Amateur decoding of deep space missions

Dr. Daniel Estévez (EA4GPZ / M0HXM)

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About the speaker

- Licensed since 2014 (EA4GPZ).
- Based in Madrid, Spain.
- Currently works as consultant in satellite communications.
- Blog with radio & space technical articles/experiments: `http://destevez.net`
- Best known for gr-satellites: a collection of GNU Radio decoders for amateur satellites.

Brief recap about deep space communications

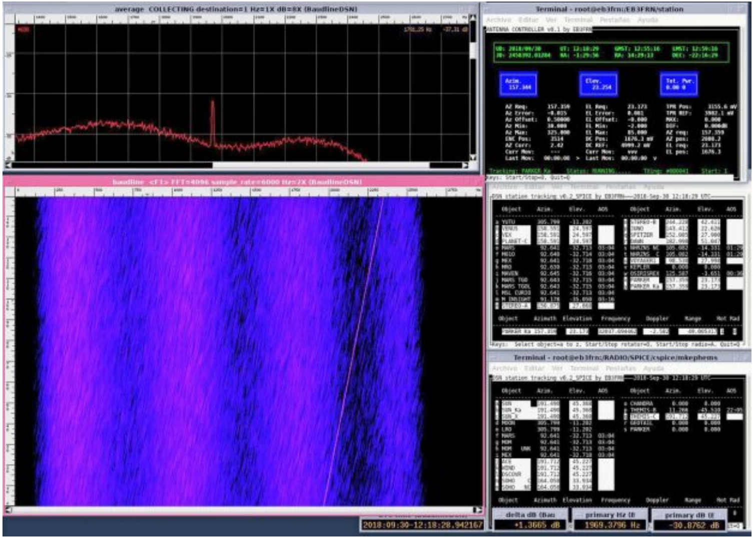
- RF signals are transmitted between spacecraft and Earth for: telemetry, telecommand and navigation.
- Typical downlink bands: S-band (2.2 GHz), X-band (8.4 GHz), more recently K_a-band (32 GHz) and K-band ($\sim$26 GHz, near space).
- Free space losses are huge. Large antennas used on ground (30m - 70m typical).
- Deep Space Networks operate with several sites distributed on Earth to give global coverage: NASA DSN (Madrid, Goldstone, Canberra), ESA Estrack deep space (Cebreros, New Norcia, Malargüe), China Deep Space Network...
- Standard protocols used often, to simplify inter-agency collaboration.
- Lots of documentation publicly available: CCSDS books, NASA Telecommunications Link Design Handbook.
- Ephemerides available online in NASA HORIZONS.
- DSN Now - NASA's eyes (currently under cybersecurity review).

Amateur DSN

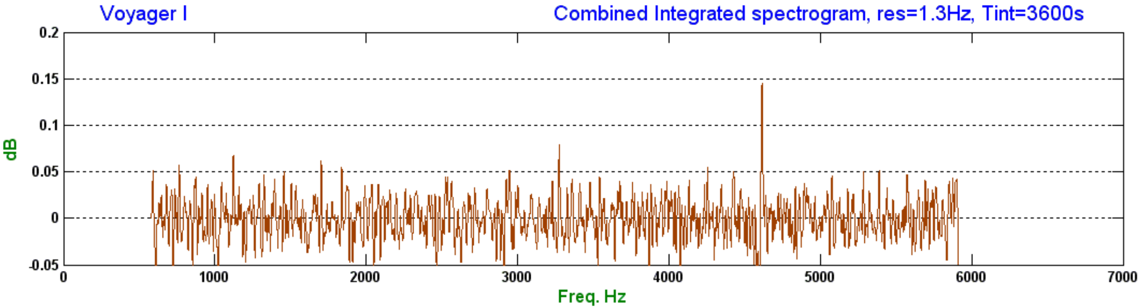
- Reception of deep space satellites by amateurs, typically with relatively small antennas.
- Traditionally, limited to the detection of the signal (residual carrier). Information cannot be decoded due to too low SNR.
- Activity popular within microwave enthusiasts: home-made 8.4 GHz receivers due to the lack of affordable off-the-shelf hardware.
- Typical achievements by the community: detection of signals as far as Jupiter or Saturn, some detections of Voyager 1.

Typical Amateur DSN station: Iban Cardona EB3FRN's 1.8m dish (here set up with 8.4 GHz feed).

Detection of Parker Solar Probe at 32 GHz by EB3FRN



Detection of Voyager-1 in 2006 by Luis Cupido CT1DMK.

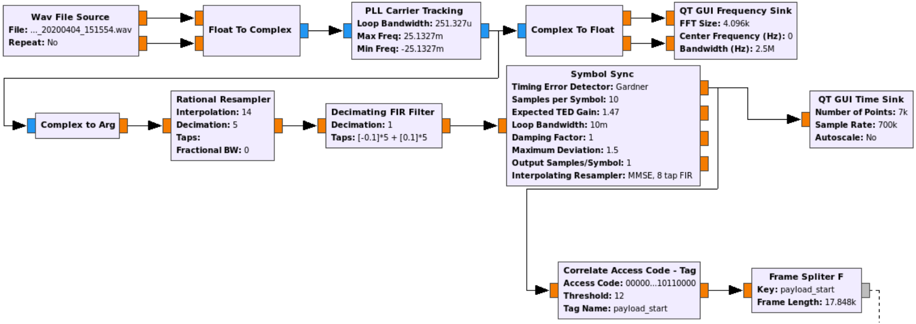


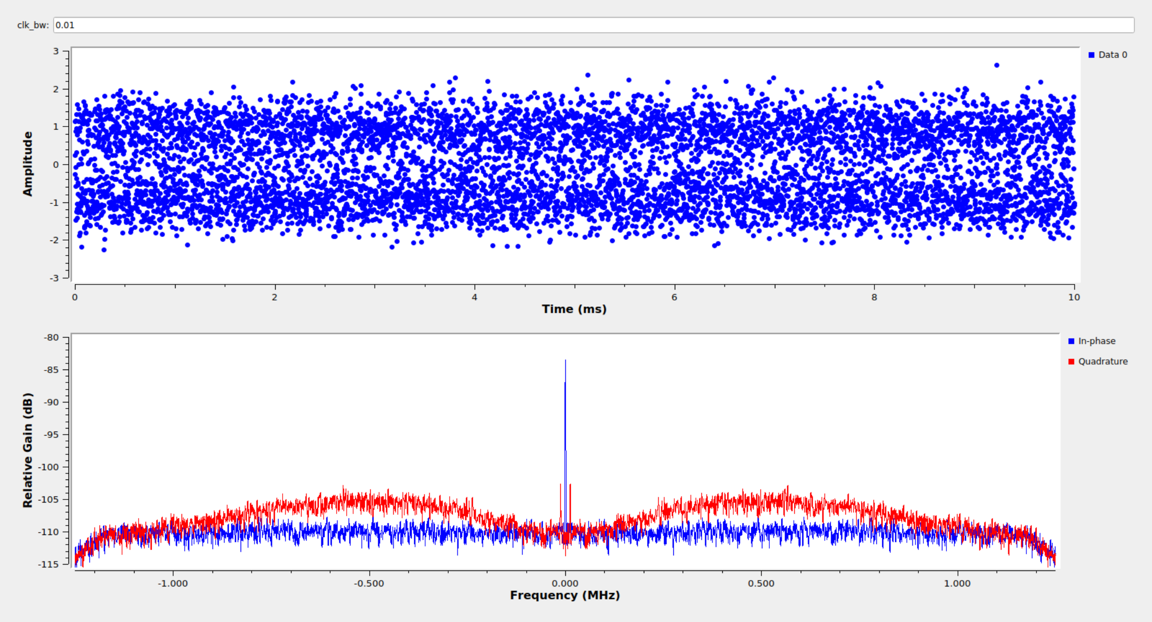
A new trend in Amateur DSN: decoding telemetry

- Shortly after launch and during Earth flybys the signal is strong enough to be demodulated and decoded.
- Many decoding opportunities over the last few years, due to a higher number of launches.
- Recent small lunar satellites are also good targets.
- Additional opportunities due to collaboration with larger sites:
  - Bochum Observatory, 20m antenna, managed by AMSAT-DL.
  - Dwingeloo radiotelescope, 25m antenna, managed by CAMRAS (only S-band).
  - The Allen Telescope Array, 42x 6.1m antennas, managed by SETI Institute.
- Increase of readily available software to decode these signals:
  - GNU Radio decoders by D. Estévez.
  - SatDump, by Aang23.
  - Decoders by r00t.cz.

Beginning of my deep space decoding activities

- February 2020, launch of ESA Solar Orbiter.
- April 2020, BepiColombo Earth flyby.
- Worked with recordings done by Paul Marsh M0EYT.
- More time for this new interest due to COVID19.

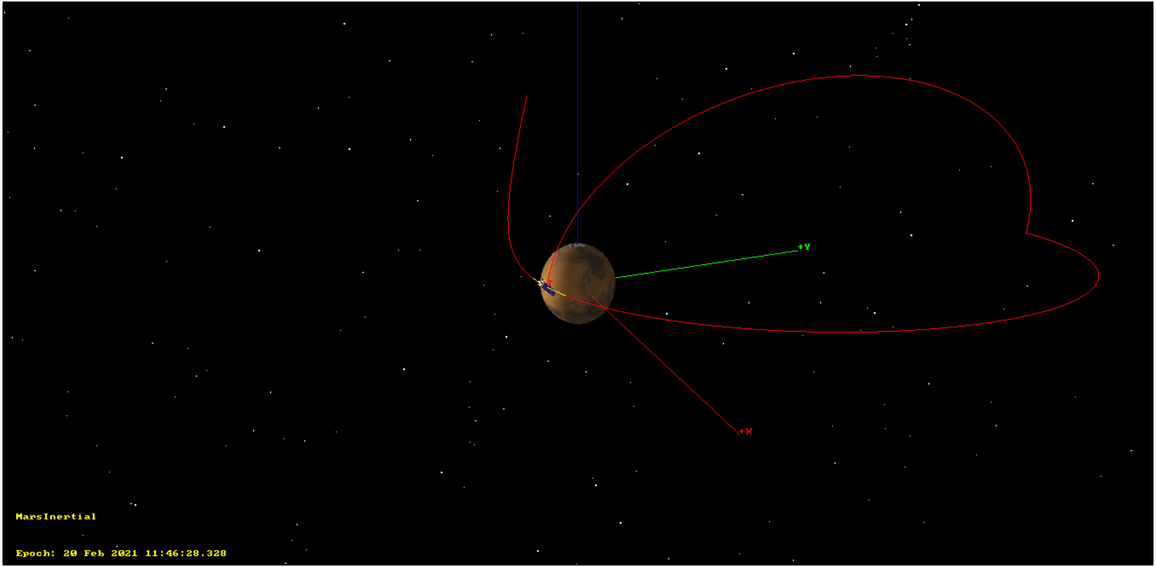



clk_bw: 0.01
Data 0
Amplitude
Time (ms)
In-phase
Quadrature
Relative Gain (dB)
Frequency (MHz)

Tianwen-1

- First Chinese mission to Mars, launched in July 2020 (same window as Emirates Mars Mission and Perseverance).
- Ephemerides not publicly available.
- I discovered that the spacecraft was transmitting its own position and velocity in the telemetry (heliocentric ICRF cartesian state vector).
- This allowed us to make our own ephemerides and continue tracking with the Bochum 20m antenna.
- The ephemerides were published in HORIZONS, thanks to Jon Giorgini.
- Huge community interest in tracking the operations of this mission. YouTube livestreams by AMSAT-DL on key events.
- Bochum continues tracking Tianwen-1 daily and collecting telemetry.

GMAT simulation of Mars orbit injection and plane change.

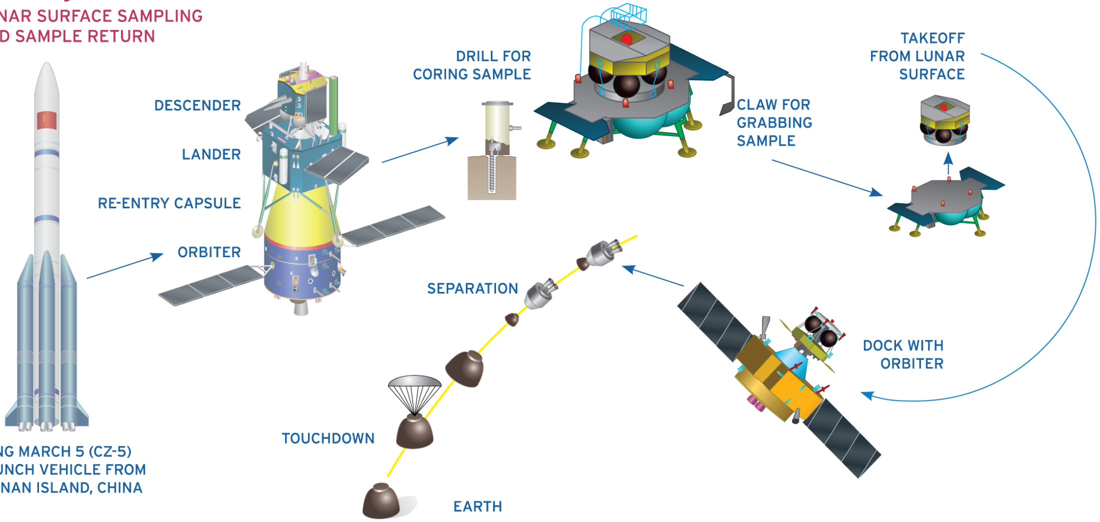


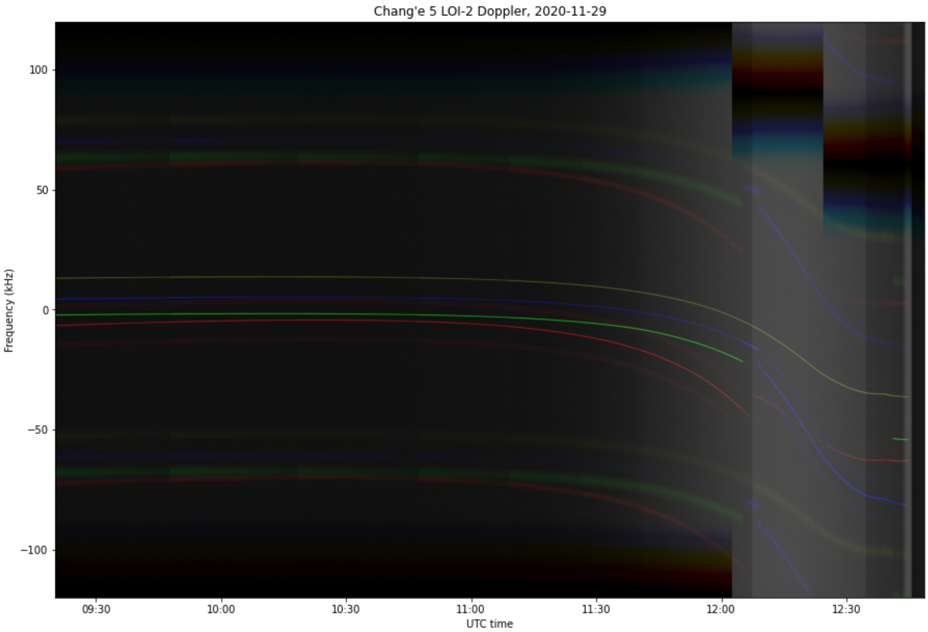
Chang'e 5

- Chinese lunar sample return mission, Nov - Dec 2020.
- Tracked the mission events by looking at changes in the RF signals and telemetry.
- Ephemerides not publicly available. Telemetry didn't include spacecraft position.
- Made some crude orbit determination using right ascension and declination data from Allen Telescope Array and optical observations.
- Studied signal polarization to try to get information about spacecraft attitude.

Chang'e-5

LUNAR SURFACE SAMPLING
AND SAMPLE RETURN





Chang'e 5 LOI-2 Doppler, 2020-11-29
Frequency (kHz)
100
50
0
−50
−100
09:30
10:00
10:30
11:00
11:30
12:00
12:30
UTC time

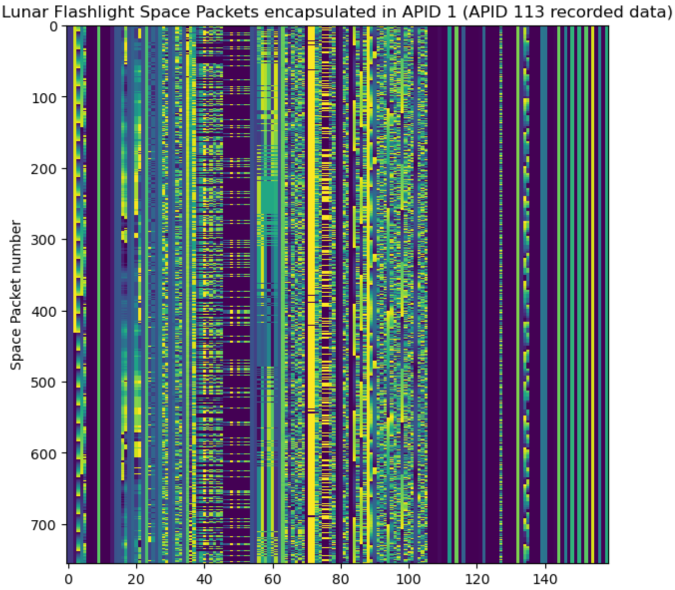
List of spacecraft decoded (many recordings are publicly available)

- ESA Solar Orbiter
- BepiColombo
- Emirates Mars Mission (Hope), Tianwen-1, Mars 2020 (Perseverance)
- Chang’e 5
- Voyager-1
- Lucy
- DART
- Queqiao (Chang’e 4 relay satellite)
- JWST
- KPLO (Danuri)
- STEREO-A
- INTEGRAL
- Artemis I: Orion, LunaH-Map, EQUULEUS, ArgoMoon
- Hakuto-R M1, Lunar Flashlight

Interpretation of telemetry data

- Up to the link layer, all the protocol stack is usually CCSDS standard.
- The formatting of telemetry frames is custom for each mission, and not publicly documented.
- Interpretation (reverse engineering) of the telemetry is usually difficult: we don't know what data is transmitted, or how it is encoded.
- Sometimes it's possible to understand certain patterns in the data, or even find exactly how the data is formatted.
- ADCS information seems one of the most feasible to interpret succesfully (so far, managed for Tianwen-1, LunaH-Map, Hakuto-R M1 and Lunar Flashlight). Finding 4 numbers with constant sum of squares strongly suggests unit quaterions.

Raster maps usually help:



Conclusions

- Decoding of telemetry data is a relatively new activity in Amateur DSN.
- It provides new technical challenges and things to learn.
- Combined with traditional signal detection and Doppler tracking, it can give amateurs more information about a mission.
- There is more to explore: reception and analysis of navigation signals (sequential & PN ranging, DOR tones).