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ECLIPSES BY THE EARTH AND BY THE MOON AS CONSTRAINTS ON THE AXAF MISSION

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Abstract The Advanced X-ray Astrophysics Facility (AXAF) is scheduled for launch on September 1, 1998, on a mission lasting ten years. During this time AXAF will be subject to eclipses by the Earth and the Moon. Eclipses by the Earth will occur during regular 'seasons' six months apart. AXAF requires that none last longer than 120 minutes, and this constrains the orbit orientation. Eclipses by the Moon occur infrequently, but may pose serious operational problems. The AXAF perigee altitude can be chosen, once the other initial conditions are known, so that objectionable Moon-eclipses can be avoided by targeting the final burn.

The Advanced X-ray Astrophysics Facility (AXAF) is scheduled for launch on September 1, 1998, on a mission lasting ten years. This satellite is the third in NASA's Great Observatories series of spacecraft. It will be able to observe celestial x-ray sources with unprecidented resolution. Its initial orbit will be highly elliptical, with an apogee altitude of approximately 140,000 km and a perigee altitude in excess of 10,000 km. During the mission the orbit will be perturbed by the gravitational influences of the Moon and the Sun, and the AXAF will be subject to eclipses when it passes through the shadows of the Earth and of the Moon. Below I briefly discuss the operational problems associated with eclipses, describe eclipses by the Earth and by the Moon, and discuss the approaches used to manage the overall eclipse problem.

Operational Problems due to Eclipses

The AXAF configuration is as shown in Figure 1. The spacecraft depends for its electrical power on solar panels mounted on either side of the spacecraft bus. The bus provides propulsion via the Integral Propulsion System (IPS), plus navigation, attitude control,

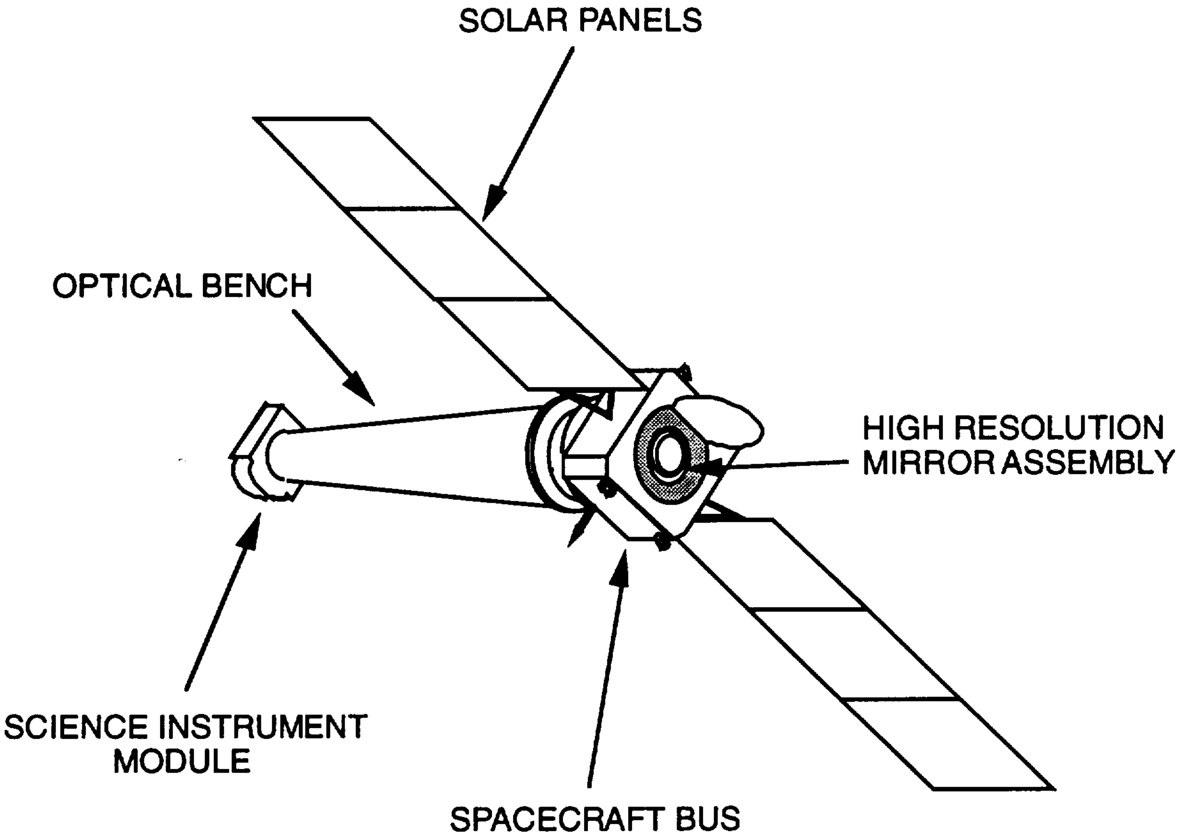

FIGURE 1.(a) AXAF On-Orbit Configuration

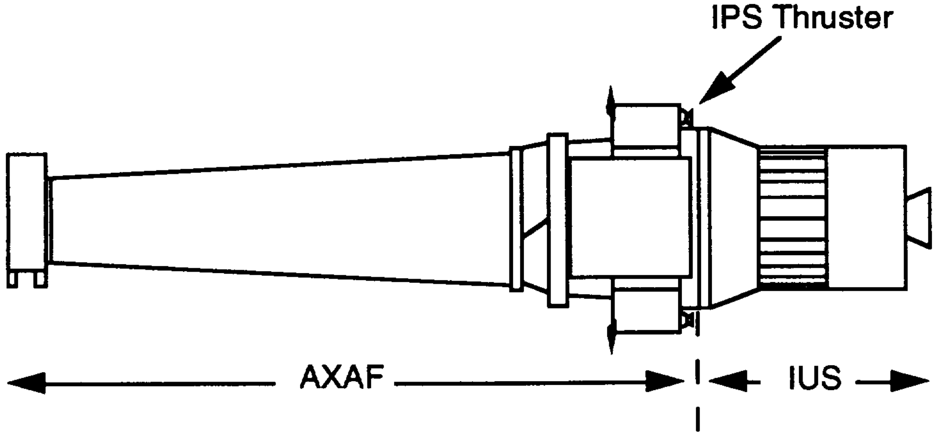

FIGURE 1.(b) AXAF - IUS Stack Configuration

and other functions, and supports the High Resolution Mirror Assembly that focuses x-rays on a focal plane at the Science Instrument Module (SIM). The optical bench connects the bus and SIM and maintains them in the correct separation and alignment.

An eclipse will occur whenever the Sun, an occulting body (Earth or Moon), and the spacecraft come into near alignment. As the Sun is progressively occulted the number of photons impinging on the solar panels decreases, so consequently the current drops. At the same time the panels cool due to the decreased radiant flux, and the output voltage from the panels increases, at least up to a point. Output power declines to zero as total darkness is approached. During the emergence from eclipse the process is reversed, with the voltage excursion being somewhat higher due to the lower starting temperature of the solar panels, which have cooled as long as the level of sunlight was declining or zero. The AXAF power system has been designed to operate at a peak of 35 volts, but the voltage excursions during partial eclipse phases may reach 40+ volts. Also, the voltage could remain high for a short time after complete emergence from eclipse, the time required for the solar panels to warm to their equilibrium operating temperature. These voltage excursions have the potential to damage the spacecraft electronics due to the over-voltage condition. Recent operational plans are to use the three onboard batteries to buffer the voltage during eclipses. However, if the batteries are in a high state of charge when the high voltage current begins to flow from the solar panels, overheating or other damage may occur to them. An operational strategy to deal with this problem is to bring the batteries online well before the start of an eclipse, and to off-point, or 'feather', the solar arrays from the direction toward the sun to modify the output voltage and current.

Another operational fact is that AXAF's optical bench and instruments need to be maintained above a minimum temperature of about 50 ^{o}F, so when the spacecraft enters eclipse and begins to cool, heaters automatically come on to keep the craft warm. The heaters operate off a thermostat and are not commandable from the ground. Left on long enough they would completely discharge the batteries. In practice a depth of discharge greater than 80 percent is considered non-recoverable. Using this figure, plus a one-battery-out redundancy assumption, a maximum allowable eclipse time of 120 minutes has been established for this satellite. The combination of voltage buffering, solar panel feathering, and temperature control maintenance means that the spacecraft will require continuous monitoring by ground personnel prior to and during every eclipse. Every eclipse may need to be treated as a unique event.

Earth-eclipses

Figure 2 shows an example of the geometry involved in producing eclipses by the Earth and the Moon. Eclipses by the Earth (Earth-eclipses) will occur during regular 'seasons' centered six months apart when the Earth's shadow cone axis lies near the line of nodes of the AXAF orbit plane with respect to the ecliptic plane. Individual Earth-eclipses occur primarily near the 'perigee end' of the eccentric AXAF orbit. Consequently the particular orientation chosen for the orbit will determine the number, timing, and duration of Earth-eclipses. During the ten-year mission the orbit will evolve due to perturbations from the Earth's oblateness, the Moon, and the Sun, with long cycles in eccentricity and inclination. This evolution causes Earth-eclipses to occur at altitudes ranging from 10,000 km to as much as 80,000 km over the mission lifetime.

The altitude of eclipses may be important in managing the electrical system, since a draw-down of battery charge would require that some minimum number of devices be operating, and devices in the SIM may not be operating at low altitudes. This is because the science instruments, especially the X-ray detectors, are sensitive to ionizing radiation, and the flux of this radiation depends on the abundance of charged particles trapped in the Earth's magnetic field, which is a function of altitude. Early thinking was that the SIM would be shut down below an altitude of 60,000 km, but this is only a benchmark figure; the actual shut down altitude will be determined during the mission be measuring the ambient flux. In any event, the SIM may be nominally operational at the altitudes of some eclipses, but not of others. Operations will need to be modified accordingly to properly manage the electrical system.

The Earth-eclipse case is well behaved, since the occulting body is fixed at the focus of the orbit. With the Moon-eclipse case the occulting body is constantly in motion with respect to the satellite orbit. The duration of Moon-eclipses is quite variable, since the eclipse need not occur very close to the AXAF perigee, and directions of relative motion between the satellite and the Moon can be parallel, antiparallel, perpendicular, or skewed. Altitudes of these eclipses range from 10,000 km to over 90,000 km.

Earth-eclipse Management

The target ascending node of the AXAF orbit, 200 °, has been chosen to put the orbit plane far out of the ecliptic plane; the argument of perigee, 270 °, has been chosen to place the long axis of the orbit well out of the ecliptic plane, at least initially, so that any Earth-eclipses occur near AXAF's perigee. Together these characteristics minimize the number and duration of Earth-eclipses. The final bounds about this orientation target were set by the 120 minute eclipse limit . In simulations of orbits that adhere to these constraints, an average of 145 Earth-eclipses occurred during a ten-year period.

In Figure 3, the upper panel shows eclipse seasons as a series of spikes. The spikes occur at intervals about six months apart. The lower panel shows a closeup of the first three eclipse seasons. The data points on each spike represent the duration of individual eclipses. During a given eclipse season the duration of eclipses increases then decreases in a systematic fashion. The seasons last different numbers of revolutions, with the longer seasons typically having shorter individual eclipse durations than the shorter seasons, e.g., eclipse season two lasts 13 revs, with a longest eclipse of about 53 minutes, while eclipse season three lasts only 7 revs, but its longest eclipse lasts about 88 minutes.

Earth-eclipses almost always consist of partial eclipse entry and exit phases of about 4 minutes duration each, with a total phase in between. However, from time to time near the start or end of an eclipse season no total phase occurs; rather the satellite experiences a partial eclipse of up to a few tens of minutes duration as it skirts the edge of the Earth's shadow.

Moon-eclipses

Eclipses by the Moon (Moon-eclipses) occur on those infrequent occasions when the Sun, Moon, and satellite are nearly aligned. There are an average of 9 Moon-eclipses during any ten-year period. The durations of these eclipses vary from a few minutes to a few hours. The Moon's shadow cone is much smaller than that of the Earth, owing to its smaller physical size. Its umbral cone vanishes at the point along the Sun-Moon line where the Moon's angular size just equals that of the Sun. The exact position where this occurs varies with the distance between the Sun and Moon, which is a function of the lunar phase and time of year, but a typical distance from the center of the Moon to this point is 373,600 km. If an object is further out along the Sun-Moon line, some of the Sun will be visible around the disc of the Moon, so that an annular eclipse will be seen instead of a total eclipse.

While most Moon-eclipses last a few tens of minutes and are only partial, some of them are of long duration and/or of great 'depth' (degree of coverage of the Sun). These they may pose problems for the power system, and so should be avoided if possible. Likewise, the occurrence of a Moon-eclipse before or after an Earth-eclipse could be problematic if there were insufficient time between events for the batteries to reach the necessary state of charge. Another geometry type which may cause problems occurs when the trajectory crosses the Moon's shadow cone as shown in Figure 4. If the satellite's projected path extends beyond the shadow cone boundary, a pair of Moon-eclipses closely spaced in time will be seen; otherwise a long Moon-eclipse with a W-shaped depth profile will be seen. Either of these cases could cause the operational problems mentioned above, and they should also be avoided if possible.

Moon-eclipse Management

To manage the Moon-eclipse problem, changes must be made in the initial conditions that are free parameters. Most of the initial conditons are not free parameters, but are constrained as follows:

The inclination is fixed by the shuttle's ability to put a payload as heavy as AXAF into a low parking orbit: a due east launch is necessary, thus limiting the inclination to the Kennedy Space Center (KSC) latitude of 28.465 °.

Right ascension of the ascending node (RAAN) and argument of perigee (AoP) are constrained by the Earth-eclipse criteria as discussed above. Actually there are two zones centered on a RAAN of 180 ° and an AoP of either 90 ° or 270 ° , as shown in Figure 5, which meet the 120 minute limit. Since AXAF will communicate through the Deep Space Network (DSN) ground stations in California, Spain, and Australia, the AoP of 270 ° is preferred, because this orientation places the long axis of the orbit in the northern hemisphere, thus giving the two northern stations a view of the spacecraft most of the time.

Another criterion is the need for the AXAF to spend as much time as possible above the dense trapped radiation region, to maximize the time for collection of science data. As mentioned above a benchmark altitude of 60,000 km was assumed as a lower limit in designing the orbit. Taking into account the propulsive capability of the AXAF - Inertial Upper Stage (IUS) combination, a target orbit with an apogee altitude of 140,000 km and a perigee altitude of 10,000 km was originally selected. Since that time, there have been changes in weights and propellant quantities, so that now a perigee as high as 15,000 km may be reachable. Thus the initial perigee altitude is a somewhat-free parameter.

The last parameter subject to variation is the launch date. Although the target insertion date is September 1, 1998, any delays in completion of the scientific instruments, software development, testing, integration, and shuttle processing, or other problems, could delay the actual launch. For any given launch date a specific launch window exists during which the target orientation can be reached, so once the launch date is fixed the launch window on that date also becomes fixed.

Small changes in the AXAF orbit's initial semimajor axis, orientation, and starting time alter the relative geometry history between the Earth, Sun, Moon, and spacecraft that will be experienced during the 10-year mission. Thus, for example, a burn sequence that produces a perigee altitude of 11,450 km instead of a target value of 11,500 km may cause a Moon-eclipse to be missed that would have occurred, or one to occur that would have been missed. Given that the perigee altitude and start date are the only free variables, I ran simulations over a subset of the reachable perigee altitudes, for several start dates. For any insertion date and initial perigee altitude, numerous Moon-eclipses may occur during the ten-year simulation interval: I saw as few as 2 and as many as 21 in my simulations.

The Moon-eclipse patterns for a given insertion date differ from those of any other insertion date. Without performing the simulations one does not know in advance how similar or different these patterns may be. Figure 6 shows results for the case of insertion on Sep. 15, 1998, for insertion perigee altitudes between 11,500 and 11,600 km. Only two eclipses appear which exceed the 120 minute limit. These happen if the insertion perigee altitude is 11,577 or 11,578 km. To avoid these eclipses one would target to some other altitude. This is the approach currently being studied to avoid problematic Moon-eclipses. The burn sequence will consist of two IUS burns, which begin one hour after deployment from the Shuttle; the first IPS burn, centered on a perigee passage after the IUS burns; the second IPS burn, centered on the subsequent perigee passage (this fixes the AXAF orbit apogee); the third IPS burn, centered on an apogee passage (this raises perigee to near the target value); and the final IPS burn at apogee, which can be considered a vernier burn to raise perigee to the target value.

No matter what the starting date, one will not know the exact orbit orientation and apogee altitude until the penultimate burn is completed, and a state vector is provided from DSN tracking data. This state is expected to be accurate to within plus or minus 150 m in altitude. The 3-sigma error in final perigee altitude due to the final fourth IPS burn is expected to be about 27 km. Thus when selecting a target perigee altitude to avoid Moon-eclipses, one needs to find a 54-km-wide window between any of these troublesome events, e.g., from a plot such as in Figure 6.

Owing to the sensitivities of the situation, simulations to determine acceptable perigee altitude targets will have to await the completion of the third IPS burn, when an accurate state vector can be determined. The final phase of the powered flight segment of the AXAF mission will find the ground support staff busy indeed.

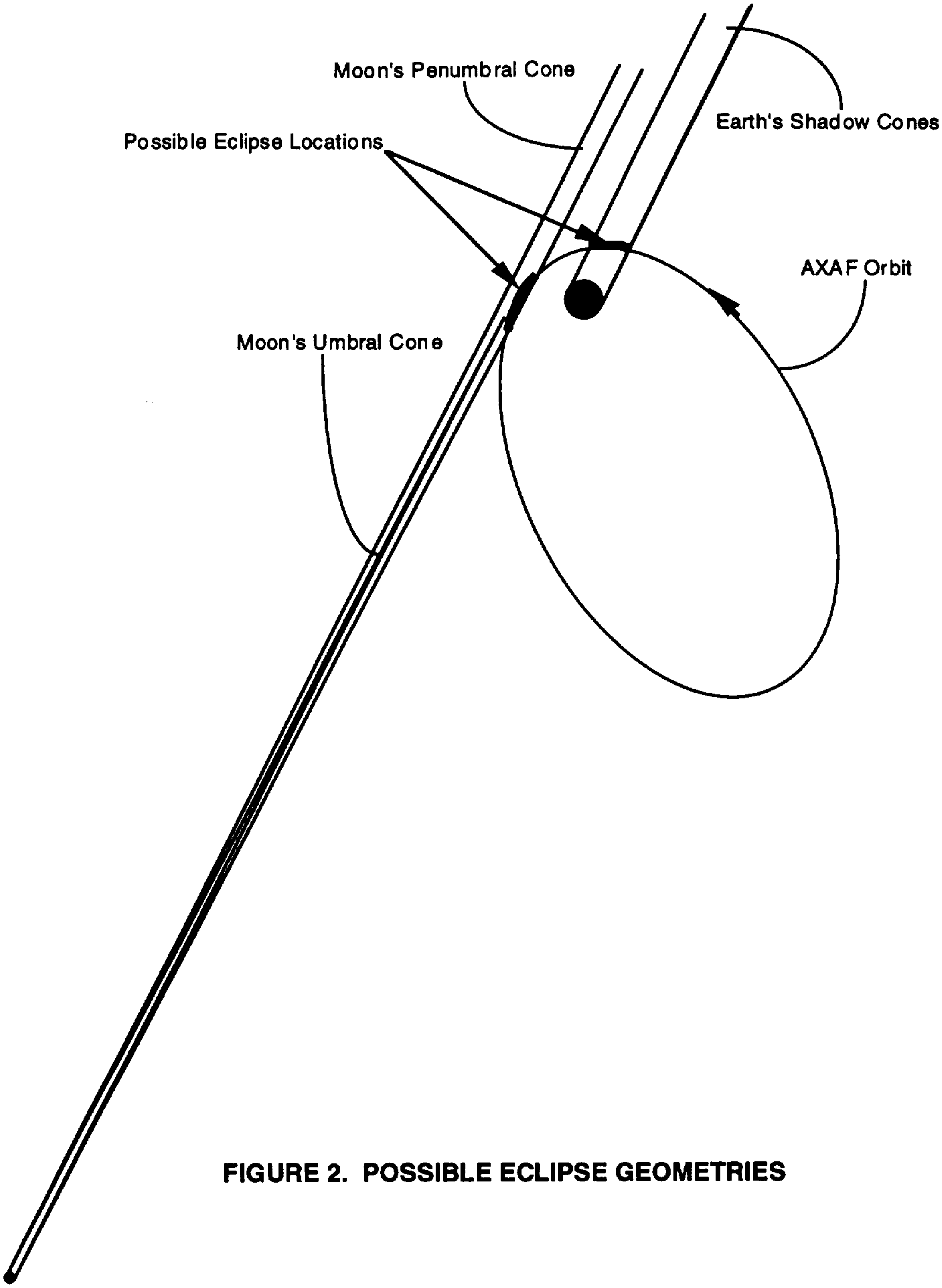

FIGURE 2. POSSIBLE ECLIPSE GEOMETRIES

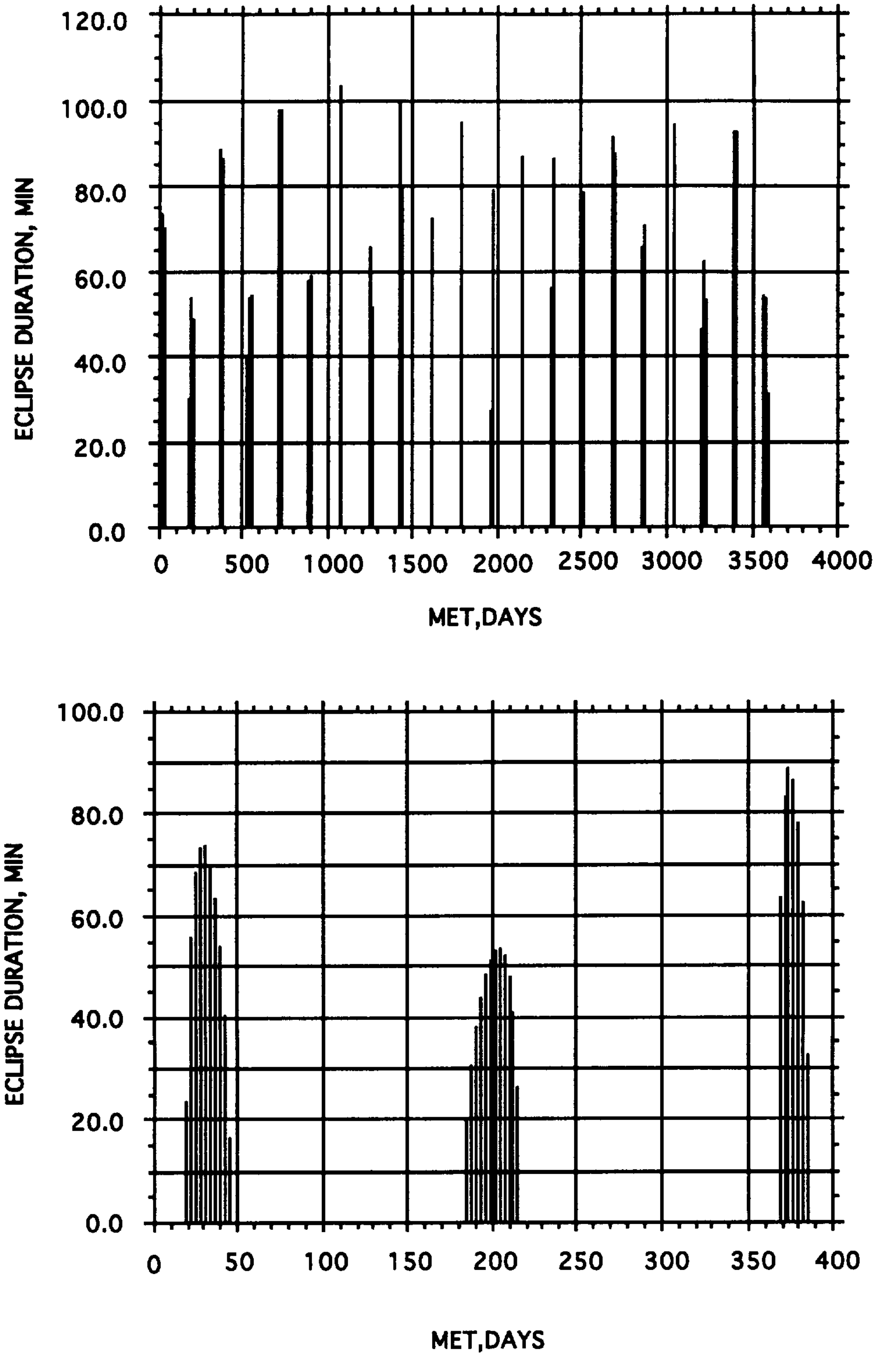

FIGURE 3. Top: Eclipse Seasons During Ten Years;
Bottom: First Three Seasons (Detail)

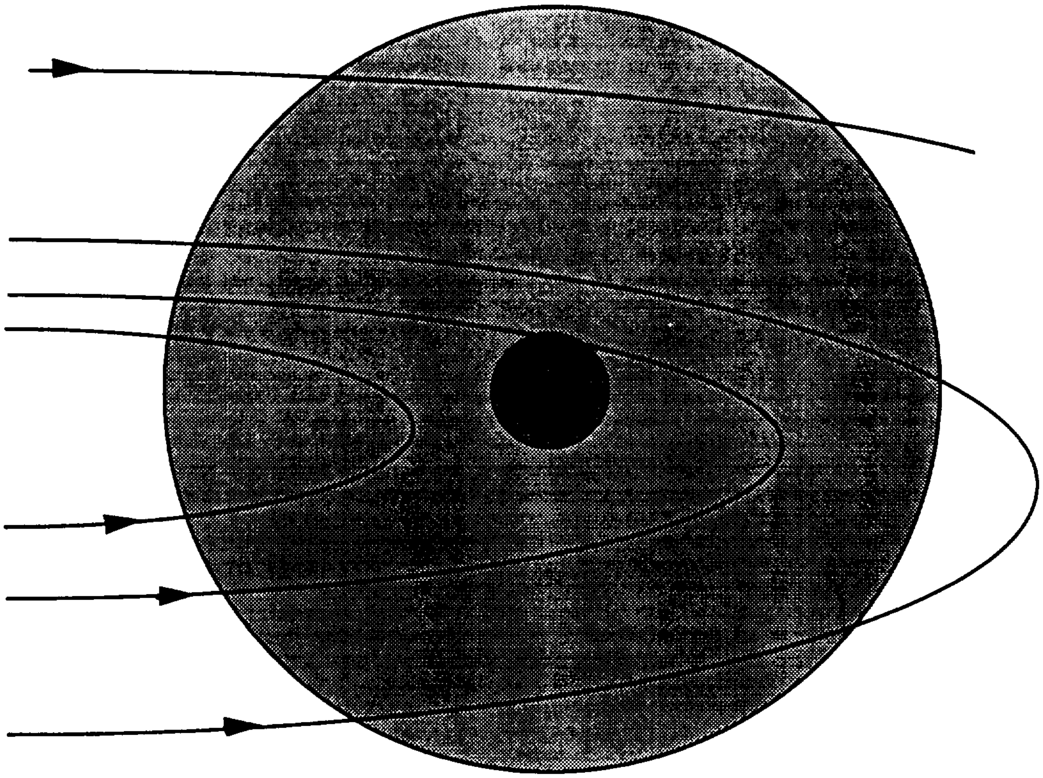

FIGURE 4. Satellite Trajectories Projected on a Plane Perpendicular to the Moon's Shadow Cones

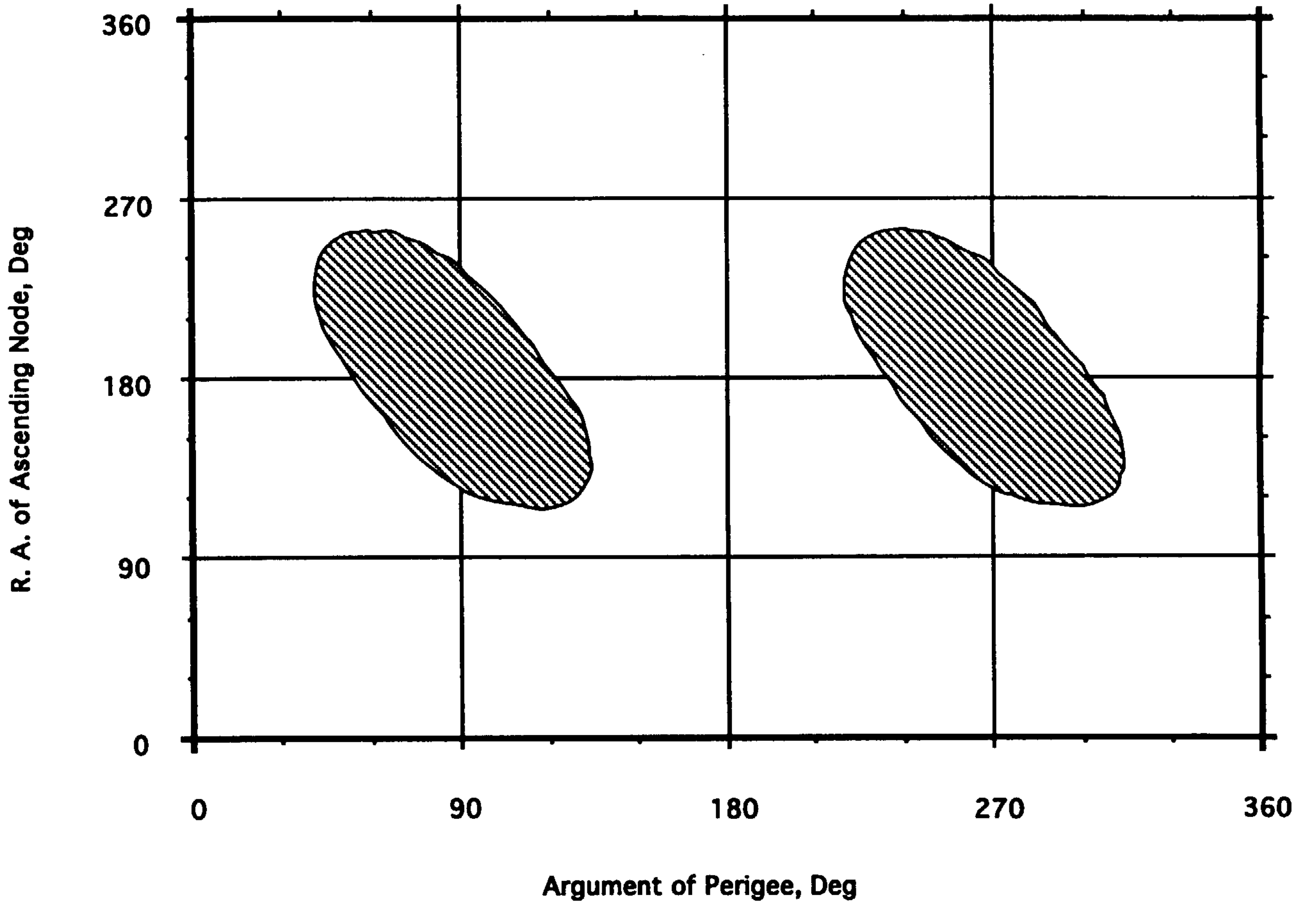

FIGURE 5. ORIENTATION ZONES WHERE THE EARTH-ECLIPSE LIMITS ARE OBSERVED

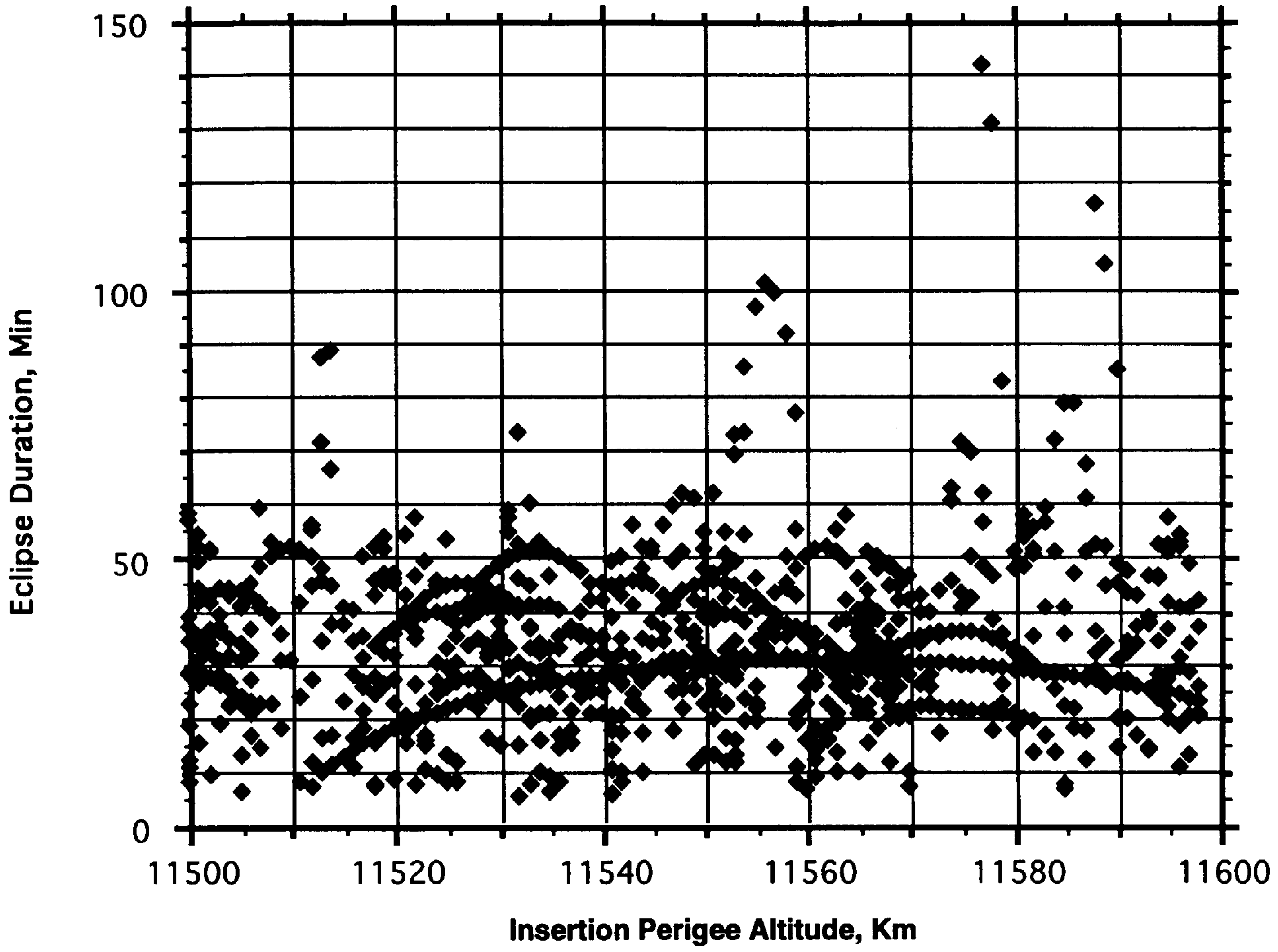

FIGURE 6. Eclipse Duration as a Function of Perigee Altitude, with 140,000 Km Apogee