Amateur Decoding of Deep Space Missions

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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 (usually).
- DSN Now and ESTRACKnow (live DSN status).

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.

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.
- An increasing number of Moon missions lately.
- Recent inferior conjunction of STEREO-A.
- 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 Alan Antoine F4LAU.
  - Decoders by r00t.cz.

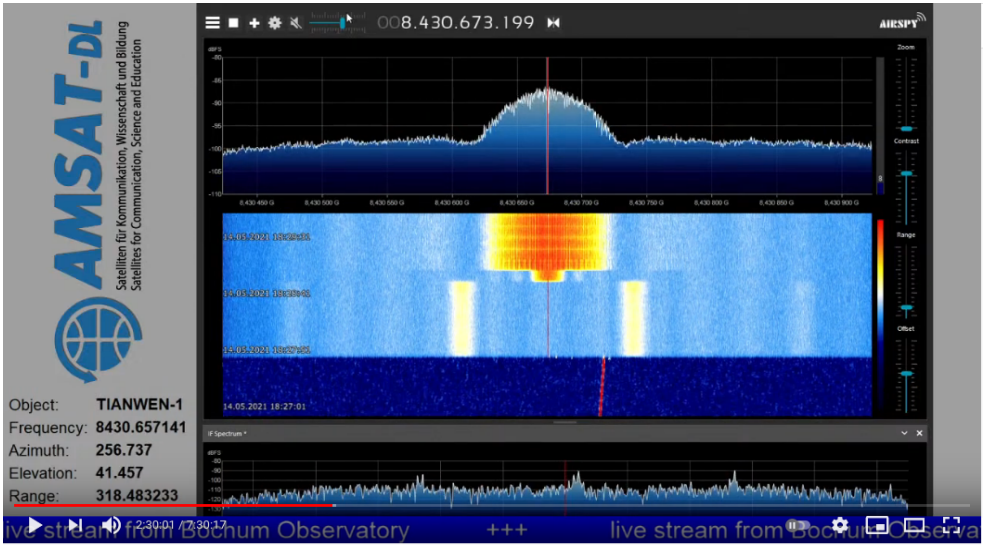
My involvement in deep space decoding

- Started at the beginning of 2020, with some ESA Solar Orbiter and BepiColombo recordings by Paul Marsh M0EYT.
- Made some GNU Radio decoders for these.
- In July 2020, Tianwen-1 launched to Mars. Huge tracking project with AMSAT-DL and Bochum.
- Continued decoding and blog posting about most deep space missions launched since then.

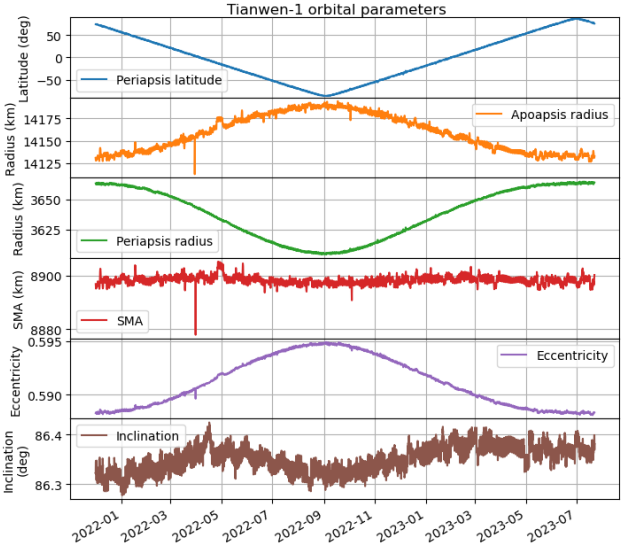
Tianwen-1

- Chinese Mars orbiter, lander and rover.
- Key dates:
  - July 2020, launch.
  - February 2021, Mars orbit injection.
  - May 2021, Zhurong rover landing.
  - November 2021, remote sensing orbit.
- Orbit information not public, but we found it in the telemetry.
- Bochum has been receiving some telemetry almost daily since the beginning of the mission, and until the present date.
- Tracked the mission with as much detail as possible.
- AMSAT-DL's YouTube livestream covering key events in the mission.
- Paper with Mario DL5MLO and Peter DB2OS published in GRCon21's proceedings: Deep space reception of Tianwen-1 by AMSAT-DL using GNU Radio.

YouTube livestream during Zhurong's landing



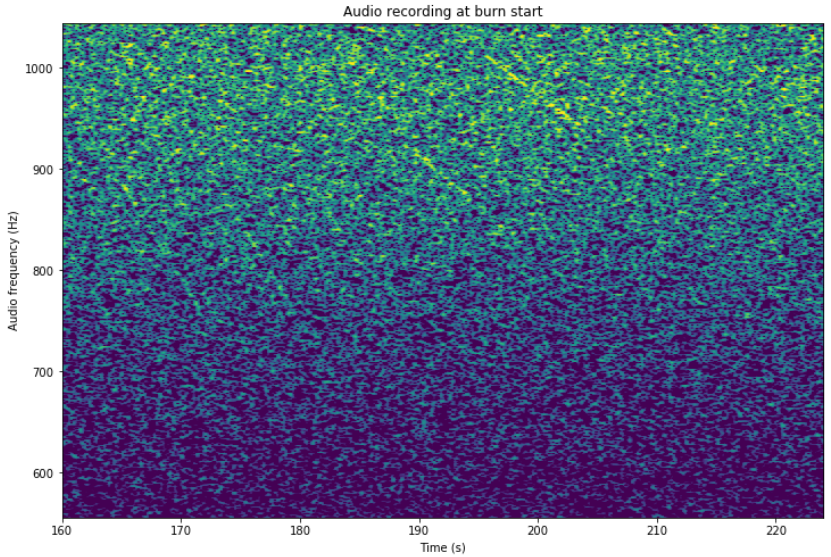
Tianwen-1's remote sensing orbit



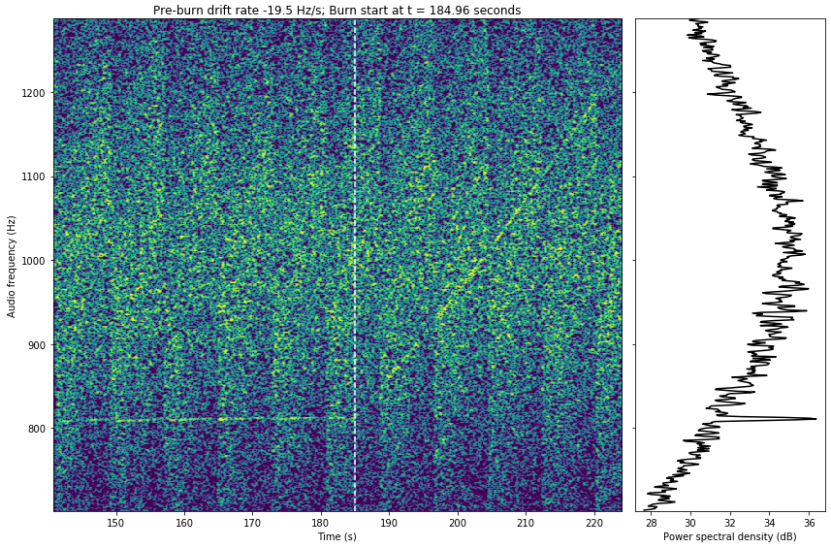
Emirates Mars Mission Mars orbit injection

- Emirates Mars Mission (Hope) launched in July 2020 (same launch window as Tianwen-1 and Mars 2020 Perseverance).
- AMSAT-DL livestreamed the Mars orbit injection in February 2021.
- The audio from the livestream can be used for Doppler analysis.
- But this is cumbersome. Recording IQ data would be much better!

Waterfall of livestream audio

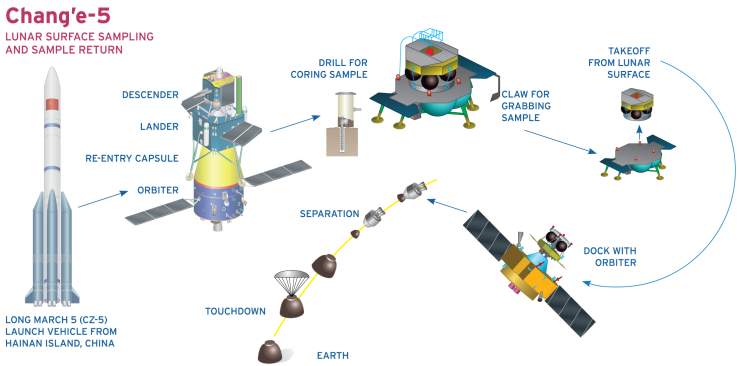


After fixing the sawtooth Doppler correction and correcting for drift



Chang'e 5

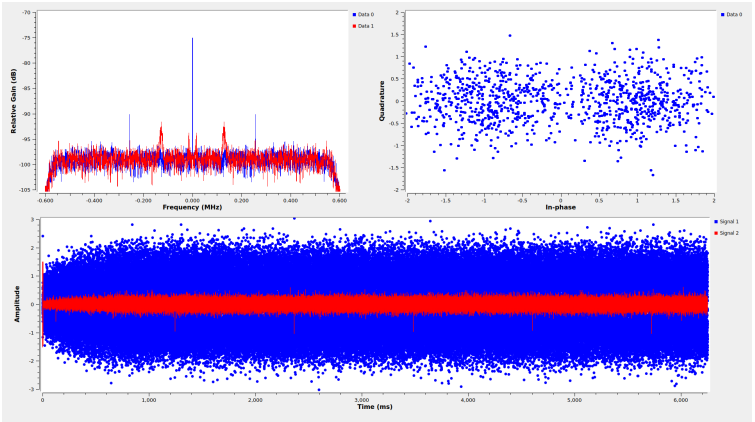
- Chinese lunar sample return mission (December 2020).
- Stack of four spacecraft transmitting different signals: orbiter, re-entry capsule, lander, descender.
- Tracked mainly with the Allen Telescope Array.
- Bochum received some 5 Mbps data from the lander on the lunar surface at X-band.



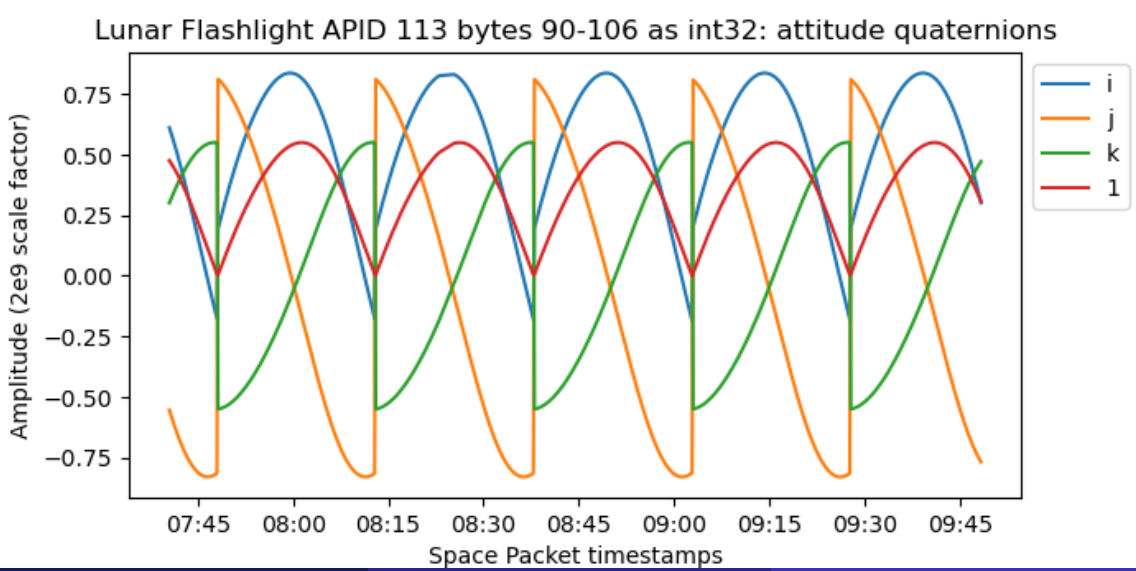
Hakuto M1 and Lunar Flashlight

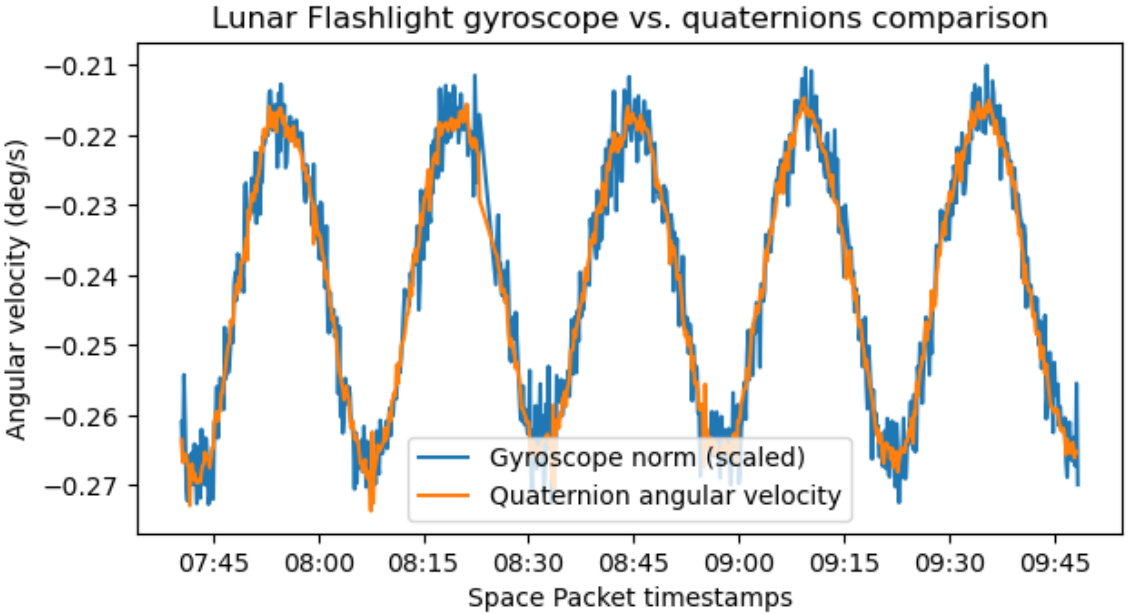
- Launched together to the Moon on December 2022 (one month after Artemis I).
- Both received by Bochum in the days following launch.

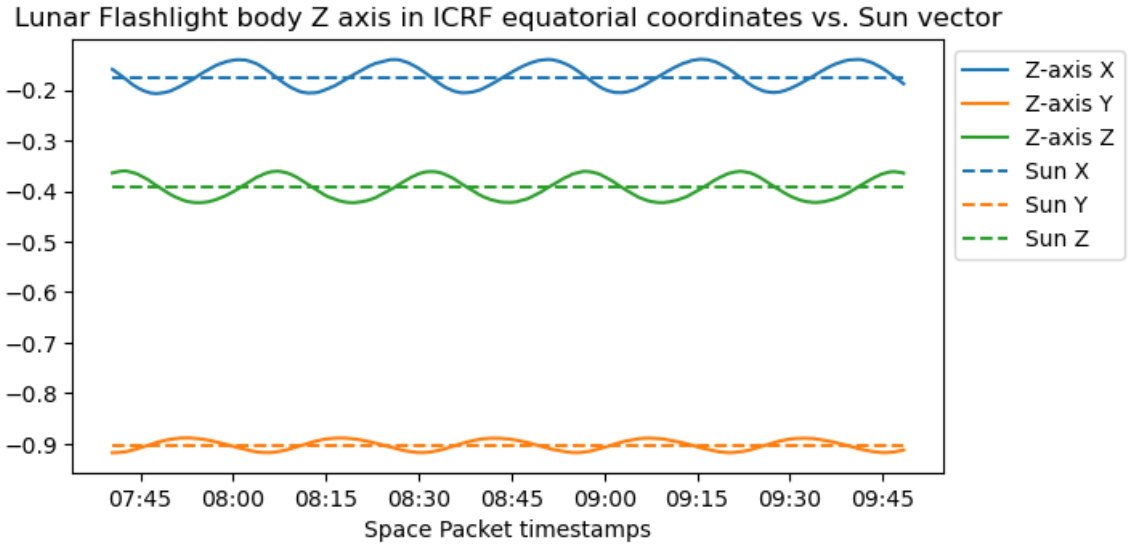
GNU Radio decoder for Hakuto M1:



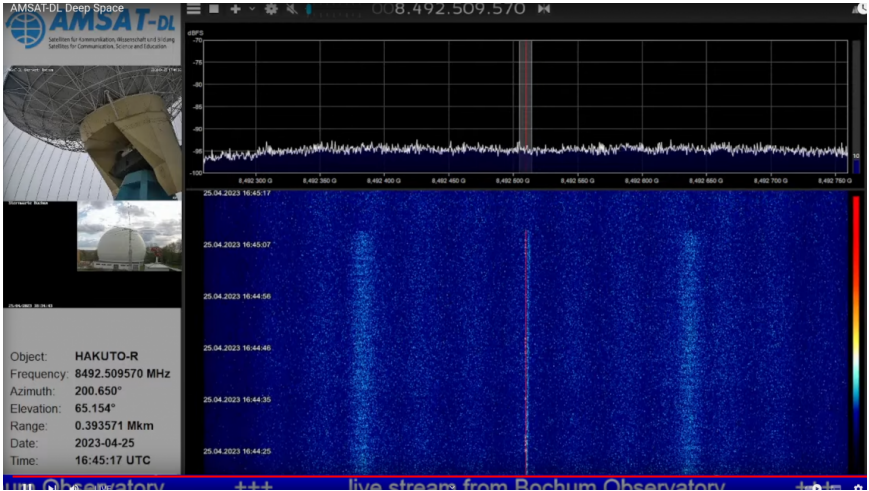
Attitude quaternions for Lunar Flashlight




Lunar Flashlight gyroscope vs. quaternions comparison
Angular velocity (deg/s)
−0.21
−0.22
−0.23
−0.24
−0.25
−0.26
−0.27
Gyroscope norm (scaled)
Quaternion angular velocity
07:45
08:00
08:15
08:30
08:45
09:00
09:15
09:30
09:45
Space Packet timestamps


Lunar Flashlight body Z axis in ICRF equatorial coordinates vs. Sun vector
−0.2
−0.3
−0.4
−0.5
−0.6
−0.7
−0.8
−0.9
07:45
08:00
08:15
08:30
08:45
09:00
09:15
09:30
09:45
Space Packet timestamps
Z-axis X
Z-axis Y
Z-axis Z
Sun X
Sun Y
Sun Z

Hakuto M1 crashing on the Moon (April 2023)



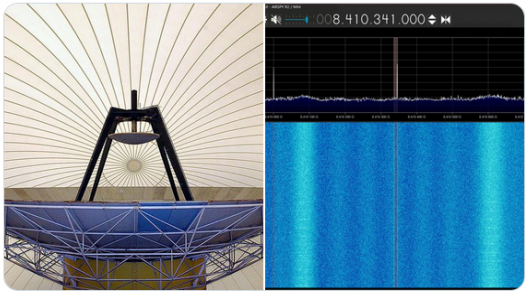
Report with Iban EB3FRN, Peter DB2OS, Edgar DF2MZ and James G3RUH

A Sign in Space (May 2023)

- Art project by Daniela de Paulis, in collaboration with SETI Institute, ESA and INAF.
- Transmission of a simulated alien message from ESA TGO Mars orbiter.
- X-band signal recorded with Green Bank Telescope (100m dish), Medicina telescope (32m dish), and the Allen Telescope Array (20x 6.1m dishes).
- Raw IQ recordings published for the public to extract and interpret the message (interpretation still ongoing).
- Exposure to deep space communications for a much wider audience.
- Bochum and RAEGE 13.2m dishes in Yebes and Santa Maria also joined at short notice.

AMSAT-DL ✓
@amsatdl

We are happy to inform that we recorded 10GB of IQ data during the @asigninspace @danieladepaulis @ESA_TGO live event signal with the 20m dish @SternwarteBO and that we received most of the message with good SNR to decode. Thanks to @ea4gpz who checked the recording using the same procedure as for the other telescopes. Only a few frames failed to be decoded. The recording started a few minutes after the beginning of the message reception. Almost all the message can be recovered from the Bochum Observatory recording, except for a few small pieces due to the lost frames, and a small part at the beginning. Dani is currently working on trying to improve the decoder to see if he can get to zero lost frames.



5:21 PM · May 27, 2023 · **20.2K** Views

STEREO-A inferior conjunction

- This summer, STEREO-A has been much nearer to Earth for the first time since launch.
- Possible to decode the 633 bps space weather beacon with small stations (60cm dish).
- Receiving this beacon is Bochum's "day job".
- Many amateurs worldwide have joined this activity.
- Obtain sun images thanks to some reverse-engineering by Alan F4LAU and Scott VE7TIL.
- Global collection of decoded data led by Scott VE7TIL.

Animation of one solar day worth of data

Outlook

- These are exciting times for deep space mission tracking.
- More exciting times are coming (recent news that NASA DSN is under pressure from growing demand).
- Large facilities such as Bochum play a central role in amateur tracking.
- A lot of dedication is needed to track these missions. Some missed opportunties due to lack of operators. More people involved and/or automation needed.
- Try to record data in the rawest format possible (often IQ data), to allow for more powerful analysis.
- Share the data. Share observation details.