The Consultative Committee for Space Data Systems

ESA PROTOTYPE IMPLEMENTATION FOR THE PN DOR CODES

DRAFT CCSDS RECORD

SLS-RFM_23-06

FOREWORD

[Foreword text specific to this document goes here. The text below is boilerplate.]

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DOCUMENT CONTROL

Document	Title and Issue	Date	Status
CCSDS 000.0-Y-0	[Document Title], Draft CCSDS Record, Issue 0	November 2010	Current draft

CONTENTS

1 INTRODUCTION

1.1 PURPOSE

This document is a record of an independent implementations of the Spread Spectrum Differential One-way ranging (alias *PN DDOR*) by the CCSDS Delta-DOR and Radio Frequency Modulation Working Groups.

In order to complete the conversion into a CCSDS recommended standard, CCSDS A02.1-Y-4 requires that "at least two independent and interoperable prototypes or implementations must have been developed and demonstrated […] The WG Chairs are responsible for documenting the specific implementations that qualify the specification for CCSDS Recommended Standard status, along with reports relevant to their testing". This document serves that purpose.

Document CCSDS A02.1-Y-4 also requires, "If patented or otherwise controlled technology is required for the separate implementations, they each must also have resulted from separate exercise of the licensing process". Section 4 contains a note about patented technology.

1.2 SCOPE

This document is not part of any CCSDS recommended standard.

1.3 ORGANIZATION OF THIS REPORT

This document is organized as follows:

- Section 2 reports a description of the ESA/Thales X-Band transponder implementation and the testing that was performed;
- Section 3 provides test results
- Section 4 describes licensing agreements
- Section 5 draws conclusions.

1.4 REFERENCES

The following publications are referenced in this document. At the time of publication, the editions indicated were valid. All publications are subject to revision, and users of this document are encouraged to investigate the possibility of applying the most recent editions of the publications indicated below. The CCSDS Secretariat maintains a register of currently valid CCSDS publications.

[1] CCSDS 401.0-B-31, "Radio Frequency and Modulation systems – Part 1, Earth Stations and Spacecrafts", February 2021.

[2] *White paper REC 2.5.7B*, “SPREAD SPECTRUM DIFFERENTIAL ONE-WAY RANGING” Recommendation.

[3] CCSDS 401 (2.5.6B) B-4.2, “DIFFERENTIAL ONE-WAY RANGING FOR SPACE-TO-EARTH LINKS IN ANGULAR SPACECRAFT POSITION DETERMINATION, CATEGORY B”.

[4] SLS-RFM_20-03, A. Modenini, G. Boscagli, “Preliminary assessment of WB-DDOR parameters vs transponder implementation” presented to SLS-RFM in Spring 2020.

2 ESA PROTOTYPE IMPLEMENTATION

2.1 OVERVIEW

A PN DOR standard was introduced in a draft recommendation 2.5.7B [2] that was presented and discussed at the CCSDS 2019 Spring Meetings in Mountain View, again at the Fall 2019 Meetings, and again at the Spring 2020 Meetings. The recommendation included a recommendation for the Gold Code sequence, the shaping filter parameters, and the transmitter chip rate and frequencies.

This section describes the transponder implementations that was done in X-Band, followed by a summary of the test results.

2.2 IMPLEMENTATION AT ESA

This section provides the description of the implementation that was done at ESA, by Thales Alenia Space, as part of the Integrated Deep Space Transponder (IDST) development.

The top-level diagram of the IDST is shown in Figure 1, and it is composed internally of two RF sections, for receiving and transmitting in both X- and Ka-Band, and digital baseband core, implemented by means of a FPGA.

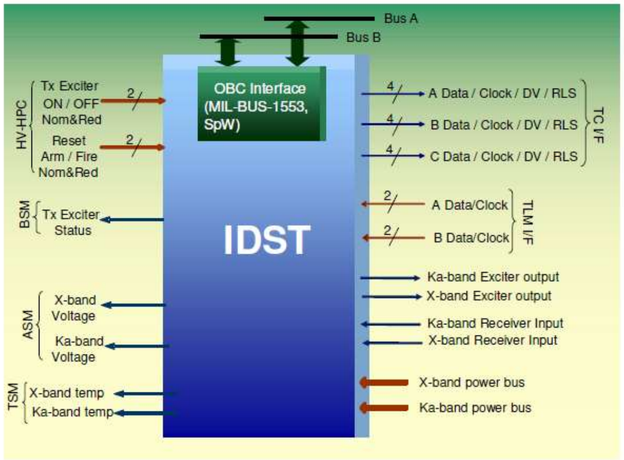


Figure 1.Top-level diagram of IDST

The IDST is able to support standard DDOR and the Spread Spectrum DDOR as per CCSDS 401 (2.5.6B) and (2.5.7B) respectively [1].

The DDOR was implemented in digital, inside the IDST FPGA, as a modulation of the downlink carrier by two subcarriers which, in-turn, are BPSK modulated by the relevant pseudo-noise (PN) code. Namely, the two subcarriers read

$$\sum_k c_{k,1} p(t-kT)\sin(2\pi f_1 t) + c_{k,2} p(t-kT)\sin(2\pi f_2 t),$$

where $c_{k,1}$ and $c_{k,2}$ are the chips belonging to two PN code sequences, f_1 and f_2 the subcarrier frequency, T the chip time, and $p(t)$ is a squared-root raised cosine shaping pulse

A block diagram of the actual digital implementation is shown in Figure 2. Two numerically controlled oscillators (NCOs) drives the PN sequences generation that are then, in turns, are filtered, up-sampled, and finally modulating the subcarriers.

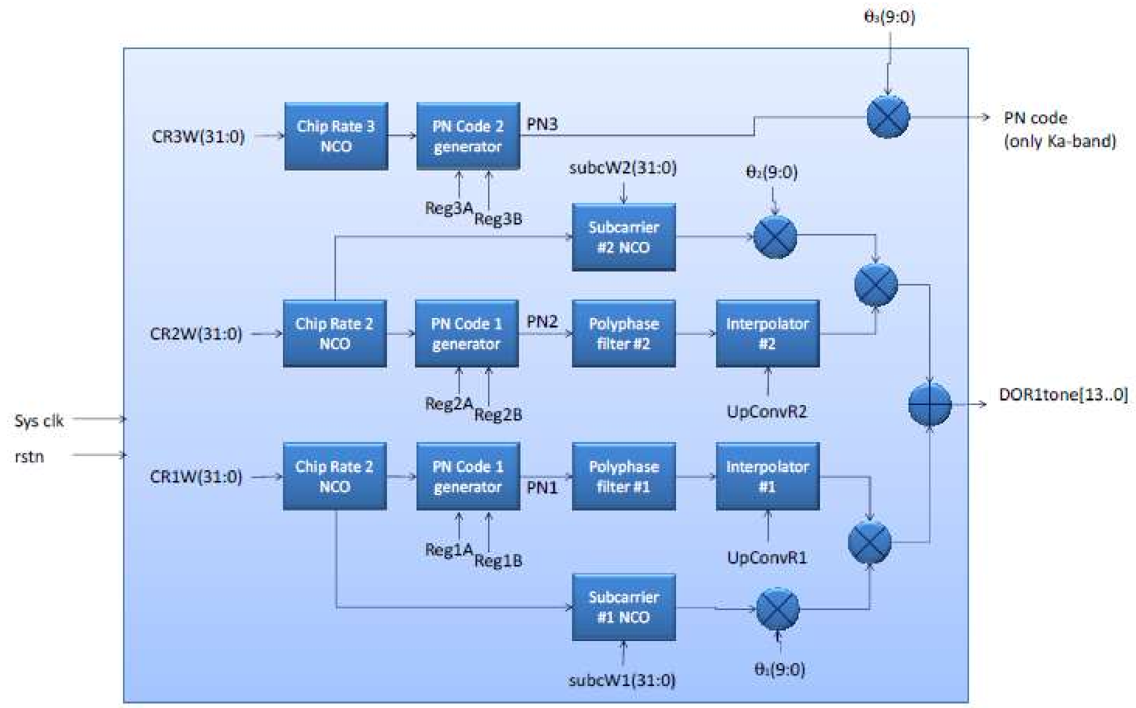


Figure 2: block diagram of IDST Spread Spectrum DDOR.

The sequences of chips $c_{k,1}$ and $c_{k,2}$ are generated as two Gold code generators as depicted in Figure 3. The Register B is pre-loaded with values that ensure a balanced code. Instead the Register A and C are decided depending on the code that shall be implemented.

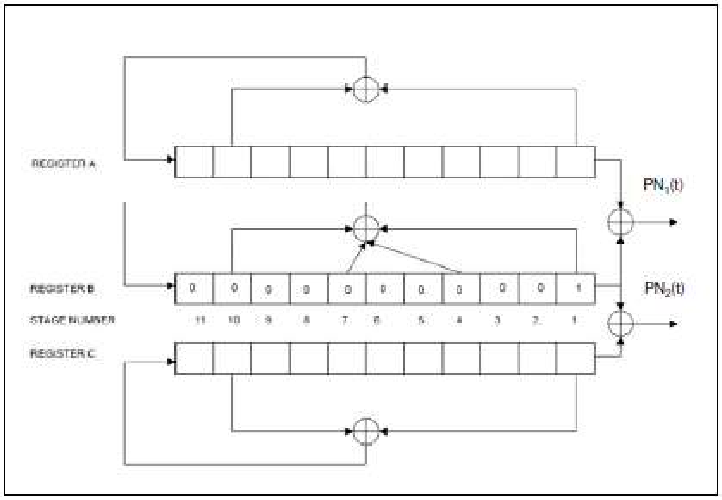


Figure 3: PN sequences generator

In case of classical DDOR, in compliance to [3], the IDST can set that $c_{k,1} = c_{k,2} = 1$, and $p(t) = rect(t/T)$, thus generating $s(t)$ as two pure tones at frequency f_1 and f_2 equal to about ~4 and ~19 MHz.

In the case of PN DDOR, in compliance to draft recommendation 2.5.7B [2], the sequence $c_{k,2}$ can be deactivated, while $c_{k,1}$ is the PN sequence, filtered with $p(t)$ being SRRC with a settable roll-off. The sub-carrier tone f_1 is selected about 19 MHz. On the other hand, it is pointed out that the PN sequence generator implemented in the IDST was originally not fully compliant, in terms of feedback lines, to the Gold code generator in Annex A of [2] for 8 GHz. This was corrected for the testing described in section 3.

Although not part of the standards, the IDST can implement also PN DDOR with both the sub-carrier tones enabled, and with frequency ~5 MHz, and ~19 MHz.

2.3 IN FACTORY TESTING

Prior to the tests described in section 3, the IDST was tested in factory using the test setup reported in Figure 4, where the unit under test is connected to an X/Ka uplink generator (including TC sub-carrier, BPSK modulator, PM modulator, etc.), debuggers, a logic analyzer, and finally a spectrum analyzer.

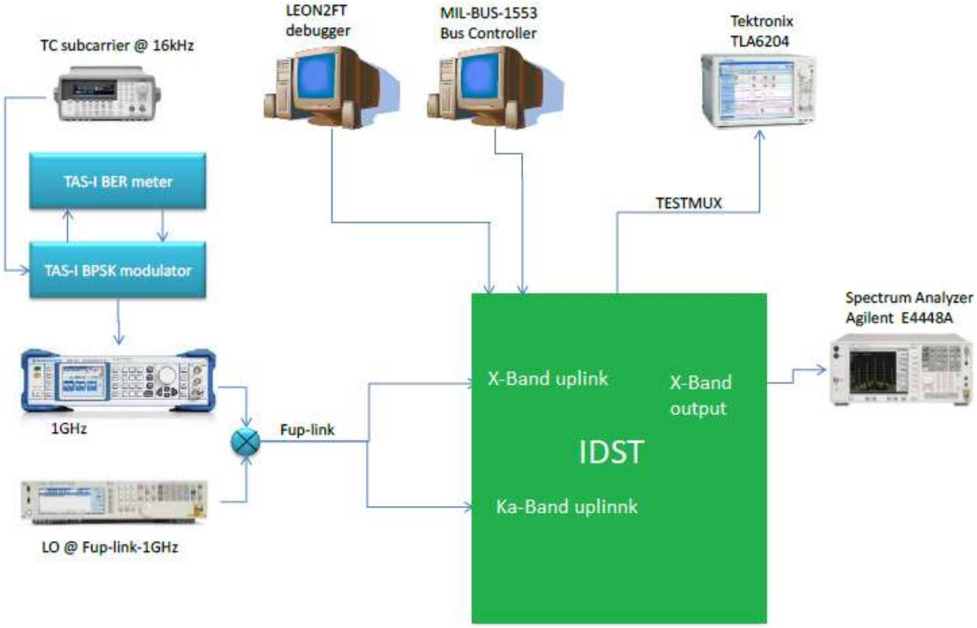
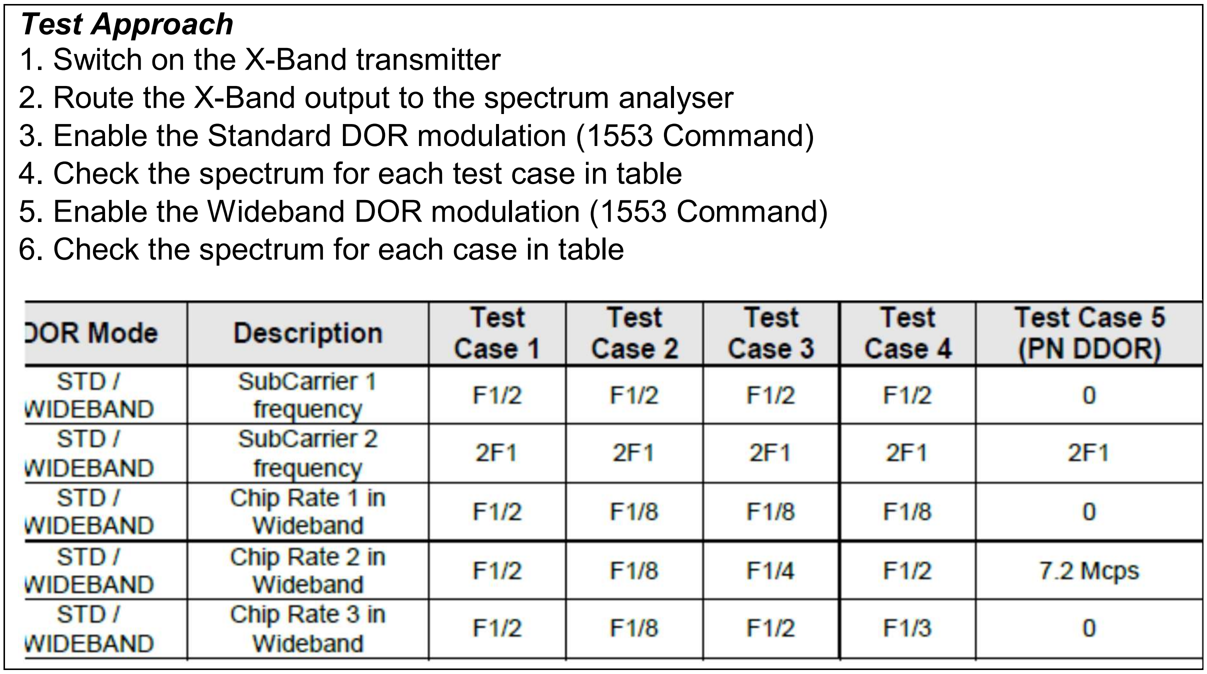


Figure 4: IDST test bench

For DDOR, both classical and PN DDOR were tested with the procedure reported below, where F1 refers to 9.6 MHz.



Test Approach

1. Switch on the X-Band transmitter
2. Route the X-Band output to the spectrum analyser
3. Enable the Standard DOR modulation (1553 Command)
4. Check the spectrum for each test case in table
5. Enable the Wideband DOR modulation (1553 Command)
6. Check the spectrum for each case in table

DOR Mode	Description	Test Case 1	Test Case 2	Test Case 3	Test Case 4	Test Case 5 (PN DDOR)
STD / WIDEBAND	SubCarrier 1 frequency	F1/2	F1/2	F1/2	F1/2	0
STD / WIDEBAND	SubCarrier 2 frequency	2F1	2F1	2F1	2F1	2F1
STD / WIDEBAND	Chip Rate 1 in Wideband	F1/2	F1/8	F1/8	F1/8	0
STD / WIDEBAND	Chip Rate 2 in Wideband	F1/2	F1/8	F1/4	F1/2	7.2 Mcps
STD / WIDEBAND	Chip Rate 3 in Wideband	F1/2	F1/8	F1/2	F1/3	0

In following, the test result limited to PN DDOR Test case 1 and Test Case 5 are reported.

For first test case, Figure 5 shows the spectrum of the PN DDOR, while Figure 6 shows the measurement of the flatness across the SRRC spectrum of the first sub-carrier. It can be seen that the total occupied bandwidth (-2 dB) is about 4.4 MHz, i.e., 91.6% w.r.t. the chip rate. If this value is scaled for 7.2 Mcps and 8 MHz quasar bandwidth, provides a flatness of 82.5% as indicated by the standard (and previously shown in SLS-RFM_20-03, [4]).

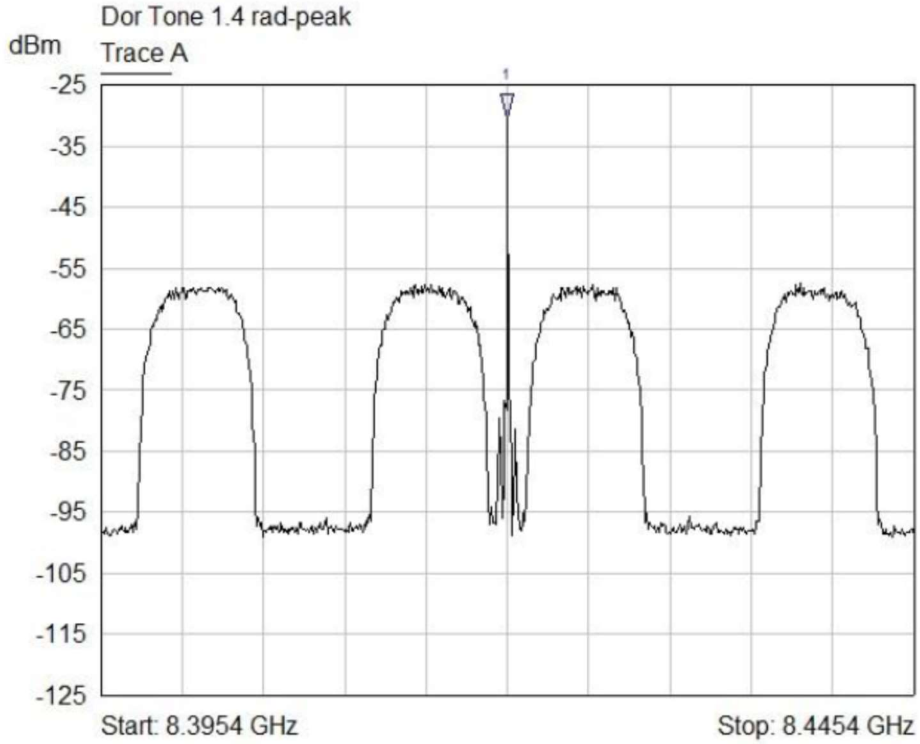
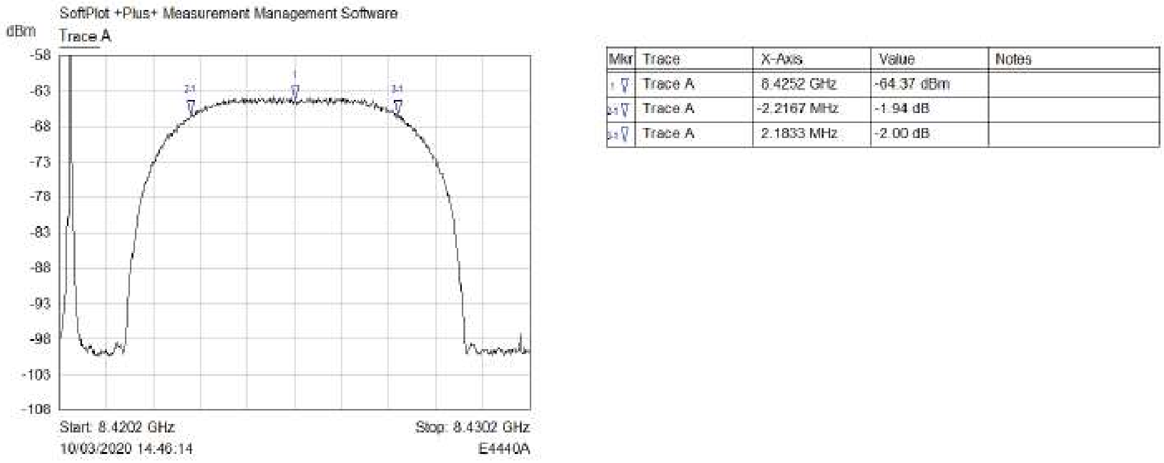


Figure 5: spectrum of PN DDOR (test case 1)



Mkr	Trace	X-Axis	Value	Notes
1 ▽	Trace A	8.4252 GHz	-64.37 dBm	
2-1 ▽	Trace A	-2.2167 MHz	-1.94 dB	
3-1 ▽	Trace A	2.1833 MHz	-2.00 dB	

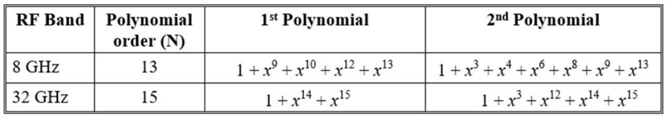
Figure 6: measurement of the flatness on the first sub-carrier (test case 1)

3 IDST TESTING

3.1 X-BAND

The IDST was tested at the Ground Station Reference Facility (GSRF) of ESOC from Dec 5th to Dec 16th, 2022.

Transponder performance was tested against the recommends in [2]:

<table>
<tr><th>#</th><th><i>Recommendation’s text:</i></th><th><i>Validation</i></th></tr>
<tr><td>1</td><td>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;</td><td>By design.</td></tr>
<tr><td>2</td><td>that the baseband DOR signal shall be phase modulated on the Radio Frequency (RF) carrier;</td><td>By design</td></tr>
<tr><td>3</td><td>that the PN code shall be a Gold code;</td><td>By design</td></tr>
<tr><td>4</td><td>that the Gold code shall use the characteristic polynomials[1] 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

<table>
<tr><th>RF Band</th><th>Polynomial order (N)</th><th>1st Polynomial</th><th>2nd Polynomial</th></tr>
<tr><td>8 GHz</td><td>13</td><td>$1 + x^9 + x^{10} + x^{12} + x^{13}$</td><td>$1 + x^3 + x^4 + x^6 + x^8 + x^9 + x^{13}$</td></tr>
<tr><td>32 GHz</td><td>15</td><td>$1 + x^{14} + x^{15}$</td><td>$1 + x^3 + x^{12} + x^{14} + x^{15}$</td></tr>
</table>
</td><td>Implicitly validated as part of PN DDOR correlation (signal despreading required)</td></tr>
<tr><td>5</td><td>that the PN code shall be pulse shaped by a Square Root Raised Cosine Filter</td><td>3.1.1</td></tr>
<tr><td>6</td><td>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;</td><td>3.1.1</td></tr>
</table>

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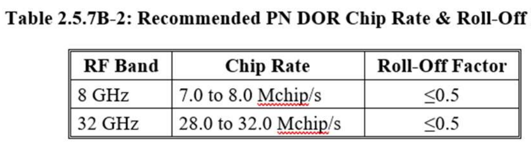
[1] The initial linear feedback shift registers seeds require inter-agency coordination in order to avoid potential interference for spacecraft that have spectral overlap and might fall within the same antenna beam.

<table>
<tr><td></td><td>
Table 2.5.7B-2: Recommended PN DOR Chip Rate & Roll-Off Factor
<table>
<tr><th>RF Band</th><th>Chip Rate</th><th>Roll-Off Factor</th></tr>
<tr><td>8 GHz</td><td>7.0 to 8.0 Mchip/s</td><td>≤0.5</td></tr>
<tr><td>32 GHz</td><td>28.0 to 32.0 Mchip/s</td><td>≤0.5</td></tr>
</table></td><td></td></tr>
<tr><td>7</td><td>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;</td><td>3.1.1, predistortion filter is used</td></tr>
<tr><td>8</td><td>that the sine-wave subcarrier frequency used in the 8 GHz or the 32 GHz band shall be in the range given in

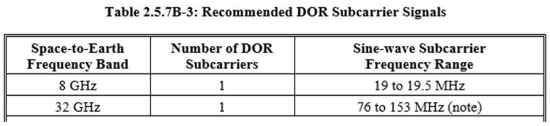



Table 2.5.7B-3: Recommended DOR Subcarrier Signals
<table>
<tr><th>Space-to-Earth Frequency Band</th><th>Number of DOR Subcarriers</th><th>Sine-wave Subcarrier Frequency Range</th></tr>
<tr><td>8 GHz</td><td>1</td><td>19 to 19.5 MHz</td></tr>
<tr><td>32 GHz</td><td>1</td><td>76 to 153 MHz (note)</td></tr>
</table></td><td>3.1.1</td></tr>
<tr><td>9</td><td>that DOR subcarrier and the chip rate shall be coherent with the downlink RF carrier frequency if carrier-aided detection is used;</td><td>By design, tone is 1/440 of carrier frequency</td></tr>
<tr><td>10</td><td>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);</td><td>3.1.4</td></tr>
<tr><td>11</td><td>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</td><td>3.1.1 & 3.1.5</td></tr>
</table>

	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);	3.1.1 (plots provided for m=0.025, 0.05, 0.1 & 0.2 rad)
13	that no discrete component (as modulation products) in the DOR signal RF spectrum shall exceed 30 dBHz;	3.1.1 (worst discrete component is at -53.37dBc) & 3.1.5 (worst case of 22.7 dBHz)
14	Out of band Power flux density < -211 dBW/m^2	3.1.3 & 3.1.5
15	that the RF DOR signal shall not overlap with the 31.3–31.8 GHz band	N/A for X-band

Table 1. Recommends in [2] and their validation

The following settings were used during the test:

- Non-coherent downlink frequency: 8451669191 Hz
- DOR tones: 1/440 ratio with respect to carrier, therefore ±19208339 Hz with respect to carrier
- Chip rate: 8 Mcps
- Roll-off factor: 0.1
- Modulation index: 0.025, 0.05, 0.1 and 0.2 radians.

3.1.1 PNDOR SPECTRUM

m=0.025 rad

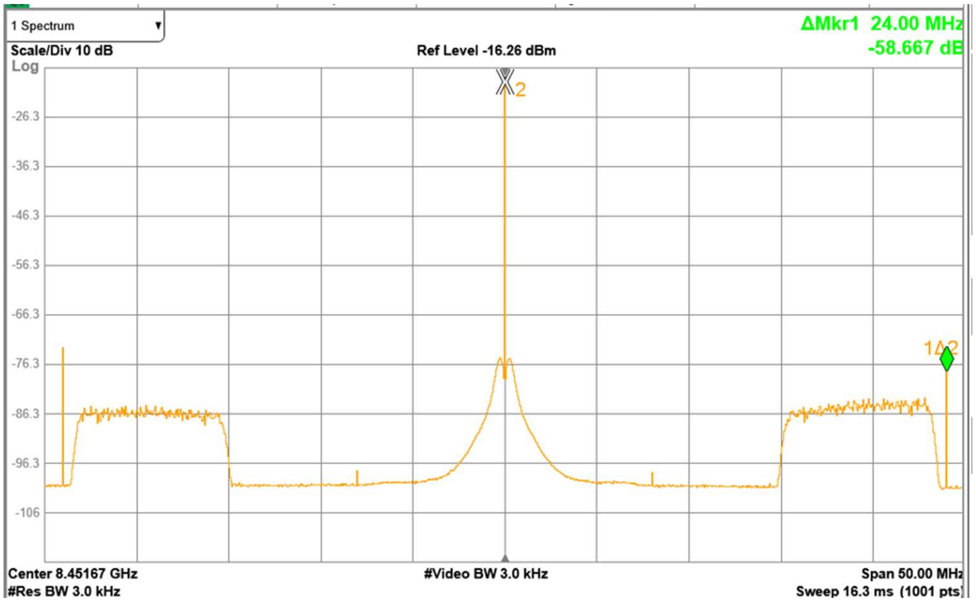
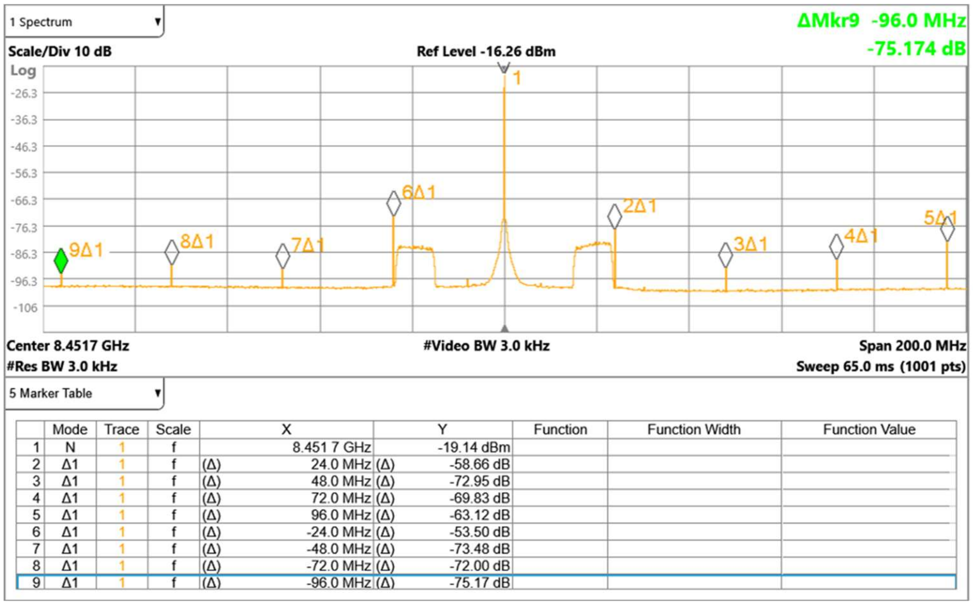


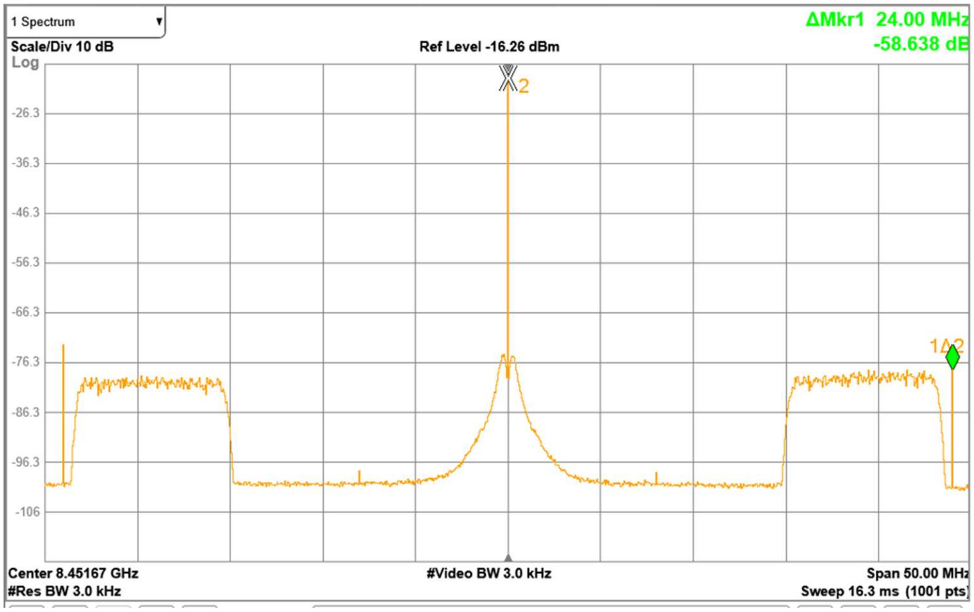
Figure 7.PNDOR spectrum - m=0.025 rad – 50 MHz span



	Mode	Trace	Scale	X	Y	Function	Function Width	Function Value
1	N	1	f	8.451 7 GHz	-19.14 dBm			
2	Δ1	1	f	(Δ) 24.0 MHz	(Δ) -58.66 dB			
3	Δ1	1	f	(Δ) 48.0 MHz	(Δ) -72.95 dB			
4	Δ1	1	f	(Δ) 72.0 MHz	(Δ) -69.83 dB			
5	Δ1	1	f	(Δ) 96.0 MHz	(Δ) -63.12 dB			
6	Δ1	1	f	(Δ) -24.0 MHz	(Δ) -53.50 dB			
7	Δ1	1	f	(Δ) -48.0 MHz	(Δ) -73.48 dB			
8	Δ1	1	f	(Δ) -72.0 MHz	(Δ) -72.00 dB			
9	Δ1	1	f	(Δ) -96.0 MHz	(Δ) -75.17 dB			

Figure 8. PNDOR spectrum - m=0.025 rad – 200 MHz span

m=0.05 rad



1 Spectrum

Scale/Div 10 dB

Ref Level -16.26 dBm

ΔMkr1 24.00 MHz
-58.638 dB

Center 8.45167 GHz

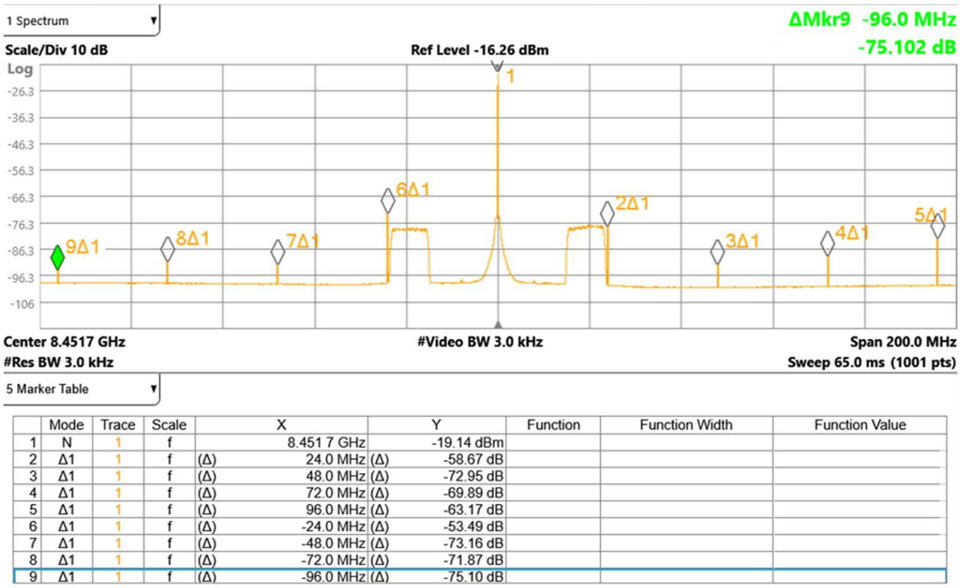
#Res BW 3.0 kHz

#Video BW 3.0 kHz

Span 50.00 MHz

Sweep 16.3 ms (1001 pts)

Figure 9 PNDOR spectrum - m=0.05 rad – 50 MHz span



Scale/Div 10 dB

Ref Level -16.26 dBm

ΔMkr9 -96.0 MHz
-75.102 dB

Center 8.4517 GHz

#Res BW 3.0 kHz

#Video BW 3.0 kHz

Span 200.0 MHz

Sweep 65.0 ms (1001 pts)

	Mode	Trace	Scale		X		Y	Function	Function Width	Function Value
1	N	1	f		8.451 7 GHz		-19.14 dBm			
2	Δ1	1	f	(Δ)	24.0 MHz	(Δ)	-58.67 dB			
3	Δ1	1	f	(Δ)	48.0 MHz	(Δ)	-72.95 dB			
4	Δ1	1	f	(Δ)	72.0 MHz	(Δ)	-69.89 dB			
5	Δ1	1	f	(Δ)	96.0 MHz	(Δ)	-63.17 dB			
6	Δ1	1	f	(Δ)	-24.0 MHz	(Δ)	-53.49 dB			
7	Δ1	1	f	(Δ)	-48.0 MHz	(Δ)	-73.16 dB			
8	Δ1	1	f	(Δ)	-72.0 MHz	(Δ)	-71.87 dB			
9	Δ1	1	f	(Δ)	-96.0 MHz	(Δ)	-75.10 dB			

Figure 10. PNDOR spectrum - m=0.05 rad – 200 MHz span

m=0.1 rad

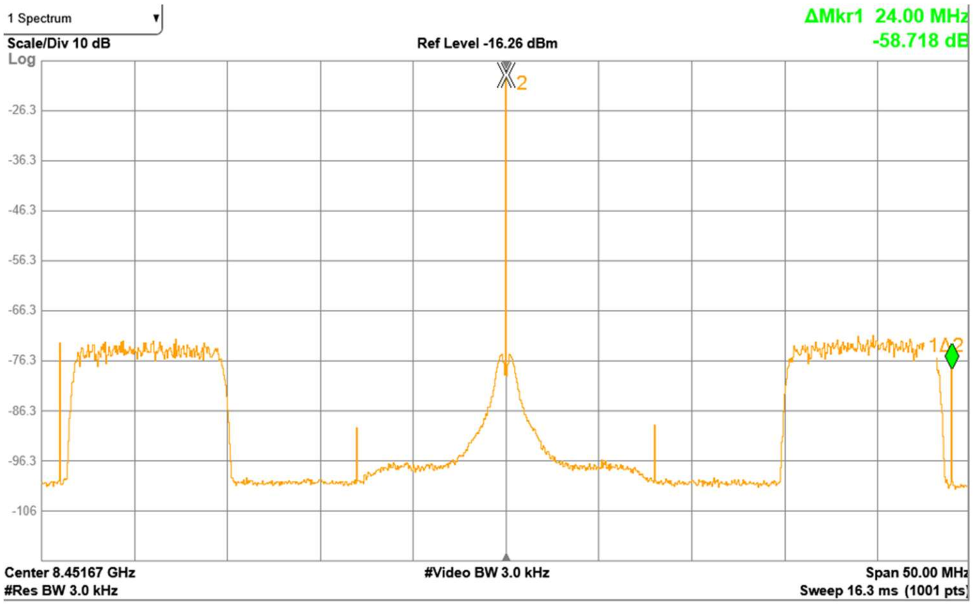
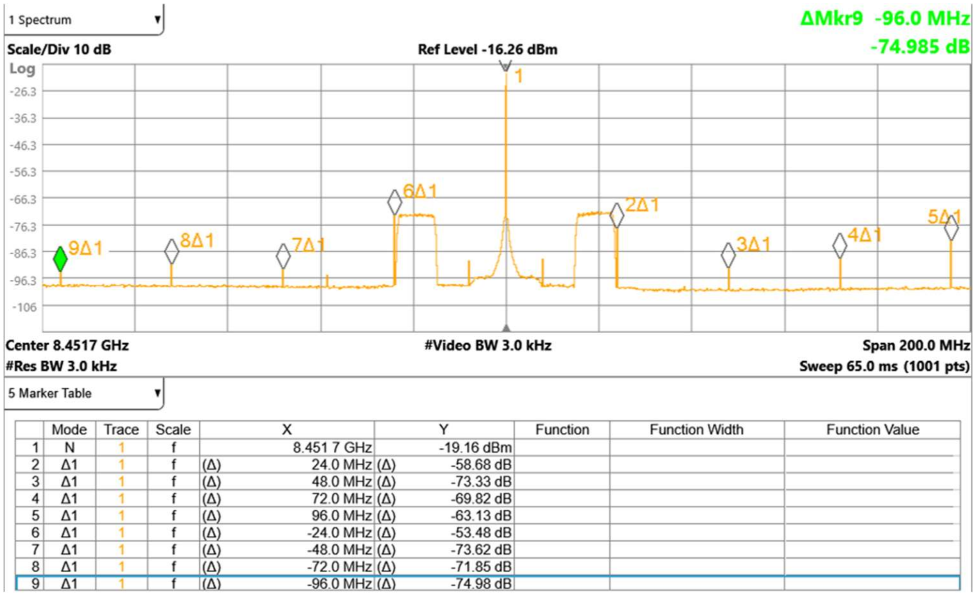


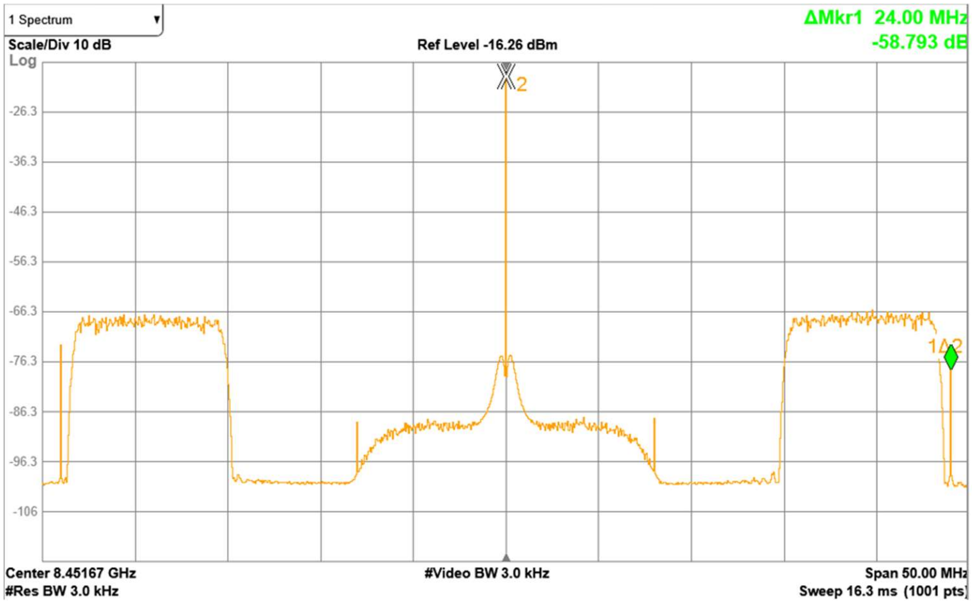
Figure 11.PNDOR spectrum - m=0.1 rad – 50 MHz span



	Mode	Trace	Scale	X	Y	Function	Function Width	Function Value
1	N	1	f	8.451 7 GHz	-19.16 dBm			
2	Δ1	1	f	(Δ) 24.0 MHz	(Δ) -58.68 dB			
3	Δ1	1	f	(Δ) 48.0 MHz	(Δ) -73.33 dB			
4	Δ1	1	f	(Δ) 72.0 MHz	(Δ) -69.82 dB			
5	Δ1	1	f	(Δ) 96.0 MHz	(Δ) -63.13 dB			
6	Δ1	1	f	(Δ) -24.0 MHz	(Δ) -53.48 dB			
7	Δ1	1	f	(Δ) -48.0 MHz	(Δ) -73.62 dB			
8	Δ1	1	f	(Δ) -72.0 MHz	(Δ) -71.85 dB			
9	Δ1	1	f	(Δ) -96.0 MHz	(Δ) -74.98 dB			

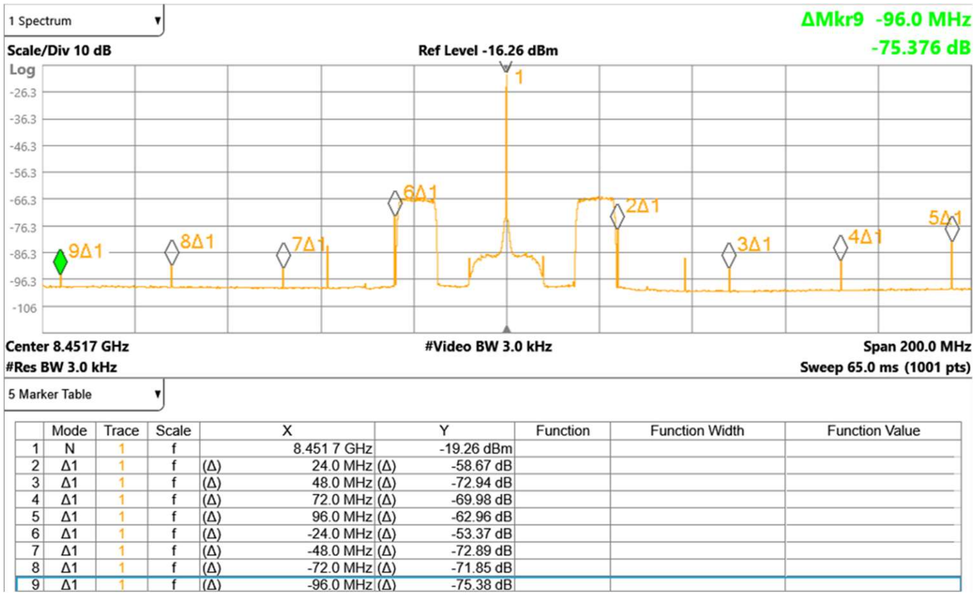
Figure 12. PNDOR spectrum - m=0.1 rad – 200 MHz span

m=0.2 rad



Scale/Div 10 dB
Ref Level -16.26 dBm
Center 8.45167 GHz
#Res BW 3.0 kHz
#Video BW 3.0 kHz
Span 50.00 MHz
Sweep 16.3 ms (1001 pts)

Figure 13 PNDOR spectrum - m=0.2 rad – 50 MHz span



Scale/Div 10 dB
Ref Level -16.26 dBm
Center 8.4517 GHz
#Res BW 3.0 kHz
#Video BW 3.0 kHz
Span 200.0 MHz
Sweep 65.0 ms (1001 pts)

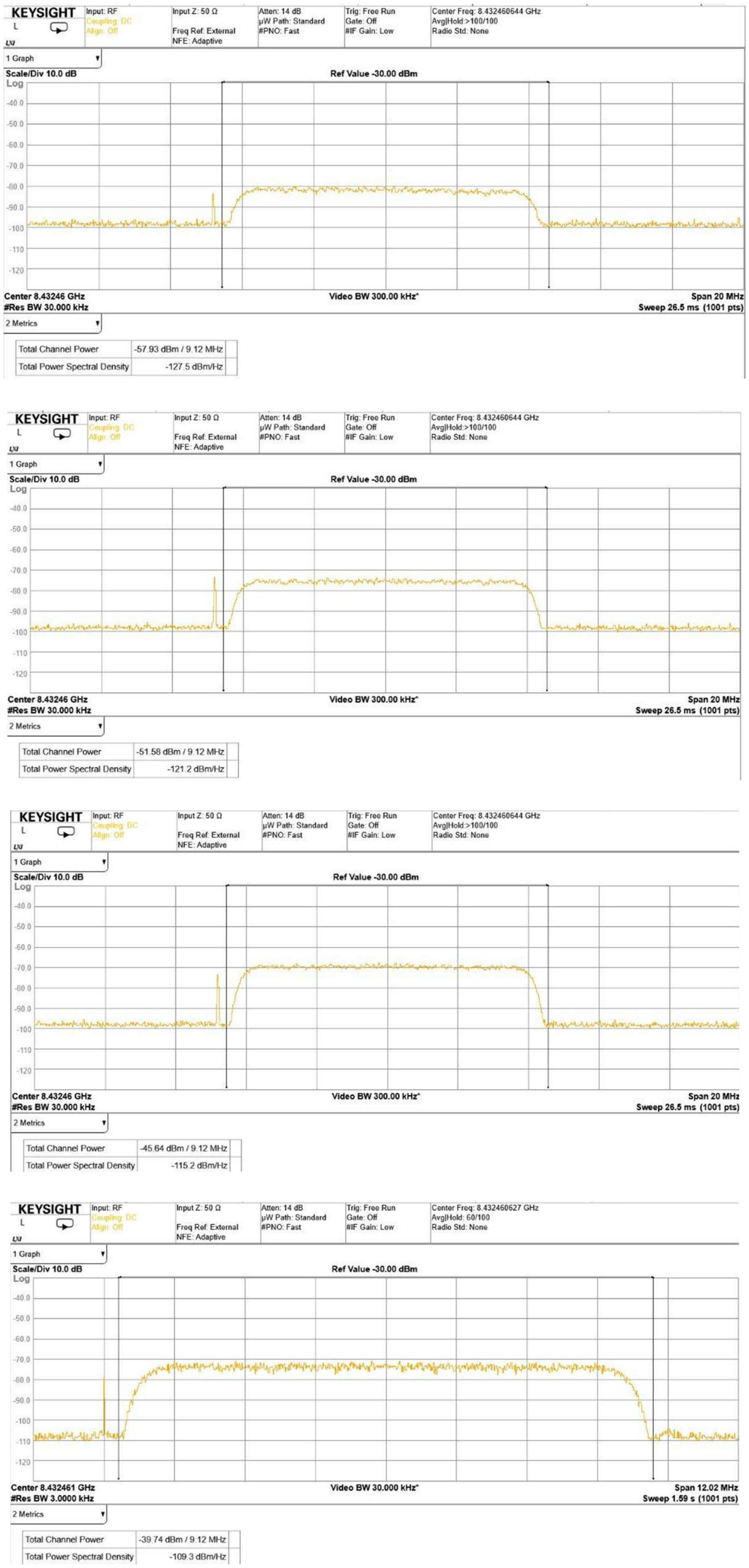
	Mode	Trace	Scale	X	Y	Function	Function Width	Function Value
1	N	1	f	8.451 7 GHz	-19.26 dBm			
2	Δ1	1	f	(Δ) 24.0 MHz	(Δ) -58.67 dB			
3	Δ1	1	f	(Δ) 48.0 MHz	(Δ) -72.94 dB			
4	Δ1	1	f	(Δ) 72.0 MHz	(Δ) -69.98 dB			
5	Δ1	1	f	(Δ) 96.0 MHz	(Δ) -62.96 dB			
6	Δ1	1	f	(Δ) -24.0 MHz	(Δ) -53.37 dB			
7	Δ1	1	f	(Δ) -48.0 MHz	(Δ) -72.89 dB			
8	Δ1	1	f	(Δ) -72.0 MHz	(Δ) -71.85 dB			
9	Δ1	1	f	(Δ) -96.0 MHz	(Δ) -75.38 dB			

Figure 14. PNDOR spectrum - m=0.2 rad – 200 MHz span

Note:

Worst discrete component is -53.4 dBc at -24 MHz from carrier (similar value for all modulation indexes).

3.1.2 POWER IN PNDOR SIDEBANDS



Input: RF
Coupling: DC
Align: Off
Input Z: 50 Ω
Freq Ref: External
NFE: Adaptive
Atten: 14 dB
μW Path: Standard
#PNO: Fast
Trig: Free Run
Gate: Off
#IF Gain: Low
Center Freq: 8.432460644 GHz
Avg|Hold:>100/100
Radio Std: None

Scale/Div 10.0 dB
Ref Value -30.00 dBm
Center 8.43246 GHz
#Res BW 30.000 kHz
Video BW 300.00 kHz*
Span 20 MHz
Sweep 26.5 ms (1001 pts)

Total Channel Power	-57.93 dBm / 9.12 MHz
Total Power Spectral Density	-127.5 dBm/Hz

Input: RF
Coupling: DC
Align: Off
Input Z: 50 Ω
Freq Ref: External
NFE: Adaptive
Atten: 14 dB
μW Path: Standard
#PNO: Fast
Trig: Free Run
Gate: Off
#IF Gain: Low
Center Freq: 8.432460644 GHz
Avg|Hold:>100/100
Radio Std: None

Scale/Div 10.0 dB
Ref Value -30.00 dBm
Center 8.43246 GHz
#Res BW 30.000 kHz
Video BW 300.00 kHz*
Span 20 MHz
Sweep 26.5 ms (1001 pts)

Total Channel Power	-51.58 dBm / 9.12 MHz
Total Power Spectral Density	-121.2 dBm/Hz

Input: RF
Coupling: DC
Align: Off
Input Z: 50 Ω
Freq Ref: External
NFE: Adaptive
Atten: 14 dB
μW Path: Standard
#PNO: Fast
Trig: Free Run
Gate: Off
#IF Gain: Low
Center Freq: 8.432460644 GHz
Avg|Hold:>100/100
Radio Std: None

Scale/Div 10.0 dB
Ref Value -30.00 dBm
Center 8.43246 GHz
#Res BW 30.000 kHz
Video BW 300.00 kHz*
Span 20 MHz
Sweep 26.5 ms (1001 pts)

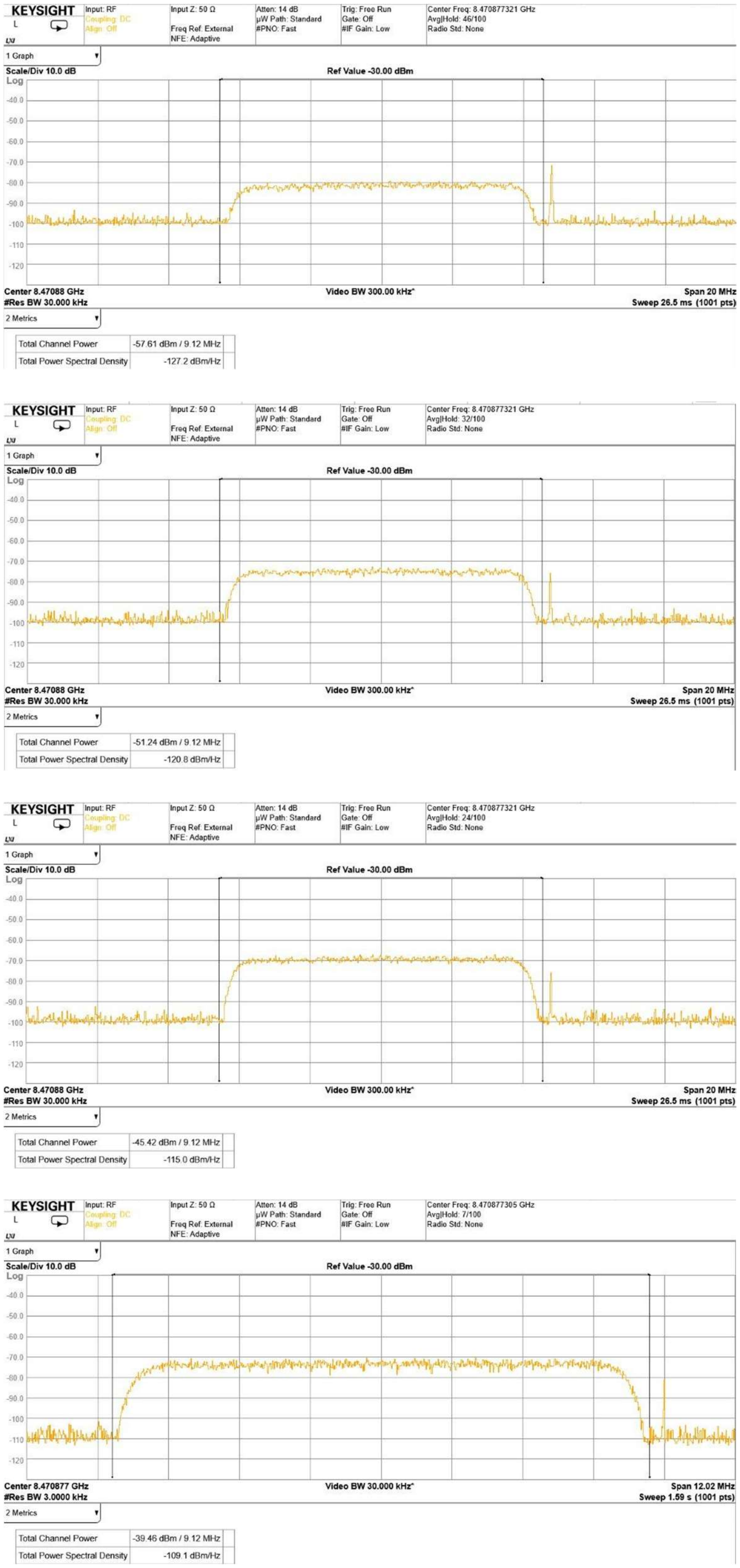
Total Channel Power	-45.64 dBm / 9.12 MHz
Total Power Spectral Density	-115.2 dBm/Hz

Input: RF
Coupling: DC
Align: Off
Input Z: 50 Ω
Freq Ref: External
NFE: Adaptive
Atten: 14 dB
μW Path: Standard
#PNO: Fast
Trig: Free Run
Gate: Off
#IF Gain: Low
Center Freq: 8.432460627 GHz
Avg|Hold: 60/100
Radio Std: None

Scale/Div 10.0 dB
Ref Value -30.00 dBm
Center 8.432461 GHz
#Res BW 3.0000 kHz
Video BW 30.000 kHz*
Span 12.02 MHz
Sweep 1.59 s (1001 pts)

Total Channel Power	-39.74 dBm / 9.12 MHz
Total Power Spectral Density	-109.3 dBm/Hz

Figure 15. Power in lower PNDOR sideband (Top to bottom: m=0.025; m=0.05; m=0.1;m=0.2 rad)



Input: RF
Coupling: DC
Align: Off
Input Z: 50 Ω
Freq Ref: External
NFE: Adaptive
Atten: 14 dB
µW Path: Standard
#PNO: Fast
Trig: Free Run
Gate: Off
#IF Gain: Low
Center Freq: 8.470877321 GHz
Avg|Hold: 46/100
Radio Std: None
Scale/Div 10.0 dB
Ref Value -30.00 dBm
Center 8.47088 GHz
#Res BW 30.000 kHz
Video BW 300.00 kHz*
Span 20 MHz
Sweep 26.5 ms (1001 pts)

Total Channel Power	-57.61 dBm / 9.12 MHz
Total Power Spectral Density	-127.2 dBm/Hz

Input: RF
Coupling: DC
Align: Off
Input Z: 50 Ω
Freq Ref: External
NFE: Adaptive
Atten: 14 dB
µW Path: Standard
#PNO: Fast
Trig: Free Run
Gate: Off
#IF Gain: Low
Center Freq: 8.470877321 GHz
Avg|Hold: 32/100
Radio Std: None
Scale/Div 10.0 dB
Ref Value -30.00 dBm
Center 8.47088 GHz
#Res BW 30.000 kHz
Video BW 300.00 kHz*
Span 20 MHz
Sweep 26.5 ms (1001 pts)

Total Channel Power	-51.24 dBm / 9.12 MHz
Total Power Spectral Density	-120.8 dBm/Hz

Input: RF
Coupling: DC
Align: Off
Input Z: 50 Ω
Freq Ref: External
NFE: Adaptive
Atten: 14 dB
µW Path: Standard
#PNO: Fast
Trig: Free Run
Gate: Off
#IF Gain: Low
Center Freq: 8.470877321 GHz
Avg|Hold: 24/100
Radio Std: None
Scale/Div 10.0 dB
Ref Value -30.00 dBm
Center 8.47088 GHz
#Res BW 30.000 kHz
Video BW 300.00 kHz*
Span 20 MHz
Sweep 26.5 ms (1001 pts)

Total Channel Power	-45.42 dBm / 9.12 MHz
Total Power Spectral Density	-115.0 dBm/Hz

Input: RF
Coupling: DC
Align: Off
Input Z: 50 Ω
Freq Ref: External
NFE: Adaptive
Atten: 14 dB
µW Path: Standard
#PNO: Fast
Trig: Free Run
Gate: Off
#IF Gain: Low
Center Freq: 8.470877305 GHz
Avg|Hold: 7/100
Radio Std: None
Scale/Div 10.0 dB
Ref Value -30.00 dBm
Center 8.470877 GHz
#Res BW 3.0000 kHz
Video BW 30.000 kHz*
Span 12.02 MHz
Sweep 1.59 s (1001 pts)

Total Channel Power	-39.46 dBm / 9.12 MHz
Total Power Spectral Density	-109.1 dBm/Hz

Figure 16. Power in higher PNDOR sideband (Top to bottom: m=0.025; m=0.05; m=0.1;m=0.2 rad)

m	Carrier Power (dBm)	Lower PNDOR SB power (dBm) (dBc)	Upper PNDOR SB power (dBm)(dBc)	Total (lower + upper) power (dBm)(dBc)
0.025	-19.7	-57.93 -38.23	-57.61 -37.91	-54.76 -35.06
0.05	-19.5	-51.58 -32.08	-51.24 -31.74	-48.40 -28.90
0.1	-19.5	-45.64 -26.11	-45.42 -25.89	-42.52 -22.99
0.2	-19.6	-39.74 -20.14	-39.46 -19.86	-36.59 -16.99

Table 2. Sideband power summary

3.1.3 OUT OF BAND POWER

For simplicity, the out of band power calculation has been performed including any signal content beyond the spread spectrum sidebands. This calculation therefore includes the two tones at ±24 MHz from the carrier, even though the likelihood that both fall within the allocated band (therefore not being OOB terms) is high.

An example of OOB power is shown in Table 3 Table 1for m=0.2 rad, using the values in Figure 14.

Freq (MHz)	dBc (Hz)	Power (dBm)
24	-58.67	-77.93
48	-72.94	-92.2
72	-69.98	-89.24
96	-62.96	-82.22
-24	-53.37	-72.63
-48	-72.89	-92.15
-72	-71.85	-91.11
-96	-75.38	-94.64
Total OOB Power:		-70.96 dBm
Total signal power (Pc + carrier supp.):		-19.17 dBm
OOB power to signal power ratio:		-51.78 dB

Table 3. OOB calculation for m=0.2 rad (Pc=-19.26 dBm)

m	OOB/Signal Power (dBc)
0.025	-51.80
0.05	-51.80
0.1	-51.81
0.2	-51.78

3.1.4 COMPLIANCE TO RECOMMEND 10 – ALLAN DEVIATION

The Allan deviation resulting from a long duration integrated phase measurement (after downconversion to L-band) is shown in has been performed and has been used for the calculation of Δf/f.

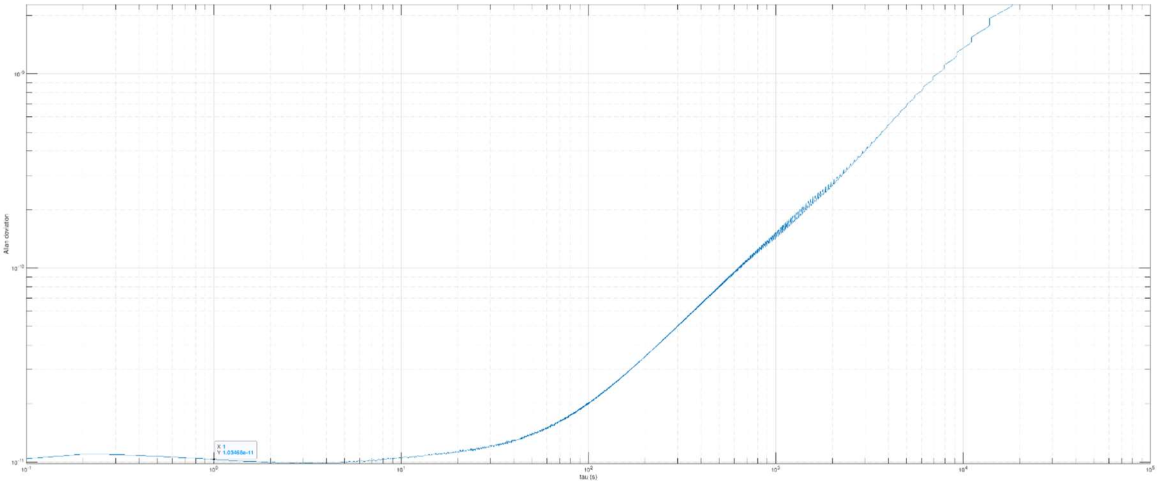


Figure 17. ADEV one-way stability results

3.1.5 LINK BUDGET SCENARIOS AND COMPLIANCE TO RECOMMENDATIONS 11, 13 AND 14.

In agreement with the CCSDS RF&MOD WG, compliance to recommendations 11, 13 and 14 will be checked for three different mission scenarios:

- Mission to Jupiter
- Mission to Mars
- Lunar mission

Basic formulas used:

1) $Despread\ \frac{P}{N0}(dBHz) = \frac{C}{N0} - dBCvalueInTable2$

2) $Worst\ discrete\ component\ (dBHz) = \frac{C}{N0} - 53.37$

3) $Out\ of\ Band\ power\ flux\ density = Power\ flux\ density - dBcvalueInTable4$

PNDOR modulation index:

- 0.025 rad -> Carrier Suppression: 0.001 dB; mod.loss: 35.05 dB
- 0.05 rad -> Carrier Suppression: 0.005 dB; mod.loss: 29.03 dB
- 0.1 rad -> Carrier Suppression: 0.02 dB; mod.loss: 23.02 dB
- 0.2 rad -> Carrier Suppression: 0.087 dB; mod.loss: 17.03 dB

3.1.5.1 Jupiter

Distance to Earth: 6.49 AU (only free space losses considered).

Onboard EIRP: 61 dBW (HGA); 45 dBW (MGA)

G/T: 53 dB/k f=8425MHz

On-board Antenna	Flux (dBW/m^2)	S/N0 (dBHz)	C/N0 (dBHz)	Despread Ptone/N0 (dBHz)	Worst discrete component (dBHz)	OOB flux (dBW/ m^2)
HGA	-189.8	51.9	51.8	51.8-19.8= 32.0	51.8-53.4= -1.6	-189.8-51.8 = -241.6
MGA	-205.8	35.9	35.8	35.8-19.8= 16.0	35.8-53.4= -17.6	-205.7-51.8= -257.5

Table 4. Estimate figures for recommendations 11, 13 & 14 for Jupiter's most distant case (HGA and MGA cases, m=0.2 rad)

3.1.5.2 Mars

Largest distance to Earth: 2.4 AU.

Closest distance to Earth: 0.4 AU

Onboard EIRP: 61 dBW (HGA); 45 dBW (MGA)

G/T: 53 dB/k f=8425MHz

On-board Antenna	**Flux (dBW/m^2)**	**S/N0 (dBHz)**	**C/N0 (dBHz)**	**Despread Ptone/N0 (dBHz)**	**Worst discrete component (dBHz)**	**OOB flux (dBW/ m^2)**
HGA	-181.1	60.5	60.5	60.5-25.9= 34.6	60.5-53.4= 7.1	-181.1-51.8= -232.9
MGA	-197.1	44.5	44.5	44.5-25.9= 18.6	44.5-53.4= -8.9	-197.1-51.8= -248.9

Table 5. Estimate figures for recommendations 11, 13 & 14 for most distant case to Mars (HGA and MGA cases, m=0.1 rad) – Only free space losses have been considered

On-board Antenna	**Flux (dBW/m^2)**	**S/N0 (dBHz)**	**C/N0 (dBHz)**	**Despread Ptone/N0 (dBHz)**	**Worst discrete component (dBHz)**	**OOB flux (dBW/ m^2)**
HGA	-165.6	76.1	76.1	76.1-37.9= 38.2	76.1-53.4= 22.7	-165.6-51.8= -217.4
MGA	-181.6	60.1	60.1	60.1-25.9= 34.2	60.1-53.4= 6.7	-181.6-51.8= -233.4

Table 6. Estimate figures for recommendations 11, 13 & 14 for closest case to Mars. HGA case estimated for m=0.025 rad; MGA case estimated for m=0.1 rad. – Only free space losses have been considered

3.1.5.3 Lunar

Onboard EIRP: 3 dBW

Distance: 0.025 AU

G/T: 53 dB/k

On-board Antenna	**Flux (dBW/m^2)**	**S/N0 (dBHz)**	**C/N0 (dBHz)**	**Despread Ptone/N0 (dBHz)**	**Worst discrete component (dBHz)**	**OOB flux (dBW/ m^2)**
3dBW	-199.5	42.2	42.1	42.1-25.9= 16.2	42.1-53.4 -11.3	-199.5-51.8 -251.3

Table 7. Estimate figures for recommendations 11, 13 & 14 for lunar cubesat (onboard EIRP estimated at 3 dBW) - m=0.1 rad – Only free space losses have been considered

3.1.6 END TO END TESTING

Results for the end to end test performed in the ESOC Ground Station Reference Facility are shown in this section.

A PNDOR acquisition was tested, with the following settings:

Spacecraft – Quasar- Spacecraft sequence:	240 sec - 60 sec - 240 sec
Chip rate	8 Mcps
Roll-off factor	0.1
Mod. Index	0.1 rad
Pcarrier/N0:	43.5 dBHz
Ptone/N0:	17.6 dBHz

Table 8. Configuration used for end to end test in X-band

A 43.52 nsec delay was generated for the second spacecraft scan, by adding a cable of known delay to the output of one of the Xband downconverters. Measurement setup and results are shown in Figure 18 and Figure 19 respectively.

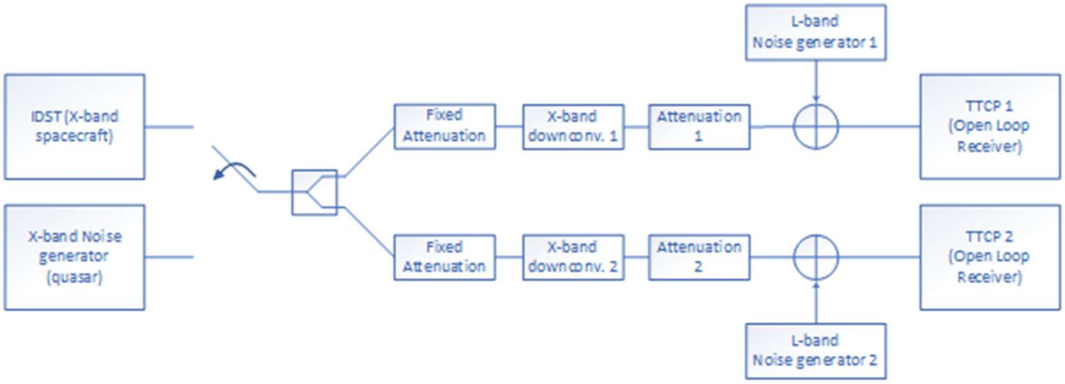


Figure 18. End to End measurement setup

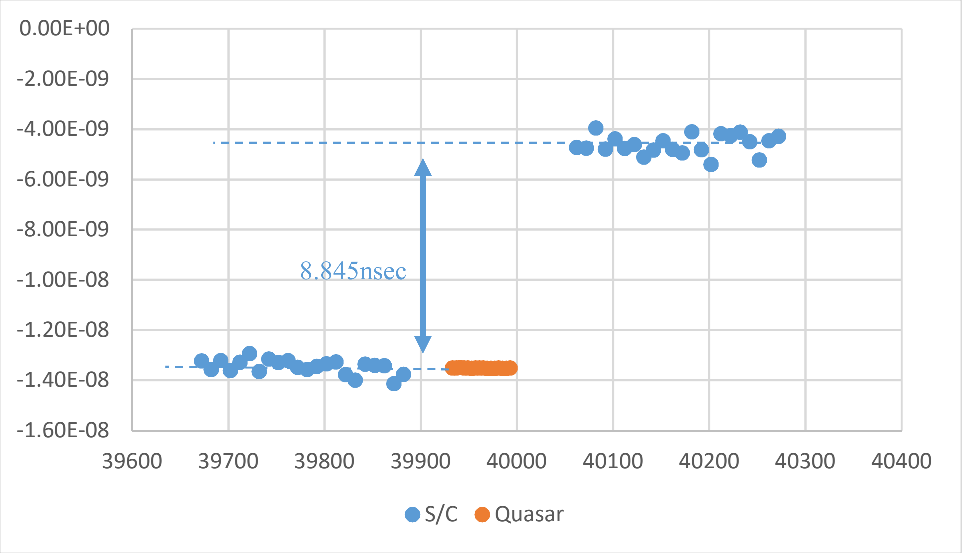


Figure 19. End to end results (prior to ambiguity correction)

Once corrected for ambiguity, the overall measurement results in (1/19208339)-8.845E-9=43.21 nsec.

Note:

For an 8 Mcps signal, the 8191 chip code duration of the PN code allows ambiguity resolution up to about 1 msec. The current implementation of the correlator measures ambiguity by correlation of the code, but does not yet feed that value to the final result. This will be done in future upgrades of the correlator.

3.2 KA BAND

The current implementation on the IDST of PNDOR in Ka band makes use of the same tones (e.g. same spanned bandwidth) used in X-band. The validation in Ka band has been performed making use of a Vector Signal Generator for the generation of the RF signal from I&Q samples. The following signal was used for the test:

DDOR tone frequency	76 MHz
Chip rate	32 Mcps
Chip code length	32767 chips
Roll-off factor	0.25
Modulation index:	0.2 rad

Table 9. Configuration used for Ka band tests

3.2.1 PN DOR SPECTRUM

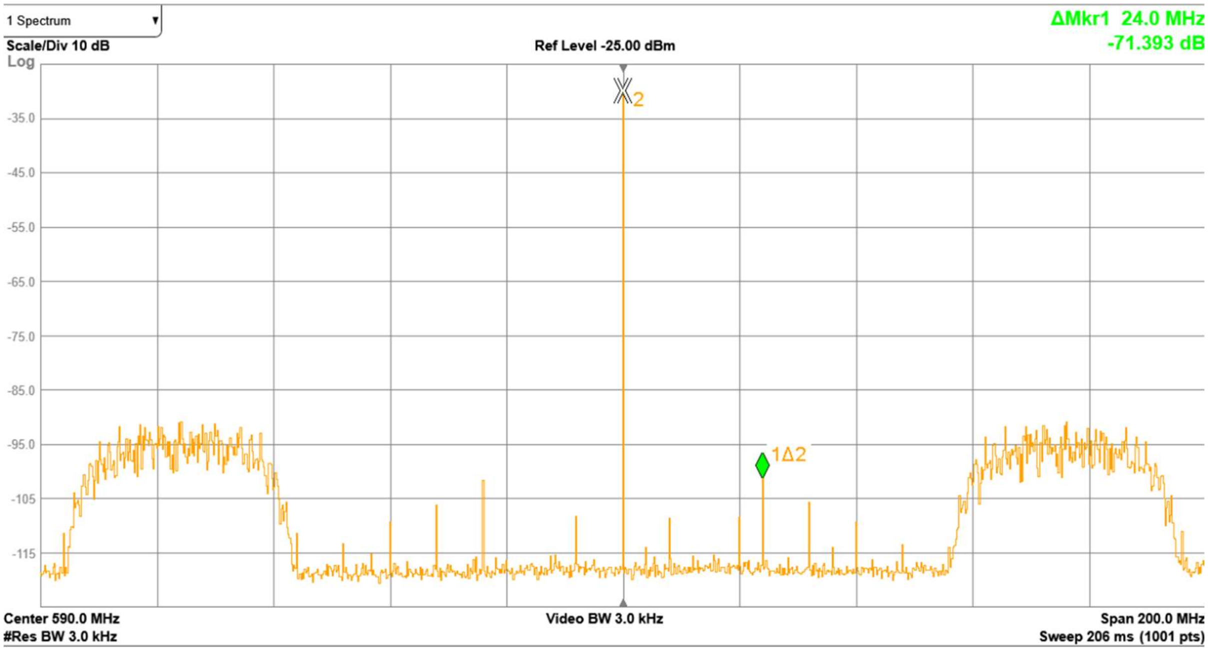


Figure 20. PN DOR spectrum (200 MHz span)

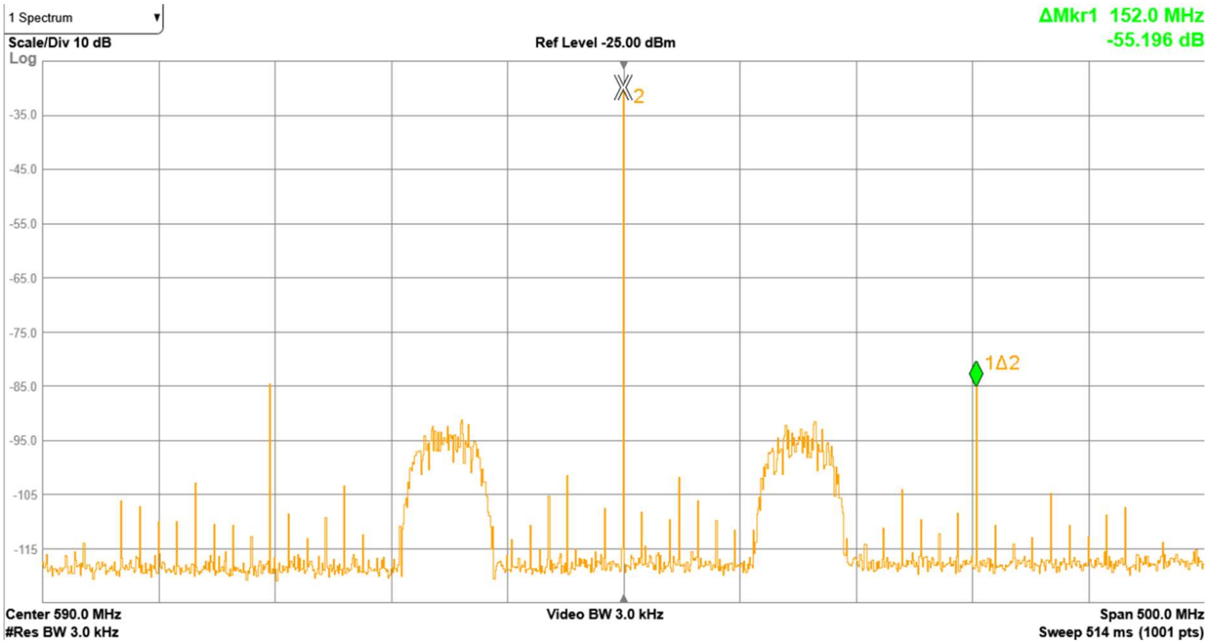
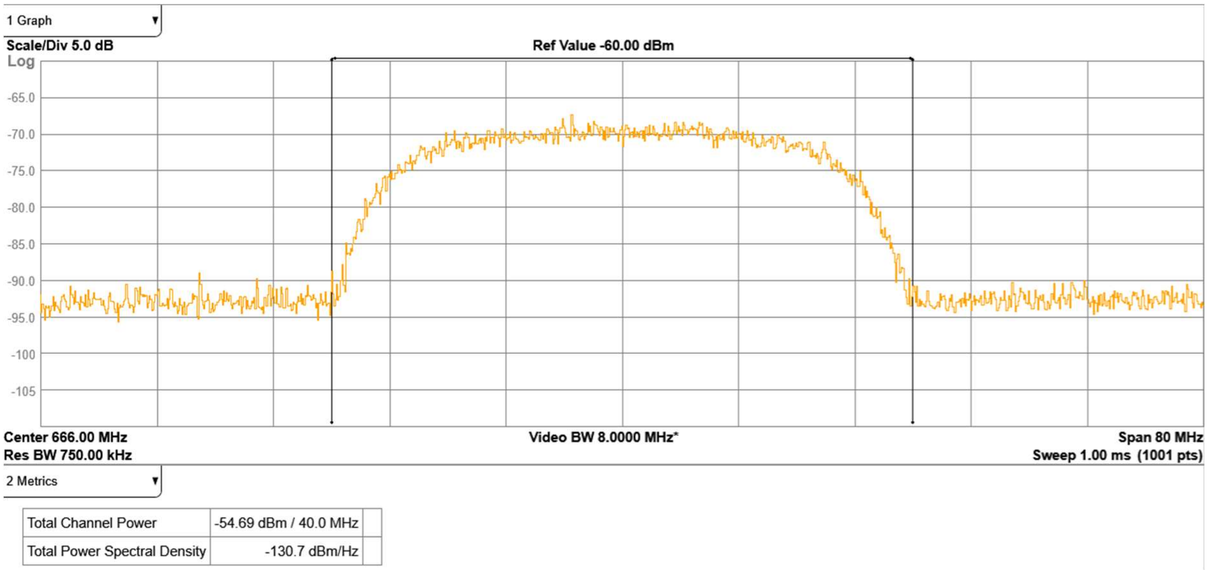


Figure 21. PN DOR spectrum (500 MHz span)



Scale/Div 5.0 dB

Ref Value -60.00 dBm

Center 666.00 MHz

Res BW 750.00 kHz

Video BW 8.0000 MHz*

Span 80 MHz

Sweep 1.00 ms (1001 pts)

Total Channel Power	-54.69 dBm / 40.0 MHz
Total Power Spectral Density	-130.7 dBm/Hz

Figure 22. Power in upper PNDOR sideband

3.2.2 END TO END TESTING

An ~5.1 nsec delay was generated for the second spacecraft scan, by adding a cable of known delay to the input of one of the receivers. Measurement results are shown in Figure 23. No ambiguity correction was required in this case since the cable delay was less than the 13.15 nsec ambiguity resulting from the use of the 76 MHz tone.

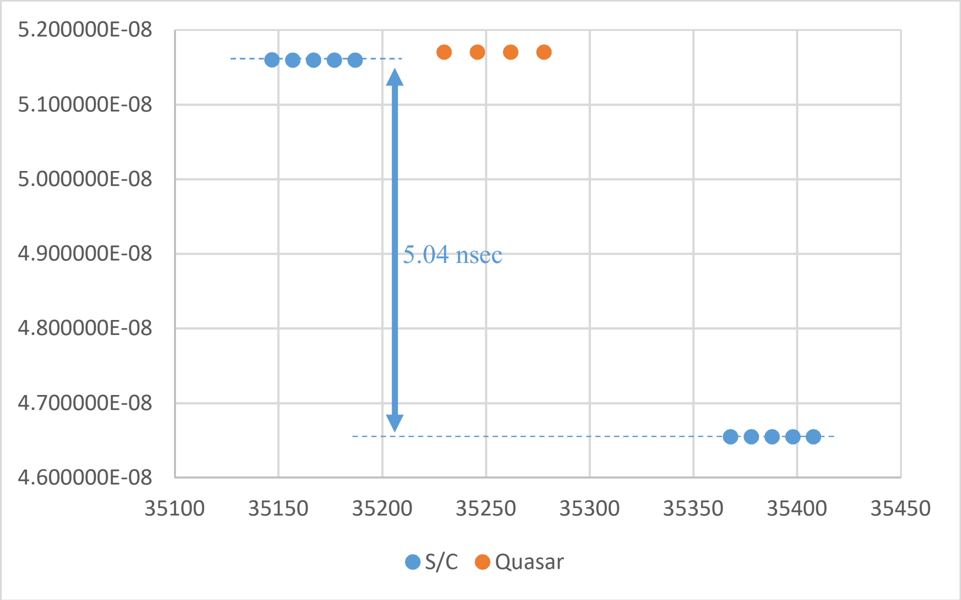


Figure 23. End to end results – Ka band

4 LICENSE AGREEMENTS

Implementers should be aware that the Spread Spectrum DDOR described in this Yellow Book relates to CCSDS Recommended Standards (reference [1]), and that patents relating to those Recommended Standards are described in those references. At the time of publication, CCSDS was not aware of any other claimed patent rights applicable to implementing the provisions of this Recommended Standard.

5 CONCLUSIONS

The development and testing of an ESA prototype for PNDOR is described in this document, as required (two independent implementations from two space agencies) for the publication of the related recommendation in [1].