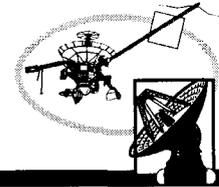


Operations Comparison of Deep Space Ranging Types: Sequential Tone vs. Pseudo-Noise

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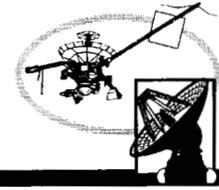
Scott Bryant, Jeff Berner
Jet Propulsion Laboratory

What is “Deep Space” Ranging?

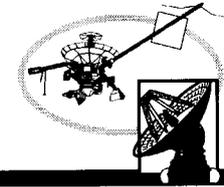


- NASA’s Deep Space Network (DSN) ranging system measures the distance from a ground station to a spacecraft. This implies:
 - Large distances. Anywhere from LEO (300 km) to Neptune (4.5 billion km).
 - Weak signals, down to -10 dB-Hz. But must also handle up to +50 dB-Hz.
 - Precision measurements to support critical spacecraft navigation for aerobraking and flybys. Requires the ranging systematic error sources be less than 1.25 m 1-sigma (1-way distance in meters). Actual precision also depends on ranging SNR.
- Ranging measurements improve flight team navigation solutions.
 - Doppler resolution limited by the carrier loop bandwidth. Ranging measures absolute distance to a resolution limited by ranging signal strength and integration time.
 - Orbit solutions from Doppler and range have smaller error ellipses than Doppler-only solutions. Reduces tracking needs or improves ephemeris.
- The cost of doing ranging:
 - Ranging tones take power away from the telemetry channel.
 - Ranging system inputs require link margin analysis by the flight team.
 - Ranging can increase the tracking duration for long RTLT.

Inputs to the Ranging System



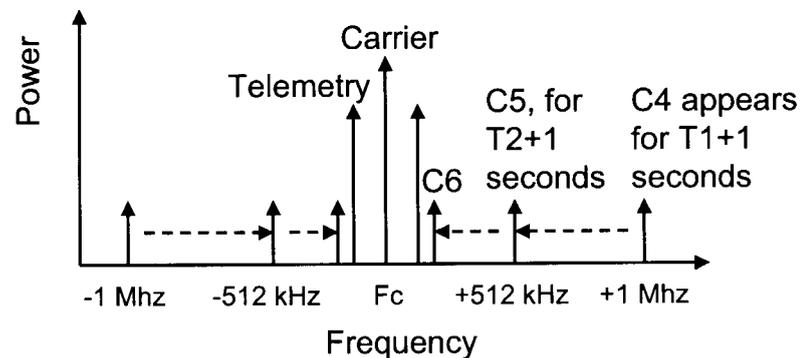
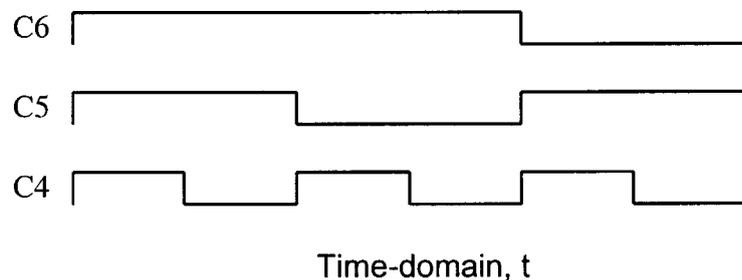
- The ranging system requires inputs that define:
 - The short (high frequency) and longest (lowest frequency) codes.
 - The integration time of each code.
- The Spacecraft flight team determines the inputs based on:
 - The distance uncertainty, or ranging ambiguity, determines the required code length. E.g. if the spacecraft distance has an uncertainty of 100 km, the longest code must be at least 100 km long, or $(c/2)/100 = 1500$ Hz.
 - The ranging power and desired variance in the range measurement determine the code integration times. Typically on the order of minutes.
 - The integration times are also a function of the desired probability of acquiring the ambiguity-resolving tones.
 - The spacecraft flight team *pays for X range points of variance σ by taking power from telemetry* and requesting the code types, code lengths, and integration times using the ranging operation formulas.
- The upcoming DSN ranging system offers 2 types of ranging tones
 - The DSN Network Simplification Project will support the existing sequential tone range and provide a new pseudo-noise (PN) range capability.
 - PN ranging can provide *more range points of lower σ for less power*. Comparisons based on matching 1 or more ranging variables.

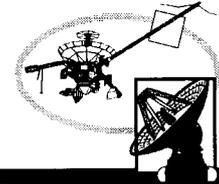


Sequential Tone Ranging



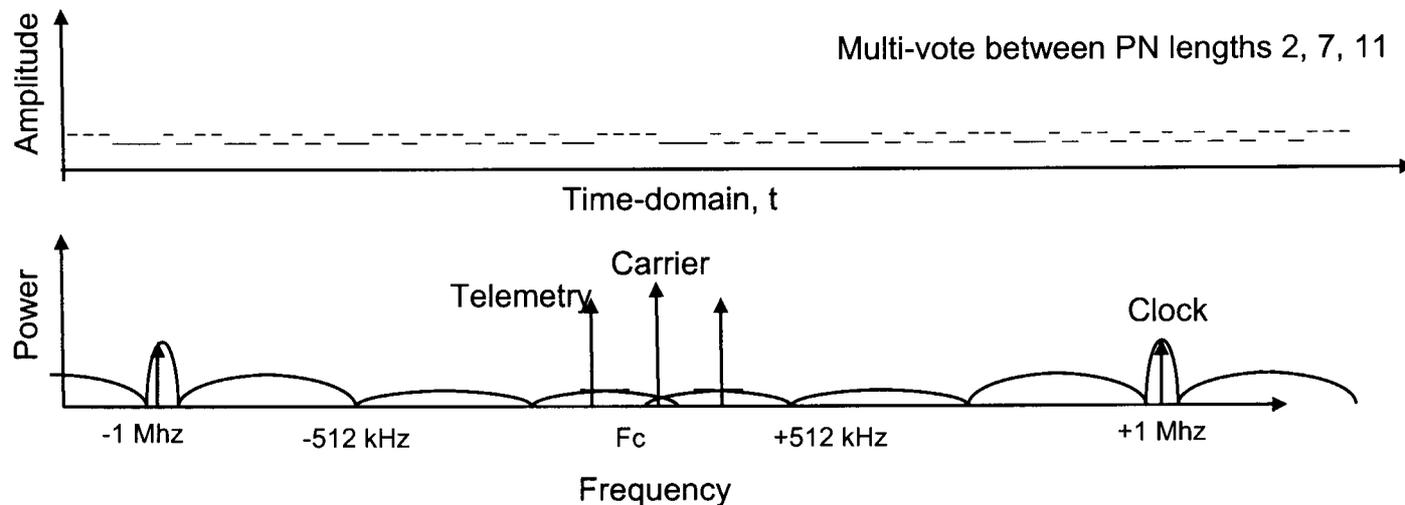
- Sequential ranging uses a time sequence of squarewave tones identified by Component Number, C#.
 - Highest frequency tone, “clock” tone, is about 1 MHz (C4).
 - The next tone is exactly $\frac{1}{2}$ the frequency, C_{n+1} is $\frac{1}{2}$ the frequency of C_n.
 - Sequence ends between C9 (31 KHz) and C24 (1 Hz), at “last” component.
- The various tones have settable durations
 - The “Clock” tone is T1 seconds long, followed by 2 second dead time.
 - All other tones are T2 seconds long, and separated by 1 sec. dead times.
 - The entire pattern repeats after $T1 + 3 + (\text{Last} - \text{Clock}) \times (T2 + 1)$ seconds, called the “cycle time”. T1 and T2 durations are also the integration times.

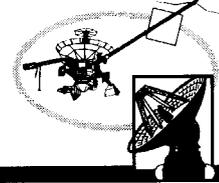




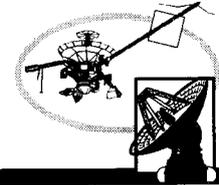
Pseudo-Noise Ranging

- PN patterns are Boolean combinations of several short and relatively prime length PN subsequences. Length expressed in symbols.
 - Logical combinations can use AND, OR, XOR, and multi-vote. Research shows multi-vote leads to optimal correlation properties.
 - Overall PN length is the product of the subsequence lengths.
 - Typical PN patterns have a spread-spectrum nature that allows them to share the spectrum with the telemetry tones.
 - Length 2 “clock” tone gets more power to improve measurement precision.
- All tones are present all the time, not sequentially.
- Integration time specified independent of PN pattern.





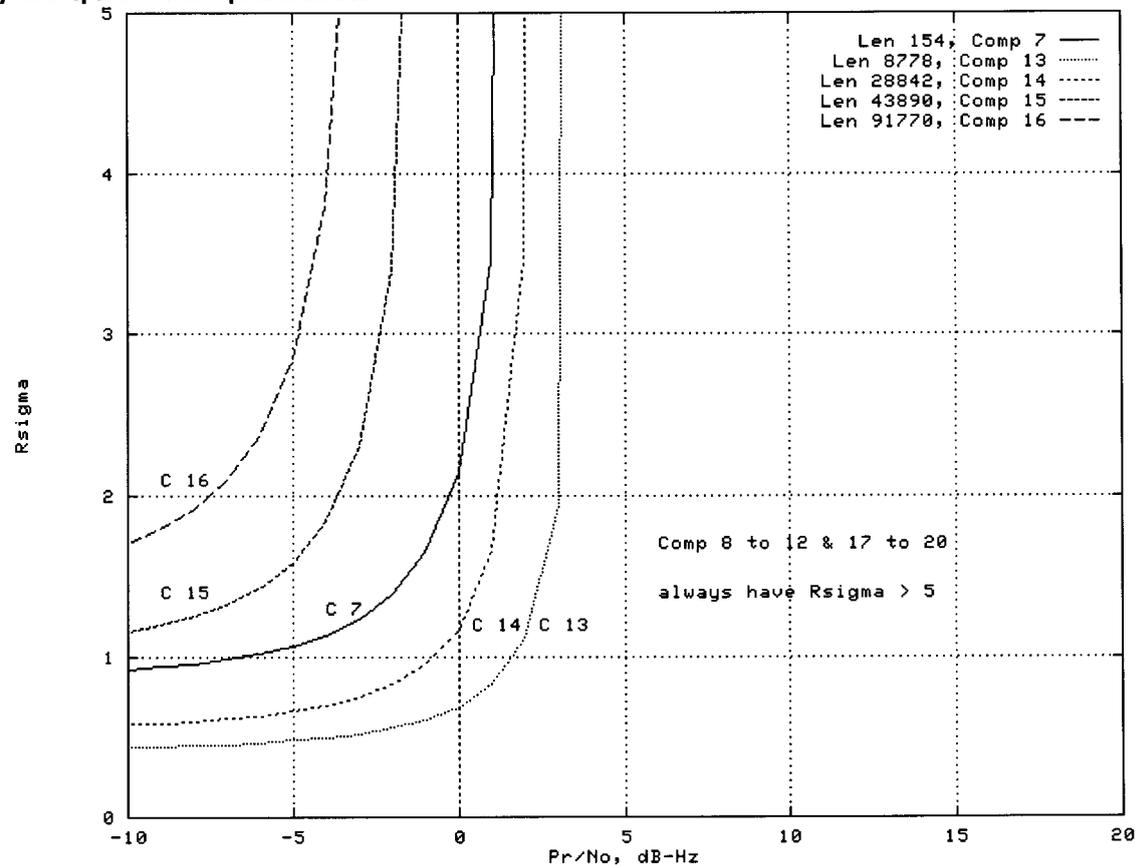
- PN and Sequential tone ranging are compared 3 ways:
 - Ratio of variance: For two patterns with the same ambiguity resolution (pattern length), equal acquisition probability, and integration times; compare the ratio of range variance as a function of power.
 - Ratio of integration times: For two patterns with the same ambiguity resolution (pattern length), equal acquisition probability, and range variance; compare the ratio of integration times as a function of power.
 - Crossover power: For two patterns with the same ambiguity resolution (pattern length), equal acquisition probability, and range variance; solved for the ranging signal to noise density where the integration times are equal.
- For all comparisons, the hard part is finding 2 patterns with matching ambiguity resolution.
- Generally, PN ranging has the advantage because the 'dead times' in the sequential pattern increase the cycle time, but aren't used in the signal integration.

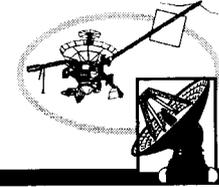


Compare by Range Variance



- Patterns are matched by finding a PN pattern of symbol length, X , with nearly the same ambiguity as sequential tone sequence with last component, N .
- Both patterns use the same 'Clock' frequency.
- The PN pattern is superior when R_s greater than 1. All PN patterns are better when ranging SNR > 2 dB-Hz. Some PN patterns are always better than their matching sequential pattern.

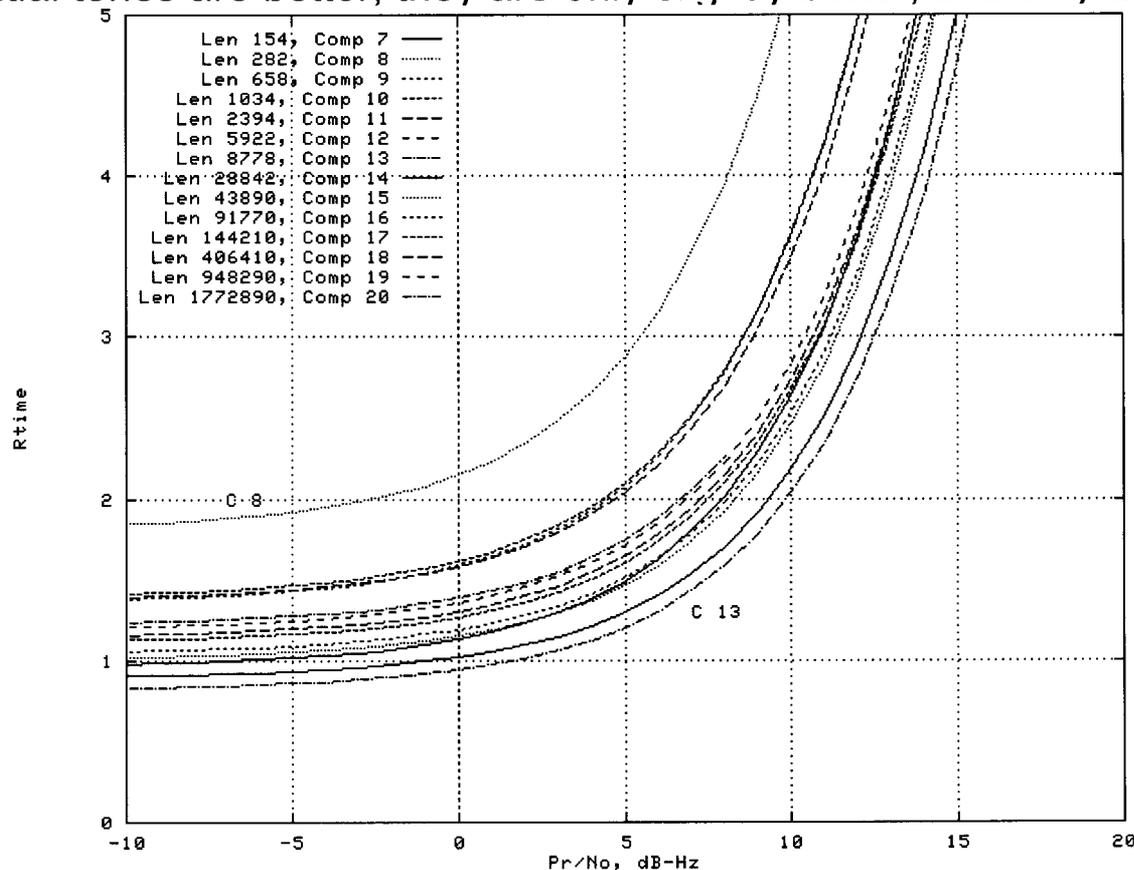




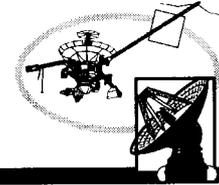
Compare by Integration Time



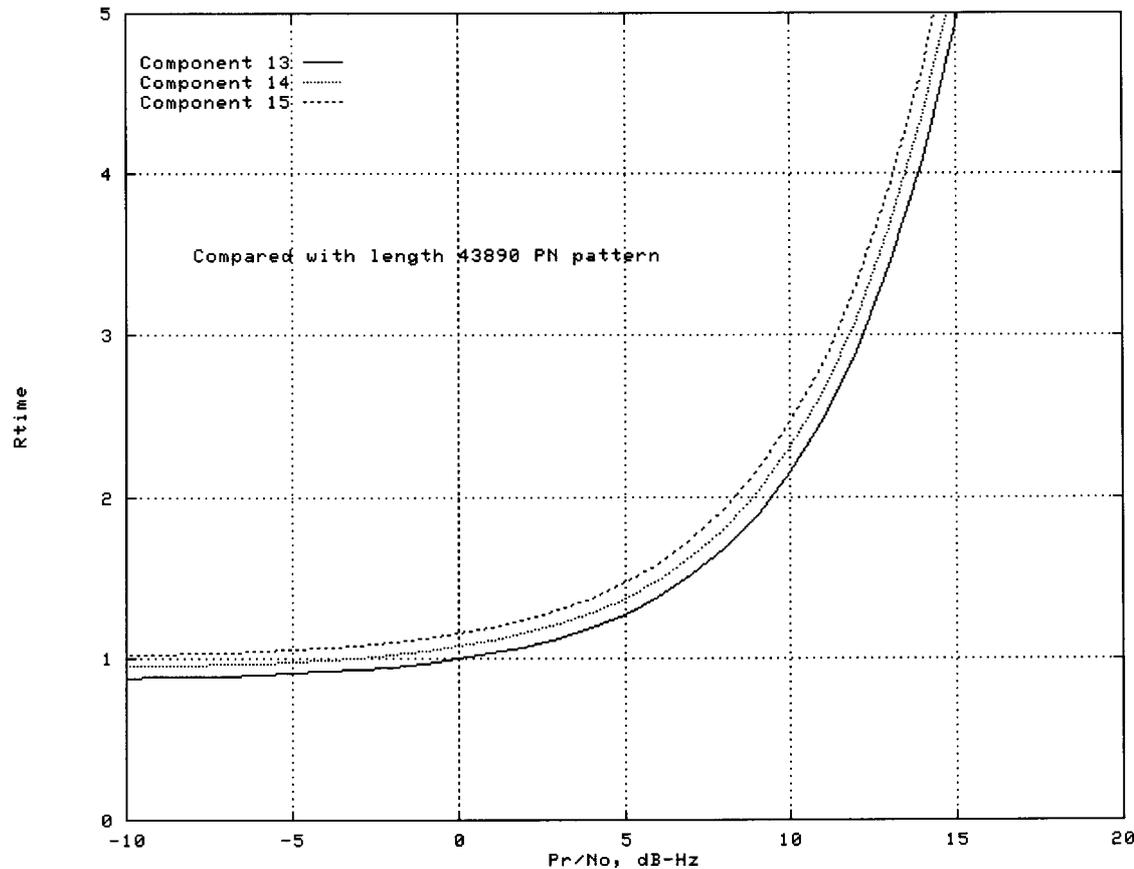
- The PN pattern is superior when Rtime greater than 1. All PN patterns are better when ranging SNR > 2 dB-Hz.
- Same information as Rsigma plot, but the result here is more points for the same range variance.
- The PN pattern is vastly superior over most of the operating region. When sequential tones are better, they are only slightly better, and only at low power.



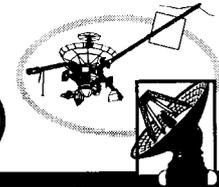
Down-selection between PN patterns



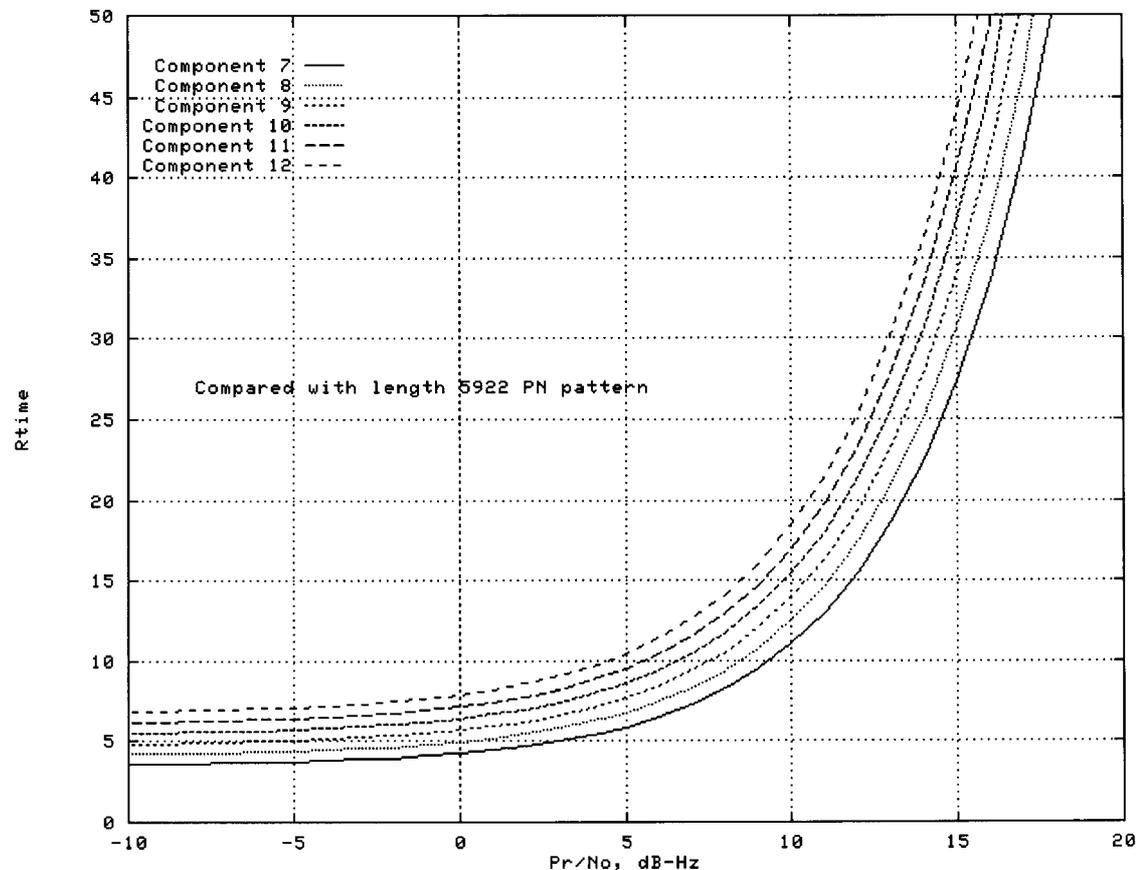
- Crossover powers reveal certain PN patterns are superior to many sequential tone lengths, not just the one with matching ambiguity resolution.
- *Two PN patterns can cover the operation region.* The PN length 43890 pattern covers launch conditions for high power, large ambiguity. This PN pattern is made from subsequences of lengths 2, 7, 11, 15, and 19.



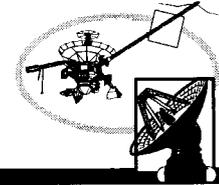
Down-selection between PN patterns (cont.)



- The other PN pattern covers covers cruise and arrival conditions. These are lower power, but have smaller ambiguity because of the navigation history.
- The PN length 5922 pattern is superior to all sequential tones of comparable or less ambiguity for all operating power levels. This PN pattern is made from subsequences of lengths 2, 47, and 63.



Conclusions



- The PN patterns offer increased performance over sequential tones. The advantage can be used to get more points or less variance.
- PN ranging also easier for flight teams to use:
 - PN needs only one integration time to be computed, versus sequential which requires T1 and T2 to be computed.
 - The PN codes cover many ranging ambiguities. Sequential should be updated whenever the ambiguity changes by a factor of two, otherwise performance suffers.
- Planned improvements allow the DSN to compute integration times.
 - The DSN ranging system will get prediction of the received ranging SNR.
 - The PN pattern and the target range sigma will be stored in a configuration file for each spacecraft.
 - The DSN ranging system could compute the integration time from these inputs. Thus eliminating many flight team updates.
 - The integration time can be changed in real-time to deal with unexpected problems. If the downlink power is lower than predicted, the integration time can be changed to compensate.