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OPAL CubeSatellite Flight and Line of Sight Integration Modeling

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Abstract

The Optical Profiling of the Atmospheric Limb (OPAL) mission is funded by NSF to gather global thermosphere temperatures. OPAL will be able to resolve the temperature profiles through observing day-time emissions of O_2 A-band (~760nm) emissions. This is done by using integrated line-of-sight measurements of the A-band through a tangential view of the atmosphere down to 90km and up to 140 km (shown in Figure 1). The OPAL instrument is on a 3U CubeSatellite (30cm×10cm×10cm) and is expected to follow the International Space Station (ISS) orbit (~400km altitude). Having an accurate model of the OPAL CubeSatellite's position and the attitude of its optical system are crucial in checking the instruments' ability to detect space weather signatures in the temperature data (i.e. solar flares and gravity waves). Using Matlab and Analysis Graphics Inc.'s (AGI) System Tool Kit (STK) for mission modeling and analysis, we modeled position of OPAL and its line of sight, and this information in the future will be combined with other information about the data interpretation and collection.

1. Introduction

Understanding the lower thermosphere, the range of 90km to 140km above the surface of the Earth, is a growing interest for many areas of research within space weather. This region of the atmosphere constitutes space weather due to waves coming up from below, and disturbances happening on the Sun. Large temperature changes that occur at that altitude are due to the absorption of the solar extreme ultraviolet (EUV) radiation. This region has the O_2 A-band (~760nm), which is excited from the EUV radiation and deviates due to different temperatures. The known temperature changes in the waveband caused it to be the focus of the OPAL instrument. The OPAL CubeSattelite is shown on the right side (of Figure 1) with the field of view (FOV) in blue with region of interest between the yellow lines. This figure remains constant throughout the flight of the CubeSat because the FOV will remain fixed in that range of altitudes as it traverses the Earth. Over time, the OPAL CubeSat will create a map of temperature changes in this region across the Earth.

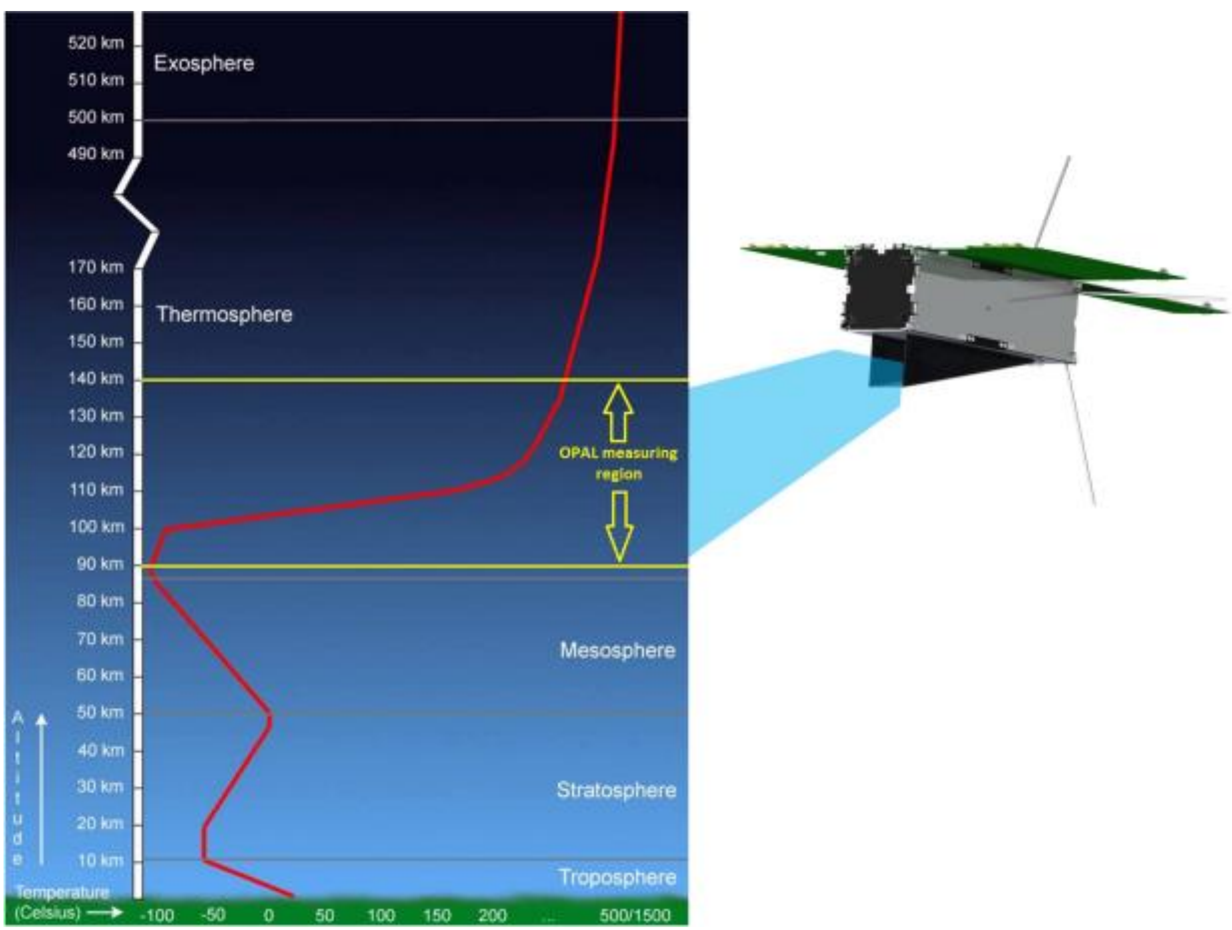

Figure 1: The OPAL CubeSat shown with its intended field of view (FOV) in the lower thermosphere. [2,6]

2. Problem

In order to examine if OPAL is capable to resolve space weather we need to have software ready to analyze the OPAL CubeSattelite output on the ground without actual OPAL measurements of the lower thermosphere. A model of the OPAL line of sight (LOS) with a model of the atmosphere emission of the O_2 A-band needs to be used to create a model of the expected output of OPAL. To obtain a model of the LOS there needs to be a model of the OPAL orbit and its field of view (FOV).

3. Model of the OPAL Orbit

Analysis Graphics Inc. (AGI) made the System Tool Kit (STK) for mission modeling and analysis. The OPAL flight model is based on the International Space Station (ISS) orbit because it is planned to be launched from the ISS. The model made is from April 26th 2015 at 18:00 to April 27th 2015 at 18:00(UTCG) with step sizes of 1 second. Orbit model is based off of the World Geodesic System 1984 (WGS84) which is what modern Global Positioning System (GPS) uses as its model of the Earth-centered and Earth-fixed terrestrial reference system.

Parameter	**Units**	**Value**
Latitude (t=0)	rad	0.44646
Longitude (t=0)	rad	0.05221
Altitude (t=0)	m	401662.97866
Position X (t=0)	m	6110480.31200
Position Y (t=0)	m	319377.810910
Position Z (t=0)	m	2910673.78130
Vtot (t=0)	m/s	7672.09245
Vx (t=0)	m/s	-2669.65492
Vy (t=0)	m/s	5141.47641
Vz (t=0)	m/s	5029.82757
Semi-major Axis	m	6378137.0
Flattening Factor of the Earth		298.257223563
Normal Mean Angular Velocity of the Earth	rad/s	7292115×10^{-11}
Geocentric Gravitational Constant (including mass of the atmosphere)	m^3/s^2	$3.986004418 \times 10^{14}$

Table 1: Parameters of the OPAL CubeSat modeled as a body orbiting the Earth [2].

A single orbit in this period is shown in Figure 2 with each tick mark is the one second step with latitude and longitude. The position in latitude and longitude was not an output option for STK software. Instead we were able to use WGS84 (Earth-centered) Cartesian coordinates to be exported in a text file and converted in a Matlab function created for the transform from Earth centered Cartesian to latitude, longitude, and altitude.

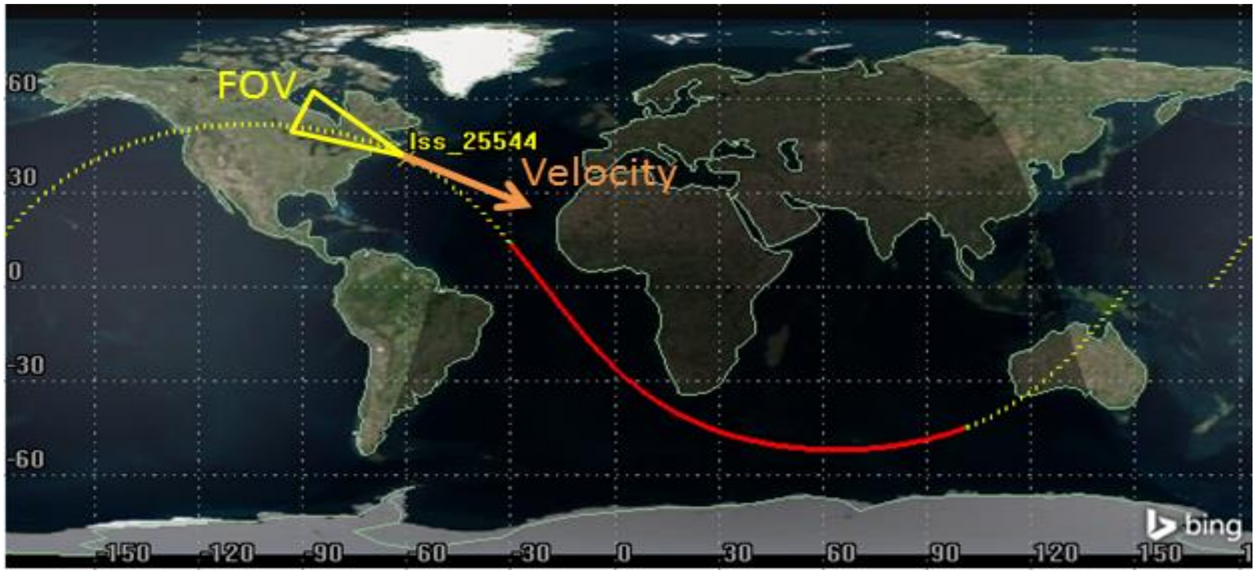

Figure 2: 2-D map of the flight path with yellow representing OPAL in sunlit regions and red in the umbra. Umbra and sunlit regions are not correlated exactly with the shadowed regions on the Earth because of the altitude of the CubeSat.

4. OPAL Field of View

In reference to the map, the CubeSat is transiting from left to right along the path, but the OPAL optics are looking out the aft (back) of the velocity of CubeSat. As shown in Figure 1, there must be a downward angle to get the field of view (FOV) to completely encompass the region of interest (90-140km

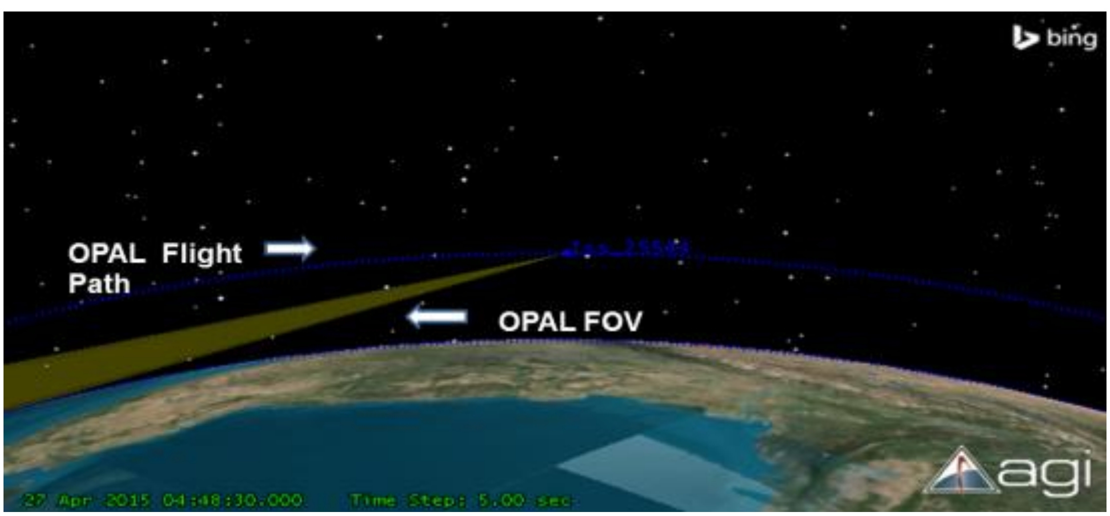

Figure 3: View of the tangential nature of the line of sight (LOS).

altitude). Figure 3 shows a side-view of FOV relative to the orbit of the CubeSat in order to better understand the comparison to the velocity and FOV.

5. Line of Sight Calculation

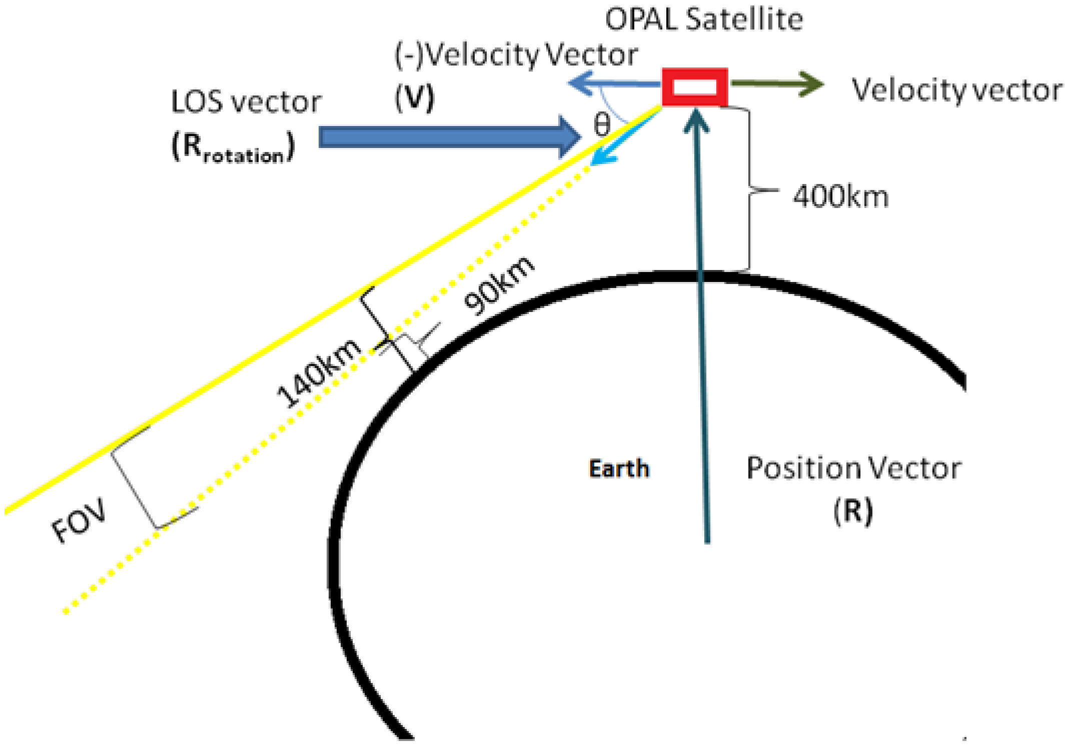

Figure 4: Visual interpretation for the use of the Rodrigues' rotation formula, and its use in the LOS and FOV.

This downward angle between the OPAL flight path and the FOV was calculated mathematically using Rodrigues' rotation formula. As seen in Figure 3, the cross-sectional FOV and the flight path are coplanar. Starting with a vector pointing out of the page, as a perpendicular pivot point to the FOV plane, it can be rotated an angle θ to have a new vector $R_{rotation}$ that points along the line of sight (LOS) down the middle of the FOV to a tangent point at 90km (the minimum viewing altitude). The perpendicular vector k, denoted in Figure 5, is found

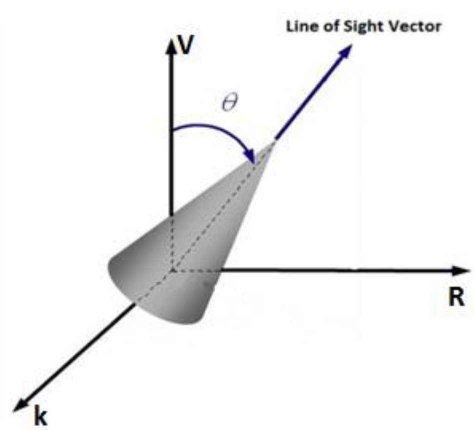

Figure 5: Visual interpretation for the use of the Rodrigues' rotation formula.

by taking the cross-product of vectors R and V. Where position vector R (X,Y,Z) of OPAL with the $V_{roatation}$ is the velocity vector pointing backwards -V (-Vx,-Vy,-Vz). Then vectors k and $V_{roatation}$ are used in the Rodrigues' rotation formula which is defined below[1].

$$\boldsymbol{V_{Rotation} = V cos\theta + (k \times V) sin\theta + k(k \cdot V)(1 - cos\theta)}$$

Once the $V_{roatation}$ calculation is made into a Matlab function, it is normalized to 1km. Then going through different angles of theta (in the above equation) that produces $V_{roatation}$ pointing at the minimum altitude of the 90km was the next challenge. An angle of 17.3° gives a minimum altitude of 93.3483km and 17.4° has the minimum at 89.8163km, and shows that knowing how accurately the CubeSat can point will be a key to having accurate altitude range seen by OPAL. Figure 5 is a plot of that check for accuracy, as it starts from the CubeSat altitude of 400 km and views the atmospheric limb down to the desired minimum altitude and climbs in altitude back out the other side of the limb at an angle of 17.394° to a minimum altitude of 90.0287km. Table 2 has the elevation angle defined as 17 ° for the OPAL instrument, and the calculations for the rotation formula has confirmed it at ~17 ° elevation. This discrepancy might be due to defining the orientation of the CubeSat. The calculations presented had the satellite pointing along the velocity vector, while the Sullivan paper might have had the CubeSat oriented tangential to the Earth.

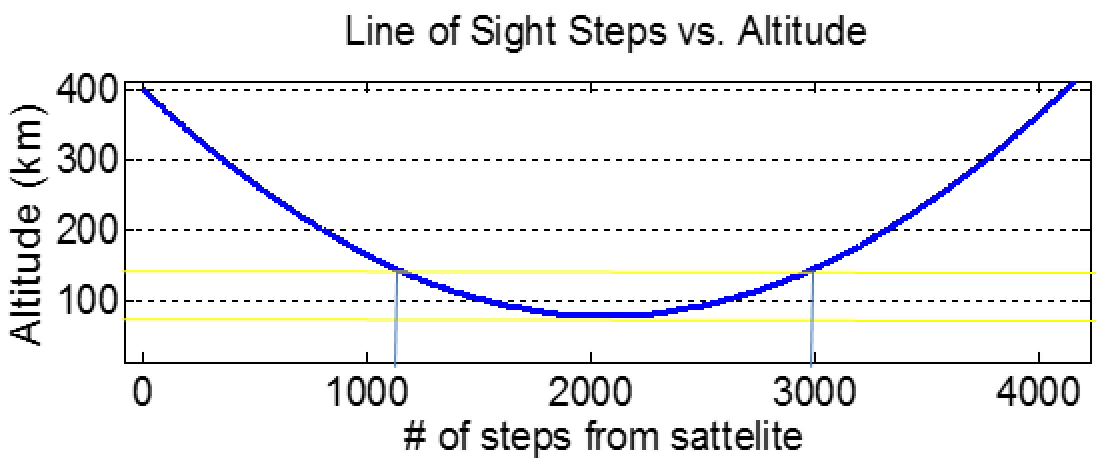

Figure 6: Having a proper LOS gives the above graph of altitude as you step along the LOS. Starting from the altitude OPAL (400km) and a minimum of the tangential FOV of 90km before exiting the atmosphere out the other side and gaining altitude again; we have the yellow lines denoting the encased LOS, and the light blue represents the region that we are integrating the O_2 A-band.

Now a LOS is defined from the OPAL CubeSat down to the tangential altitude of 90km in 1 km steps. The FOV is, however, more than just that one line; it is an entire region of space defined by the optical entrance of the OPAL system (shown in Figure 6). A rectangular FOV is used for OPAL and more detail is given in Table 2. The parameters specified in Table 2 were also imported into STK as the sensor's FOV and is seen in Figure 6.

FOV	
Height	2.5º
Width	11º
Orientation	
Azimuthal	180º
Elevation	17º

Table 2: FOV parameters [6]

6. Future Work

This LOS is now around 2000 points within the region of interest with complete longitude, latitude, and altitude coordinates. From here another group member's atmospheric model can give emission intensity and wavelength as a function of altitude, latitude, longitude, temperature, and solar zenith angle as a function of time of day. The emission data at every point along the LOS is summed from the 140km region from the right to the left of the 90km minimum of Figure 5. Summed emission is plotted as a function of intensity vs. wavelength as a model of what the detector would send as its output. Our third group member then takes this model of OPAL output and uses Abel inversion techniques to reinterpret our model to get back a function of altitude and temperature that was in our atmospheric model. Currently this can only be done along the one LOS.

Final step in the LOS is to expand it to the entire FOV. This requires stepping the rotation of the pointing vector from initial position on the bottom-middle of the FOV by intervals of angles across the bottom and all the way to the top tangential altitude of 140km. Once that is done, the entire outlined procedure for the one LOS is done hundreds of more times for that 1 sec step of the OPAL CubeSat position. This integration is repeated over total integration time of 20 seconds, and as OPAL steps along its orbit, the FOV and LOS rotate to adjust to the new pointing vector that makes the 90km altitude tangential minimum (as described by Figures 4,5).

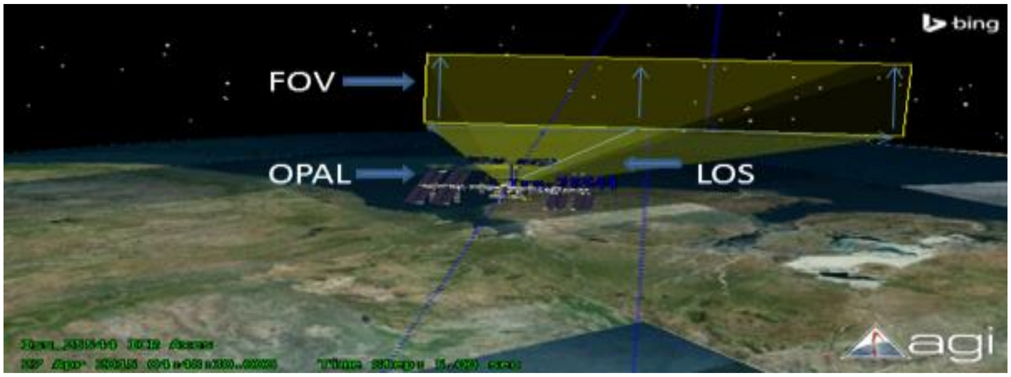

Figure 6: Model of the OPAL (3D-modeled with the ISS) orbit (blue), FOV (yellow), and light blue line denoting the originally calculated LOS with the light blue arrows showing where the line of sight needs to be included to the entire FOV to get a complete picture of the OPAL instrument's output.

References

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