The Consultative Committee for Space Data Systems

Draft Recommendations for Space Data System Standards

RADIO FREQUENCY AND MODULATION SYSTEMS—

PART 1

EARTH STATIONS AND SPACECRAFT

DRAFT RECOMMENDED STANDARD

CCSDS 401.0-B-28.1

RED/PINK SHEETS

July 2018

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DOCUMENT CONTROL (continued)

DOCUMENT	TITLE	DATE	STATUS/REMARKS
CCSDS 401.0-B	Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft, Recommended Standard, Issue 24	October 2014	Updates recommendations 2.4.12A, 2.4.18, and 2.5.6B.
CCSDS 401.0-B	Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft, Recommended Standard, Issue 25	February 2015	Adds new recommendations 2.4.22A and 2.4.22B and updates recommendation 4.1.5.
CCSDS 401.0-B	Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft, Recommended Standard, Issue 26	October 2016	Adds new recommendation 2.4.23.
CCSDS 401.0-B	Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft, Recommended Standard, Issue 27	October 2017	– Updates recommendations 2.4.18 and 2.5.6B; – clarifies wording in 2.4.19 (editorial update); – applies editorial updates to 2.6.1–2.6.10A for consistency among related recommendations.
CCSDS 401.0-B	Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft, Recommended Standard, Issue 28	February 2018	– Updates recommendations 2.1.4A and 2.1.4B; – deletes recommendations 2.1.8A and 2.1.8B; – adds new recommendation 2.6.11A.
CCSDS 401.0-B	Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft, Draft Recommended Standard, Issue 28.1	July 2018	– Updates recommendations 2.4.17A, 2.4.22A, and 2.4.22B; – adds new recommendations 2.4.24 and 3.1.7.

NOTE – Markup is used to show changes to recommendations 2.4.17A, 2.4.22A, and 2.4.22B; new recommendations 2.4.24 and 3.1.7 are presented without markup.

2.4.17A MODULATION METHODS FOR HIGH SYMBOL RATE TRANSMISSIONS, SPACE RESEARCH, SPACE-TO-EARTH, CATEGORY A

The CCSDS,

considering

(a) that efficient use of RF spectrum resources is imperative with the increasing congestion of the frequency bands;

(b) that the SFCG has approved a Recommendation~~,~~[1] specifying a spectrum mask for *Space Research* Category-A Space-to-Earth links operating in certain bands~~;~~,[2] and a Recommendation[3] limiting the maximum bandwidth in the 8450–8500 MHz band to 10 MHz per mission;

(c) that suppressed carrier modulation techniques, such as GMSK[4] ~~and~~, baseband filtered OQPSK,[5] and filtered SRRC–8PSK[6] modulations, can meet the SFCG Recommended[1] spectrum mask for symbol rates in excess of 2 Ms/s;

(d) that since GMSK modulation is inherently differential in nature, the use of GMSK with precoding is necessary to optimize bit error rate performance;

(e) that GMSK[4] and baseband filtered OQPSK[5] modulation types can be demodulated using a conventional OQPSK receiver, but with differing end-to-end losses;

(f) that GMSK[4] and baseband filtered OQPSK[5] modulations have only a small performance degradation as compared with ideal unfiltered suppressed carrier systems, and that the performance degradation of filtered SRRC-8PSK[6] can be compensated by missions requiring higher symbol rates;

(g) that some space agencies currently have no plans to modify their existing OQPSK ground station receivers to optimize reception of GMSK[4] and baseband filtered OQPSK[5] signals, so that these two modulation techniques will incur greater losses than unfiltered OQPSK;[5]

(h) that GMSK and baseband filtered OQPSK modulations have immunity to interference (wideband and narrow band) comparable to unfiltered BPSK when demodulated with an OQPSK receiver matched to an unfiltered OQPSK waveform; the interference immunity of these modulations when demodulated with matched filter receivers is equivalent to or better than BPSK;

(i) that a phase imbalance of less than 5 degrees and an amplitude imbalance of less than 0.5 dB should result in acceptable performance degradations;

NOTES:

[1] See SFCG Recommendation 21-2R~~2~~4 or latest version.

[2] Category A bands are: 2200-2290 MHz and 8450-8500 MHz.

[3] See SFCG Recommendation 5-1R5 or latest version.

[4] Gaussian Minimum Shift Keying ($BT_S = 0.25$), with pre-coding as in figure 2.4.17A-1 (see CCSDS 413.0-G-3). B refers to the one-sided 3-dB bandwidth of the filter.

[5] Filtered (Square Root Raised Cosine $\alpha = 0.5$) Offset QPSK; Butterworth 6 poles, $BT_S = 0.5$; agencies may also utilize filtered OQPSK modulation with other types of bandpass filters provided that the equivalent baseband BT_S is not greater than 0.5 and they ensure compliance with SFCG Recommendation 21-2R2 (or latest version) and interoperability with the cross-supporting networks. B refers to the one-sided 3-dB bandwidth of the filter.

[6] Square Root Raised Cosine filter with $\alpha = 0.35$ (see Annex 1).

2.4.17A MODULATION METHODS FOR HIGH SYMBOL RATE TRANSMISSIONS, SPACE RESEARCH, SPACE-TO-EARTH, CATEGORY A (Continued)

noting

that the constellation bit mapping for SRRC-8PSK is different in CCSDS 131.2-B-1 and CCSDS 131.3-B-1;

that the sensitive deep space allocation (Category B) at 8400–8450 MHz has to be protected from Category A emission in the adjacent 8450–8500 MHz band;

recommends[7]

(1) that, to comply with the SFCG Recommendation[1,3] and to ensure an ability to obtain cross-support in certain *Space Research* service bands[2] GMSK[4] or baseband filtered OQPSK[5] be used for space-to-Earth transmissions when the telemetry data symbol rates exceed 2 Ms/s.

(2) that, to comply with the SFCG Recommendations,[1,3] SRRC-8PSK[6] be used for space-to-Earth transmissions when the data symbol rates exceed approximately 10 Ms/s in the 8450–8500 MHz band;

(3) that the modulator's phase imbalance shall not exceed 5 degrees, and the amplitude imbalance shall not exceed 0.5 dB between the constellation points;

(4) that Category A missions in the 8450–8500 MHz band consider using a post-HPA filter to protect adjacent Category B missions.

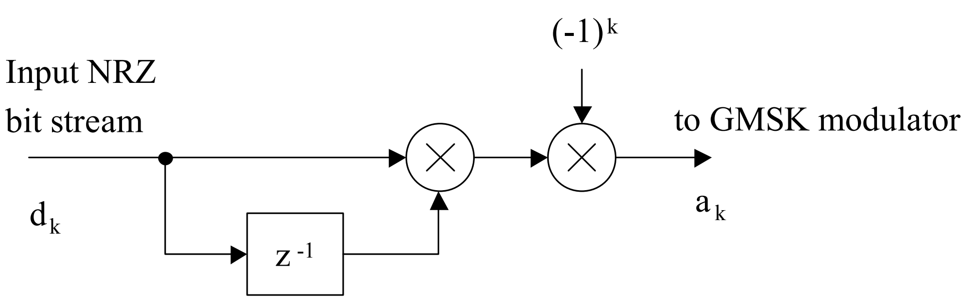

Figure 2.4.17A-1: GMSK Precoder

[7] Space agencies requiring cross-support should consider the performance degradation of the filtered OQPSK and GMSK modulation techniques when received with unmatched demodulators at existing ground stations (see performance data in CCSDS 413.0-G-3); the ordering of modulation types does not imply a preference.

2.4.17A MODULATION METHODS FOR HIGH SYMBOL RATE TRANSMISSIONS, SPACE RESEARCH, SPACE-TO-EARTH, CATEGORY A (Continued)

ANNEX 1

8PSK Modulation Definition

(Normative)

A1.1 GENERAL

The modulation formats here specified shall follow the template provided in table 2.4.17A-1.

Table 2.4.17A-1: Modulation Definition

Item	8PSK
Number of constellation concentric circumferences	1
Number of uniformly spaced points per circumference	N_1=8
Ratio of outer circle to inner circle radius	N.A.
Radii relation for unit average symbol level (average symbol energy =1)	N.A.
Bit-to-symbol mapping	Bits 3i (MSB), 3i+1, and 3i+2 (LSB) determine the i^{th} 8PSK symbol.
Constellation proper	(See figures 2.4.17A-4 and 2.4.17A-5.)

A1.2 SRRC CHANNEL FILTERING

The transfer function of the SRRC filter shall be:[8,9]

$$H(f)=1 \qquad \text{if } |f|<f_N(1-\alpha)$$

$$H(f)=\sqrt{\frac{1}{2}+\frac{1}{2}\sin\left\{\frac{\pi}{2f_N}\left(\frac{f_N-|f|}{\alpha}\right)\right\}} \qquad \text{if } f_N(1-\alpha)\le|f|\le f_N(1+\alpha)$$

$$H(f)=0 \qquad \text{if } |f|>f_N(1+\alpha)$$

where $f_N=1/(2\,T_{chs})=R_{chs}/2$ is the Nyquist frequency and α is the roll-off factor. The specified value for the roll-off factor is α = 0.35.

[8] SRRC filtering can be practically implemented with baseband filters able to fulfill SFCG Recommendation 21-2R4 (see CCSDS 413.0-G-3).

[9] This formulation yields an impulse-response function with dimensions of Hz (or 1/s). Sometimes in literature the transfer function is shown with a multiplication factor $\sqrt{T_{chs}}$ in front.

2.4.17A MODULATION METHODS FOR HIGH SYMBOL RATE TRANSMISSIONS, SPACE RESEARCH, SPACE-TO-EARTH, CATEGORY A (Continued)

ANNEX 1 (Continued)

A1.3 PHASE NOISE

The phase noise for all the oscillators of the communication chain shall be limited according to the mask given in figure 2.4.17A-2 for channel symbol rates above 1 Ms/s.

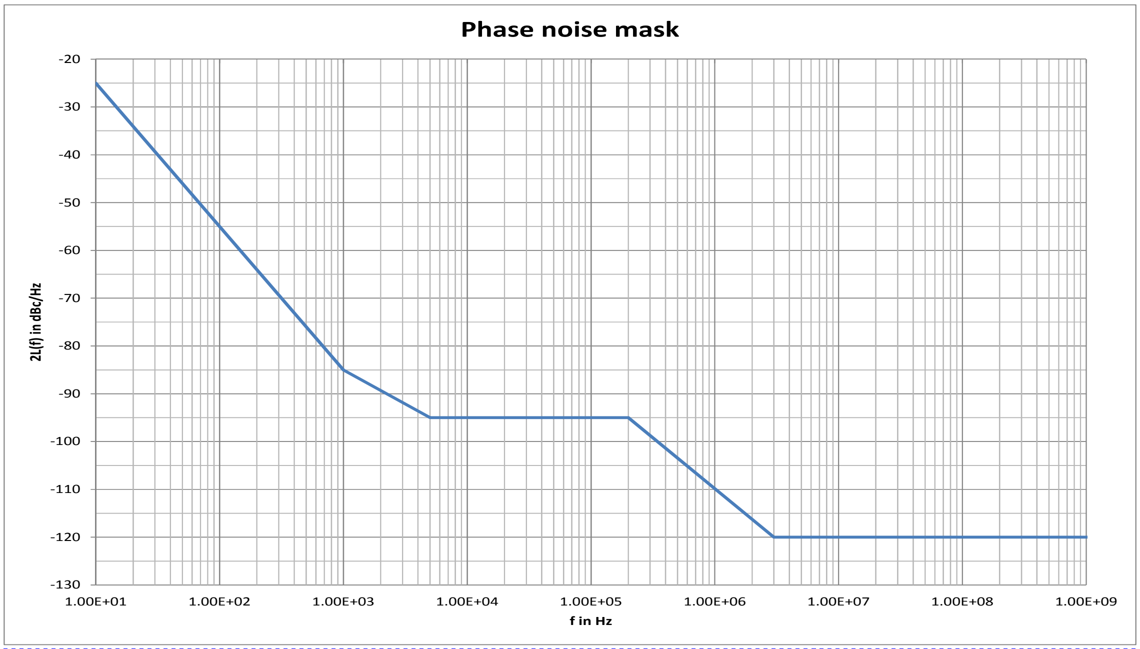

Figure 2.4.17A-2: Phase Noise Mask Recommendation

A1.4 BIT MAPPING TO CONSTELLATION

The following convention is used to identify each bit in an *N*-bit field. The first bit in the field to be transmitted (i.e., the most left justified when drawing a figure) is defined to be 'Bit 0', the following bit is defined to be 'Bit 1', and so on up to 'Bit *N*−1'. When the field is used to express a binary value (such as a counter), the Most Significant Bit (MSB) shall be the first transmitted bit of the field, i.e., 'Bit 0' (see figure 2.4.17A-3).

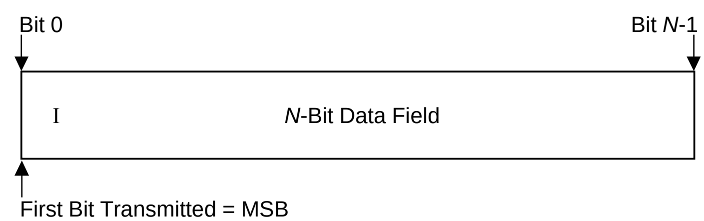

Figure 2.4.17A-3: Bit Numbering Convention

2.4.17A MODULATION METHODS FOR HIGH SYMBOL RATE TRANSMISSIONS, SPACE RESEARCH, SPACE-TO-EARTH, CATEGORY A (Continued)

ANNEX 1 (Continued)

For instance, bits 3i, 3i+1, 3i+2 of the modulator input determine the i^{th} 8PSK symbol, where i = 0, 1, 2,…, $(N/3)-1$, and N is the block size to be transmitted.

Modulations with coding in accordance with CCSDS 131.2-B-1 shall employ a conventional Gray-coded constellation with absolute mapping (no differential coding) as in figure 2.4.17A-4 and with associated bit numbering convention as in figure 2.4.17A-3.

Modulations with coding in accordance with CCSDS 131.0-B-3 and 131.3-B-1 shall employ a conventional Gray-coded constellation with absolute mapping (no differential coding) as in figure 2.4.17A-5 and with associated bit numbering convention as in figure 2.4.17A-3.

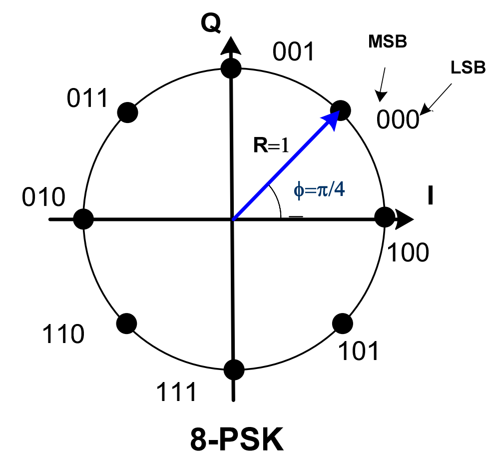

Figure 2.4.17A-4: 8PSK Symbol Mapping into Constellation (CCSDS 131.2-B-1)

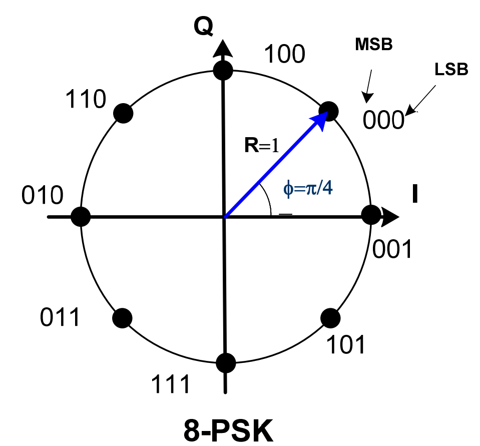

Figure 2.4.17A-5: 8PSK Symbol Mapping into Constellation (CCSDS 131.0-B-2 and 131.3-B-1)

2.4.17A MODULATION METHODS FOR HIGH SYMBOL RATE TRANSMISSIONS, SPACE RESEARCH, SPACE-TO-EARTH, CATEGORY A (Continued)

ANNEX 1 (Continued)

A1.5 CODING OPTIONS

Any coding option[10,11] among the following subsets shall be used:

CCSDS 131.0-B-2 LDPC 2/3, LDPC 4/5, LDPC 223/255
CCSDS 131.2-B-1 ACM9, ACM10, ACM11, ACM12
CCSDS 131.3-B-1 MODCOD13, MODCOD14, MODCOD15, MODCOD16, MODCOD17

Such choice allows transmitting in the 10–15 Ms/s range while fitting into a 10-MHz channel[3] as specified for the 8450–8500 MHz allocation.

In case the data rate does not need to be higher than 10 Ms/s but SRRC-8PSK is preferred, any coding options[10,11] among the following subset may also be used:

CCSDS 131.0-B-2 LDPC 1/2
CCSDS 131.2-B-1 ACM7, ACM8
CCSDS 131.3-B-1 MODCOD12

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[10] CCSDS 131.0-B-2, CCSDS 131.2-B-1, and CCSDS 131.3-B-1 include many coding options to be used in conjunction with VCM or ACM for the Earth Exploration-Satellite Service. For the Space Research Service applications covered by this recommendation, only the few options recommended here are deemed necessary.

[11] The given list is not in order of preference.

2.4.22A MODULATION METHODS FOR SIMULTANEOUS TRANSMISSION OF HIGH SYMBOL RATE TELEMETRY AND PN RANGING, SPACE RESEARCH 8.45–8.50 GHz BAND, SPACE-TO-EARTH, CATEGORY A

The CCSDS,

considering

(a) that GMSK[1] and baseband filtered OQPSK[2] are recommended for space-to-Earth transmissions when the telemetry data symbol rates exceed 2 Ms/s in the 2 and 8 GHz bands;

(b) that GMSK[1] or baseband filtered OQPSK[2] transmission is incompatible with simultaneous conventional residual modulation of a ranging signal;

(c) that some missions have a need for both high symbol rate telemetry and high accuracy ranging;

(d) that the use for telemetry of residual carrier modulation[3] when ranging is transmitted and of suppressed carrier modulation when ranging is not transmitted requires a dual-mode modulator, is not spectrally efficient, and may reduce the telemetry data volume significantly;

(e) that spacecraft design and operations are simplified by using the same modulation scheme for low as well as high symbol rate telemetry transmission including also a ranging signal which can be switched on and off with only marginal effect on the emitted spectrum and the telemetry performance and therefore allows for an always-on capability;

(f) that PN ranging[4] can be regenerated on board and retransmitted with a small modulation index due to the removal of the on-board thermal noise from the down-link;

(g) that a phase modulator can be used to combine GMSK[1] telemetry with on-board regenerated PN ranging[4] and that such scheme is inherently insensitive to on-board transmitter non-linearities because of its constant envelope, differently from baseband filtered OQPSK;[2] and allows for a simple and robust spacecraft implementation;

(h) that before correlating the PN ranging signal, the telemetry receiver can be used to estimate the telemetry signal and subtract it from the received signal;

(i) that GMSK[1]+PN ranging[4] with sine-wave shaping is spectrally efficient, and the telemetry losses[5] can be bounded to the range[6] 0.2–1.0 dB by selecting the appropriate ranging modulation index;

---

[1] Gaussian Minimum Shift Keying ($BT_S = 0.25$), with pre-coding as in CCSDS Recommendation 401 (2.4.17A) B-1. Parameter B refers to the one-sided 3-dB bandwidth of the filter (see CCSDS 413.0-G-2).

[2] Filtered (Square Root Raised Cosine $\alpha = 0.5$) Offset QPSK, etc., as per CCSDS Recommendation 401 (2.4.17A) B-1.

[3] CCSDS Recommendations 401 (2.4.3), 401 (2.4.7), 401 (2.14A), and 401 (2.4.15A).

[4] Section 3 of Pseudo-Noise (PN) Ranging Systems, Recommended Standard, Issue 2, CCSDS 414.1-B-2.

[5] The actual value depends on the selected configuration (see CCSDS 413.1-G-1).

[6] All performance numbers reported here are without ranging cancellation, unless otherwise noted.

2.4.22A MODULATION METHODS FOR SIMULTANEOUS TRANSMISSION OF HIGH SYMBOL RATE TELEMETRY AND PN RANGING, SPACE RESEARCH 8.45–8.50 GHz BAND, SPACE-TO-EARTH, CATEGORY A (Continued)

(j) that the PN ranging[4] SNR degradation,[7] in terms of acquisition time for a probability of acquisition greater than 99.9 percent, due to GMSK[1] telemetry can be bounded to the range 0.3–3.0 dB by limiting the telemetry symbol error rate to 0.1 and compensated by increasing the acquisition time;

(k) that the increase[8] of PN ranging[4] signal jitter variance due to GMSK[1] telemetry can be bounded to the range 0.3–1.5 dB by limiting the telemetry symbol error rate to 0.1 and compensated by reducing the ranging chip synchronizer bandwidth if allowed by Doppler rate dynamics;

(l) that the increase of carrier jitter variance[9] due to PN ranging[4] can be bounded to the range 0.2–1.0 dB by selecting the appropriate ranging modulation index and compensated by reducing the carrier synchronizer bandwidth;

(m) that increasing the PN ranging chip rate to telemetry symbol rate ratio generally improves the performance of the system;

(n) that the telemetry losses given in considering (i), can be significantly lowered by adding a ranging cancellation before the telemetry demodulation, leading to losses below 0.1 dB for comparable conditions[9] or allowing extension of the use cases of the scheme while maintaining losses below 0.5 dB;

recommends

(1) that GMSK[1]+PN ranging[4] shall be used as in figures 2.4.22A-1 and 2.4.22A-2 for space-to-Earth transmissions when ~~the telemetry data symbol rates exceed 2 Ms/s in the 8 GHz band, and simultaneous PN ranging is needed~~considering (a), (c), and (e) are of primary concern;

(2) that sine-wave shaping shall be used for PN ranging[4] whereby the impulse response of the ranging channel is given by

$$h(t) = h_{\sin}(t) = \begin{cases} \sin(\pi t / T_C) & \text{for } t = [0, T_C] \\ 0 & \text{otherwise} \end{cases}$$

where $T_C = 1/R_{RG}$ is the ranging chip interval, and R_{RG} is the ranging chip rate;

---

[7] This degradation is in addition to the one specified in section 3.5.4 of Pseudo-Noise (PN) Ranging Systems, Recommended Standard, Issue 2, CCSDS 414.1-B-2. The actual value depends on the selected configuration (see CCSDS 413.1-G-1).

[8] This increase is relative to the jitter specified in section 3.5.6 of Pseudo-Noise (PN) Ranging Systems, Recommended Standard, Issue 2, CCSDS 414.1-B-2. The actual value depends on the selected configuration (see CCSDS 413.1-G-1).

[9] The actual value depends on the selected configuration (see CCSDS 413.1-G-1).

2.4.22A MODULATION METHODS FOR SIMULTANEOUS TRANSMISSION OF HIGH SYMBOL RATE TELEMETRY AND PN RANGING, SPACE RESEARCH 8.45–8.50 GHz BAND, SPACE-TO-EARTH, CATEGORY A (Continued)

(3) that the PN ranging[4] peak modulation index m_{RG} shall be selected between 0.2 and 0.45 rad (without ranging cancellation) and between 0.2 and 0.7 rad (with ranging cancellation);

(4) that the PN ranging[4] code T4B shall be used when the ranging accuracy is of primary concern and T2B shall be used when the acquisition time is of primary concern;

(5) that the PN ranging chip rate to telemetry symbol rate[10] ratio shall be a non-integer[11] number (with or without ranging cancellation) higher than 1 (only required for the case without ranging cancellation), noting that the performance figures of considerings (i), (j), (k), and (l) are limited to the range 1 to 3 and the performance figures of considering (n) (with ranging cancellation) are limited to the range 1/3 to 10;

(6) that without ranging cancellation a PN ranging chip rate to telemetry symbol rate[7] ratio slightly smaller than 1 may be used in case of mission need and provided that the link margins are adequate, noting that the performance figures of considerings (i), (j), (k), and (l) may not be met;

(7) that the telemetry signal level shall be set such that the resulting symbol error rate at the receiver is better than 0.1.[12]

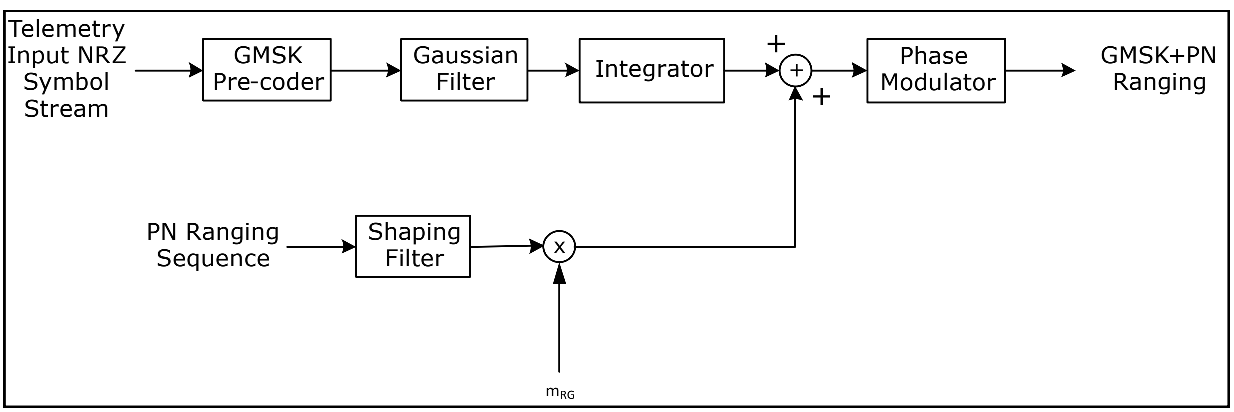

Figure 2.4.22A-1: GMSK+PN Ranging Modulation Schematics

[10] Recommendation SFCG 5-1R5 limits the occupied bandwidth for telemetry-only transmission to 10 MHz in the 8450-8500 MHz band.
[11] Under nominal conditions, PN ranging chip rate and telemetry symbol rate are not coherent.
[12] This value allows a simpler receiver implementation with telemetry cancellation (subtraction) at symbol level. The scheme is able to operate with a symbol error rate as high as 0.2 but may require a more complex cancellation or additional system margins.

2.4.22A MODULATION METHODS FOR SIMULTANEOUS TRANSMISSION OF HIGH SYMBOL RATE TELEMETRY AND PN RANGING, SPACE RESEARCH 8.45–8.50 GHz BAND, SPACE-TO-EARTH, CATEGORY A (Continued)

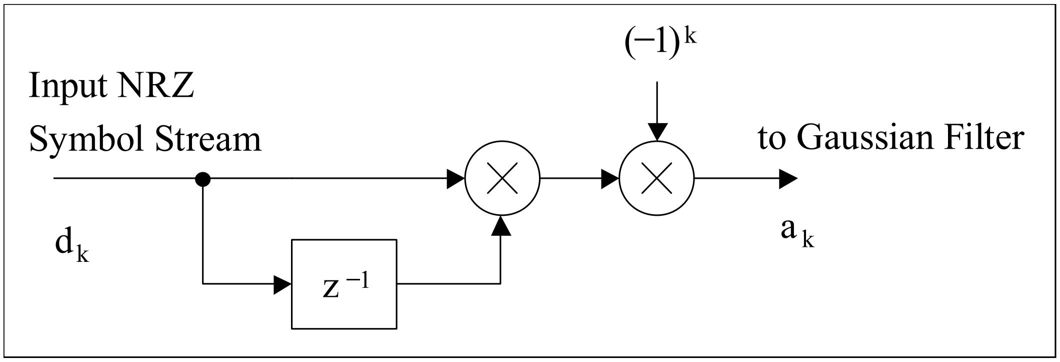

Figure 2.4.22A-2: GMSK Precoder

2.4.22A MODULATION METHODS FOR SIMULTANEOUS TRANSMISSION OF HIGH SYMBOL RATE TELEMETRY AND PN RANGING, SPACE RESEARCH 8.45–8.50 GHz BAND, SPACE-TO-EARTH, CATEGORY A (Continued)

Appendix A (Informative)—GMSK+PN Ranging Main Equations

The composite transmitted signal can be expressed as:

$$x(t) = \sqrt{2P_T}\cos[2\pi f_c t + \varphi_{TM}(t-\tau_{TM}) + \varphi_{RG}(t-\tau_{RG})] \quad (1)$$

where P_T is the transmit power,

f_c is the carrier frequency,

$\varphi_{TM}(t)$ is the phase of the pre-coded GMSK signal with symbol interval $T_s = 1/R_s$ given by:

$$\varphi_{TM}(t) = \pi \sum_k a_k q(t - kT_S) \quad (2)$$

being

$$q(t) = \int_{-\infty}^{t} \frac{1}{4T_S}\left[erfc\left(\frac{\tau - T_S}{\sqrt{2}\sigma}\right) - erfc\left(\frac{\tau}{\sqrt{2}\sigma}\right)\right] d\tau$$

with $\lim_{t\to\infty} q(t) = 1/2$

$\sigma^2 = \ln(2)/(4\pi^2 B^2)$

$BT_S = 0.25$

and a_k are the precoded symbols to be transmitted obtained from the ±1 level telemetry symbols by $a_k = (-1)^{k+1} d_k d_{k-1}$ (see figure 2.4.22A-2),

and

$$\varphi_{RG}(t) = m_{RG} \sum_k c_k h_{\sin}(t - kT_c) \quad (3)$$

is the phase of the PN ranging signal, being

m_{RG} the peak PN ranging modulation index in radians,

$c_k = \pm 1$ the k^{th} chip of the PN ranging sequence,

$T_C = 1/R_{RG}$ the PN ranging chip interval,

$h(t) = h_{\sin}(t) = \begin{cases} \sin(\pi t / T_C) & \text{for } t = [0, T_C] \\ 0 & \text{otherwise} \end{cases}$ the PN ranging shaping filter impulse response,

and τ_{TM} and τ_{RG} are random variables that model the absence of synchronization between the telemetry and the ranging signal.

2.4.22A MODULATION METHODS FOR SIMULTANEOUS TRANSMISSION OF HIGH SYMBOL RATE TELEMETRY AND PN RANGING, SPACE RESEARCH 8.45–8.50 GHz BAND, SPACE-TO-EARTH, CATEGORY A (Continued)

Appendix B (Informative)—GMSK+PN Ranging Cancellation

Figure 2.4.22A-3 shows an example of a high-level block diagram of a GMSK+PN RG receiver with ranging cancellation.[13]

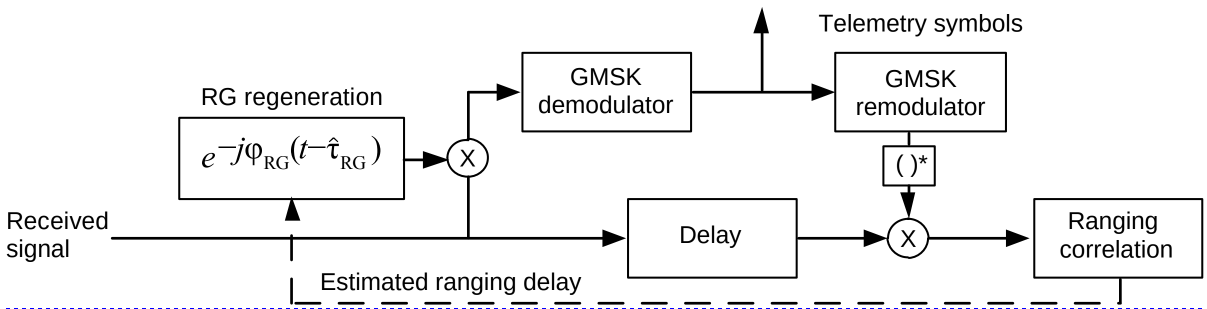

Figure 2.4.22A-3: High-Level Diagram of GMSK+PN RG Receiver with Ranging Cancellation

[13] More information on the ranging cancellation can be found in CCSDS 413.1-G-1.

2.4.22B MODULATION METHODS FOR SIMULTANEOUS TRANSMISSION OF HIGH SYMBOL RATE TELEMETRY AND PN RANGING, SPACE RESEARCH 8.40–8.45 GHz AND 31.8–32.3 GHz BANDS, SPACE-TO-EARTH, CATEGORY B

The CCSDS,

considering

(a) that GMSK[1] is recommended for high data rate transmissions whenever practicable and in any case for rates in excess of 2 Ms/s ~~in communications systems operating~~ in either the 2 or 8 GHz bands and in excess of 20 Ms/s in communications systems operating in the 32 GHz band, provided that in no case the transmission bandwidth (B25)[2] is higher than that recommended[2] by the SFCG;

(b) that GMSK[1] transmission is incompatible with simultaneous conventional residual modulation of a ranging signal;

(c) that some missions have a need for both high symbol rate telemetry and high accuracy ranging;

(d) that the use for telemetry of residual carrier modulations[3] when ranging is transmitted and of suppressed carrier modulation when ranging is not transmitted requires a dual-mode modulator, is not spectrally efficient, and may reduce the telemetry data volume significantly;

(e) that spacecraft design and operations are simplified by using the same modulation scheme for low as well as high symbol rate telemetry transmission including also a ranging signal which can be switched on and off with only marginal effect on the emitted spectrum and the telemetry performance and therefore allows for an always-on capability;

(f) that PN ranging[4] can be regenerated on board and retransmitted with a small modulation index due to the removal of the on-board thermal noise from the down-link;

(g) that a phase modulator can be used to combine GMSK[1] telemetry with on-board regenerated PN ranging[4] and that such scheme is inherently insensitive to on-board transmitter non-linearities because of its constant envelope and allows for a simple and robust spacecraft implementation;

(h) that before correlating the PN ranging signal, the telemetry receiver can be used to estimate the telemetry signal and subtract it from the received signal;

(i) that GMSK[1]+PN ranging[4] with sine-wave shaping is spectrally efficient, and the telemetry losses[5] can be bounded to the range[6] 0.2–1.0 dB by selecting the appropriate ranging modulation index;

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[1] Gaussian Minimum Shift Keying ($BT_S = 0.5$), with precoding as in figure CCSDS Recommendation 401 (2.4.17B) B-1 and 401 (2.4.20B) B-1. Parameter B refers to the one-sided 3-dB bandwidth of the filter (see CCSDS 413.0-G-2).

[2] SFCG Recommendation 23-1 or latest version.

[3] CCSDS Recommendations 401 (2.4.3), 401 (2.4.7), 401 (2.14.B), and 401 (2.4.15B).

[4] Section 3 of Pseudo-Noise (PN) Ranging Systems, Recommended Standard, Issue 2, CCSDS 414.1-B-2.

[5] The actual value depends on the selected configuration (see CCSDS 413.1-G-1).

[6] All performance numbers reported here are without ranging cancellation, unless otherwise noted.

2.4.22B MODULATION METHODS FOR SIMULTANEOUS TRANSMISSION OF HIGH SYMBOL RATE TELEMETRY AND PN RANGING, SPACE RESEARCH 8.40–8.45 GHz AND 31.8–32.3 GHz BANDS, SPACE-TO-EARTH, CATEGORY B (Continued)

(j) that the PN ranging[4] SNR degradation,[7] in terms of acquisition time for a probability of acquisition greater than 99.9 percent, due to GMSK[1] telemetry can be bounded to the range 0.3–3.0 dB by limiting the telemetry symbol error rate to 0.1 and compensated by increasing the acquisition time;

(k) that the increase[8] of PN ranging[4] signal jitter variance due to GMSK[1] telemetry can be bound to the range 0.3–1.5 dB by limiting the telemetry symbol error rate to 0.1 and compensated by reducing the ranging chip synchronizer bandwidth if allowed by Doppler rate dynamics;

(l) that the increase of carrier jitter variance[9] due to PN ranging[4] can be bounded to the range 0.2–1.0 dB by selecting the appropriate ranging modulation index and compensated by reducing the carrier synchronizer bandwidth;

(m) that increasing the PN ranging chip rate to telemetry symbol rate ratio generally improves the performance of the system;

(n) that the telemetry losses given in considering (i), can be significantly lowered by adding a ranging cancellation before the telemetry demodulation, leading to losses below 0.1 dB for comparable conditions[9] or allowing extension of the use cases of the scheme while maintaining losses below 0.5 dB;

recommends

(1) that GMSK[1]+PN ranging[4] shall be used as in figures 2.4.22B-1 and 2.4.22B-1 ~~for high data rate transmissions~~ whenever considering (a), (c), and (e) are of primary concern~~practicable and in any case for rates in excess of 2 Ms/s in communications systems operating in the 8 GHz band, when simultaneous PN ranging is needed~~;

(2) that sine-wave shaping shall be used for PN ranging[4] whereby the impulse response of the ranging channel is given by

$$h(t) = h_{\sin}(t) = \begin{cases} \sin(\pi t / T_C) & \text{for } t = [0, T_C] \\ 0 & \text{otherwise} \end{cases}$$

where $T_C = 1/R_{RG}$ is the ranging chip interval, and R_{RG} is the ranging chip rate;

[7] These losses are in addition to the ones specified in section 3.5.4 of Pseudo-Noise (PN) Ranging Systems, Recommended Standard, Issue 2, CCSDS 414.1-B-2. The actual value depends on the selected configuration (see CCSDS 413.1-G-1).

[8] This increase is relative to the jitter specified in section 3.5.6 of Pseudo-Noise (PN) Ranging Systems, Recommended Standard, Issue 2, CCSDS 414.1-B-2. The actual value depends on the selected configuration (see CCSDS 413.1-G-1).

[9] The actual value depends on the selected configuration (see CCSDS 413.1-G-1).

2.4.22B MODULATION METHODS FOR SIMULTANEOUS TRANSMISSION OF HIGH SYMBOL RATE TELEMETRY AND PN RANGING, SPACE RESEARCH 8.40–8.45 GHz AND 31.8–32.3 GHz BANDS, SPACE-TO-EARTH, CATEGORY B (Continued)

(3) that the PN ranging[4] peak modulation index m_{RG} shall be selected between 0.2 and 0.45 rad (without ranging cancellation) and between 0.2 and 0.7 rad (with ranging cancellation);

(4) that the PN ranging[4] code T4B shall be used when the ranging accuracy is of primary concern and T2B shall be used when the acquisition time is of primary concern;

(5) that the PN ranging chip rate to telemetry symbol rate[10] ratio shall be a non-integer[11] number (with or without ranging cancellation) higher than 1 (only required for the case without ranging cancellation), noting that the performance figures of considerings (i), (j), (k), and (l) are limited to the range 1 to 3 and the performance figures of considering (n) (with ranging cancellation) are limited to the range 1/3 to 10;

(6) that without ranging cancellation a PN ranging chip rate to telemetry symbol rate[7] ratio slightly smaller than 1 may be used in case of mission need and provided that the link margins are adequate, noting that the performance figures of considerings (i), (j), (k), and (l) may not be met;

(7) that the telemetry signal level shall be set such that the resulting symbol error rate at the receiver is better than 0.1.[12]

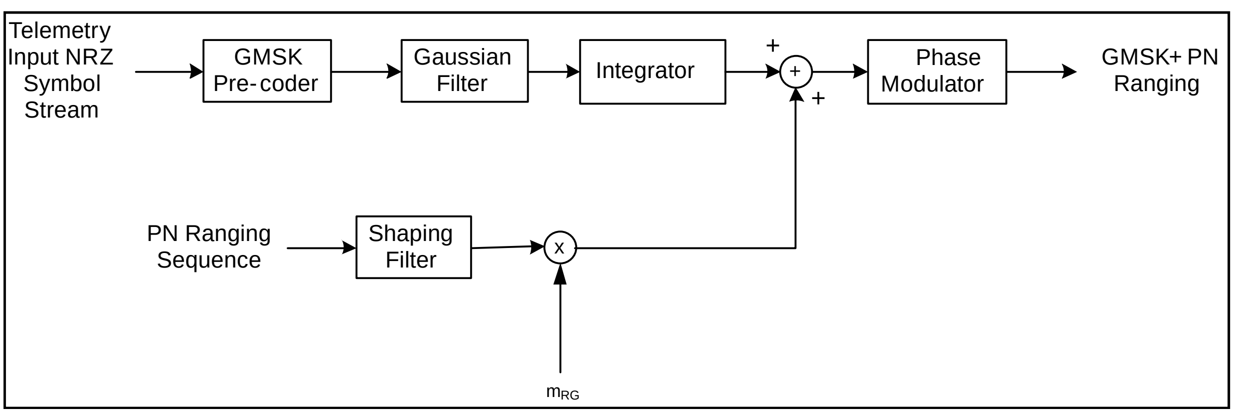

Figure 2.4.22B-1: GMSK+PN Ranging Modulation Schematics

[10] Under the SFCG (Recommendation 23-1) 12 MHz bandwidth limitation for 8 GHz band non-Mars missions on a non-interfering basis, the maximum telemetry symbol rate using GMSK BT_S=0.5 is 9.3 Ms/s. For 8 GHz band Mars missions and non-Mars missions which interfere with Mars missions, the maximum telemetry symbol rate using GMSK BT_S=0.5 is 6.2 Ms/s.

[11] Under nominal conditions, PN ranging chip rate and telemetry symbol rate are, however, not coherent.

[12] This value allows a simpler receiver implementation with telemetry cancellation (subtraction) at symbol level. The scheme is able to operate with a symbol error rate as high as 0.2 but may require a more complex cancellation or additional system margins.

2.4.22B MODULATION METHODS FOR SIMULTANEOUS TRANSMISSION OF HIGH SYMBOL RATE TELEMETRY AND PN RANGING, SPACE RESEARCH 8.40–8.45 GHz AND 31.8–32.3 GHz BANDS, SPACE-TO-EARTH, CATEGORY B (Continued)

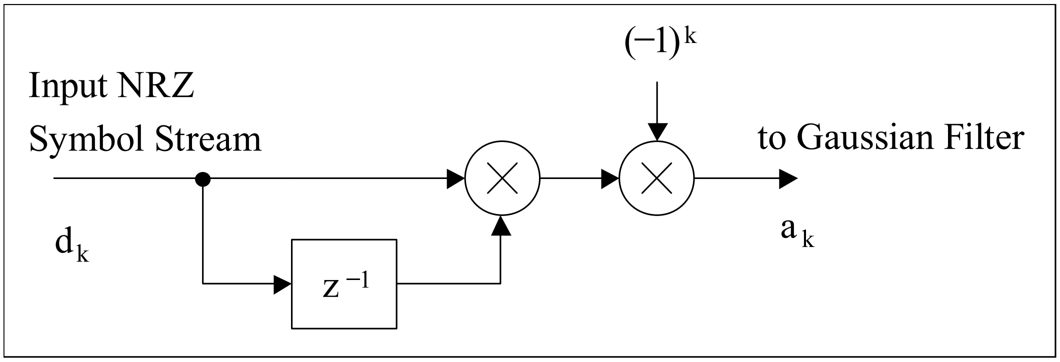

Figure 2.4.22B-1: GMSK Precoder

2.4.22B MODULATION METHODS FOR SIMULTANEOUS TRANSMISSION OF HIGH SYMBOL RATE TELEMETRY AND PN RANGING, SPACE RESEARCH 8.40–8.45 GHz AND 31.8–32.3 GHz BANDS, SPACE-TO-EARTH, CATEGORY B (Continued)

Appendix A (Informative)—GMSK+PN Ranging Main Equations

The composite transmitted signal can be expressed as:

$$x(t) = \sqrt{2P_T}\cos[2\pi f_c t + \varphi_{TM}(t-\tau_{TM}) + \varphi_{RG}(t-\tau_{RG})] \tag{1}$$

where P_T is the transmit power,

f_c is the carrier frequency,

$\varphi_{TM}(t)$ is the phase of the pre-coded GMSK signal with symbol interval T_s=1/R_s given by:

$$\varphi_{TM}(t) = \pi \sum_k a_k q(t-kT_S) \tag{2}$$

being

$$q(t) = \int_{-\infty}^{t} \frac{1}{4T_S}\left[erfc\left(\frac{\tau - T_S}{\sqrt{2}\sigma}\right) - erfc\left(\frac{\tau}{\sqrt{2}\sigma}\right)\right] d\tau$$

with $\lim_{t\to\infty} q(t) = 1/2$

$\sigma^2 = \ln(2)/(4\pi^2 B^2)$

$BT_S = 0.5$

and a_k are the precoded symbols to be transmitted obtained from the ±1 level telemetry symbols by $a_k = (-1)^{k+1} d_k d_{k-1}$ (see figure 2.4.22B-1),

and

$$\varphi_{RG}(t) = m_{RG} \sum_k c_k h_{\sin}(t-kT_c) \tag{3}$$

is the phase of the PN ranging signal, being

m_{RG} the peak PN ranging modulation index in radians,

$c_k = \pm 1$ the k^{th} chip of the PN ranging sequence,

$T_C = 1/R_{RG}$ the PN ranging chip interval,

$h(t) = h_{\sin}(t) = \begin{cases} \sin(\pi t / T_C) & \text{for } t = [0, T_C] \\ 0 & \text{otherwise} \end{cases}$ the PN ranging shaping filter impulse response,

and τ_{TM} and τ_{RG} are random variables that model the absence of synchronization between the telemetry and the ranging signal.

2.4.22B MODULATION METHODS FOR SIMULTANEOUS TRANSMISSION OF HIGH SYMBOL RATE TELEMETRY AND PN RANGING, SPACE RESEARCH 8.40–8.45 GHz AND 31.8–32.3 GHz BANDS, SPACE-TO-EARTH, CATEGORY B (Continued)

Appendix B (Informative)—GMSK+PN Ranging Cancellation

Figure 2.4.22B-2 shows an example of a high-level block diagram of a GMSK+PN RG receiver with ranging cancellation.[13]

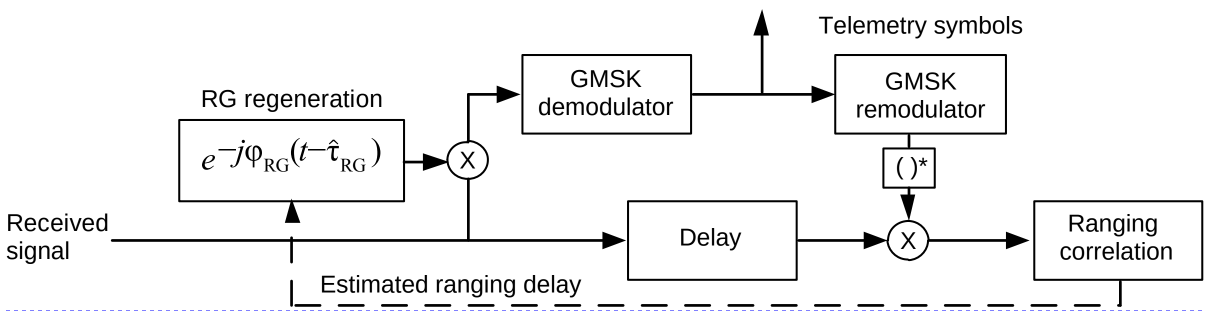

Figure 2.4.22B-2: High-Level Diagram of GMSK+PN RG Receiver with Ranging Cancellation

[13] More information on the ranging cancellation can be found in CCSDS 413.1-G-1.

2.4.24 TELEMETRY RANGING FOR SPACE RESEARCH 8.40–8.50 GHz BAND, SPACE-TO-EARTH, CATEGORIES A AND B, AND 31.8–32.3 GHz BAND, SPACE-TO-EARTH, CATEGORY B

The CCSDS,

considering

(a) that some missions have a need for simultaneous high-symbol-rate telemetry and high-accuracy ranging;

(b) that it is advantageous to total telemetry data volume when

- interference to the telemetry signal from ranging signal(s) is eliminated;
- the telemetry symbol rate is not constrained or dependent on the ranging chip rate;

(c) that it is advantageous to a ranging system when

- the full power of the received downlink signal can be used;
- ranging products are available whenever telemetry is received, providing an always-on capability that simplifies mission planning and operations;
- no interfering in-band transmission is present;
- telemetry cancellation is not needed in the ground receiver;

(d) that the spacecraft transponder tracking an uplink PN ranging signal generated in accordance with CCSDS 414.1-B-2 can be readily modified to record the range code phase and Frame Counter (FC) of a telemetry frame[1] as part of a telemetry ranging system shown in figure 2.4.24-1;

(e) that a ground receiver can readily measure the arrival time of a telemetry frame, and, together with the range code phase and FC pair, compute range;

(f) that such telemetry ranging is compatible with GMSK or baseband filtered OQPSK transmissions at telemetry data symbol rates exceeding 2 Ms/s, and with other CCSDS modulations at lower telemetry data symbol rates;

(g) that 40 bits can be used to represent the range code phase of a 2 Mchips/s PN sequence generated in accordance with CCSDS 414.1-B-2, to a resolution of 1 ps;

(h) that such telemetry ranging can achieve a standard deviation in range accuracy of 1 m when the symbol rate is 200 ks/s or larger, under the conditions described in appendix B;

(i) that such telemetry ranging incurs a loss in telemetry throughput up to 4 percent from transmission of range code phase and FC pairs;

[1] Telemetry frames can be TM or AOS Transfer Frames. The type (master or virtual channel), position, and size of the FC depends on the selected frame type.

2.4.24 TELEMETRY RANGING FOR SPACE RESEARCH 8.40–8.50 GHz BAND, SPACE-TO-EARTH, CATEGORIES A AND B, AND 31.8–32.3 GHz BAND, SPACE-TO-EARTH, CATEGORY B (Continued)

recommends

(1) that telemetry ranging shall be used for space-to-Earth transmissions when considering (a), (b), and (c) are of primary concern;

(2) that as part of a telemetry ranging system, the spacecraft shall track an uplink PN ranging signal generated in accordance with CCSDS 414.1-B-2 and latch the range code phase according to a signal triggered by the transmission of a codeword, along with the FC of the associated telemetry frame;

(3) that each range code phase shall be recorded as a 40-bit number, representing the number of chips times 2^{20}, rounded to an integer, and stored in 5 octets, with bit 0 being the MSB and bit 39 being the LSB;

(4) that the recorded range code phase and FC pairs shall be subsequently transmitted in telemetry frames.[2,3]

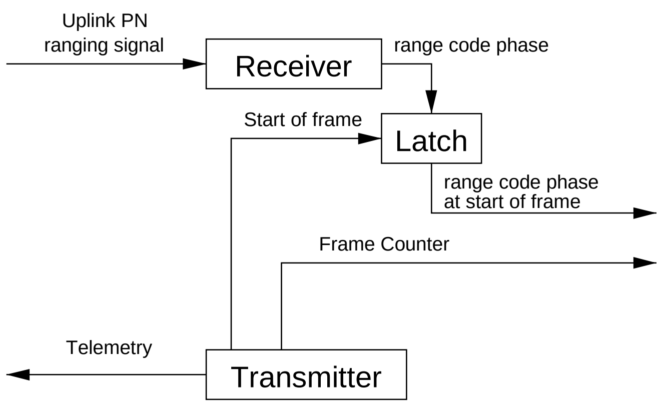

Figure 2.4.24-1: Telemetry Ranging on Spacecraft Transponder

[2] This recommendation does not prescribe the manner in which the range code phase and FC pairs are formatted or inserted into telemetry frames. Such implementations are mission-specific.
[3] A test of telemetry ranging requires the additional capability to generate frames and insert the range code phase and FC pairs into telemetry.

2.4.24 TELEMETRY RANGING FOR SPACE RESEARCH 8.40–8.50 GHz BAND, SPACE-TO-EARTH, CATEGORIES A AND B, AND 31.8–32.3 GHz BAND, SPACE-TO-EARTH, CATEGORY B (Continued)

Appendix A (Informative)—Telemetry Ranging Equations and Overview

The uplink PN ranging signal, consistent with CCSDS 414.1-B-2, can be expressed as:

$$x(t) = \sqrt{2P_{\mathrm{t}}} \cos[2\pi f_{\mathrm{c}} t + \phi_{\mathrm{RG}}(t - \tau_{\mathrm{RG}})],$$

where

- P_{t} is the total received power;
- f_{c} is the carrier frequency in Hz;
- $\phi_{\mathrm{RG}}(t) = m_{\mathrm{RG}} \sum_{k=0} c_k h_{\sin}(t - kT_{\mathrm{c}})$;
- m_{RG} is the peak modulation index in radians;
- $c_k \in \{-1, +1\}$ is a range code (PN-like sequence) defined in CCSDS 414.1-B-2;
- $h_{\sin}(t)$ is the baseband shaping filter impulse response defined in CCSDS 414.1-B-2;
- T_{c} is the chip duration.

At any time $t > 0$, the range code phase of $x(t)$ is the number of whole and fractional parts of chips, modulo the chip period, that have been transmitted since time 0, given by:

$$\psi(t) = \frac{t}{T_{\mathrm{c}}} \bmod L,$$

where L = 1,009,479 is the period of the range code. The range code phase observed on the spacecraft is delayed by the one-way light time. Standard techniques can be used to acquire and track this range code phase: such an implementation is common to conventional 2-way PN ranging and telemetry ranging systems.

Figure 2.4.24-2 shows the structure of the telemetry ranging system in space and on the ground.

2.4.24 TELEMETRY RANGING FOR SPACE RESEARCH 8.40–8.50 GHz BAND, SPACE-TO-EARTH, CATEGORIES A AND B, AND 31.8–32.3 GHz BAND, SPACE-TO-EARTH, CATEGORY B (Continued)

Appendix A (Informative)—Telemetry Ranging Equations and Overview (Continued)

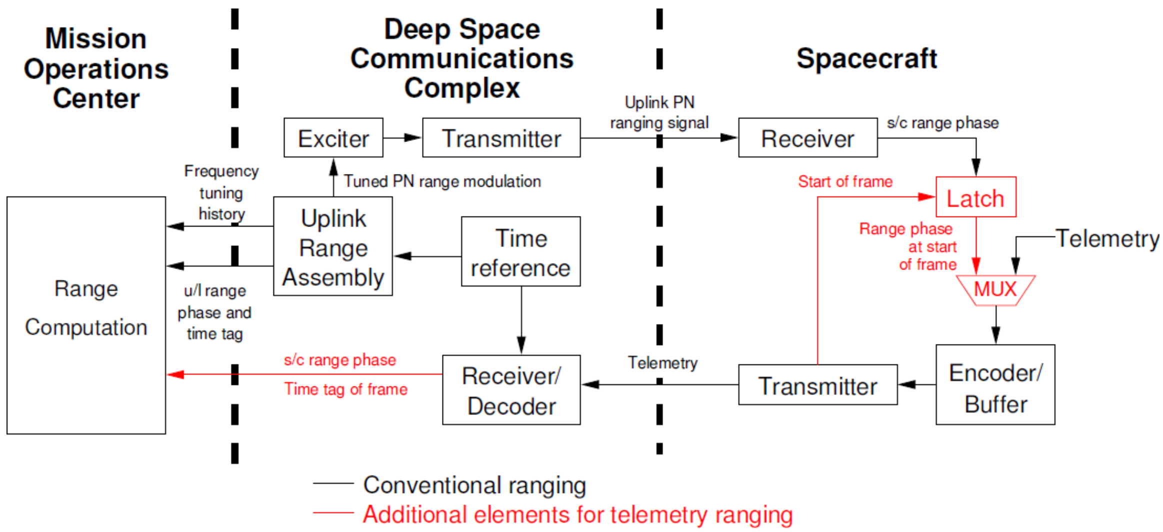

Figure 2.4.24-2: Functional Block Diagram of Telemetry Ranging System

The data flow for making a range computation is as follows:

- A PN ranging signal is sent on uplink; as it is transmitted, its phase is periodically recorded and time-tagged on the ground (as usual with 2-way PN ranging).
- The spacecraft records the phase of the acquired uplink PN signal at the moment when a telemetry frame FC is transmitted. There is no downlink PN ranging signal.
- The range code phase and FC pair is transmitted to the ground as telemetry.
- Range is computed from the known uplink frequency tuning history, time-tagged PN phase from uplink range assembly, PN phase recorded on the spacecraft, and time tag of the telemetry frame. The range computation algorithm remains nearly unchanged.

2.4.24 TELEMETRY RANGING FOR SPACE RESEARCH 8.40–8.50 GHz BAND, SPACE-TO-EARTH, CATEGORIES A AND B, AND 31.8–32.3 GHz BAND, SPACE-TO-EARTH, CATEGORY B (Continued)

Appendix B (Informative)—Range Delay Error Budget

An uplink PN ranging signal transmitted with a half-sine pulse shape and received using a DPLL (a matched filter to the sinewave) has a ranging measurement error variance in m^2 given by[4]

$$\sigma_u^2 = \frac{c^2 T_{\mathrm{c}}^2 N_0 B_{\mathrm{L}}}{\pi^2 P_{\mathrm{r}}}$$

where c is the speed of light, T_{c} is the PN chip duration, N_0 is the noise spectral density, B_{L} is the PN chip tracking single-sided loop bandwidth, and $P_{\mathrm{r}} = P_{\mathrm{t}} \sin^2(m_{\mathrm{RG}})$ is the ranging power entering the PN tracking loop, where P_{t} is the total received power and m_{RG} is the range modulation index.

On the downlink, a ground receiver tracking a codeword arrival with a DTTL has a ranging measurement error variance in m^2 given by

$$\sigma_d^2 = \frac{c^2 T_{\mathrm{s}}^2 W N_0 B_{\mathrm{L}}}{2 S_{\mathrm{L}} P_{\mathrm{d}}}$$

where T_{s} is the telemetry symbol duration, W is the DTTL window fraction, B_{L} is the DTTL single-sided loop bandwidth, S_{L} is the squaring loss of the DTTL, and $P_{\mathrm{d}} = P_{\mathrm{t}} \sin^2(m_{\mathrm{TLM}})$ is the received power in the telemetry.

The two-way range error variance of the tracking loops is given by $\sigma_{ud}^2 = \sigma_u^2 + \sigma_d^2$. Additional sources of error relating to uncertainties in the geometry of the ground reference point, and ground and spacecraft delay calibrations may also be present.

A representative example is as follows:

- Uplink (PN transmission):
  - $T_{\mathrm{c}} = 0.5 \times 10^{-6}$ s (i.e., 2 Mchip/s);
  - $P_{\mathrm{t}} / N_0 = 50$ dBHz;
  - $m_{\mathrm{RG}} = 0.4\pi$ radians;
  - DPLL PN tracking loop bandwith $B_{\mathrm{L}} = 10$ Hz;
- Downlink (telemetry transmission):
  - $P_{\mathrm{t}} / N_0 = 55$ dBHz;
  - Modulation index $m_{\mathrm{TLM}} = 0.4\pi$ radians;

[4] This expression is consistent with Equation (13) of CCSDS 413.1-G-1, noting that the energy per chip is $E_{\mathrm{cl,sin}} = P_{\mathrm{r}} T_{\mathrm{c}}$.

2.4.24 TELEMETRY RANGING FOR SPACE RESEARCH 8.40–8.50 GHz BAND, SPACE-TO-EARTH, CATEGORIES A AND B, AND 31.8–32.3 GHz BAND, SPACE-TO-EARTH, CATEGORY B (Continued)

Appendix B (Informative)—Range Delay Error Budget (Continued)

- $T_s = 0.5 \times 10^{-6}$ (i.e., 200 ks/s);
- DTTL tracking loop bandwith $B_L = 0.5$ Hz;
- $W = 1/4$.

In this case, the squaring loss is $S_L = 0.80$, and plugging into the equations above results in a two-way range error standard deviation of $\sigma_{ud} < 1$ m.

3.1.7 METHODS FOR SPACE RESEARCH EARTH STATION SUPPORT OF MULTIPLE SPACECRAFT PER APERTURE

The CCSDS,

considering

(i) that there has been an increasing number of space research missions operating in close proximity to each other, such as in the vicinity of Mars or as part of a flying formation;

(j) that these missions often require Earth station support for simultaneous telecommand and telemetry as well as Doppler and ranging;

(k) that space agencies have only a limited number of Earth-station antennas available to support these missions, because of the cost of constructing and operating large aperture antennas;

(l) that it is desirable to maximize the utilization of the available Earth-station antennas in order to increase the number of missions that can be supported with existing resources;

(m) that there are several methods, broadly called Multiple Spacecraft Per Aperture (MSPA), whereby a single Earth-station antenna can be used to support multiple spacecraft located within its antenna beamwidth;

(n) that several space agencies have already used MSPA to simultaneously receive downlink telemetry from multiple spacecraft using a single Earth-station antenna, in cases where each spacecraft is transmitting on a different frequency;

(o) that there are various approaches for MSPA on the uplink, which have their own relative merits and drawbacks in terms of implementation complexity and operational impacts;

(p) that the preferred approach for MSPA may be different depending on the time frame being considered;

recommends

that CCSDS agencies use one of the methods described in table 3.1.7-1 when supporting multiple spacecraft using a single Earth-station antennas.

Table 3.1.7-1: RECOMMENDED MSPA METHODS

Method Name	**Description**	**Advantages**	**Disadvantages**	**Recommended Time Frame**
Time Multiplexed Uplink MSPA	Earth station transmits an uplink to each spacecraft in its antenna beam sequentially and separated in time. Each spacecraft uses a different uplink and downlink frequency, which are related by the standard CCSDS turnaround ratios.	Least amount of change required. Could be implemented with existing Earth stations and spacecraft.	No simultaneous uplinks; time available for each spacecraft for uplink commands, coherent Doppler, and ranging is reduced as the number of MSPA satellites increases. Earth-station receiver needs to re-acquire downlink each time spacecraft receiver acquires and loses the uplink.	Short term
Flexible Turnaround Ratio MSPA	Earth stations transmits an uplink using a single frequency common to all the spacecraft in the antenna beam. Uplink commands are separated using the spacecraft identifier and valid command syntax for each mission. Each spacecraft transponder uses a different turnaround ratio so that the telemetry downlinks are on separate frequencies.	Provides method for simultaneous uplink and downlink MSPA. Existing Software-Defined Radios (SDRs) offer flexibility in programming different turnaround ratios.	Acquisition bandwidth of the spacecraft receiver must accommodate potentially large differences in uplink Doppler frequency between the spacecraft in the antenna beam. Changes in existing non-SDR spacecraft transponders and Earth stations are needed to accommodate flexible turnaround ratios.	Intermediate term (Relevant recommendation 401 (2.1.9) under development; interested reader should consult future version of this book.)
Multiple Uplink carrier MSPA	The Earth station transmits multiple uplink frequencies simultaneously through the high power amplifier to all spacecraft in its antenna beam. Each spacecraft has a different uplink and downlink frequency, which are related by the standard CCSDS turnaround ratios.	Provides method for simultaneous uplink and downlink MSPA. Requires no change to the existing spacecraft transponder.	Transmission of multiple uplink carriers through the Earth-station High Power Amplifier (HPA) will result in intermodulation products, which could cause interference to other missions or exceed spurious emission limits. Backoff of the HPA to reduce the intermod products will reduce the efficiency of the transmitter and available uplink EIRP. A linearizer is another possible solution, but would require changes to the existing Earth station.	Intermediate term (Relevant recommendation 401 (2.6.13) under development; interested reader should consult future version of this book.)
Code Division Multiple Access (CDMA) MSPA	The Earth station transmits simultaneous CDMA uplinks on a single frequency. Each spacecraft will use a different CDMA code. Downlinks will be transmitted on a single frequency also using CDMA codes.	Provides simultaneous uplink and downlink MSPA. CDMA techniques already developed and used for near-Earth orbiters.	Requires significant changes to existing deep space spacecraft transponders and Earth stations. High data rates may be limited by the PN chip rate.	Long term (Studies currently ongoing.)