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PN Ranging Requirements (AI_03-03 from CCSDS Fall Meeting)

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1. Scope

Scope of this document is to provide a set of preliminary requirements (on PN ranging) to be used for further discussions inside the CCSDS Ranging Working Group, whose target is to generate the CCSDS Recommendations for this novel ranging technique. Note that the PN ranging codes have not yet been decided. ESA has started with Prof. J.Massey an activity (see REF-7); the preliminary results will be presented at this CCSDS section (see paper RNG_04-03). In spite of this situation (we are still in a preliminary phase), it was decided to organise the document addressing in detail all the paragraphs. Of course the document is full of TBC and TBD, however several notes have been added in order to help the discussion.

At present the intention is to cope both the following approaches: the on-board regenerative case and the transparent solution.

2. Introduction

There are several up-coming missions requiring more accurate spacecraft position and orbit determination. In several cases, a possible solution to cope with these new requirements might be the application of the regenerative ranging. As indicated in [*REF-2*], the *Regenerative Ranging* will present several advantages with respect to the classical *Sequential Ranging*, which is the approach at present used both by ESA and NASA ground station. This novel technique requires the use of PN codes with important impacts for on-board transponder design, ground station processing and ranging procedure.

However, even though the advantages of the regenerative ranging are mainly relevant to the low SNR case (for instance in deep space missions), in the following we want to consider also the approach based on PN ranging and transparent on-board processing. This solution results very attractive in presence of good link margin (for instance in near Earth applications) or when accurate performances are not needed. Indeed the transponder based on transparent ranging channel present a reduced complexity with respect to the regenerative case, still keeping the compatibility in terms of signal modulation and measurement procedure.

3. References Documents

[*REF-1*] *“Operation Comparison of Deep Space Ranging Types: Sequential Tone vs Pseudo-Noise’’*, J.F.Berner, S.C.Bryan, IEEE 2002

[*REF-2*] *“Advantages of Regenerative Ranging for Deep Space Navigation”,* J.F.Berner, P.W.Kinman, J.M.Layland, presentation at DESCANSO Symposium

[*REF-3*] *“Regenerative Pseudo-noise Ranging for Deep Space Applications”,* J.F.Berner, J.M.Layland, P.W.Kinman, R.Smith, TMO Progress Report 42-137, May 1999

[*REF-4*] *“The NASA Spacecraft Transponding Modem”,* J.F.Berner, S.Kayalar, J.D.Perret, IEEE 2000

[*REF-5*]: “*Fast Acquisition Sequences”*, J.Ganz, A.P.Hilgen, J.L.Massey, Proc.6th Int Symp. on Comm. Theory and Appl., Ambleside, England, 15-20 July 2001, pp471-476

[*REF-6*] *"Regenerative Ranging"*, G.Boscagli, L.Simone, D.Gelfusa, CCSDS SLS-RFM_03-05, October 2003

[*REF-7*] *“Study of PN Ranging Code for Future Mission*", DTOS-GS-SOW-1001-TOS-OW, 12 November 2003.

4. Requirements

4.1 Signal structure

4.1.1 Transparent and Regenerative Case

The same signal (same modulation format and codes) shall be used independently by the on-board processing approach (whether for regenerative or transparent[1] case).

[1] For instance in case of Smith/Tausworth/Titsworth code family, different performances are expected at ground station when selecting different codes of the family [*REF-1*]. In this case the optimum selection of the code family and code set must be done considering the best acquisition performances both for the regenerative and transparent case.

4.1.2 PN Code Family

The code type (family) is TBD[2]. The code shall be selected according to the following items[3]:

- performances in terms of acquisition time/probability in particular for low SNR
- ambiguity resolution (ambiguity after code acquisition > 150000 Km, TBC)
- optimised spectral occupancy to minimise interference effects on telecommand, telemetry and contiguous channel.

4.1.3 Use of the PN codes in the Ranging Measurements

The chip rate and the performances of the chip-tracking loop (both for on-board and ground station receiver) characterise the accuracy of the ranging measurement. The length of the whole sequence defines the ambiguity of the measurement.

4.1.4 Up-link Signal Modulation

The up-link signal modulation is based on linear phase modulation[4]. The modulation index shall be selected in the range according to the present standard (TBC) based on sequential ranging.

4.1.5 Up-link Chip Rate

The chip rate shall be $Fchip < \mathrm{TBD}$[5] Mchip/sec.

The ranging signal shall be frequency coherent with the up-link carrier ($F\_carrier\_up$)[6]:

$$Fchip = F\_carrier\_up \frac{N}{M}.$$

[2] At present there are implementations based on Smith/Tausworth/Titsworth codes, however the selection of the ranging codes is subjected to the final decision in the frame of the CCSDS Ranging Working Group (see REF-6 and REF-7). ESA has placed a study contract with Prof. J.Massey for the study of the PN codes to be used for ranging application. Annex-1 reports the preliminary specification annexed to the contract.

[3] Note that the Smith/Tausworth/Titsworth codes present a structure very similar to a square-wave, this simplifies the acquisition processing with good performances in case of operation at low SNR.

[4] The use of residual carrier minimises the impact on the current design (both for on-board and ground stations) and on operation procedures. Besides it is the best approach in case of low SNR (as for deep space mission).

[5] As first cut, at an increasing of the chip rate value, we can consider the following:

- Better accuracy in the ranging measurement (for high Ec/No, Ec=chip energy, No=noise spectral density)
- Reduced performances at low Ec/No with increasing of ranging operative threshold
- Stronger impact regarding on-board complexity, including on the filtering actions to avoid interference on contiguous channels and on the TC and TM signal components.

[6] This allows simplifying the on-board processing for code signal acquisition/tracking.

N and M are integer values defined accordingly to the following table (TBC)[7].

	S-Band (RX freq = 221F1)		X-Band (RX freq = 749F1)	
Chip Rate [(a)]	**N**	**M**	**N**	**M**
(1/18) F1≈*530 KHz*	1	221*18	1	749*18
(2/18) F1≈*1.06 MHz*	1	221*9	1	749*9
(3/18) F1≈*1.60 MHz*	1	221*6	1	749*9
(4/18) F1≈*2.12 MHz*	2	221*9	2	749*9
(5/18) F1≈*2.66 MHz*	5	221*18	5	749*18

The selection of the chip rate value shall be performed in order:

- To avoid spurious contribution at the transponder receiver frequency
- To avoid spurious contribution at the transponder transmitter frequency
- To avoid interference on up-link TC, downlink TM and contiguous channels
- To optimise the acquisition/tracking performances and the accuracy of the ranging measurement

4.1.6 In-flight Chip Rate selection

It could be required from some missions to command in-flight the transponder. This allows the proper chip rate selection according to the mission profile[8]. The selection of the proper chip rate shall be performed among the values indicated in section 4.1.5 and stored inside the transponder before the launch

4.1.7 Down-link Signal Modulation

The downlink signal can be Linear Phase[9] or Suppressed Carrier[10] (TBC) modulated, as detailed in the following sections. The Suppressed Carrier modulation is applicable in case of regenerative ranging only; in this case we have a hybrid transponder approach based on linear phase modulation in up-link and suppressed carrier modulation for the downlink.

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[7] There are also other proposals for N and M figures. For the X-band case, in [REF-3] we have N=221, M=23968*32= (749*32)*32.

[8] This solution allows to cope, during the mission, with different requirements for instance due to link dynamics (Doppler, signal to noise ratio, etc) and interference issues (TM, TC and contiguous channels).

[9] The use of residual carrier minimises the impact on the current design (both for on-board and ground stations) and on operation procedures. Besides it is the best approach in case of low SNR (as for deep space mission).

[10] Suppressed Carrier modulation might be particular useful in case of high TM data return. It must be underlined that in this case, the use of balanced or “quasi-balanced” codes (same or “quasi-same” number of “1” and “-1” logical level) is mandatory in order to have the proper carrier suppression and to avoid degradation in the carrier tracking and TM demodulation at the ground station receiver. Indeed a non-balanced code will generate a residual component at carrier frequency (orthogonal in phase w.r.t. the TM component), which will degrade the demodulation performances.

4.1.8 Down-link Chip Rate

The down-link chip rate shall be frequency coherent with the up-link chip rate. In case of transponder in coherent mode (*K* = carrier coherent turn around ratio), the ranging signal shall be frequency coherent with the downlink carrier as in the following:

$(F\_carrier\_down = F\_carrier\_up \times K)$[11]

$Fchip = F\_carrier\_down \dfrac{N}{M \times K}$, where *N* and *M* are as above defined (see para.4.1.5).

4.2 On-baord transparent processing[12]

4.2.1 Processing Functions

a. The on-board transponder shall implement the following ranging functions[13]:
   - Carrier tracking and ranging signal demodulation
   - Video Ranging signal filtering and ALC control (to control the down-link modulation index)
   - Down-link signal modulation.

b. The following two independent mode selections shall be accessible by telecommand:
   - Transponder coherent / non-coherent[14]
   - Ranging modulation on/off.

c. These requirements shall be applied in all the operational modes as up-link TC on/off and down-link TM on/off.

4.2.2 Ranging channel non lineraities[15]

a. In-band group delay variation (TBC) - For minimization of spectral distortion, the end-to-end in band group delay variation of the ranging channel shall be constant to within +/- 1/(30* $Fchip$) in the range from ($Fchip$/4) to (7* $Fchip$/4).

b. Gain flatness (TBC) - The end-to-end in band gain deviation from an ideally flat gain shall be constant to within +/- 0.1 dB in the range from ($Fchip$/2) to (3* $Fchip$/2).

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[11] This allows simplifying the ground station processing for code signal acquisition/tracking.
[12] Commonality with the present specification relevant to sequential ranging should be considered. In this way the same transponder could be used for both transparent approaches: PN and sequential.
[13] The same function performed by the transparent channel in case of sequential ranging approach.
[14] In case of carrier coherent turn around approach, the signal received at ground station is carrier and code coherent as well (as the up-link); this can be used at the ground station for code aided acquisition/tracking loop in particular in case of low SNR.
[15] Requirements needed for the minimization of spectral distortion.

4.2.3 3-dB Bandwidth (TBC)

The –3dB frequencies shall be below ($Fchip/4$) and above ($7*Fchip/4$) from the carrier.

4.2.4 One-side Noise bandwidth

The one-side noise bandwidth shall be $\leq 2.5*Fchip$ (TBC).

4.2.5 Ranging delay variation

a. For the purpose of ranging measurement, the end-to-end ranging delay shall be constant to within +/- $1/(30*Fchip)$[16] (TBC).

NOTE 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.

b. If specified by mission analysis, the capability of knowing the total on-board delay at any time to a mission-specific accuracy, by means of predicted Doppler and telemetered data of input level, power supply voltage, and temperature shall be implemented.

NOTE Typical values of calibration accuracy are +/- $1/(500*Fchip)$[17] (TBC).

4.2.6 Down-link Modulation

a. The video ranging signal after filtering and ALC control shall be applied to the down-link modulator for linear phase modulation

b. All the requirements from the present standard (based on sequential ranging) shall be kept, as modulation index selection range, modulator linearity, etc.

4.3 On-baord regenerative processing

4.3.1 Processing Functions

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

– carrier tracking and ranging signal demodulation

[16] +/-33 nsec for $Fchip$ =1 Mcps

[17] +/-1 nsec for $Fchip$ =2 Mcps

- chip rate selection via proper command (see section 4.1.6)
- chip rate acquisition and tracking[18],
- phase-code acquisition and tracking
- coherent retransmission of recovered code on the down-link signal.

b. The following two independent mode selections shall be accessible by telecommand:

- Transponder coherent / non-coherent [19]
- Ranging modulation on/off.

c. These requirements shall be applied in all the operational modes as up-link TC on/off and down-link TM on/off.

4.3.2 Ranging Signal Acquisition Performances

a. The on-board receiver shall acquire the PN code for the whole dynamic of input signal power (down to the minimum ranging power over noise spectral density, Pr/No), frequency shift (Df/F) and Doppler rate (R).

These values depend on the selected mission[20].

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 particular useful in case of low Pr/No.

b. Acquisition Time and Probability – The on-board receiver shall acquire the ranging code phase in a time (Tacq) less than TBD sec with a probability of acquisition greater that TBD% and a probability of false acquisition less than TBD% [21]. The acquisition performances are related to the input signal power

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[18] Coherent carrier and code up-link signal allows the use of on-board code aided acquisition/tracking loop; this is particular useful in case of low SNR

[19] In case of carrier coherent turn around approach, the signal received at ground station is carrier and code coherent as well (as the up-link); this can be used at the ground station for code aided acquisition/tracking loop in particular in case of low SNR.

[20] As first cut we can assume the following two operative ranges (TBC):

- Pr/No < 30 dBHz, Df/F≤30 ppm, R<0.01 ppm/sec.
- Pr/No > 30 dBHz, Df/F = +/-30 ÷ +/-60 ppm, R<0.1 ppm/sec.

Note that REF-3 and REF-6 (based on Smith/Tausworth/Titsworth code family) specify a minimum on-board Pr/No of about 27 dBHz, this value is justified in terms of acquisition performances (time and probability) as indicated in point b.

[21] As reference, for the Smith/Tausworth/Titsworth code family (see REF-6), we have the following preliminary requirements for a chip rate of 2Mcps: Pr/No= 27 dBHz, Tacq < 700 sec, Pd > 99.5%, Pfd < 10^{-6}; where Pd is the detection probability and Pfd is the false detection probability. Both probabilities are on a single test basis, for this kind of codes we need a maximum of 23 tests (correlations) to recover the phase of incoming code.

(Pr/No), frequency shift (Df/F), Doppler rate (R) and selected ranging code (code family and chip rate).

4.3.3 Ranging Lock Status

a. Two separate lock status (TBC) shall be provided as telemetry information to the on-board computer:

- the chip rate code tracking loop status (lock/unlock) (TBC)
- the code phase detection status (detected/no-detected)

b. The code phase detection status (which gives the global result on the code acquisition/tracking algorithm) shall be used to activate the ranging turn-around function with the application of the recovered ranging signal to the downlink modulator for transmission.

4.3.4 On-board Ranging Stability

a. For the purpose of ranging measurement, the end-to-end ranging delay shall meet the following requirements.

- The average ranging delay (when averaged over a period of TBD sec[22] shall be constant to within +/- 1/(30* *Fchip*)[23] (TBC).
- The rms value (as measured in TBD sec) shall be less than TBD nsec[24].

NOTE 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.

NOTE The chip rate tracking loop performances are crucial for the overall ranging accuracy. Two different tracking errors must be considered: the jitter and the steady state error.

- The jitter is mainly due to the SNR in the loop and related to the up-link signal power (Pr/No) and the tracking loop bandwidth
- The steady state error is mainly due to the input signal dynamic and the loop characteristics. Note that, for a first order

[22] It is strongly related to the uplink signal power (Pr/No).

[23] +/-33 nsec for *Fchip* =1 Mcps

[24] It depends on the uplink signal power (Pr/No).

loop, any frequency shift (Doppler) of the input chip rate will appear as a steady state error in the tracking loop. Besides this error is frequency shift dependent. This can be eliminated implementing a second order loop or using the aided acquisition /tracking approach (in case of carrier and code coherent signal)[25].

b. If specified by mission analysis, the capability of knowing the total on-board delay at any time to a mission-specific accuracy, by means of predicted Doppler and telemetered data of input level, power supply voltage, and temperature shall be implemented.

NOTE Typical values of calibration accuracy are +/- $1/(500 * F_{chip})$[26] (TBC).

4.3.5 Down-link Modulation

4.3.5.1 Linear Phase Modulation

a. The regenerated ranging signal shall be applied to the down-link modulator for linear phase modulation

b. All the requirements from the present standard (based on sequential ranging) shall be kept, as modulation index selection range, modulator linearity, etc.

c. Base-band shaping might be required (TBC) on the PN ranging signal[27].

d. TX non-linearities[28]

- Phase non-linearity – The deviation from the phase non-linearity must not exceed TBD degrees over the frequency range of +/- TBD MHz.
- Gain flatness - The Tx in band gain deviation from an ideally flat gain shall be constant to within +/- TBD dB.

[25] Note that Doppler rate is in general negligible.
[26] +/-1 nsec for F_{chip} =2 Mcps
[27] Base-band shaping filter might be required in order to reduce the interference effects on the TM signal. Besides, the knowledge (on-ground) of the on-board filtering on the ranging signal component might improve the ranging measurement, when using the proper matched filtering at the receiver ground station. The overall ranging performances shall be analysed versus on-board shaping filtering as well.
[28] Requirements needed for the minimization of spectral distortions on the downlink ranging signal.

4.3.5.2 Suppressed Carrier Modulation (TBC) [29]

a. The regenerated ranging signal shall be applied to the Q-branch (TBC) of the down-link modulator. The I-branch will be used for down-link telemetry data[30].

b. Balanced (QPSK) or un-balanced UQPSK Modulation can be used depending on the required link performances. The Q/I ratios are: TBD (depending on the link budget, TM symbol rate and overall ranging performances).

c. Base-band shaping (SRRC, TBC) might be required (TBC) on the PN ranging signal in order to avoid interference on contiguous RF channels[31].

d. TX non-linearities[32]

- Phase non-linearity – The deviation from the phase non-linearity must not exceed TBD degrees over the frequency range of +/- TBD MHz.
- Gain flatness - The Tx in band gain deviation from an ideally flat gain shall be constant to within +/- TBD dB.
- AM/PM Conversion – The AM/PM conversion induced between the modulator and the transmitter output shall not exceed TBD degrees/dB.

4.4 Ground Station

4.4.1 TX Processing Functions

The ground station transmitter shall implement the ranging function according to the following points:

- Modulation of the up-link carrier with the PN code
- Chip rate coherent with the carrier frequency
- Base-band shaping (TBC) on the PN sequence[33].

NOTE Ranging shall be applied only after on-board carrier acquisition.

[29] Suppressed carrier modulation could be very useful in case of high data rate needs (due to considerable scientific data return). This is applicable also for deep space missions (as missions to Mars and Mercury), which make use of on-board High Gain antennas and High Power Amplifier. In this case, un-balanced QPSK, with more power for TM signal, can be also considered.

[30] Note that different (and un-correlated) symbol rates are present on I-channel (TM data) and Q-channel (PN ranging signal).

[31] Note that the knowledge (on-ground) of the on-board shaping filtering on the ranging signal component might improve the ranging measurement, when using the proper matched filtering at the receiver ground station. The overall ranging performances shall be analysed versus on-board shaping filtering as well.

[32] Requirements needed for the minimization of spectral distortions on the down-link TX signal.

[33] Base-band shaping might be used due to spectral constrains and to avoid interference on the other signal components: TC and TM (in case of on-board transparent processing).

NOTE Ranging and telecommand functions can be performed at the same time.

4.4.2 RX Processing Functions

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

- carrier tracking and ranging signal demodulation
- chip rate acquisition and tracking[34],
- phase-code acquisition and tracking,
- comparison of TX and RX code epochs for ranging delay evaluation

NOTE Ranging and telemetry functions can be performed at the same time.

NOTE These functions shall be implemented both for downlink residual and suppressed carrier modulation. In the first case a PLL is needed for carrier acquisition and tracking, while in the second case an architecture based on Costas loop is foreseen.

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

ANNEX–1

(From [*REF-7*] *“Study of PN Ranging Code for Future Mission*",
DTOS-GS-SOW-1001-TOS-OW, 12 November 2003)

Table A-1. Preliminary Specification for on-board PN Regenerative Ranging

	Parameter Value
1- Forward Link (signal received on-bard)	
1.1- Carrier frequency (Fr)	7.1 GHz and 34.0 GHz
1.2 - Linear phase modulation: ranging signal modulation index	0.1-1.4 rad. pk
1.3 - Onboard carrier (un-modulated) signal to noise spectral density	C/No > 26 dBHz (TBC)
1.4 - Ranging signal to noise spectral density	Pr/No = 10 dBHz and 30 dBHz
1.5 - Chip Rate (Fc)	1 - 2 Mcps
1.6 - Chip Rate: carrier and code coherent	Fr/Fc
2- Transponder	
2.1 - Carrier regeneration, ranging signal regeneration and coherent turn-around (carrier and code coherently retransmitted)	
2.2 – Baseband processing based on Digital Signal Processing for signal demodulation and modulation	
2.3 - Ranging signal acquisition: both aided and not-aided strategy shall be considered (*): Aided Not Aided *(*) Depending on transponder architecture and frequency plan*	 Knowledge of chip rate from carrier tracking Knowledge of the chip with a frequency uncertainty of TBD ppm
2.4 - Ranging signal acquisition after reception of the proper command : RNG ON	
2.5 - Ranging signal acquisition performances	Tacq < TBD sec Prob > TBD %
2.6 - Transmitted Carrier frequency (Ft)	8.4 GHz and 32.0 GHz
2.7 - Return Chip Rate: carrier and code coherent	Ft/Fc
2.8 - Down-link ranging signal modulation (linear phase modulation)	
2.9 – Ranging signal modulation index	0.1-0.7 rad pk
3- Return Link (signal received at the ground station)	
3.1 - On-ground carrier (un-modulated) signal to noise spectral density	C/No > 21 dBHz
3.2 - On-ground ranging signal to noise spectral density	Pr/No > TBD dBHz
3.3 - Ranging signal acquisition performances	Tacq < TBD sec Prob > TBD
3.4 – Ranging performances versus integration time	TBD meter (rms)

Table A-2: Preliminary Specification for PN Ranging and on-board transparent channel

3- Return Link (signal received at the ground station)	
3.1 - Carrier frequency (Ft)	8.4 GHz and 32.0 GHz
3.2 - Return chip rate Fc (coherent carrier and chip rate)	Ft/Fc
3.3 - Linear phase: effective modulation index	As per link budget
3.4 - On-ground carrier (un-modulated) signal to noise spectral density	C/No > 21 dBHz
3.5 - On-ground ranging signal to noise spectral density	Pr/No > -10 dBHz or lower
3.6 - Ranging signal acquisition performances	Tacq < TBD sec Prob > TBD %
3.7 - Ranging performances versus integration time	TBD meter (rms)