A Model-based Approach to Asteroid Characterisation

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Abstract

This current work demonstrates the first steps for a novel method that utilises a model based approach to classify and detect asteroids and other near Earth objects. When the illuminator transmits a continuous wave (CW) signal, the signal contains a single Fourier component in the form of the sine wave that is emitted. The sine wave reflected on each part of the asteroid performs a perturbation of this Fourier component by tweaking its amplitude through absorption, and frequency and phase through relative movement and rotation. When using conventional Fourier transform based analysis methods this would be revealed as a Doppler spread in the periodograms. Additionally, some of the electromagnetic properties of the signal are perturbed such as the signal polarisation. This can be caused by multiple reflections and surface material properties. In theory, the entire backscattered signal could be modelled using a Fourier series. In practice, this will however be challenging, since the number of Fourier components and their parameters will be large.

A model based asteroid detection and characterisation method would allow more detail to be extracted from an observation since one, instead of correlating sine waves through a Fourier transform, would be correlating matched filters. This will improve the signal to noise ratio while simultaneously indicating what matched filter results in a high signal to noise ratio. The matched filters can be obtained through radar simulations with an asteroid model.

This work presents early results on the comparison of laboratory results using an anechoic chamber, computer simulation studies and a comparison of early results to the observations of 2024 ON.

Introduction

The Southern Hemisphere Asteroid Radar Program (SHARP) has been detecting and classifying asteroids using the Canberra Deep Space Communication Complex (CDSCC) (Figure 1), Parkes and Australian Telescope Complex Array (ATCA) (Figure 2) radio telescopes since 2015. The CDSCC uses either an 34 m or 70 m antenna as an illuminator with a right-hand circularly polarised (RHCP) transmitter. ATCA acts as a receiver featuring both RHCP and left-hand circularly polarised (LHCP) antennae on 5 different antennae that can be configured in with different baselines. This configuration allows the measurements of reflections with different polarisations. This results in two voltage measurement streams. From this data, we can extract signal strength and Doppler spread. To date, the CDSCC has only been able to transmit non-coded sine waves, also called continuous wave (CW) signals. The use of a CW waveform limits the measurements to Doppler only, since no time-of-flight of the signal can be estimated. The resulting radar echos are typically analysed using a combination of coherent and non-coherent integration for each channel. We can thus analyse polarisation ratios, i.e. the difference between RHCP and LHCP polarisation, Doppler spread and signal strength. Observing these over time gives an idea of the asteroid shape and potential companions. The polarisation ratio can be used to characterise the asteroid's surface roughness and composition.

Figure 1:The Canberra Deep Space Communication Complex.

Figure 2:The Australian Telescope Compact Array.

Any periodic continuous time signal can be represented using the Fourier series as a composition of sinusoids.

$$s(t) = \sum_{k=-\infty}^{\infty} a_n e^{jn\omega_0 t}, \tag{1}$$

with a_n being the n^{th} Fourier coefficient given by

$$a_n = \frac{1}{T}\int_{-T/2}^{T/2} s(t) e^{-jn\omega_0 t}\, dt. \tag{2}$$

This means, that the backscatter signal of the asteroid for each polarisation can be presented as a sum of sinusoids.

Typically, the asteroid return signal is analysed using the Fourier transform, i.e. the correlation of individual sinusoids, each with their own frequency. The Fourier transform trades of time and frequency resolution. The result of this is a number of "bins", each representing a sinusoid with its magnitude and phase. The linearity of the Fourier series allows the return signal $s(t)$ to be reconstructed by adding the sinusoids.

The above means, that we should be able to construct asteroid models that produce a backscatter signal of a similar pattern as the received signal. This would allow us to find asteroid shapes that could produce the same echo signal. Tracking asteroids over sufficient time would limit the number of asteroid shapes that can produce the same echo signal. This would thus provide us with an image of what the asteroid shape could look like.

Typical terrestrial and aerospace surveillance radar uses micro-Doppler analysis to determine the shape of features and entire objects based on the radar backscatter signal. In this work we will investigate the prospects for using model-based and micro-Doppler-based approaches to detect and characterise asteroids. We present initial results obtained in anechoic chambers and simulations and compare these to some observed asteroids

Anechoic chamber experiments

Anechoic chamber experiments were performed to generate signal recordings of objects while being rotated around a single axis. The anechoic chamber setup is illustrated in Figure 3 with the transmit and receive antennae located next to each other. A simple metal choke was used to limit crosstalk between the antennae with additional crosstalk being removed in the digital signal processing. A signal generator was used to generate a 5.85 GHz CW. The signal generator also provided a frequency reference for the Ettus B200 software defined radio (SDR) that was used to receive the backscattered signal. The objects were made using aluminium foil and were rotated at 1 rpm in the anechoic chamber. The distance between the antennae and object in the chamber is 4 m with the object being 50 cm along its longest axis. This results in a lensing effect of less than 1 cm with the wavelength being 5.1 cm.

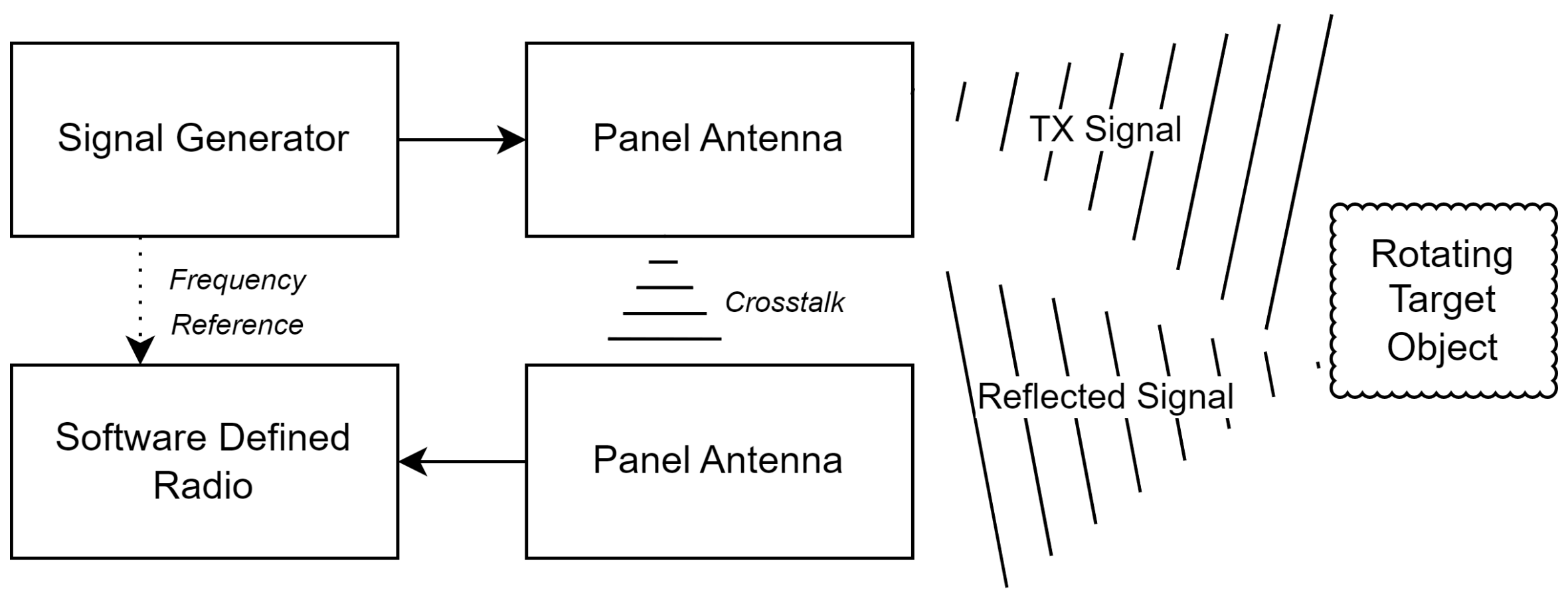

Figure 3:The setup of the anechoic chamber

Figure 4:Image of an anechoic chamber model of a fused binary shaped asteroid

Computer simulations

The radar simulation is performed with Matlab's radar toolbox using 3D point clouds. These point clouds are either created using Blender and exported, or created using parameterised geometric shape models. A diagram of the flow of the simulation is illustrated in Figure 5. The target motion velocities for each point is computed based on the angular rate of the object.

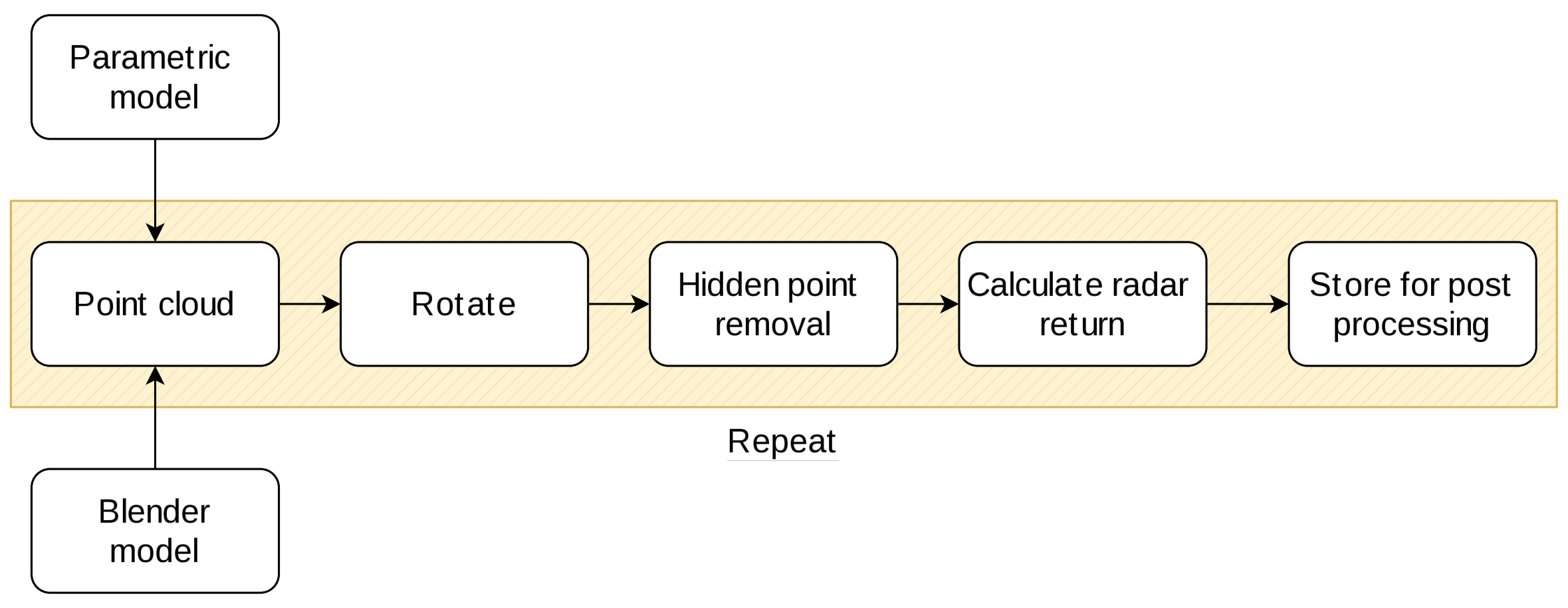

Figure 5:Block diagram of the computer simulation.

An example of a Blender model of a fused binary asteroid with a course surface is shown in Figure 6. The Blender model is exported as a point cloud with the points uniformly spread across the surface. Simple parametric models have also been used for tests and verification.

The simulation outputs voltage data, that then is plotted as a waterfall. We currently do not consider polarisation in the simulation. A waterfall of a simulation using the asteroid model shown in Figure 6 is shown in Figure 8.

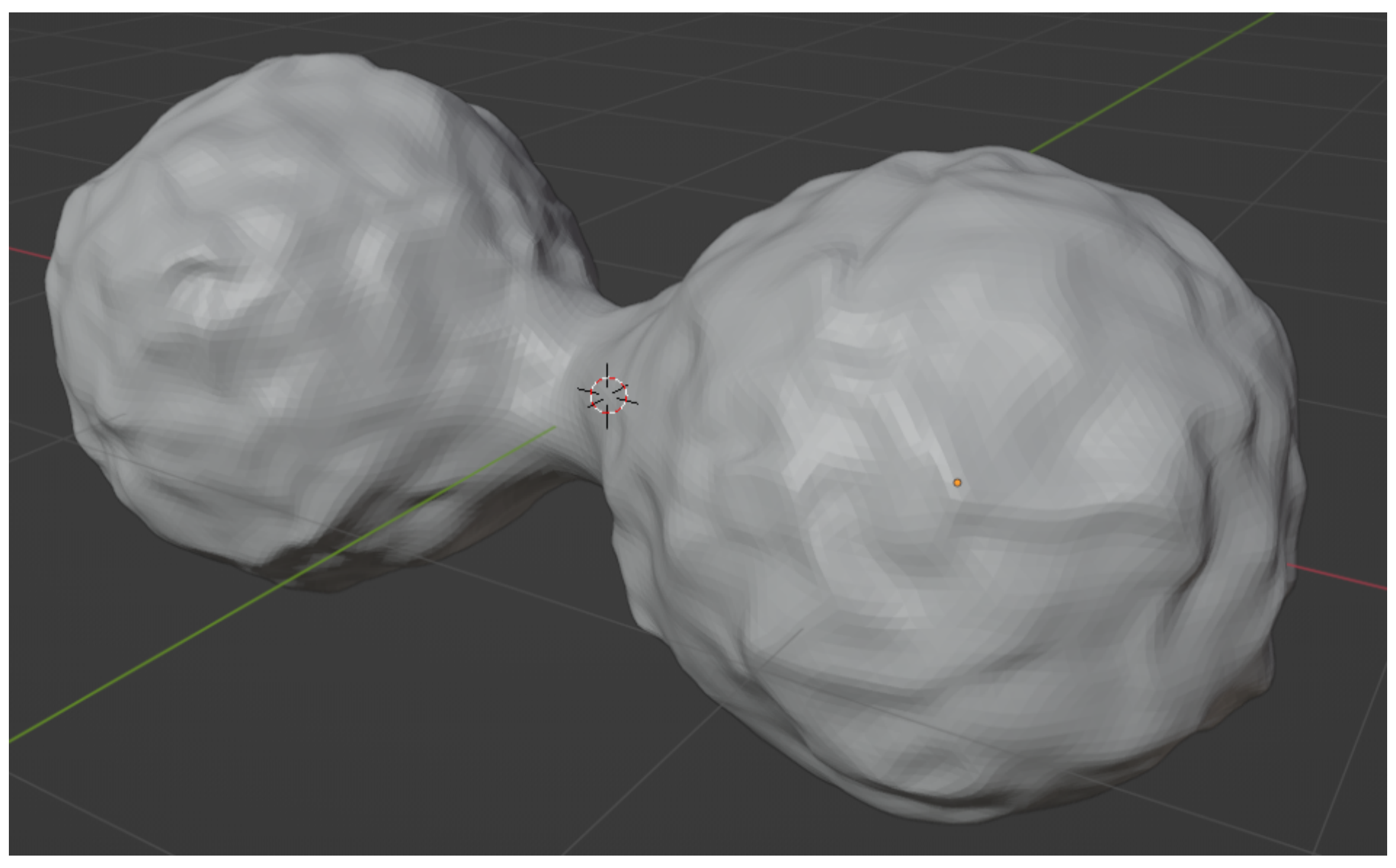

Figure 6:Image of a Blender model of a fused binary shaped asteroid.

2024 ON

Asteroid 2024 ON was discovered on 27 July 2024 by the ATLAS-MLO. SHARP observed 2024 ON on the 18th of September 2024 using DSS-34 at CDSCC as transmitter and ATCA as receiver. 2024 ON is a contact-binary with an estimated length of 300 m and passed Earth at a distance of 3 Lunar distance (LD) on closest approach and is of interest since this is a fast spinning asteroid with an estimated 6 hr rotation period. Figure 7 shows the waterfall for both polarisations of the observation with Figure 8 showing a computer simulation waterfall of a contact-binary shape.

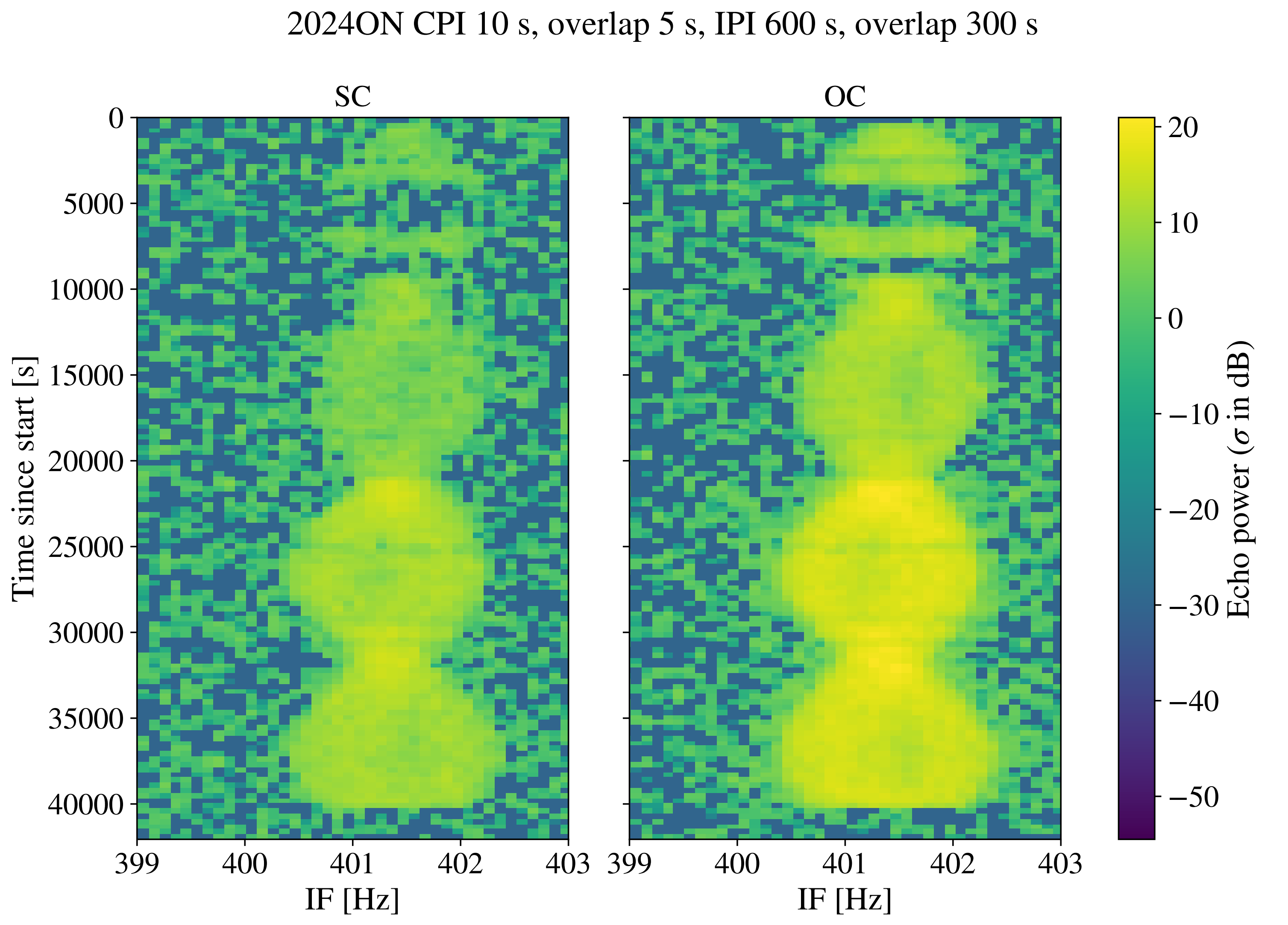

Figure 7:2024 ON Waterfall with the RHCP (SC) and LHCP (OC) polarisations of 2024 ON. Observed on 18 September 2024 using CDSCC and ATCA.

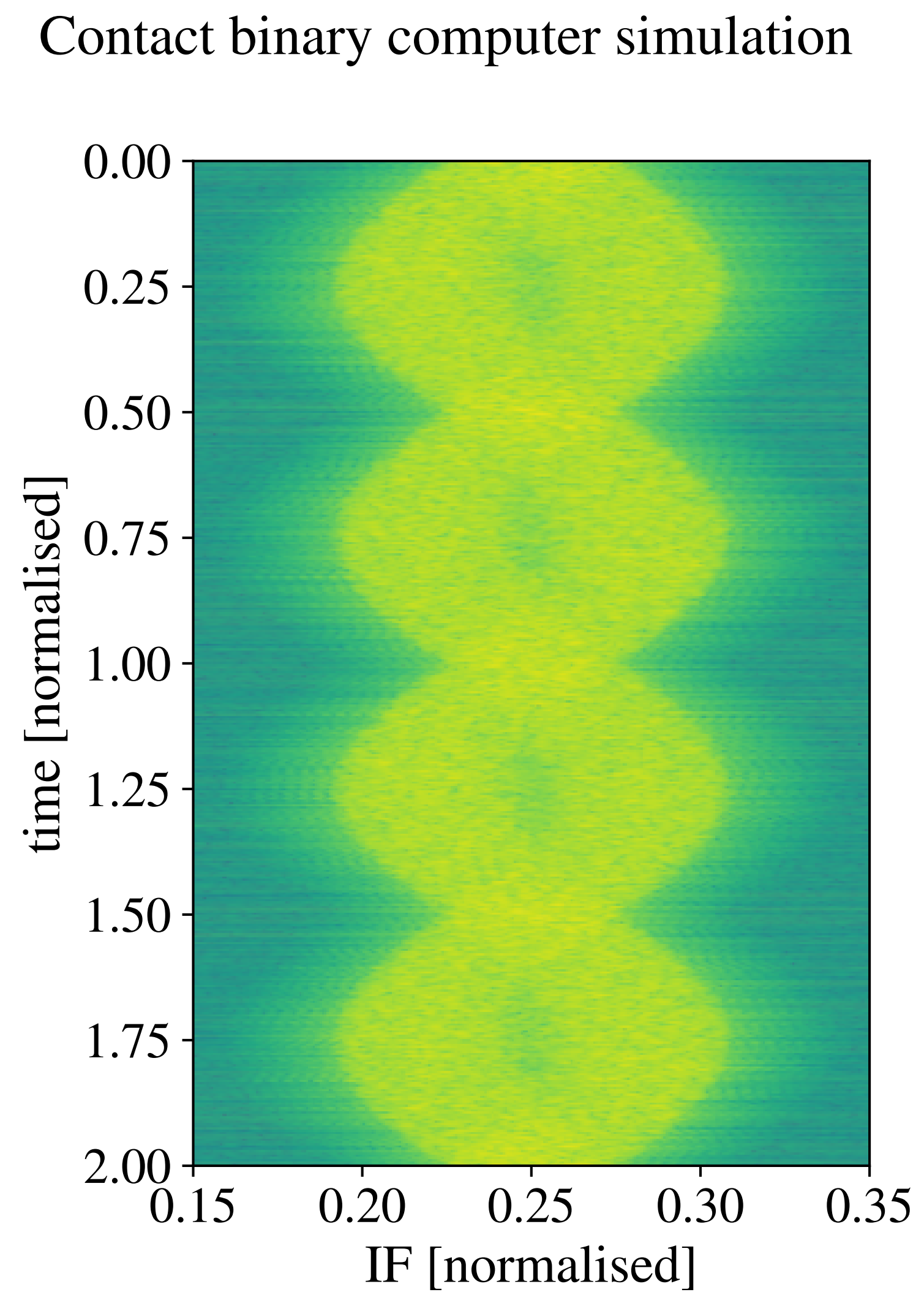

Figure 8:Waterfall of two revolutions of the simulated asteroid illustrated in Figure 6

The waterfalls in Figure 7 show two full revolutions of 2024 ON and indicate that the object has a secondary rotational axis. The simulated model shown in Figure 8 rotates around a single axis.

Computer correlations

Cross correlations, also referred to as the cross-ambiguity function, are used for typical radar signal processing approaches. These utilise matched filters where the correlation filter matches the expected waveform. Coherent communication receivers use similar filters. The filter which results in the largest cross correlation magnitude indicates the symbol or match of the received signal. For an asteroid we would be able to generate a matched filter that could match the received voltage signal. The large number of parameters that affect the signal backscattered of the asteroid make this a challenging problem.

Early results show that simple models can result in successful correlations, but point clouds with more than 100 parameters seem to not correlate well. Issues have been identified with the Matlab radar simulation toolbox.

Future work

This early study shows promising results. Further work is however required to investigate model based detection and characterisation. Future work includes:

- Apply principal component analysis methods to parameterise waterfalls similar to what is done in other micro Doppler analysis
- Investigate the requirements of parameter accuracy in further detail
- Incorporate polarimetric measurements in the simulations
- Investigate image processing methods on the waterfalls to limit the feature space

It is worth noting that most asteroid observations merely cover part of a rotation. This increases the difficulty of characterising the object.