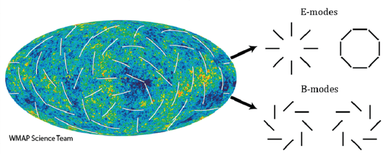
Investigating Starlink Interference in SPIDER' s Field of View for CMB Observation

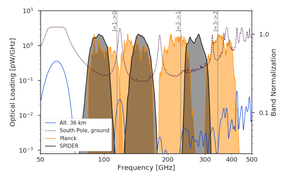
Suvinay Goyal, Jeffrey P Filippini

University of Illinois Urbana-Champaign

SPIDER Searches For The CMB

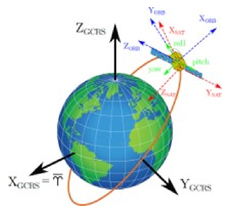
- SPIDER: Balloon Borne Microwave Telescope
  - First launch on January 1, 2015.
  - Second launch on Dec 22, 2022, both from McMurdo Station, Antarctica.
  - Aimed to probe for the signature B-Mode polarization left by primordial gravitational waves (PGW) on the Cosmic Microwave Background (CMB).



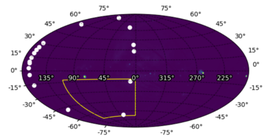


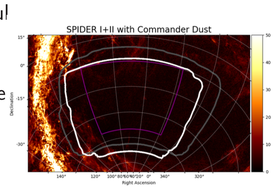
Astrometric Analysis and Algorithm

- Reference Frames
  - Default Satellite Reference Frame: GCRS (Geocentric Reference System), TEME (True Equator Mean Equinox); Default GPS Reference Frame: WGS 84
  - What we need: SPIDER centric moving reference frame. And visibility only in the SPIDER scan region.



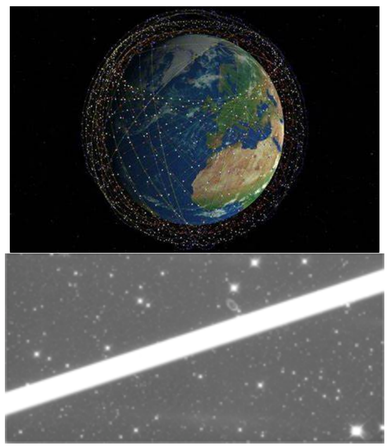
- SGP4 Propogation Routine
  - Simplified General Perturbations 4 Propagator is an analytic method based on a general perturbation theory for generating ephemerides for satellites in earth-centered orbits from TLE format data. Returns the position in the TEME frame.
  - Doesn't treat the satellite orbit as a simple ellipse and uses TLE arguments to give positions accurate to about a km at the epoch, which degrades quickly and is useful! $\pm 1 - 2$ weeks from the epoch.
  - Skyfield high level library built over base FORTRAN code gives access to coordinate conversions and data loading in Python.
  - Mean Eccentricity for all Starlinks = 0.000249, affects the mean anomaly and the perturbations.





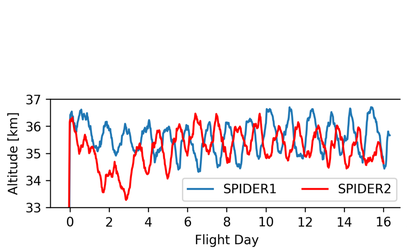
Why Do Starlinks Matter?

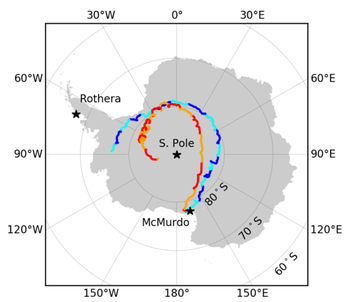
- Number of Starlinks in LEO(Low Earth Orbit) during SPIDER 1 flight : 0.
- Number of Starlinks in LEO during SPIDER 2 flight : 3376.
- Number of Starlinks in the LEO now: 5488
- **SPIDER** frequencies: 82-108, 130-170, 240-305 GHz
- **Starlink** frequencies: Ku (12-18), Ka (27-40), E (60-90) bands. Moreover, proprietary details about side lobes and harmonics are unknown.



Analysis Pipeline

- Find the Alt-Az wrt SPIDER given a specific Starlink object and a timestamp.
- Vector operations to find the Ra-Dec and check the scan region bounds.
- Reference Frame Conversions, coordinate conversions and vector operations to obtain position wrt SPIDER. Substantial parallax effects the projection of Starlinks onto Ra-Dec from SPIDER's altitude.
- Loop over all available datetime stamps and the Starlinks from 1 Jan Epoch.
- Find the Healpix (nsides = 512) mapping to the given coordinates
- Use all the Starlink Hits data to compute Starlinks' Entry-Exit Instances in the scan region using that a Starlink's Mean Motion $\approx 15\frac{rev}{day}$ and the maximum satellite occurrence timestamp difference $\approx$ 880s.
- Visualization : Interpolate the SPIDER timestamps and GPS position to 30s intervals and recompute the Astrometric analysis to get a sense of how Starlinks move through the scan region as viewed by SPIDER.





Data Preprocessing and Acquisition

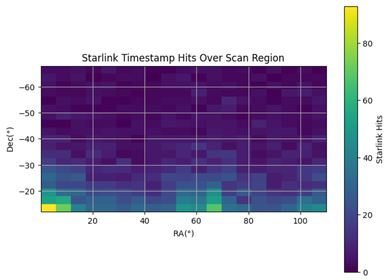
- SPIDER GPS data: Latitude, Longitude, Altitude, Irregular Datetime Intervals. Data Preprocessing: 2430 datapoints $\longrightarrow$ 1699 datapoints.
- Starlink Data: TLE (Two Line Element Set) format. Usable with the SGP4 Progation Algorithm for low earth orbital calculation.
- Use a lookup data structure and get the data for the **right Epoch**.

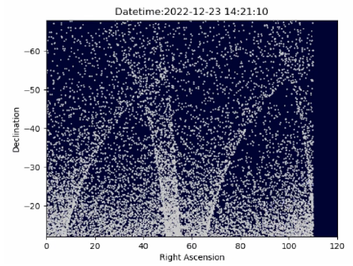
Column	Description
1	Line number
3-7	Catalog number
9-16	Inclination [degrees]
18-25	Right Ascension of the Ascending Node [degrees]
27-33	Eccentricity (decimal point assumed)
35-42	Argument of Perigee [degrees]
44-51	Mean Anomaly [degrees]
53-63	Mean Motion [revolutions per day]
64-68	Revolution number at epoch [revolutions]
69	Checksum (modulo 10)

Column	Description
1	Line number
3-7	Catalog number[1]
8	Classification ('U' for unclassified, 'C' for classified, 'S' for secret)
10-11	International designator (Last two digits of launch year)
12-14	International designator (Launch number of the year)
15-17	International designator (Piece of launch)
19-20	Epoch year (Last two digits of year)
21-32	Epoch (Day of the year and fractional portion of the day)
34-43	First Time Derivative of the Mean Motion
45-52	Second Time Derivative of the Mean Motion (decimal point assumed)
54-61	B* drag term (decimal point assumed)
63	Ephemeris type [2]
65-68	Element number
69	Checksum (modulo 10)

Results and What Next?

- 3814 different hits of the Starlinks in the SPIDER scan region at a given timestamp and 3590 different entry-exit instances.
- Next Steps : Packagizing the availability of the script, Automating a bad pixel flagging system....
- Aim is to make it generalizable for all "balloon borne" telescopes and ground telescopes.





Acknowledgements

SPIDER is supported by NASA under grant 80NSSC21K1986, issued through the Science Mission Directorate