COMPARISON OF GNSS-R DELAY DOPPLER MAP PROCESSING ALGORITHMS

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ABSTRACT

There are several established algorithms for processing Global Navigation Satellite System Reflected (GNSS-R) signals. The goal of these techniques is to generate delay Doppler maps (DDMs) of the magnitude distribution of the reflected/scattered signal power over the surface. The resulting DDMs are then used to estimate geophysical surface parameters such as ocean surface wind speed or near surface soil moisture. Each of these techniques have their unique application specific advantages and disadvantages. This presentation will present three of the most common GNSS-R DDM processing algorithms and compare them from the perspective of signal quality and calculation efficiency, and make recommendations for their suitability for various remote sensing applications and instrument design considerations.

Index Terms— GPS, GNSS, Reflectometry, Bistatic Radar

1. INTRODUCTION

The foundation of GNSS-R remote sensing lies in the accurate capturing of the reflected signal power in the delay (time) and Doppler dimensions as a delay Doppler map. The DDM provides the Level 0 observation which is then calibrated and used in geophysical parameter estimation. There are three well established processing algorithms used for generating GNSS-R DDMs.

1. Delay FFT: Correlates the received signal power using an FFT across the entire delay space dimension over a range of fixed Doppler frequencies.
2. Zoom FFT: Correlates the received signal power using short frequency dimension FFTs across a range of fixed time delays.
3. Pixel Correlator: Correlates the received signal power using a brute force pixel by pixel correlation over the desired delay and Doppler ranges.

The NASA PO-DAAC released CyGNSS raw IF data products are generated using ground processing software using the Delay FFT algorithm [1]. Alternatively, the TechDemoSat and CyGNSS on-board real-time DDM generation is performed using a Zoom FFT algorithm [2, 3].

Each of these techniques will ideally arrive at the same final DDM of the surface reflected power. However, they vary significantly in their initialization requirements and processing efficiency which can have large impacts on when and how they are optimally implemented (i.e. on-board processing vs ground based processing).

Each of these techniques will be evaluated in the context of different GNSS-R application scenarios based on the following criteria: DDM quality as estimated by an apples-to-apples signal to noise (SNR) comparison, complexity of the algorithm initialization requirements and overall processing speed and resource efficiency.

2. DDM PROCESSING ALGORITHMS

2.1. Full Delay FFT Processing

The Delay FFT DDM processing algorithm leverages the well known technique of using a frequency domain multiplication to achieve time domain correlation, a technique often used in traditional GPS receiver signal acquisition algorithms [4]. This technique can be assisted by knowledge of the visible GPS satellites and an estimate of their center Doppler frequencies. By the nature of the technique itself, it eliminates the requirement of any knowledge of the delay/time offset of the signal as it searches over the entire delay space at every digital sample by application of the delay dimension FFT. For example, the GPS L1 C/A signal consists of a repeated sequence of 1023 chips every 1ms, making the small range of a few chips where the signal is present detectable using a full range of delay offset correlations. This technique is ideal when the application has very limited information on the visible signals and can be used as a brute force acquisition engine scanning over multiple GPS satellites and large Doppler ranges to achieve reliable initial signal detection.

The disadvantage of this technique is that it is performing long FFTs to achieve the equivalent large number of delay correlations, most of which contain no signal, thus making it relatively computationally inefficient. An outline of the de-

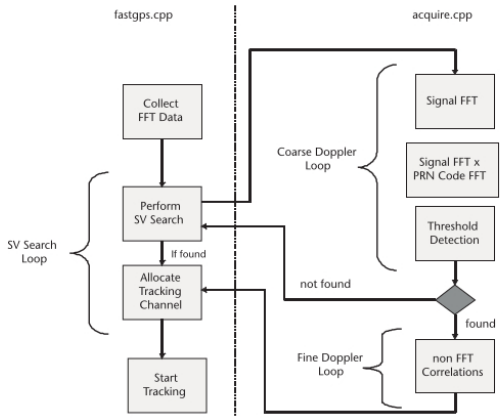


Figure 5.6 The fastgps software receiver acquisition algorithm.

Fig. 1. Full delay FFT acquisition algorithm, from [4].

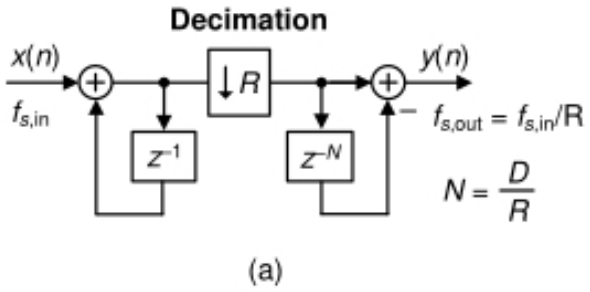


Fig. 2. Cascaded Integrator Comb (CIC) filter used in Zoom FFT processing, taken from [6].

lay FFT search and acquisition algorithm is shown in Figure 1 (from [4]). This algorithm can be straightforwardly adapted to process reflected signals as detailed in [5]. This includes defining the Coarse Doppler loop to be the Doppler frequency bins of the desired GNSS-R DDM, and skipping the Fine Doppler loop and Tracking channel aspects of the acquisition algorithm shown in the figure. Where the Doppler range of the DDM is defined using a predicted a-priori estimate of the reflected signal Doppler range.

2.2. Zoom FFT Processing

The Zoom FFT processor leverages an established signal processing technique that is based on a down sampling and filtering technique in the time domain and a subsequent frequency domain FFT at a series of fixed time delays. After the time domain samples are combined with the GPS code replica at a specific delay offset, a Cascaded Integrator Comb (CIC) filter with a down sampling decimator (by factor of R) is applied as shown in Figure 2 (from [6]). Subsequently, a short vector FFT is taken to map the receive reflected power in the frequency dimension. The spacing of the Doppler bins is dependent on the CIC filter configuration and is not as flexible as the Delay FFT algorithm. More details of this technique can be found in [6] for the general theory, and [7] as applied specifically to the generation of GNSS-R DDMs.

This algorithm ideally requires knowledge of the GPS satellites present, an estimate of their center Doppler frequencies and an accurate estimate of the signal location in the quickly changing delay space. The primary advantage of this algorithm is that it is much more computationally efficient as the frequency FFT dimension length is much shorter than the entire delay space sample length, thus focusing the processing on the delay range where the signal is believed to be present. The disadvantage is that the reflected signal delay needs to be well estimated or the Zoom FFT output correlations will miss the signal entirely. In real time applications it is usually possible to link the reflected signal open loop tracking algorithm to a real-time GPS navigation solution (combined with reflection point prediction) to estimate the delay offset center for the Zoom FFT scan of the reflected DDM, as is the case for the TDS and CyGNSS instruments.

2.3. Pixel Processing

The third DDM processing algorithm to be included in this analysis is a delay and Doppler pixel-by-pixel correlation scan. This is meant to provide an "FFT free" version of the DDM signal processing for comparison. This technique also requires knowledge of the GPS signals present, center Doppler frequencies and delay center estimates, but without the processing speed advantages of the two FFT based techniques. Nevertheless, with increases in FPGA capability, it can be used as a real-time DDM processor, but with reduced performance with respect to the other two techniques.

3. ALGORITHM COMPARISON

The CyGNSS instrument is able to periodically capture and download short (nominally 60 second) bursts of raw IF data samples for processing on the ground. The CyGNSS ground processor is able to process DDMs from these raw IF collections using all three methods discussed above. This enables the CyGNSS science operations center (SOC) to regularly process and compare the outputs of each of these techniques on the same data set, from which a detailed assessment of the signal quality and processing resources required can be quantified. Notably, the ground processing can then be compared with the real-time on-orbit processing of the instrument using its specific configuration of the Zoom FFT technique.

An example Zoom FFT DDM using downloaded raw IF data and the ground based Zoom FFT processor is shown below with reduced Doppler bin spacing (125Hz), as compared to the CyGNSS real-time (500Hz) DDM outputs is shown in

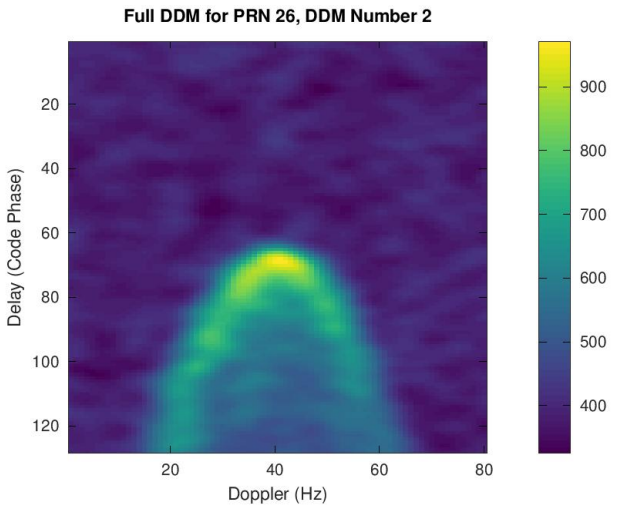


Fig. 3. Example DDM generated using Zoom FFT correlator at 125Hz Doppler bin resolution and 1/4 chip delay resolution.

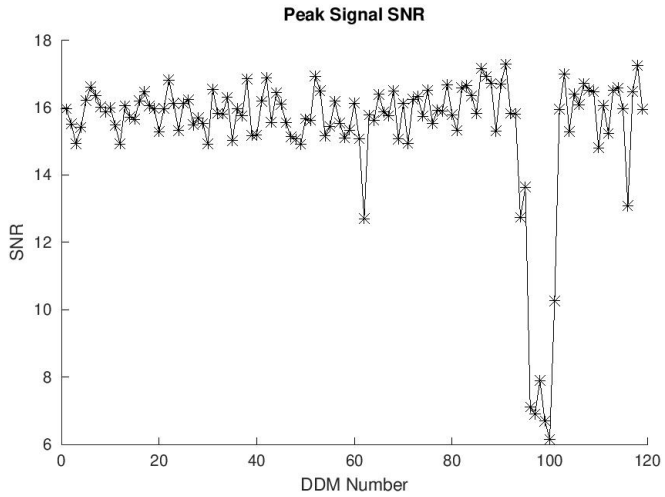


Fig. 4. Example 2Hz Delat FFT DDM sequence generated over all 60 seconds of a CyGNSS raw IF collection, showing fluctuations in SNR vs time. The dip in SNR at DDMs number 95 to 100 is due to a black body calibration load switch.

Figure 3. By adjusting the length and decimation intervals of the CIC filter, it is possible to adjust the Doppler bin spacing of the DDM. This provides options for finer Doppler spacing than what is provided by the real-time CyGNSS instrument processing, with only minor impacts to processing efficiency.

An entire 2Hz 60 second sequence of peak signal to noise (SNR) Delay FFT DDMs is shown in Figure 4. The drop in SNR leading up to the 100th DDM is due to the automatic black body calibration load switch, where no reflected signal is present. Over the duration of the collection with reflected signal the resulting SNR is relatively stable. The same SNR sequence using the Zoom and Pixel processing algorithms produced similar results, but with some dependencies on the processing configuration. This presentation will investigate in detail the optimal processing strategy for each technique with respect to both real-time and post processing applications.

A summary of the initial results for all three DDM processing algorithms is summarized in Table I for an example raw IF data collection. It can be observed that from these initial results all three processing algorithms achieve very close to the same signal quality as indicated by the very similar mean SNRs. However, the processing times are significantly different with the Zoom FFT performing much faster (with the correct delay offset initialization) than the Delay FFT algorithm and both FFT based algorithms are significantly faster than the pixel-by-pixel two dimensional looped correlation processing. It is important to note that these initial results are highly dependent on the configuration of each of the algorithms, including: DDM delay spacing, DDM Doppler spacing, overall DDM dimensions and amount of aiding provided to the algorithm (i.e. good estimates of the center delay and Doppler of the reflected signal).

4. PRESENTATION SUMMARY

The IGARSS 2024 presentation of this abstract will include detailed comparisons of these three GNSS-R DDM processing techniques using several CyGNSS raw IF collections. Each processing technique will be tested over a range of possible configurations in an attempt to reveal any subtle differences in the DDM quality between methods and to enable optimal design decisions for post-processing implementations for science operation centers as well as on-board real-time processing instrument algorithm design.

This analysis will provide important in-sights on the advantages and disadvantages to each of these processing techniques and their applicability to a range of remote sensing applications. In order to optimize the science capabilities of GNSS-R satellites it is critical to better understand the tradeoffs of these three processing techniques for the generation of the Level 0 GNSS-R science data for both real time and post-processing based science applications.

5. REFERENCES

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Metric	Delay FFT	Zoom FFT	Pixel-by-Pixel
Mean SNR	15.84	15.82	15.39
Processing Time (secs)	332	180	2245

Table 1. Summary of initial processing results for an example CyGNSS raw IF collection.

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