Detecting Voyager 1 with the Allen Telescope Array

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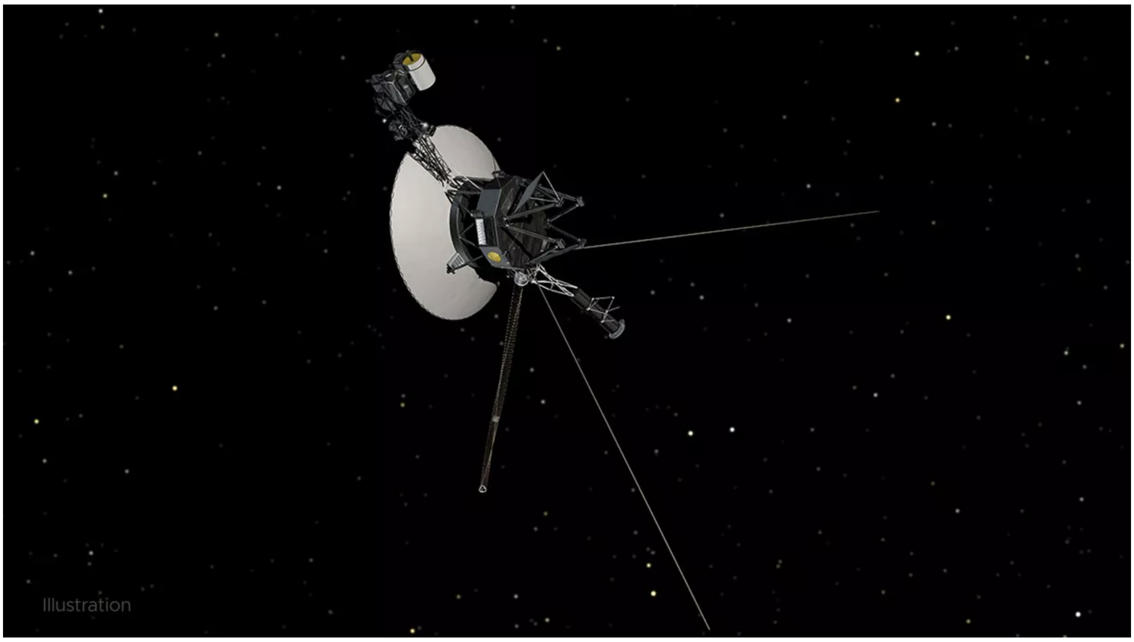

Figure 1: Artist's impression of Voyager 1 (Credit: NASA/JPL-Caltech)

1 Introduction

Almost 45 years after its launch, Voyager 1 is the farthest human-made object from our home planet. Located 156 AU, or 23.3 billion km, (at the time of writing) towards constellation Ophiuchus, voyager 1, along with its twin Voyager 2, is set on a mission to explore the boundaries of the heliosphere and the interstellar medium. Communications with the space probe is still underway using large dishes of the Deep Space Network, and commands/data are sent back and forth between earth and Voyager 1, most of the time at a rate of 40 bits per second.

This write-up describes the observation and detection of the Voyager 1 carrier signal using the Allen Telescope Array.

2 The refurbishment of the Allen Telescope Array

The Allen Telescope Array is an interferometer hosted at the Hat Creek Radio Observatory, some 5-hour drive north of San Francisco. The telescope comprises 42 fully-steerable 6.1m-diameter telescopes, of which 20 are fitted with wideband cryogenically cooled feeds. The feeds sense electromagnetic waves within the frequency range of 1 to 12 GHz. A refurbishment program has been underway since early 2020 aimed at upgrading the feeds along with the digital signal processing hardware and software. As part of the ongoing refurbishment, a new digital correlator and beamformer were tested and installed on the newly deployed ATA computer cluster.

A beamformer, in the receiving paradigm, is the process of coherently combining multiple receptors in order to maximize their sensitivity towards a particular spatial

Figure 2: The Allen Telescope Array (Credit: Joe Marfia)

direction. Beamforming is a very rich topic and I won't go into details here, but in short, a beamformer requires a calibration scheme to compute the instrumental delays and phases (with respect to a reference) of each station of an array. For the ATA beamformer system, we utilize a correlator – a software suit that multiplies signals from each pair of antennas together – to derive the needed delay and phase solutions.

3 Observations

On July 9th, 2022, the 20 available antennas of the Allen Telescope Array were used to observe the voyager 1 space probe. The coherent downlink frequency of voyager 1, in the x-band, is 8420.43 MHz (with a spectral width of 1 Hz), therefore the ATA was tuned at a center frequency of 8400 MHz. Ten minutes of data on a nearby quasar were collected using the correlator, and a delay/phase solution was derived for the beamformer. The antennas were then pointed at the position of voyager 1 as determined using the ephemeris obtained from the solar system dynamics NASA/JPL webpage (ICRF RA = 17:13:41.13, Dec = +12:23:49.9). Fifteen minutes of complex beamformed baseband data were then recorded and stored on disk.

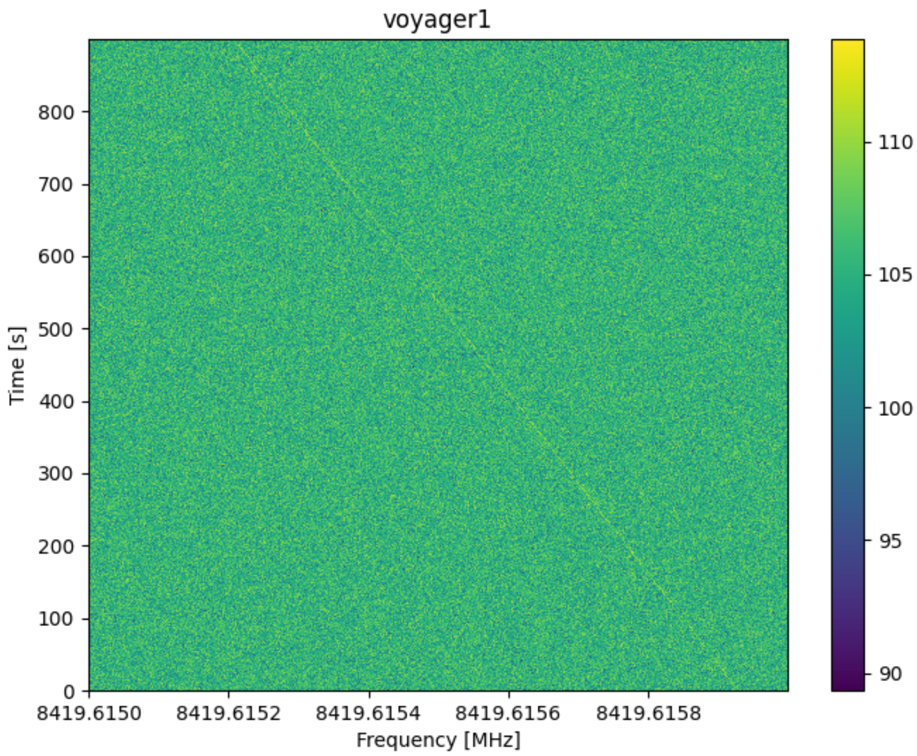

Figure 3: A waterfall (frequency vs time) plot displaying the Voyager 1 spacecraft as seen by the Allen Telescope Array. The color scale represents the flux density in units of dB. The narrowband signal is clearly seen drifting in frequency, as expected of a transmitter accelerating with respect to a receiver.

4 Data Analysis

A large FFT was applied to the recorded data to bring the spectral resolution to a value close to that of the spectral width of the carrier frequency. Due to the fact that a relative acceleration exists between earth and voyager 1, the received carrier frequency will inevitably be doppler shifted and drifting in time. The doppler shift was then calculated (special thanks to Danni Estévez), and a waterfall plot of the total intensity data was displayed. Figure 3 shows the dynamic spectrum of the voyager 1 downlink signal.

The data were de-doppler'ed at a drift rate of $\sim -0.84\,\mathrm{Hz/s}$, and a carrier-to-noise of 11.5 dB was measured in the recorded 900 second segment.

5 Link budget calculation

Voyager 1 is equipped with a $P_t = 22.4\,\mathrm{W}$ transmitter and it utilizes a $G_t = 48\,\mathrm{dBi}$ high gain directional antenna pointed straight at earth (to read more about Voyager's specification, see this). The spacecraft, at the time of writing, is at a distance of $r = 23.3 \times 10^9\,\mathrm{km}$ from earth.

Power density:

$$P_D = \frac{P_t \times G_t}{4 \times \pi \times R^2} = \frac{22.4 \times 10^{4.8}}{4 \times \pi \times (23.3 \times 10^{12})^2} = 2.07 \times 10^{-22}\,\mathrm{W.m^{-2}}$$

Next, we'll calculate the received power by the ATA beamformer. We use $N_{ant} = 20$ antennas in our observation, each antenna is 6m in diameter with an aperture efficiency of $\epsilon_A \sim 0.6$ in the X-band:

Collecting area:

$$A = N_{ant} \times \pi \times r^2 \times \epsilon_A = 339.3\,\mathrm{m}^2$$

Power received:

$$P = P_D \times A = 7.03 \times 10^{-20}\,\mathrm{W} = -161.53\,\mathrm{dBm}$$

Next, we'll calculate the ATA thermal noise:

$$N_0 = k_B \times T_{rec} \times BW = 1.38 \times 10^{-23} \times 120 \times 1 = 1.66 \times 10^{-21}\,\mathrm{W} = -177.81\,\mathrm{dBm}$$

The above assumes a receiver temperature of 120 kelvin at 8.2 GHz.

Finally, the expected carrier-to-noise ratio is:

$$C/N_0 = P - N_0 = 16.3\,\mathrm{dB}$$

6 Conclusion

The measured carrier-to-noise ratio in the 900s segment of our ATA data is $\sim 5\,\mathrm{dB}$ less than what is expected. This is due to many factors. Firstly, the Voyager 1 downlink polarization produced at X-band is circular, whereas the ATA feeds are linearly polarized. Receiving circular polarization on linear feeds would entail a 3dB reduction in C/N_0. Although synthesizing circular polarization using the ATA feeds is possible, it is beyond the scope of this work. Moreover, the Voyager 1 signal was only incoherently de-doppplered. In other words, the effect of doppler shifting within each of FFT channels was not corrected for. This will introduce some reduction in C/N_0. Finally, the beamformer was assumed to have perfect efficiency, which is not the case in real-world scenarios.

The detection of Voyager 1, the farthest human-made object, with the refurbished Allen Telescope Array is an excellent display of the telescope's capabilities and strengths, and a representation of the outstanding hard work put by the ATA team since the start of the refurbishment program in 2019.