Mission Analysis Techniques for Attached Shuttle Payloads

Scott D. Lambros*
NASA Goddard Space Flight Center, Greenbelt, Maryland

Visibility times, i.e., times at which desired targets are visible to a payload, are examined for attached Shuttle payloads. These times are affected by a number of constraints. Some constraints are examined along with mathematical or computer modeling techniques used to determine their effects. The constraints include occulation of the Earth, moon, and Sun, and limb avoidance angles of these bodies; orbit parameters such as inclination and ascending node, along with sensitivity to changes in these parameters; tracking and data relay satellite system acquisition; South Atlantic anomaly avoidance, nighttime viewing only; bright Earth avoidance angles; the field of view; Shuttle attitude; and Orbiter operational constraints. All of this information is integrated and, with computer programs, a schedule of observations and Shuttle attitudes is obtained.

Introduction

WITH the advent of the Shuttle, new opportunities have opened up for flying payloads into space. In particular, the former sounding rocket user can look forward to increased time in space, from a few minutes to possibly many hours or days. He might also find lower costs since a sounding rocket is expendable, where an experiment container onboard the Shuttle is not. There are many factors involved which must be taken into account by the new user flying a payload onboard the Shuttle. Some factors which affect the observation of desired targets are discussed in this paper as well as the mathematical formulation or computer modeling of each of these factors. This is not an exhaustive list, only currently typical. The purpose in presenting them here is twofold: 1) to make the experimenter flying a payload on the Shuttle first aware that there are constraints affecting the amount of visible time of his desired targets and, then, what some of these constraints are and how to determine their effect; and 2) to present at least an overview of these computer modeling or mathematical techniques in a common arena—the context of mission analysis techniques for attached Shuttle payloads.

Figure 1 shows the target/visibility scenario graphically. Among the targets considered are the stars, planets, sun, moon, tracking and data relay satellite (TDRS), and points or areas of the Earth's surface.

Many of the examples and much of the results presented here were taken from a study done for NASA's Office of Space Science-3 (OSS-3) mission. This uses a Shuttle pallet with three experiments mounted on a pointing system. Not all experiments flying on the Shuttle, particularly the sounding rocket type, will have their own pointing system. Nor may the experimenter have any say in Shuttle attitude or orbital characteristics. The reader should be aware of this and note that not all the information in this paper may apply to him, but he should extract what does affect his particular situation.

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*Aerospace Engineer. Member AIAA.

Constraints or Factors Affecting Visibility and Their Determination

Occultation and Limb Constraints

In determining a line-of-sight visibility from the target to the Shuttle, the greatest time-limiting factor is occultation by the Earth. Presented here are two ways of calculating this factor. The first method makes use of a given Orbiter state vector and computes whether or not the target is visible at that one point in the orbit.[1] To find visibility times for a complete mission, then, the target must be examined for each step along the orbit for the entire mission. The state vectors are determined by an ephemeris computer program which is discussed in further detail in the section on construction of a schedule of observations. The second method is an analytical scheme which uses the orbit parameters to determine the true anomalies of the orbit where the target is first and last seen. This can then be converted into a percentage of the orbit, or time, if desired. A circular orbit is assumed, with true anomaly defined as being measured from the ascending node, since there is no perigee in a circular orbit.

To determine Earth occultation of a target in the sky, consider Fig. 2. The half-angle subtended by the Earth from Shuttle position θ, and the angle between the Shuttle-Earth vector and Shuttle-target vector ϕ, can be calculated by simple trigonometric relations and vector algebra.

Occultation is then determined as follows: If $\phi > \theta$, the target is visible; if $\phi \leq \theta$, the target is occulted.

Occultation by the sun and moon can be determined in a similar manner. When there is a limb constraint, i.e., an angular distance from the limb or edge of the Earth, sun, or moon within which no observations are allowed, the angle θ is altered accordingly. For example, if there was a 25-deg Earth limb constraint, θ would be computed as

$$\theta = \sin^{-1}(R_e/R_A) + 25 \text{ deg} \tag{1}$$

This assures that the target must be outside the constraint angle in order to be considered visible. For the sun, θ is usually just defined as its limb constraint, for without it, the sun subtends a half-angle of only about 0.25 deg.

The check for visibility of an Earth target is done in the following way: Given the latitude, longitude, and height of the target, a geocentric inertial vector is constructed to the point by using the Greenwich hour angle at the given time. Subtracting the Orbiter state vector from this yields the vector

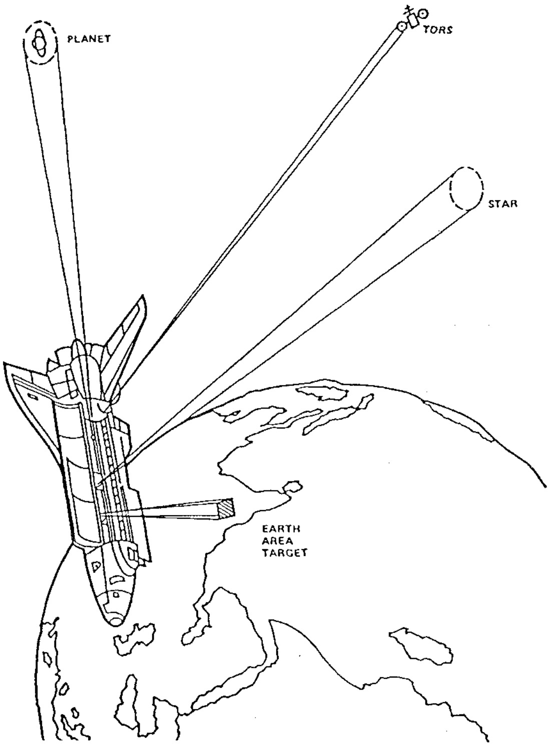


Fig. 1 Targets for attached Shuttle payloads.

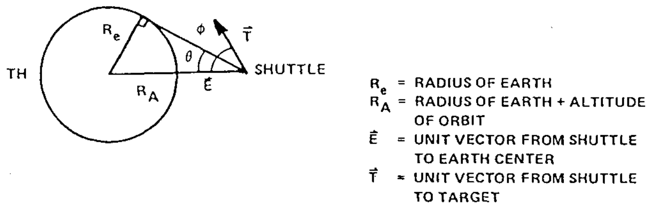


Fig. 2 Earth occultation geometry.

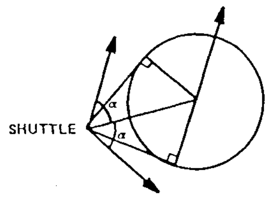


Fig. 3 Earth occultation with limb constraint.

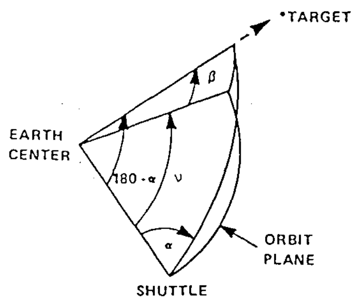


Fig. 4 Conditions for target first visible.

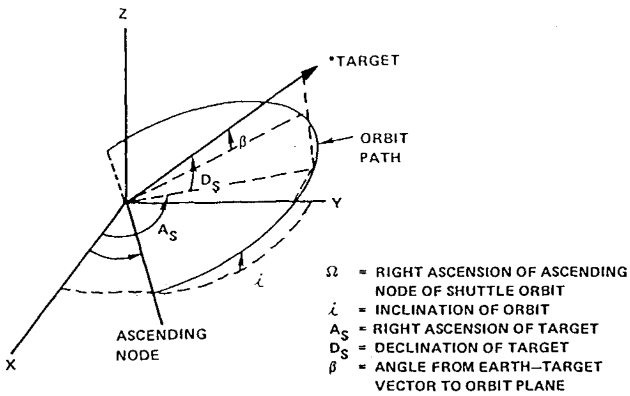


Fig. 5 Shuttle orbit and target in inertial coordinates.

from the Shuttle to the desired spot on Earth. The angle between this Shuttle-target vector and the Earth center-target vector (call it γ) is then analyzed for the following cases: If $\gamma \geq 90$ deg, the target is visible; if $\gamma < 90$ deg, the target is occulted by the Earth.

The second method used to determine visibility times considers occultation by the Earth plus the Earth limb constraint angle for celestial targets only. The Earth plus limb constraint angle forms a cone of nonvisibility around the Earth with a radius of α in Fig. 3. To solve for the true anomaly when the target first appears, notice that the condition for this is the Earth-Shuttle-target angle equals α. Also, the Shuttle-Earth-target angle equals 180-α, since the two vectors to the target are parallel because the star is considered to be at infinity. Figure 4 shows this situation on a unit sphere, considering the orbit plane.

By spherical trigonometry (the law of cosines):

$$\cos(180-\alpha) = \cos\beta\cos\nu + \sin\beta\sin\nu \cdot 0 \tag{2}$$

$$\cos(180\text{-}\alpha) = \cos\beta\cos\nu \tag{3}$$

To solve for β and ν in terms of true anomaly, consider Fig. 5. This shows the geometry of the Shuttle orbit and the target in Earth-centered inertial coordinates. Note that the coordinates of the target are ($\cos A_s \cos D_s$, $\sin A_s$ $\cos D_s$, $\sin D_s$). These can be transformed into orbit plane coordinates (with the X-axis vector to the ascending node) by first rotating the XYZ coordinate system counterclockwise about the Z axis through Ω, then rotating the new $X'Y'Z'$ about X' through i. This gives a transformation matrix which can now be used to transform the target coordinates to give (x_0, y_0, z_0):

$$x_0 = \cos\Omega\cos A_s\cos D_s + \sin\Omega\sin A_s\cos D_s$$

$$y_0 = -\sin\Omega\cos i\cos A_s\cos D_s + \cos\Omega\cos i \times \sin A_s\cos D_s + \sin i\sin D_s \tag{4}$$

$$z_0 = \sin i\sin\Omega\cos A_s\cos D_s - \sin i\cos\Omega \times \sin A_s\cos D_s + \cos i\sin D_s$$

Note that $\sin\beta = z_0$, so, after reducing,

$$\beta = \sin^{-1}[\sin i\cos D_s\sin(\Omega - A_s) + \cos i\sin D_s] \tag{5}$$

To solve for ν, consider that the angle ω equals the angle from the ascending node to the projection of the Earth-target line on the orbit plane:

$$\omega = \nu + \theta \tag{6}$$

where θ is the true anomaly of the Shuttle. (See Fig. 6.) Also,

$$\omega = \tan^{-1} y_0/x_0 \tag{7}$$

where x_0, y_0 are defined in Eq. (4).

This reduces to

$$\omega = \tan^{-1}[\cos i \sin(A_s - \Omega) + \sin i \tan D_s / \cos(A_s - \Omega)] \quad (8)$$

Now recall from Eq. (3) that, at conditions of target first visible,

$$\cos(180 - \alpha) = \cos\beta \cos\nu$$

Substituting Eq. (6) and solving for θ yields

$$\theta = \omega - \cos^{-1}[\cos(180 - \alpha)/\cos\beta] \quad (9)$$

so, the target is first seen when

$$\theta_1 = \omega - \cos^{-1}[\cos(180 - \alpha)/\cos\beta] \quad (10)$$

and last seen when

$$\theta_2 = \omega + \cos^{-1}[\cos(180 - \alpha)/\cos\beta] \quad (11)$$

where ω is defined in Eq. (8) and β is defined in Eq. (5).

Orbit Parameters

A typical Shuttle orbit, e.g., the orbit used in the OSS-3 analysis, is circular, has a 28.5 deg inclination, a 296-km altitude, and an ascending node that varies with the launch time of day. With this orbit, the half-angle to the Earth limb (from the Shuttle) is 72.87 deg, so a large portion of the sky is cut out for observations at any given time (plus any Earth limb constraint angle imposed). To consider the effects of changing the inclination and the ascending node, results of a study done on viewing Halley's Comet from the Shuttle are presented here. The second method described in the previous section was used to determine the percentage of an orbit in which the comet is visible. Fig. 7 illustrates some typical results, plotting the visibility of the comet as it changes with inclination, going from 0 to 90 deg (there is also a 25-deg Earth limb constraint that limits the maximum visibility time to approximately 47%). Inclination change has very little effect in curve A—about 46 to 47% across the board. The difference between curves A and B is a different ascending node (launch time of day). With the node used in curve B, the inclination has a profound effect—ranging from approximately 46 to 0% visibility. The conclusion, then, is that the launch time of day, coupled with the orbital inclination can have an important effect on visibility times achieved for a desired target. To illustrate the point even further, consider Fig. 8. This shows, for eight different inclinations, the percentage of visibility of the comet as the launch time varies plus or minus 2 h from maximum launch (i.e., plus or minus 30 deg from the maximum ascending node). As can be seen, one inclination, say, 60 deg, may have the highest maximum visibility, but varies drastically with a launch slip, whereas 25 deg varies much less but has a lower peak.

An important point to mention here is precession of the node and mission duration. Because of perturbations of the orbit, the ascending node precesses an amount dependent on orbital altitude, eccentricity, and inclination. In Fig. 8 with the inclination at 60 deg, the ascending node precesses −4.24 deg/day (negative means in the opposite direction of the Earth's rotation). With the inclination at 25 deg, precession is −7.73 deg/day. The implication of this is that this information must be taken into account coupled with mission duration and compared with a chart of the sort in Fig. 8 to compute how much visibility time can be expected over the course of the entire mission.

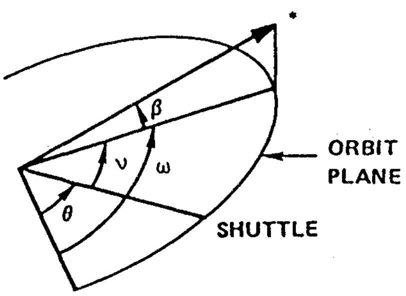


Fig. 6 Shuttle and target relative to ascending node.

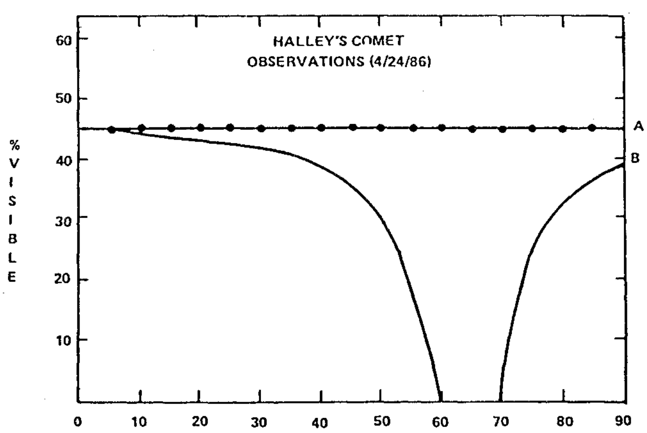
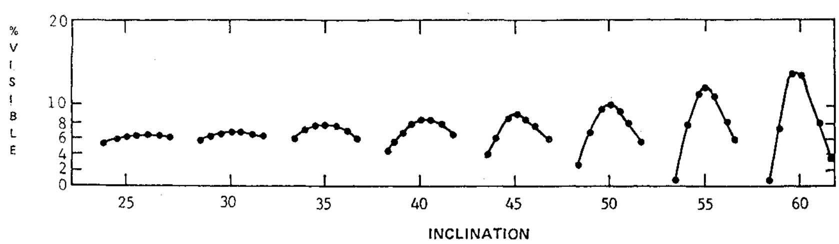


Fig. 7 Effects of inclination and ascending node on visibility.

Tracking and Data Relay Satellite System (TDRSS)

Some experiments require a real-time data link via one of the two planned TDRSs. This means that, in order for a target to be considered visible, a TDRS must be in view. The TDRS communications which are transmitted and received through the Ku-band use an antenna on the Shuttle located near the right front corner of the cargo bay (other bands are also used). To determine a line of sight between the Shuttle and satellite, the position of the antenna is not important. This line-of-sight visibility can be determined analytically similar to the second method presented for determining Earth occultation of targets in the preceding section on occultation and limb constraints. However, when a Shuttle attitude is chosen, the antenna position becomes critical in determining whether the Orbiter itself blocks the line of sight from the antenna to the satellite. A picture of this "mask" of the Orbiter body is shown in Fig. 9. The coordinates are Orbiter body coordinates, but shifted so the origin is at the base of the antenna. The area inside the figure is the area of the sky where the antenna is blocked by the Orbiter body: The nose of the Shuttle is the large region on the right; the tail is the pointed

Fig. 8 Effects of launch slip for different inclinations.



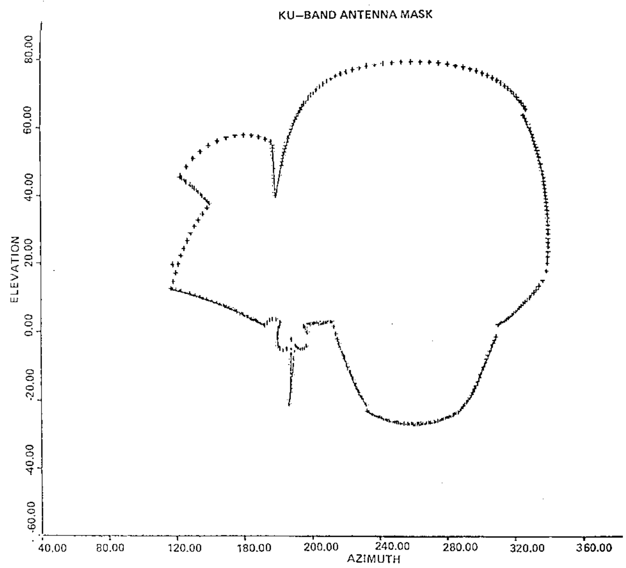


Fig. 9 KU-band antenna mask.

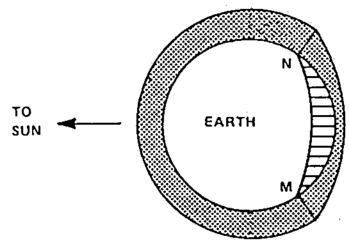


Fig. 10 Constraint angle from closest bright Earth.

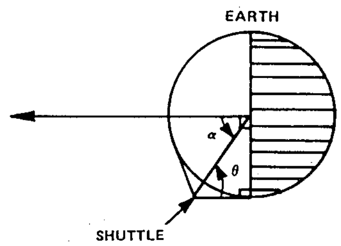


Fig. 11 Terminator geometry.

shape near the bottom center; and the starboard bay doors and radiator panels are on the left (no payload is shown in this mask). Given a Shuttle attitude, then, a TDRS must be outside this blocked region for transmission of data to occur. The way this is determined is to use the same method that determines whether a target is within the field of view of an experiment. This is described in the section on masks.

South Atlantic Anomaly (SAA)

There is an area over the South Atlantic where proton and electron magnetic flux levels are too great for some experiments to operate at certain altitudes; this is called the South Atlantic Anomaly (SAA). These flux levels must be examined by the experimenter to define exactly the region where the experiment cannot collect data.† The amount of time the Shuttle spends in this region per day is dependent on the altitude and inclination of the orbit and the allowable flux levels. The SAA passage times can be determined in the following manner: The ephemeris can be used to give the Shuttle position at each step along the orbit. If not given directly from the ephemeris, the latitude and longitude can be calculated from the inertial right ascension and declination, given the particular date and time. This position must then be compared with the current SAA model to see if it falls within that region. This checking can be done in many ways. One such way is the method described in the section on masks.

The time of launch for the OSS-3 mission was chosen to put the right ascension of the ascending node at the right ascension of the sun plus 90 deg. This assures that the Shuttle will be in the northern hemisphere at night, minimizing SAA interference, since many targets could be viewed only at orbit night. The typical amount of time spent in the SAA region for one day using the OSS-3 orbit is about 86 min.

Shadow

Some experiments can only view their targets during orbit night (Earth's shadow). In the OSS-3 orbit (296 km altitude circular), the shadow time is approximately 36 min out of a 90-min orbit.

There are several good analytic shadow determination routines available. One such routine is given in Ref. 1. This determines whether the spacecraft is in shadow or not, given an inertial state vector. Reference 3 gives another routine which computes the true anomalies of shadow entrance and exit times.

†There are publications with these contours. One such publication is Ref. 2; however, these contours are now out of date.

Terminator

Some experiments cannot view targets within a certain angular distance to any "bright" Earth. This means that when the Shuttle is in sunlight and sees only a sunlit Earth beneath it, there is an Earth limb constraint angle in effect. When the Shuttle is in shadow and sees only a dark Earth beneath it, the limb constraint is not in effect and the target can be viewed right up until it is occulted by the Earth. When the Shuttle sees both bright and dark Earth beneath it, the limb constraint is measured from the bright Earth closest to the target (as seen from the Shuttle), be it the bright limb of the Earth or a point on the terminator (the line dividing the sunlit half of the Earth from the dark half). This is shown graphically in Fig. 10.

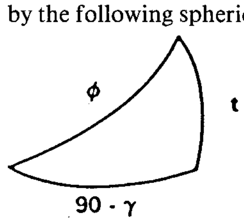
The area of the Earth shown in Fig. 10 is the area seen by the Shuttle at a discrete point in the orbit. The lined area is dark Earth. The dotted area is the sky around the Earth where targets cannot be viewed because of the given constraint angle (the constraint angle here is arbitrary). To determine the nearest bright Earth to the target, the following method was devised:

1) First determine which part of the Earth is currently seen by the Shuttle (bright, dark, or both-terminator).

The half-angle subtended by the Earth (θ in Fig. 11) and the sun-Earth-Orbiter angle α are calculated using trigonometric relations and the dot product of the unit vectors to the sun and Shuttle (Earth-centered). Then, if $\alpha \leq 90\text{-}\theta$, only bright Earth is seen; if $\alpha \leq 90+\theta$, only dark Earth is seen. Otherwise, the terminator is seen.

2) When it is determined that the terminator is seen, the next step is to find the two endpoints of it—points M and N Fig. 10.

First, define the axis of rotation: A is the direction of sun vector; C is the sun vector multiplied by the orbiter vector; and $B = C \times A$. In Fig. 12, u_1 is the unit vector to sun; u_2 the unit vector to the Shuttle; and to u_3 the unit vector to the endpoint in question.γ is the angle between u_1 and u_2; ϕ the angle between u_2 and u_3; and t the angle between B and u_3. The coordinates of u_3, then, are (0,cos$t$, sin$t$). There is a corresponding endpoint (0, cos$t$, - sin$t$). Solve for cos t, sin t by the following spherical triangle relations:



$$\cos\phi = \cos t \cos(90\text{-}\gamma) \tag{12}$$

$$\cos t = \cos\phi / \sin\gamma \tag{13}$$

$$\sin t = \sqrt{1\text{-}\cos^2 t} \tag{14}$$

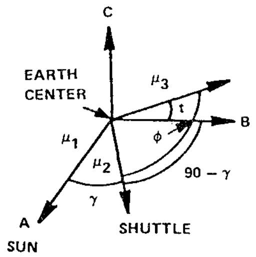


Fig. 12 Terminator endpoints in rotated coordinates.

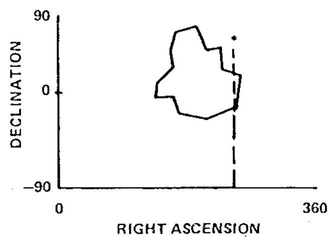


Fig. 13 Experiment mask.

Observe,

$$\phi = \cos^{-1} R_e / (R_e + \text{Alt}) \tag{15}$$

where R_e is the radius of the Earth, and Alt is the altitude of Shuttle orbit.

We have now solved for the two vectors to the endpoints of the terminator of the rotated coordinate system. To get back to geocentric inertial coordinates, simply multiply by the correct transformation matrix.

3) Determine whether the target, as viewed from the Shuttle, is over the bright Earth limb or over the dark limb:

a) Sun-Earth-Orbiter angle <90 deg: If the Earth-target vector lies between the plane containing the first endpoint, Earth center, and Orbiter and the plane containing the second endpoint, Earth center, and Orbiter, then it is over the dark limb. If not between the two planes, it is over the bright limb.

b) Sun-Earth-Orbiter angle >90 deg: If the target vector lies between the two planes described above, then it is over the bright limb. If not, then it is over the dark limb.

c) Sun-Earth-Orbiter angle $=90$ deg: If the sun-Earth-target angle <90 deg, it is over the bright limb. If the sun-Earth-target angle >90, it is over the dark limb.

If the target is over the bright limb, perform regular Earth limb constraint check. If over the dark limb, the closest point on the terminator must be found. Then the angle between this point-Shuttle-target must be compared with the constraint angle to see if the target is visible or not.

4) Find the point on the terminator which is closest to the target. This is done by an iteration routine. The two endpoints and the point on the terminator that is halfway between them (measured geocentric inertially) are examined to see which is closest to the target (i.e., the smallest point-Shuttle-target angle). The closest point is taken and examined with two new points: the ones halfway between this point and the two points from the previous iteration that were on either side of this one. The angle between two iteration points is successively halved, each time choosing the point which is closest to the target, until a desired tolerance is reached. The angle between this point and the target (Shuttle-centered) can then be compared with the given constraint angle to see if it is visible or not.

Mask and Attitude

So far, all constraints discussed (except TDRS) have been in the context of line-of-sight visibility. In reality, whether or not a target is visible to a payload depends on which way the Shuttle bay is pointing and how much of the sky is visible to the payload (i.e., not blocked by the bottom or sides of the Shuttle, or other instruments in the bay). If the payload has only one viewing direction, then the Shuttle attitude is the only determining factor for visibility of a particular target. However, if there is more than one viewing direction, or if, as in the case of OSS-3, the experiments are on a movable pointer, then there needs to be some way of describing the area of possible viewing. The description of this area is called a "mask." Following is a description of a simple computer algorithm which determines whether or not a given target is within a given experiment mask at a given attitude. Consider Fig. 13, which shows a mask graphically in right ascension vs declination Shuttle-centered coordinates.

The target in question must first be transformed into this Shuttle-centered coordinate system at this particular attitude. The mask is input to the computer as a group of points that are internally connected by line segments. A reference point with its visibility status (whether inside or outside the mask) must also be input. This is the point of the $-Z$ axis in Shuttle coordinates that is defined as straight out of the bay. In Fig. 13, it is the point denoted by the abscissa (-90 deg declination, any right ascension—remember Fig. 13 denotes a spherical coordinate system). The algorithm, then, draws a straight line between the target and the reference point (a great circle path in spherical coordinates): the dotted line in Fig. 13. If this line crosses the mask boundaries an even number of times, the status of the point is the same as the reference point. If it crosses the mask boundaries an odd number of times, it is opposite the status of the reference point.

Orbiter Operational Constraints

There are certain operational constraints which need to be considered when flying on the Shuttle. These include things such as crew shift handovers, meal times, and Inertial Measurement Unit (IMU) realignments. These need to be checked for the current requirements.

Construction of Attitude Timeline and Schedule of Observations

In constructing a schedule of observations and Shuttle attitudes, a library of about 200 computer routines is used. Three main programs are used: the ephemeris generator, the visibility program, and the scheduler program. As mentioned earlier, the ephemeris generator creates an ephemeris of Shuttle position and velocity at discrete steps along the orbit, throughout the mission. It integrates the equations of motion, using a fourth-order Runge-Kutta integration with modified Fehlberg coefficients. The state vectors obtained are then input to the visibility program. This program takes the ephemeris information, a list of targets, and all the applicable constraints (as discussed in this paper so far) and computes the line-of-sight visibility times for each target. With the use of the scheduler program, then, a schedule of observations and attitudes is obtained. The scheduler is an interactive program which assists the user in devising a schedule—it does not do it for him. The user must decide which attitude the Shuttle should take at a particular time; which target the experiment should be looking at and for how long before moving to another target; or, perhaps, schedule no observations to wait for the crew shift handover. The scheduler program basically presents the data to the user on a computer terminal in an easily understandable format so that he can make the decisions. The program also considers attitude so that, given an attitude and mask, it will present to the user a list of visible targets. When putting together this schedule, an attempt must be made to keep the Shuttle reorientations to a minimum, thereby using as little fuel as possible.

Conclusions

Certain factors affecting the amount of time desired targets are visible to a payload flying on the Shuttle, have been discussed. Also, a way of computing the determination of the effects of these factors has been given, be it a mathematical formulation or a computer modeling technique. It is important for the user to be aware of these limiting factors when designing his own mission. Also, he should be aware of any other factors not mentioned here that affect his unique situation. This paper was designed to draw attention to this whole area.

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