow the usual conventions of physics. When a S/C is going away, DSN Doppler measurements will increase, as in Figure 7, while the whistle of a receding train would be lower in pitch. This causes no problem (except for people who would like to understand the system!). Under the DSN convention, Doppler rates are directly proportional to S/C velocity.

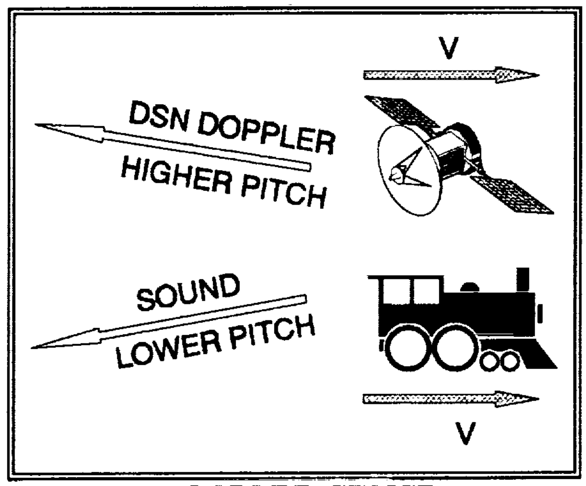

Figure 7 DOPPLER SENSE

3. Scaling. Since the coders operate on 66 MHz while the Doppler system works with uplink and downlink frequencies, the SRA's Doppler scalers modify the extracted Doppler signals to ***un-do*** the differences.

   a. Exciter. The 66-MHz reference is multiplied by 32 to produce the S-Band carrier, so the scalers divide Doppler by 32 (=d).

   b. Spacecraft. The S/C multiplies the uplink frequency (by 240/221 for S-Band[7]) to produce the downlink, so the scalers multiply the Doppler by 221/240 (=m/n).

   c. Bias. The Doppler has 5 MHz added to it, so the SRA subtracts a 5-MHz reference that has been scaled as in steps a. and b.

   d. Programmability. The CPU automatically controls the ***Doppler Scaler Values*** (d, m, and n) as a function of ***Band*** selection.

4. Synchronization. A fraction of a second before T0 (the start of an acquisition) the SRA performs these actions:

   a. Disable. The SYNC command suspends doppler scaling of the RCODERs, so they are running in step with XCODER.

b. Sync. SYNC now copies the state of XCODER into both RCODERs. They are now synchronized with XCODER, and the effective range is zero.

c. Enable. Exactly on the second, the SYNC command ends, re-enabling doppler scaling at T0, and the RCODERs then run in step with the received code.

B. **Bands vs Channels**. The SRA has two independent channels; it often works with two receivers -- one S-Band and the other X-Band. The user must specify the band for each SRA channel, so as to set the values used by the doppler scalers, and to control doppler signal switching if needed.

1. Background. Current receiver designs connect the IF of receiver 1 to SRA channel 1, regardless of Band. Doppler is switched so that S-Band doppler comes out on a particular cable, regardless of the receiver that produced it. If receiver 1 is on S-Band, and receiver 2 on X-Band, the SRA uses them directly. However if receiver 1 is on X-Band, the SRA interchanges the doppler signals so that rate-aiding is correctly applied. The BAND directive identifies up- and down-links for each channel.

C. **Correlation Process**. Demodulated data from the IF passes via a digital filter to the correlator, which uses a Multiply-ACcumulate (MAC) LSI circuit. The MAC multiplies the filtered signals by +1 if the current RCODER state is high, or by -1 if it is low. The MAC sums the products, reading them out to the CPU and clearing itself every one-tenth second. The filter's programmable characteristics provide two correlation types:

1. Square Wave. The filter can be configured as an ***All-Pass*** device, which does not change the information, so square-wave signals are cross-correlated against square-wave models. The cross-correlation function of this process is a triangular wave. This approach is sensitive to distortion caused by band-limiting in the Radio systems.

2. Sine Wave. If the filter is configured as a low-pass filter, it removes all harmonics of the received square-wave data, so the sine-wave fundamental of the signal is cross-correlated against square-wave models. The cross-correlation function of this process is a sinusoid. Since distortion introduces harmonics and the filter discards them, this tactic reduces the effects of distortion.

NOTE: The CPU can directly program the filter to have a low-pass response of 1-MHz or 500 kHz for use with the C4 and C5 clocks. For lower clock frequencies the CPU directs that the 10-MHz system clock that times the filter be divided by powers of 2, to give cut-off frequencies from 250 kHz down to 16 kHz, to match clocks C6, C7, C8, C9, and C10.

SRA's internal delay approximately doubles for each step from C5 on down to lower clocks.

Since a station delay measurement is made before and after each track, this change in delay does not affect the data. (However, the first time an operator sees this effect he is likely to think something is badly wrong. Since this only happens for sine-wave correlation, it has caused some projects to unnecessarily switch to square-wave operation.)

D. **Polarity**. The SRA's demodulator produces a stream of Baseband bytes that embody the data content of the IF signal. Depending on the RF equipment leading to the IF, those bytes may be upright or inverted. For instance, if the reference frequency to the front-end mixer is higher than the signal, the output will be inverted. (NOTE: some spacecraft also invert the signal -- doubling the complications.)

When ranging was being developed, only BLK-III receivers were in use; they invert the spectrum. This combination was defined as ***Normal*** polarity. The BLK-IV receiver which came later did not invert, but relative to standard it was inverting in its effect. This led to an ***INV*** operator directive (OD) in the SRA to control whether the CPU accumulates correlation values by adding or by subtracting.

The ***INV*** OD has two options, ***E*** for enable and ***D*** for disable. We are currently in the process of proposing a change in the software, re-naming it ***POL*** for Polarity, and making the choices ***POS*** and ***NEG***, so they reflect actual receiver properties.

E. **Chopping**. As a ranging acquisition advances through the sequence of components of lower and lower frequency, the modulation spectrum moves toward the RF carrier.

1. Problem. If no corrections were made, by the time C24 was reached, the Tracking Loop of the receiver would follow the waveform, and ***track***[8] it out.

2. Cure. To prevent this, the modulation signal is formed by ***chopping*** (multiplying[9]) the components by some higher signal, usually the clock. Thus, when C7 (125 kHz) is in use, the signal is C4 x C7, which comes out as 4 μsec of upright C4 followed by 4 μsec of inverted C4. Now, the low frequency components become centered on a 1-MHz sideband rather than the carrier. Figure 8 shows a few components being chopped by the 1-MHz clock, C1. The dotted lines indicate where the edges of the components would be without chopping. Note that C4⊕C5 is exactly like C5 shifted 1/4 cycle to the left. This always happens when a component is chopped by a component of twice the frequency.

3. Disable. Under some conditions, notably when the S/C is on the far side of the sun and the signals pass through the solar corona, it may be better to disable chopping with a ***CHOP D*** directive. However, to prevent the unwanted effects noted in the first paragraph, the SRA unconditionally turns chopping ON when it reaches C10 (about 16 kHz) so that the signal is never closer to the carrier than 16 kHz.

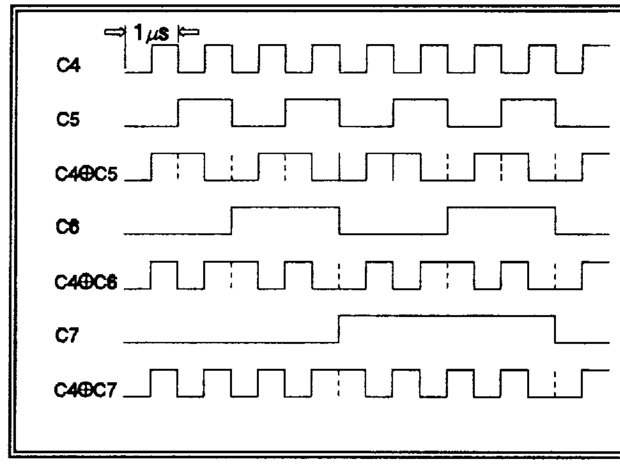

Figure 8 CHOPPING (by C4)

4. Low Chop. Still another option offered, also relevant when the signals pass through corona, is to chop with some signal lower than the clock. To use C7, for example, the OD would be ***CHOP E 7***.

F. **DRVID**. To use DRVID, three parameters must be specified; T3 -- integration time, DRVN -- number of DRVID points taken for each range point, and SERVO.

1. T3. As noted above, DRVID integration time should be somewhat less than T1 -- 7/8 of T1 is a good choice.

2. DRVN. The number of points depends on the relative importance of tracking data vs. Radio Science. Sometimes other factors come in; both the Ulysses and Galileo projects elected to take 3 DRVIDs per range point when they found that it seemed to cure some anomalies in their data. Later analysis showed that the anomalies were cured because the DRVIDs introduced a delay that gave the SRA and MDA enough time to complete other tasks. One DRVID, even a short one, would have had the same effect. (The SRA software and hardware have since been modified to cure the original problem.)

3. SERVO. When charged-particle effects are causing large DRVID values, they may shift the local model away from the 45° point, (which is where the system has the best signal-to-noise ratio for determining DRVID). The CPU can enable the SERVO function, so that whenever a non-zero DRVID is found, the clock phase may be adjusted to return to 45°, or at least move closer to 45°.

a. Enable/Disable. When enabling servo (SERVO E), the operator also specifies a gain. If gain = 1.0, all DRVID is removed immediately; if gain = 0.5, half of each measurement will be ***servo-ed*** out.

b. Gain. The choice of gain depends on the noise in the data: if the data is clean, noiseless, use 1.0. If the data is so noisy that one is afraid of over-correcting, use a lower figure, 0.5 or less.

G. **Signal-to-Noise Ratio**. At the end of clock phase measurement, the SRA calculates P_R/N_0, where P_R is ***Power in Ranging***, and N_0 is ***noise spectral density***. The calculation is based on all the data samples that entered into Final Cut. It uses the sum-of-squares of data samples for signal power, and the variance of the samples as noise power. The result is given in decibels, and is loosely (but imprecisely) called ***SNR*** for Signal-to-Noise Ratio.

H. **Figure of Merit**. The user of range data needs an indicator of the quality of the data. The SRA calculates a figure-of-merit (FOM) that indicates the probability of a successful acquisition. The FOM is computed just after clock phase measurement, and considers the SNR just measured, T2, and the number of components. The SRA uses these values to estimate the probability of success in the rest of the acquisition. This is an *a priori* estimate, and is valid if conditions do not change. The user specifies an FOM and the SRA marks all range values with a greater FOM as ***good***; those with lesser FOMs are marked as ***bad*** data.

I. **Modulation**. The amplitude of the modulation signal is controlled directly and linearly with the MOD directive, ***MOD nnn***, where nnn goes from 0 to 255.

Many projects want to specify the amount of carrier suppression in decibels (dB). This uses a station-dependent table, delivered to the SRA by the MDA, which gives the empirical relation between MOD numbers and dB of carrier suppression. The OD to use the table is of the form, ***CSV <m.m>***, where <m.m> is the desired suppression. The SRA looks up <m.m> in the table, interpolates if necessary, and generates the appropriate ***MOD nnn*** command to the hardware.

J. **Pipelining**. The SRA has a PIPELINE directive which controls the following options:

1. Single.	***PIPE D***	do one acquisition and quit
2. Infinite.	***PIPE E***	do acquisitions indefinitely
3. Number.	***PIPE E P***	repeat until ***P*** acquisitions have been done, where ***P*** can go from 1 to 32767.

Any acquisition will be followed by ***D*** DRVIDs if DRVN is >0 and ***T3*** is also >0.

K. **Timing Options**. Ideally, a flight project selects optimum integration times T1, T2, and T3, according to ranging theory, by referring to DSN document 810-5 (see Sec. V.B). Usually, however, other considerations may lead to deviations from theoretical values, generally increasing them. Here are some cases:

1. RTLT. At times the RTLT may change by as much as 10 seconds during a long track. The project increases all times by 10 seconds or more to compensate. A mismatch between real and predicted RTLT is not a problem, providing the time when the model matches the signal is at least as long as the required integration time.

2. Operational Considerations. Missions usually start near earth where times can be short, and go a long way out where times are long. To avoid continually changing the instructions to the operators, the project chooses a set of parameters that will be satisfactory all the way to Jupiter, for instance, and uses them for the whole mission.

3. 3-Way. In 3-way ranging,[10] the remote station may miss the first scheduled acquisition and need to start later. It is convenient to make the length of an acquisition, known as ***cycle time***, an even number such as 10 minutes. The project can increase integration times and number of DRVIDs, to pad the cycle time out to a convenient number.

V. SUMMARY. I hope that the material above will help users to make knowledgeable selections of the parameters that affect the quality of their ranging data. More detailed explanations are available in other documents:

A. **SOM**. The ***Software Operator's Manual***, DOK-5392-OP, covers all the Operator Directives, modes of operation, and the displays that are available in the SRA software.

B. **810-5**. ***Deep Space Network/Flight Project Interface Design Handbook, Volume I: Existing DSN Capabilities*** describes the characteristics of the DSN. Module TRK-30 covers the Ranging portion of the Tracking System.

C. **TM03401A**. ***Technical Manual -- Sequential Ranging Assembly -- Operation and Maintenance.***

NOTE: All three items above are internal documents produced at the Jet Propulsion Laboratory, Pasadena, California. They are revised periodically; use the latest date available.

VI. ADDITIONAL REFERENCES, historical and theoretical may be found in the following JPL documents:

A. Technical Memorandum -- ***Mu-II Ranging*** -- TM 33-768, May, 1977

B. Goldstein, ***Ranging With Sequential Components*** -- Space Program Summary 37-52, July, 1968, Vol.II, pp. 46-49. (Referenced in TM 33-768)

C. Martin, ***Information Systems: A Binary-Coded Sequential Acquisition Ranging System*** -- Space Program Summary 37-57, May, 1969, Vol.II, pp.72-81. (Referenced in TM 33-768)

D. Martin, ***Information Systems: Performance of the Binary-Coded Sequential Acquisition Ranging System*** -- Space Program Summary 37-62, March, 1970, Vol.II, pp.55-61. (Referenced in TM 33-768)

E. MacDoran, Martin, ***A First-Principles Derivation of the Differenced Range Versus Integrated Doppler (DRVID) Charged Particle Calibration Method*** -- Space Program Summary 37-62, March, 1970, Vol.II, pp.28-34. (Referenced in TM 33-768)

F. MacDoran, Martin, ***DRVID Charged Particle Measurement With a Binary-Coded Sequential Acquisition Ranging System*** -- Space Program Summary 37-62, March, 1970, Vol.II, pp.34-41. (Referenced in TM 33-768)

G. Molinder, ***Digital Telemetry and Command: Mean-Square Error and Bias of Phase Estimator for JPL Sequential Ranging System*** -- Space Program Summary 37-64, August, 1970, Vol.II, pp.27-28. (Referenced in TM 33-768)

H. Layland, Zygielbaum, Hubbard, ***On Improved Ranging*** -- DSN Progress Report 42-46, June, 1978 (Referenced in DSN Progress Report 42-66)

I. Zygielbaum, ***Installation of the MU2 Ranging System in Australia*** -- DSN Progress Report 42-51, June, 1979 (Referenced in DSN Progress Report 42-66)

J. Martin, Layland, ***Binary Sequential Ranging with Sine Waves*** -- DSN Progress Report 42-31, February, 1976 (Referenced in DSN Progress Report 42-66)

K. Timor, ***Sequential Ranging With The Viterbi Algorithm*** -- JPL Technical Report 32-1526, Vol.II, pp.75-79. (Referenced in TDA Progress Report 42-62)

L. Coyle, ***Posterior**** ***Error Probability in the MU-II Sequential Ranging System*** -- TDA Progress Report 42-62, March, 1981

M. Tausworthe, ***Tau Ranging Revisited*** -- TDA Progress Report, 42-91.

N. Tausworthe, Smith, ***A Simplified, General Purpose Deep-Space Ranging Correlator Design*** -- TDA Progress Report, 42-92.

NOTE: All the above items above are external documents produced at the Jet Propulsion Laboratory, Pasadena, California.

*** This should have been A Posteriori Error ...

VII. NOTES

1. *Coherent* means that the downlink carrier frequency and the uplink carrier frequency have the ratio of two integers, e.g., 240/221. *Turn-around* means that the transponder detects the uplink modulation, conditions it by limiting and/or filtering, and uses that signal to modulate the downlink.

2. The MDA is the assembly in the tracking station that controls the SRA, collects its results, and transmits the data to Navigation.

3. Baseband data is information that is not modulated on a carrier or subcarrier, i.e., it has been *detected*.

4. The local clock is shifted by inserting or deleting cycles of 66 MHz, which are 16 RU (definition). Thus, all shifting is in 16-RU steps.

5. As charged particle effects get stronger, the group velocity (at which the code information travels) decreases, while the phase velocity (which affects doppler) increases. Their product is a constant equal to the square of the speed of light. The rate aiding now moves the local model faster than the received signal, and they slide out of agreement. This DRVID always has the same sign, and its magnitude is usually only a few or fractional RU.

   Spin of the spacecraft also generates an apparent doppler which can be in either direction, producing DRVID of either sign, with a magnitude of several tens of RUs. (If the S/C project needs confirmation of their normal spin-sensing data, they could derive the spin from DRVID.)

6. The Doppler Extractor includes a down-conversion where the reference frequency is higher than the signal frequency. This causes an inversion of the frequency spectrum at that point.

7. The corresponding ratio for X-band downlink with S-band uplink is 880/221. There are similar (but more complicated) numbers for these ratios when one is using an X-Band uplink.

8. Receivers (both on the ground and in the S/C) use a phase-locked loop that acts as a low-pass filter. Any signals or noise within its bandwidth are removed in the process of tracking (following) a carrier.

9. When one is working with square-waves, *multiplication* of non-return-to-zero (NRZ) waveforms is mathematically equivalent to the logical operation of *Modulo-2 Addition* of 0s and 1s, which is represented by the symbol "$\oplus$". Thus, "C4$\oplus$C6", (interpreted as 0s and 1s) is the same as passing the NRZ waveforms for C4 and C6 through an analog multiplier. These operations are known to radio engineers as *mixing*.

10. When a station which transmits to a S/C receives and processes the returned signal itself, that mode of operation is termed *2-Way* operation. When one station transmits and another receives and processes the returns, that is called *3-Way* operation. 3-way operation is necessary when the RTLT is so long that the 2-way window is not long enough for worthwhile operations. 3-Way mode may be used in the future even if the RTLT is short, because it can provide differential data that is useful to the Navigation team.

VIII. APPENDIX

A. PN RANGING.

1. Status. A capability is now (May, June 1993) being added to the SRA which will use PN[1] codes instead of sequential square waves. The addition requires the addition of two cards to the standard SRA card cage, and an alternate version of the software.

2. Theory. The code is composed of a clock and five PN sequences with lengths of 7, 11, 15, 19, and 23. Using a 1 MHz clock, the sequence repeats about twice a second. This is comparable to the longest SRA sequential code, which repeats about once a second.

3. Implementation. The codes are generated by digital hardware and special read-only-memory (ROM) units; the correlation process is performed by digital hardware, the ROMs, and software, with the correlation values accumulated in random-access-memory (RAM) circuits.

4. Process. The transmitter code can be turned on at any time, and may be broadcast continuously. (It only needs to be turned off if it might interfere with Command or Telemetry.) The reception process can be begun at any time, but at least one RTLT must have elapsed before the data is valid.

5. Advantages. PN ranging has several advantages, both in performance and in operational simplicity.

   a. Operations. Once having initialized and started transmitting the uplink code, the operators don't need to pay any attention to it. It needs no scheduling or manipulation. The only options are the choice of clock frequency and the modulation level.

   b. Performance. PN ranging can operate at signal levels at least 2 dB lower than sequential ranging. (This advantage prompted the Galileo project to be the first to request a demonstration of the technique.) It acquires its data faster -- for comparable signal levels, the whole process takes about the time (T1) used by sequential ranging to acquire the clock phase. There is only the one step to the process.

1. *PN* stands for Pseudo Noise, a term coined over 35 years ago, probably by S. W. Golomb, then at JPL. It refers to binary sequences that have statistical properties similar to those of random sequences. PN codes also have two-level autocorrelation functions. That is, a code of length n correlated with all shifts of itself will have two values: +1, at only one phase, and -1/n at all other phases.