CYCLONE GLOBAL NAVIGATION SATELLITE SYSTEM (CYGNSS)

Algorithm Theoretical Basis Document for	**UM Doc. No.**	**148-0397-01**
High Resolution and Extended DDM Products	**SwRI Doc. No.**	
	Revision	**1**
	Date	**19 June 2020**
	Contract	

Algorithm Theoretical Basis Documents (ATBDs) provide the physical and mathematical descriptions of the algorithms used in the generation of science data products. Internal and external data flows are also described.
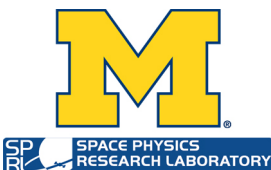
CYCLONE GLOBAL NAVIGATION SATELLITE SYSTEM (CYGNSS)

Algorithm Theoretical Basis Document for High Resolution and Extended DDM Products	UM Doc. No.	148-0397-01
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REVISION NOTICE

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1.   Introduction and Background

The primary mission of the CYGNSS Project is to collect measurements of ocean surface winds through variations in the reflected Global Positioning System (GPS) signals. Since its launch in late 2016, CYGNSS observations have also demonstrated sensitivity to land related climate variables such as near surface soil moisture and surface flat water detection. CYGNSS Level 2 and higher science datat products are obtained through fitting the calibrated data collected by the eight CYGNSS microsatellite observatories to empirical or modeled functions. The fundamental observation of the CYGNSS instrument is the Delay-Doppler Map (DDM), which maps the spread of received surface power into delay (time domain) and Doppler (frequency domain) dimensions for use in inferring the underlying surface properties.

The CYGNSS instrument generates Level 0 DDM observations for up to four parallel surface reflections. The CYGNSS instrument, the delay-Doppler mapping instrument (DDMI), first digitizes the incoming radio frequency (RF) streams from three input antenna channels (2 nadir oriented science antennas and one zenith oriented navigation antenna). These raw IF samples are then processed over a large domain of delay and frequency space into what is known as the Full DDM. An example of four Full DDMs generated with one second of incoherent averaging by the DDMI as shown below in Figure 1.

Figure 1 shows the full delay and Doppler dimensions of the on-board processed DDM. In normal operations, these four DDMs are pre-processed by a compression algorithm [1] that identifies the peak power power bin using a low-pass filter and then crops a smaller range of delay and Doppler bins from the Full DDM. Table 1 summarizes the delay and Doppler dimensions of both the Full and compressed DDMs.

This ATBD addresses the two data formats collected by the DDMI instrument which are not regularly downloaded: The raw IF samples (before any digital signal processing is performed) and the Full DDMs, like those shown in Figure 1. These two additional data products can provide significant science advantages for some applications, yet are not downloaded regularly due to the greatly increased storage and data downlink bandwidth required. The remainder of this ATBD describes the background and scientific value of occassional collection of these two data products, as well as their exact formats and a description of available processing tools needed to use them.
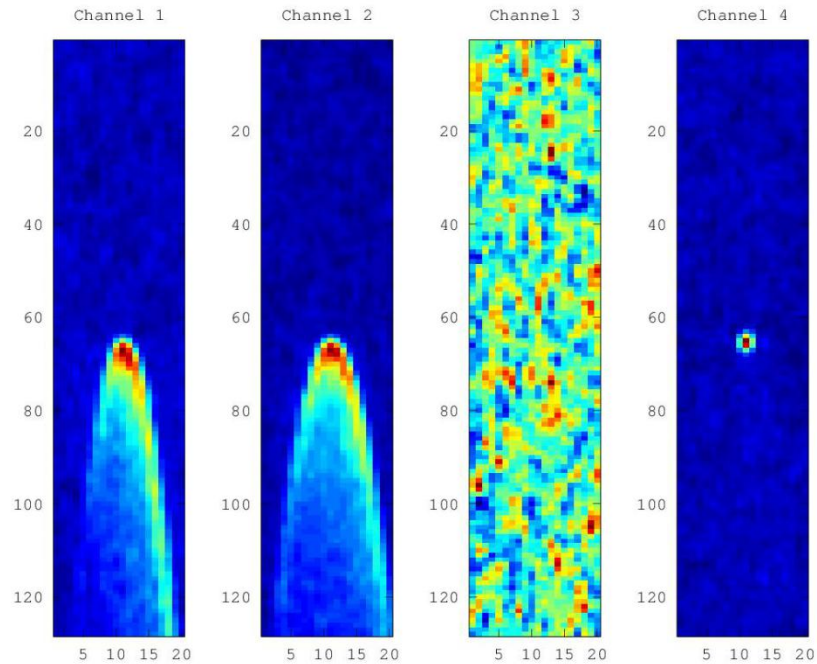
Figure 1, Four Full DDMs generated by the CYGNSS DDMI on parallel tracking channels. The channel 1 and 2 DDMs are reflections from the ocean, the channel 4 DDM is from a land reflection, while Channel 3 is transitioning to a new observation.

Data Product	Delay Bins	Doppler Bins
Full DDM	128 delay bins, 0.25 C/A chip spacing (~73m), specular point near center delay bin 64	20 Doppler bins at 500 Hz spacing, specular point near center Doppler bin 10
Compressed DDM	17 delay bins, 0.25 C/A chip spacing, specular point near center delay bin 9.	11 Doppler bins at 500 Hz spacing, specular point near center Doppler bin 6

Table 1, Delay and Doppler dimensions and bin spacing for Full and compressed DDMs.

2.   Science Background and Objectives

2.1   *Need for Raw IF Data*

The raw IF samples collected by the DDMI instrument contain the highest possible resolution over delay and Doppler space. Access to the raw IF samples allows ground processing of this high resolution data stream in a myriad of ways not possible in real time by the instrument. For example, the raw IF samples can be processed to extract in-phase and quadrature phase information for high resolution processing of coherent surface reflections. Additionally, raw IF ground processing permits users to make detailed examinations of the received power over the surface using variable delay and Doppler spacing and integration times, thus permitting extremely high resolution DDMs for advanced science applications. A summary of the additional processing possible using ground processed raw IF from CYGNSS is summarized in Table 2. An example of a fine resolution DDM processed from a raw IF collection off the coast of Japan on May 15 2020 is show in Figure 2.

Capability	Range	Resolution	Processing Tool	Comment
GNSS satellites	GPS L1, SBAS, Galileo E1	As below	GPS L1 only	Limited by DDMI antenna and front end.
Delay Space	0 to 1023 chips (full)	0.0625*X chip, X = integer	Full delay space, 0.0625 to 1 chip resolution	Processed with delay dimension FFT
Doppler Space	No limit	No limit	No limit	Limited by DDMI antenna and front end.
Incoherent integration	1ms to length of data set	1ms * X, where X is an integer	No limit with 1ms resolution	Typical values: 1ms (for phase) 100ms, 500ms, 1 second

Coherent integration	1 sample and greater	1 sample (0.0625 chip)	1ms fixed	Limited by signal coherency
I/Q phase processing	As above	As above	Yes, at 1ms coherent processing.	Phase reconstruction limited by actual signal coherence

Table 2, Additional processing options possible with raw IF data.

The additional processing options listed in Table 2 represent only a sub-set of all of the processing possibilities using the raw IF data. Additional upgrades to the public raw IF processing tool are possible, as the code is open source, to allow users to implement custom processing algorithms. The precise input formats of the raw IF data are described in detail below allowing users to design their own processing tools.
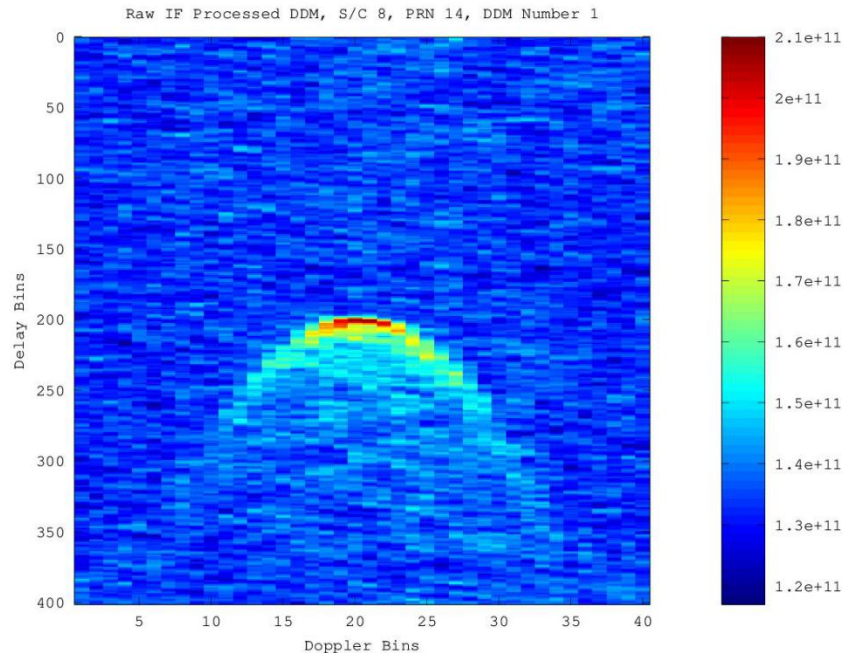

Figure 2, Example of a raw IF processed uncalibrated DDM. Processed using 1ms coherent integration, 1000ms incoherent integration over the full range of delay space and at 100

Hz Doppler bin spacing. A typical CYGNSS raw IF collection is 60 seconds in duration.

2.2   *Need for Full DDM Products*

The Full DDM product by CYGNSS is based on the DDMI's standard processing outputs. However, for many science applications, the dimensions of the down-linked compressed DDMs are insufficient. In these cases, it is useful to have access to the low level DDMI processed products with the expanded delay and Doppler ranges shown in Figure 1 and described in Table 1.

One notable application of the Full DDMs in place of the standard compressed DDM product is for techniques being explored to use the full power delay/Doppler profile to better estimate the maximum winds and size of tropical cyclones. In these applications, the much longer delay space captured in the Full DDM provides advantages in observing hurricanes and other large storms due to the greatly expanded size of the glistening zone in high wind conditions. It is often the case that the CYGNSS observatories collect (for downlink) both raw IF data and Full DDM data over hurricane events to enable more detailed processing techniques to be applied over these events.

3.   Data Product Overview

3.1   *Raw IF Data*

The raw IF data format was initially documented in UM Document 148-0354, CYGNSS Raw IF Data File Format, September 2017 by S. Musko and T. Butler [2]. Some of the material from that document has been duplicated here. The SOC delivers two files for each raw IF data collection: a Raw IF Metadata file and a Raw IF Data file. Each are described below

3.1.1   Byte Ordering and Data Types

All multi-byte values are stored in big endian order. The DDMI uses the ANSI/IEEE 754 standard for binary floating-point arithmetic. The "FLOAT" floating point number is stored using four bytes (32 bits: 1 sign bit, 8 bit exponent and 23 bit fraction). The first byte consists of the sign bit followed by the 7 most significant bits of the biased exponent. The second byte contains the

least significant bit of the biased exponent and the 7 most significant bits of the fraction. The remaining 2 bytes complete the fraction.

In the double precision format, "DOUBLE", more bits are used in the mantissa (for increased precision) and the exponent (for increased range). The first byte contains the sign bit of the mantissa and 7 most significant bits of the biased exponent. The second byte holds the 4 least significant bits of the biased exponent followed by the 4 most significant bits of the fraction. The remaining 6 bytes hold the remaining bits of the fraction.

3.1.2 Raw IF Metadata File Contents

The Raw IF Metadata file contains the ID of the spacecraft, a single Data Recorder Track 0 (DRT0) packet and one or more Pulse per Second (PPS) tables. The format of the raw IF meta data packet is included in Tables 3, 4 and 5 below.

Bytes	Description	Notes
0	Spacecraft SCID from SwRI document 17790-ObsID, Observatory Unique Identifier Specification	0xF7: CYGNSS 1 0xF9: CYGNSS 2 0x2B: CYGNSS 3 0x2C: CYGNSS 4 0x2F: CYGNSS 5 0x36: CYGNSS 6 0x37: CYGNSS 7 0x49: CYGNSS 8 0x00: end to end simulator 0x0E: engineering model 0x0D: default
1-35	DRT0 packet (Table 4).	
36-83	First PPS packet (Table 5).	
84-N	Additional PPS packets (Table 5).	

Table 3, Raw IF meta data file format

Bytes	Description	Notes
0-3	Packet Type ASCII "DRT0"	Four ASCII chars
4-5	GPS weeks at start	Weeks since Jan 6 1980, unsigned integer
6-9	GPS seconds at start	Second of week, unsigned integer
10	Data format: Real samples for all three CYGNSS antenna channels (Table 7).	
11-14	Sample Rate	unsigned integer, Hz
15	Channel 0: Frontend selection	
16-19	Channel 0: LO Frequency	unsigned integer, Hz
20	Channel 1: Frontend selection	
21-24	Channel 1: Carrier Frequency	unsigned integer, Hz
25	Channel 2: Frontend selection	
26-29	Channel 2: LO Frequency	unsigned integer, Hz
30	Channel 3: Frontend selection	
31-34	Channel 3: LO Frequency	unsigned integer, Hz

Table 4, Data Recorder Track 0 (DRT0) packet format

The PPS packet provides the sample index of the data recorder latched on each measurement tick. Since the nominal measurement tick rate is 10Hz this packet contains 10 sample index values. This information can be used when post-processing the raw data recorded from the receiver to align the post-processing calculations with the correct samples in the raw IF data file. This permits comparison of post-processed data with the real-time navigation solution etc. Tick 0 is the PPS tick on which the measurements used for the DDMI's navigation solution are latched.

Bytes	Description	Notes

0-7	GPS seconds of last PPS	GPS seconds of week, DOUBLE
8-11	Tick 0 Sample Index (PPS Tick)	Unsigned integer
12-15	Tick 1 Sample Index	"
16-19	Tick 2 Sample Index	"
20-23	Tick 3 Sample Index	"
24-27	Tick 4 Sample Index	"
28-31	Tick 5 Sample Index	"
32-35	Tick 6 Sample Index	"
36-39	Tick 7 Sample Index	"
40-43	Tick 8 Sample Index	"
44-47	Tick 9 Sample Index	"

Table 5, Pulse-per-second (PPS) packet format

All raw IF data collected by the CYGNSS mission to date has included byte interleaved data from all three antenna channels of the DDMI, numbered as follows:

1) Zenith navigation antenna.

2) Nadir starboard side science antenna.

3) Nadir port side science antenna.

All samples for all channels are saved as 2-bit values and interleaved as described in Tables 6 and 7 below.

3.1.3   Raw IF Data File Contents

Raw IF data files contain the binary raw IF data. The binary data of a capture is emitted by the DDMI in a series of File Transfer Packet Data packets, whose full format is shown in Table 6. Only the data portion, Byte 9 through Byte N, is stored in the Raw IF file. The source of the binary

raw IF data is Byte 9 through Byte N of the File Transfer Packet Data (FD00) packets emitted by the DDMI. The complete contents of the FD00 packet is included in Table 6.

Bytes	Description	Notes
0	SpW Target Logical Address	Unsigned integer
1	SpW Protocol ID	"
2-5	Packet Type ASCII "FD00"	"
6-7	Packet Length – Length of data excluding all header bytes	"
8	Sequence Byte	"
9	Data byte 0, binary raw IF data	
10	Data byte 1	
11	Data byte 2	
…	…	
N	Last data byte	

Table 6, File Transfer Packet data format, including the packed raw IF data bytes samples. See Table 7 for bit packing format.

The raw IF file contains Bytes 9-N of multiple contiguous FD00 packets. The FD00 packets are expected to contain consecutive Sequence Byte numbers. If a missing FD00 packet is detected, 2048 zero bytes are inserted in the raw IF file in place of the missing data.

Note that the first FD00 packet in the stream carries a DRT0 header block (see Table 4) at the beginning of the data bytes. For convenience, this DRT0 header is duplicated into the beginning of the Raw IF file. Afterwards, the file is composed of the binary raw IF sample data. The interleaving of the individual 2-bit (sign bit and magnitude bit) samples of the 3 antenna channels is described in detail in Table 7.

Data format: 2 Data format name: Channel 0, 1, 2. Sampling: I only, 2bit				
Byte number	Bit number	Channel number	Sample number	ADC bit
0	7	0	0	Sign
0	6	0	0	Mag.
0	5	0	1	Sign
0	4	0	1	Mag.
0	3	0	2	Sign
0	2	0	2	Mag.
0	1	0	3	Sign
0	0	0	3	Mag.
1	7	1	0	Sign
1	6	1	0	Mag.
1	5	1	1	Sign
1	4	1	1	Mag.
1	3	1	2	Sign
1	2	1	2	Mag.
1	1	1	3	Sign
1	0	1	3	Mag.
2	7	2	0	Sign
2	6	2	0	Mag.
2	5	2	1	Sign
2	4	2	1	Mag.
2	3	2	2	Sign
2	2	2	2	Mag.
2	1	2	3	Sign
2	0	2	3	Mag.
Repeating…	Repeating…	Repeating…	4	Repeating…

Table 7, Interleaving of raw IF data bytes for 3 channel sampling.

3.2   Full DDM Data

The default science mode for the CYGNSS DDMI instruments is to generate four Full DDMs per second. Each of these DDMs is then compressed to smaller dimensions for transmission to the ground. An example of a 1Hz set of Full DDMs is shown in Figure 1. However, an option exists in the spacecraft flight software to log the Full DDMs for downlink and subsequent analyses. When stored and downlinked to the CYGNSS Science Operations Center (SOC), the Full DDM products are converted to a netcdf file for easier post-processing. The data dictionary for Full DDM

netcdf files is contained in University of Michigan Document 148-0273, CYGNSS Full DDM netCDF Data Dictionary [3]. A summary of the netcdf parameters is duplicated in Table 8.

Parameter	Dimensions	Units	Description
sample	Per sample	-	Sample index
ddm	ddm	Reflectometry channel	0 to 3
ddm_timestamp_utc	Per sample	Seconds	Seconds from epoch
spacecraft_id	Per sample	Hex ID	See Table 3, Byte 0
spacecraft_num	Per sample	FM number	CYGNSS 1 to CYGNSS 8
ddm_sample_index	Per sample	-	Index link into standard Level 1 netcdf file for same day and FM
prn_code	Sample, ddm channel	GPS satellite number	GPS satellite 1 to 32
sp_lat	Sample, ddm channel	Degrees	Estimates latitude of the surface specular point.
sp_lon	Sample, ddm channel	Degrees	Estimate longitude of surface specular point.
raw_counts	Sample, ddm channel, delay, Doppler	Index, channel, delay bin, Doppler bin	See below

Table 8, Select list of important Full DDM netcdf parameters.

The Full DDMs are stored in the netcdf variable "raw_counts", which contains 4 dimensions. The first dimension is the sample index which corresponds to the relative time index

in the normal CYGNSS Level 1 netcdf data products. Additional information on the meta-data for the Full DDMs generated by the instrument at this epoch can be extracted using this link to the Level 1 netcdf which includes a significantly larger set of spacecraft and instrument meta-data (such as receive antenna gain, science antenna, spacecraft attitude, etc). The second dimension is the instrument science processing channel (1 to 4), where the DDMI generates 4 Full DDMs every second on parallel channels. The last two dimensions are the delay and Doppler bins, respectively of the Full DDM. There are 128 delay bins, each spaced at roughly 0.25 C/A code chip spacing. There are 20 Doppler bins, each spaced at 500 Hz.

4. Description of Processing Utilities Available

4.1 *Raw IF Data*

A C-code utility is available which is capable of processing CYGNSS raw IF data collections. The code is released under a GPLv3 open source license for the benefit of the CYGNSS Science Team. Additionally, a script is available to parse the key parameters from the raw IF meta data file and link with the standard Level 1 data products.

4.1.1 Raw IF Meta Data Processing Scripts

The script "process_rawif_metadata.m" extracts the GPS time and FM information from the raw IF meta data file described above. The GPS time and FM number link directly to the standard Level 1 netcdf products (GPS week and time can be converted to UTC date using standard conversion tools, including web-based tools). After the corresponding Level 1 netcdf file is downloaded from the NASA PO-DAAC, the script "plot_rawIF_Tracks.m" can be used to index into the Level 1 netcdf file and extract meta data on the standard 4 DDM tracked by the instrument (including providing PRN and Doppler information which is useful in initializing the raw IF processor described below). The raw IF data will contain the 4 observation processed in real time by the DDMI, but also additional satellite reflections from other GNSS satellites (including from the Galileo constellation), which are not processed by the instrument.

4.1.2   Build Information for Raw IF DDM Processor

This C-program requires the math (-lm) and fftw3 development FFT library (libfftw3-dev). In Linux, this can be downloaded and installed using most Linux package managers (i.e. synaptic on Ubuntu). The program has also been tested using a Terminal on Mac OS (Xcode, gcc and libraries above are required). On both Mac OS and Linux the program is built using the command line with make command:

> make

And then run with,

> ./CYGNSS_DDM_Processor

The output is then saved in the file "Processed_DDMs.bin" and can be post processed with the Octave/Matlab script "plot_FFT_DDMs_binary1.m". The output file format is determined by the input configuration file described below. Note that Octave is a Matlab "clone", and the scripts below have been tested in Matlab.

4.1.3   DDM Processor Configuration File

The configuration file "CYGNSS_DDMP_config.dat" contains the following entries which completely configure the processing performed and the outputs generated. Entries are "commented in" using the "^" character in the configuration text file. If the "^" is not at the start of a line, it will have no effect on the processing (it is "commented out"). Table 9 contains a list of the available command line configuration options available.

Key Character/Parameters	Purpose	Example
"C"	Cold Search Option	
Parameter 1	1 for cold search, 0 for user defined search	^C 0
"T"	Time Processing	^T 1 60 1

Parameter 1	Start second	1 = start second 1 of raw IF data
Parameter 2	End second	60 = Process until second 60 of raw IF data
Parameter 3	Second step (seconds)	1 = 1 second step between DDMs
"F"	Binary Filename	^F raw_IF_data.bin
Parameter 1	filename	Including full path, not in quotes
"D"	PRN, Antenna and Doppler Processing	^D 32 2 10000 200 4000 -10.6 0
Parameter 1	GPS satellite PRN number	32 = GPS satellite with PRN 32
Parameter 2	CYGNSS Antenna: 1 is zenith, 2 is starboard, 3 is port.	2 = CYGNSS starboard antenna
Parameter 3	Doppler range (Hz)	10000 = process 5000 Hz to each side of the Doppler center.
Parameter 4	Doppler step (Hz)	200 Hz Doppler bin steps
Parameter 5	Doppler center (Hz)	4000 = center Doppler bin of processed DDM
Parameter 6	Delta Doppler (Hz/s)	Applied relative to the start second if not 0

Parameter 7	Delta Doppler rate (Hz/s^2)	Applied relative to the start second if not 0
"P"	Misc Parameters	^P 16036200 3872200 3 1000 4
Parameter 1	Sampling Frequency (Hz)	16.036200 MHz, hard configured in DDMI
Parameter 2	Intermediate Frequency (Hz)	3.872200 MHz, hard configured in DDMI
Parameter 3	Intermediate Frequency (Hz)	3 = number of raw IF channels logged.
Parameter 4	Non-coherent summation interval (at 1ms resolution)	1000 = 1 second of non-coherent sums of 1ms coherent correlations (looks)
Parameter 5	Sample rate divider, integer 1 to 16	4 = process every 4th sample in delay. This determines the delay bin resolution.

Table 9, Raw IF data processor configuration file processing options.

A couple of notes are provided here on key processing configuration parameters with respect to the examples given above. The Doppler processing configuration is defined by a range, step and center. In the example above, the Doppler bins process will start at -1000 Hz (4000 - 5000), proceed in steps of 200, and finish at Doppler 9000 (4000 + 5000). The center Doppler is output from the processing of the meta data and Level 1 netcdf described above.

Regarding the "P" control character, the sampling and IF frequencies are determined by instrument and are constant, the number of channels is 3 for all existing CYGNSS raw IF collections. It is strongly recommended not to change these default values. The integration interval (Parameter 4) is expressed in 1ms units, where by 1000 is a 1 second integration, 500 is a 0.5 second integration, etc. The delay bin spacing (Parameter 5) is determined by the sampling rate.

All the processor can do is down sample (i.e. skip samples in time). A value of 1 (no down sampling) in Parameter 5 will process all samples (slowest but highest delay resolution option possible). The full sampling rate corresponds to roughly 1/16 of a C/A chip delay spacing. A value of 4 (process every 4th sample) is equivalent to the normal DDMI Full DDM processing, or approximately 1/4 C/A code chip delay spacing. In summary: 1=1/16 chip, 2=1/8 chip, 4=1/4 chip, 8=1/2 chip, 16=chip delay spacing.

4.1.4   Post Processing the DDM Processor Output Files

When the CYGNSS DDM Processor is finished processing it will output a binary file of all the processed DDMs in the execution directory called "Processed_DDMs.bin". This file can be processed with an Octave (or Matlab) script called "plot_FFT_DDMs_binary1.m", which is included with the Raw IF DDM processor. This file performs peak detection and cropping of the Full DDMs and displays both the cropped DDM image and a series of delay waveforms.

4.2   Full DDM Data

The Full DDM data products are provided in a netcdf format, with the full data dictionary described in University of Michigan Document 148-0273, as well as Table 8 above. Standard netcdf processing tools can be used to load and display this the parameters with these netcdf data files.

5.   References

1. Gleason, S., 2013: CYGNSS DDM Calibration: General Level 1A and 1B Data Products. *Algorithm Theoretical Basis Documents*, Univ. of Michigan.

2. *University of Michigan Document 148-0354, CYGNSS Raw IF Data File Format.*

3. *University of Michigan Document 148-0273, CYGNSS Full DDM netCDF Data Dictionary.*