Wide Band Passive RF data Aggregation and Frequency Estimation for Space Domain Awareness Purposes

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ABSTRACT

The number of satellites in low earth orbit (LEO) is expanding at the fastest rate in human history. Current and planned LEO constellations look set to introduce up to 50 000 satellites in close proximity to Earth and identifying, tracking and cataloguing this proliferation of objects becomes more important than ever. Traditional space domain awareness (SDA) methods combine optical observations and narrow band radio frequency (RF) observations of actively transmitting satellites. Radar observations of the LEO belt, both bistatically and monostatically can add additional information on passive debris and non cooperative non-RF emitting satellites, but this comes with the complications of frequency compatible RF emitters and spectrum licensing. The current state of passive RF SDA requires a-priori information in the form of the timing of transit windows, transmitting frequency and modulation schemes and is typically processed offline. To keep the data collected in a typical LEO satellite pass to practical storage limits, narrow band captures with software defined radio (SDR) receivers is commonly performed. In this work, we detail a wide band approach using low cost commercially available commercial off the shelf (COTS) SDR receivers. Instead of narrow field of view RF sensors we employ wide field of view omni-directional antennas, reducing the need for troublesome and unreliable antenna rotators and accurate orbit information for pointing. The low cost and ever more capable computational resources of consumer grade graphics processing units (GPUs) are leveraged. This allows large RF bandwidths to be processed in real time. Open modular network based message protocols allow block based software units to connect to network sockets and receive both decimated and full rate RF data. Data products generated by the software pipeline include visual frequency vs time waterfall plots, time and frequency estimation via digital signal processing algorithms implemented to run in real-time utilizing GPUs and traditional in-phase quadrature-phase (IQ) capture for Doppler analysis. This work offers several advantages over a traditional SDA processing pipeline. Wide band frequency capture allows for the possibility of object detection, negating the need for a-priori Public Satellite Research and Analysis (PSRA) intelligence. Continuous capture means that patterns of life studies and anomaly can be performed for particular frequency ranges. We present a system developed to capture and analyse wide band UHF spectra of up to 60 MHz, which is the limit of the SDR hardware at hand. The system will use omni-directional antennas to capture the entire sky. The proposed processing pipeline produces data in real-time, and reduces a 60 MHz IQ data stream to information of mere mega bytes per minute. The information includes visual aggregated spectograms for visual inspection and time frequency estimations that can be used for orbit determination (OD) and target identification. Future work will focus on the addition of accurate time tagging information to allow increased accuracy for OD. Additionally, other bands can be studied through the consideration of the novel antenna structures such as aperture phased arrays and switched antenna networks. Once the quality of this pipeline is proven, data products can further be analysed by machine learning algorithms and ingested into mission systems.

1. INTRODUCTION

The number of near-Earth resident space objects (RSOs) is set to grow by an order of magnitude by the end of the decade [4, 7, 8]. Developing new space traffic management (STM) systems is critical to mitigate the risk of on-orbit collisions from the rapidly growing population of spacecraft.

Space domain awareness (SDA) relies upon numerous sensing technologies, amongst them:

- Optical tracking

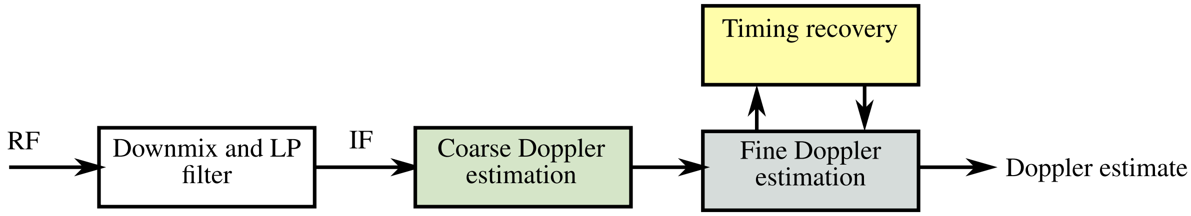

Fig. 1: Simplified flow chart of the implemented passive RF Doppler estimation SDR algorithm.

sample rate	second	minute	hour	day
100 kHz	0.4 MB	24 MB	1.44 GB	34.56 GB
1 MHz	4 MB	240 MB	14.4 GB	345.6 GB
10 MHz	40 MB	2.4 GB	144 GB	3.46 TB
60 MHz	240 MB	14 GB	864 GB	20.74 TB

Table 1: Data volume generated for various SDR in-phase quadrature-phase (IQ) sample rates.

- Active radar
- Passive radar
- Passive radio frequency (RF)

UNSW Canberra Space research on passive RF detection of RSOs was presented at AMOS 2022 [10]. The development of several passive RF reception sites occurred and a Doppler analysis pipeline was developed.

Passive RF observations rely on capturing of signals emitted or reflected by objects in space, and extract positional and identification data from these. In the current stage of this project, the focus is on the capture and processing of signals emitted directly by orbiting spacecraft, such as their communication signals and/or periodic beaconing signals.

Passive RF tracking can be done using a single station with one or multiple antennas or multiple geographically dispersed stations with one or multiple antennas at each station [12]. When only a single aperture is used for receiving RF signals at a single station, the only direct information that can be extracted from the received RF signal is the frequency offset caused by the Doppler effect due to the relative velocity between the transmitter (satellite) and receiver (ground station) [1, 6]. The Doppler frequency can be estimated and the range rate computed from this can be used for orbit determination (OD) using existing tools. Multiple co-located receivers at one receiver station can be used to determine the angle of arrival of a emitted signal. Passive multi-station methods utilise geographically dispersed receivers. With the appropriate synchronisation, the time and frequency of observations between stations will differ. The emitter's location can then be determined through the difference of the arrival frequencies and times as well as the geometry of the receivers. Typical methods within this category are time difference of arrival (TDoA) and frequency difference of arrival (FDoA) [3, 6, 9].

Data collected from individual stations using SDRs can be analysed to estimate the Doppler frequency offset of the received signal using a variety of methods. The method most frequently used utilises matched filters, which are templates of the expected signal, to estimate the frequency offset of the received signal. Further detail on the implemented Doppler analysis is found in [11]. A simplified flow diagram of the algorithm is depicted in Fig. 1. Further details on this algorithm are found in [10]. The output of the algorithm for a SARAL pass are shown in Fig. 2. While the matched filter SDR Doppler estimation algorithm requires a-priori knowledge of the modulation scheme and data rate of the signal, the Doppler estimates feature a high time and frequency accuracy compared to the signal to noise ratio (SNR) of the received RF signal.

2. WIDE BANDWIDTH RF RECEPTION

Generally, SDRs feature 12 bit or 14 bit analog to digital converters (ADCs). These samples are padded to 16 bit or 2 B. For an IQ sample, the SDR uses two ADCs, resulting in a total of 4 B per sample. The data generated for various periods of time for a number of supported sample rates are shown in Table 1.

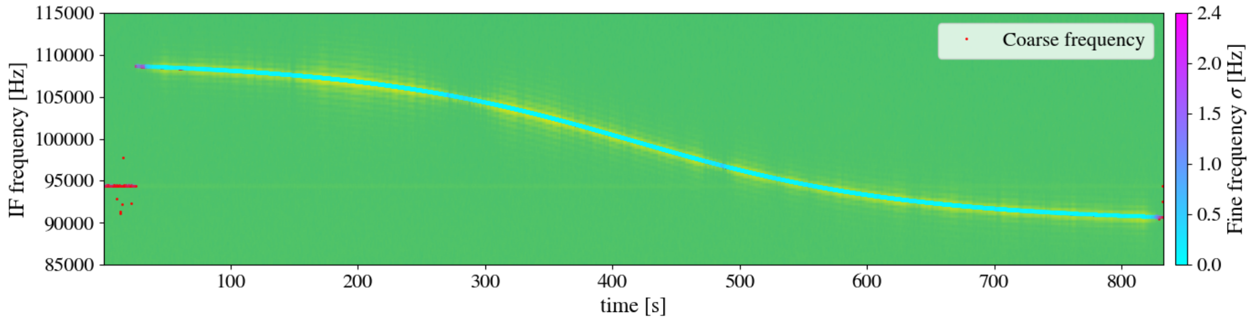

Fig. 2: Waterfall of Saral (NID 39086) with coarse and fine frequency estimation overlayed. The colour intensity of the fine estimate indicates the standard deviation.

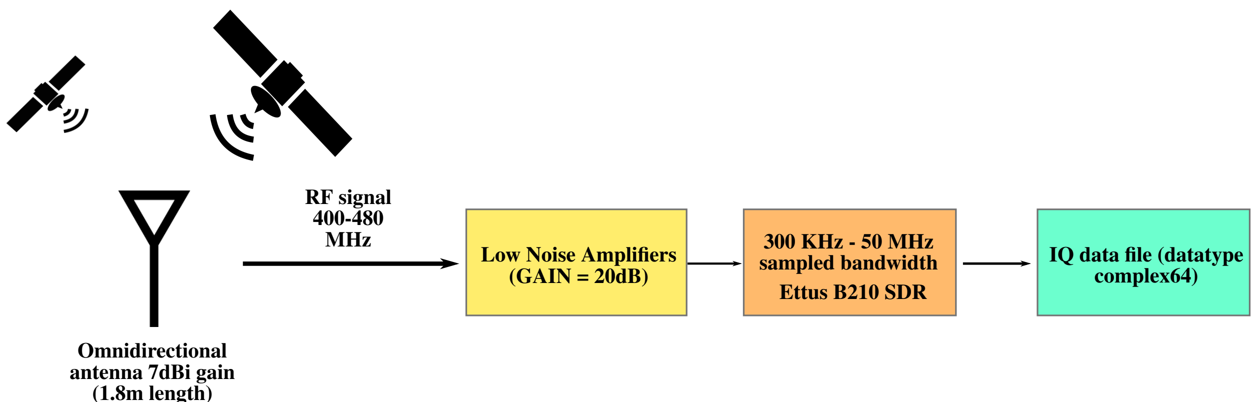

Fig. 3: Block diagram of the UHF receive chain.

Typically passive RF observations, in order to keep the data volume of the collected data to a minimum, capture only a relatively narrow bandwidth around a known centre frequency, typically 200 kHz to 500 kHz. The timing of data acquisition is typically scheduled with reference to the predicted orbit of the satellite based on a-priori orbital information, such as a state vector or the two line element (TLE). Additionally, the duration of captures tend to be determined by the expected time of visibility where the target is above the horizon. In this mode of observation, little extra information on the RSO population is to be expected, as known objects in known orbits are being observed. Despite this, data volumes of over 2 GB can still be easily generated in a single low earth orbit (LEO) pass for a single satellite. While these style of observations are effective for orbit refinement, pattern of life detection and manoeuvre detection, only a limited part of orbit regime is monitored. This is both spatially in frequency due to the narrow bandwidth observations not capturing spacecraft emitting out of band, while also temporally, since the limited observation time windows exclude emissions in and out of band when not capturing.

In order to increase the spectral and temporal cover of passive RF observations, continuous wide-band recordings are required. As shown in Table 1, these generate large amounts of raw data. For example, an entire day of capturing 60 MHz of bandwidth of passive RF generates $60\,\mathrm{MHz} * 2 * 2\,\mathrm{B} * 86400\,\mathrm{s} \approx 20.7\,\mathrm{TB/d}$. Clearly, this is impractical for wide area and constant monitoring of the RF spectrum.

An obvious method to processing wide bandwidth captures and reducing the data collection storage requirements is found in radio astronomy and remote sensing applications in the form of the fast Fourier transform (FFT) spectrometer. The integration function of the spectrometer allows the spectral range of the captured signal to be preserved while still compressing the data volume. An example of the application of an FFT spectrometer to radio astronomy is detailed here [2]. Further similar work from the remote sensing field is found in the work [5].

In this work, we present a method whereby the FFT is performed in the real-time capture pipeline. Once the spectrum is channelised, we then perform a complex data (IQ) to magnitude conversion, which reduces the data storage requirements while discarding the phase information. The magnitude spectral data is then time averaged by a selectable integer ratio, further reducing data storage requirements. A flow diagram of our proposed decimator algorithm is

Bandwidth	Duration	Data volume (raw IQ)	Data volume (decimated)
300 kHz	10 minutes	0.67 GB	13.7 MB
300 kHz	1 hr	4.02 GB	82.4 MB
300 kHz	1 day	96.05 GB	2 GB
60 MHz	10 minutes	134 GB	2.68 GB
60 MHz	1 hr	805 GB	16.1 GB
60 MHz	1 day	19 TB	386.2 GB

Table 2: RF capture data requirements

illustrated in Fig. 4.

The proposed algorithm and system concept introduced is illustrated using examples from the ultra-high frequency (UHF) satellite band, spanning approximately from 400 MHz to 470 MHz. However, it can be applied to any of the other common bands used for satellite to ground transmission. Extensions to the very-high frequency (VHF) band (144 MHz) and S-band (2200 MHz to 2400 MHz) are of particular interest for applications of sensing spacecraft in the LEO regime.

The scheduled tasking pipeline we developed as part of a collaborative cooperative research centre project (CRC-P) project [10] utilised an Ettus SDR writing IQ data to file. Typically, FFTs were used to visualise the spectral contents of the signal in a so-called waterfall plots, where the active RF emission from the target satellite as well as terrestrial and other interference can be observed.

Spectral methods, such as Welch's method [6], as well as temporal methods, such as matched filters [10] were used to extract parameters, such as the frequency of arrival. These algorithms can process the narrow band IQ data in real-time, or post process data dumped to files.

The observed frequency of a spacecraft is given by

$$f_o = f_c + f_d \tag{1}$$

where f_c is the carrier frequency and the frequency offset due to the Doppler effect is given by

$$f_d = \frac{v_r}{\lambda} = f_c \frac{v_r}{c} \qquad \text{[Hz]}, \tag{2}$$

where v_r is the rangerate or relative velocity between the emitter and receiver, $\lambda = \frac{c}{f_c}$ is the wavelength, with speed of light $c = 3 * 10^8\,\mathrm{m/s}$. Thus the Doppler excursion for a LEO satellite moving at approximately 8000 m/s, the Doppler frequency is $\pm 12\,500$ Hz. Over a typical LEO pass of approximate 10 minute duration, this equates to an averaged Doppler rate of 40 Hz/s. Thus, when sampling at 2 samples per second, 100 Hz per channel is deemed appropriate. The FFT length is then determined by

$$N_{\text{FFT}} = \frac{f_s}{\text{bin size}}, \tag{3}$$

with f_s being the sample rate. Thus, for a 1 MHz sample rate, the FFT size would be 10 000.

In order to reduce the FFT rate to 1 or 2 samples per second, we use a decimation factor of 50 or 100. This controls the number of sequential frames that are incoherently detected and integrated. As we reduce the IQ stream from the FFT block to an incoherent product, further compression of the data by a factor of 2 occurs. Thus a data reduction factor of 100 is possible still storing FFT outputs twice per second.

Table 2 shows data volumes associated with raw IQ capture and the decimated outputs from our proposed pipeline for various observation lengths.

3. RESULTS FROM RF DECIMATOR

In this work, we present results from experimental data captures to demonstrate the proof of concept. A remote site near Captains Flat, NSW, that was referenced in the work [10], was used to perform data collection. The specific RF

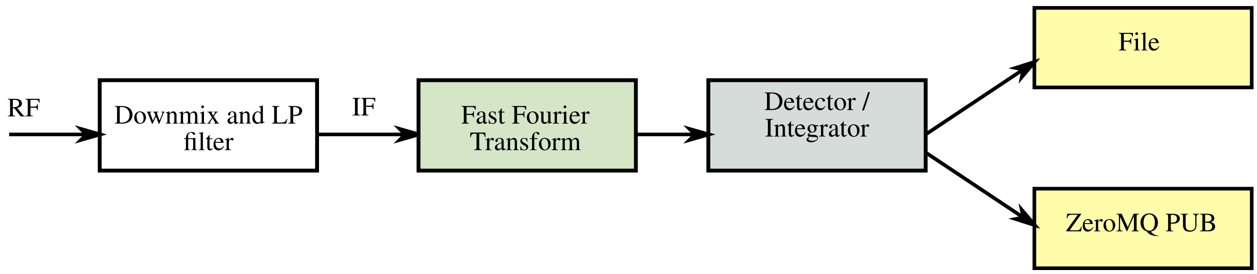

Fig. 4: Flow chart of the RF decimator algorithm.

path used was a Diamond X50N 70cm/2m basestation antenna, a low noise amplifier (LNA) and a BladeRF SDR from NUAND, Inc.

RF data collection focused on 2 regions of the UHF satellite band. Results are presented at the low end of the band around 400 MHz due to the variety of satellite transmitters in this part of the spectrum. Further results are also presented at 465 MHz where there are several larger Earh orbiting (EO) satellites such as SARAL and the METOP-C spacecraft.

Figure 5 shows a capture below 401.5 MHz with 5 samples per second (lesser decimation factor) and at least 4 distinct satellites in the wide area survey. Slightly less than 2 hrs duration.

Figure 6 shows a capture near 400.5 MHz with 5 samples per second, clearly showing 2 distinct satellites in the field of view, one with clear frequency shift keying (FSK) modulation (the lower trace).

Figure 7 demonstrates the capability to survey a band of frequency for an entire day. The sampled band was at the upper extent of the UHF band for satellites. FFT index around 7000 has numerous S-curves from satellites emitting at 465.988 MHz which is where SARAL (39086), METOP-C (43689) and other ARGOS format transmitting EO satellites broadcast.

Figure 8 clearly shows the zoom of 9 satellites within the 24 hour period. Only 5 transits can be attributed to SARAL.

Figure 9 and Fig. 10 are 2 distinct ARGOS transmission transits where we can infer the left mini plot was a higher elevation pass, and the right plot is a lower elevation pass that was probably quite close to the horizon.

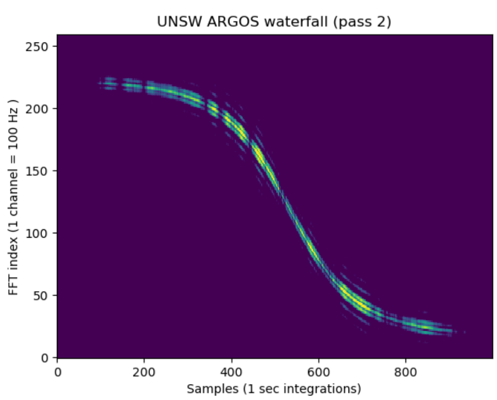

Fig. 9: Single ARGOS satellite pass RF waterfall from the RF decimator algorithm.

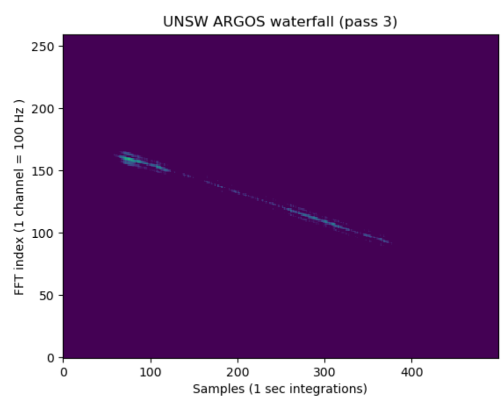

Fig. 10: Another ARGOS satllite pass RF waterfall from the RF decimator algorithm.

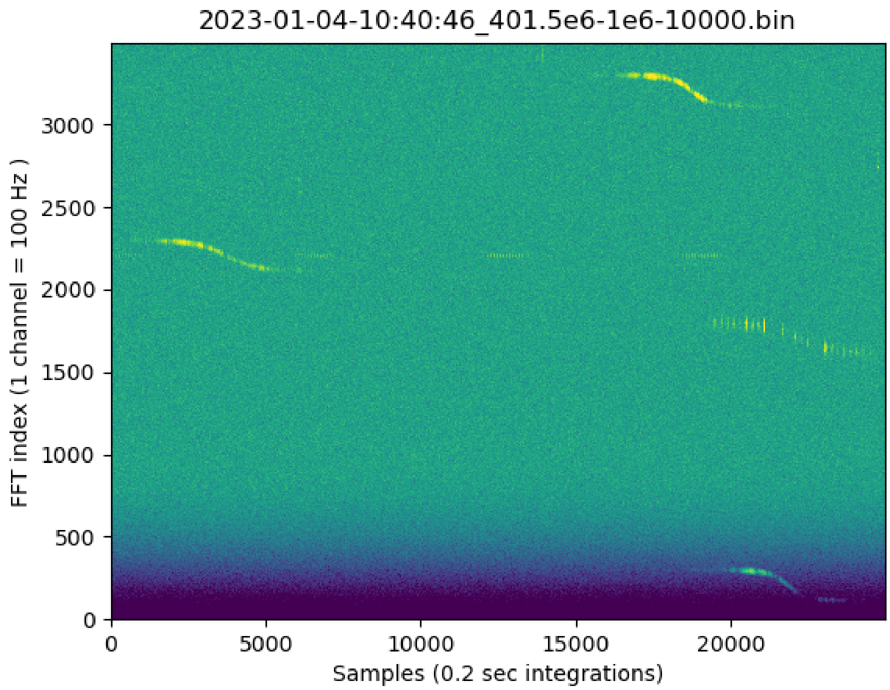

Fig. 5: 401.5 MHz waterfall showing 4 distinct satellites.

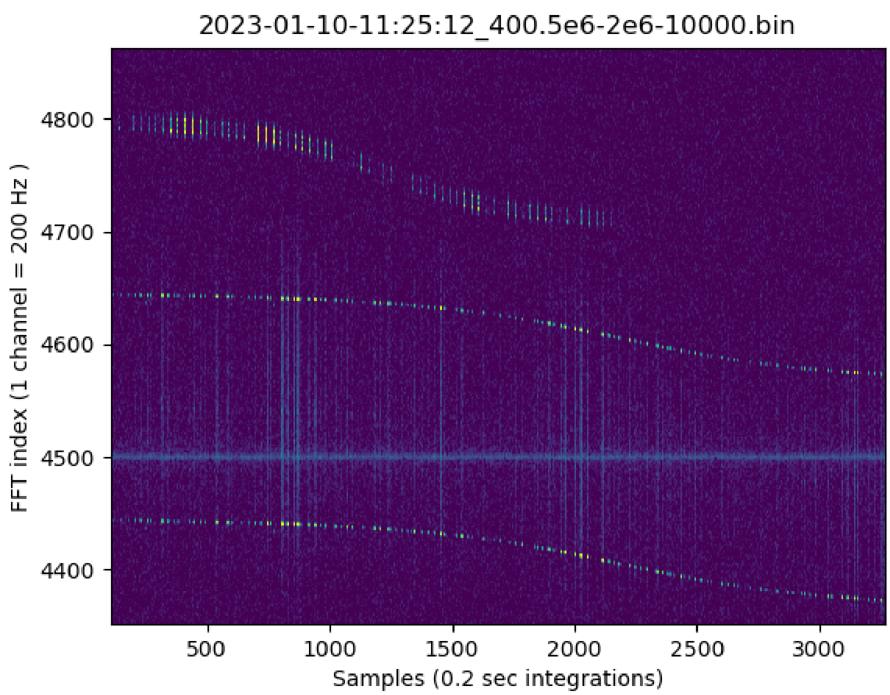

Fig. 6: 400.5 MHz waterfall showing 2 distinct satellites, one a pulsed in time transmission, the other with FSK modulation.

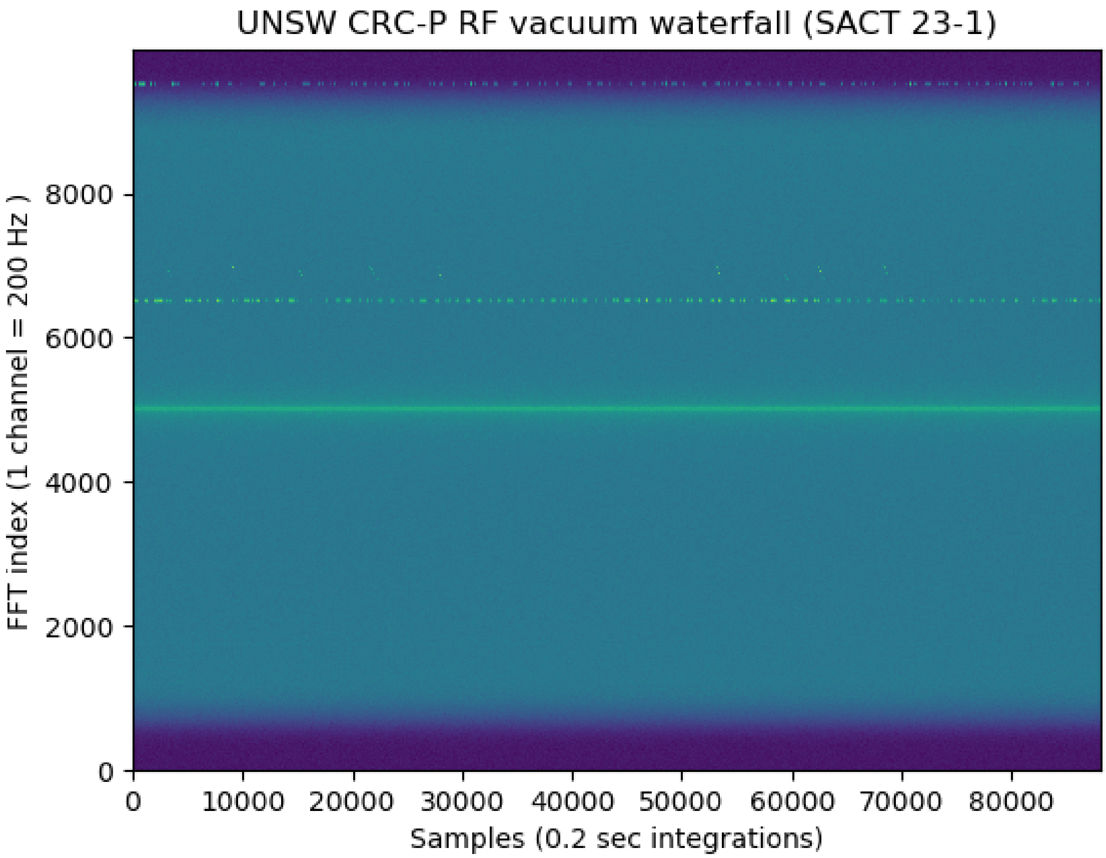

Fig. 7: Whole day capture of 1MHz bandwidth from the RF decimator algorithm.

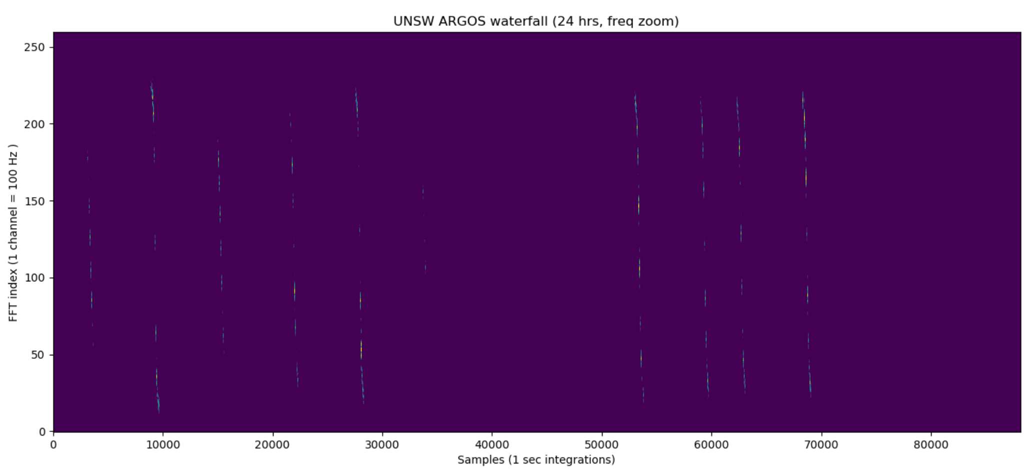

Fig. 8: Whole day capture of the ARGOS band (465.9875 MHz) from the RF Decimator algorithm.

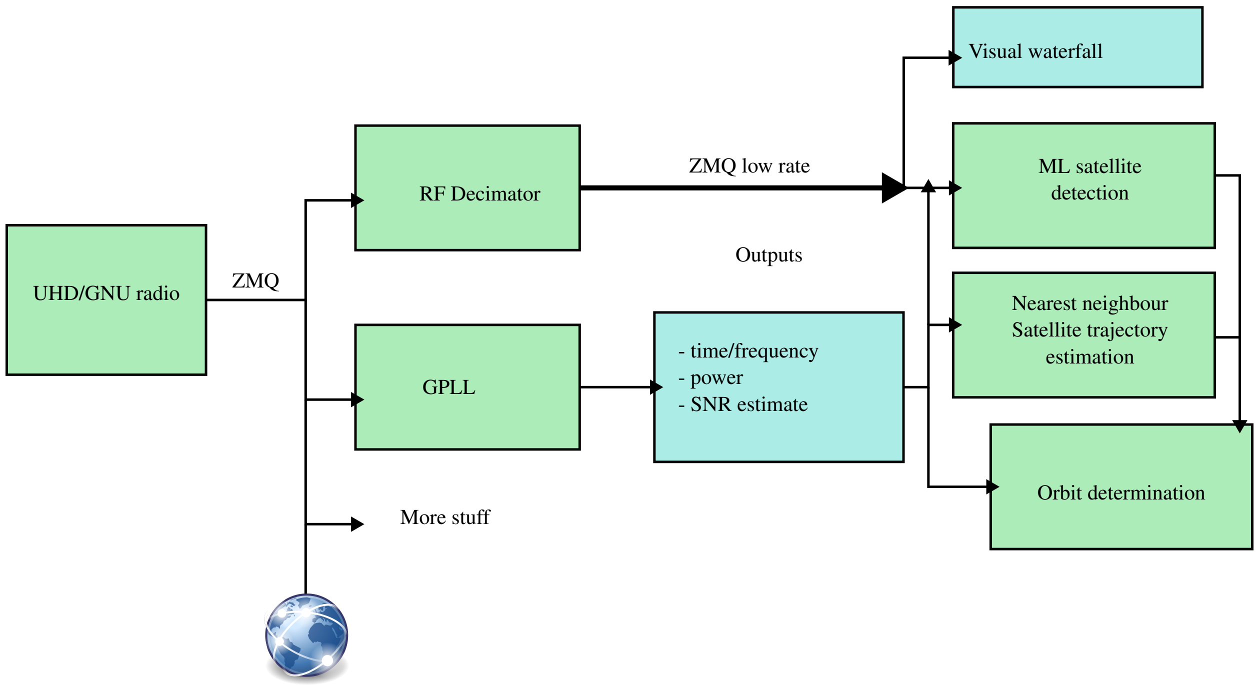

Fig. 11: Block diagram of the proposed data processing chain.

4. AN EXTENSIBLE AND MODULAR DATA PROCESSING CHAIN

In Fig. 11 we present the proposed data processing architecture. It utilises the Ettus UHD library and/or GNURadio to interface the SDR. We utilise several ZeroMQ network interfaces to allow numerous independent data processing blocks to connect to the IQ stream output from the SDR and to share outputs. For instance, the visual waterfall module can run connected to the output from the RF decimator. Similarly, outputs from the RF decimator can be utilised by a proposed machine learning (ML) satellite detection block or any number of other data processing subsystems.

5. APPLICATIONS

There are many possible applications of the output of the RF decimator. By monitoring the RF emissions in particular bands, it could be used to perform functions that do not require high fidelity IQ captures. As previously mentioned, the importance of Public Satellite Research and Analysis (PSRA) is lessened as a-priori frequencies are not needed. Some of the applications can include:

5.1 Target identification

The course time series products from the RF Decimator can be combined with TLE or state vector overlays to help identify targets.

5.2 Resident Space Object detection

Given one of either time of signal acquisition (at a particular site), or frequency of transmission, the continuous recording of data and practical storage requirements may enable association between an object's orbit and frequency of transmission. If a catalogue of known objects in given bands is maintained along with a catalogue of orbital parameters, new objects can potentially be discovered. Additionally, the type of modulation used may be possible to be readily identified from the visual spectra. An example is the clear spectrum of a FSK modulation scheme of a satellite in depicted in Fig. 6.

5.3 Pattern of life analysis

By continuously acquiring RF wide band data from an SDR and processing via FFT analysis and utilising ZeroMQ style architecture, a large number of objects can be monitored for pattern of life analysis.

5.4 Initial Orbit Determination

Whilst not sufficiently accurate for precision orbit determination, the low fidelity products from the RF decimator could be applied to the problem of real-time initial OD. Additionally, upon detection of an emitting object, high fidelity Doppler analysis could be applied to either the full rate IQ stream, or a selected narrow band channel in the IQ stream.

5.5 Learning-based techniques for Space Domain Awareness

It is anticipated that with a growing population of spacecraft, the tracking, identification, and characterisation of these becomes increasingly difficult. Also, data aggregation itself is a high degree complex problem when dealing with the large number of entities. The computational complexity of traditional methods is too high to address this multi-dimensional, complex, and dynamic problem for the space network. Artificial intelligence and ML algorithms appeal as a suitable approach to address this problem. Moreover, learning-based algorithms can provide cost effective, less-computationally intensive and robust solutions for aggregating and analysing data for SDA. With simple thresholding in the frequency domain, active emitting sources could be identified and sent to a ML pipeline for object detection, classification and analysis.

6. FUTURE WORK

There are many considerations for future work following this proof of concept. Some future directions to be considered are:

- Investigation of coherent vs incoherent detection in the decimator pipeline
- Dilution of bursty RF transmission within the context of sampling at relatively low rates of 2 samples/second
- ML and data archival aspects of wide area search
- Applications to other wider RF bands such as S-band, X-band and Ku-band
- Precision OD triggered from object detection in decimated real-time output

7. CONCLUSION

With an ever increasing number of satellites in orbit around the Earth, particularly in low earth orbit (LEO), the challenges of moving from a narrowband and scheduled tasking environment for passive radio frequency (RF) observations to a wide-area and constantly sampled passive RF regime are clear. We have presented a scheme moving from tasked scheduling of catalogued LEO satellites to a search pipeline that allows for detection of objects across a broad range of RF emission. Some of the ideas presented here add to existing passive RF techniques to help gain a more complete picture of the dynamic resident space object population.

Future work includes parameter extraction from wide-band sampled RF data using signal processing and machine learning (ML) algorithms. Additionally, the design will be expanded to capture wider bandwidths using dedicated hardware, such as RF-SOCs with the processing occuring directly on the hardware.

8. ACKNOWLEDGEMENTS

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