The Consultative Committee for Space Data Systems

Recommendation for Space Data System Standards

PSEUDO-NOISE (PN) RANGING SYSTEMS

RECOMMENDED STANDARD

CCSDS 414.1-B-3

BLUE BOOK

January 2022

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DOCUMENT CONTROL

Document	Title	Date	Status
CCSDS 414.1-B-1	Pseudo-Noise (PN) Ranging Systems, Recommended Standard, Issue 1	March 2009	Original issue, superseded
CCSDS 414.1-B-2	Pseudo-Noise (PN) Ranging Systems, Recommended Standard, Issue 2	February 2014	Issue 2, superseded
CCSDS 414.1-B-3	Pseudo-Noise (PN) Ranging Systems, Recommended Standard, Issue 3	January 2022	Current issue: adds a ranging-signal-chip-rate parameter value for Ka-Band uplinks

NOTE – Changes from the original issue are marked with change bars in the inside margin.

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1 INTRODUCTION

1.1 PURPOSE

The purpose of this document is to provide a Recommendation for Space Data System Standards in the area of transparent[1] and regenerative Pseudo-Noise (PN) ranging systems. The PN ranging system is used to measure the round-trip light time between a ground station and a spacecraft. Regenerative ranging is primarily relevant for low Signal-to-Noise Ratio (SNR) cases like those seen in deep space missions; transparent ranging is more suitable for high SNR cases or when high accuracy ranging is not required.

1.2 SCOPE

This Recommended Standard defines both transparent and regenerative PN ranging systems for non–data relay satellite users. The specification for PN code components and generation, on-board spacecraft regenerative/transparent processing, ground station processing, and uplink and downlink signal modulation are defined in this document. This Recommended Standard does not specify a) individual implementations or products, b) implementation of service interfaces within real systems, or c) the management activities required to configure and control the protocol.

1.3 APPLICABILITY

The Recommended Standard specified in this document is to be invoked through the normal standards programs of each CCSDS Agency and is applicable to those missions for which cross support based on capabilities described in this Recommended Standard is anticipated. Where mandatory capabilities are clearly indicated in sections of the Recommended Standard, they must be implemented when this document is used as a basis for cross support. Where options are allowed or implied, implementation of these options is subject to specific bilateral cross support agreements between the Agencies involved.

1.4 RATIONALE

The CCSDS believes it is important to document the rationale underlying the recommendations chosen, so that future evaluations of proposed changes or improvements will not lose sight of previous decisions. Concept and rationale behind the decisions that formed the basis for this Recommended Standard are found in the CCSDS Pseudo-Noise Ranging Systems Green Book (reference [C1]).

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[1] The term *'transparent ranging'* is used in this standard to mean non-regenerative ranging or turn-around ranging.

1.5 CONVENTIONS AND DEFINITIONS

1.5.1 DEFINITIONS

The following definitions apply throughout this Recommended Standard:

chip rate: rate at which the PN code bits (or ‘chips’) are transmitted.

coherent transponder: transponder for which the downlink carrier is phase-coherent with the received uplink carrier.

component sequences: family of shorter-length PN sequences used to form the ranging PN code using logic operations.

range clock: PN component code with the highest frequency (i.e., shortest period); determines the range resolution.

regenerative ranging: type of ranging where the spacecraft demodulates and acquires the ranging code by correlation with a local code replica from the uplink ranging signal, and regenerates the ranging code on the downlink.

transparent ranging: type of ranging where the spacecraft frequency-translates the uplink ranging signal to the downlink without code acquisition (i.e., non-regenerative ranging or turn-around ranging).

one-way jitter: ranging jitter in meters resulting from measuring the round-trip light time and halving the measurement to compute the distance.

1.5.2 NOMENCLATURE

The following conventions apply through this Recommended Standard:

– the words ‘shall’ and ‘must’ imply a binding and verifiable specification;

– the word ‘should’ implies an optional, but desirable, specification;

– the word ‘may’ implies an optional specification;

– the words ‘is’, ‘are’, and ‘will’ imply statements of fact.

1.5.3 CONVENTIONS

In this document, the following convention is used:

– A ‘+1’ ranging chip corresponds to a binary 0 value;

– A ‘−1’ ranging chip corresponds to a binary 1 value.

1.6 REFERENCES

The following documents contain provisions which, through reference in this text, constitute provisions of this Recommended Standard. At the time of publication, the editions indicated were valid. All documents are subject to revision, and users of this Recommended Standard are encouraged to investigate the possibility of applying the most recent editions of the documents indicated below. The CCSDS Secretariat maintains a register of currently valid CCSDS Recommended Standards.

[1] *Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft*. Issue 32. Recommendations for Space Data System Standards (Blue Book), CCSDS 401.0-B-32. Washington, D.C.: CCSDS, October 2021.

NOTE – Informative references are provided in annex C.

2 OVERVIEW

Several upcoming missions require higher accuracy spacecraft position determination compared to currently supported missions. One solution to cope with these new requirements is the use of regenerative PN ranging systems. *Regenerative ranging* presents several advantages with respect to the classical *non-regenerative ranging*, which is the approach at present used by CCSDS Agencies supporting deep space missions. The regenerative ranging technique requires the use of PN codes with important impacts for on-board transponder and Earth station design, differing from non-regenerative systems for which transparent transponders are commonly used.

Even though the advantages of regenerative ranging are mainly relevant to the low SNR case (e.g., deep space missions), the use of PN ranging with transparent on-board processing is also possible. This solution is attractive in presence of good link margin or when very accurate ranging is not needed with performance similar to non-PN ranging systems. A transponder based on a transparent ranging channel will have reduced complexity compared with the regenerative case. The spacecraft demodulates a large frequency range around the carrier and re-modulates the entire bandpass including the uplink noise onto the downlink carrier. With a transparent system, the ranging SNR at the station is proportional to $1/r^4$ where r is the distance to be measured. In a regenerative PN ranging system, a PN ranging code is phase modulated on the uplink carrier and transmitted from the ground station to the spacecraft. This ranging signal is derived using a logical combination of a ranging clock and several component PN codes. Received by the spacecraft, the ranging signal is demodulated by the spacecraft transponder, and the ranging code is acquired. The spacecraft then regenerates the ranging code coherently with the uplink code and phase modulates the downlink carrier with the locally generated version of the ranging code. Back at the ground station, the station receiver demodulates the downlink and correlates the received ranging signal with a local model of the range clock and component PN codes to determine the round-trip light time. The ranging SNR at the station is therefore proportional to $1/r^2$ where r is the distance to be measured.

Selection of the ranging clock frequency determines the range precision. Likewise, the component codes structure and combination logic affect the code acquisition time and probability, range ambiguity, and range precision. The PN codes in this Recommended Standard have been selected to provide high ranging accuracy while maintaining a reasonable code acquisition time.

For transparent PN ranging, the uplink process is exactly the same as in the regenerative ranging case. However, in transparent PN ranging the spacecraft does not attempt to acquire the ranging code; instead, it phase modulates the uplink ranging signal as received on board onto the downlink without further processing. The ground station receiver demodulates the downlink and performs the PN ranging correlation in the same manner as for regenerative ranging. Because any uplink noise is re-modulated onto the downlink, transparent ranging accuracy will generally not be as good as with regenerative ranging; however, transparent ranging requires less complexity in the spacecraft transponder.

This Recommended Standard is divided into two main parts covering regenerative PN ranging and transparent PN ranging. This Recommended Standard contains sections on the selection of PN code structure and modulation scheme, ground station uplink processing, on-board spacecraft processing, and ground station downlink processing.

3 REGENERATIVE PSEUDO-NOISE RANGING

3.1 OVERVIEW

This section provides recommendations for regenerative PN ranging. Specifically, recommendations are made for the PN code structure and modulation scheme, ground station transmit (uplink) processing, on-board regenerative processing, and ground station receive (downlink) processing.

3.2 PN CODE STRUCTURE

3.2.1 OVERVIEW

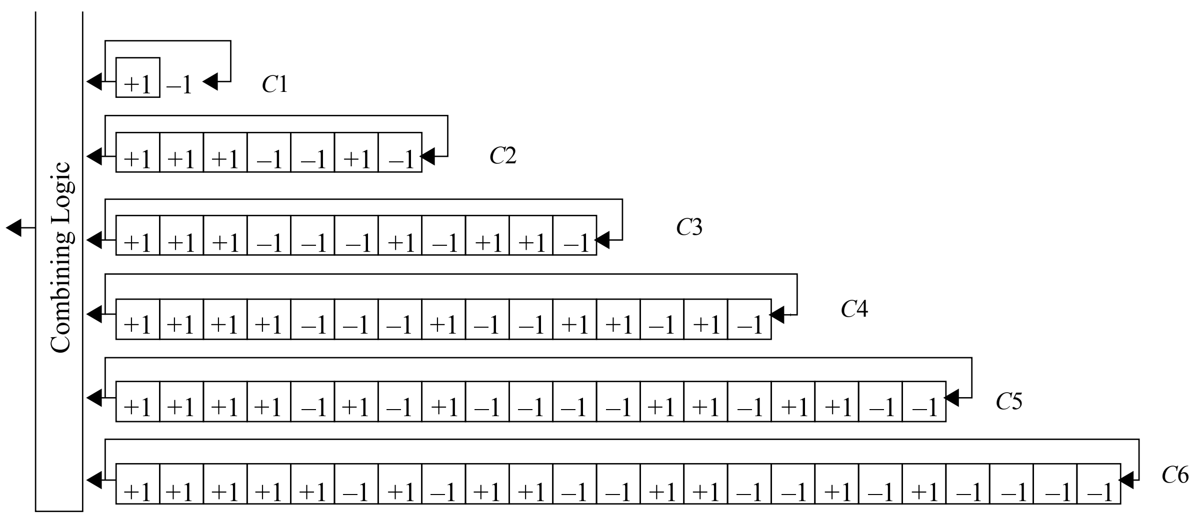
This subsection defines the PN ranging code components and combination logic for generating the regenerative PN ranging codes.

3.2.2 WEIGHTED-VOTING BALANCED TAUSWORTHE, ν=4

For range measurements where the ranging accuracy is of primary concern, the PN ranging code called Weighted-voting balanced Tausworthe, ν=4 (T4B) shall be selected.

The code is made up of six binary (±1) periodic 'component sequences' with a combination algorithm based on giving ν=4 votes to the clock component $C1$ as shown in figure 3-1.

The resulting ranging sequence C is periodic with length $L = 2 \times 7 \times 11 \times 15 \times 19 \times 23 =$ 1,009,470 chips.



where the combined sequence is $C = sign(4C1 + C2 - C3 - C4 + C5 - C6)$

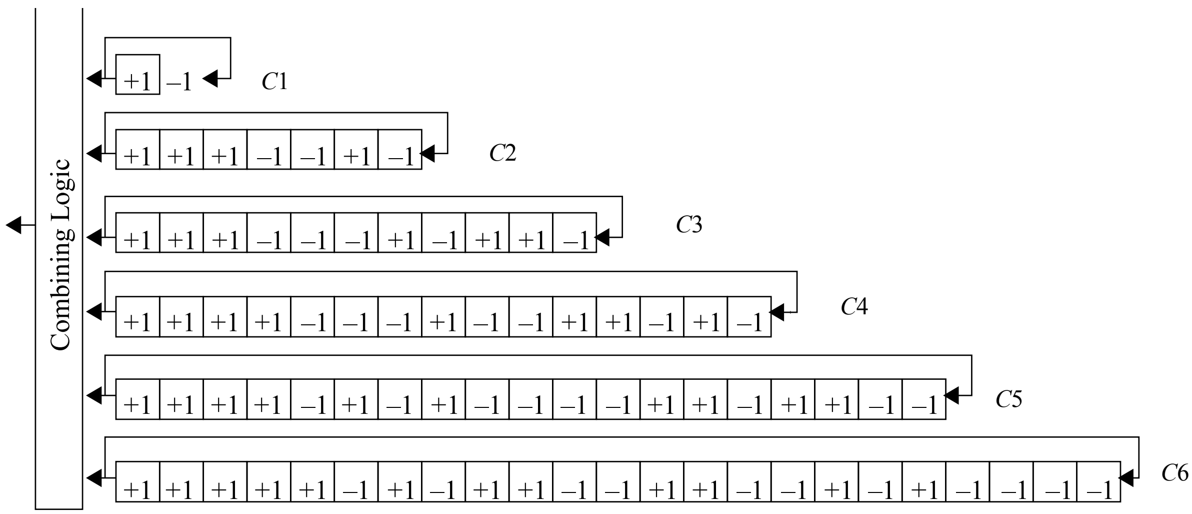
Figure 3-1: Regenerative T4B PN Code Generation

3.2.3 WEIGHTED-VOTING BALANCED TAUSWORTHE, ν=2

For range measurements where the acquisition time is of primary concern, such as for missions where the ranging signal will be very weak, the PN ranging code called Weighted-voting balanced Tausworthe, ν=2 (T2B) shall be selected.

The Weighted-voting (ν=2) Tausworthe ranging code is made up of the same six binary (±1) periodic 'component sequences' as the T4B code, but with a different combination algorithm based on giving ν=2 votes to the clock component *C*1 as shown in figure 3-2.

The resulting ranging sequence *C* is periodic with length $L = 2 \times 7 \times 11 \times 15 \times 19 \times 23 =$ 1,009,470 chips.



where the combined sequence is $C = sign(2\,C1 + C2 - C3 - C4 + C5 - C6)$

Figure 3-2: Regenerative T2B PN Code Generation

3.3 GROUND STATION UPLINK PROCESSING

3.3.1 OVERVIEW

This subsection provides recommendations for ground station uplink (transmit) processing for PN ranging.

3.3.2 UPLINK MODULATION

3.3.2.1 Modulating Signal

The ground station transmitter shall modulate the uplink carrier with the PN code specified in 3.2.

3.3.2.2 Modulation Scheme

The ranging signal shall be linearly phase modulated on the uplink carrier; i.e., a positive transition of -1 to $+1$ in the base-band code shall result in an advance of the transmitted RF carrier phase.

3.3.2.3 Base-Band Shaping

Base-band shaping should be used on the PN ranging signal to conserve bandwidth at high chip rates and high modulation indexes.[2]

3.3.2.4 Base-Band Shaping Filter Impulse Response

The shaping filter shall have the following impulse response:

$$h(t) = h_{\sin}(t) = \begin{cases} \sin(\pi t / T_c) & t \in [0, T_c] \\ 0 & elsewhere \end{cases}$$

where T_c is the chip duration.

3.3.2.5 Ranging and Telecommand

Ranging according to this standard and telecommand as specified in CCSDS 401.0-B 2.2.4 and 2.2.7 (reference [1]) may be performed at the same time.

[2] Reference [C1] may be consulted for the analysis of occupied bandwidth versus modulation index.

3.3.3 UPLINK CHIP RATE

The ranging signal chip rate shall be frequency coherent with the uplink carrier as given by the following expression (for k=6 and l={1,2,…,12,16,32, 64, or 94} or for l=2 and k={8,9, or 10}). The value l=94 shall only be used for Ka-band uplinks. See also an example of available chip rates in annex B.

Table 3-1: Uplink Chip Rates

$F_{chip} = 2F_{clock} = l \cdot \frac{f_{S-band}}{128 \cdot 2^k}$	*for S-band uplinks*
$F_{chip} = 2F_{clock} = l \cdot \left(\frac{221}{749}\right) \cdot \frac{f_{X-band}}{128 \cdot 2^k}$	*for X-band uplinks*
$F_{chip} = 2F_{clock} = l \cdot \left(\frac{221}{3599}\right) \cdot \frac{f_{Ka-band}}{128 \cdot 2^k}$	*for Ka-band uplinks*[3]

where

F_{chip} is the chip rate in Mchip/s

F_{clock} is the ranging clock in MHz

$f_{S\text{-}band}$, $f_{X\text{-}band}$, $f_{Ka\text{-}band}$ are the S-band, X-band, and Ka-band uplink frequencies, respectively, in MHz

For interoperability reasons, the Earth stations shall as a minimum support two chip rate values: the preferred value of approximately two Mchip/s obtained by selecting l=8 and k=6 in the equations of table 3-1 and a lower value of approximately one Mchip/s obtained by selecting l=4 and k=6 in the equations of table 3-1.

The configuration of some CCSDS Agencies' ground stations may not be able to easily implement the above ratios between chip rate and carrier frequency. In such cases, the offset expressed in Hz between the generated value and the theoretical value shall be < 10 mHz for all the chip rates in table 3-1. However, the chip rate shall remain locked to the station frequency reference.

[3] 34200–34700 MHz.

3.4 ON-BOARD PROCESSING

3.4.1 OVERVIEW

This subsection defines the on-board spacecraft functions and performances for regenerative ranging. Subsections 3.4.2, 3.4.6.1, 3.4.6.2, 3.4.6.3, 3.4.6.4 and 3.4.6.6 are required for cross support while subsections 3.4.3, 3.4.4, 3.4.5, and 3.4.6.5 are based on good engineering practice and could be relaxed depending on the specific mission requirements.

3.4.2 PROCESSING FUNCTIONS

The on-board transponder shall implement the following ranging functions:

- carrier tracking and ranging signal demodulation;
- chip rate acquisition and tracking;[4]
- code acquisition and tracking;
- coherent retransmission of regenerated[5] code on the downlink signal.

As far as the processing of the ranging signal is concerned, either a frequency coherent or non-coherent transponder can be used.[6] The performance specification in this standard assumes a frequency coherent transponder.[7]

These requirements shall apply to all operational modes like telecommand on/off and telemetry on/off.

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[4] An uplink carrier coherent with the PN code chip rate allows for the use of an on-board code-aided acquisition/tracking loop; this is particularly useful in case of low SNR.
[5] The same code structure used for the uplink is used for the downlink.
[6] In case of carrier coherent turnaround approach, carrier and PN code chip rate received at the ground station are coherent (as in the uplink case); this can be used at the ground station for code-aided acquisition/tracking loop, for instance, in case of low SNR.
[7] The correlation loss for non-coherent operations can be found in the PN Ranging Systems Green Book (see reference [C1]).

3.4.3 RANGING SIGNAL ACQUISITION PERFORMANCES

3.4.3.1 General

The on-board receiver shall be able to acquire the PN code for the whole dynamic range of input signal power (down to the minimum ranging power over noise spectral density, P_r/N_o), frequency shift ($\Delta f/f$) and Doppler rate (R). These values depend on the selected mission. The following two operating regions are foreseen:[8]

– 10 dBHz ≤ P_r/N_o ≤ 30 dBHz; $\Delta f/f \leq 30$ ppm; R<0.01 ppm/sec;

– P_r/N_o > 30 dBHz; $\Delta f/f \leq 60$ ppm; R<0.1 ppm/sec.

NOTE – An aided acquisition strategy (using the carrier frequency to estimate the chip rate value) can help keep the ranging signal in the loop pull-in when a narrow code loop bandwidth is used. This is particularly useful in case of low P_r/N_o. In this case, the transponder shall be able to acquire and track a chip rate offset expressed in Hz of up to 10 mHz, for all the chip rates in table 3-1.

3.4.3.2 On-Board Nonlinearities

The phase response shall not deviate more than ±5 degrees from a linear phase-frequency relationship over the frequency range of $\pm 1.5 * F_{\text{chip}}$.

The transmit in-band gain deviation from an ideally flat gain shall be constant to within ±0.5 dB over $\pm 1.5 * F_{\text{chip}}$.

3.4.3.3 Acquisition Time and Probability

The on-board receiver shall be able to acquire the ranging code phase in a time (T_{acq}) corresponding to an SNR degradation of less than two dB relative to the theoretical acquisition time given in table 3-2 for a probability of acquisition greater than 99.9%. The acquisition performances are related to the ranging power over noise spectral density (P_r/N_o) and to the selected ranging code (code family and chip rate) given in 3.2 and 3.3.3. For other P_r/N_o ratios, the maximum acquisition time shall be computed by dividing the value in table 3-2 by $10^{(P_r/N_o - 30)/10}$.

[8] The frequency shifts and rates given here correspond to typically expected values. The P_r/N_o ratios are the currently expected lower limits of typical deep space missions; the PN ranging equipment may be able to operate at a lower threshold.

Table 3-2: Theoretical Ranging Code Phase Acquisition Time for the On-Board Receiver

Sequence	Theoretical acquisition time[9] T_{acq} at P_r/N_o=30 dBHz
Balanced Weighted-voting Tausworthe, ν=4	85.7 s
Balanced Weighted-voting Tausworthe, ν=2	5.2 s

3.4.4 ON-BOARD RANGING DELAY STABILITY

For the purpose of ranging measurement, the on-board ranging delay shall meet the following requirements:

– the average ranging delay shall be constant to within ±1/(30* F_{chip}) or ±20 ns, whichever is larger;[10]

– it shall be possible to calibrate the transponder delay from engineering status telemetry such as uplink frequency and power level, power supply voltage, and temperature to an accuracy of ±1/(500* F_{chip}) or ±1 ns, whichever is larger.

3.4.5 ON-BOARD RANGING JITTER PERFORMANCE

The on-board receiver shall track the ranging chip rate with a jitter corresponding to an SNR degradation of less than two dB relative to the theoretical jitter given in table 3-3 for a chip tracking loop bandwidth B_L=1 Hz and a chip rate of 2.068 Mchip/s. The tracking performance is related to the ranging power over noise spectral density (P_r/N_o), and to the selected ranging code (code family and chip rate) given in 3.2 and 3.3.3.

Table 3-3: Theoretical (One-Way) Ranging Jitter for the On-Board Receiver

Sequence	Theoretical jitter[11] at P_r/N_o=30 dBHz
Balanced Weighted-voting Tausworthe, ν=4	0.87 m
Balanced Weighted-voting Tausworthe, ν=2	1.29 m

[9] Assuming six parallel correlators under ideal conditions and with soft quantization of the chip detection filter output.

[10] This specification applies for any values within the nominal range of carrier frequency (taking into account Doppler shift), input level, modulation index, power supply, temperature, and lifetime.

[11] Assuming uplink baseband shaping or on-board filtering, and on-board chip tracking loop under ideal conditions.

3.4.6 DOWNLINK MODULATION

3.4.6.1 Modulating Signal

The on-board transmitter shall modulate the downlink carrier with the on-board regenerated ranging signal.

3.4.6.2 Modulation Scheme

The ranging signal shall be linearly modulated on the downlink carrier; i.e., a positive transition of −1 to +1 in the base-band code shall result in an advance of the transmitted RF carrier phase.

3.4.6.3 Base-Band Shaping

Base-band shaping should be used on the PN ranging signal to conserve bandwidth at high chip rates and high modulation indexes.[12]

3.4.6.4 Base-Band Shaping Filter Impulse Response

The shaping filter shall have the following impulse response:

$$h(t) = h_{\sin}(t) = \begin{cases} \sin(\pi t / T_c) & t \in [0, T_c] \\ 0 & elsewhere \end{cases}$$

where T_c is the chip duration.

3.4.6.5 On-Board Nonlinearities

The phase response shall not deviate more than ±5 degrees from a linear phase-frequency relationship over the frequency range of $\pm 1.5 * F_{\text{chip}}$.

The transmit in-band gain deviation from an ideally flat gain shall be constant to within ±0.5 dB over $\pm 1.5 * F_{\text{chip}}$.

3.4.6.6 Downlink Chip Rate

The downlink chip rate shall be frequency coherent with the uplink chip rate. When the transponder is in coherent mode, the downlink chip rate shall also be frequency coherent with the downlink carrier. The phase of the transmitted code shall also be coherent with the received code phase.

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[12] Reference [C1] may be consulted for the analysis of occupied bandwidth versus modulation index.

3.5 GROUND STATION DOWNLINK PROCESSING

3.5.1 OVERVIEW

This subsection provides recommendations for ground station downlink (receive) processing for PN ranging.

3.5.2 RECEIVER DOWNLINK PROCESSING

The ground station receiver shall implement the following ranging functions:

– carrier tracking and ranging signal demodulation when the downlink modulation is as specified in 3.4.6;

– chip rate acquisition and tracking;[13]

– code acquisition and tracking;

– comparison of transmit and receive code epochs for ranging delay evaluation.

NOTE – Ranging and telemetry functions are typically performed at the same time.

3.5.3 STATION PERFORMANCE

The station receiver shall be able to acquire the PN code for the whole dynamic range of input signal power (down to the minimum P_r/N_o), frequency shift ($\Delta f/f$), and Doppler rate (R). These values will depend on the selected mission. The following two operating regions are foreseen:[14]

– -10 dBHz $\leq P_r/N_o \leq 30$ dBHz; $\Delta f/f \leq 60$ ppm; R<0.02 ppm/sec;

– $P_r/N_o > 30$ dBHz; $\Delta f/f \leq 120$ ppm; R<0.2 ppm/sec.

NOTE – The aided acquisition strategy (using the carrier frequency to estimate the chip rate value) helps keep the ranging signal within the loop pull-in range when using a narrow code loop bandwidth. This is particularly useful in case of low P_r/N_o.

3.5.4 ACQUISITION TIME AND PROBABILITY

The station receiver shall be able to acquire the ranging code phase in a time (T_{acq}) corresponding to an SNR degradation of less than 0.5 dB relative to the theoretical acquisition time given in table 3-4, for a probability of acquisition greater than 99.9%. The acquisition performances are related to the received P_r/N_o, and to the selected ranging code (code family and chip rate) given in 3.2 and 3.3.3. For other P_r/N_o ratios, the maximum acquisition time shall be computed by dividing the value in table 3-4 by $10^{(P_r/N_o-30)/10}$.

[13] Coherent carrier and code downlink signal allows the use of on-ground code-aided acquisition/tracking loop; this is particularly useful in case of low SNR.

[14] The frequency shifts and rates given here correspond to typically expected values. The P_r/N_o ratios are the currently expected lower limits of typical deep space missions; the PN ranging equipment may be able to operate at a lower threshold.

Table 3-4: Theoretical Ranging Code Phase Acquisition Time for the Station Receiver

Sequence	Theoretical acquisition time[15] T_{acq} at P_r/N_o=30 dBHz
Balanced Weighted-voting Tausworthe, ν=4	4.3 s
Balanced Weighted-voting Tausworthe, ν=2	0.26 s

3.5.5 STATION GROUP DELAY STABILITY

The station group delay shall be constant to within ±2 ns over a period of 12 hours.

3.5.6 STATION RANGING JITTER PERFORMANCE

The station receiver shall track the ranging chip rate with a jitter[16] corresponding to an SNR degradation of less than one dB relative to the theoretical jitter given in table 3-5 for a chip tracking loop bandwidth B_L=1 Hz and a chip rate of 2.068 Mchip/s. The tracking performance is related to the ranging power over noise spectral density (P_r/N_o), and to the selected ranging code (code family and chip rate) given in 3.2 and 3.3.3.

Table 3-5: Theoretical (One-Way) Ranging Jitter for the Station Receiver

Sequence	Theoretical jitter[17] at P_r/N_o=30 dBHz
Balanced Weighted-voting Tausworthe, ν=4	0.78 m
Balanced Weighted-voting Tausworthe, ν=2	1.17 m

3.5.7 STATION TIME TAGGING ACCURACY

The station receiver shall time tag the ranging delay measurement with an uncertainty relative to UTC of less than one microsecond.

[15] Assuming 76 parallel correlators under ideal conditions and with soft quantization of the matched filter output.
[16] The worst-case end-to-end ranging jitter performance is given by the Root Sum Squared (RSS) of the on-board and station contributions. Depending on the ratio of on-board and station loop bandwidths, the actual performance can be better than the RSS value.
[17] Assuming downlink baseband shaping and station matched receiver under ideal conditions. In case of open loop receiver based on I-Q correlator, the same performance is obtained by setting the integration time T equal to $1/(2B_L)$ or 0.5 sec for B_L=1 Hz.

4 TRANSPARENT PSEUDO-NOISE RANGING

4.1 OVERVIEW

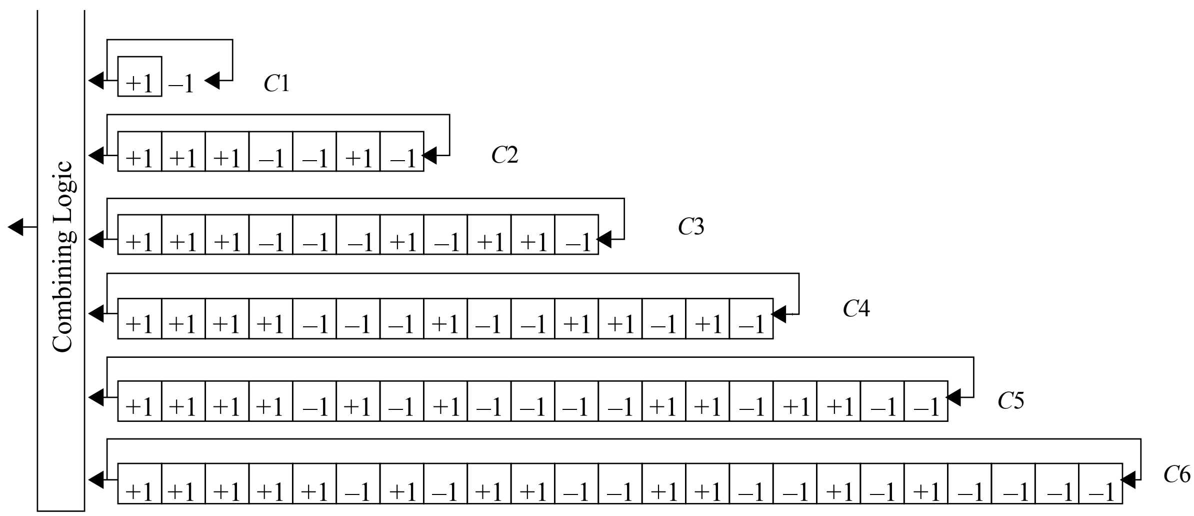
This section provides recommendations for transparent PN ranging. Specifically, recommendations are made for the PN code structure, ground station transmit (uplink) processing, on-board transparent processing, and ground station receive (downlink) processing.

4.2 PN CODE STRUCTURE

For transparent range measurements, the PN ranging code called Weighted-voting balanced Tausworthe, ν=2 (T2B) shall be selected.

The code is made up of six binary (±1) periodic ‘component sequences’ with a combination algorithm based on giving ν=2 votes to the clock component *C*1 as shown in figure 4-1.

The resulting ranging sequence C is periodic with length $L = 2 \times 7 \times 11 \times 15 \times 19 \times 23 =$ 1,009,470 chips.



where the combined sequence is $C = sign(2\,C1 + C2 - C3 - C4 + C5 - C6)$

Figure 4-1: Transparent T2B PN Code Generation

4.3 GROUND STATION UPLINK PROCESSING

4.3.1 OVERVIEW

This subsection provides recommendations for ground station uplink (transmit) processing for PN ranging.

4.3.2 UPLINK MODULATION

4.3.2.1 Modulating Signal

The ground station transmitter shall modulate the uplink carrier with the PN code specified in 4.2.

4.3.2.2 Modulation Scheme

The ranging signal shall be linearly phase modulated on the uplink carrier; i.e., a positive transition of −1 to +1 in the base-band code shall result in an advance of the transmitted RF carrier phase.

4.3.2.3 Base-Band Shaping

Base-band shaping should be used on the PN ranging signal to conserve bandwidth at high chip rates and high modulation indexes.[18]

4.3.2.4 Base-Band Shaping Filter Impulse Response

The shaping filter shall have the following impulse response:

$$h(t) = h_{\sin}(t) = \begin{cases} \sin(\pi t / T_c) & t \in [0, T_c] \\ 0 & elsewhere \end{cases}$$

where T_c is the chip duration.

4.3.2.5 Ranging and Telecommand

Ranging according to this standard and telecommand as specified in CCSDS 401.0-B 2.2.4 and 2.2.7 (reference [1]) may be performed at the same time.

4.3.3 UPLINK CHIP RATE

The ranging signal chip rate shall be frequency coherent with the uplink carrier as given in 3.3.3.

[18] Reference [C1] may be consulted for the analysis of occupied bandwidth versus modulation index.

4.4 ON-BOARD TRANSPARENT PROCESSING

4.4.1 OVERVIEW

This subsection defines the on-board spacecraft functions and performances for transparent ranging. Sections 4.4.2 and 4.4.7 are required for cross support while sections 4.4.3, 4.4.4, 4.4.5, and 4.4.6 are based on good engineering practice and could be relaxed depending on the specific mission requirements.

4.4.2 PROCESSING FUNCTIONS

The on-board transponder shall implement the following ranging functions:

– carrier tracking and ranging signal demodulation;

– video ranging signal filtering and Automatic Level Control (ALC);

– downlink signal modulation.

As far as the processing of the ranging signal is concerned, either a frequency coherent or non-coherent transponder can be used.[19] The performance specification in this standard assumes a frequency coherent transponder.[20]

These requirements shall be applied in all the operational modes such as telecommand on/off and telemetry on/off.

4.4.3 RANGING CHANNEL NON-LINEARITIES

4.4.3.1 In-Band Group Delay Variation

The end-to-end in-band group delay variation of the ranging channel shall be constant to within ±1/(30* F_{chip}) in the range from (F_{chip} /8) to (1.0* F_{chip}).

4.4.3.2 Gain Flatness

The end-to-end in-band gain deviation from an ideally flat gain shall be constant to within ±0.5 dB in the range from (F_{chip} /8) to (1.0* F_{chip}).

[19] In case of coherent approach, carrier and PN code chip rate received at the ground station are coherent (as in the uplink case); this can be used at the ground station for code-aided acquisition/tracking loop, for instance, in case of low SNR.

[20] The correlation loss for non-coherent operations can be found in the PN Ranging Systems Green Book (see reference [C1]).

4.4.4 3-DB BANDWIDTH

The –3 dB frequencies shall be below (F_{chip}/50) or 3 kHz, whichever is larger, and above (1.5* F_{chip}) from the carrier.

4.4.5 ONE-SIDED NOISE BANDWIDTH

The one-sided noise bandwidth shall be ≤ 1.8* F_{chip}.

4.4.6 ON-BOARD RANGING DELAY STABILITY

For the purpose of ranging measurement, the on-board ranging delay shall meet the following requirements:

- the average ranging delay shall be constant to within ±1/(30* F_{chip}) or ±20 ns, whichever is larger;[21]
- it shall be possible to calibrate the transponder delay from engineering status telemetry such as uplink frequency and power level, power supply voltage, and temperature to an accuracy of ±1/(500* F_{chip}) or ±1 ns, whichever is larger.

4.4.7 DOWNLINK MODULATION

The baseband ranging signal after filtering and ALC control shall be applied to the downlink modulator using linear phase modulation; i.e., a positive phase shift on the Earth-to-space link shall give rise to a positive shift on the space-to-Earth link.

4.5 GROUND STATION DOWNLINK PROCESSING

4.5.1 OVERVIEW

This subsection provides recommendations for ground station downlink (receive) processing for PN ranging.

4.5.2 RECEIVER DOWNLINK PROCESSING

The ground station receiver shall implement the ranging function according to the following requirements:

- carrier tracking and ranging signal demodulation;

[21] This specification applies for any values within the nominal range of carrier frequency (taking into account Doppler shift), input level, modulation index, power supply, temperature, and lifetime.

- chip rate acquisition and tracking;[22]
- code acquisition and tracking;
- comparison of transmit and receive code epochs for ranging delay evaluation.

NOTE – Ranging and telemetry functions are typically performed at the same time.

4.5.3 STATION PERFORMANCES

The station receiver shall be able to acquire the PN code for the whole dynamic of input signal power (down to the minimum ranging power over noise spectral density, P_r/N_o), frequency shift ($\Delta f/f$), and Doppler rate (R). These values depend on the selected mission. The following two operating regions are foreseen:[23]

- 10 dBHz $\leq P_r/N_o \leq$ 30 dBHz, $\Delta f/f \leq$ 30 ppm, R<0.01 ppm/sec;
- $P_r/N_o >$ 30 dBHz, $\Delta f/f \leq$ 60 ppm, R<0.1 ppm/sec.

NOTE – The aided acquisition strategy (using the carrier frequency to estimate the chip rate value) allows keeping the ranging signal in the loop pull-in also in case of narrow code loop bandwidth. This is particularly useful in case of low P_r/N_o.

4.5.4 ACQUISITION TIME AND PROBABILITY

The station receiver shall be able to acquire the ranging code phase in a time (T_{acq}) corresponding to an SNR degradation of less than 0.5 dB relative to the theoretical acquisition time given in table 4-1 for a probability of acquisition greater than 99.9%. The acquisition performances are related to the input signal power (P_r/N_o), and to the selected ranging code (code family and chip rate) given in 4.2 and 4.3.3. For other P_r/N_o ratios, the maximum acquisition time shall be computed by dividing the value in table 4-1 by $10^{(Pr/No-10)/10}$.

Table 4-1: Theoretical Ranging Code Phase Acquisition Time for the Station Receiver (Transparent Ranging)

Sequence	Theoretical acquisition time[24] T_{acq} at P_r/N_o=10 dBHz
Balanced Weighted-voting Tausworthe, ν=2	26.2 s

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[22] Coherent carrier and code down-link signal allows the use of on-ground code-aided acquisition/tracking loop; this is particularly useful in case of low SNR.

[23] The frequency shifts and rates given here correspond to typically expected values. The P_r/N_o ratios are the currently expected lower limits of typical L1/L2 Lagrangian point missions; the PN ranging equipment may be able to operate at a lower threshold.

[24] Assuming 76 parallel correlators under ideal conditions and with soft quantization of the matched filter output.

4.5.5 STATION GROUP DELAY STABILITY

The station delay shall be constant to within ±2 ns over a period of 12 hours.

4.5.6 STATION RANGING JITTER PERFORMANCE

The station receiver shall track the ranging chip rate with a jitter corresponding to an SNR degradation of less than one dB relative to the theoretical jitter given in table 4-2 for a chip tracking loop bandwidth B_L=0.1 Hz and a chip rate of 2.068 Mchip/s. The tracking performance is related to the ranging power over noise spectral density (P_r/N_o), and to the selected ranging code (code family and chip rate) given in 4.2 and 4.3.3.

Table 4-2: Theoretical (One-Way) Ranging Jitter for the Station Receiver (Transparent Ranging)

Sequence	Theoretical jitter[25] at P_r/N_o=10 dBHz
Balanced Weighted-voting Tausworthe, ν=2	3.7 m

4.5.7 STATION TIME TAGGING ACCURACY

The station receiver shall time tag the ranging delay measurement with an uncertainty relative to UTC of less than one microsecond.

[25] Assuming downlink baseband shaping and station matched receiver under ideal conditions. In case of open loop receiver based on I-Q correlator, the same performance is obtained by setting the integration time T equal to $1/(2B_L)$ or 5 sec for B_L=0.1 Hz.

5 SECURITY

5.1 INTRODUCTION

The PN ranging system has several potential areas of security concern.

One security concern involves radio frequency jamming of the uplink and/or downlink ranging signal. Jamming of the ranging signal could lead to the total loss of ranging data, and potential navigation errors.

Another concern involves spoofing of the ranging signal. Spoofing could lead to erroneous range measurements, which could cause incorrect trajectory determination and, in the worst case, could lead to the failure or loss of the mission.

Likewise, interception and either modification or corruption of ranging measurements could lead to incorrect trajectory determination and possible loss of mission.

5.2 SECURITY CONCERNS WITH RESPECT TO THE CCSDS DOCUMENT

The PN ranging signal is vulnerable to jamming, although there are several mitigating factors. With respect to a deep space ranging scenario, there is limited availability of equipment capable of generating enough uplink power to effectively jam the spacecraft receiver at interplanetary distances. In addition, ranging passes are often over long durations, making it easy to detect and find the jamming signal source. All RF-based transmissions are subject to jamming unless they have been designed with anti-jam features (e.g., frequency hopping, spread spectrum).

Trajectory solutions are a combination of Doppler, ranging, and Delta-DOR measurements, and so spoofing of the ranging signal alone would be detectable because it would differ from the other measurements.

Undetected alteration/corruption of range data could cause erroneous trajectory solutions, resulting in navigation errors. Interception of range data could allow adversaries to locate and more accurately target the victim spacecraft. Alteration or corruption of range data could result in navigation errors or mission loss.

While these are all valid security concerns, they fall outside the purview of this standard, which applies only to the PN ranging physical layer.

5.3 POTENTIAL THREATS AND ATTACK SCENARIOS

Jamming of the ranging signal could result in the loss of ranging measurements. During a critical maneuver (e.g., spacecraft orbit insertion), jamming could cause uncertainty in the spacecraft trajectory or, in the worst case, cause navigation errors leading to loss of the spacecraft.

Spoofing of the PN ranging signal in such a manner to cause erroneous range measurements during critical trajectory maneuvers could have the same effect.

Intercepted and modified (or corrupted) range measurements could be sent to the control center and later to the navigation team. This could also result in navigation errors and loss of mission.

5.4 CONSEQUENCES OF NOT APPLYING SECURITY TO THE TECHNOLOGY

While these security issues are of concern, they are out of scope with respect to this document. This document specifies the PN ranging physical layer. Providing protection for the PN ranging, as well as for all other ranging services, should be provided by higher layers.

Range measurement integrity provides protection against undetected alternation/modification of range measurements. If range measurement integrity is not implemented, erroneous range measurements may result, which in turn may cause loss or failure of the mission.

Range measurement confidentiality provides protection against both undetected modification as well as unauthorized disclosure of the ranging data. If confidentiality is not implemented, range measurements could be intercepted by unauthorized entities, which could gain precise knowledge of the spacecraft location and range.

Jamming denies all range measurement data, and protection must be accomplished by physical-layer techniques such as spread spectrum and/or frequency hopping. This problem is somewhat mitigated by the amount of power and the size of antennas needed to communicate with spacecraft.

ANNEX A

SPECIFICATIONS FOR PN RANGING

(NORMATIVE)

Table A-1: Key Specifications for On-Board PN Regenerative Ranging

	Parameter Value
1 - Earth-to-Space Link (signal received on-board)	
1.1- Carrier frequency	2.1 GHz, 7.1 GHz, or 34.0 GHz bands
1.2 - Ranging signal-to-noise spectral density[26]	$P_r/N_o \geq$ 10 dBHz
1.3 - Chip Rate (F_{chip})	1 and 2 Mchip/s
1.4 - Carrier frequency and chip rate	Frequency coherent
2 - Spacecraft Transponder	
2.1 - Ranging signal acquisition performance degradation	< 2 dB from theoretical T_{acq} for Prob_acq > 99.9 %
2.2 - Transmitted carrier frequency (Ft)	2.2 GHz, 8.4 GHz or 32.0 GHz bands
2.3 - Transmitted carrier frequency and chip rate	Frequency coherent
2.4 - Ranging jitter performance degradation	< 2 dB from theoretical
3 - Space-to-Earth Link (signal received at the ground station)	
3.1 - Ranging signal-to-noise spectral density[26]	$P_r/N_o \geq -10$ dBHz
3.2 - Ranging signal acquisition performance degradation	< 0.5 dB from theoretical T_{acq} for Prob_acq > 99.9 %
3.3 - Ranging jitter performance degradation	< 1 dB from theoretical
3.4 – Ranging measurement time-tagging uncertainty	< 1 µs from UTC

[26] These are currently expected lower P_r/N_o limits of typical deep space missions; the PN ranging equipment may be able to operate at a lower threshold.

Table A-2: Key Specifications for PN Ranging and On-Board Transparent Channel

	Parameter Value
1 - Earth-to-Space Link (signal received on-board)	
1.1 - Carrier frequency	2.1 GHz, 7.1 GHz, or 34.0 GHz bands
1.2 - Ranging signal-to-noise spectral density[27]	$P_r/N_o \geq 10$ dBHz
1.3 - Chip Rate (F_{chip})	1 and 2 Mchip/s
1.4 - Carrier frequency and chip rate	Frequency coherent
2 - Space-to-Earth Link (signal received at the ground station)	
2.1 - Carrier frequency	2.2 GHz, 8.4 GHz, 32.0 GHz bands
2.2 - Transmitted carrier frequency and chip rate	Frequency coherent
2.3 - Effective ranging modulation index	As per link budget
2.4 - Carrier (unmodulated) signal-to-noise spectral density	C/No > 21 dBHz
2.5 - Ranging signal-to-noise spectral density[27]	$P_r/N_o \geq +10$ dBHz
2.6 - Ranging signal acquisition performance degradation	< 0.5 dB from theoretical T_{acq} for Prob_acq > 99.9 %
2.7 - Ranging jitter performance degradation	< 1 dB from theoretical
2.8 – Ranging measurement time-tagging uncertainty	< 1 µs from UTC

[27] These are currently expected lower P_r/N_o limits of typical L1/L2 Lagrangian point missions; the PN ranging equipment may be able to operate at a lower threshold.

ANNEX B

EXAMPLE OF AVAILABLE CHIP RATES

(INFORMATIVE)

An example of available chip rates for an uplink frequency of 7179.000 MHz is shown in table B-1. The highlighted chip rates (obtained by using l=4, k=6 and l=8, k=6) correspond to the cross support (interoperability) rates.

Table B-1: Example of Available Chip Rates

l	*k*	F_{chip}, kchips/s
2	10	32.322
2	9	64.643
2	8	129.287
1	6	258.574
2	6	517.148
3	6	775.721
4	6	1034.295
5	6	1292.869
6	6	1551.443
7	6	1810.016
8	6	2068.590
9	6	2327.164
10	6	2585.738
11	6	2844.311
12	6	3102.885
16	6	4137.180
32	6	8274.361
64	6	16548.721

ANNEX C

INFORMATIVE REFERENCES

(INFORMATIVE)

[C1] *Pseudo-Noise (PN) Ranging Systems*. Issue 2. Report Concerning Space Data System Standards (Green Book), CCSDS 414.0-G-2. Washington, D.C.: CCSDS, January 2014.

[C2] J. B. Berner, et al. "Regenerative Pseudo-Noise Ranging for Deep-Space Applications." *TMO Progress Report* 42-137 (May 15, 1999). <http://tmo.jpl.nasa.gov/progress_report/42-137/137G.pdf>

[C3] *Pseudo-Noise and Regenerative Ranging*. Module 214 in *DSN Telecommunications Link Design Handbook*. DSN No. 810-005. Pasadena California: JPL, April 8, 2013.

[C4] R. C. Titsworth.[28] "Optimal Ranging Codes." IEEE Transactions on Space Electronics and Telemetry 10, no. 1 (March 1964): 19–30.

[C5] J. L. Massey, "Study on PN Ranging Codes for Future Missions," Final Report, ESA/ESOC Contract No. 17954/03/D/CS(SC), November 2004.

[C6] J. L. Massey, "Study on PN Ranging Codes for Transparent Channels," Final Report, ESA/ESOC Contract No. 20432/07/D/CS(SC), November 2007.

NOTE – Normative references are provided in 1.6.

[28] Subsequent to publication of this paper, the author changed his surname to Tausworthe.

ANNEX D

ABBREVIATIONS AND ACRONYMS

(INFORMATIVE)

Term	Definition
ALC	automatic level control
F_{chip}	chip rate
PN	pseudo-noise
ppm	parts per million
RSS	root sum squared
SNR	signal-to-noise ratio
T_C	chip duration
UTC	universal time (coordinated)