The Consultative Committee for Space Data Systems

CCSDS RADIO FREQUENCY AND MODULATION SYSTEMS —

NASA PROTOTYPE IMPLEMENTATION FOR THE PN DOR CODES

CCSDS RECORD

CCSDS xxx.0-Y-1
(SLS-RFM_21-10)

YELLOW BOOK
May 2021

FOREWORD

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DOCUMENT CONTROL

Document	Title	Date	Status
CCSDS xxx.0-Y-1	NASA Prototype Implementation for the PN DOR Codes	May 2021	Current issue

CONTENTS

1 INTRODUCTION

1.1 PURPOSE

This document is a record of the NASA prototype implementation of the PN DOR codes proposed for addition to CCSDS 401.0-B, “Radio Frequency and Modulation Systems” [1]. Formal Agency Review has been completed for the proposed new recommendation 2.5.7B. In order to complete the process, document CCSDS A02.1-Y-4, “Restructured Organization and Processes for the Consultative Committee for Space Data Systems” [2] requires that “at least two independent and interoperable prototypes or implementations must have been developed and demonstrated in an operationally relevant environment, either real or simulated …. The WG Chair is responsible for documenting the specific implementations that qualify the specification for CCSDS Recommended Standard status, along with reports relevant to their testing”. This document provides one implementation.

Document CCSDS A02.1-Y-2 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”. No patents of concern have been identified.

1.2 SCOPE

This document is not a part of any CCSDS Recommended Standard.

1.3 ORGANIZATION OF THIS REPORT

This document is divided into three parts. Section 1 (this section) presents the purpose and organization. Section 2 documents one implementation of the PN DOR codes and tests for validity. Section 3 contains a note about patented technology.

2 NASA PROTOTYPE IMPLEMENTATION OF PN DOR

2.1 OVERVIEW

A PN DOR standard was introduced in a draft recommendation 2.5.7B [3] 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.

Transponder implementations for codes to be used at X-band and at Ka-band are described in Section 2.2. The correlation processing of received PN DOR signals is described in Section 2.3. A test of delay measurement, to validate PN DOR, is presented in Section 2.4.

2.2 TRANSPONDER IMPLEMENTATION AT NASA JET PROPULSION LABORATORY

The PN DOR functionality was implemented on the Iris radio and the UST radio firmware in 2019. Both of these implementations are described in Reference [4]. The implementation was then tested using DSN test equipment in 2020. The testing showed that the PN DOR signal was successfully transmitted from the radios and could be processed successfully. The test results are also briefly described in Reference [4]. An newer version of the UST radio called UST-Lite was then developed and tested in April 2022 which supports a wider digital bandwidth than the version tested in 2019.

The Gold Code sequence implemented in each transponder matched the recommended parameters presented in *pre-BLUE REC 2.5.7B* [3], Table 2.5.7B-1, and are repeated below in Table 2-1.

Table 2-1. CCSDS Recommended Gold Code Polynomials for PN DDOR

RF Band	N Bits	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	$1 + x^{14} + x^{15}$	$1 + x^3 + x^{12} + x^{14} + x^{15}$

The order of each term in the polynomial denotes which feedback taps shall be used in the Gold Code generator circuit. For example, Figure 2-1 below shows the Gold Code generator circuit which corresponds to the 8 GHz polynomials listed in Table 2-1. The intial seeds used for these prototypes were [0,0,0,0,0,0,0,0,0,0,0,0,1] and [0,0,0,0,0,0,0,0,0,0,0,0,0,0,1], but are configurable for future missions.

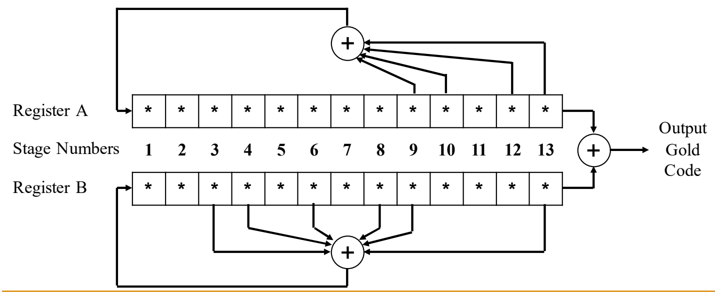

Figure 2-1. 16 Example Gold Code Generator Circuit

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The implemented chip rate and roll-off factor were also guided by the recommended parameters in Table 2.5.7B-2. The parameters used for each implementation are listed in Table 2-2.

Table 2-2. Implemented PN DDOR Parameters for JPL Transponders

Radio	RF Band	Chip Rate	Roll-Off Factor
Iris	8 GHz	7.14 Mcps	0.120
UST	8 GHz	7.14 Mcps	0.120
UST-Lite	32 GHz	31~~0~~.25~~0~~ Mcps	0.100~~067~~

The roll-off factor is an input to the Square Root Raised Cosine (SRRC) filter which is used to shape the gold code prior to transmission. This shaping is necessary to produce a flat, quasar-like spectrum. The frequency response of a SRRC filter is listed in Equation 1 below, and depends on both the chip rate, R, and the roll-off factor, β.

$$H(f) = \begin{cases} 1 & for \quad \left(0 \le |f| \le \frac{R(1-\beta)}{2}\right) \\ \sqrt{\frac{1}{2}\left\{1+\sin\left[\frac{\pi}{R\beta}\left(\frac{R}{2}-|f|\right)\right]\right\}} & for \quad \left(\frac{R(1-\beta)}{2} \le |f| \le \frac{R(1+\beta)}{2}\right) \\ 0 & for \quad \left(|f| > \frac{R(1+\beta)}{2}\right) \end{cases} \quad (1)$$

Using DSN test equipment, a 16 MHz channel was recorded centered at the PN DOR signal transmitted by the Iris radio. This spectrum, Figure 2-~~1~~2, shows that the CCSDS recommended X-Band PN DOR parameters create a flat 8 MHz spectrum that closely resembles the quasar signal.

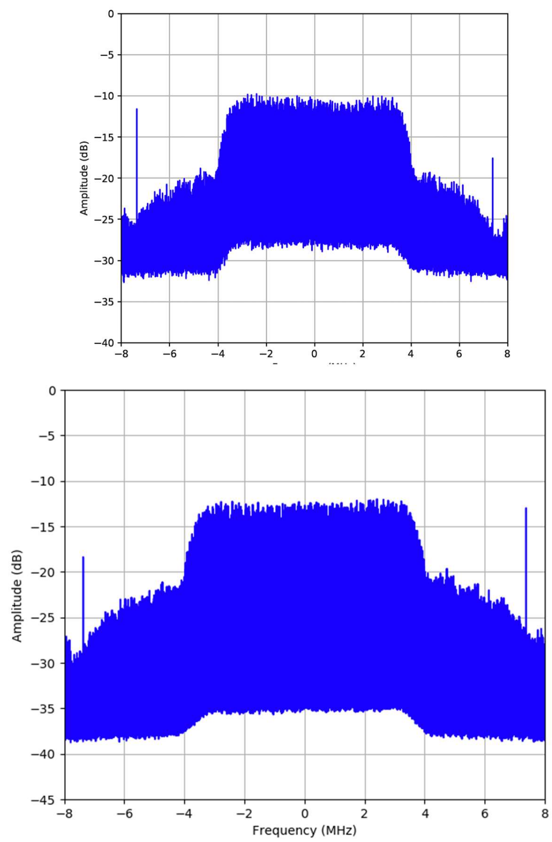

Figure 2-2221. 16 MHz Recorded Iris X-band PN DOR Spectrum

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This test was repeated for the UST transponder at X-band, but only an 8 MHz channel was recorded. The resulting spectrum is shown in Figure 2-2 3 and again shows a flat spectrum which closely resembles the quasar signal.

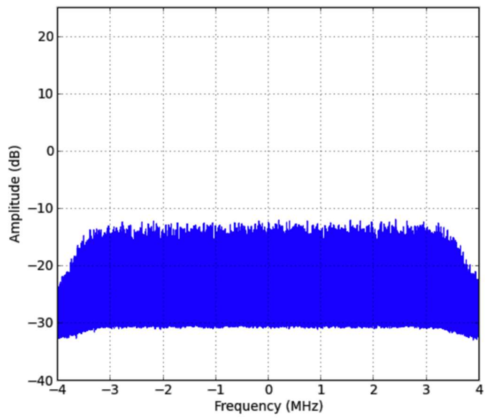

Figure 2-3332. 8 MHz Recorded UST X-band PN DOR Spectrum

Similarly, for testing the Ka-band spectrum a 5032 MHz channel was recorded centered at the PN DOR signal transmitted by the UST-Lite radio. This spectrum, Figure 2-34, shows that the CCSDS recommended Ka-band PN DOR parameters create a fairly flat 32 MHz spectrum that closely resembles the quasar signal. In the final transponder implementation, the slope across the bandwidth will be flattened by a pre-distortion filter.

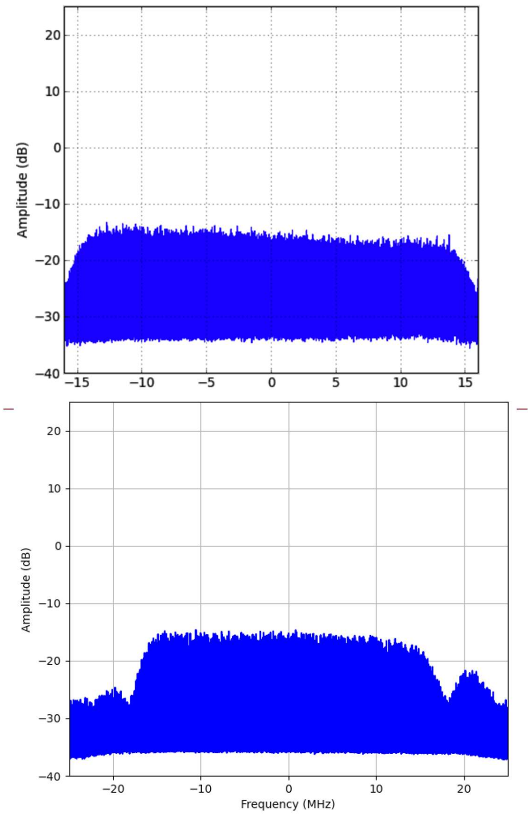

Figure 2-4443. 32 MHz Recorded UST Ka-band PN DOR Spectrum

Recall that the full transmitted spectrum includes the carrier and PN DOR signals on either side of the carrier. The PN DOR tones are offset by the DOR tone frequency, which is typically ±19 MHz for X-band and ±50 76 MHz for Ka-band. The resulting 200 MHz X-band spectrum from the Iris transponder is shown in Figure 2-4 5 and shows the ±19 MHz PN DOR signals of the X-band configuration. This spectrum capture was made before the pre-distortion filter was installed, thus there is a slope of approximately 3 dB across the PN signal as visible in Figure 2-5 and Figure 2-6..

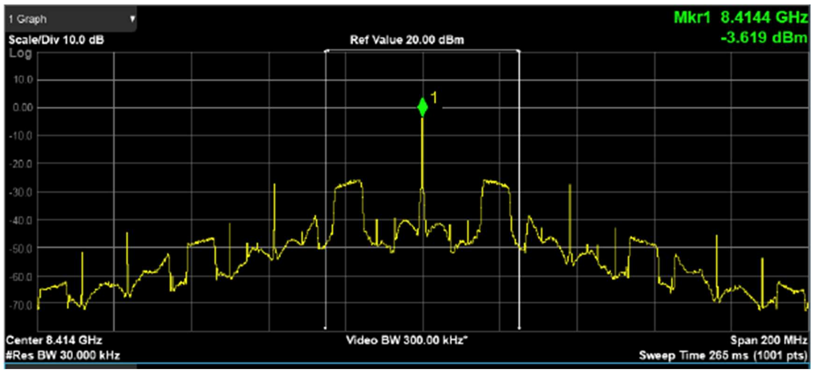

Figure 2-5554. 200 MHz Iris X-band PN DOR Spectrum before Pre-Distortion Filter

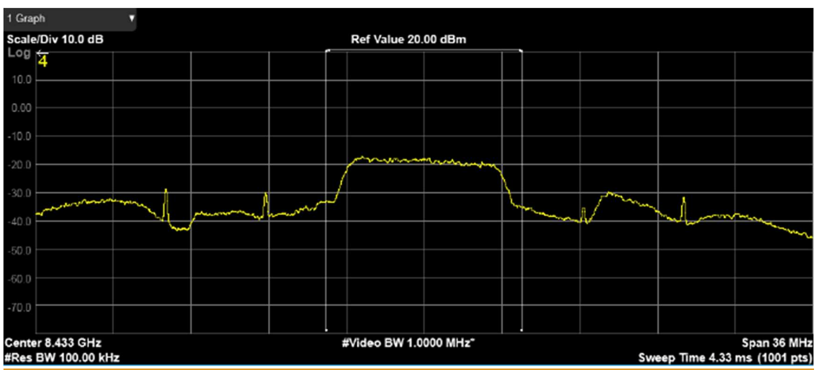

Figure 2-6. 36 MHz Iris X-band PN DOR Spectrum before Pre-Distortion Filter

A pre-distortion filter was then integrated to offset this slope to ensure a flat spectrum signal. The results of this pre-distortion filter are shown in Figure 2-7.

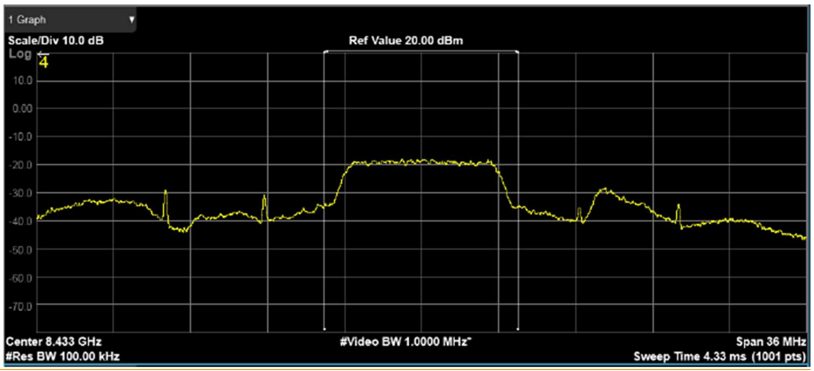

Figure 2-7. 36 MHz Iris X-band PN DOR Spectrum after Pre-Distortion Filter

Figure 2-8 below shows a 250 MHz bandwidth centered on the UST-Lite spectrum. The DOR Tones are centered at ±76 MHz about the carrier frequency. Since the UST-Lite has a digital bandwidth of 187.5 MHz, there is distortion above ±93.75 MHz which is just beyond the edge of DOR tones at ±92 MHz (76 MHz center frequency plus 32/2 MHz spreaded frequency).

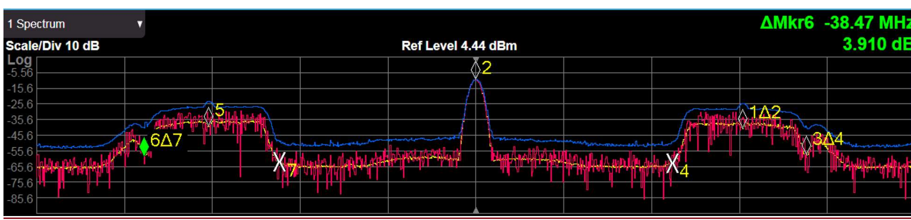

Figure 2-8. 250 MHz UST Ka-band PN DOR Spectrum before Pre-Distortion Filter

Figure 2-9, below, shows a 70 MHz spectrum centered at the +76 MHz DOR tone on the UST-Lite.

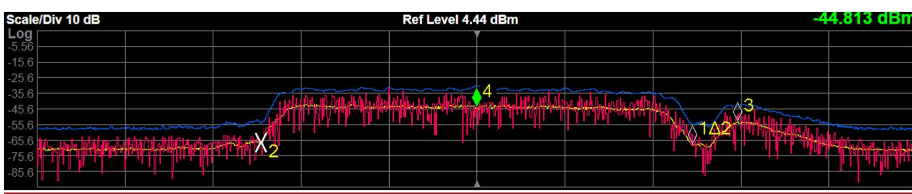

Figure 2-9. 70 MHz UST Ka-band PN DOR Spectrum before Pre-Distortion Filter

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2.3 CORRELATION PROCESSING

Next, JPL's PN DDOR processing software was used to process the recorded signal. First, the recorded data was downconverted to baseband by mixing with a model of the underlying DOR tone phase. Next, the PN sequence is recovered from this baseband data. Figure 2-85 shows the baseband data superimposed over multiple repetitions of the code. The x-axis is time past the start of the recording normalized by the chip period.

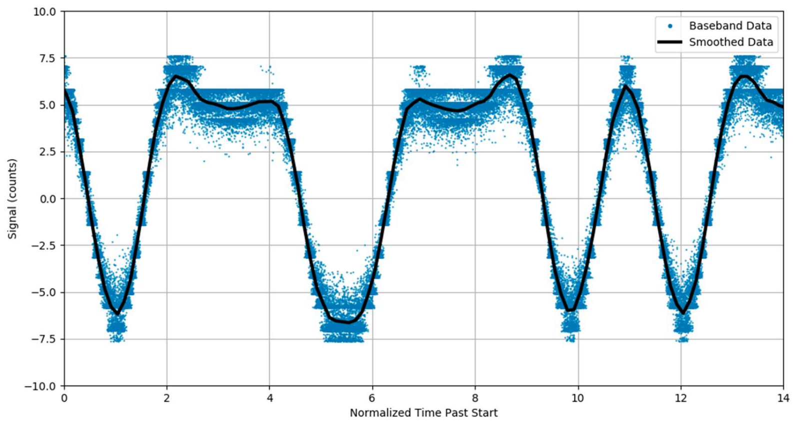

Figure 2-101085 –X-Band PN DOR Signal

Next, the smoothed data were correlated against the pulse-shaped reference PN sequence. The output of this correlation is the PN phase which is used in the ambiguity resolution in the DOR observable. The correlation results for the Iris X-band configuration are shown below in Figure 2-69. Similar results were observed in the UST X-band and Ka-band testing.

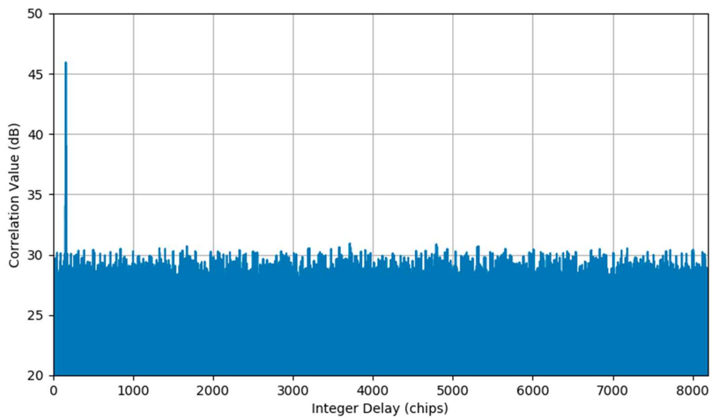

Figure 2-111196 – X-Band PN DOR Correlation Results

2.4 PATH DELAY TEST RESULTS

To verify that the PN DOR signals create the same delay measurement as the sinusoidal DOR signals specified in CCSDS Blue Book 401.0-B-31 [1] Section 2.5.6B, a laboratory experiment was devised to measure the delay caused by a length of cable. In this experiment the spacecraft transponder signal was split with one signal routed to the Open Loop Receiver (OLR) with a short 6 foot long cable, and the other signal routed to the recorder with an approximately 95 foot long cable. This experiment configuration is briefly illustrated in Figure 2-7-10.

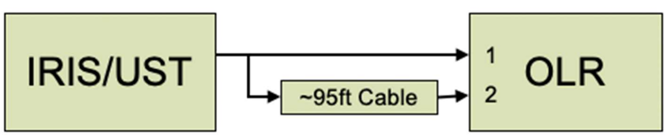

Figure 2-1212107. PN DOR Laboratory Test Experiment Illustration

The RF cables used in the lab typically transmit signals at approximately 60% the speed of light. So, the resulting approximate 90 foot difference in cable lengths should result in a delay of approximately 150 ns. This back-of-the-envelope calculation provides a sanity check on the final delay measurement.

The Iris transponder was first set to transmit the sinusoidal DOR signals, which were recorded on the OLR and then processed using existing DDOR software. The Iris radio was then configured to transmit the X-band PN DOR signals, which were again recorded on the OLR and processed using modified DDOR software. The measured delay for both sinusoidal DOR and PN DOR agreed within 20 picoseconds, as shown in Table 2-3, below.

Field Code Changed

Field Code Changed

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Table 2-3. Measured Cable Delay using Sinusoidal DOR and PN DOR

DOR Tone Mode	Measured Cable Delay (ns)
Sinusoidal DOR	140.445
Sinusoidal DOR	140.448
Sinusoidal DOR	140.449
Sinusoidal DOR	140.447
Sinusoidal DOR	140.453
PN DOR	140.469
PN DOR	140.458
PN DOR	140.464
PN DOR	140.463

This test was repeated with the UST transponder, which showed again that the sinusoidal DOR signal and PN DOR signal produced consistent delay measurements.

Overall, the JPL prototypes prove that the recommended CCSDS PN DOR implementation successfully results in the desired performance, the PN signal transmission can be integrated into today’s spacecraft transponders, and an algorithm for dispreading can be implemented in the correlator data processing system.

3 LICENSING AGREEMENTS FOR THE PN DOR CODES

JPL has not filed any patents specific to the proposed PN DOR codes, and is not aware of any patents that apply to these codes in particular.

4 REFERENCES

[1] *Radio Frequency and Modulation Systems – Part 1 Earth Stations and Spacecraft*. CCSDS 401.0-B-31, Blue Book, Washington, D.C., February 2021.

[2] *Restructured Organization and Processes for the Consultative Committee for Space Data Systems*. CCSDS A02.1-Y-4. Yellow Book. Washington, D.C., April 2014.

[3] ~~*pre-BLUE*~~ *REC 2.5.7B* *SPREAD SPECTRUM DIFFERENTIAL ONE-WAY RANGING FOR SPACE-TO-EARTH LINKS IN ANGULAR SPACECRAFT POSITION DETERMINATION*, CCSDS 401.0-B-31, Draft Red Book, Washington, D.C..~~red book draft of SPREAD SPECTRUM DIFFERENTIAL ONE-WAY RANGING Recommendation~~

[4] Towfic et al. *"Improved Signals for Differential One-Way Range."* IEEE Aerospace and Electronic Systems Magazine, March 2020.