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Attitude-Dependent Launch Window Analysis for the Hubble Space Telescope Mission

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ABSTRACT

Launch window analysis for Space Shuttle missions determines the launch times which will ensure that all payload and Shuttle requirements for the mission are met. Attitude and pointing analysis determines Shuttle Orbiter attitudes that meet various communication, viewing, and thermal requirements for the Orbiter and its payloads. Historically, launch window analysis and attitude and pointing analysis for Shuttle missions have been done separately, without directly influencing each other. However, methods have been developed to consider simultaneously dependencies between launch window and attitude and pointing requirements if they arise. These methods were developed from the launch window analysis for STS-31, the Hubble Space Telescope (HST) deployment mission.

To release the HST, the Orbiter attitude had to remain inertially fixed while pointing the HST at the Sun. The Orbiter release attitude and the HST release time were determined from the position of the Sun and varied with launch time and launch date. The launch window analysis for STS-31 centered on how to determine the range of launch times for a given launch date that would allow the Shuttle to release the HST and simultaneously satisfy communication, attitude, and lighting requirements for the deployment operations.

This paper discusses how the HST deployment requirements determined the launch window and how the Orbiter release attitude affected the launch window.

INTRODUCTION

Launch Window and Attitude and Pointing Analysis for Shuttle Missions

The orbital trajectory of the Space Shuttle is made up of a series of events that must occur at precise times to meet the objectives of the mission. The timing of these events usually originates from requirements to operate or deploy Shuttle payloads at locations that ensure certain orbital conditions are met, such as communication, viewing, lighting, and thermal exposure. These orbital conditions usually have a certain geometrical relationship relative to Earth-fixed targets or celestial targets. The times that these mission events occur are also influenced by crew schedules, Shuttle performance limitations, and duration of the mission. For all planned events to occur in sequence and satisfy the objectives of the mission, the Shuttle can launch only at certain predetermined times.

A launch window for a particular Shuttle payload is the range of launch times, on a given launch date, that achieve the payload's orbital objectives and satisfy the crew, Shuttle, and mission requirements and constraints. The launch window for the Hubble Space Telescope (HST), for example, is constrained by several objectives, such as deploying the satellite on a particular orbit, ensuring orbital lighting at deployment, pointing the HST at the Sun at release, and maintaining communication with the Tracking and Data Relay Satellite System (TDRSS) during deployment.

Attitude and pointing analysis is another specialized area of Shuttle orbital flight analysis. Attitude and pointing analysis determines Shuttle attitudes that satisfy the communication, viewing, lighting, thermal, and microgravity requirements of the Orbiter and its payloads at certain times during a mission. Such analysis, for example, determines the attitude that is required at a certain time to point the Orbiter's star trackers and recalibrate the onboard navigation platform. This pointing analysis is necessary because of the Orbiter's own operational requirements. But payloads may also require specific Orbiter attitudes at certain times during a mission, and they may require their own special attitude and pointing analysis. The attitude and pointing analysis for the HST mission determined the Orbiter attitudes that were needed to make contact with TDRSS and still point HST at the Sun before its release from the Orbiter's robotic arm.

Orbiter attitudes are usually determined separately from the orbital times required for deploying or operating Shuttle payloads; therefore, attitude and pointing requirements are usually independent of launch time. However, attitude and pointing analysis for STS-31, the Shuttle mission to deploy the HST, showed that Orbiter attitudes affect the orbital conditions required at HST deployment, and that the availability of these conditions due to Orbiter attitudes varied with launch time. Special analysis was required to analyze this interdependency between Orbiter attitude requirements and launch time.

HST PAYLOAD REQUIREMENTS FOR DEPLOYMENT

Three deployment requirements dominated the launch window analysis for the HST mission: (1) there had to be communication with TDRSS throughout the deployment period, (2) the Orbiter had to be in a particular attitude to deploy HST and separate from it, and (3) HST release had to occur in orbital daylight.

Communication Constraints

For ground control to uplink commands and receive telemetry from HST during the deployment operations, the Orbiter had to relay Ku-band transmissions through one of the two TDRSS satellites, TDRS-West or TDRS-East. Since these geosynchronous satellites are fixed with respect to the Earth, the orbiting Shuttle continually moves into and out of contact with each satellite, creating certain times of TDRSS acquisition of signal (AOS) and loss of signal (LOS) due to Earth occultation. The release of HST had to occur at least 5 minutes after AOS and at least 25 minutes before LOS on a given TDRSS pass. The 5 minutes before release were needed for the Orbiter's directional Ku-band antenna to begin tracking the TDRSS satellite. The 25 minutes after release were needed to ensure the HST maneuvered to a stable attitude.

Attitude Constraints

While HST was in its release position on the Orbiter's robotic arm, the Orbiter was required to point the satellite's aft end, or -V1 axis, at the Sun. The aft end contains coarse Sun sensors that allow HST's attitude control system to determine and stabilize the satellite's orientation after release. The release orientation was further constrained by the need to protect the telescope during the Orbiter's separation burn that occurred 2 minutes after release. To prevent recontact with the HST or contaminating the HST with the Orbiter jet plumes during the burn, the Orbiter's Z-body axis had to remain in the orbit plane and point in the direction of orbital motion at the time of HST release.

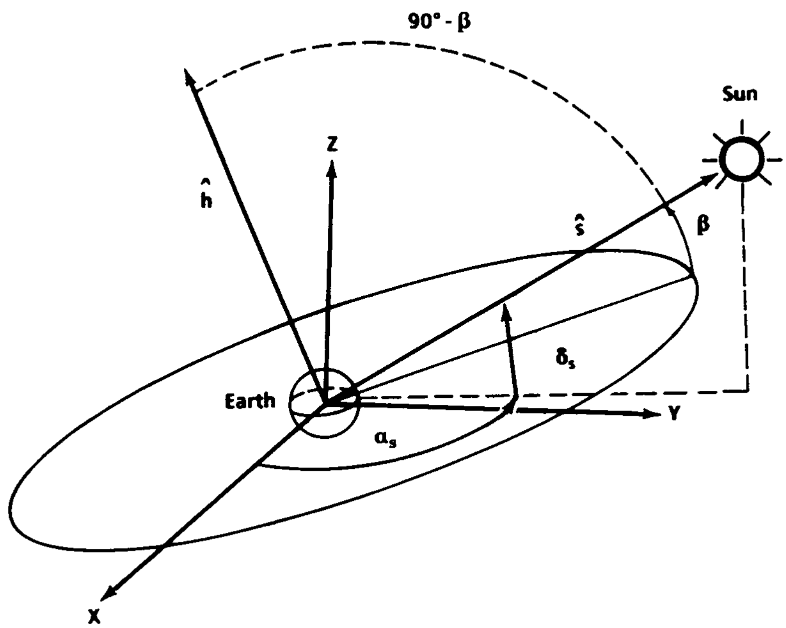
Lighting Constraints

To ensure that HST's solar arrays were deployed and to verify the Orbiter's safe separation from the HST, the Shuttle crew had to be able to observe the telescope in orbital daylight before and after its release. To meet this lighting requirement throughout the deployment sequence, the release was timed to coincide approximately with the location of orbital noon. Since orbital noon is approximately halfway into the daylight portion of an orbit, HST release near orbital noon would provide sufficient lighting during the deployment operations.

ANALYSIS AND DEVELOPMENT OF THE HST LAUNCH WINDOW

The primary objective of the STS-31 mission was to release HST on the earliest deployment opportunity after satisfying HST checkout requirements and crew activity constraints. This opportunity occurred on orbit 19. The actual time of release on orbit 19 was based on the combination of the communication, attitude, and lighting requirements that constrained release.

First, HST release had to occur while the Orbiter was in contact with one of the TDRSS satellites on orbit 19. Second, the release time also had to satisfy the specific attitude and lighting constraints during this period of contact. To determine the actual release time after orbital noon, a formula was derived in which the incidence angle between the Sun and the orbit plane was the only variable. This angle is generally called the solar Beta angle and is illustrated in the HST release time derivation in Figure 1.



α, δ_s = right ascension and declination to the Sun, respectively, measured in the inertial X-Y-Z plane

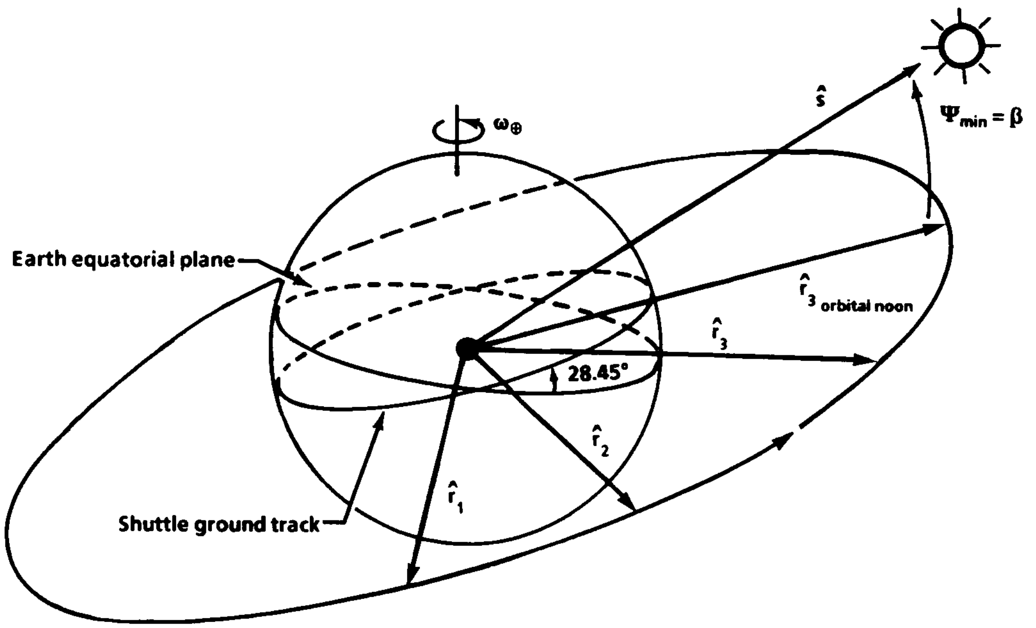
$\hat{h}$ = the direction of the orbital angular momentum vector, perpendicular to the orbit plane

$\hat{s}$ = the direction of the Sun pointing vector from the center of the Earth

β = the solar Beta angle measured from the orbit plane to the Sun pointing vector

$$\beta = 90° - \cos^{-1}(\hat{h} \cdot \hat{s})$$

(a) Definition of solar Beta angle.
Figure 1.– Derivation of the HST release time.



$\hat{r}$ $\equiv$ the direction of the position vector for the Shuttle at a particular time

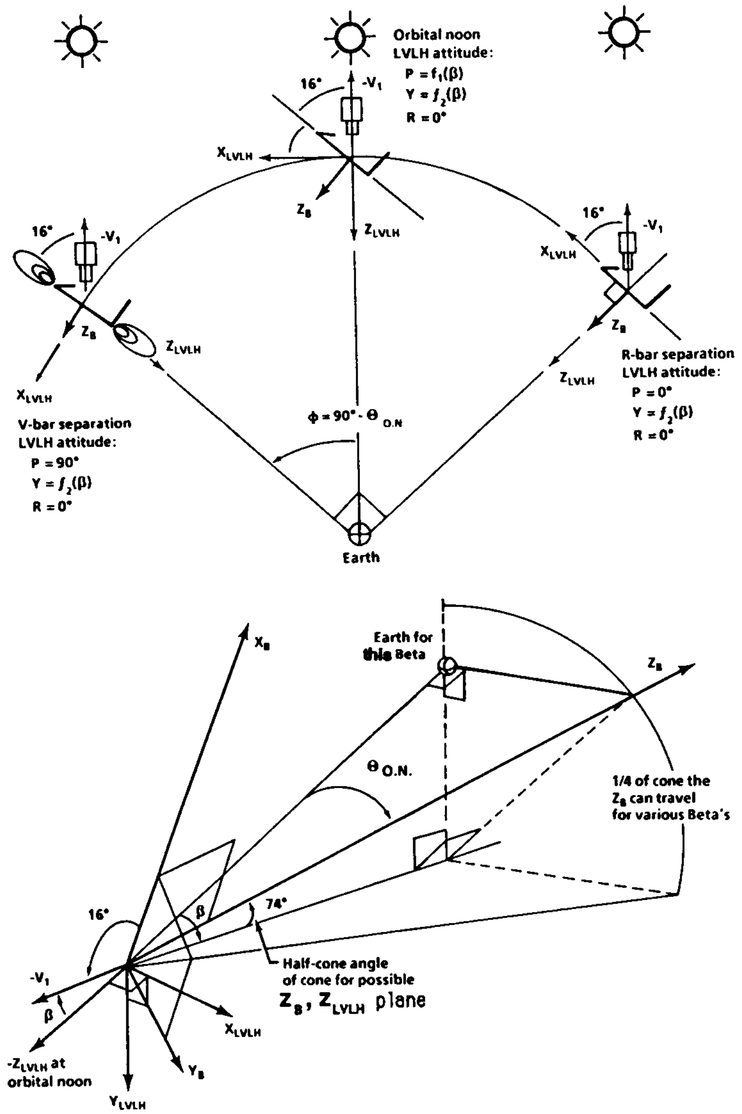
Ψ = Sun angle $\equiv$ the geometric angle between the Shuttle's position vector, $\hat{r}$, and the Sun pointing vector, $\hat{s}$

Orbital noon occurs when the Sun angle is at a minimum:

$$\Psi_{min} = |\beta|$$

(b) Definition of orbital noon.
Figure 1.– Continued.

LVLH $\equiv$ Local Vertical, Local Horizontal coordinate system whose origin is at the spacecraft's center of mass. The z-axis points towards the Earth along the spacecraft's position vector, the y-axis is in the opposite direction of the orbital angular momentum vector, and the x-axis completes the orthogonal coordinate system. The Euler rotation sequence for spacecraft attitudes referenced to the LVLH system is usually pitch, yaw, roll (P,Y,R)



LVLH pitch angle of Orbiter at orbital noon is:

$$\theta_{O.N.} = \cos^{-1}\left[\frac{\cos 74°}{\cos\beta}\right] = f_1(\beta)$$

(c) Derivation of the Orbiter LVLH pitch angle at orbital noon.
Figure 1.– Continued.

Central angle from orbital noon to the V-bar separation is:

$$\Phi = \theta_{sep} - \theta_{O.N.} = 90° - \cos^{-1}\left[\frac{\cos 74°}{\cos\beta}\right]$$

where β = solar Beta angle

θ_{sep} = Euler pitch angle of the Orbiter, in the LVLH coordinate system, at the V-bar separation; equal to 90°

$\theta_{O.N}$ = Euler pitch angle of the Orbiter, in the LVLH coordinate system, at orbital noon

Φ = central angle from orbital noon to the V-bar separation

The time from orbital noon to the V-bar separation is:

$$\Delta t_{sep} = \frac{\Phi}{360°} \cdot T$$

where ϕ = central angle from orbital noon to the V-bar separation

T = orbital period

Δt_{sep} = the time from orbital noon to the V-bar separation

Finally, the time from orbital noon to HST release is:

$$\Delta t_{release} = \Delta t_{sep} - 2 \text{ min}$$

(d) Derivation of the central angle and time between orbital noon and HST release.
Figure 1.– Concluded.

The launch window was calculated from the range of release times on orbit 19 that simultaneously satisfied the communication, attitude, and lighting requirements for the HST deployment. Figure 2 shows how each of these requirements combine to produce the range of acceptable release times from which the launch window can be determined.

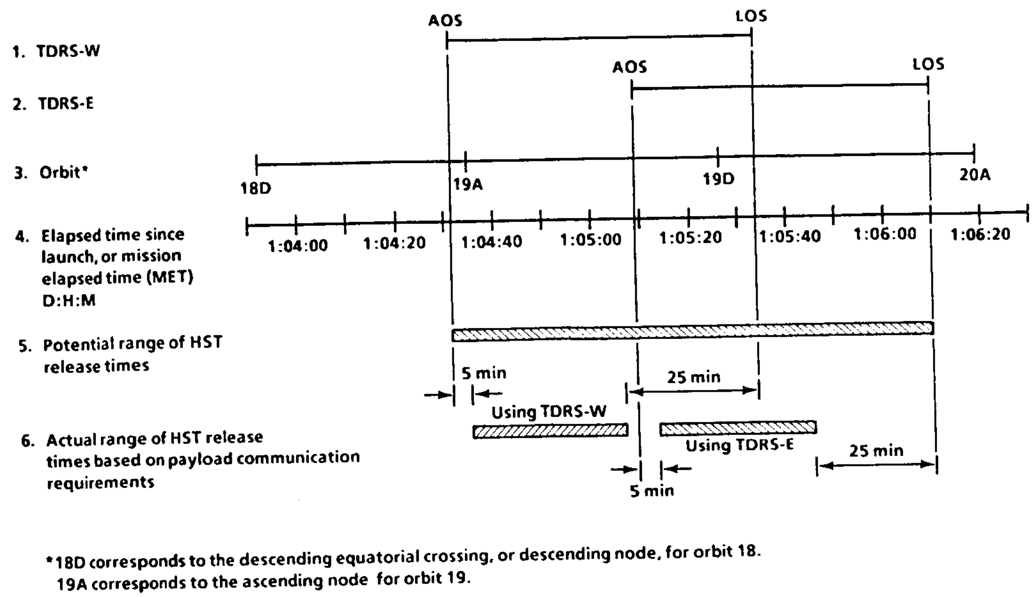


Figure 2.– Acceptable HST release times on orbit 19 .

For an orbital trajectory with a given geometry and orientation, the variation in launch time over a range of possible launch days will depend on how the orbital conditions required for payload operations change with time. Because the TDRSS satellites are geosynchronous, their orbital period is equal to the Earth's sidereal day, and communication with TDRSS is considered contact with an Earth-fixed target. Since TDRSS is an Earth-fixed target, the mission elapsed time of TDRSS acquisition on a given orbit does not vary with launch time. However, the position of the Sun, and therefore orbital lighting, does vary with time, so the mission elapsed time of HST release on orbit 19 also varied with launch time and date. This variation of release time due to a change in launch time can be seen in Figure 3.

By simulating the trajectories resulting from various launch times over a 24-hour period, the launch window analyst can determine all possible launch times that produce the required orbital conditions at the desired time of payload operations. For the HST mission, the launch time was varied on a specified launch date until the release time, calculated from the orbital noon time and solar Beta angle, matched an acceptable time from the HST deployment timeline in Figure 2. This day-long launch window would ensure that the deployment conditions were met during the allowable period of release times on orbit 19.

The variation in launch time over a day or period of days is typically displayed as a graph showing the opening and closing of the launch window that meets the payload requirements. The day-long and year-long HST launch windows in Figure 4 show how the HST deployment requirements that open and close the launch window change with time.

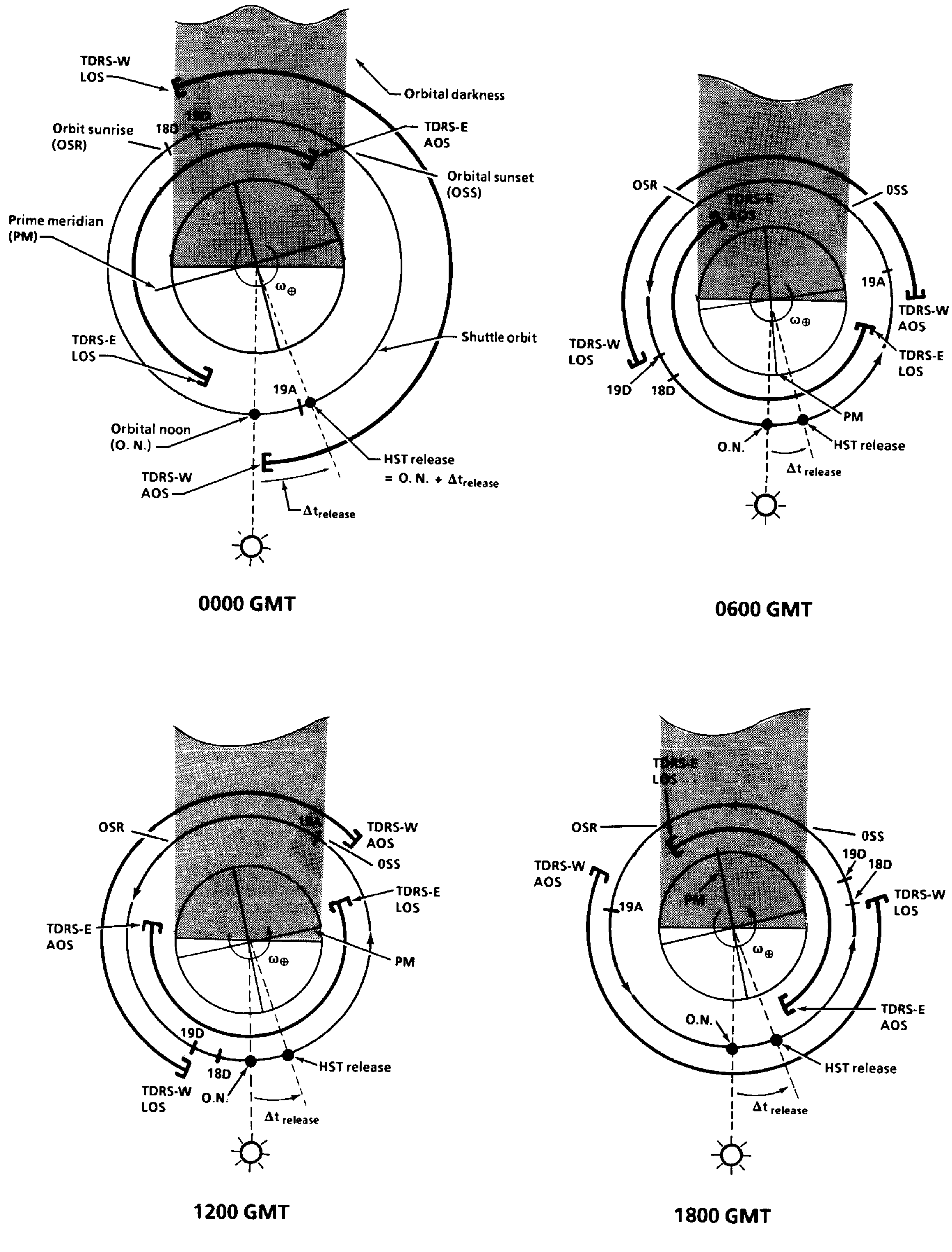


Figure 3.- Change in HST release time relative to TDRSS for various November 11, 1988, launch times.

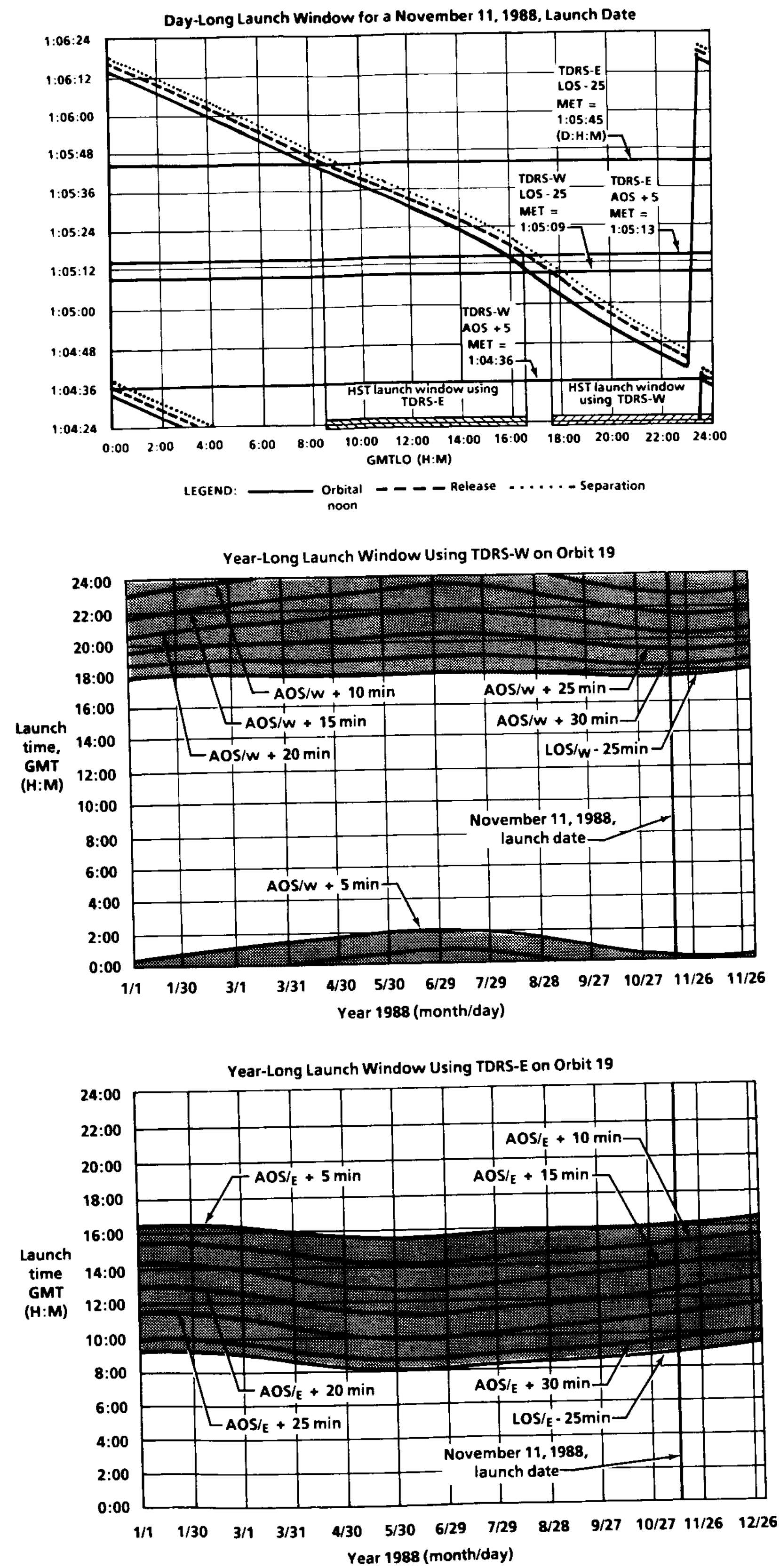


Figure 4.– Day-long and year-long HST launch windows for an orbit 19 deployment.

EFFECT OF ORBITER ATTITUDE REQUIREMENTS ON THE HST LAUNCH WINDOW

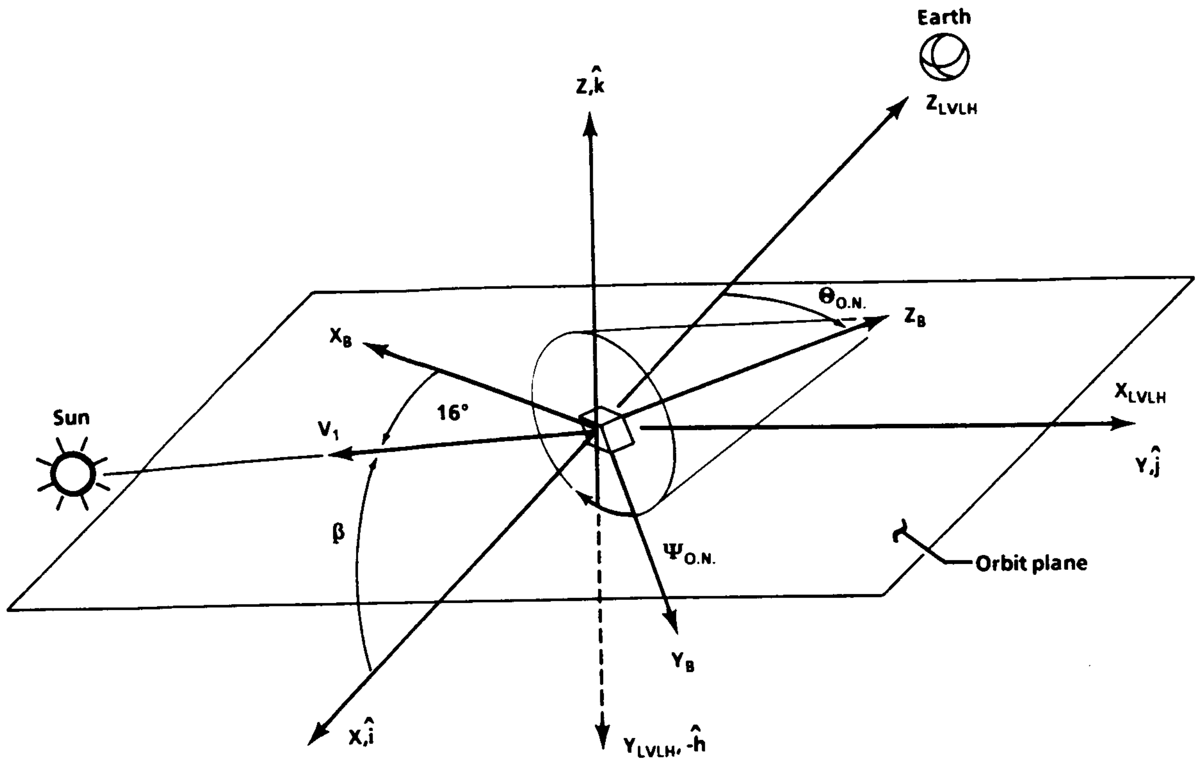
All launch times between the opening and closing of the HST launch window in Figure 4 ensured that communication, attitude, and lighting requirements could be met during the HST deployment on orbit 19. However, since launch time determined the Orbiter release attitude, certain launch times actually caused the Orbiter body to block the Ku-band antenna's line-of-sight communication with TDRSS. The launch times causing these unacceptable Orbiter release attitudes must be eliminated from the launch window.

To determine whether Orbiter attitudes required for payload operations affect a launch window, the analyst must first determine the attitudes that satisfy the payload requirements during the mission. Typically, more than one Orbiter attitude will meet the operational requirements of a free-flying or attached Shuttle payload. The analyst would limit this range of acceptable attitudes either by fixing the Orbiter orientation relative to the orbit plane or celestial sphere, or by requiring the Orbiter maintain an attitude that continually tracks a desired target.

Although the Orbiter attitude had to point the HST's -V1 axis at the Sun during the deployment, only one release attitude also aligned the Orbiter's Z-body axis with the orbital velocity vector at the separation burn. A formula was determined for this Sun-tracking, inertial attitude based on the known attitude and pointing constraints and the solar Beta angle at orbital noon. This geometrical derivation is illustrated in Figure 5. Like the HST release time, the Orbiter release attitude also varies with launch time and date because the solar Beta angle changes with launch time and date.

The Orbiter release attitudes could conceivably affect the lighting or communication required for HST deployment. However, the lighting requirement was met as long as HST was pointing at the Sun and its release was timed to coincide with orbital noon. But, determining whether the Orbiter release attitude interfered with TDRSS communication required special analysis, since the attitude varied with launch time and date. To assess the effect of attitude on communication, the launch window analyst had to construct a spherical look angle plot, or blockage pattern.

The blockage pattern is a graphical tool used in attitude and pointing analysis to determine the effect of Orbiter attitudes on the acquisition of targets relative to the Orbiter and payload. This plot represents a 360° spherical perspective from a pointing instrument, such as an antenna, sensor, or camera, that must make contact with a target. Plotting the time-varying and attitude-dependent positions of a target on the blockage pattern determines whether contact with the target can be made by the pointing instrument.



$\hat{h} \equiv$ orbital angular momentum vector

$-\hat{h} = -\hat{k}$

$Y_B \cdot -\hat{h} = \cos \Psi_{O.N}$

$$\Psi_{O.N.} = \cos^{-1}\left[\frac{\sin\theta_{O.N.}\cos\beta}{\sqrt{\sin^2\beta + \sin^2\theta_{O.N.}\cos^2\beta}}\right]$$

Therefore, the Orbiter LVLH attitude at orbital noon is:

$$P = \theta_{O.N.} = f_1(\beta)$$
$$Y = \Psi_{O.N.} = f_2(\beta)$$
$$R = 0^{\circ}$$

Figure 5.– The Orbiter attitude at orbital noon.

Knowing that Orbiter-to-TDRSS communication during the deployment would occur on Ku-band frequencies, a blockage pattern was created for the Orbiter's Ku-band antenna, as shown in Figure 6. The positions of the TDRSS satellites relative to the Orbiter on orbit 19 were plotted on the Ku-band antenna blockage pattern for the different launch times and the varying release attitudes that the Orbiter would be in over the duration of the launch window. The locations of the TDRSS satellites for a November 11, 1988, launch date can be seen in Figure 7. This plot shows that communication is affected by Orbiter and HST structures within the field-of-view of the Ku-band antenna, and by Earth occultation due to relative orbital motion between the Orbiter and a TDRSS satellite.

By plotting TDRSS satellite positions on the Orbiter Ku-band blockage pattern for launch window durations over different days of the year, the analyst determined the launch times that produced Orbiter release attitudes that would allow contact with TDRSS and simultaneously point HST at the Sun while the Orbiter was in the proper separation attitude. The effect of the Orbiter release attitude on the year-long HST launch window is shown in Figure 8.

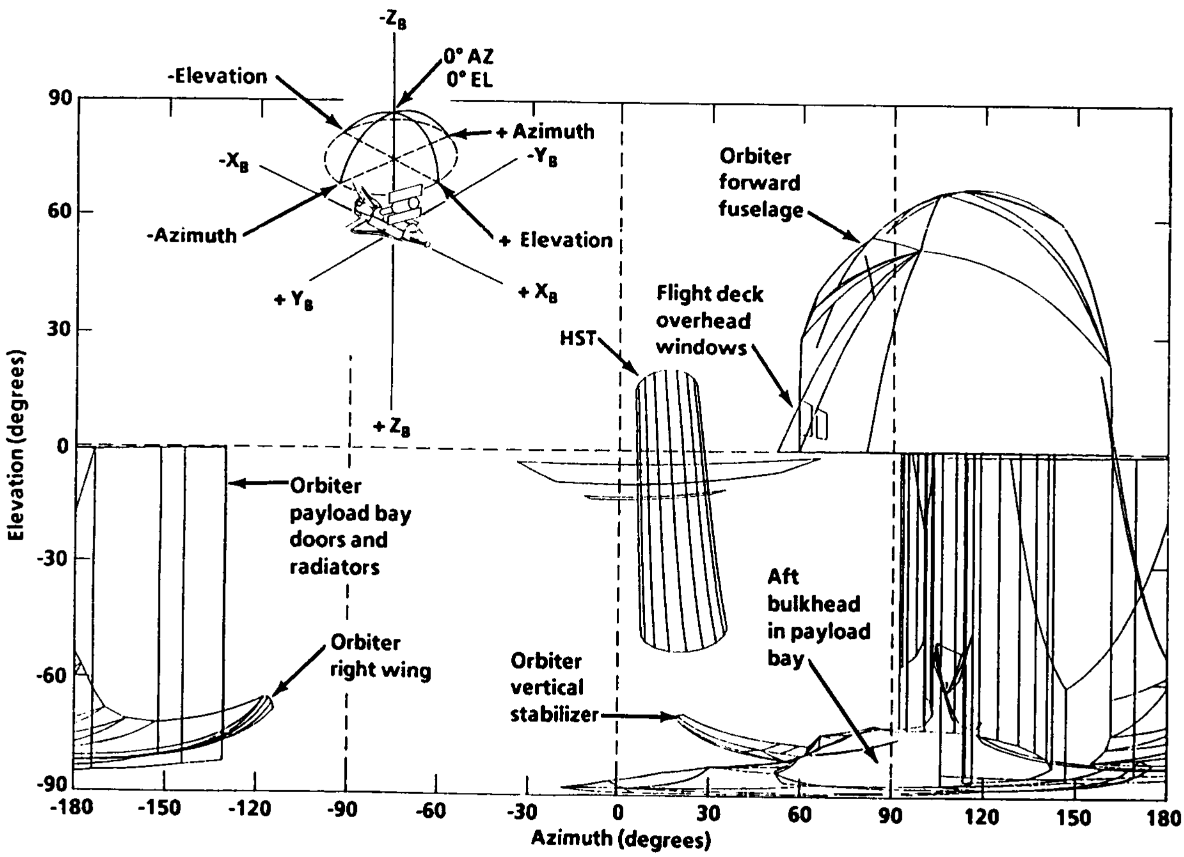
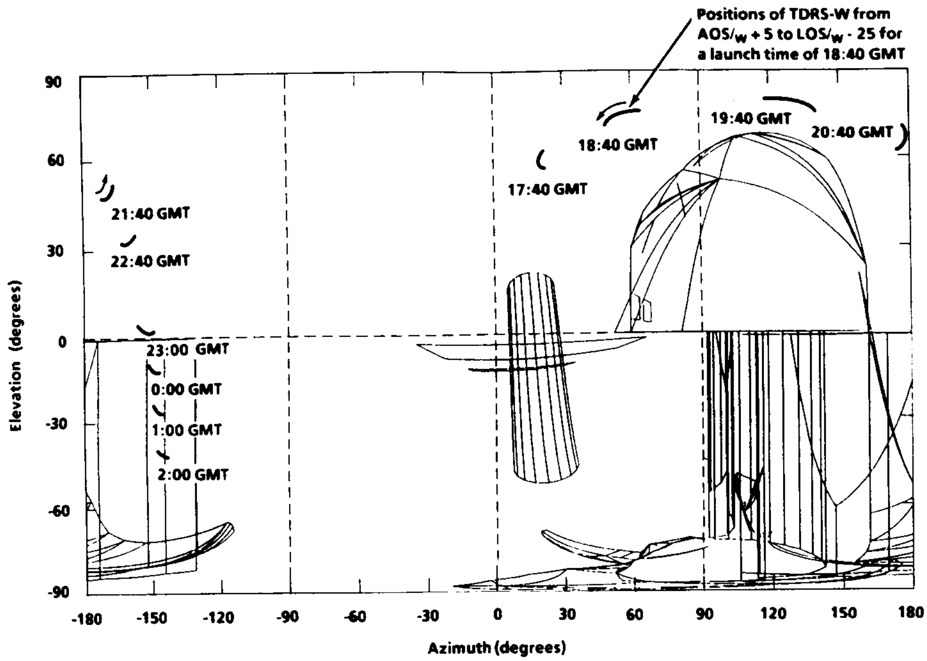
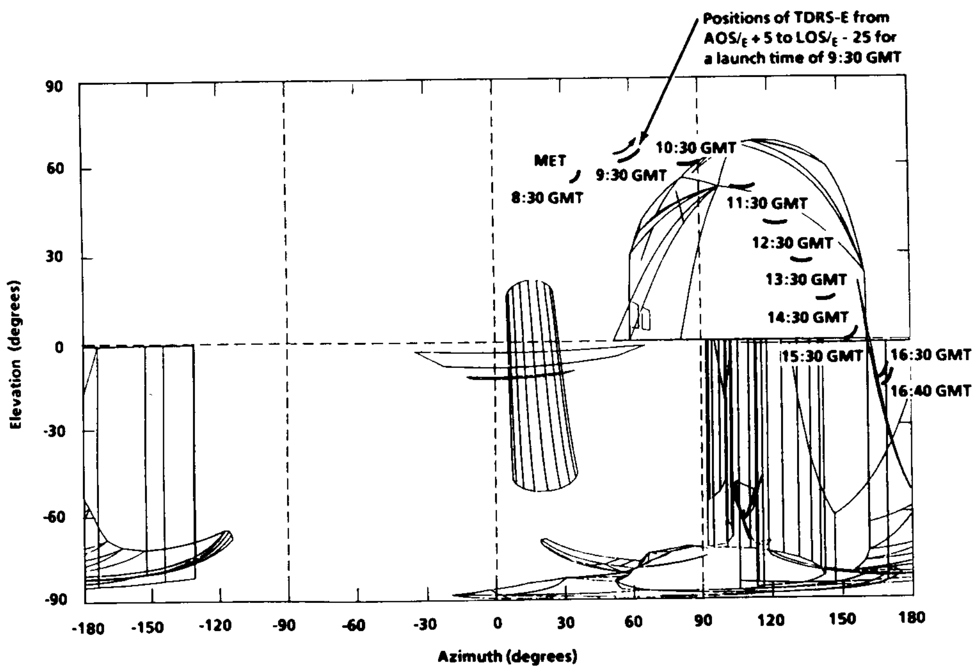


Figure 6.- Ku-band antenna blockage pattern.



(a) Positions of TDRS-W for the HST launch window using TDRS-W.



(b) Positions of TDRS-E for the HST launch window using TDRS-E.

Figure 7.– Positions of TDRSS from the Ku-band antenna for launch times on November 11, 1988.

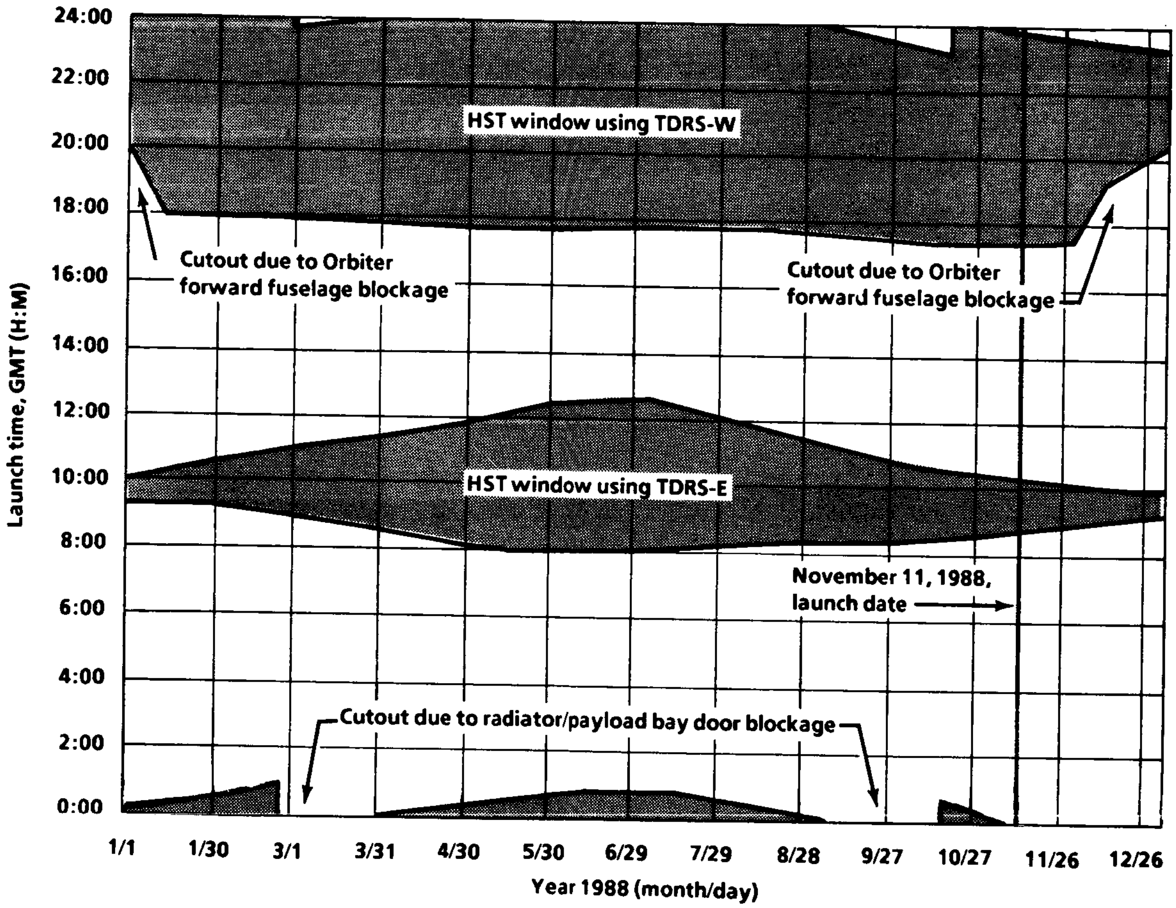


Figure 8.- HST launch window using Ku-band antenna for orbit 19 deployment.

SUMMARY

The launch window analysis described in this paper was used to determine the Shuttle launch times to deploy the HST. Shuttle attitudes that are required for payload operations are usually independent of launch time, but analysis for STS-31 showed that the Shuttle Orbiter attitude required to release the HST varied with launch time and date. The results of the analysis also showed that launch time determined the acceptable times to deploy the HST. The launch window that was eventually developed for STS-31 allowed the mission planner to determine the Orbiter release attitude and HST release time for a specific launch time, and to make prelaunch decisions if a launch delay occurred or if a TDRSS satellite was not available.

Analytical solutions were derived for the HST release time and the Orbiter release attitude based on the requirements for the deployment operations. A spherical look angle plot, or blockage pattern, was a visualization tool used to predict the effect of the Orbiter release attitude and the HST release time on the launch window. The methods developed from the HST launch window analysis can also be used in the launch window analysis for Shuttle missions with payloads with communication, pointing, and lighting requirements similar to HST, such as Spacelab missions or missions deploying low Earth-orbiting satellites.

For the HST deployment mission, a change in launch time rotated the Shuttle's trajectory in inertial space so the required orbital conditions for HST release occurred at a particular time. Changing the orientation of the orbital trajectory with launch time was the basis for the HST launch window analysis. However, the trajectory profile for the HST mission could have been altered by other means to obtain the orbital period, altitude, inclination, or Earth-latitude crossing that would ensure the required orbital conditions for the HST deployment. This could have been accomplished by a number of design options, such as ascent yaw-steering, nonstandard inclinations, alternative insertion altitudes, alternative days for payload operations, and orbit adjust maneuvers. Although some of these options were considered for the HST mission, discussion of these options is an entire subject by itself and was not covered in this paper.

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REFERENCES

1. Hubble Space Telescope Payload Integration Plan, National Aeronautics and Space Administration, rev C, NSTS-14009, Aug. 1988.

2. Cargo Systems Manual: Hubble Space Telescope, All Flights, vol. I, rev A, JSC-2206, July 1988.