National Aeronautics and Space Administration

Illuminating spin state evolution of cis-lunar and geosynchronous satellites with DSN X-band radar

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Objectives: Our primary objective was be to perform a series of follow-up DSN X-band bi-static radar experiments on retired GEO satellites to extract their spin periods and poles. These will be compared to our previous estimates to better understand how inactive satellite spin states evolve. The defunct GEO satellites will be used to determine to impact of solar radiation torques, via the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect, to the spin evolution. Finally, we will extend the investigation into the important cis-lunar regime where, due to the much reduced SNR, spin state extraction will be a challenge.

Background: In 2019 and 2020, we conducted a series of successful bi-static Doppler radar demo with DSN 34m antennas to estimate the spin periods and spin vectors (poles) of four inactive geosynchronous satellites over time. The rich data set showed detailed satellite features with indications of uniform rotation vs. non-principal axis tumbling.[1] Further analysis yielded spin periods and spin vectors with significant evolution over time[1] consistent with dynamical modeling of solar radiation torques.[2] Modeling suggests that inactive satellite poles evolve significantly too, in some cases tracking and precessing about the time-varying sun direction.[2] However, unambiguous pole measurements are needed to validate this possible pole motion. Dynamical modeling indicates that the angle between the pole and sun direction largely drives spin state evolution.[2] Estimating and predicting inactive satellite spin states is important for spacecraft anomaly resolution, active debris removal, satellite servicing, and broader space situational awareness. Radar echo SNRs depend on the satellite spin period, pole direction, and attitude-dependent radar cross section, resulting in SNR variations of several orders of magnitude for a given target.[3] This is particularly relevant for *cis-lunar radar tracking* efforts where the large relative distances and resulting low SNRs pose a significant challenge for target detection

Approach and Results:

For this work, we observed both uniformly rotating and tumbling defunct GEO satellites and rocket bodies with Deep Space Network (DSN) antennas at NASA's Goldstone Deep Space Communications Complex in California. Building on our earlier study [1,4,5], we first revisit the previously observed GOES 8-12 satellites to compare spin periods/pole directions and gain insight about their ongoing evolution. This will help us better understand how YORP drives defunct satellites spin states. We then present radar observations of two rocket bodies, the first near GEO and the second in a highly elliptic orbit.

Two 34 meter DSN antennas were used in a bi-static configuration with one antenna transmitting and the second receiving. The transmitted signal consisted of continuous wave carrier at X-band. Reflection of the signal off of the rotating target and back to the receiving antenna yielded time-varying Doppler spectra. Each target was observed periodically over the course of several hours to sample different viewing geometries. The targets were observed in this manner on a number of days in early May 2021. Typical Doppler echoes for GOES 8 and GOES 9 are provided in Figures 1 and 2 respectively and Doppler echoes for GOES 11 and 12 echos are provided in Figures 3 and 4 respectively. Comparison of the extracted spin rate of GOES 9 from May1'st to May 9'th shows an increase in the procession period from $P_{\bar{\phi}} \approx$ 715 s $\text{to } 724\,s$. This shows that the satellite spin rate increased even during this short span of time. The near Cis-lunar object Titan 3C, a Transtage rocket body at a range of ~118,000 km, was observed with echos shown in Figure 5.

In this work, Doppler radar and optical light curve observations were used to estimate the spin periods and pole directions of both uniformly rotating and tumbling debris objects near and above GEO. Doppler echoes obtained for the Titan 3C Transtage at a range of 118,000 km demonstrate that the 34 m Deep Space Network antennas can observe sizeable targets in near cislunar space. These observations further demonstrate the spin state diversity and continued evolution of the defunct GOES 8-12 satellites. Most notably, GOES 8 remains captured in a 5:1 tumbling period resonance with an evolving spin rate, while GOES 12 spun up rapidly from Dec. 2019 to May 2020. *These findings are consistent with the GOES satellite spin states being driven primarily by solar radiation torques.*

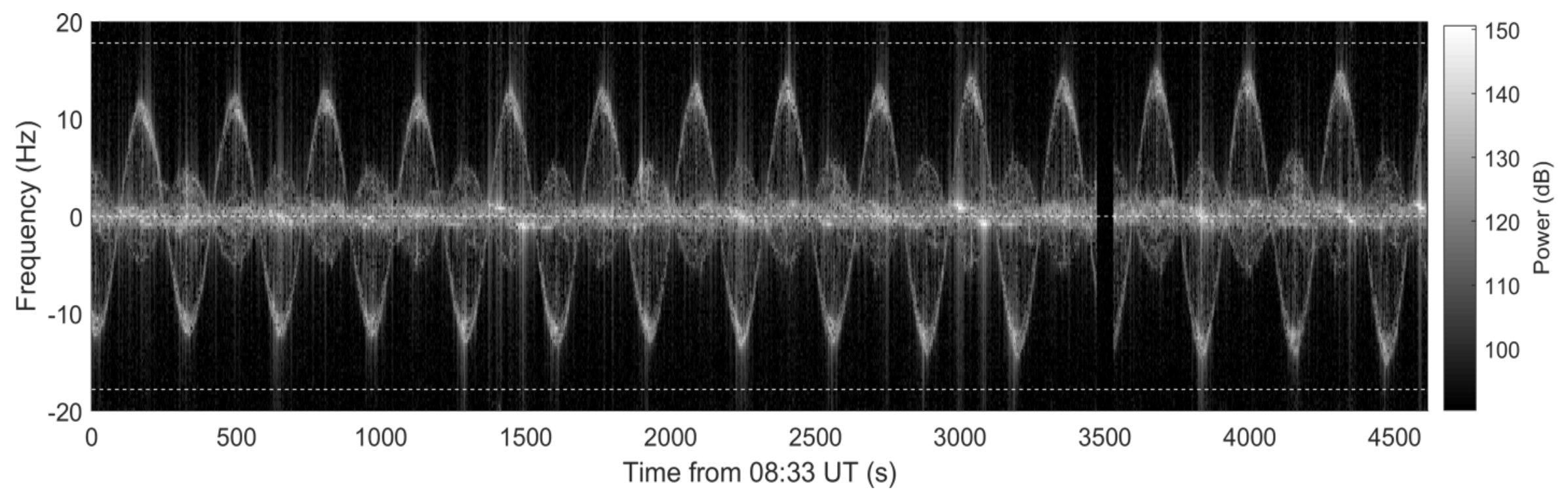

Figure 1. May 1, 2021 GOES 8 Doppler echoes ($P_{\bar{\phi}} \approx$ 318 s, 5.3 min)

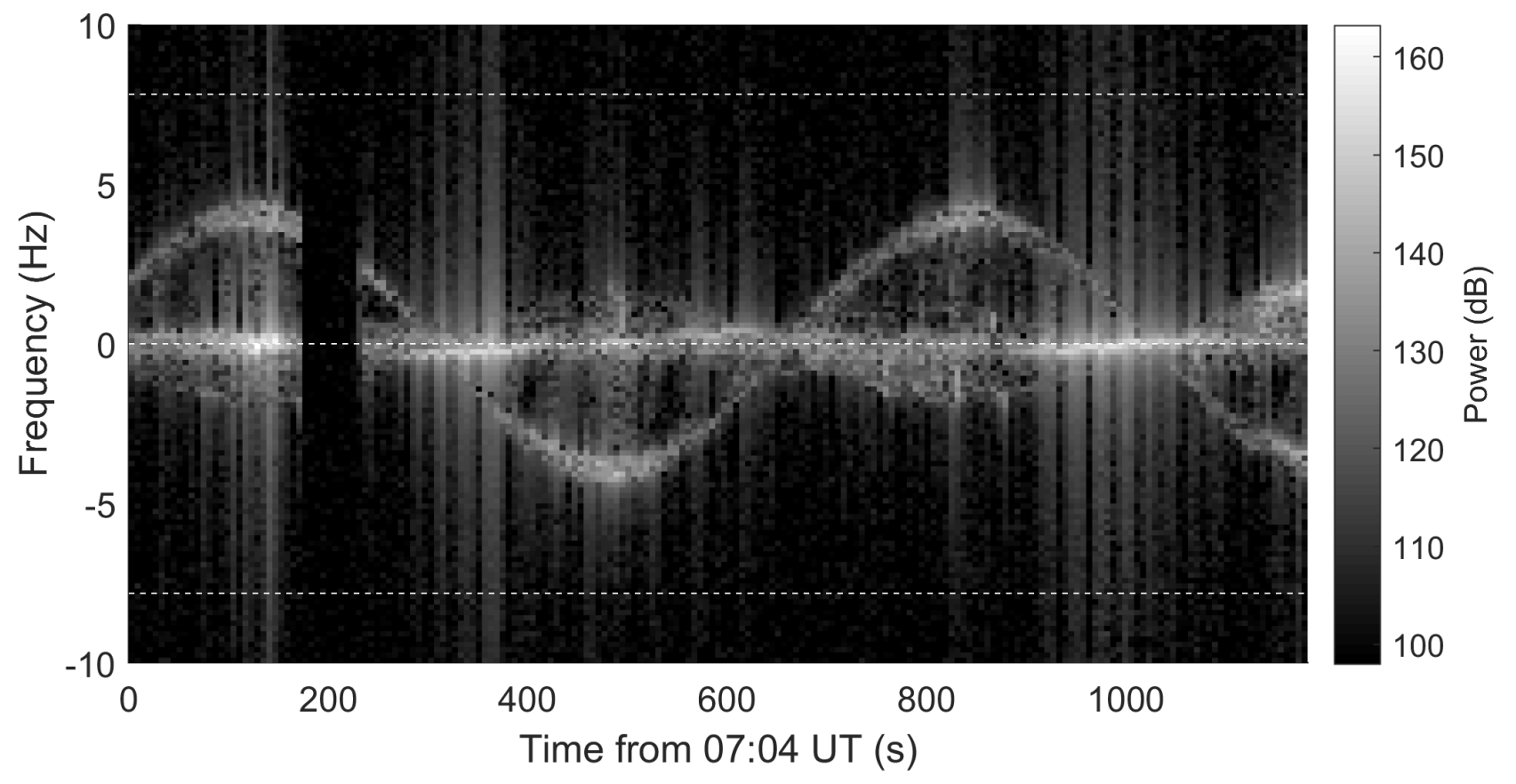

Figure 2. May 9, 2021 GOES 9 Doppler echoes ($P_{\bar{\phi}} \approx$ 715 s, 11.9 min)

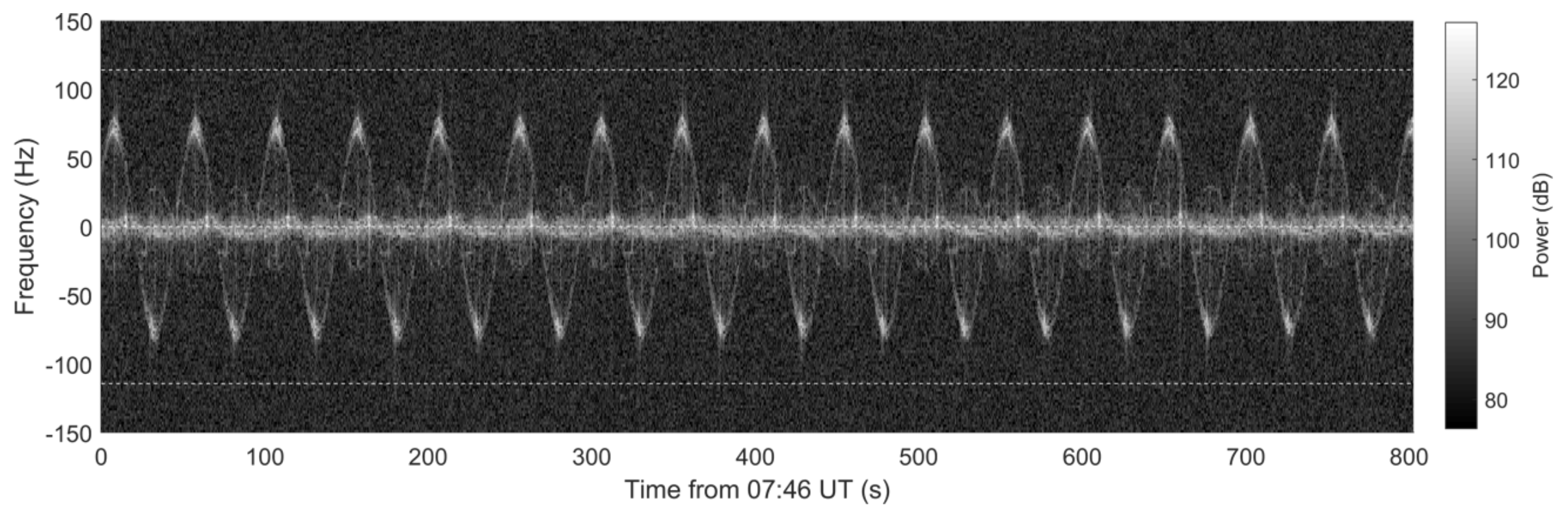

Figure 4. May 8, 2021 GOES 12 Doppler echoes ($P_{\bar{\phi}} \approx$ 49.75 s)

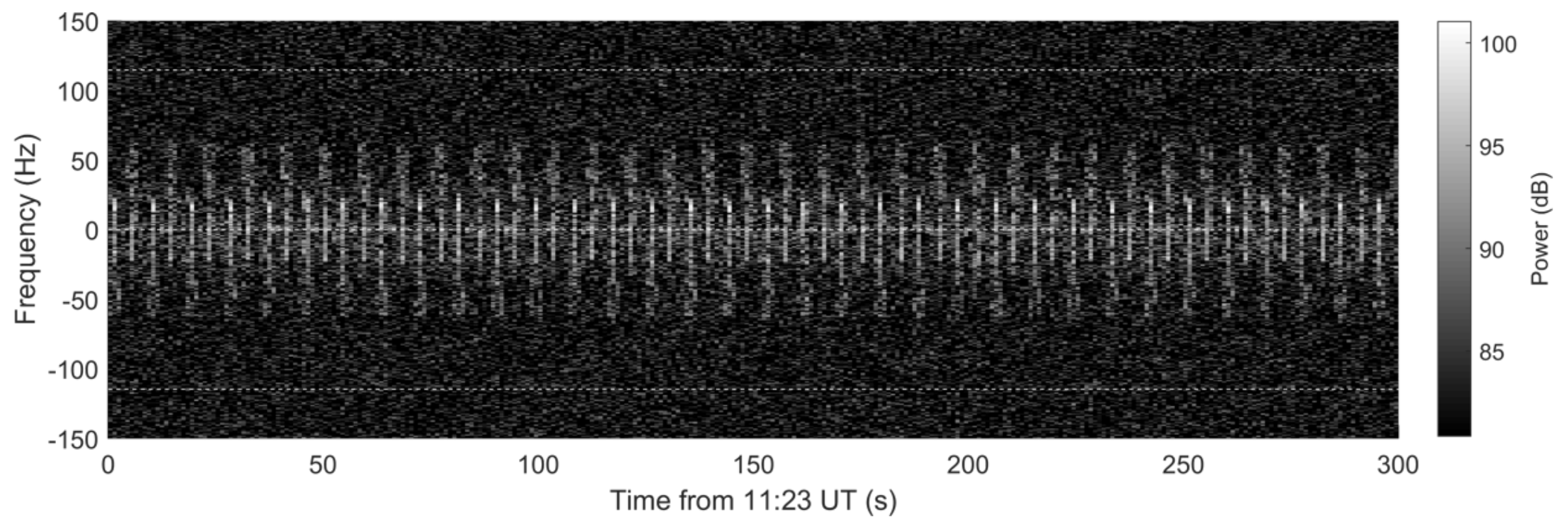

Figure 5. May 1, 2021 Titan 3C Transtage Doppler echoes ($P_{\bar{\phi}} \approx$ 8.9 s)

Significance/Benefits to JPL and NASA: The GEO debris population keeps growing with continued launches and no natural deorbit mechanisms. Observations show that the spin states of defunct geosynchronous (GEO) satellites are diverse and can change significantly over time. Understanding the long-term dynamical evolution of these debris is necessary to protect active assets and preserve GEO for future use. A better understanding of long-term defunct satellite spin state evolution would aid GEO space situational awareness, material shedding predictions, modeling of attitude-dependent solar radiation pressure, active debris removal (ADR), and satellite servicing. ADR and servicing promise to figure prominently in future efforts to manage the GEO debris population and lower satellite costs. As a result, a number of organizations are developing ADR/servicing missions. These missions will require accurate spin state estimates to grapple and de-spin large target satellites. With evolving spin states and many potential targets, early spin state predictions will be extremely valuable for mission planning and execution. Spin state estimates are also valuable for satellite anomaly resolution and recovery.

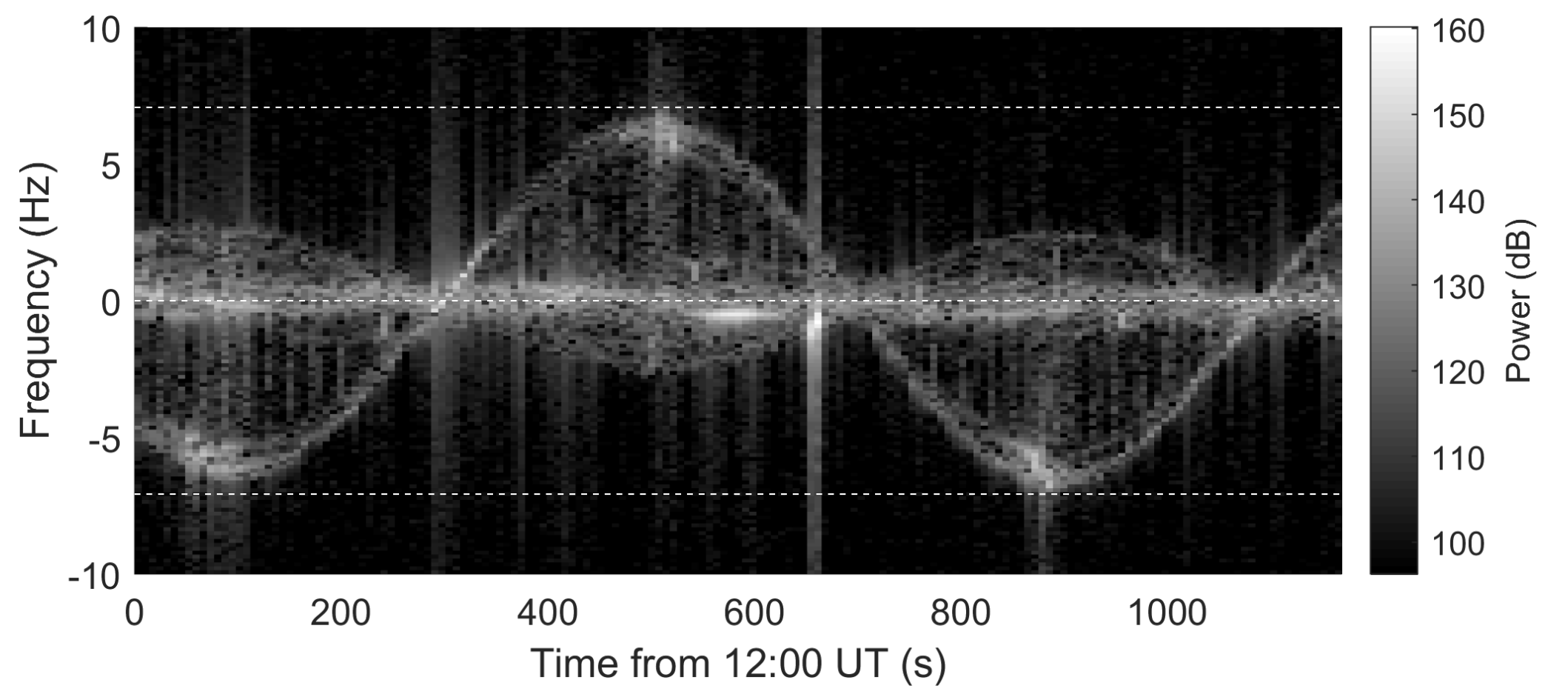

Figure 3. May 1, 2021 GOES 11 Doppler echoes ($P_{\bar{\phi}} \approx$ 799 s, 13.35 min)

References:

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[2] C.J. Benson, D.J. Scheeres**, "**Averaged Solar Torque Rotational Dynamics for Defunct Satellites", *Journal of Guidance, Control, and Dynamics*, *Journal of Guidance, Control, and Dynamics*, Vol. 44(4), pp. 749-766, 2021.

[3] M. Brozovic, R.S. Park, et al., "Radar Observations of Spacecraft in Lunar Orbit", https://echo.jpl.nasa.gov/asteroids/brozovic.etal.2017.lunar.spacecraft.paper.pdf

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[5] C. Benson, C. Naudet, S. Lowe, "Radar Study of Inactive Geosynchronous Earth Orbit Satellite Spin States**,"** JPL IPN Progress Reports, 8/15/20

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