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Satellite Orbit Prediction Processor: Mitigating Satellite RFI to Radio Astronomy

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***Abstract*—Radio astronomy telescopes are designed to pick up weak radio signals from space and are thus extremely sensitive to noise from radio frequency interference (RFI). While placing radio astronomy facilities in remote locations helped mitigate this problem in the past, the increasing number of satellites orbiting the earth has decreased the efficacy of this measure. Satellites passing over radio astronomy facilities can cause serious interference to observations and are a nuisance to astronomers. This paper presents the Satellite Orbit Prediction Processor (SOPP), an open-source tool for predicting satellite interference to RA observation using both orbit prediction methods and satellite frequency data [1]. SOPP is designed to help astronomers schedule observations to minimize interference from satellite sources[1].**

***Index Terms*—Satellite Interference, Radio Astronomy, RFI, Spectrum Sharing**

I. Introduction

When it comes to radio frequency interference, satellites are the great equalizer[2]. As they orbit the earth, they are not constrained by geographic separation, one of the elements relied on for RF coexistence (along with time and frequency separation) and can cause RFI in traditionally hard to reach locations that were previously unaffected. As more satellites enter orbit, the potential for interference is increasing rapidly. This is an especially pertinent problem for radio astronomy. Radio telescopes are sensitive instruments designed to distinguish faint radio signals from background noise at sources far from the earth and are pointed directly into the sky to accomplish their observations. Many of these telescopes have been built in "quiet zones" or rural areas where they will be protected from radio interference from terrestrial sources and are placed on large plots of land with strict regulation on the use of wireless devices on the property. However, satellites are not constrained by this geography and because of the nature of these telescopes, a satellite passing overhead transmitting near the observation frequency can appear extremely loud and spike the power levels seen in the observation. Radio astronomers have developed methods to excise this interference from their observations but the fewer interference events they have over the course of an observation, the easier it is for them to properly observe their target.

This is then, essentially, a spectrum sharing dilemma with two constraints: the satellites cannot, in general, be instructed to cease transmission over radio astronomy areas and radio astronomers will have specific windows in which they can conduct observations. The goal of this research is to design a system that will allow the astronomers to optimize their observations within the specific window to include as little satellite interference as possible. For instance, an astronomer may have three separate hour-long observations of different targets to be run over an eight-hour period and needs to decide how to schedule these observations. The system should provide information about how much interference the observation(s) are likely to experience for each target throughout the 8-hour window so they can correctly strategize how to minimize interference to each observation through proper scheduling. Predicting satellite position using orbital dynamic information provided by two-line element (TLE, or 3LE) files is already widely known, but to solve this problem for radio astronomy, it must be applied to predict all the satellites visible during an observation. The Satellite Orbit Prediction Processor, or SOPP, is an attempt to solve this problem [1]. In this paper, SOPP is introduced as a preliminary solution to determining the interference to radio astronomy observations as satellites cross the main observation beam of a RA telescope, as well as the satellites that are visible above the horizon during the observation period that may cause side-lobe interference. Since most observations are not stationary but instead track a target as it moves through the sky, the calculations need to take in account the movement of the telescope as well as the movement of the satellites. Satellite downlink frequency is considered in order to identify only satellites that are likely to interfere based on the frequency of the radio astronomy observation and to reduce the amount of computation required.

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II. Previous Work

Researchers at the Giant Metrewave Radio Telescope (GMRT) in Pune, India previously tried to solve this problem by creating a similar tool and their work was published in proceedings of RFI 2016 [2]. The researchers created a tool for calculating the times when a satellite pass intersects with a scheduled observation track at GMRT looking at satellites known to transmit in the P and L bands. This tool does not appear to include any frequency filtering capabilities, however, and is not publicly available for review. Additionally, their tool appears to be specifically tailored to the GMRT servo system and may not be widely applicable across RA facilities. SOPP attempts to avoid this issue and keep the system generically applicable to any RA facility by not basing the input on a specific telescope control script and instead taking in the right ascension and declination of any observation target and calculating the telescope's change in azimuth and elevation within the tool itself. They [2] did include an interesting method to calculate what they term as the "zone of avoidance," which is the area in which the measurement of the GMRT receiver began to increase as it neared a satellite. They found that +/- 2 degrees in azimuth or elevation from the satellite is where this happens for most satellite positions.

A 2023 paper investigates how to model the effects of satellite interference on RA systems [3]. This varies depending on the type of service a satellite is providing, which changes how the beam is downlinking. For instance, satellites providing broadband internet services may have several beams in varying directions that change how the RA facility is affected depending on which is in use at a given time. Satellites also may not be actively downlinking when they are above the RA facility. The authors present ways to assess the probability of beam activation, as well as other factors that could affect interference. This illustrates the complexity of determining the actual interference experienced at the RA telescopes, which is discussed more in the testing section of this paper.

In [11] and [12] Depree et al provide an overview and testing results for the NRAO and SpaceX have undertaken a series of coordinated radio frequency (RF) measurement tests to gauge the impact of Starlink User Terminals (UTs) uplink (14.0-14.5 GHz) and downlink (10.7-12.7 GHz) transmissions on the normal operations of the Very Large Array (VLA), the Very Long Baseline Array (VLBA) and the Green Bank Telescope (GBT). In this activity StarLink satellite downlink transmissions are coordinated in time with the GBT/VLBA ground locations. The key requirement is that the (StarLink) satellites have the capability to either pause downlink transmission or move to a non-interfering band for downlink when overpassing the RA facility.

The SOPP capabilities can augment active satellite downlink automation for the modern (circa 2020) satellites that possess the attendant control capabilities **and** provides the generalized capability of minimizing or eliminating satellite induced RFI for any known satellite regardless of age.

III. Methodology

A. Design

To assess potential satellite RF interference in Radio Astronomy observations, the SOPP Python library is introduced and described. This section overviews the library's design, input and configuration parameters, operation and computation, and the resulting outputs.

SOPP is crafted to function as a Python library, offering end users the flexibility to integrate it into their RA observation workflows. Users can install the library and leverage its API within their established processes. For those seeking immediate utility without coding, a user-friendly command line tool is also included, providing a quick entry point to SOPP functionalities. The package is conveniently accessible on the Python Package Index (PIP), ensuring straightforward installation using standard Python package installation procedures (see [1]).

SOPP uses the Python library Skyfield, an astronomy library built atop the SGP4 Python package, to perform satellite position calculations. The SGP4 Python package compiles C++ code, accelerating the execution of SGP4 calculations compared to native Python code.

The SOPP library delivers its core functionality through the `sopp` class, which implements two key methods:

- `get_satellites_crossing_main_beam`: Returns the satellites that cross the main beam during the observation window.
- `get_satellites_above_horizon`: Returns the satellites visible above the horizon during the observation window.

When utilizing SOPP, users will typically follow a straightforward pattern to acquire potential RF interference events during an observation window. This involves inputting the observation characteristics, as detailed further in Section B, creating an instance of the `sopp` class and subsequently invoking one of the provided methods. The resulting output interference data can then be processed according to the astronomers' requirements.

B. Input and Configuration Parameters

To retrieve satellite RF interference data, users must define observation parameters that characterize the RA observation. These parameters are utilized to construct a configuration object, which is subsequently provided to the `sopp` class. The configuration parameters encompass typical characteristics of any RA observation along with runtime settings. At a high level, the required inputs from the user encompass facility location, antenna characteristics, observation time window, observation target and a Two-Line Element (TLE) file containing satellite data.

Facility Characteristics
The user is tasked with providing characteristics of the observation facility, required for accurate satellite position calculations. This includes specifying the latitude, longitude, and elevation of the facility. Latitude and longitude pinpoint the geographical coordinates of the observation site, while elevation indicates the height above sea level.

Antenna Characteristics:
Users must specify the beamwidth, bandwidth, and frequency of the desired observation. Beamwidth represents the antenna's angular coverage, bandwidth denotes its frequency range, and the frequency parameter aligns the observation with the desired RF spectrum.

Observation Time Window:
The user must define the observation time window. This is a begin and end time for when the observation will take place.

Observation Target:
Users can define an observation target, choosing between a static observation point or a custom antenna observation path. When specifying an observation target, users provide the right ascension and declination of the celestial point. A static observation point is defined by altitude and azimuth, while a custom antenna observation path is a dynamic list of altitude and azimuth points over time, catering to diverse observation strategies.

TLE File
Users are required to supply a TLE file containing satellite data. For optimal accuracy, the TLE file data should ideally be close to the desired observation time. SOPP offers added convenience by providing functionality to automatically fetch the latest TLE data from either Space-Track [4] or CelesTrak [5].

Runtime Settings
In addition to the observation characteristic configuration parameters discussed earlier, users can specify runtime settings that influence the computation and execution time of SOPP's intermediary computations. These settings encompass the time interval resolution for satellite position calculations, with the default value set at one second. Additionally, users can define a concurrency level, determining the number of concurrent processes employed for calculating satellite positions.

C. Output

After a user provides the necessary configuration parameters, invokes the requisite methods, and SOPP completes its computations, a list of interference events is yielded.

Every potential interference event is encapsulated by an OverheadWindow class. Each OverheadWindow includes information about the satellite causing the interference and a list of PositionTimes, providing details of when the satellite intersects the RA observation. The PositionTime class is constructed to capture a specific point in time, offering details about the satellite's position relative to the observation location—specified in terms of altitude and azimuth—along with the distance from the observation location. The design of the output provides users with comprehensive information providing a basis for informed decisions regarding their RA observation.

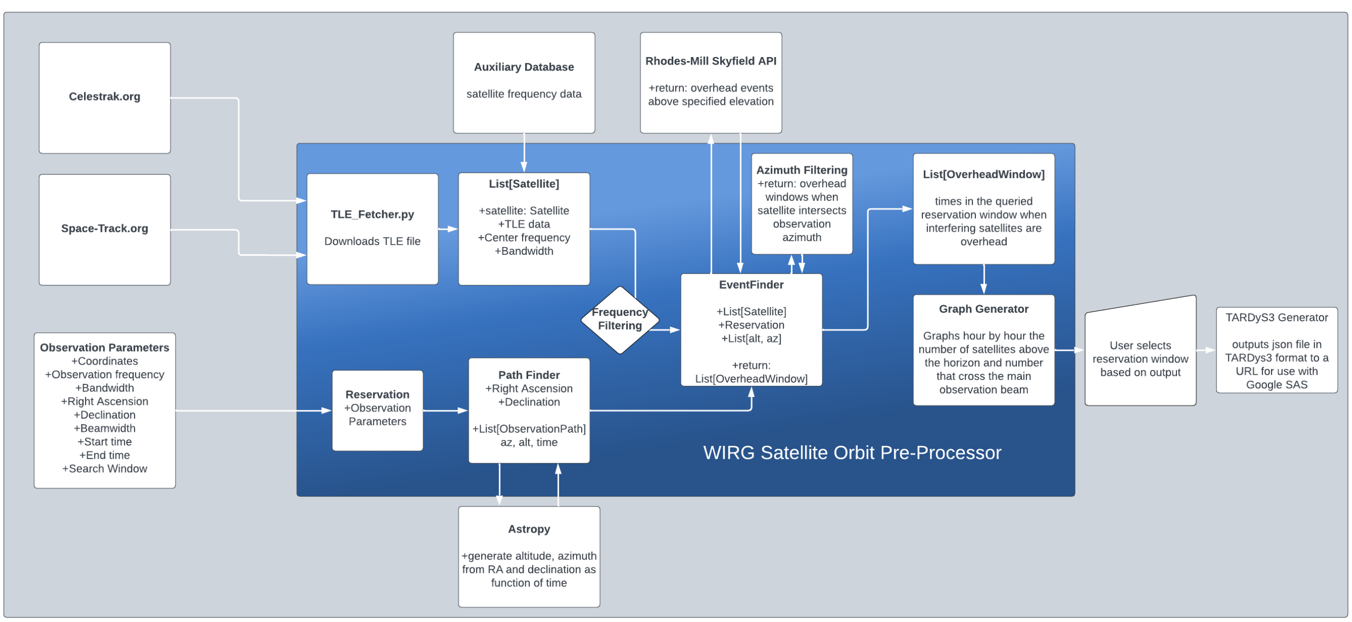

Figure 1: Functional block diagram (FBD) of the SOPP architecture

Figure 1 provides a functional block diagram of the Satellite Orbit Prediction Processor (SOPP). S.O.P.P. has the functionality to auto-generate CBRS standard-based spectrum reservations which are utilized to coordinate spectrum sharing with CBSS transmitters (CBSDs) that may be deployed surrounding a radio astronomy observatory facility (see [19]).

D. Satellite Supplementary Databases

A supplementary project goal is to catalog relevant information concerning any and all satellites for which accurate information is readily available online, with the objective being a fully conceived database detailing the name, NORAD ID, downlink frequency (as well as its corresponding bandwidth/baud and power level), orbital class, and activity status for each entry. This is realized via a tool that uses web-scraping techniques where an API is not available to draw satellite information from available online sources.

US Radio Guy [13] is operated by an independent satellite imaging enthusiast. It offers data for 848 entries that includes satellite name, space agency, launch date, end of life date, service, direction, downlink frequency, bandwidth, polarization, data rate, and activity status. Notably the source lacks NORAD ID's, orbital classes, and power levels; althoughthe latter is not available in any of the available sources.

SatNOGS [14] owned by the Libre Space Foundation, is an open source project which seeks to monitor satellite missions and networks which provides satellite names, NORAD ID's, downlink frequencies, bauds, and activity statuses for 2,215 entries. No information is available with respect to orbital classes.

The FCC's official website [15] information provides names and downlink frequencies from their provided excel file for 241 satellites. Also included are orbital locations (not to be confused with orbital classes), licensees, associated administrations, services, launch dates, polarization and coverage information, as well as orbital debris information.

The Observing Systems Capability Analysis and Review Tool, also known as OSCAR [16] is a resource provided by the World Meteorological Organization with the intention of aiding earth observations. The website also hosts databases for 2,292 satellite entries. Information includes names, downlink frequencies, and their corresponding bandwidths. Also provided are associated space agencies, launch and EOL dates, services, directions, emission designators, and polarizations.

AMSAT [17] the Radio Amateur Satellite Corporation, is an organization composed primarily of volunteer radio scientists who work to construct and manage communication satellites. Information consists of satellite names, NORAD ID's, downlink frequencies, bandwidths, and statuses for 1,642 entries.

The Union of Concerned Scientists [18] is a non-profit organization involved in a range of climate-advocacy programs. Information icludes NORAD ID's, operators, purposes, launch dates, and orbital information including (though not limited to) orbital classes for 7,560 satellites.

CelesTrak [5] is a non-profit, though primarily dedicated to providing TLE data to the radio science community. As such, their database details - in addition to names and NORAD ID's - a host of orbital data for each of the 8,446 entries: epoch, mean motion, eccentricity, inclination, mean anomaly, ephemeris type, classification type, etc. From this data the orbital class of each entry can be deduced.

The last source for supplementary satellite information is SpaceTrack [4] which was initialized by the US Air Force to assist in tracking all active satellites. The SpaceTrack online database consists of 58,768 entries, each of which details the satellite name, object type, country of origin, launch date, decay date, period, inclination, apogee, and perigee for the respective satellites. The orbital class of each entry can be deduced.

Each resource provides a different range of information for its entries, no two sources contain the same number of entries, no single source has every field needed, and not one website of the eight provides downlink power levels. This constitutes a limitation when seeking to combine and eliminate redundant satellite entries, additional technical challenges are encountered due to ambiguities in naming conventions. Since websites evolve, any processing code must adapt as well.

At the time of publication there are 22,138 entries in the supplementary satellite database, about 87% of which are complete with NORAD ID's, ~38% with downlink frequencies, ~23% with bandwidths/bauds, ~59% with activity statuses, and ~74% with orbital classes. This is visualized in the "completion table" provided below (see **Figure 2**), where the yellow-colored segments represent completed fields, in contrast to the navy-colored vacancies.

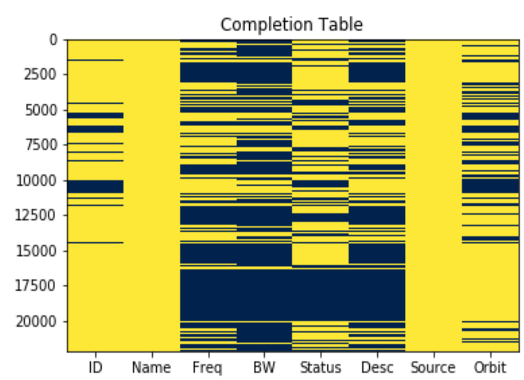

Figure 2 – Supplementary satellite database (note missing downlink frequencies**)**

IV. SOPP OPERATION AND COMPUTATION

It is clear that data is lacking for many entries - particularly those of the bandwidth and downlink frequencies - an issue which may only be remedied by drawing from an increasing number of sources. As the supplementary satellite database, and web-scraping tool, continues to evolve, missing data (especially frequency) will be gradually eliminated.

SOPP's operational workflow is initiated by interpreting user-defined configuration parameters that encapsulate the specifics of the desired observation. This includes generating an antenna observation path to outline the trajectory the antenna will follow, ensuring continuous observation of the specified target. Subsequently, SOPP conducts satellite position calculations at the provided time interval resolution. The core objective is to analyze the intersection of satellite positions with the antenna trajectory path, facilitating the identification of potential satellite RF interference events.

To address the computational expense associated with calculating positions for numerous satellites over the observation window, SOPP has undergone optimization efforts to enhance performance. Leveraging the Skyfield library for satellite position calculations, SOPP benefits from the underlying SGP4 library—C++ compiled code that significantly accelerates the execution of calculations compared to native Python code. Within SOPP's internal satellite position calculating classes, there is a caching mechanism for Skyfield's expensive-to-generate internal time objects. Additionally, the satellite position calculation process is designed to exploit Skyfield and SGP4's array acceleration, enabling faster calculations across an array of desired times. In pursuit of further runtime reduction, SOPP is developed to execute satellite position calculations concurrently. Users can specify a concurrency level during the initial configuration, enabling SOPP to run an equivalent number of processes simultaneously during satellite position calculations.

SOPP recognizes the variability of satellites, each residing in different orbits, possessing varied downlink transmission frequencies, and exhibiting distinct operational statuses. The library introduces a feature—satellite list filtering—allowing users to refine the list based on their specific criteria. While SOPP provides a set of built-in filters, it also encourages extensibility, allowing users to define custom filters tailored to their unique needs. A common and practical filtering option is to focus solely on satellites with downlink transmission frequencies that overlap with the frequency of the desired RA observation. Filtering can aid in streamlining computations and focusing on satellites that pose potential interference to the intended RA observation.

V. TESTING AND DISCUSSION

In collaboration with Hat Creek Radio Observatory (HCRO), S.O.P.P.'s satellite prediction functionality was tested in December 2023 and March 2024 using the Allen Telescope Array (ATA). Several different satellite spotting observations have been conducted – see Table 1 below.

Satellite	Expected	Occurred	dT (sec)	Az	Elevation
NAVSTAR 62	2023-12-27 13:55:30	2023-12-27 13:55:35	4.9999	95.558	51.37
NAVSTAR 69	2023-12-27 14:50:31	2023-12-27 14:50:50	19.000	111.502	62.73
NAVSTAR 80	2023-12-27 15:13:06	2023-12-27 15:13:12	5.9999	39.299	64.88
NAVSTAR 71	2023-12-28 12:12:15	2023-12-28 12:12:30	14.999	149.573	54.42
NAVSTAR 71	2023-12-28 12:31:54	2023-12-28 12:31:42	-11.999	153.442	44.85
NAVSTAR 54	2023-12-29 17:32:39	2023-12-29 17:32:36	-3.0000	42.739	60.95
NAVSTAR 54	2023-12-29 17:49:06	2023-12-29 17:49:04	-1.9999	45.759	53.56
NAVSTAR 69	2023-12-30 15:48:55	2023-12-30 15:48:57	1.9999	137.832	32.41
NAVSTAR 80	2024-03-01 16:14:02.89	2024-03-01 16:13:59.16	3.7039	63.254	50.39

Table 1 – Satellite spotting observations with a single ATA telescope at the Hat Creek radio Observatory

After running SOPP, it was determined that NAVSTAR80 GPS satellite would pass over (overflight) HCRO with a predicted time of 16:14:02.8918 UTC and is transmitting at a frequency of 1575.42 MHz. An observation was started several minutes prior to the predicted time to gather baseline noise measurements and ensure the satellite was captured. Figure 3 shows all spectra time series for the observation with the satellite detected in the main beam. The actual time of the overflight and detection by the ATA main beam was 16:13:59.1608 UTC. This is an error of 3.7039 seconds. The uncertainty on the antenna pointing on the satellite is considered a prime reason for the observed timing inaccuracy.

The argument for the impact of the pointing uncertainty is this:

- ATA points at a given (Az, El) - along the SOPP predicted sky-trajectory of the satellite
- ATA should be able to pick up the satellite (because of the finite size of the main-beam, which is NOT simply a single ray) over a significant swath of this trajectory
- The hypothesis is that the peak power recorded by the ATA, however, will be when all the antennas align, and this should happen when the satellite is at the EXACT (Az, El) that we point the ATA to, and this should

happen EXACTLY at the time that SOPP predicts that the satellite will be at this (Az, El).

- Note: SOPP discretizes the trajectory into several steps - nominally spaced 1s apart, and the expected time of the 'pass', and the expected location are both selected from the output of the SOPP.

However, this hypothesis may not hold, if the main-beam of the satellite transmitter is not along the ATA dish's boresight at the time that it is *positionally* in the main beam. Conversely, the maximum received power may occur when the antenna beams are aligned, rather than when the satellite body is physically within the main beam. Since the GPS transmit antenna pattern is not strongly directional, the effect of such a 'misalignment' should be small. Nonetheless, further investigation is warranted.

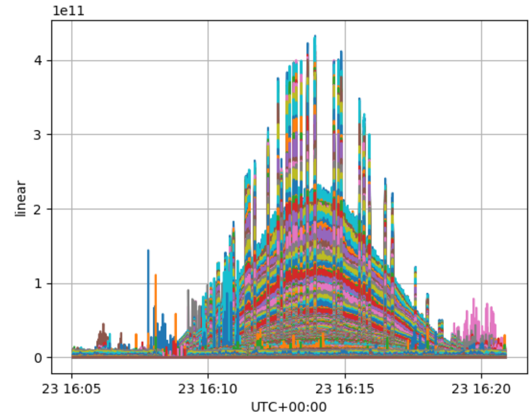

Figure 3 – All spectra time series for the NAVSTAR80 satellite spotting verification test.

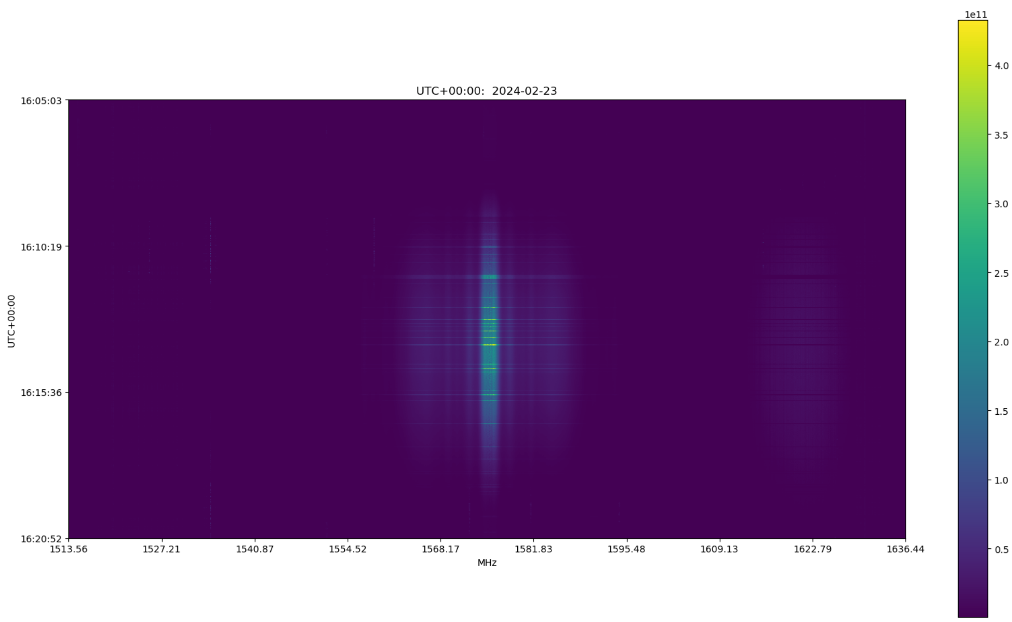

Figure 4 – Waterfall spectrum plot for the NAVSTAR80 satellite spotting verification test.

Potential other reasons for a larger than expected error (aside from aged TLEs) are hypothesized to be as follows:

Pointing error of the ATA dish. The ATA status control reports the dish pointing precision in Azimuth and Elevation to one hundredth of a degree. Looking at the two consecutive discrete points in the SOPP trajectory, and computing the angular difference between them, we can get an average sky traversal speed (in degrees/second) of the satellite and can back out the time error of rounding off the ATA pointing precision to the 2^{nd} decimal, while the SOPP prediction is on the 3^{rd} decimal. The traversal speed is different for every observation, but in this case, it amounted to about 0.229 degrees in azimuth over one second, which shakes out to about 0.001 degrees every 4 ms, or - equivalently, a timing error of about 20 ms for 0.005 degrees.

Binning in the time-domain: The IQ stream is converted to a stream of blocks, with each block defining the number of samples used to compute an FFT, and to establish the RF power content in a time-segment that spans the block. This is currently 8.192k samples, and a sampling rate of 122.88M. This shakes out to a time-segment length of about 67.148 ms. i.e. we only have power measurements every 67 ms, and therefore, this imposes a separate limit on how precise our measurement of the exact moment of satellite conjunction with the main beam is.

Spurious noise that may affect the power in the channel, and therefore throw off the timing. Note that there are some horizontal streaks in the waterfall plot, which would be characteristic of broadband noise, or a burst. This could be out-of-band noise (and it may appear to have the same frequency extent as the full-band of the GNSS signal, because that could be the passband for the filter). Additionally, since the values from the SDR are normalized there may be some automatic stretching of the dynamic range, which would distort the scale from time-segment to time-segment.

SOPP's accuracy could be verified to a greater extent using the following approaches:

1. Track a satellite through the trajectory. This way, the satellite is constantly expected to be in the beam, and we have a multi-point verification of the expected and observed trajectory. Utilize multiple ATA antennas to spot the satellite at various locations in the trajectory (no need to constantly slew a single antenna which gives rise to inaccuracies).

2. Computing the expected power (looking at the changing range of the satellite, as well as some secular swivel, and a rotation of the alignment of the transmit antenna), and incorporate that in the fitting, prior to the determination of the actual overflight instant.

3. Leverage the fact that the GNSS satellites which are being tracked have had the latest orbital elements uploaded to them via their control segments. This is (very likely) done at a much higher cadence for the GNSS satellites given their sole remit is to be able to help perform localization, and distributed timing. So, we can record the GNSS signal can be recorded for the same GNSS vehicle that is being tracked, demodulate, and extract the frames, and get a much more refined expected (or, actual, real) position, which can then be compared to the RF-actual position.

VI. Conclusion

SOPP is an open-source proof of concept for determining the satellite interference seen during radio astronomy observations. The tool applies the modules described in this paper to solve the problems that are not already fixed by a single tool, such as radio telescope movement and frequency filtering. The power of this project is in how it fits all the components together to make something greater than the sum of its parts, rather than in any one feature. It is designed to provide base capabilities that can be built upon by other researchers in this space to continuously improve the community's ability to deal with satellite interference to radio astronomy. It is the fervent hope of this team that continued development will help ease the burden on radio astronomers and improve coexistence between users of the radio spectrum.

VII. Future Work

There is still much that can be done to improve the SOPP tool to better alleviate the problems of satellite interference on radio astronomy. One of the most significant areas for improvement is in the satellite frequency database. There is currently no single trusted source to go to find information on satellite frequency and antenna characteristics. The auxiliary frequency database developed in connection with the SOPP project is a good start, but not only are more frequencies needed but the inclusion of other antenna characteristics will go a long way in improving the usefulness of this tool. Expanding the database to include information such as trans- mission power level and antenna scanning patterns will not only improve the accuracy of satellite interference predictions but will allow further development to provide more useful information for astronomers to base their observation decisions on.

Additionally, more work should be done in the visualization and reporting functionality of SOPP. Additional information such as the mean distance of satellites from the observation beam or even heat maps to show areas of interference in the sky as a function of time could improve how useful this tool is to astronomers and provide them with more information on which to base observation schedules.

Acknowledgment

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