Simulation and Analysis of the Detection Opportunities for the Multi-Azimuth/Multi-Waveband Ultraviolet Imager on Tiangong-02 Spacecraft Based on STK 10

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Abstract. Aiming at the detection mission of the multi-azimuth/multi-wave band ultraviolet (UV) imager on Tiangong-02 spacecraft, a simulation and analysis method of the detection opportunities based on Satellite Tool Kit 10(STK 10) is introduced. The UV imager has more than one working modes such as limb viewing, nadir viewing, solar occultation viewing. A detection model considering multiple conditions such as orbit, attitude, installation angle, field of view, lighting, etc. is provided by using the Analysis Workbench Tools of STK 10. Calculated results are used in the ground operating control system to schedule the detection plan. By analysis the actual detection images, the simulation method is proved to be effective and credible. This research can provide references for design and system simulation of space-based imaging payload, as well as the flight control task arrangement.

1. Introduction
Space-based atmospheric remote sensing detection is an internationally hotspot at present and plays an important role in the atmospheric environment monitoring and protection. It can be divided into three different detection modes: nadir viewing, solar occultation viewing and limb viewing. Each has its own characteristic and detection conditions. The nadir viewing has lower vertical resolution and cannot satisfy the research requirements for the interaction between atmospheric upper layer and lower layer, and the global change process. The solar occultation viewing has higher vertical resolution but lower space coverage than other two modes, because the detection opportunities are limited to the sunup and sunset. The limb viewing has enough vertical resolution and space coverage, so it finds favour with people increasingly and becomes the main detection mode [1].

At the early stage, the imager developed usually had only one detection mode. Some prime imagers for nadir viewing were Ozone monitoring instrument (OMI) [2] and ultraviolet ozone vertical profile for FY-3A meteorological satellite (SBUVS) [3]. The OMPS developed by the USA was an imager for limb viewing [4]. In recent years, the imagers with more than one detection modes have been developed, for example the UV panoramic sounder for nadir and limb viewing [5,6]. It is a trend that the designs of the imager are becoming more complex.

The multi-azimuth/multi-waveband ultraviolet (UV) imager on Tiangong-02 spacecraft launched in 2016 has three detection modes. The Annular detector and the front detector are integral parts of the imager and have different working modes and detection conditions as shown in the Table 1. The annular detector can detect nadir and limb atmosphere simultaneously and the front detector can detect...
limb and solar occultation separately. The lighting condition plays an important role in the detection as shown in the Table 1. Some working modes require that the camera must avoid direct sunlight otherwise it will be burned, but some other working modes require that the camera must receive direct sunlight. Because of the complexity of the imager and the multiple detection conditions, the simulation and analysis of detection opportunities is a great challenge for the flight control task arrangement. It is, moreover, important for ensuring the payload security.

### Table 1. Working modes and detection conditions

| Working modes          | Detection modes     | Field of view | Detection conditions                                                                 |
|------------------------|---------------------|---------------|--------------------------------------------------------------------------------------|
| Annular working mode one | limb/nadir viewing  | 70°~73° (limb) ±5° (nadir) | The atmosphere in the field of view is in the sunlight; The camera must avoid direct sunlight. |
| Annular working mode two | limb/nadir viewing  | 70°~73° (limb) ±5° (nadir) | The atmosphere in the field of view enters the umbra totally; The camera must avoid direct sunlight. |
| Front working mode one  | limb viewing        | 0.024° × 1.6° | The atmosphere in the field of view is in the sunlight; The camera must avoid direct sunlight. |
| Front working mode two  | limb viewing        | 0.024° × 1.6° | The atmosphere in the field of view enters the umbra totally; The camera must avoid direct sunlight. |
| Front working mode three | solar occultation viewing | ±7° | The sunlight can get into the field of view through the atmosphere (100km). |
| Front working mode four | solar occultation viewing | ±7° | The sunlight can get into the field of view but higher than the atmosphere (100km). |

In this paper, we describe a simulation and analysis method of the detection opportunities based on Satellite Tool Kit 10 (STK 10). Using the older versions such as STK 9, we can only do some simulation and analysis with simple and a small amount of conditions, and rely on other software to get further analytic results. A lot of researches have been made in combined simulation with STK and other software. Cui Chengguang [7] et al. introduced a method of passive multi-mode space-based atmospheric sounding spectrometers nadir and limb matching in flight with a combination of MATLAB and STK. Li Yaqiong [8] et al. made an application of MATLAB and STK combined simulation for design of spaceborne antenna servo system. By using the Analysis Workbench Tools, which are new and improved in STK 10, we can do some simulation and analysis with complex and a great amount of conditions and get the final analytic results directly. Calculated results are used in the ground operating control system of the Tiangong-02 spacecraft to schedule the detection plan. By analysis the actual detection images, the simulation method is proved to be effective and credible. This research can provide references for design and system simulation of space-based imaging payload, as well as the flight control task arrangement.

### 2. Geometry and mathematical model

#### 2.1. Geometry and mathematical model of the annular detector

The annular detector can detect nadir and limb atmosphere simultaneously. The two working modes both require that the camera must avoid direct sunlight. The camera with ±5° field of view for nadir viewing can avoid direct sunlight at any time because of the protection of the Earth. However, the camera with 70°~73° field of view for limb viewing will be exposed to the direct sunlight, when the angle $\alpha_0$ as shown in the Figure 1 and Figure 2 is between 70° and 73°. To avoid direct sunlight, the equation (1) as below must be satisfied.
73° < α₀, or α₀ < 70°  \hspace{1cm} (1)

As shown in the Figure 1, when the equation (2) is satisfied, the atmosphere in the field of view is in sunlight, both in limb and nadir viewing.

\[ \beta₀ + \theta₀ < 90° \]  \hspace{1cm} (2)

As shown in the Figure 2, when the equation (3) is satisfied, the atmosphere in the field of view enters the umbra totally, both in limb and nadir viewing.

\[ \beta₀ - \theta₀ > 90° \]  \hspace{1cm} (3)

The angle \( \theta₀ \) cannot be calculated exactly, because the Earth is a spheroid and not a sphere, the atmospheric thickness is approximate, and the orbit decays every day. As the field of view is between 70° and 73°, the angle \( \theta₀ \) must be between 17° and 20° or larger. The angle \( \theta₀ \) is significant for ensuring the accuracy of the result, so if necessary it can be magnified. We will give the final result in the Section 3.

2.2. Geometry and mathematical model of the front detector
The centroid orbit coordinate system is described in the Figure 3. The original point \( O₀ \) is the barycenter of the spacecraft, and \( O₀Z₀ \) is in the orbit plane and pointing to the Earth Centre. \( O₀X₀ \) is in the orbit plane perpendicular to \( O₀Z₀ \) and pointing to the flight direction. The sense of \( O₀Y₀ \) is determined as a matter of fixed convention by the right hand rule. The front detector is installed in \( Y₀Z₀ \) and pointing to the negative direction of \( O₀X₀ \) with a rotation of 18.5° to \( O₀Z₀ \). It has two different cameras, one for limb viewing with 0.024° × 1.6° field of view and another for solar occultation viewing with ±7° field of view.

2.2.1. Geometry and mathematical model for limb viewing. The field of view for limb viewing is 0.024° × 1.6°. We can magnify the field of view to ±0.8°. As shown in the Figure 4 and the Figure 5, when the angle \( \alpha₁ \) is greater than 0.8°, the camera can avoid direct sunlight. The equation can be expressed as follow.

\[ \alpha₁ > 0.8° \]  \hspace{1cm} (4)
The geometry and the mathematical model cannot be given exactly because the detection region is irregular. It is a special case when the sun is parallel with the orbit plane in the Figure 4 and Figure 5.

![Figure 4. Geometry model for front working modes for limb viewing.](image1)

![Figure 5. Geometry model for front working modes limb viewing.](image2)

As shown in the Figure 4 and Figure 5, when the equation (5) and the equation (6) are both satisfied, the atmosphere in the field of view is in sunlight. The equations can be merged to the equation (2).

\[
\beta_2 + \theta_2 \leq 90^\circ \\
\beta_2 - \theta_2 \leq 90^\circ
\]

(5)  
(6)  

When the equation (7) and the equation (8) are both satisfied, the atmosphere in the field of view is in sunlight. The equations can be merged to the equation (3).

\[
\beta_1 + \theta_1 > 90^\circ \\
\beta_1 - \theta_1 > 90^\circ
\]

(7)  
(8)  

We can get a conclusion that the front detector for limb viewing can take the same model with the annular detector.

2.2.2. Geometry and mathematical model for solar occultation viewing. The two working modes for solar occultation viewing both require that the sunlight can get into the field of view. As shown in the Figure 6, when the angle \( \alpha_2 \) is less than \( 7^\circ \), the detection condition can be satisfied. The equation can be expressed as follows.

\[
\alpha_2 \leq 7^\circ
\]

(9)  

![Figure 6. Geometry model for solar occultation viewing.](image3)

![Figure 7. Geometry model for solar occultation viewing.](image4)

The detection conditions that the sunlight getting into the field of view through the atmosphere (100km) or higher than the atmosphere (100km) can be described in the Figure 7. When the equation (10) is satisfied, the sunlight can get into the field of view higher than the atmosphere (100km).

\[
R_2 - R_1 > 100\text{km}
\]

(10)  

When the equation (11) is satisfied, the sunlight can get into the field of view through the atmosphere (100km).

\[
R_2 - R_1 < 100\text{km}
\]

(11)
3. Simulation and analysis based on STK 10

In this section, the simulation and analysis for the geometry and mathematical models are given. The STK Analysis Workbench Tools contain three different tools, the Vector Geometry Tool (VGT), the Calculation Tool, and the Time Tool. The vectors and angles described in the geometry and mathematical models can be defined by using VGT, and the equations can be defined by using the Calculation Tool. We can get the results when the equations are satisfied by using the Time Tool.

3.1. Simulation and analysis of the annular detector

The angle $\alpha_0$ and the angle $\beta_0$ can be defined as follows by using VGT.

- Define the vectors $V_1, V_2, V_3$ and $V_4$ by using the vector geometry component, and the options are shown in the Table 2.
- Define the angle $\alpha_0$ by using angle component, select “Between Vectors” for the “Type” option, and from the vector $V_1$ to the vector $V_2$.
- Define the angle $\beta_0$ by using angle component, select “Between Vectors” for the type option, and from the vector $V_3$ to the vector $V_4$.

| $V_1$ | Displacement | the spacecraft centre | the earth centre |
| $V_2$ | Displacement | the spacecraft centre | the sun centre |
| $V_3$ | Displacement | the earth centre | the spacecraft centre |
| $V_4$ | Displacement | the earth centre | the sun centre |

The equation (1), the equation (2) and the equation (3) can be defined as follows by using the Calculation Tool.

- Add a scalar calculation component named Alpha0, select “Angle” for the “Type” option and select the angle $\alpha_0$ for the “Input Angle” option.
- Add a scalar calculation component named Beta0, select “Angle” for the “Type” option and select the angle $\beta_0$ for the “Input Angle” option.
- Define the conditions Equation1, Equation2, Equation3 by using condition component, and the options are shown in the Table 3.

| Equation1 | Alpha0 | Outside Minimum and Maximum | 70 deg | 73 deg |
| Equation2 | Beta0 | Below Maximum | -- | 111 deg |
| Equation3 | Beta0 | Above Minimum | 69 deg | -- |

We can get the results when the equations are satisfied by using the Time Tool, and the options are shown in the Table 4.

| Equation1 and2 | Merged | -- | Equation1 | Equation2 | AND |
| Equation1 and3 | Merged | -- | Equation1 | Equation3 | AND |
The intervals calculated from Equation 1 and 2 as shown in the Table 5 are detection opportunities for the annular working mode one. As shown in the Figure 8 and Figure 9, when the angle $\theta_0$ is 21°, the atmosphere in the field of view is in sunlight totally.

The intervals calculated from Equation 1 and 3 as shown in the Table 6 are detection opportunities for the annular working mode two. When the angle $\theta_0$ is 17°, the atmosphere in the field of view is in umbra seemingly, but it may still be lighten by the atmospheric scattering, so we use $\theta_0 = 21°$ to calculate the results as shown in the Figure 10 and Figure 11.

|          | Start Time (UTCG) | Stop Time (UTCG) | Duration (sec) |
|----------|-------------------|------------------|----------------|
| 1        | 1 Mar 2018 18:30:46.881 | 1 Mar 2018 19:04:56.217 | 2049.336       |
| 2        | 1 Mar 2018 20:02:34.735 | 1 Mar 2018 20:36:45.201 | 2050.466       |
| 3        | 1 Mar 2018 21:34:22.583 | 1 Mar 2018 22:08:34.267 | 2051.684       |
| 4        | 1 Mar 2018 23:06:10.457 | 1 Mar 2018 23:40:23.334 | 2052.877       |

Table 6. Partly detection opportunities for annular working mode two

|          | Start Time (UTCG) | Stop Time (UTCG) | Duration (sec) |
|----------|-------------------|------------------|----------------|
| 1        | 1 Mar 2018 19:16:39.063 | 1 Mar 2018 19:50:50.030 | 2050.967       |
| 2        | 1 Mar 2018 20:48:26.916 | 1 Mar 2018 21:22:39.020 | 2052.105       |
| 3        | 1 Mar 2018 22:20:14.844 | 1 Mar 2018 22:54:28.024 | 2053.180       |
| 4        | 1 Mar 2018 23:52:02.789 | 2 Mar 2018 00:26:16.991 | 2054.202       |

Every day has 16 detection opportunities and each detection opportunity lasts 1850 seconds to 2150 seconds both for the two annular working modes. We can also use the results for the two front working modes for limb viewing as described in Section 2.2.1.
3.2. Simulation and analysis of the front detector

The angle $\alpha_2$ can be defined as follows by using VGT.

- Define the angle $\alpha_2$ by using angle component, select “Between Vectors” for the “Type” option, and from the vector $V_2$ to the vector Boresight which is represent the optical axis of the camera.

The vectors $R_1$ and $R_2$ can be defined as follows by using VGT.

- Define the vectors $N_1$, $N_2$ by using the vector geometry component, and the options are shown in the Table 7.
- Add a plane geometry component named Plane1, select “Normal” for the “Type” option, select the vector $N_2$, the vector $V_2$ for the “Normal Vector” and “Reference Vector” option, and select the sun centre for the “Reference Point” option.
- Add a point geometry component named $P_1$, select “Projection” for the “Type” option, select the earth centre for the “Source Point” option and select the plane Plane1 for the “Reference Plane” option.
- Add a point geometry component named $P_2$, select “Surface” for the “Type” option, select “Earth” for the “Central Body”, select the point $P_1$ for the “Reference Point” option, select “Ellipsoid” for the “Reference Shape Type” option, and select “Detic” for the “Surface Point Type” option.
- Define the vectors $R_1$ and $R_2$ by using the vector geometry component, and the options are shown in the Table 8.

| Type   | Vector A          | Vector B          |
|--------|-------------------|-------------------|
| $N_1$  | Cross Product     | the vector $V_1$  |
| $N_2$  | Cross Product     | the vector $N_1$  |

Table 7. The options for the vectors $N_1, N_2$

| Type   | Origin point      | Destination point |
|--------|-------------------|-------------------|
| $R_1$  | Displacement      | the earth centre  |
| $R_2$  | Displacement      | the earth centre  |

Table 8. The options for the vectors $R_1, R_2$

The equation (9), the equation (10) and the equation (11) can be defined as follows by using the Calculation Tool.

- Define the scalars $\alpha_2$, $R_1$, $R_2$, $R_1-R_2$ by using the condition component, and the options are shown in the Table 9.
- Define the conditions Equation9, Equation10, Equation11 by using the condition component, and the options are shown in the Table 10.

| Type   | Input Angle | Input Vector | Function | Operation | the x argument | the y argument |
|--------|-------------|--------------|----------|-----------|----------------|----------------|
| Alpha2 | Angle       | $\alpha_2$   | --       | --        | --             | --             |
| $R_1$  | Vector Magnitude | $R_1$    | --       | --        | $R_1$          | $R_2$          |
| $R_2$  | Vector Magnitude | $R_2$    | --       | --        | $R_1$          | $R_2$          |
| $R_1-R_2$ | Function (x, y) | --       | --       | --        | a*x-b*y        | AND

Table 9. The options for the intervals.
Table 10. The options for the conditions Equation9, Equation10, Equation11

| Scalar          | Operation                                      | Minimum | Maximum |
|-----------------|------------------------------------------------|---------|---------|
| Equation9       | Alpha2 Between Minimum and Maximum             | 0deg    | 73deg   |
| Equation10      | $R_1-R_2$ Above Minimum                        | 100km   | --      |
| Equation11      | $R_1-R_2$ Between Minimum and Maximum          | 0km     | 100km   |

We can get the results when the equations are satisfied by using the Time Tool, and the options are shown in the Table 11.

Table 11. The options for the intervals.

| Type            | condition      | the Intervals A | the Intervals B | Operation |
|-----------------|----------------|-----------------|-----------------|-----------|
| Equation9       | Satisfaction   | Equation9       | --              | --        |
| Equation10      | Satisfaction   | Equation10      | --              | --        |
| Equation11      | Satisfaction   | Equation11      | --              | --        |
| Equation9and10  | Merged         | --              | Equation9       | Equation10 AND |
| Equation9and11  | Merged         | --              | Equation9       | Equation11 AND |

The intervals calculated form Equation9and10 are the detection opportunities as shown in the Table 12. Every day has 16 detection opportunities and the maximum of the duration is 70 seconds. The sunlight can get into the field of view higher than the atmosphere (100km) as shown in the Figure 12 and the Figure 13. The intervals calculated form Equation9and11 are the detection opportunities as shown in the Table 13. Every day has 16 detection opportunities and the maximum of the duration is only 43 seconds. The sunlight can get into the field of view through the atmosphere as shown in the Figure 14, the Figure 15.

Table 12. Partly detection opportunities calculated form Equation9and10.

| Start Time (UTC) | Stop Time (UTC) | Duration (sec) |
|------------------|-----------------|----------------|
| 1                | 7 Mar 2018 15:57:32.940 | 69.882 |
| 2                | 7 Mar 2018 17:29:18.162 | 70.137 |
| 3                | 7 Mar 2018 19:01:03.614 | 70.177 |
| 4                | 7 Mar 2018 20:32:49.311 | 69.958 |

Table 13. Partly detection opportunities calculated form Equation9and11.

| Start Time (UTC) | Stop Time (UTC) | Duration (sec) |
|------------------|-----------------|----------------|
| 1                | 7 Mar 2018 15:58:42.822 | 43.295 |
| 2                | 7 Mar 2018 17:30:28.299 | 43.284 |
| 3                | 7 Mar 2018 19:02:13.792 | 43.281 |
| 4                | 7 Mar 2018 20:33:59.269 | 43.290 |

Figure 12. The beginning time of one detection opportunity calculated form Equation9and10.

Figure 13. The ending time of one detection opportunity calculated form Equation9and10.
4. Conclusions

In this paper, we provide a simulation and analysis method of the detection opportunities based on Satellite Tool Kit 10 (STK 10). By using the Analysis Workbench Tools, we can do some simulation and analysis with complex and a great amount of conditions and get the final analytic results directly. We use the calculated results in the ground operating control system of the Tiangong-02 spacecraft to schedule the detection plan. By analysis the actual detection images, we find that the simulation method is effective and credible. This research can provide references for design and system simulation of space-based imaging payload, as well as the flight control task arrangement.

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