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-RP-30.1

RED/PINK SHEETS

August 2020

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-RP-30.1

RED/PINK SHEETS

August 2020

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 30	February 2020	Current issue: – updates recommendation 2.3.7; – adds new recommendations 2.1.9, 2.4.24, and 2.6.14; – applies editorial changes for added clarity.
CCSDS 401.0-B	Radio Frequency and Modulation Systems—Part 1: Earth Stations and Spacecraft, Draft Recommended Standard, Issue 30.1	August 2020	Current draft update: – updates recommendations 2.5.6B and 3.1.6B; – adds new recommendation 2.5.7B.

NOTE – Because recommendation 2.5.7B is new in its entirety, it is present without markup.

2.5.6B DIFFERENTIAL ONE-WAY RANGING FOR SPACE-TO-EARTH LINKS IN ANGULAR SPACECRAFT POSITION DETERMINATION, CATEGORY B

The CCSDS,

considering

(a) that Very Long Baseline Interferometry (VLBI) measurement allows determination of geometric delay for space radio sources by the simultaneous reception and processing of radio signals at two stations;

(b) that using the VLBI geometric delay measurements from two stations, the angular position of a spacecraft can be accurately determined for navigational purposes;

(c) that the VLBI technique requires differencing phase measurements of sinusoidal tones or harmonics[1] (known as Differential One-way Ranging [DOR] tones), modulated on the spacecraft's downlink RF carrier, which have been acquired at two (or more) stations;

(d) that VLBI accuracy depends, among other parameters, upon a priori knowledge of both the length and orientation of the baseline vector between the stations, the station clock drift, and the media delays;

(e) that measurement errors can be greatly reduced by observing a quasar or Extra-Galactic Radio source (EGRS) that is angularly near the spacecraft, and then differencing the delay measured from the ERGS observation with the delay measured from observing the spacecraft (ΔDOR);

(f) that the spacecraft delay measurement's precision depends upon the received DOR tone power-to-noise density ratio (P_{DOR}/N_0) in each of the two most widely spaced DOR tone fundamental harmonics, f_{BW} Hz apart, as shown in the error relationship:

$$\varepsilon_{\tau_{SC}} = \frac{1}{\pi f_{BW}\sqrt{2\frac{P_{DOR}}{N_0}T_{obs}}} \text{ seconds, where:}$$

f_{BW} = DOR tone spanned bandwidth[2] (Hz);
T_{obs} = observation time (s);
P_{DOR}/N_0 = power to noise density ratio of one fundamental harmonic (lower or upper) of DOR tone (Hz);

(g) that a narrow spanned bandwidth is needed for integer cycle ambiguity resolution because the ΔDOR time delay ambiguity equals the reciprocal of the minimum spanned bandwidth;

(h) that delay ambiguities in observables generated from wider bandwidths are resolved successively by using delay estimates from the narrower spanned bandwidths, thereby using multiple tones;

(i) that, contrary to considering (g), a wide spanned bandwidth is needed for high measurement accuracy;

---

[1] For each tone that phase modulates the downlink carrier, upper and lower fundamental harmonics are created.
[2] The spanned bandwidth is the widest separation between detectable tones in the downlink spectrum. This is usually given as twice the frequency of a sinusoidal 'DOR Tone' modulated onto the carrier.

2.5.6B DIFFERENTIAL ONE-WAY RANGING FOR SPACE-TO-EARTH LINKS IN ANGULAR SPACECRAFT POSITION DETERMINATION, CATEGORY B (Continued)

(j) that a typical ΔDOR error budget is dominated by errors due to low quasar SNR, quasar position uncertainty, instrument phase ripple, and the troposphere;

(k) that EGRS delay measurement precision and instrument errors vary as $1/f_{BW}$;

(l) that direct phase modulation of a sine-wave DOR tone on the downlink RF carrier is more spectrum efficient than square-wave modulation;

(m) that the received spacecraft DOR tone power must be adequate for tone detection, with the threshold approximately determined by:

$$Threshold = \left[\frac{P_{DOR}}{N_0}\right] = 13 \text{ dBHz if no carrier aiding is used;}$$

(n) that the DOR tone threshold reduces to:

$$Threshold = \left[\frac{P_{DOR}}{N_0}\right] = 1 \text{ dBHz}$$

provided that the spacecraft RF carrier's SNR is greater than 13 dB and that the extracted carrier phase is used to aid in tracking the DOR tone whose frequency is a coherent submultiple of the spacecraft's RF carrier frequency;

(o) that the stability of the spacecraft's RF carrier, over a 1-second averaging time, must be adequate for signal detection;

(p) that the *Space Research service* frequency allocation for Category B missions is 10 MHz in the 2 GHz band, 50 MHz in the 8 GHz band, 400 MHz in the 32 GHz band, and 1 GHz in the 37 GHz band;

(q) that quasar flux is reduced and system noise temperature is higher at 32 and 37 GHz as compared to 8 GHz;

(r) that DOR tones are used by many interplanetary missions and that the frequency bands used for DOR tones are shared with other satellite and terrestrial users;

(s) that missions with limited downlink tracking capability will benefit from a lower frequency DOR tone to aid with integer cycle ambiguity resolution;

recommends

(1) that DOR tones shall be sine waves;

(2) that the DOR tones shall be phase modulated on the Radio Frequency (RF) carrier;

(3) that either direct tone detection or carrier-aided tone detection shall be used;

(4) that DOR tones shall be coherent with the downlink RF carrier frequency if carrier-aided detection is used;

2.5.6B DIFFERENTIAL ONE-WAY RANGING FOR SPACE-TO-EARTH LINKS IN ANGULAR SPACECRAFT POSITION DETERMINATION, CATEGORY B (Continued)

(5) that one DOR tone shall be used in the 2 GHz band, two DOR tones shall be used in the 8 GHz band, and three DOR tones shall be used in the 32 and 37 GHz bands;

(6) that the approximate DOR tone fundamental harmonics frequencies used in each band shall be those in table 2.5.6B-1;

Table 2.5.6B-1: Recommended DOR Tones

Space-to-Earth Frequency Band	Number of DOR Tones	Approximate DOR Tone Fundamental Harmonics Frequencies	Notes
2 GHz	1	±1 or ±4 MHz	1, 2
8 GHz	2	±1 or ±4 MHz and ±20 MHz	1, 2
32 & 37 GHz	3	±1 or ±4 MHz, ±20 MHz, and ±76 MHz	1, 2

NOTES

1 The lower frequency DOR tone may be chosen as 4 MHz rather than 1 MHz for missions that will have sufficient navigation data to maintain an accurate ephemeris. The delay ambiguity that must be resolved for a 4 MHz tone is 0.25 µsec. To resolve such an ambiguity with 99-percent probability, the 1-sigma a-priori delay must be known to better than (1/6)*(0.25 µsec). This is easily accomplished for missions with long tracking passes but may not be possible for missions with limited downlink tracking that should therefore select the 1 MHz tone.

2 A telemetry signal, such as a subcarrier in the 250 kHz to 1 MHz range, can be used in place of a 1 MHz DOR tone for ambiguity resolution.

(7) that, if spacecraft DOR data are to be acquired in the one-way mode, the spacecraft's oscillator stability over a 1-second averaging time shall be:

$\Delta f/f \leq 4.0 \times 10^{-10}$ at 2 GHz,
$\Delta f/f \leq 1.0 \times 10^{-10}$ at 8 GHz,
$\Delta f/f \leq 0.3 \times 10^{-10}$ at 32 and 37 GHz

where: Δf/f denotes the spacecraft oscillator's frequency variations (square root of Allan's variance);

(8) that sufficient power shall be available in the outermost DOR tone so that the mission requirements in terms of orbit determination accuracy are met (see NOTE, below, and table 2.5.6B-2) provided that in any case P_{DOR} / N_0 shall not exceed 30 dBHz;

(9) that the capability to further reduce DOR tones power shall be implemented in the spacecraft (e.g., applying in-flight modulation index flexibility);

2.5.6B DIFFERENTIAL ONE-WAY RANGING FOR SPACE-TO-EARTH LINKS IN ANGULAR SPACECRAFT POSITION DETERMINATION, CATEGORY B (Continued)

(10) that the power flux density on the Earth of DOR tones outside the deep space band shall be limited to −211 dBW/m^2 in the 8 GHz band and −204 dBW/m^2 in the 32 GHz band;

(11) that no DOR tones in the 31.3–31.8 GHz band shall be employed.

NOTE – Good engineering practice recommends limiting the error contribution due to spacecraft delay measurement $\varepsilon_{\tau_{SC}}$ to ¼ of the total measurement accuracy requirement $\varepsilon_{\Delta\tau_{RSS}}$ when all error contributions are considered.

This implies that the minimum received P_{DOR} / N_0 depends on spanned bandwidth f_{BW} and spacecraft observation time T_{obs}, as well as on accuracy requirement. As in considering (f) above, the relation is:

$$\frac{P_{DOR}}{N_0} = \frac{1}{2\left(\pi f_{BW}\, \varepsilon_{\tau_{SC}}\right)^2 T_{obs}} \text{ in Hz.}$$

Because of geographical constraints on where stations are actually located, and related mutual visibility issues, a typical observation time T_{obs} of 5 to 10 minutes is used.

Some representative values for P_{DOR} / N_0 based on the above best practice considerations are shown in table 2.5.6B-2.

Table 2.5.6B-2: Representative P_{DOR} / N_0 for Selected Values of System Parameters[3]

$\varepsilon_{\Delta\tau_{RSS}}$ (ns)	$\varepsilon_{\tau_{SC}}$ (ns)	f_{BW} (Hz)	T_{obs} (s)	P_{DOR} / N_0 (dBHz)
0.4	0.21	38.25×10^6	600	1.0
0.22	0.054	38.25×10^6	600	13.0
0.12	0.03	38.25×10^6	600	18.1
0.06	0.015	38.25×10^6	600	24.1
0.06	0.015	38.25×10^6	300	27.1
0.03	0.0075	153×10^6	300	21.1

[3] The best practice of keeping $\varepsilon_{\tau_{SC}}$ to be no more than ¼ of $\varepsilon_{\Delta\tau_{RSS}}$ has been relaxed for the first row since thermal noise on the spacecraft delay measurement would be the dominant error source.

2.5.7B SPREAD SPECTRUM DIFFERENTIAL ONE-WAY RANGING FOR SPACE-TO-EARTH LINKS IN ANGULAR SPACECRAFT POSITION DETERMINATION, CATEGORY B

The CCSDS,

considering

(a) that the technique for supporting Delta-DOR measurements with spacecraft transmitting sinusoidal signals as given in recommendation 2.5.6B is widely used and contributes to deep space navigation;

(b) that Delta-DOR measurement accuracy for spacecraft transmitting sinusoidal DOR tones as given in recommendation 2.5.6B can be limited by spectral mismatching between spacecraft and quasar signals;

(c) that the spacecraft delay measurement precision $\varepsilon_{\tau_{SC}}$ depends upon the received DOR signal power-to-noise density ratio (P_{DOR} / N_0) in each of the two most widely spaced DOR signal fundamental harmonics, separated by spanned bandwidth,[1] f_{BW}, Hz apart, and on observation time T_{obs}, as shown in the error relationship:

$$\varepsilon_{\tau_{SC}} = \frac{1}{\pi f_{BW} \sqrt{\frac{2P_{DOR}}{N_0} T_{obs}}} \quad \text{s} ;$$

(d) that quasar data are recorded in channels centered on the spacecraft DOR signal frequencies, and that quasar delay measurement precision $\varepsilon_{\tau_{QU}}$ depends upon quasar signal-to-noise ratio within a channel, SNR_{QU}, and on the spanned bandwidth, f_{BW}, as shown in the error relationship:

$$\varepsilon_{\tau_{QU}} = \frac{\sqrt{2}}{2\pi f_{BW}} \frac{1}{SNR_{QU}} \quad \text{s} ;$$

(e) that quasar signals are broadband white noise;

(f) that measurement errors introduced by instrumental phase dispersion will cancel to the extent that the spacecraft signal spectrum matches the quasar signal spectrum;

(g) that multiplication of a sine-wave subcarrier with a PN code can generate spread-spectrum DOR signals that are broadband;

(h) that Gold PN codes have both good auto-correlation and good cross-correlation properties;

[1] The spanned bandwidth is the widest separation between detectable signals in the spacecraft downlink spectrum.

2.5.7B SPREAD SPECTRUM DIFFERENTIAL ONE-WAY RANGING FOR SPACE-TO-EARTH LINKS IN ANGULAR SPACECRAFT POSITION DETERMINATION, CATEGORY B (Continued)

(i) that the number of chips, N, in a Gold code is related to the code period, P, and chip rate, R_{chs}, by

$$N = \log_2(P \cdot R_{chs} + 1) \ ;$$

(j) that delay ambiguity can be as high as 1 millisecond for spacecraft with sparse tracking, or spacecraft with unmodeled non-gravitational accelerations, or spacecraft coming out of hibernation;

(k) that pulse shaping by a Square Root Raised Cosine (SRRC) filter can flatten the spectrum of a Gold code signal;

(l) that a sine-wave subcarrier BPSK modulated by a Gold code shaped by an SRRC filter is flat (within 2 dB) across 90 percent of a Quasar BandWidth (BW) provided that the chip rate, R_{chs}, is at least 90 percent of BW and the roll-off factor, α, is no more than 0.1;

(m) that a sine-wave subcarrier BPSK modulated by a Gold code shaped by an SRRC filter with roll-off factor 0.5 is flat (within 2 dB) across 82.5 percent of a Quasar BW if the chip rate, R_{chs}, is at least 90 percent of BW, but that in this case, a power fraction of about 0.2 dB is lost outside the bandwidth;

(n) that an analog filter after modulation of the carrier with the DOR waveform might result in a slope across each DOR sideband;

(o) that the quasar catalog is sufficiently dense with sources that can be detected with a recorded channel bandwidth of at least BW = 8 MHz in the 8 GHz band;

(p) that the quasar catalog is sufficiently dense with sources that can be detected with a recorded channel bandwidth of at least BW = 32 MHz in the 32 GHz band;

recommends

(1) that the baseband DOR signal shall be a sine-wave subcarrier BPSK modulated by a PN code when dispersive phase is the limiting factor in navigation accuracy and accuracies better than about 5 nrad are required;

NOTE – The baseband DOR signal has the form $\mathrm{PN(t)} \cdot \sin(2\pi f_s t)$ where f_s is the DOR subcarrier frequency and PN(t) is the Pseudo Random sequence (Gold code) of length N chip, period P, and chip rate R_{chs}.

(2) that the baseband DOR signal shall be phase modulated on the Radio Frequency (RF) carrier;

(3) that the PN code shall be a Gold code;

2.5.7B SPREAD SPECTRUM DIFFERENTIAL ONE-WAY RANGING FOR SPACE-TO-EARTH LINKS IN ANGULAR SPACECRAFT POSITION DETERMINATION, CATEGORY B (Continued)

(4) that the Gold code shall have the number of chips and use the characteristic polynomials[2] for the 8 GHz or 32 GHz band as shown in table 2.5.7B-1, with the code generator circuit as specified in Annex 2.5.7B-1 subsection A1.1.

Table 2.5.7B-1: Recommended PN DOR Gold Code Polynomials

RF Band	N Chips	1st Polynomial	2nd Polynomial
8 GHz	13	$1 + x^9 + x^{10} + x^{12} + x^{13}$	$1 + x^3 + x^4 + x^6 + x^8 + x^9 + x^{13}$
32 GHz	15	$1 + x^{14} + x^{15}$	$1 + x^3 + x^{12} + x^{14} + x^{15}$

(5) that PN code shall be pulse shaped by a Square Root Raised Cosine Filter, as defined in Annex 2.5.7B-1 subsection A1.2;

(6) that the chip rate and roll-off factor should be as shown in table 2.5.7B-2 for the 8-GHz or 32 GHz band;

Table 2.5.7B-2: Recommended PN DOR Chip Rate & Roll-Off Factor

RF Band	Chip Rate	Roll-Off Factor
8 GHz	7.2 to 8.0 Mchip/s	0.1 to 0.5
32 GHz	28.8 to 32.0 Mchip/s	0.1 to 0.5

NOTE – Chip Rate and Roll-Off Factor are selected as trade-offs between spectral flatness (that decreases the measurement error), power that falls outside the quasar channel bandwidth, and hardware implementation. The selection aims at providing flatness (within 2 dB) across at least 80 percent of the quasar channel bandwidth. In particular, roll-off 0.1 is expected to provide a flatness of 90 percent (or higher) across the quasar channel bandwidth, and thus a lower measurement error. Additionally, if combined with the lowest chip rate, it can minimize the power fraction outside the quasar channel bandwidth. Differently, roll-off 0.5 provides a flatness of 82.5 percent at the minimum chip rate. Larger flatness can be achieved by increasing the chip rate, at the price of a higher power fraction that will fall outside the quasar channel bandwidth.

(7) that if an analog filter after modulation of the carrier with the baseband DOR signal results in a slope across the DOR sidebands, then a pre-distortion filter should be used on the baseband DOR signal digital waveform so that the spectrum of the final RF signal can meet the recommended flatness;

[2] The initial linear feedback shift registers seeds require inter-agency coordination in order to avoid potential interference for spacecraft that have spectral overlap and might fall within the same antenna beam.

2.5.7B SPREAD SPECTRUM DIFFERENTIAL ONE-WAY RANGING FOR SPACE-TO-EARTH LINKS IN ANGULAR SPACECRAFT POSITION DETERMINATION, CATEGORY B (Continued)

(8) that the sine-wave subcarrier frequency used in the 8 GHz or the 32 GHz band shall be in the range given in table 2.5.7B-3;

Table 2.5.7B-3: Recommended DOR Subcarrier Signals

Space-to-Earth Frequency Band	Number of DOR Subcarriers	Sine-wave Subcarrier Frequency Range
8 GHz	1	19 to 19.5 MHz
32 GHz	1	76 to 153 MHz (note)
NOTE – Quasar delay precision improves linearly with spanned bandwidth. For this reason, the two DOR sidebands are spread as far apart as practical up to 306 MHz, to achieve the best navigation accuracy without impacting the out-of-band requirements. This might be easily accomplished also in case of a high frequency subcarrier, if the assigned carrier channel is near the center of the spectrum allocation.		

(9) that DOR subcarrier and the chip rate shall be coherent with the downlink RF carrier frequency if carrier-aided detection is used;

(10) that if spacecraft DOR data are to be acquired in the one-way mode, the spacecraft's oscillator stability over a 1-second averaging time shall be:

$\Delta f/f \leq 1.0 \times 10^{-10}$ for the 8 GHz band,
$\Delta f/f \leq 3.0 \times 10^{-11}$ for the 32 GHz band,

where: $\Delta f/f$ denotes the spacecraft oscillator's frequency variations (square root of Allan's variance);

(11) that sufficient power shall be available in the DOR signal so that the mission requirements in terms of orbit determination accuracy are met (see NOTE below and table 2.5.7B-4) provided that in any case, after de-spreading, the P_{DOR} / N_0 shall not exceed 40 dBHz;

(12) that the capability to further reduce DOR signal power shall be implemented in the spacecraft (e.g., applying in-flight modulation index flexibility);

(13) that no discrete component (as modulation products) in the DOR signal RF spectrum shall exceed 30 dBHz;

(14) that the power flux density on the Earth of DOR tones outside the deep space band shall be limited to −211 dBW/m^2 in the 8 GHz band and −204 dBW/m^2 in the 32 GHz band;

(15) that no DOR tones in the 31.3–31.8 GHz band shall be employed.

2.5.7B SPREAD SPECTRUM DIFFERENTIAL ONE-WAY RANGING FOR SPACE-TO-EARTH LINKS IN ANGULAR SPACECRAFT POSITION DETERMINATION, CATEGORY B (Continued)

NOTE – Good engineering practice recommends limiting the error contribution due to spacecraft delay measurement $\varepsilon_{\tau_{SC}}$ to ¼ of the total measurement accuracy requirement $\varepsilon_{\Delta\tau_{RSS}}$ when all error contributions are considered.

This implies that the minimum received P_{DOR} / N_0 depends on spanned bandwidth f_{BW} and spacecraft observation time T_{obs}, as well as on the accuracy requirement. For PN spreading, P_{DOR} is the power in the received subcarrier signal after de-spreading by local correlation with the code model. The relation between P_{DOR} / N_0 and $\varepsilon_{\tau_{SC}}$ is

$$\frac{P_{DOR}}{N_0} = \frac{1}{2\left(\pi f_{BW} \varepsilon_{\tau_{SC}}\right)^2 T_{obs}} \quad \text{in Hz} .$$

Because of geographical constraints on where stations are actually located and related mutual visibility issues, a typical observation time T_{obs} of 5 to 10 minutes is used.

Some representative values for P_{DOR} / N_0 based on the above best practice considerations are shown in table 2.5.7B-4.

Table 2.5.7B-4: Representative P_{DOR} / N_0 for Selected Values of System Parameters

$\varepsilon_{\Delta\tau_{RSS}}$ (ns)	$\varepsilon_{\tau_{SC}}$ (ns)	RF Band	f_{BW} (Hz)	T_{obs} (s)	P_{DOR} / N_0 (dB•Hz) (after despreading)
0.22	0.054	8 GHz	38.25×10^6	600	13.0
0.12	0.03	8 GHz	38.25×10^6	600	18.1
0.06	0.015	8 GHz	38.25×10^6	600	24.1
0.06	0.015	8 GHz	38.25×10^6	300	27.1
0.03	0.0075	32 GHz	153×10^6	300	27.1
0.015	0.00375	32 GHz	306×10^6	300	27.1

2.5.7B SPREAD SPECTRUM DIFFERENTIAL ONE-WAY RANGING FOR SPACE-TO-EARTH LINKS IN ANGULAR SPACECRAFT POSITION DETERMINATION, CATEGORY B (Continued)

Annex 2.5.7B-1

(Normative)

A1.1 GOLD CODE GENERATOR CIRCUITS

For the 8 GHz band the recommended Gold code generator to be used is specified in figure 2.5.7B-1.

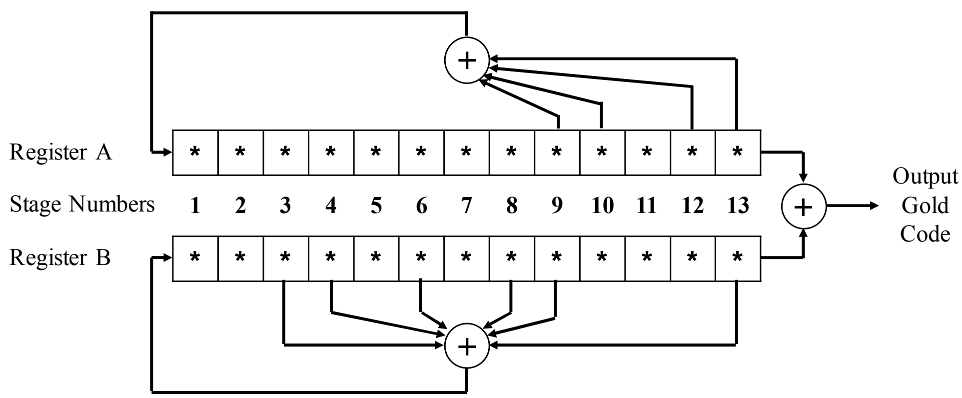

Figure 2.5.7B-1: 8 GHz Band Gold Code Generator Circuit

For the 32 GHz band the recommended Gold code generator to be used is specified in figure 2.5.7B-2.

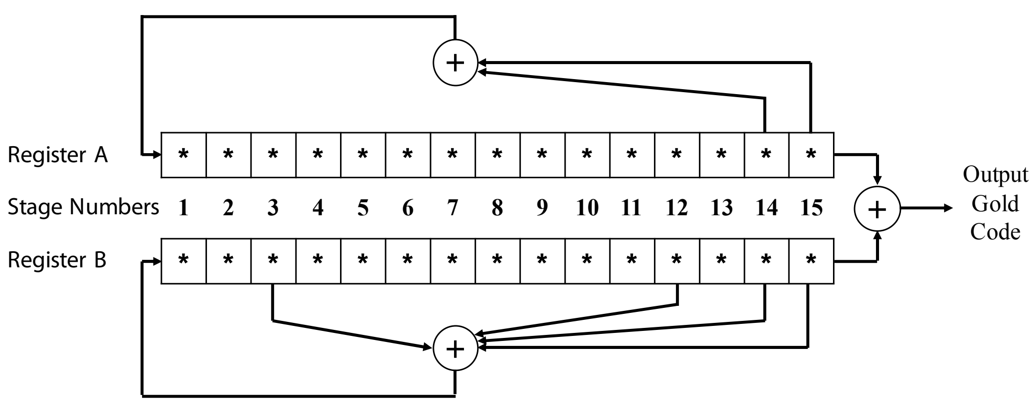

Figure 2.5.7B-2: 32 GHz Band Gold Code Generator Circuit

The initial seeds for Register A and Register B require inter-agency coordination for spacecraft that have spectral overlap and might fall within the same antenna beam. This is required to avoid potential interference between spacecraft. This is denoted by the *s in the bits of both Register A and Register B. The final design of each register on a spacecraft will have a binary initial seed.

2.5.7B SPREAD SPECTRUM DIFFERENTIAL ONE-WAY RANGING FOR SPACE-TO-EARTH LINKS IN ANGULAR SPACECRAFT POSITION DETERMINATION, CATEGORY B (Continued)

Annex 2.5.7B-1 (Continued)

NOTE – The notation used in the above diagrams is as follows. Each Gold code generator contains two Linear Feedback Shift Registers (LFSRs). The feedback tap location of each LFSR can be expressed as a function of x, where the feedback taps are the exponents of x with non-zero polynomial coefficients. For example, from recommends (4), the top LFSR in figure 2.5.7B-1 has the corresponding polynomial $f(x) = 1 + x^9 + x^{10} + x^{12} + x^{13}$, that is, the feedback taps are on the ninth, tenth, twelfth, and thirteenth taps of the 13-stage LFSR. The leading '1' in the polynomial corresponds to the zero valued coefficient of x^0, which denotes the feedback input to the first stage of the shift register. The output of the register is from the last, thirteenth, stage.

A1.2 SRRC PN CODE PULSE SHAPING

The normalized transfer function of the SRRC pulse shall be:[3]

$$\mathrm{H}(f)=\begin{cases} 1 & \textit{if} \quad |f| < f_\mathrm{N}(1-\alpha) \\ \sqrt{\dfrac{1}{2}+\dfrac{1}{2}\sin\left\{\dfrac{\pi}{2f_\mathrm{N}}\left(\dfrac{f_\mathrm{N}-|f|}{\alpha}\right)\right\}} & \textit{if} \quad f_\mathrm{N}(1-\alpha)\le|f|\le f_\mathrm{N}(1+\alpha)\,\# \\ 0 & \textit{if} \quad |f| > f_\mathrm{N}(1+\alpha) \end{cases},$$

where $f_\mathrm{N} = 1 / (2T_{\mathrm{chs}}) = R_{\mathrm{chs}} / 2$ is the Nyquist frequency and α is the roll-off factor.

[3] The PN code shall be SRRC pulse shaped and not SRRC filtered. This will guarantee that the sine-wave subcarrier modulated by the Gold code will be flat over the quasar channel bandwidth. A possible method for implementing SRRC pulse shaping is the Nyquist pulse-shaping technique provided in CCSDS 413.0-G-3.

2.5.7B SPREAD SPECTRUM DIFFERENTIAL ONE-WAY RANGING FOR SPACE-TO-EARTH LINKS IN ANGULAR SPACECRAFT POSITION DETERMINATION, CATEGORY B (Continued)

Annex 2.5.7B-2

(Informative)

A2.1 ANALOG SPECTRUM SHAPING

The SRRC filter shaping a Pseudo-Noise (PN) impulse train creates a flat baseband spectrum as specified by $H(f)^2$ in Annex 2.5.7B-1 subsection A1.2. However, after modulation on the RF carrier, any analog filters can add further unwanted shaping to the spectrum. This is common in designs that include an analog Low Pass Filter (LPF) after a digital-to-analog converter.

Figures 2.5.7B-3 and 2.5.7B-4 show as examples the resulting spectrum of a transmitter with an analog LPF that adds undesired shaping to the spectrum. This transmitter was designed with a chip rate of 7.14 Mchip/s, a roll-off factor of 0.12, and a DOR subcarrier frequency of 19.1 MHz. The measured baseband spectrum was flat within the DOR tone channels, but after the analog LPF there is approximately 3 dB of power variation across the 8 MHz PN spectrum.

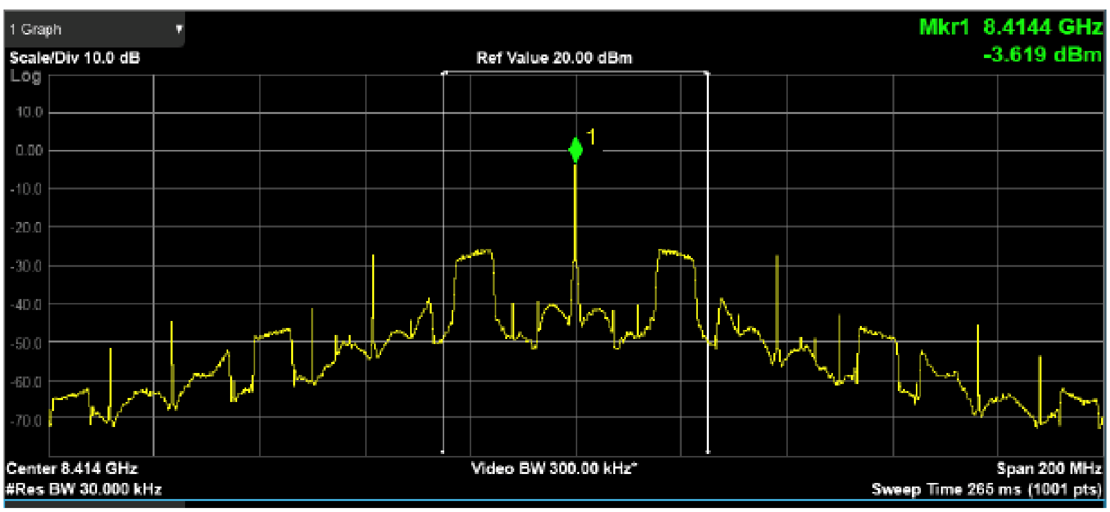

Figure 2.5.7B-3: PN Spectrum Shaping as a Result of an Analog LPF, 200 MHz Bandwidth

2.5.7B SPREAD SPECTRUM DIFFERENTIAL ONE-WAY RANGING FOR SPACE-TO-EARTH LINKS IN ANGULAR SPACECRAFT POSITION DETERMINATION, CATEGORY B (Continued)

Annex 2.5.7B-2 (Continued)

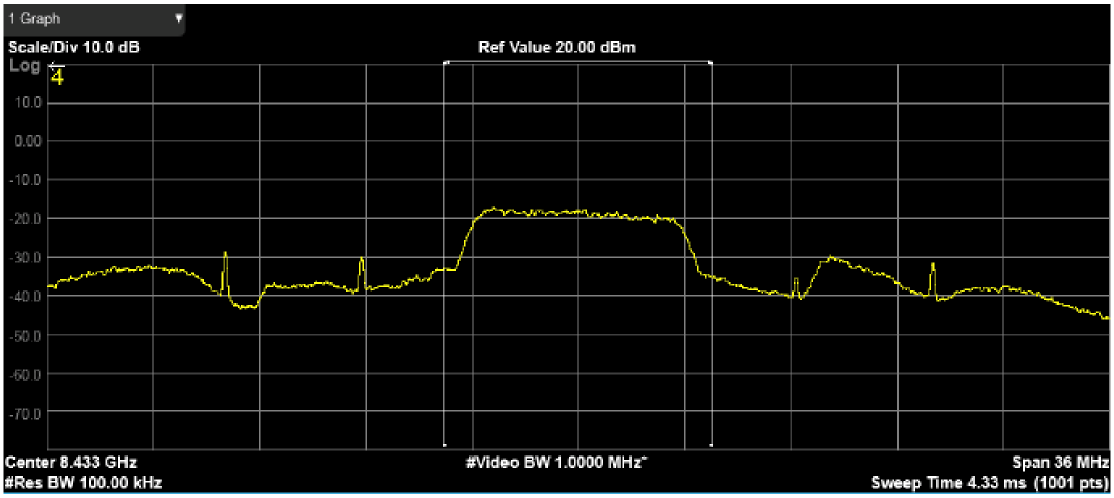

Figure 2.5.7B-4: PN Spectrum as a Result of an Analog LPF, 36 MHz Bandwidth

A corresponding equalization/pre-distortion filter can be designed to counteract this undesired shaping. The design criterion is to create a flat power spectrum over the final RF spectrum with a linear phase response. Figure 2.5.7B-5 shows the same bandwidth as figure 2.5.7B-4, but with an equalization/pre-distortion filter applied to remove the 3 dB power variation, leaving a flat spectrum.

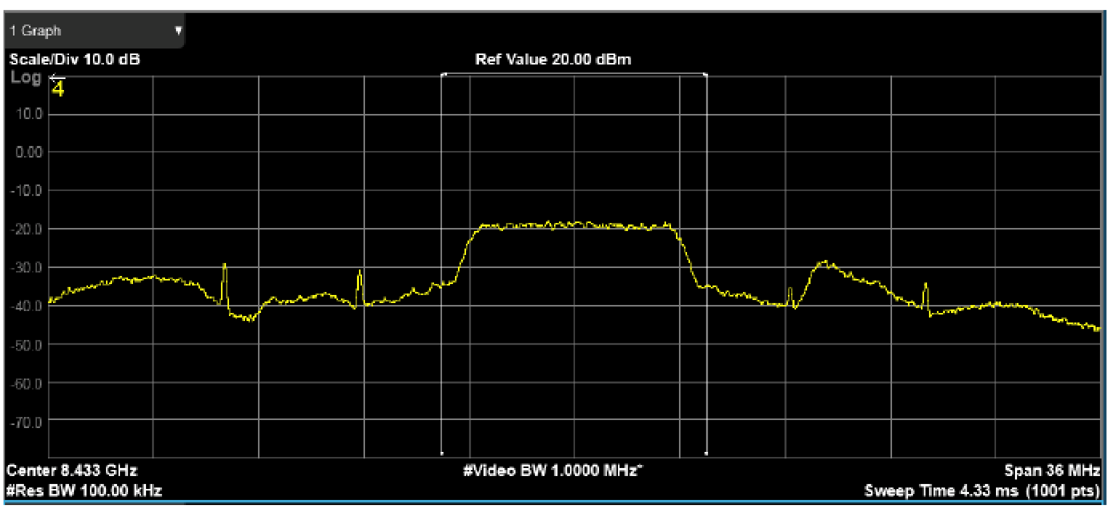

Figure 2.5.7B-5: PN Spectrum Flattened by Equalization/Pre-Distortion Filter, 36 MHz Bandwidth

For the best error reduction, the transmitted analog spectrum should be as flat as possible. This means that a digital pre-distortion filter is required for any cases in which analog filters add an unacceptable amount of shaping to the spectrum.

3.1.6B CHANNEL FREQUENCY PLAN FOR 2, 7, 8, 32, AND 34 GHZ, CATEGORY B

The CCSDS,

considering

(a) that channel frequency plans for Category B missions exist for the 2, 7, 8, 32, and 34 GHz bands;

(b) that the sets of channel frequency pairs in these existing plans are based upon the recommended turnaround ratios;

(c) that members of the Space Frequency Coordination Group (SFCG) have resolved to select frequencies for their Category B missions from the existing channel frequency plans;

(d) that most past, existing, and planned Category B missions have assigned frequencies that were selected on the basis of these existing channel frequency plans;

(e) that CCSDS agencies conducting Category B missions have coordinated the selection of frequencies from those embodied in the existing channel frequency plans in order to avoid interference between missions;

recommends

(1) that CCSDS agencies select frequencies for their Category B missions operating in the 2, 7, 8, 32, and 34 GHz bands from the channel frequency plan contained in table 3.1.6B-1;

(2) that frequency selection be coordinated with an appropriate organization, such as the SFCG, to ensure the orderly use of the channel frequency plan.

TABLE 3.1.6B-1: Channel Frequencies for Category B (Deep-Space) Missions

BAND (GHz):	2 E-S	2 S-E	7 E-S	8 S-E	32 S-E	32 S-E	32 S-E	34 E-S
FACTOR:	221	240	749	880	3328	3344	3360	3599
CHANNEL		F2DN						
1	~~* 2108.878858~~	2290.185185	7147.286265	~~* 8397.345679~~	~~#31757.234568~~	# 31909.9135~~80~~78	#32062.59259~~2~~1	# 34343.235339~~9~~7
2	~~* 2109.219908~~	2290.555556	7148.44213~~2~~1	~~* 8398.703706~~	~~#31762.370379~~	# 31915.07408~~3~~0	#32067.77778~~7~~4	# 34348.7893~~61~~58
3	~~* 2109.560957~~	2290.925926	7149.597994	8400.061729	~~#31767.506176~~	# 31920.2345~~71~~69	#32072.96296~~6~~4	# 34354.34336~~8~~5
4	~~* 2109.902006~~	2291.296296	7150.753857	8401.419752	~~#31772.641973~~	# 31925.39505~~9~~7	#32078.14814~~6~~4	# 34359.89737~~4~~2
5	2110.243056	2291.666667	7151.90972~~4~~3	8402.7777~~80~~79	~~31777.777784~~	31930.5555~~62~~59	32083.3333~~40~~37	34365.45139~~6~~3
6	2110.584105	2292.037037	7153.06558~~7~~6	8404.13580~~3~~2	~~31782.913581~~	31935.7160~~50~~48	32088.51851~~9~~7	34371.005~~402~~399
7	2110.925154	2292.407407	7154.2214~~50~~49	8405.49382~~6~~5	~~31788.049378~~	31940.87653~~8~~6	32093.70369~~9~~6	34376.55940~~8~~6
8	2111.266204	2292.777778	7155.377316	8406.851853	~~31793.185190~~	31946.037042	32098.88889~~3~~4	34382.11343~~1~~2
9	2111.607253	2293.148148	7156.533179	8408.20987~~6~~7	~~31798.320986~~	31951.19753~~0~~1	32104.07407~~3~~4	34387.66743~~7~~8
10	2111.948303	2293.518519	7157.689045	8409.567903	31803.456798	31956.358033	32109.259267	34393.2214~~60~~59
11	2112.289352	2293.888889	7158.844908	8410.925927	31808.592595	31961.518521	32114.444447	34398.775466
12	2112.630401	2294.259259	7160.000771	8412.283950	31813.728392	31966.6790~~09~~10	32119.62962~~6~~7	34404.329472
13	2112.971451	2294.629630	7161.156637	8413.641977	31818.864203	31971.839512	32124.81482~~1~~0	34409.88349~~4~~3
14	2113.312500	2295.000000	7162.312500	8415.000000	31824.000000	31977.000000	32130.000000	34415.437500
15	2113.653549	2295.370370	7163.468363	8416.358023	31829.135797	31982.160488	32135.1851~~79~~80	34420.99150~~6~~7
16	2113.994599	2295.740741	7164.624229	8417.716050	31834.271608	31987.32099~~1~~0	32140.37037~~4~~3	34426.545528
17	2114.335648	2296.111111	7165.780092	8419.074073	31839.407405	31992.481479	32145.555553	34432.099534
18	2114.676697	2296.481481	7166.935955	8420.432097	31844.543202	31997.641967	32150.740733	34437.65354~~0~~1
19	2115.017747	2296.851852	7168.091821	8421.79012~~4~~3	31849.67901~~4~~2	32002.8024~~70~~69	32155.92592~~7~~6	34443.20756~~3~~2
20	2115.358796	2297.222222	7169.247684	8423.148147	31854.814810	32007.962958	32161.11110~~7~~6	34448.76156~~9~~8
21	2115.699846	2297.592593	7170.40355~~0~~1	8424.50617~~4~~5	31859.95062~~2~~4	32013.12346~~2~~4	32166.29630~~1~~4	34454.31559~~2~~4

Note – ~~Channel frequencies marked " * " are not within the Category B band allocation.~~

Channel frequencies marked " # " may be used in conjunction with the corresponding channel in a lower frequency band if that channel is ~~not marked by " * "~~available within the Category B allocation.

F2DN = N(10/27) + 2295 MHz, where N is in the range −13 to +28 for this table. The value of F2DN is rounded to the nearest Hz. Frequencies in the ~~2~~7 GHz E-S band are then computed from F2DN and rounded to the nearest Hz. Channel numbers are equal to N + 14. Frequencies in other bands are derived from the ~~2~~7 GHz E-S frequencies by ~~using~~multiplying by the corresponding ratio of frequency factors and then rounding to the nearest Hz. Because of rounding, ratios of the uplink to downlink frequency may differ by 1 or 2 Hz from the exact turnaround ratio in some cases.

TABLE 3.1.6B-1 (Continued): Channel Frequencies for Category B (Deep-Space) Missions

BAND (GHZ):	**2 E-S**	**2 S-E**	**7 E-S**	**8 S-E**	**32 S-E**	**32 S-E**	**32 S-E**	**34 E-S**
FACTOR:	**221**	**240**	**749**	**880**	**3328**	**3344**	**3360**	**3599**
CHANNEL		**F2DN**						
22	2116.040895	2297.962963	7171.55941~~3~~4	8425.86419~~7~~8	31865.0864~~19~~22	32018.28395~~0~~2	32171.48148~~1~~3	34459.869~~598~~601
23	2116.381944	2298.333333	7172.71527~~6~~7	8427.22222~~0~~1	31870.22221~~6~~9	32023.4444~~38~~41	32176.66666~~0~~3	34465.42360~~4~~7
24	2116.722994	2298.703704	7173.871143	8428.580248	31875.35802~~7~~9	32028.60494~~1~~3	32181.85185~~4~~6	34470.97762~~6~~8
25	2117.064043	2299.074074	7175.027006	8429.938271	31880.49382~~4~~6	32033.7654~~29~~31	32187.03703~~4~~6	34476.53163~~2~~5
26	2117.405092	2299.444444	7176.18286~~8~~9	8431.29629~~4~~5	31885.62962~~1~~4	32038.9259~~17~~20	32192.22221~~3~~6	34482.0856~~39~~42
27	2117.746142	2299.814815	7177.338735	8432.654321	31890.76543~~2~~4	32044.08642~~0~~2	32197.40740~~8~~9	34487.63966~~1~~3
28	2118.087191	~~* 2300.185185~~	7178.49459~~7~~8	8434.01234~~4~~5	#31895.9012~~29~~31	# 32049.2469~~08~~10	#32202.59258~~7~~9	# 34493.19366~~7~~9
29	2118.428241	~~* 2300.555556~~	7179.65046~~3~~4	8435.37037~~1~~2	#31901.03704~~1~~2	# 32054.40741~~1~~2	#32207.777782	# 34498.7476~~89~~90
30	2118.769290	~~* 2300.925926~~	7180.806327	8436.728395	#31906.17283~~8~~9	# 32059.567~~899~~901	#32212.96296~~1~~2	# 34504.30169~~5~~7
31	2119.110339	~~* 2301.296296~~	7181.962190	8438.086418	#31911.30863~~4~~6	# 32064.72838~~7~~9	#32218.14814~~0~~2	# 34509.85570~~1~~3
32	2119.451389	~~* 2301.666667~~	7183.11805~~6~~7	8439.44444~~5~~6	#31916.4444~~46~~51	# 32069.88889~~1~~5	#32223.3333~~35~~40	# 34515.40972~~4~~9
33	2119.792438	~~* 2302.037037~~	7184.2739~~19~~20	8440.80246~~8~~9	#31921.58024~~3~~8	# 32075.0493~~79~~84	#32228.5185~~14~~20	# 34520.96373~~1~~6
34	~~* 2120.133487~~	~~* 2302.407407~~	7185.42978~~2~~3	8442.16049~~1~~3	#31926.71604~~0~~5	# 32080.2098~~67~~72	#32233.70369~~4~~9	# 34526.5177~~37~~42
35	~~* 2120.474537~~	~~* 2302.777778~~	7186.58564~~8~~9	8443.5185~~18~~20	#31931.85185~~1~~6	# 32085.37037~~0~~4	#32238.8888~~88~~93	# 34532.0717~~59~~63
36	~~* 2120.815586~~	~~* 2303.148148~~	7187.74151~~1~~2	8444.87654~~2~~3	#31936.9876~~48~~53	# 32090.5308~~58~~63	#32244.0740~~68~~73	# 34537.6257~~65~~70
37	~~* 2121.156636~~	~~* 2303.518519~~	7188.89737~~7~~8	8446.2345~~69~~70	#31942.12346~~0~~3	# 32095.69136~~1~~5	#32249.25926~~2~~6	# 34543.1797~~87~~91
38	~~* 2121.497685~~	~~* 2303.888889~~	~~* 7190.053240~~	8447.59259~~2~~3	#31947.2592~~56~~60	# 32100.8518~~49~~53	#32254.44444~~2~~6	# 34548.73379~~3~~8
39	~~* 2121.838734~~	~~* 2304.259259~~	~~* 7191.209103~~	8448.95061~~5~~6	#31952.39505~~3~~8	# 32106.0123~~37~~41	#32259.62962~~1~~5	# 34554.287~~799~~804
40	~~* 2122.179784~~	~~* 2304.629630~~	~~* 7192.364969~~	~~* 8450.308642~~	#31957.53086~~5~~8	# 32111.17284~~0~~3	#32264.81481~~6~~9	# 34559.84182~~2~~5
41	~~* 2122.520833~~	~~* 2305.000000~~	~~* 7193.520832~~	~~* 8451.666665~~	#31962.66666~~2~~5	# 32116.3333~~28~~32	#32269.99999~~5~~9	# 34565.3958~~28~~32
42	~~* 2122.861882~~	~~* 2305.370370~~	~~* 7194.676696~~	~~* 8453.024689~~	#31967.8024~~58~~62	# 32121.4938~~16~~20	#32275.18517~~4~~8	# 34570.94983~~4~~8

Note – ~~Channel frequencies marked " * " are not within the Category B band allocation.~~

Channel frequencies marked " # " may be used in conjunction with the corresponding channel in a lower frequency band if that channel is ~~not marked by " * "~~available within the Category B allocation.

F2DN = N(10/27) + 2295 MHz, where N is in the range −13 to +28 for this table. The value of F2DN is rounded to the nearest Hz. Frequencies in the ~~2~~7 GHz E-S band are then computed from F2DN and rounded to the nearest Hz. Channel numbers are equal to N + 14. Frequencies in other bands are derived from the ~~2~~7 GHz E-S frequencies by ~~using~~multiplying by the corresponding ratio of frequency factors and then rounding to the nearest Hz. Because of rounding, ratios of the uplink to downlink frequency may differ by 1 or 2 Hz from the exact turnaround ratio in some cases.