The Stellar Occultation Mission Planner

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Introduction

- Technology development program focused on answering heliophysics science questions funded through NASA ROSES Heliophysics Technology and Instrument Development for Science (H-TIDeS) [PI: Dr. Harding]
  - Investigating coupling of the middle and upper atmosphere by space weather through the nitric oxide profile in polar night
  - Energetic particles create nitric oxide (NO) in the upper atmosphere at auroral latitudes

$$N_2 + EPP \rightarrow N^* + N$$
$$N^* + O_2 \rightarrow NO + O$$

  - In polar night, nitric oxide lifetime is long enough to be transported downward to catalytically destroy ozone

$$NO + O_3 \rightarrow NO_2 + O_2$$
$$NO_2 + O \rightarrow NO + O_2$$

- This program will build on the results of sounding rocket flights as part of the PolarNOx program led by Co-PI Dr. Bailey
  - **Limited to one location, at one time, under a particular set of auroral conditions**

Program Timeline

Year 1

- Instrument design initiated
- Long lead-time procurement and manufacturing processes started
- Device optimization with commercial EMCCD camera system

Year 2

- Development of EMCCD camera electronics by JPL
- Camera system characterization by VT
- Environmental testing of camera system

Year 3

- Radiation testing
- Instrument characterization and testing

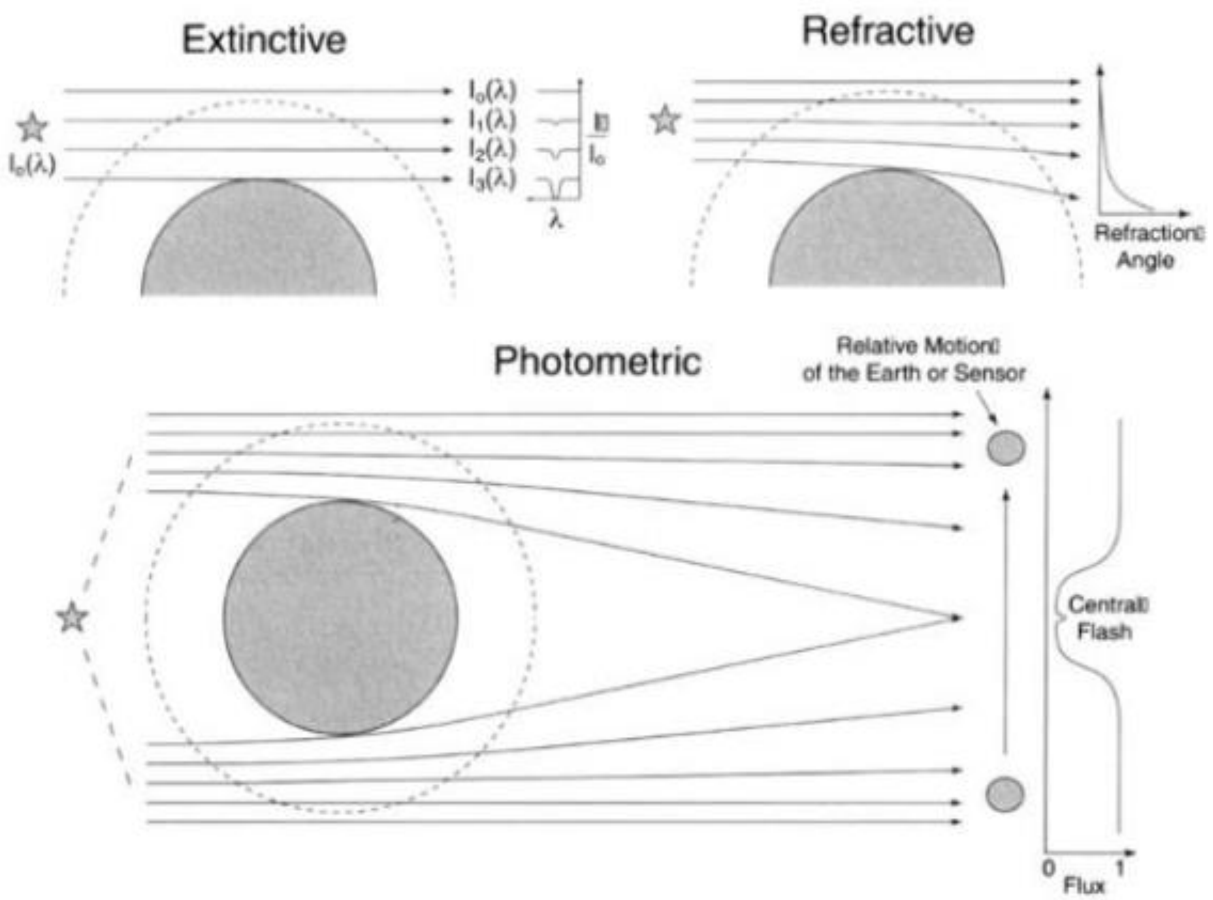
Camera system matured to TRL-6

Overview

- The Stellar Occultation Technique
- Problem Geometry
- The Stellar Occultation Mission Planner
  - Interface
  - Overview of Outputs
- Validation

Background

- The stellar occultation technique utilizes starlight passing through the atmosphere to passively measure atmospheric properties through absorption, scattering, refraction, dispersion, and polarization of light
- Useful for characterizing atmospheres where global, altitude resolved coverage is required
  - ESA EnviSat Global Ozone Monitoring by Occultation of Stars (GOMOS) instrument
  - ESA Mars Express SPectroscopy for Investigation of Characteristics of the Atmosphere of Mars (SPICAM)
  - ESA Venus Express SPICAV
- Related techniques utilize the Sun, Moon, or other satellites (GNSS occultation) as the signal source



[1]

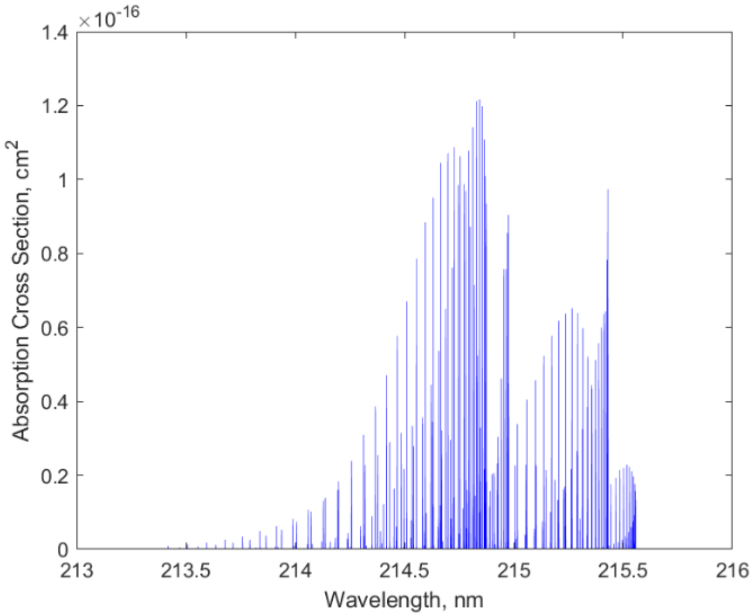
The Stellar Occultation Technique

- Focus on absorptive occultation measurements
- Occultation technique becomes an application of Beer-Lambert's Law
  - Relates amount of material along the line-of-sight between the satellite and star to the total amount of absorption measured between an occulted signal and a reference signal taken above the atmosphere

$$\frac{I_{occ}(\lambda)}{I_{ref}(\lambda)} = \exp\big(-\tau(\lambda, l, T)\big)\, d\lambda$$

  - Amount of attenuation is related to optical depth, τ

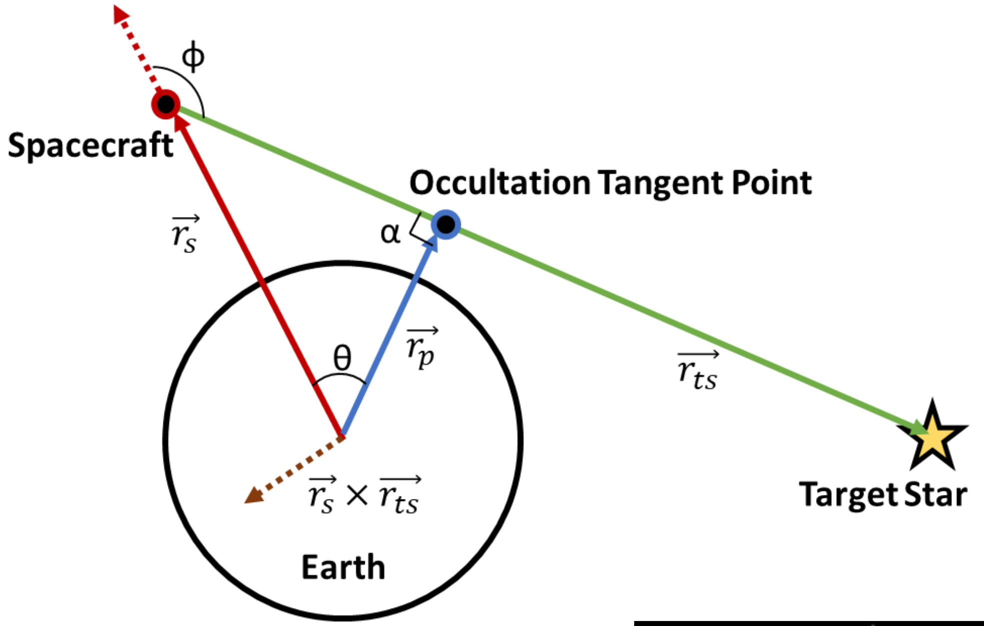
$$\tau(\lambda, l, T) = \int_{Limb\ Path} \sigma\big(\lambda, T(r(s)\big)\rho\big(r(s)\big)ds = \sigma(\lambda, T)N$$

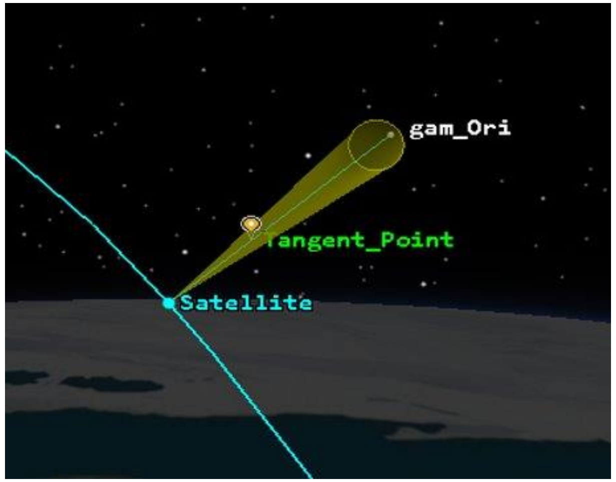


- Benefit of self-calibration
  - Resilient to detector degradation during the course of a mission

Problem Geometry

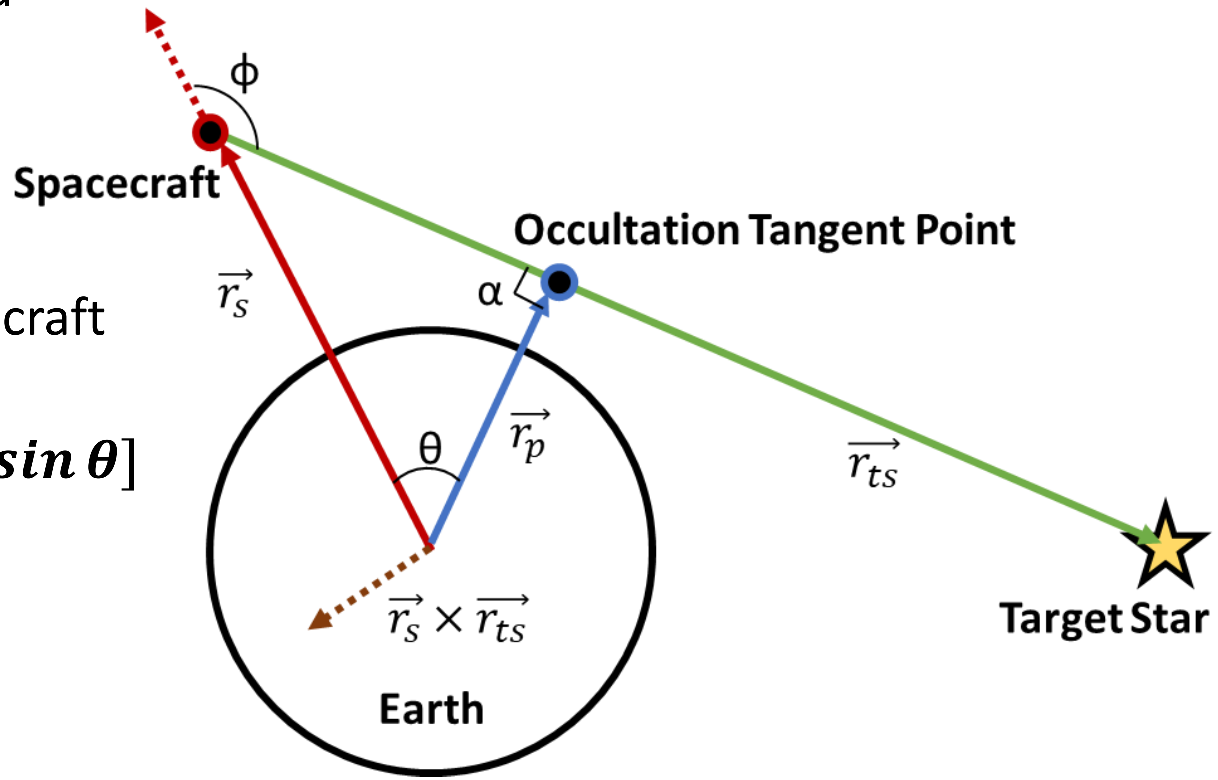
- Consider a generic orbit with a generic target star
  - Would like to relate the location of the spacecraft and direction to the target star to the **occultation tangent point**
- Find $\overrightarrow{r_p}$, the tangent point position
- **Note:** $\overrightarrow{r_{ts}}$ is a unit vector pointing to the star





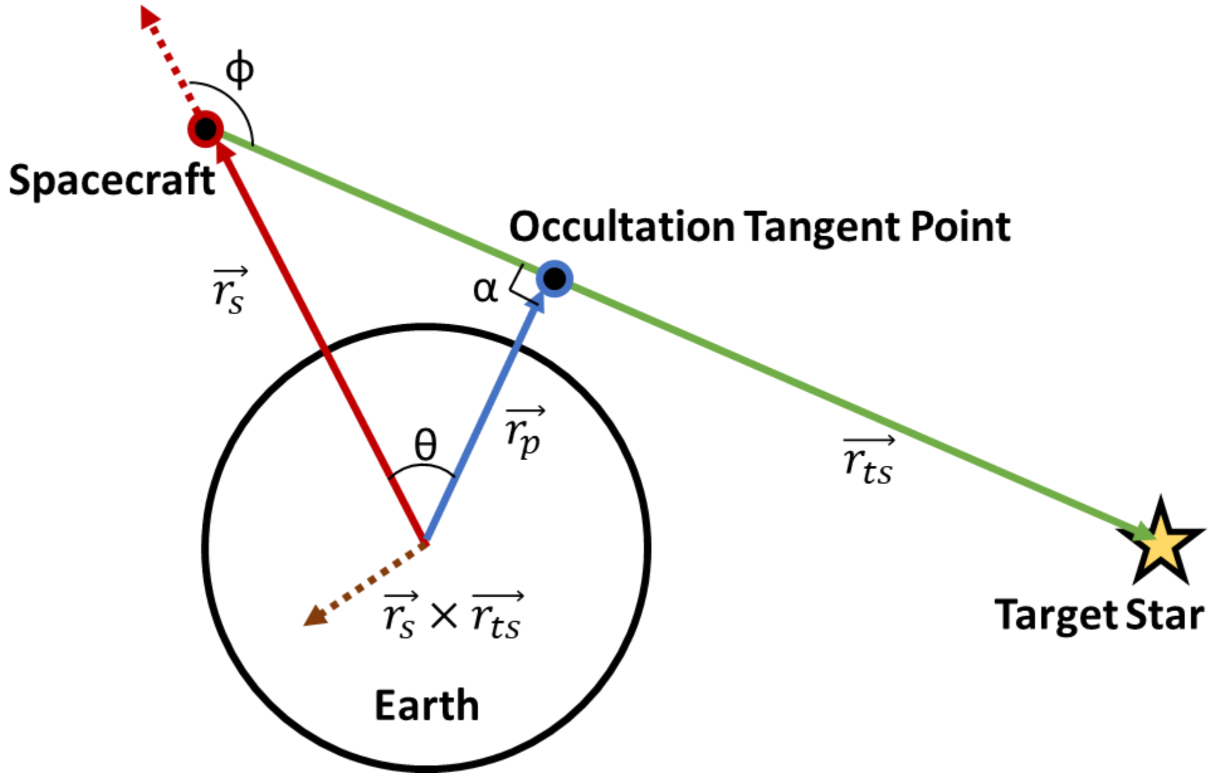
Problem Geometry

- Know: $\vec{r_s}, \overrightarrow{r_{ts}}$
- Would like to rotate the spacecraft position vector through the angle θ in the plane defined by the spacecraft and target star vectors
- $\phi = \tan^{-1}\left(\frac{|\vec{r_s} \times \overrightarrow{r_{ts}}|}{\vec{r_s} \cdot \overrightarrow{r_{ts}}}\right)$: zenith angle
- $\theta = \phi - \alpha$
- Apply Rodrigues' rotation formula to rotate the spacecraft vector about the vector $\vec{r_s} \times \overrightarrow{r_{ts}}$ through the angle θ
- $\boldsymbol{\overrightarrow{r_p}} = |\boldsymbol{\overrightarrow{r_p}}|[(\mathbf{1} - \boldsymbol{\cos\theta})(\boldsymbol{\vec{\rho}} \cdot \boldsymbol{\hat{r}})\boldsymbol{\hat{r}} + \boldsymbol{\vec{\rho}}\,\boldsymbol{\cos\theta} + (\boldsymbol{\hat{r}} \times \boldsymbol{\vec{\rho}})\,\boldsymbol{\sin\theta}]$
- Where:
  - $\vec{\rho} = \frac{\vec{r_s}}{|\vec{r_s}|}$
  - $\hat{r} = \frac{\vec{r_s} \times \overrightarrow{r_{ts}}}{|\vec{r_s} \times \overrightarrow{r_{ts}}|}$
  - $|\vec{r_p}| = |\vec{r_s}|\cos(\theta)$



Problem Geometry

- Immediately realize some constraints for determining what is a valid occultation geometry
  - The altitude of the occultation tangent point must be above the Earth's surface
  - If the zenith angle, ϕ, is less than 90°, the occultation tangent point will be behind the spacecraft



The Stellar Occultation Mission Planner

- Provide a tool for scientists and mission planners to explore different orbits and target stars to understand spatial and temporal coverage of occultation measurements
  - Study how selection of the orbit and target star impact the spatial and temporal coverage that can be achieved
    - Able to specify time period and geographic regions of interest
  - Study how occultation properties vary over time
  - Enforce additional restrictions based on mission requirements
    - Sun keep-out zone
    - Moon keep-out zone
    - Star – orbit plane angle limit
  - Does not perform analyses related to the signal / attenuation of starlight by the atmosphere
- Implemented in MATLAB and utilizes Ansys Systems Tool Kit (STK) as the orbit propagator

Configuration Options

- Specified in two config files
- First specifies generic options: config.txt
- Seconds specifies simulation specific options: run_options.txt

General Configuration Options

Option	Description
save_folder	Where to save simulation data
run_options_folder	Folder storing simulation-specific run options files
star_data_folder	Folder containing star data
sat_data_folder	Folder containing satellite data
stk_version	STK version to use
stk_scenario_folder	Folder containing base STK scenarios
stk_visible	Boolean, controls whether STK window is visible
run_select	Name of the run options file to use

Configuration Options

Specific Simulation Run Options

Option	Description
run_name	Descriptive name of the simulation run
load_data	Boolean, controls whether to run the simulation or perform analysis using saved data
save_data	Boolean, controls whether to save simulation data
import_stars	Boolean, controls whether to import stars into the STK scenario
import_sats	Boolean, controls whether to import satellites into the STK scenario
truncate_data	Boolean, controls whether to truncate occultation data to only the time / geographic region of interest
plot_data	Boolean, controls automatic plotting of occultation data
stk_scenario_file	Specifies the STK scenario file to use
star_data_file	Specifies the star data file to use
sat_data_file	Specifies the satellite data file to use
load_data_file	If loading data, specifies what data file to load
ephem_step_size	Output step size for satellite ephemeris data
occ_step_size	Output step size for occultation data

Option	Description
start_time	Start time for STK propagation
stop_time	Stop time for STK propagation
oa_start_time	Start time for occultation analysis
oa_stop_time	Stop time for occultation analysis
propagator	STK propagator to use (Two Body, J2, or HPOP)
sat_names	List of satellites to analyze
star_names	List of stars to analyze
lat_min/max	Minimum / Maximum latitude in geographic region of interest
long_min/max	Minimum / Maximum longitude in geographic region of interest
alt_min /max	Minimum / Maximum altitude in geographic region of interest
max_star_angle	Maximum angle between the star and orbit plane for a valid occultation
min_sun_angle	Specifies Sun keep-out zone
min_moon_angle	Specifies Moon keep-out zone
atmos_model	Set the atmospheric model for use with HPOP

Satellite and Star Specifications

- Satellite Specification
  - Initial Keplerian orbital elements at start of propagation
  - Drag coefficient, area-to-mass ratio
    - Optional, for use only with HPOP propagator
  - Specified in .xlsx file
- Star Specification (ICRS, J2000 epoch)
  - HD number
    - Optional
  - Right ascension, declination
  - Proper motions
  - Parallax
  - Specified in .xlsx file

Identifier	a (km)	e	i (deg)	LAN (deg)	omega (deg)	nu (deg)	drag coefficient	area mass ratio (m^2 kg^-1)
SSO_450	6828.14	0	97.2188	5	0	0	2.2	0.002083333
SSO_550	6928.14	0	97.5976	5	0	0	2.2	0.002083333
POL_450	6828.14	0	90	5	0	0	2.2	0.002083333
ISS_LIKE	6793.14	0.000603	51.6403	72.8326	93.4934	0	2.2	0.002083333

Satellite Specifications

Identifier	HD Number	Right Ascension (deg)	Declination (deg)	Proper Motion (RA) (arcsec yr^-1)	Proper Motion (Dec) (arcsec yr^-1)	Parallax (arcsec)
alf Vir	116658	201.2982474	-11.16131949	-0.04235	-0.03067	0.01306
alf CMa	48915	101.2871553	-16.71611586	-0.54601	-1.22307	0.37921
zet Ori A	37742	85.18969643	-1.942572322	0.004	0.0025	0
eps Ori	37128	84.05338894	-1.20191914	0.00144	-0.00078	0.00165
gam Ori	35468	81.28276356	6.34970326	-0.00811	-0.01288	0.01292
bet Ori	34085	78.63446707	-8.20163836	0.00131	0.0005	0.00378
bet CMa	44743	95.67493897	-17.95591871	-0.00323	-0.00078	0.00662
kap Ori	38771	86.93912017	-9.669604919	0.00146	-0.00128	0.00504
iot Ori	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Star Specifications

Outputs

- Returns results in the form of Satellite objects that contain:
  - Ephemeris data for the entire propagation period, at the specified ephemeris reporting time step
    - Satellite position and velocity data in ECI coordinates
  - Occultation objects containing occultation data, at the specified occultation reporting time step
    - Occ_Event objects include data over the course of an occultation:
      - Name of the star which is being occulted
      - Time stamps, in seconds since the propagation start time*
      - LLA of the tangent point
      - ECI position of the tangent point
      - Angle between the tangent point and star vector
        - Quality check: should always be 90 degrees
      - Angle between tangent point position and satellite position
        - Equivalent to angle θ in earlier diagrams
      - Satellite ECI position at the time stamp
- Inertial cartesian coordinates are based in the International Celestial Reference Frame
- Geographic coordinates are provided in the WGS-84 coordinate system

Code Overview

Config_Reader.m
- Reads general configuration options

Options_Reader.m
- Reads simulation specific options

Sat_Data_Importer.m
- Reads satellite data

Star_Data_Importer.m
- Reads star data

Occult_Driver.m
- Driver script for the Stellar Occultation Mission Planner

STK_Driver.m
- Controls interface between STK and MATLAB
    - Ephemeris and data retrieval for occultation calculations

Occulter.m
- Calculates occultation properties from ephemeris data

Output.m
- Produces plots and reports for the simulation

ANSYS Systems Tool Kit
- Orbit propagation
- Line-of-sight access calculation between the satellite and star

Code Overview

Satellite.m
- Object for storing satellite data, including the associated occultation data

Satellite_Collection.m
- Object for organizing the various satellite objects produced in the simulation

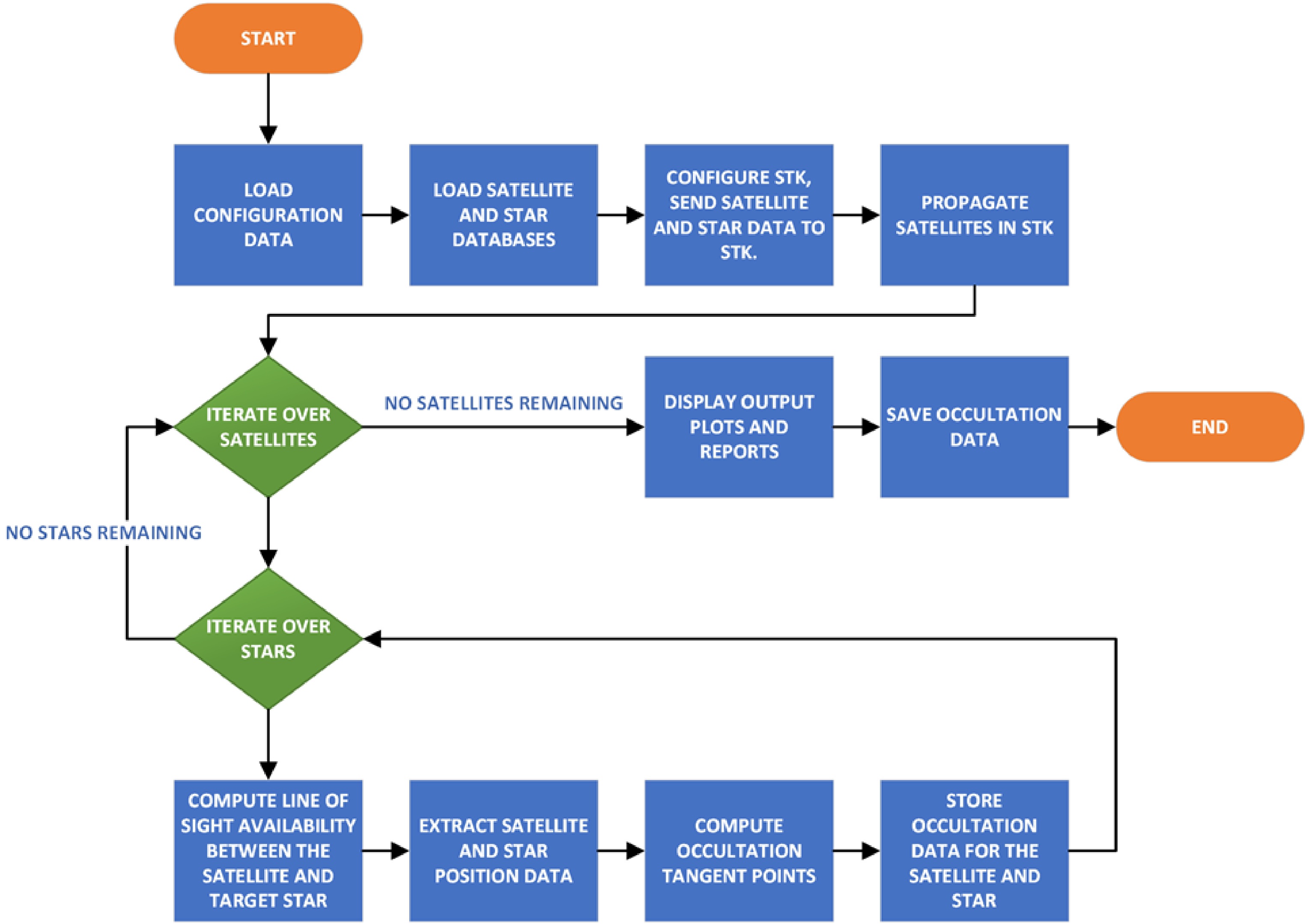
Star.m
- Object for storing star data

Star_Collection.m
- Object for organizing the various star objects produced in the simulation

Occ_Event.m
- Object for storing occultation data. Occ_Event objects are stored with the associated satellite object

Datetime_Helper.m
- Helper class with useful functions for converting between different representations of time
    - Useful for when different functions (including built-in MATLAB functions or plotting functions) require different time representations
    - Converts between date-time string formats, MATLAB DateTime objects, epoch seconds, and UTC times (various formats as needed)

Code Flow Chart



Case Study: Output Overview

- Review output options available
- Case Study:
    - Examine occultations for 5 stars during Northern hemisphere winter in the Arctic and Antarctic regions

Satellite Data

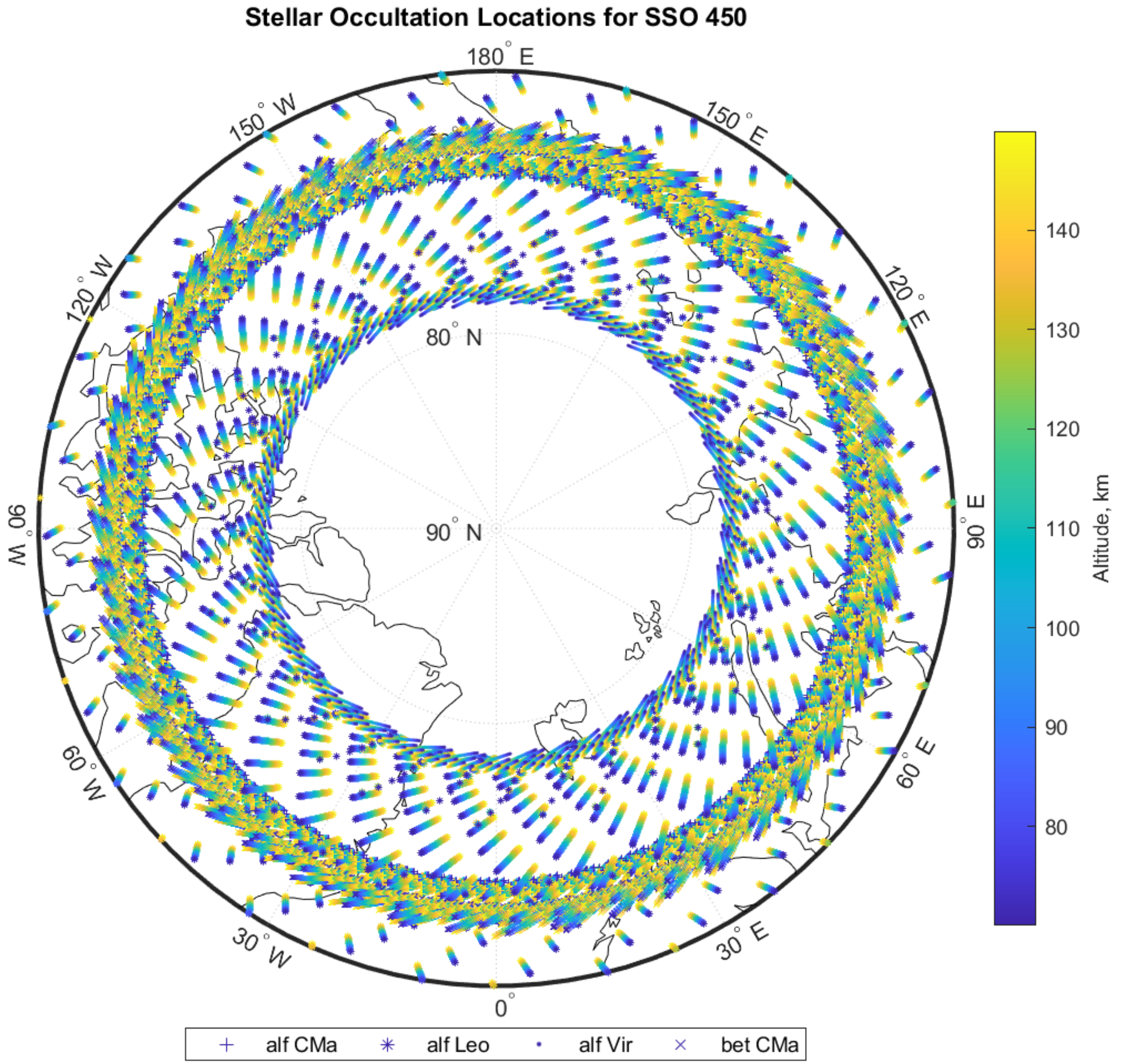
Identifier	Semi-major Axis (km)	Eccentricity	Inclination (degrees)	Longitude of Ascending Node (degrees)	Argument of Perigee (degrees)
SSO_450	6828.14	0	97.2188	5	0
SSO_550	6928.14	0	97.5976	5	0
POL_450	6828.14	0	90	5	0
ISS_LIKE	6793.14	0.000603	51.6403	72.8326	93.4934

All satellites use a drag coefficient of 2.2 and area-mass ratio of 0.002083 m^2 kg^{-1} (Corresponds to a 6U CubeSat

Option	Value
ephem_step_size	600 s
occ_step_size	0.5 s
start_time	2020:09:22:00:00:00.000
stop_time	2021:03:21:00:00:00.000
oa_start_time	2020:11:01:00:00:00.000
oa_stop_time	2021:03:21:00:00:00.000
propagator	HPOP
sat_names	
star_names	alf_Vir, alf_CMa, bet_CMa, del_Sco, alf_Leo
lat_min	66.56361, -90 degrees
lat_max	90, -66.56361 degrees
long_min	-180, -180 degrees
long_max	180, 180 degrees
alt_min	70, 70 km
alt_max	150, 150 km
max_star_angle	40 degrees
min_sun_angle	90 degrees
min_moon_anlge	45 degrees
atmos_model	eMSIS00 (NRL MSIS 2000)

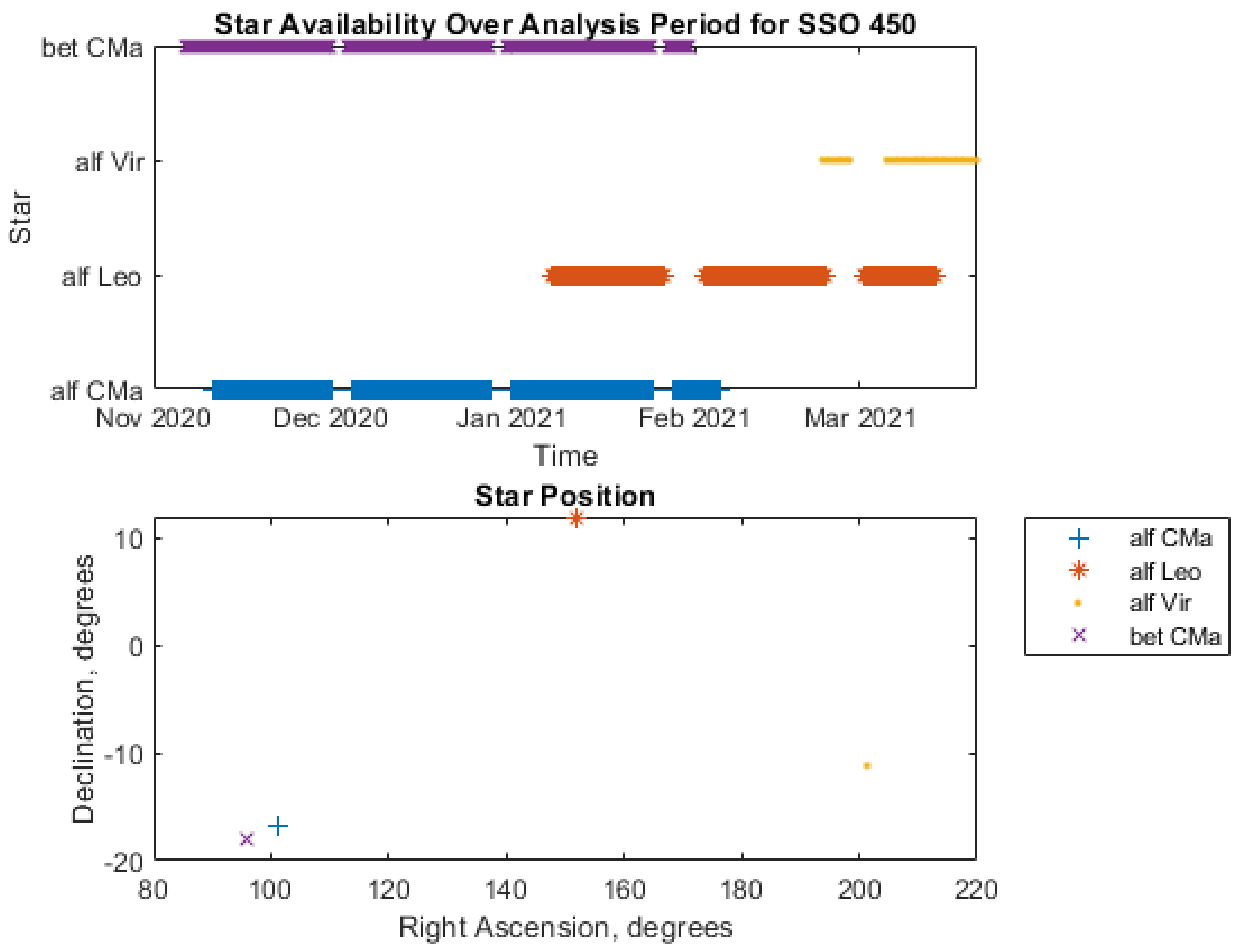
Occultation Locations on Geographic Map

- region_2d_plot
- Plots location of occultation tangent points on a geographic map for the entire occultation analysis period
  - For one geographic region of interest
- Includes all stars for which valid occultations exist



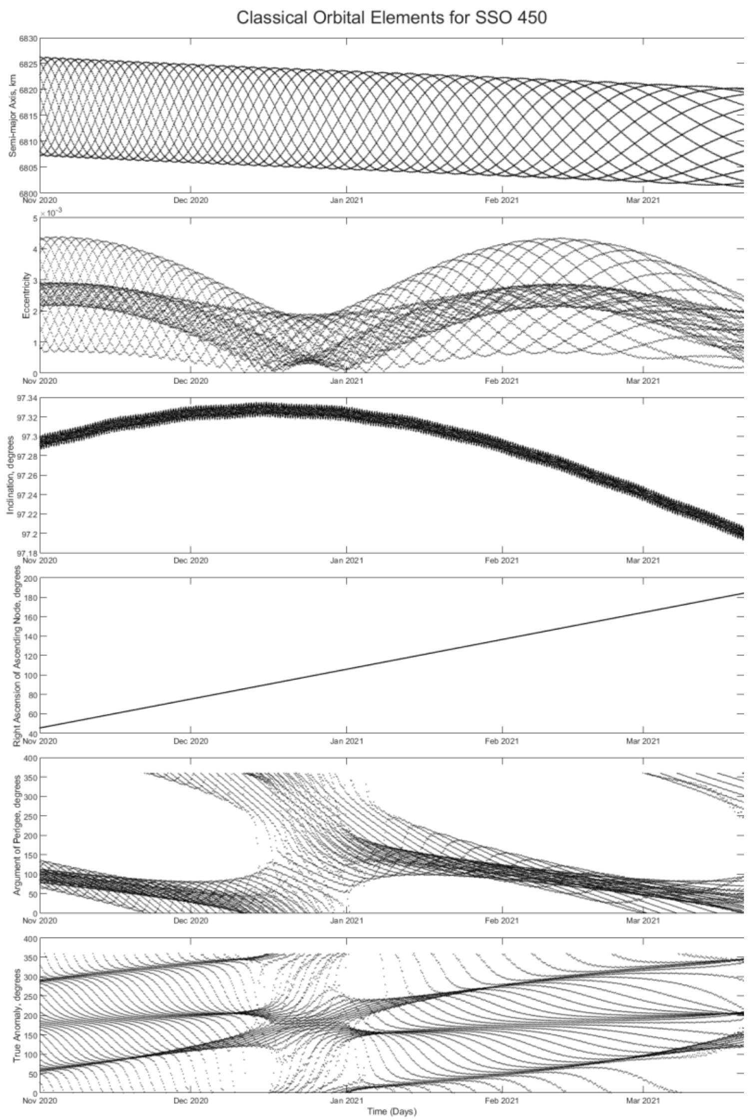
Star Availability

- star_avail
- Plots availability of the stars with valid occultations over the analysis time period
  - If a star does not show up, there were no valid occultations for it
  - Plots availability for one geographic region of interest
- Also plots the right ascension and declination of the stars



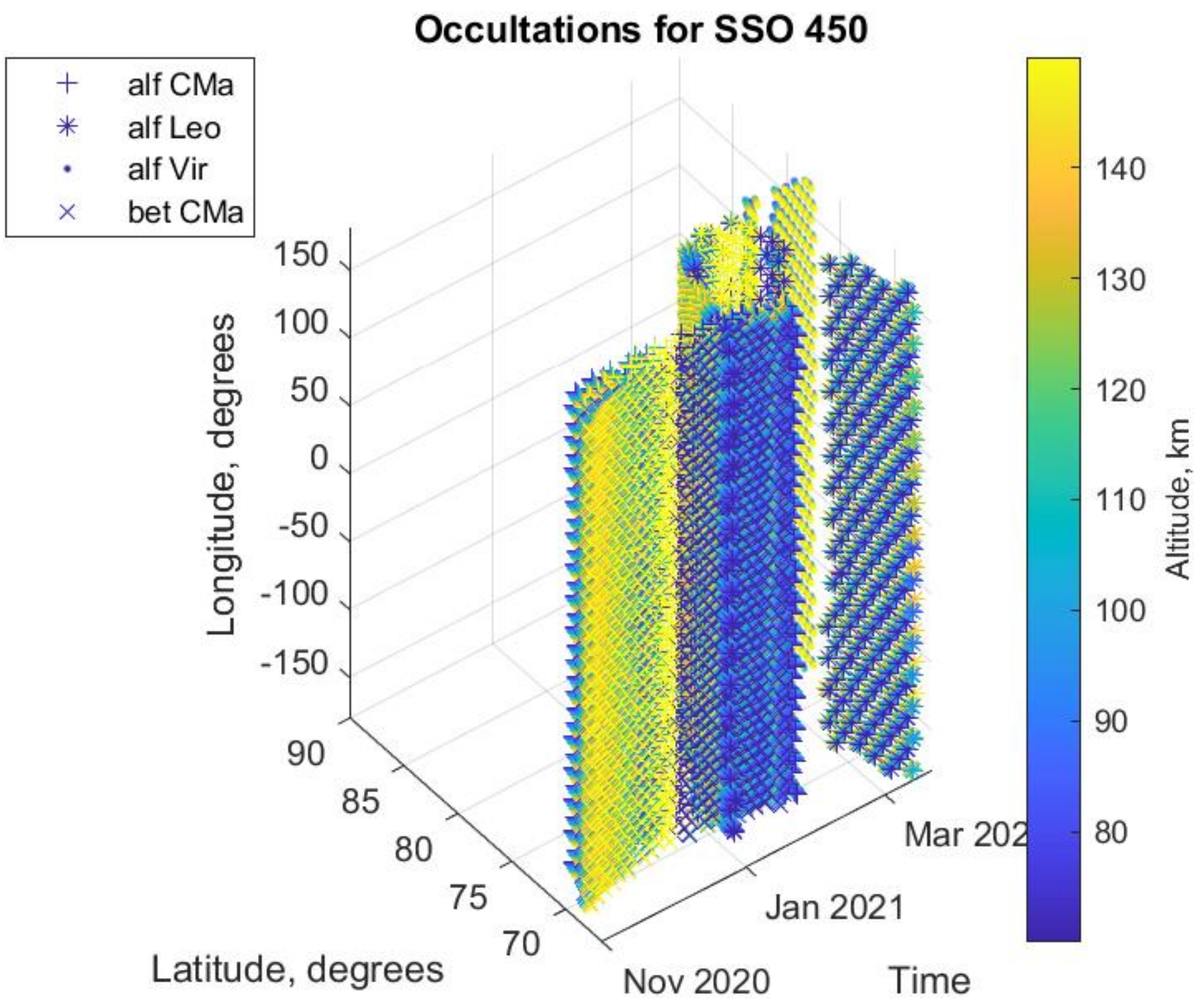
Classical Orbital Elements

- plot_classical
- Plots the classical orbital elements for the satellite being analyzed, over the analysis time period
  - Step size is determined by ephem_step_size



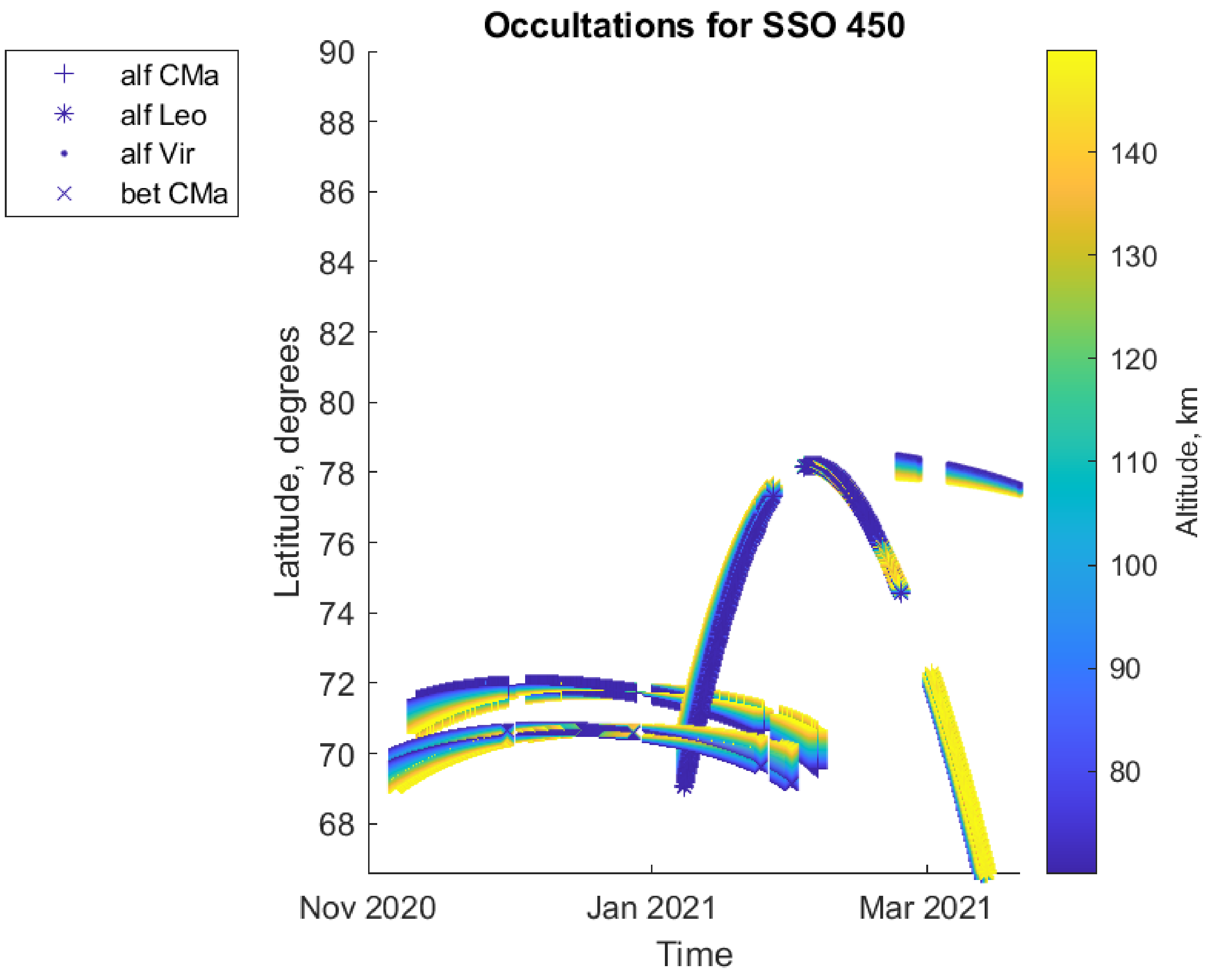
LLA of All Occultations over Time

- plot_occ_events_all
- Plots the occultations of all stars for a satellite for one geographic region of interest
- 3D plot with time, latitude, and longitude axes, colorbar indicates altitude



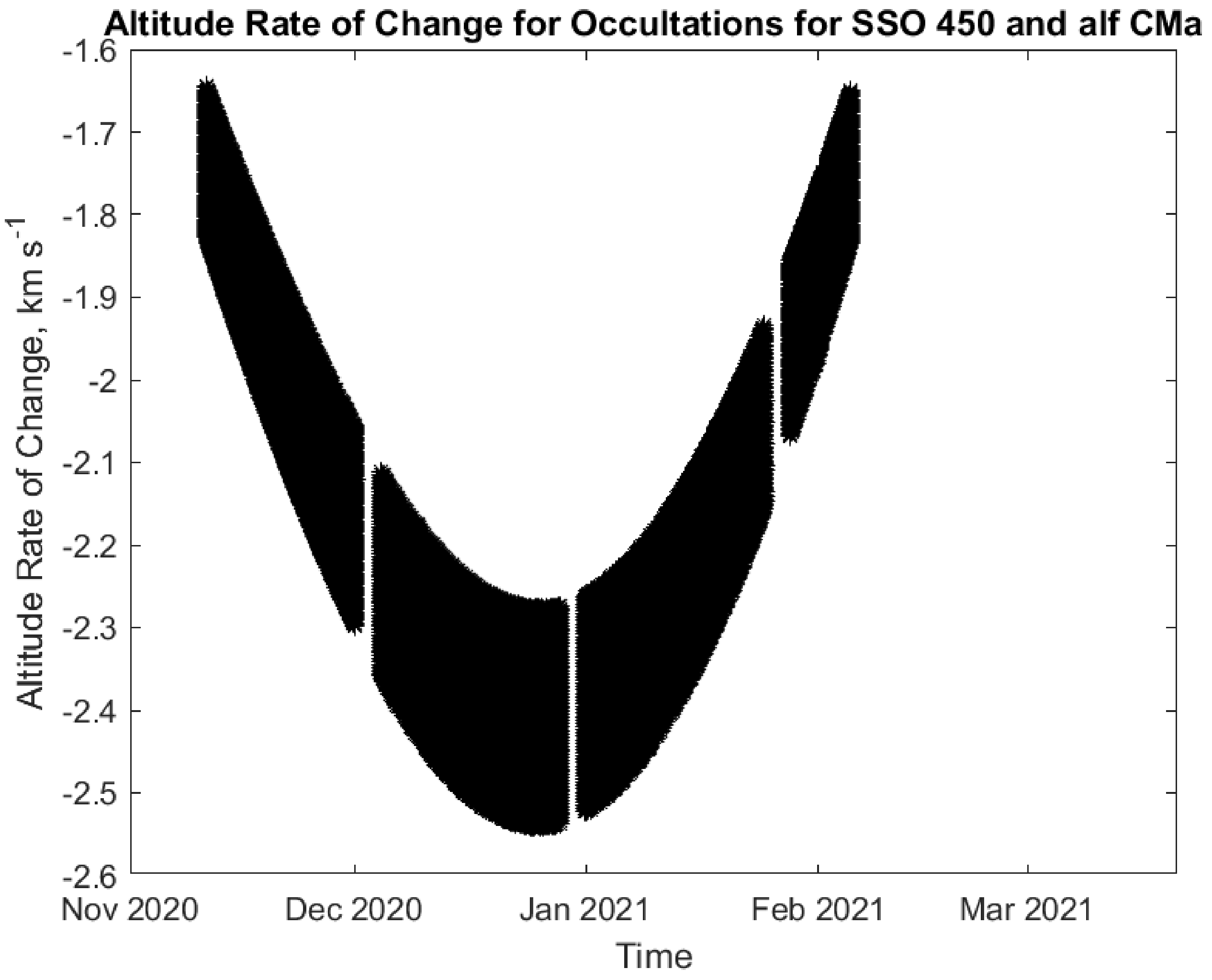
Latitude and Altitude of All Occultations over Time

- plot_occ_events_all_2
- Plots the occultations for all stars for a satellite for one geographic region of interest
- 2D plot with latitude vs time, altitude on the color bar



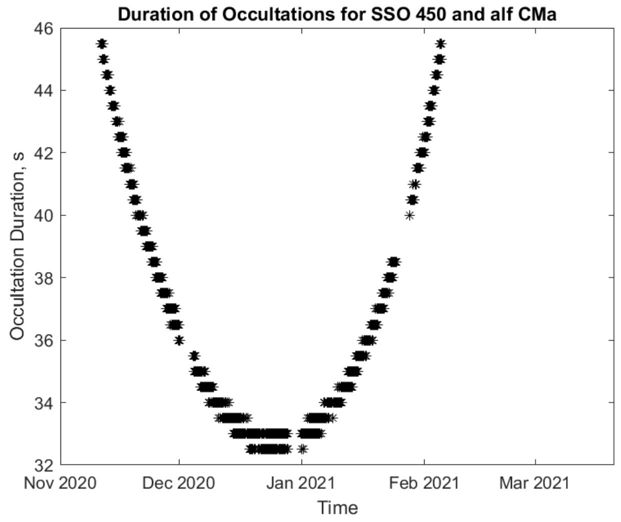
Altitude Rate of Change of the Tangent Point

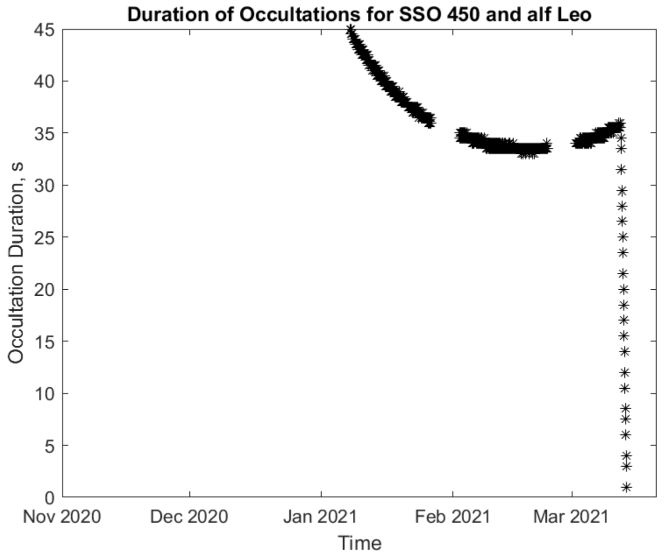
- plot_occ_events_alt_roc
- Plots the altitude rate of change for the occultation tangent point between a star and satellite over the specified time period, within a geographic range of interest
- Altitude rate of change determined by forward differencing of the tangent point altitude data



Occultation Duration

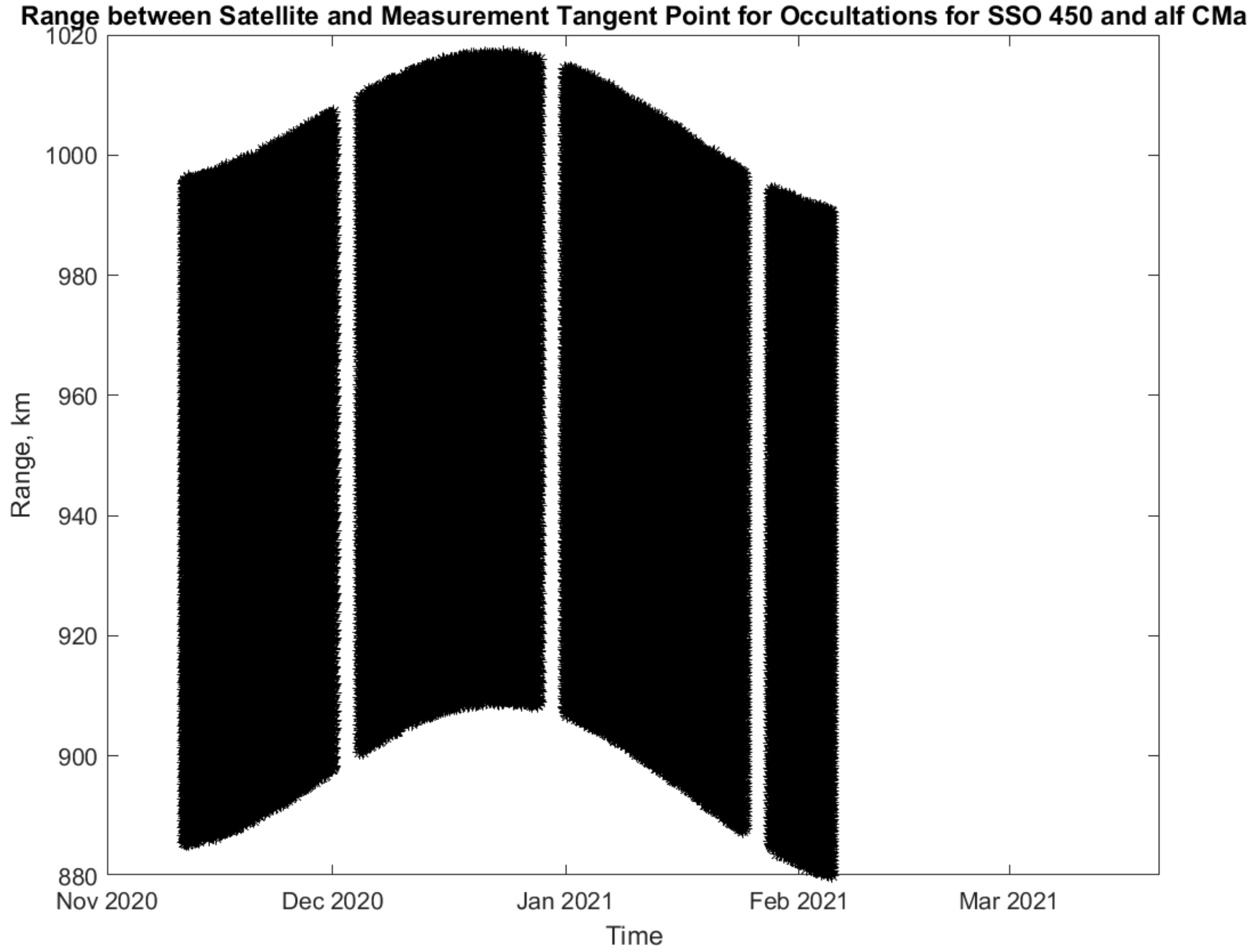
- plot_occ_events_duration
- Plots the duration of each occultation between a satellite and star
- An occultation is defined as the period between when the tangent point enters and exits the geographic region of interest
- Observed banding in the output is the result of the reporting time step (occ_step_size) that we selected in the simulation set up
  - Here, set to 0.5 s





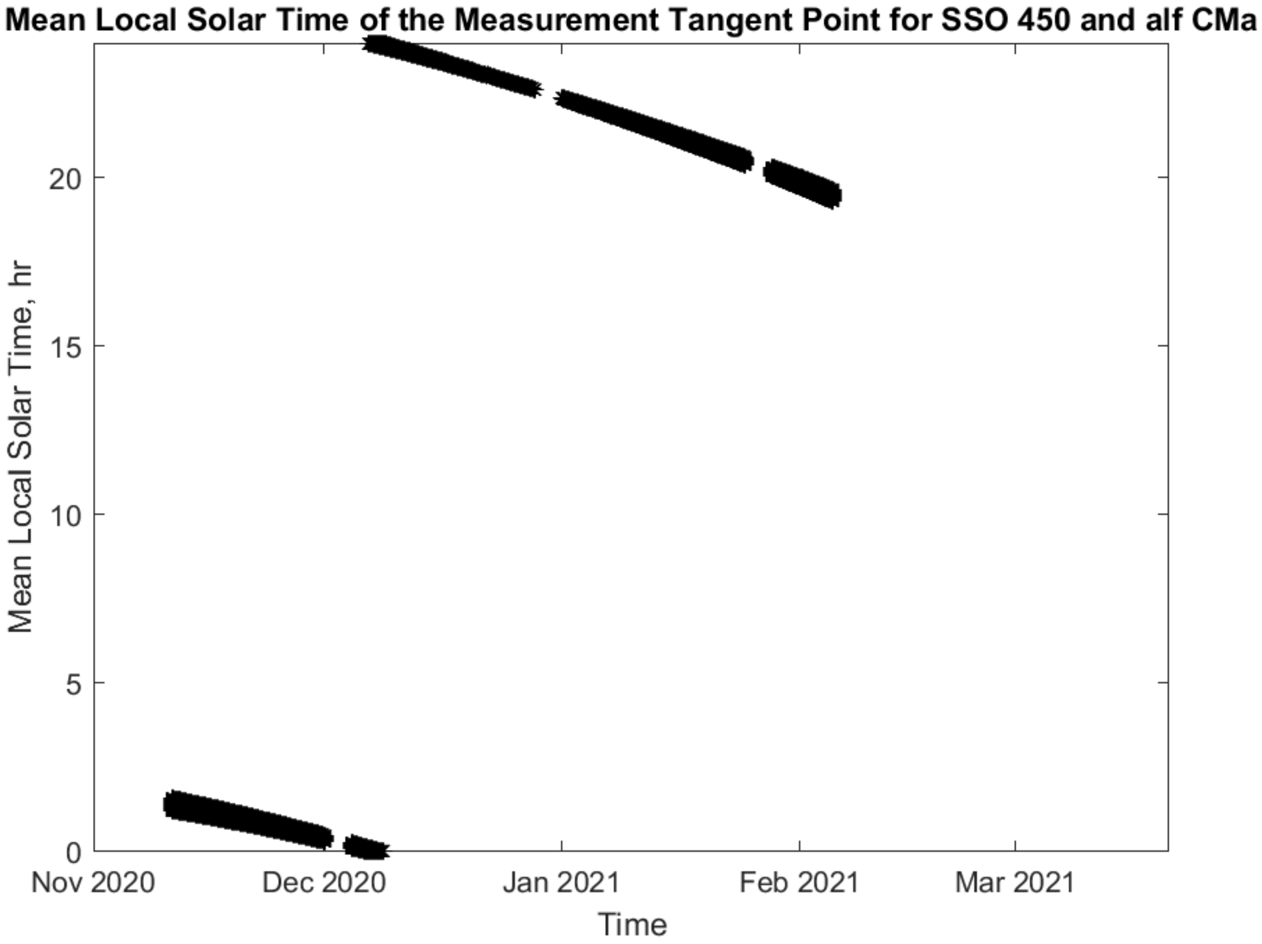
Range

- plot_occ_sat_range
- Plots the range between the satellite and the occultation tangent point for a given star, geographic region of interest, and time period



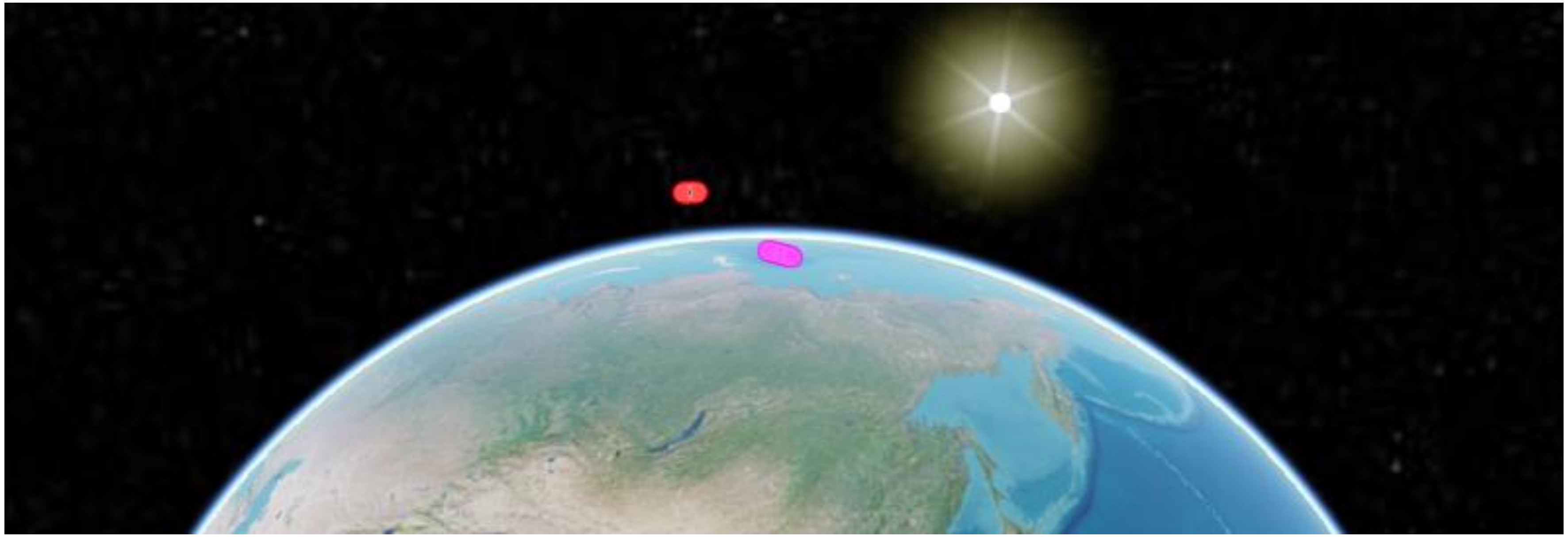
Local Solar Time of the Occultation Tangent Point

- plot_occ_lst
- Plots the local solar time for the occultation tangent points of a satellite and star, within a geographic region of interest and time period of interest
- Calculated as
  - $LST = \left(UTC + \Delta UT1 + \frac{\lambda}{15}\right) \% \ 24$



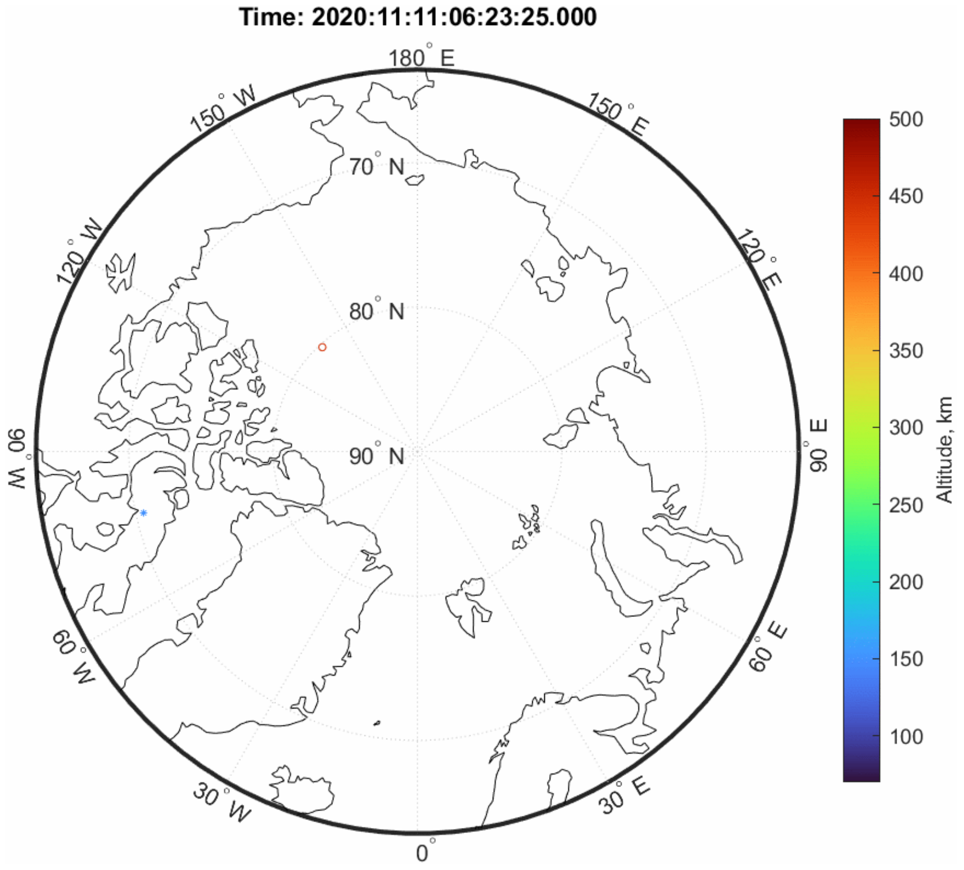
3D representation of Occultation

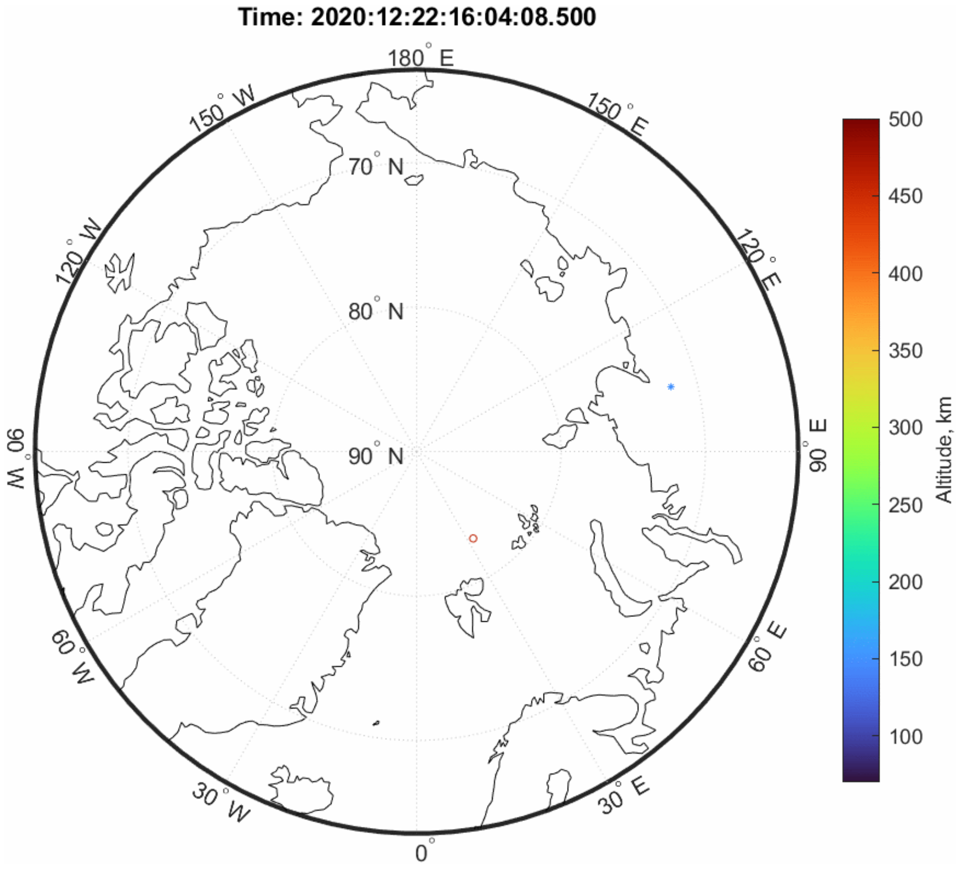
- sat_occ_geo_plot
- Creates a 3D representation of the satellite and occultation tangent point over the course of a single occultation



Occultation Animations

- region_2d_animate
- Animates the ground tracks of the satellite (red) and occultation tangent points (blue) for a satellite and star





Report

- Produces a report with summary statistics for each satellite and target star
- Reports:
  - Star Name
  - HD Number
  - Right Ascension (degrees)
  - Declination (degrees)
  - Number of Occultations
  - First time available
  - Last time available
  - Duration of occultation availability (days)
  - Minimum latitude observed (degrees)
  - Maximum latitude observed (degrees)
  - Change in observation latitude between minimum and maximum (degrees)
  - Minimum altitude observed (km)
  - Maximum altitude observed (km)
  - Maximum magnitude of the altitude rate of change (km s^{-1})

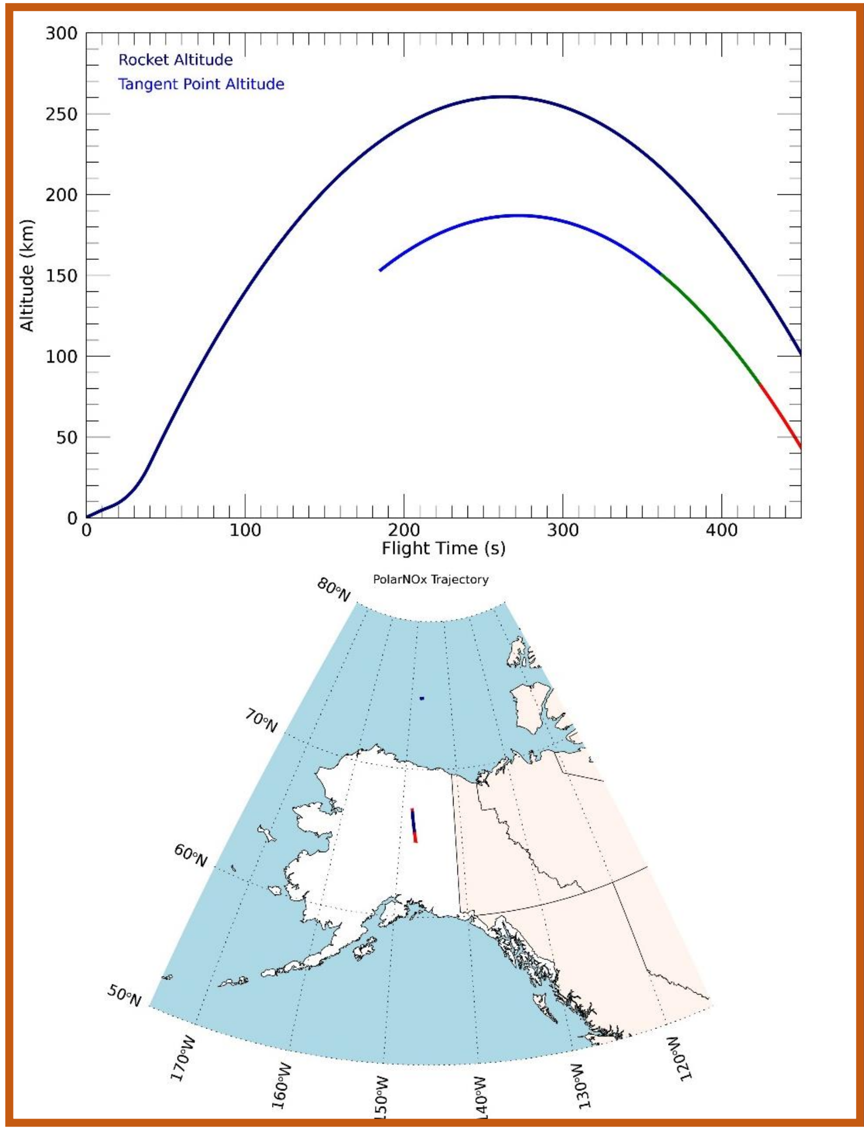
star_name	hd_num	ra	dec	num_occ	min_time	max_time	avail_dur	min_lat	max_lat	delta_lat	min_alt	max_alt	max_alt_roc
"alf_CMa"	48915	101.29	-16.716	1175	11-Nov-2020 06:23:24	05-Feb-2021 10:19:24	86.164 days	69.565	71.97	2.4048	70.002	150	2.5416
"alf_Leo"	87901	152.09	11.967	801	07-Jan-2021 21:27:54	13-Mar-2021 22:36:16	65.047 days	66.564	78.211	11.647	70	150	2.4928
"alf_Vir"	1.1666e+05	201.3	-11.161	309	22-Feb-2021 17:50:42	20-Mar-2021 22:31:13	26.195 days	77.362	78.494	1.1317	70.003	150	2.417
"bet_CMa"	44743	95.675	-17.956	1176	06-Nov-2020 15:46:51	30-Jan-2021 20:27:09	85.195 days	69.012	70.708	1.6954	70.002	150	2.5374

Validation

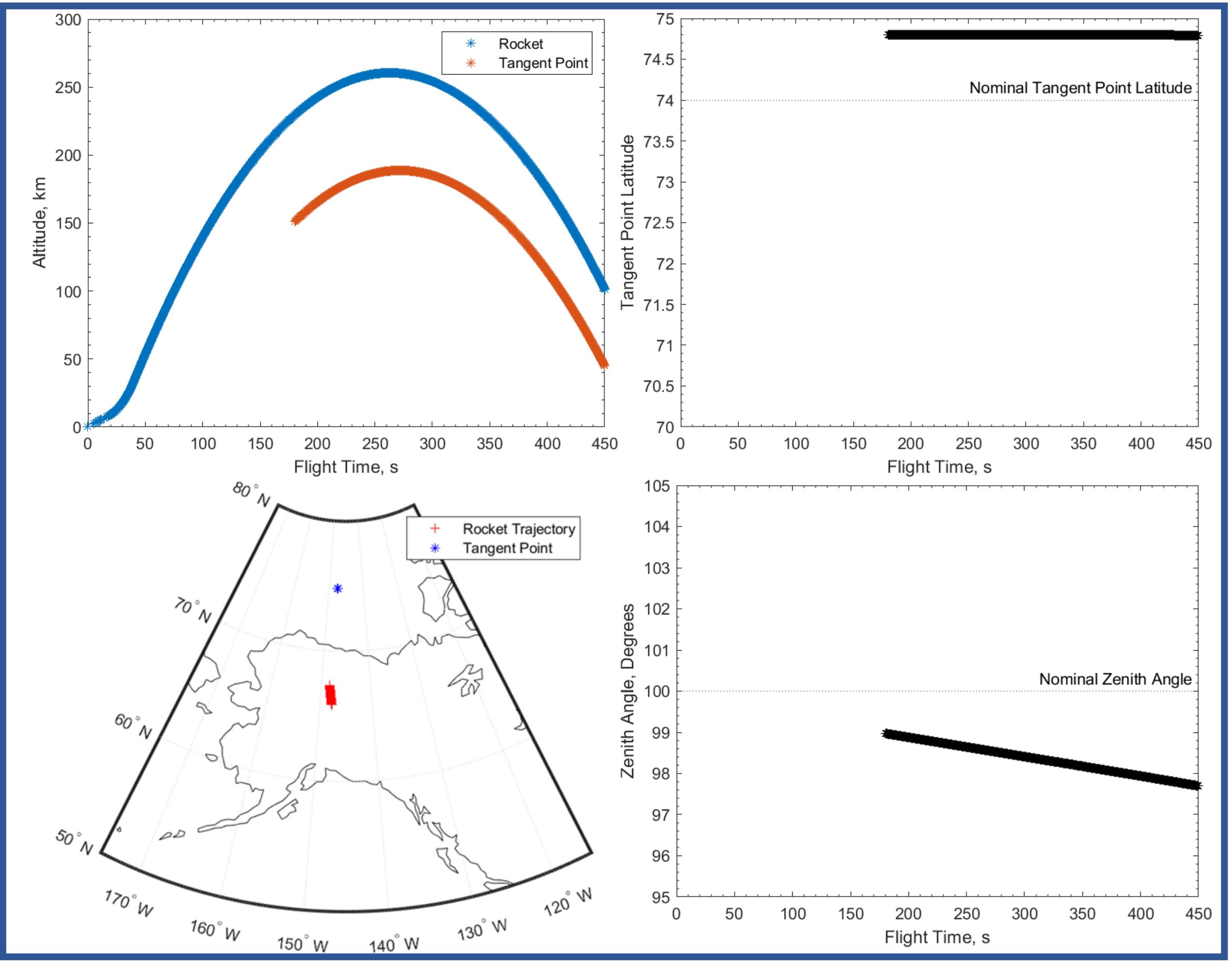
- To validate the output of the Stellar Occultation Mission Planner, data from Dr. Bailey's PolarNOx sounding rocket flight was used to calculate occultation tangent point properties and compared to the published results
  - Launch Date / Time: January 27, 2020 04:40 Local Time (Poker Flat Research Range)
  - Target Star: Algenib
    - RA: 00:13:14.1512308
    - Dec: +15:11:00.936759
  - Nominal Zenith Angle: 100°
  - Nominal Tangent Point Latitude: 74°
  - Rocket LLA data with time stamps (seconds since launch)
- "Sounding Rocket Observations of Nitric Oxide in the Polar Night"

	A	B	C	D
1	Time	Alt	Lat	Long
2	-359	0.23	65.1302	-147.483
3	-358.95	0.2301	65.1302	-147.483
4	-358.9	0.2301	65.1302	-147.483
5	-358.85	0.2301	65.1302	-147.483
6	-358.8	0.2301	65.1302	-147.483
7	-358.75	0.2301	65.1302	-147.483
8	-358.7	0.2301	65.1302	-147.483
9	-358.65	0.2301	65.1302	-147.483
10	-358.6	0.2301	65.1302	-147.483
11	-358.55	0.2301	65.1302	-147.483
12	-358.5	0.2301	65.1302	-147.483
13	-358.45	0.2301	65.1302	-147.483
14	-358.4	0.2301	65.1302	-147.483
15	-358.35	0.2302	65.1302	-147.483
16	-358.3	0.2302	65.1302	-147.483
17	-358.25	0.2302	65.1302	-147.483
18	-358.2	0.2302	65.1302	-147.483

Validation



Rocket Altitude
Tangent Point Altitude
Altitude (km)
Flight Time (s)
PolarNOx Trajectory
80°N
70°N
60°N
50°N
170°W
160°W
150°W
140°W
130°W
120°W



Rocket
Tangent Point
Altitude, km
Flight Time, s
Nominal Tangent Point Latitude
Tangent Point Latitude
Flight Time, s
Rocket Trajectory
Tangent Point
80° N
70° N
60° N
50° N
170° W
160° W
150° W
140° W
130° W
120° W
Nominal Zenith Angle
Zenith Angle, Degrees
Flight Time, s

Note on Dependencies

- Developed using:
  - MATLAB 2022a
    - Aerospace Toolbox
    - Mapping Toolbox
  - ANSYS STK version 12.2

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