Voyager 1 adventures

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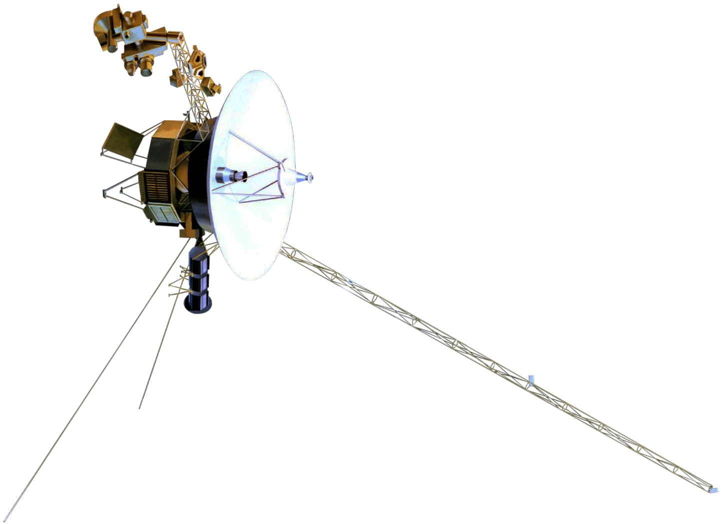
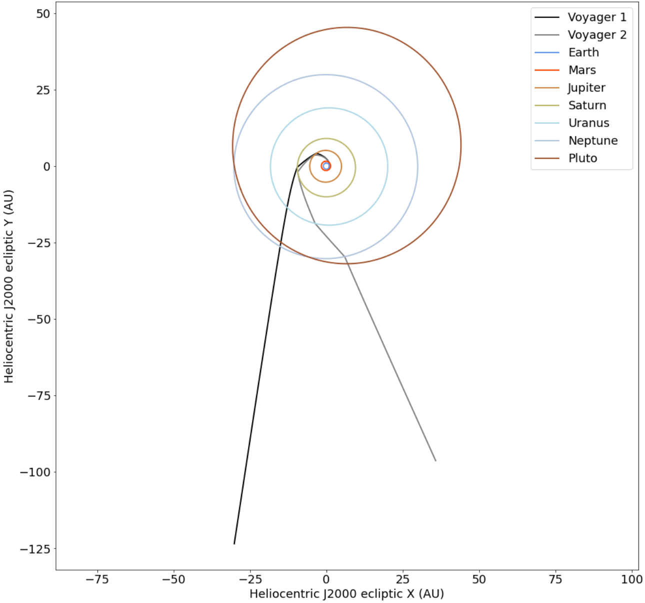
FOSDEM Free Software Radio devroom

The Voyager spacecraft



Voyager mission timeline

- 1977. Voyager 1 and Voyager 2 launch
- 1979. Voyager 1 and Voyager 2 at Jupiter
- 1980. Voyager 1 at Saturn
- 1981. Voyager 2 at Saturn
- 1985. Voyager 2 at Uranus
- 1989. Voyager 2 at Neptune
- 1990. Voyager 1 solar system “family portrait”
- 1998. Voyager 1 overtakes Pioneer 10. Becomes most distant spacecraft
- 2004. Voyager 1 enters heliosheath at 94 AU
- 2012. Voyager 1 enters interstellar space at 121 AU
- 2018. Voyager 2 enters interstellar space


Voyager 1
Voyager 2
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Pluto
50
25
0
−25
−50
−75
−100
−125
−75
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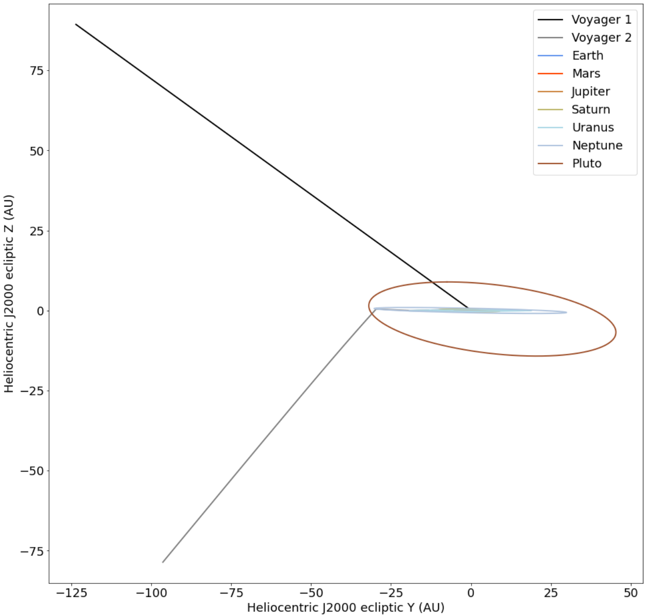
75
100
Heliocentric J2000 ecliptic X (AU)
Heliocentric J2000 ecliptic Y (AU)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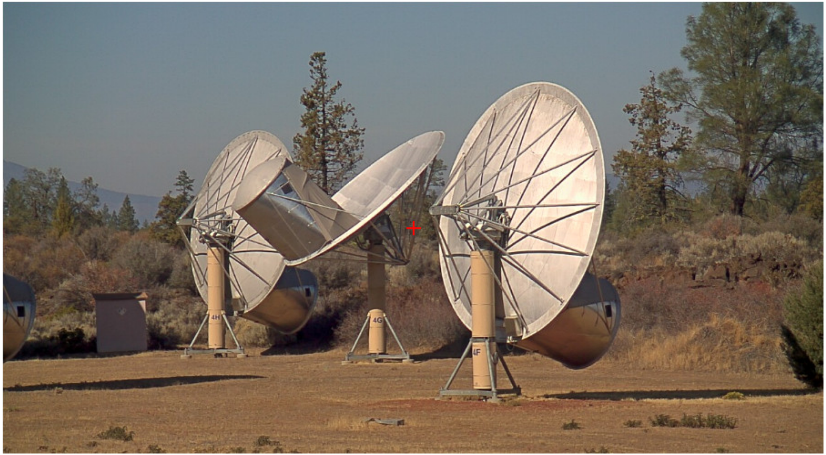
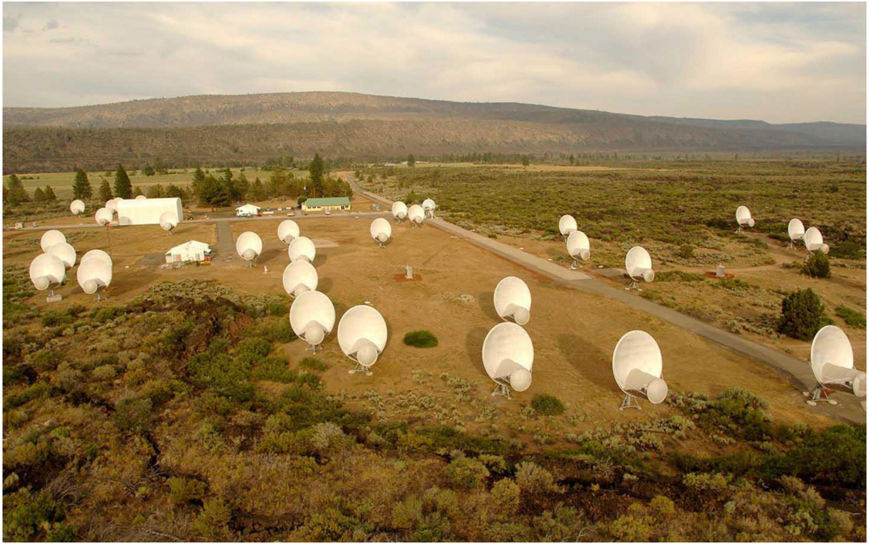
Adventure 1: detecting Voyager 1 with the Allen Telescope Array





GNU Radio testbed at ATA

- Frequency coverage of the telescope: 0.5 - 14 GHz
- Dual linear polarization
- Two USRP N32x with LO sharing
- Phase coherent and synchronized to 10 MHz and 1 PPS reference
- $\sim$700 MHz instantaneous bandwidth at 512 MHz IF into the USRPs
- Two polarizations from same antenna in each USRP
- Antennas selectable with a switch matrix
- Intel server with 40 Gb Ethernet

Detecting a weak spacecraft's signal

- NASA DSN needs a 70 m dish to receive data from Voyager 1; we have 6 m dishes at the ATA.
- The spacecraft signal has a residual carrier (a CW tone)
- Use a fine FFT resolution and integrate for long enough to detect this tone
- We need to correct for Doppler drift

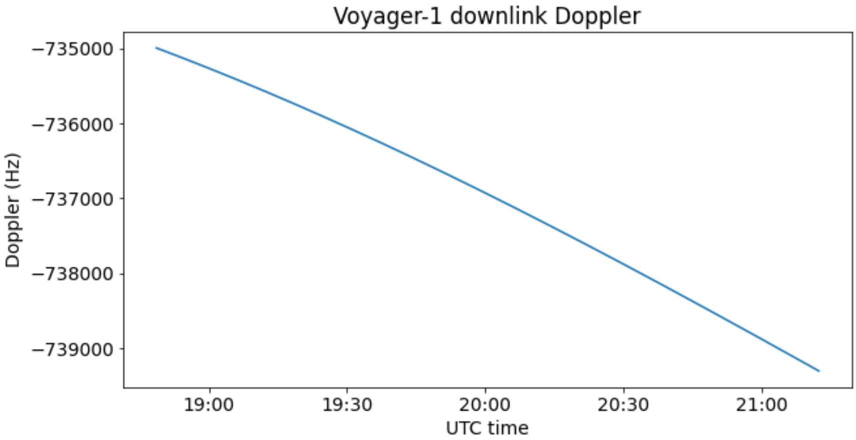
Observation set up

- Observation done on 2020-11-14 18:30 - 21:30 UTC
- Distance of Voyager 1 from Earth: 151.72 AU / 22697 million km
- Elevation 40 - 60 deg
- Use two antennas: 1a and 4g, with “old” feeds
- 4x 30 minute scans of Voyager 1, interleaved with 5 minute scans of a nearby quasar
- The quasar data was recorded in case we wanted to beamform the two antennas (but was not used)
- Spacecraft frequency is $\sim$8420.430 MHz, but there are $\sim$-700 kHz of Doppler
- Record at 8419.7 MHz, using 960 ksps IQ. Done with a GNU Radio flowgraph

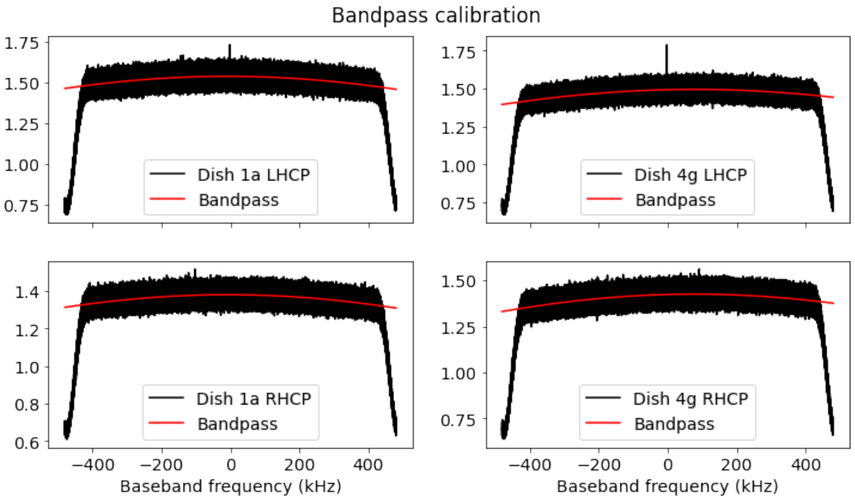
Post-processing

- Done in a Jupyter notebook with NumPy and Dask
- Grab ephemeris data from JPL HORIZONS using Astroquery (based on Nick Foster's code)
- Steps:
  1. Remove DC spike
  2. Normalize power on each channel (2x antennas, 2x polarizations)
  3. Form LHCP and RHCP polarizations (using calibration data from Tianwen-1 recorded earlier at 8431 MHz)
  4. Calculate Doppler correction with mHz precision: 8.6 seconds ephemeris from HORIZONS. Doppler linearly interpolated to 10 ms. Compute carrier phase every 10 ms. Linearly interpolate carrier phase to each sample.
  5. Correct for Doppler using this carrier phase
  6. FFT with 458 mHz resolution
  7. Integrate non-coherently each scan

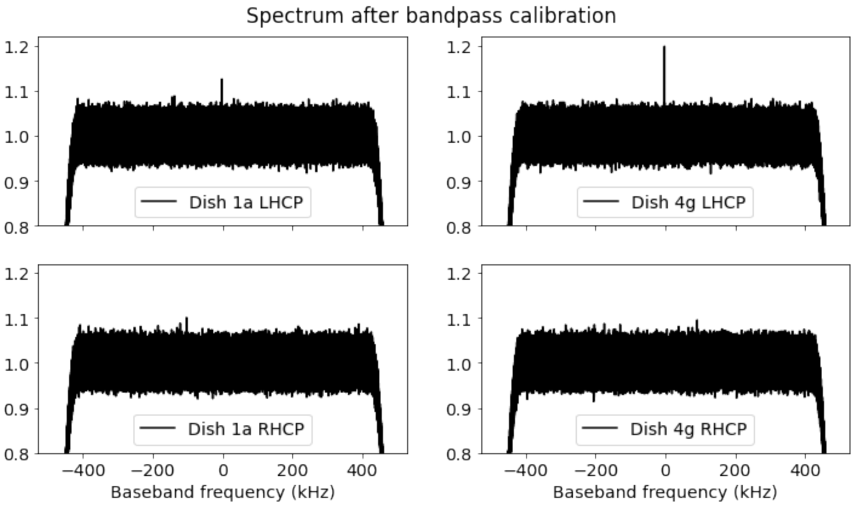
Doppler correction



Bandpass calibration

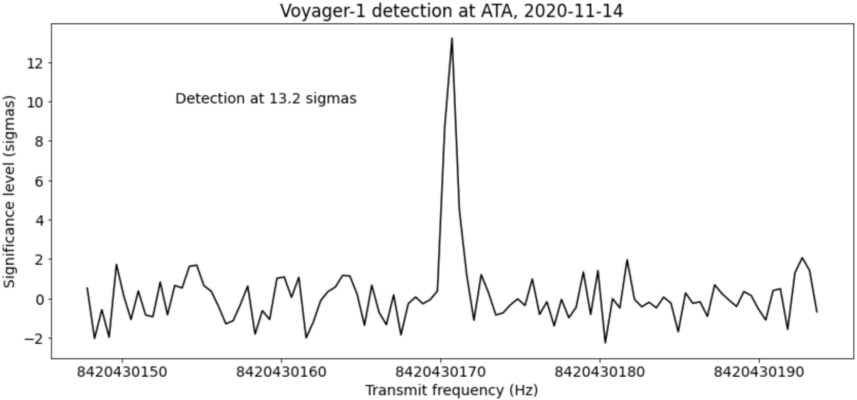


After bandpass calibration



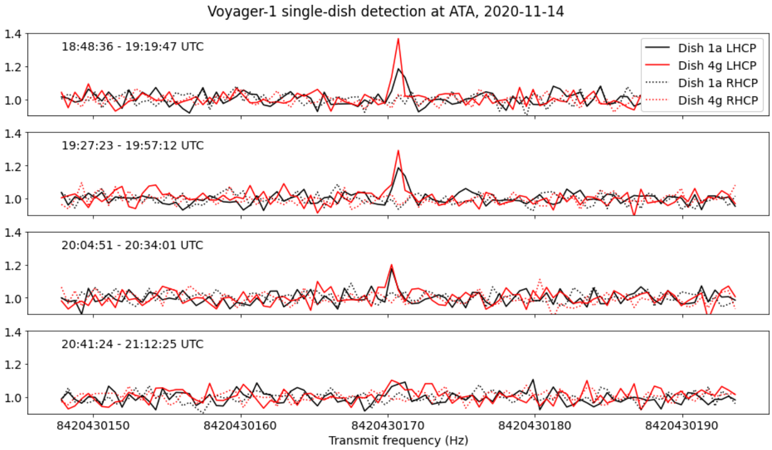
Detection statistics

Signal detected a few kHz away from the expected frequency, and with high confidence.
Data for both antennas added non-coherently:



Data for each scan

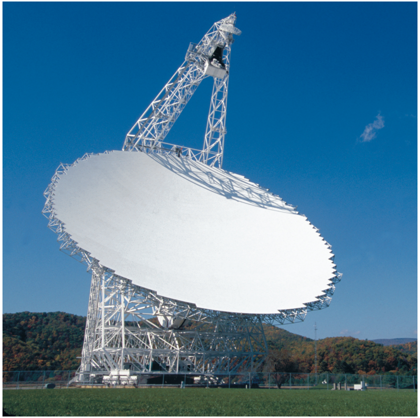
SNR estimates: -8.5 dB·Hz, -8.8 dB·Hz (1a), -6.4 dB·Hz, -6.7 dB·Hz (4g)



Takeaways

- Doppler correction and narrow FFT resolution are essential
- This also needs an accurate frequency reference on the receiver
- Compute the required integration length depending on your conditions. Maybe 5 minute as a minimum for ATA. Smaller stations will need hours.
- A lot of unexplained SNR variability, between antennas and over time
- Many things can go wrong. We tried a second time at ATA with a similar set up and didn't detect the signal.

Adventure 2: decoding Voyager 1 telemetry using Green Bank Telescope recordings



Breakthrough Listen recordings of Voyager 1

- Breakthrough Listen uses Green Bank Telescope and Parkes Telescope for SETI (also the optical APF at Lick Observatory)
- Sometimes records Voyager 1, to test their signal search algorithms (based on Doppler drift)
- Recordings from GBT in 2015
  `http://seti.berkeley.edu/opendata`
- Also recordings from 2020 (not yet available publicly)
- Recordings are in GUPPI format, using dual circular polarization
- This contains the output of a polyphase filterbank, with $\sim$3 MHz channels
- Since the signal from Voyager 1 fits in a single channel, we can just extract that channel as time-domain IQ data

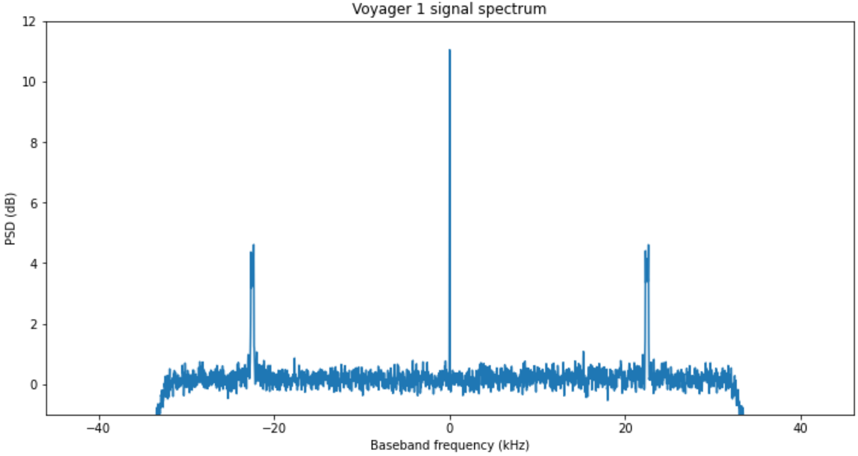
Voyager 1 telemetry modulation

- Residual-carrier phase modulation with telemetry BPSK-modulated onto a subcarrier (PCM/PM/PSK)
- Deviation 60 deg
- 22.5 kHz subcarrier
- 320 baud
- Voyager 1 predates the CCSDS standards
- $k = 7$, $r = 1/2$ convolutional code (sometimes known as "the Voyager code"). It uses the NASA-DSN convention, which is not the same as the CCSDS convention
- "Old-fashioned" syncword 0x03915ED3 rather than the modern CCSDS 0x1ACFFC1D (thanks to Richard Stephenson for pointing this out)
- 7680 bit frames (48 seconds long)

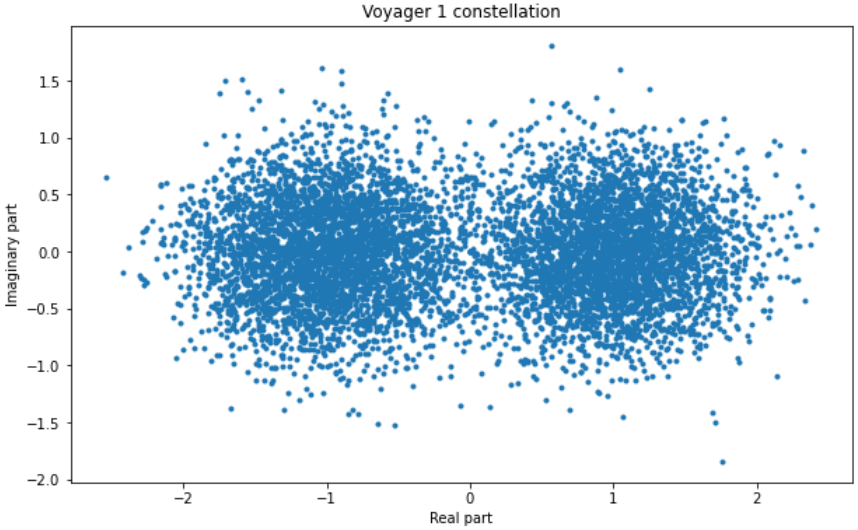
Voyager 1 recording from 2015

- Done on 2015-12-30
- SNR is relatively good
- Recording is only 22.57 seconds long (doesn't even contain a full frame!)
- Demodulation and Viterbi decoding in GNU Radio, also using some NumPy for open-loop demodulation

Signal spectrum

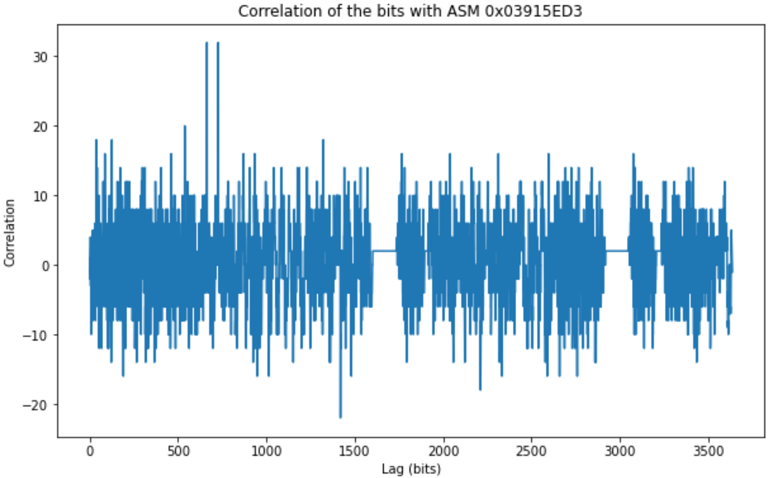


Constellation

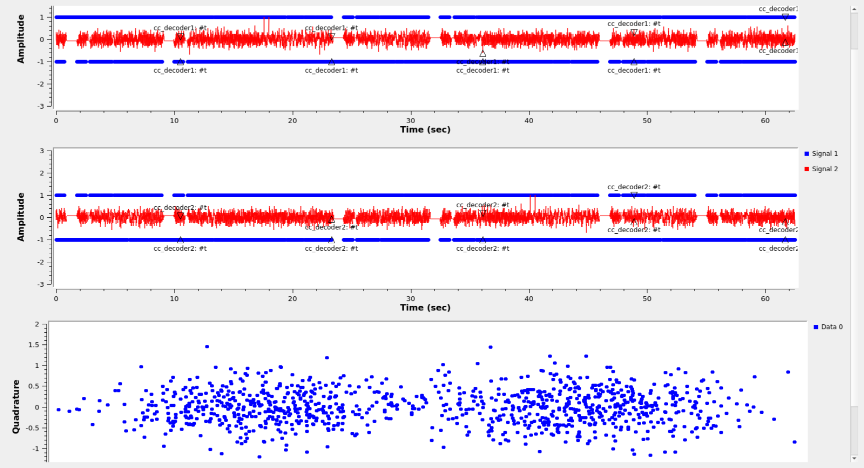


Finding the syncword

We are lucky and the recording contains the start of a frame, which has two repetitions of the syncword

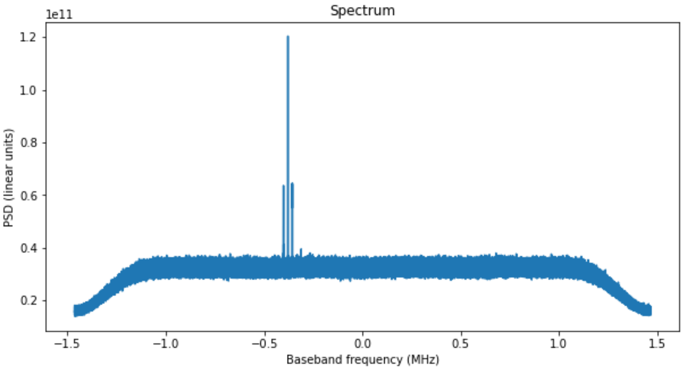


GNU Radio decoder in action



Voyager 1 recording from 2020

- Done on 2020-07-16
- 3 scans of 5 minutes each, interleaved with 5 minute scans on an “off” target
- Huge thanks to Steve Croft for giving me access to this data



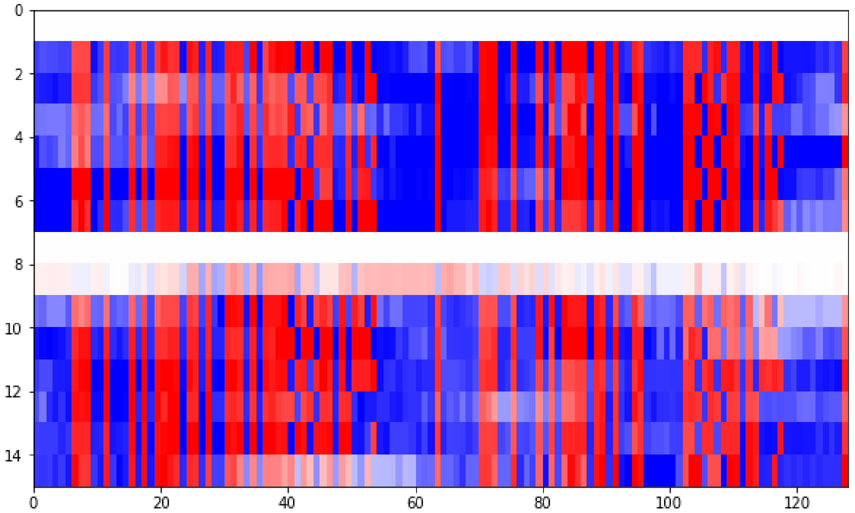
2020 recording analysis

- SNR is not as good as in the 2015 recording
- Large variability of SNR with time
- One of the 3 scans is impossible to decode due to too low SNR

Scan	Carrier C/N0 (dB)	Data Eb/N0 (dB)
11	23.74	6.33
13	20.49	3.13
15	23.21	5.90

- Use GNU Radio to demodulate, analyzing the SNR losses in each step
- There are still bit errors after Viterbi decoder $\Rightarrow$ use BCJR instead to give soft bits (much nicer for reverse engineering the data)

Soft bits organized in frames

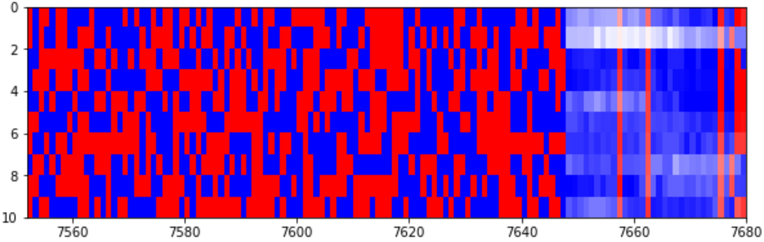


But wait, there is Reed-Solomon!

- I thought that there was only convolutional coding, because DSN people and some configuration files had told me so
- But some people pointed me to papers that strongly supported that Reed-Solomon was used after the Saturn encounter
- The explanation is that probably Reed-Solomon decoding is completely managed by the project, so the DSN doesn't care about it
- The Reed-Solomon code predates the CCSDS code. It is the most straightforward (255, 223) Reed-Solomon code that comes to mind, and has later been used in many applications.

Finding the Reed-Solomon code parameters

- Some details, such as what part of the frames constitutes a codeword, were not mentioned ⇒ some trial and error.
- The last 4 bytes of the frame are not part of the Reed-Solomon. The rest of the frame is 4 interleaved (239, 207) codewords.
- All the frames that were completely contained in the first and last recording could be decoded correctly.



References

- https://destevez.net/2021/02/voyager-1-single-dish-detection-at-allen-telescope-array/
- Nick Foster's work with a Voyager 1 recording with the ATA beamformer from 2010
  https://github.com/bistromath/voyager
- https://destevez.net/2021/09/decoding-voyager-1/
- https://destevez.net/2021/12/more-data-from-voyager-1/
- https://destevez.net/2021/12/voyager-1-and-reed-solomon/
- Voyager Space Flight Operation Schedule (SFOS)
  https://voyager.jpl.nasa.gov/mission/status/

Acknowledgements

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