DESIGNING AN ANTENNA/PEDESTAL FOR TRACKING LEO AND MEO IMAGING SATELLITES

W. C. Turner
Electro-Magnetic Processes, Inc.
Chatsworth, California

ABSTRACT

This paper takes one through the processes followed by a designer when responding to a specification for an earth terminal. The orbital parameters of Low-Earth Orbiting and Medium-Earth Orbiting (LEO and MEO) satellites that affect autotracking and pointing of an antenna are presented. The do's and don'ts of specifying (or over specifying) the antenna feed and pedestal size are discussed. The axis velocity and acceleration rates required of a Y over X and El over AZ type pedestal are developed as a function of satellite altitude, radio frequency of operation, and ground antenna terminal diameter. Decision criteria are presented leading to requiring a tilt mechanism or a third axis to cover direct and near overhead passes using an El over Az pedestal. Finally, the expressions transforming Y over X configuration position angles to azimuth and elevation axis position angles are presented.

KEY WORDS

(1) LEO Earth Terminal
(2) MEO Earth Terminal
(3) Antenna/Pedestal Design Parameter

BACKGROUND

Although the normal path of a satellite is elliptical, most imagery satellites are maneuvered into a low altitude (400 to 800 km) circular orbit. Future global communication satellite clusters will be put into mid-altitude circular orbits of 800 to 2,000 km. The cluster of GPS satellites are maintained in precise orbit at an altitude of 20,190 Km. Figure 1 shows the apparent peak overhead velocity of circularly orbiting satellites for satellite altitudes ranging from 300 to 2600 km. The mathematical expression for this parameter is developed from Newton's law of universal gravitation, $F = m(h + R_E)^2 = GMm/(h + R_E)^2$, from which;

$$V_A \approx \frac{36173.6}{h(h + R_E)^{1/2}} \qquad (1)$$

where V_A is the apparent angular velocity (from the observer's position on the surface of the Earth) in degrees/second, R_E is the earth's radius in km and h is the altitude of the satellite in km. This is the peak velocity required of the X-axis of a Y over X pedestal. or the elevation axis of an El over Az pedestal. Figure 2 shows the crossing velocity of a satellite vs. altitude with 10 degree X-angle offset. The approximate closed expression for this parameter from curve fitting is:

$$V_C \approx \frac{2000}{h(h + R_E)^{1/2}} \qquad (2)$$

This is the peak velocity of the Y (or Cross-Elevation) axis of an X-El/El pedestal. These benign rates are easily achieved by Y over X type pedestal but these type pedestals may not be available nor affordable if available. Consequently, EL over AZ type pedestals are usually specified with mechanical features that assure coverage of the "keyhole" to accommodate near or direct-overhead passes.

SIZING THE SYSTEM

In practice, the engineer sizes the antenna, then sizes the pedestal to swing the antenna. Antennas ranging in diameter from 1 to 12 meters and weighing from 25 to 550 kilograms require 1 of 5 different size pedestals to support and point them. Larger antennas requiring pedestals with greater than 25 horsepower drive trains are excluded from this discussion.

Sizing The Antenna

The antenna can be sized by merely specifying the required Effective Isotropic Radiated Power (EIRP) and uplink frequency, and the required G/T at a specific elevation angle, and downlink frequency. If these parameters are not available, provide the following:

- Downlink (Satellite to Ground Information)
  - Effective Isotropic Radiated Power (EIRP) of satellite (vs. angle due to satellite antenna pattern)
  - Satellite orbital altitude
  - Downlink carrier frequency of operation
  - Downlink data rate and modulation format

- Minimum elevation angle for acquisition
- Is autotracking required? If so, is there a beacon for tracking?

- Uplink (Ground to Satellite Information)
  - Satellite orbital altitude
  - Required power density at satellite
  - Uplink carrier frequency of operation
  - Uplink data rate and modulation format

Frequently, a system is over-specified because antenna size, gain, beamwidth, sidelobe level and G/T are all specified. These parameters are highly related to each other and often the proposal engineer must take exception to one or more of them. Although a low sidelobe envelope is mandatory for communication with geostationary satellites (in order to minimize interference with and from neighboring satellites), specifying inordinately low sidelobes for tracking of LEO satellites simply increases the cost of the system and can result in lower antenna efficiency.

Sizing The Pedestal

In order to compute the induced rates (hence horsepower and weight) of the antenna/pedestal due a satellite in a circular orbit, the following information should be provided:

- Satellite Orbital parameters (or "Elements")
  - Semi-major axis
  - Inclination angle
  - Longitude of the ascending node

From these element sets, the satellite trajectory, as well as induced velocity and acceleration of each axis of the pedestal, can be calculated. For an El over Az pedestal, the azimuth axis velocity and acceleration become significant when accommodating near or direct-overhead passes. Since the required peak acceleration is related to the required peak velocity, the dynamic analysis to establish peak velocity is developed first.

Pedestal Velocity

Frequently it is specified that downlink data flow not be interrupted during a direct or near-direct overhead satellite pass. Because the free space attenuation and atmospheric losses are at a minimum when the satellite is directly overhead, some diminution of ground antenna gain may be acceptable. Figure 3 is a plot of the 3-dB (½ power) and 6-dB beamwidth loss curves, vs. Df the product of the antenna diameter (in meters) and the operating frequency (in GHz). A frequently used expression for the half-power beamwidth of a paraboloidal antenna is:

$$BW = \frac{70\lambda}{D} = \frac{21}{Df} \tag{3}$$

where D and f are expressed in Meters and GHz respectively.

It is seen that for a 10-meter reflector operating at 2 GHz (Df = 20), the half power beamwidth is approximately one degree, and for a reflector 2-meters in diameter, at 15 GHz (Df = 30), the half-power beamwidth is 0.7 degrees. The 6-dB beamwidth curve shows that it is wider than the 3-dB beamwidth by a factor of $\sqrt{2}$. The beamwidth plots do not extend beyond a Df factor of 150 because with present technology, it is not financially practical to supply a pedestal that would maintain accurate pointing of the related narrow antenna beams on a LEO satellite. Also plotted on Figure 3 is the azimuth velocity K factor which is expressed as,

$$K_{AZ} = \log [\text{secant } (90° - BW/2)] \tag{4}$$

The antilog of this factor is used in the next plot to show how much the azimuth velocity must be increased to accommodate near-overhead satellite passes. Figure 4 is a plot of peak azimuth axis velocity required to negotiate an overhead pass within 3-dB or 6-dB of the beam peak, vs. satellite altitude with the factor Df as a parameter. The equation used is

$$\theta_{MAX} = \log \text{secant } (90° - BW/2) \tag{5}$$

Where V_A is the apparent velocity vs. satellite height from Figure 1 (equation 1) and BW is the 3 dB or 6 dB antenna beamwidth vs the prameter Df from Figure 3.

The curves show the azimuthal velocity required to keep the antenna at an elevation angle that assures no more than a 3-dB (or 6-dB) loss in received downlink power. These curves can be used to quickly determine drive motor(s) horsepower (HP), and gear ratios, as well as whether a pedestal tilt mechanism or a third pedestal axis is required. It should be noted that speed is directly proportional to horsepower and that for large pedestals, horsepower of electric motors and solid-state servo amplifiers is limited to 25 or so HP for a dual-drive system.

Pedestal Acceleration

A good approximation for calculating the peak expected acceleration is to use the following expression for a crossing vehicle from Reference (1):

$$\ddot{\theta}_{MAX} = 0.65(\dot{\theta}_{MAX})^2 57.3 \quad (6)$$

Where $\dot{\theta}_{MAX}$ is in radians/second, and $\ddot{\theta}_{MAX}$ is in degrees/sec/sec -- these are the peak rate and acceleration use in calculating the servo lag errors when computing the antenna autotracking and pointing accuracies. For a near overhead satellite pass, the peak velocity of the elevation axis occurs approximately 30 degrees before and after zenith (Reference 1); while the peak velocity of the azimuth axis occurs at zenith. However, the peak azimuth axis velocity is 10 to 20 times higher than the peak elevation velocity. The peak azimuth acceleration occurs at elevation angles above 80 degrees where the torque induced by wind on the azimuth axis is minimal. The elevation axis acceleration peaks at zenith and is more than an order of magnitude lower than the peak azimuth acceleration. The wind-induced torque is negligible on the elevation axis servo at this attitude.

The motors and servo amplifiers are sized based on the torque required to accelerate the motor armature and the antenna mass, and accommodate the torque induced by the specified peak winds. Peak torque occurs about the azimuth axis when the antenna is elevated at zero degrees. Peak torque about the elevation axis is developed when the antenna is elevated at 60 or 120 degrees. This torque is proportional to the square of the wind velocity and to the cube of the reflector diameter. For massive counterbalanced large diameter antennas, the wind induced torque is 100 times the torque required to accelerate the antenna at 6 deg/sec/sec. When the conservation of primary power and motor/servo size are of concern, the advantage of employing a protective radome becomes obvious. When the antenna is not radome protected, peak acceleration must be software limited because of the excessive available torque.

Pedestal Horsepower

The required motor horsepower may be determined from.

$$HP = \frac{T\,\omega}{550 \text{ ft-lb/HP}} = \frac{T\dot{\theta}}{9.6} \quad (7)$$

where T is in ft-lb, ω is in radians/sec, and $\dot{\theta}$ is in degrees/second. This is the horsepower delivered to the antenna axis, assuming a perfectly efficient and frictionless gearbox. The maximum torque required is the sum of the friction torque (T_F), wind-induced torque (T_W) and torque required to accelerate the mass of the counterbalance and antenna (T_A), and the reflected inertia of the motor(s) N^2 (T_A) where N is the gear reduction ratio. The wind-induced torque is typically 50 times greater than $T_A + T_F$. which indicates that the azimuth axis HP is practically independent of the antenna elevation angle.

In order to minimize HP, T_W and θ must be held to the minimum required to operate successfully. As previously stated, T_W is implicitly specified by the peak operating wind speed and the antenna diameter. Therefore, one must not specify peak operating winds nor antenna gain (diameter) arbitrarily. Even over-specifying the minimum elevation axis depression angle affects T_W as well as T_A because the antenna cannot be as closely coupled to the elevation axis. The azimuth slew velocity (θ) is typically specified much higher than required for a LEO satellite tracker. Indeed, the peak elevation axis slew velocity does not need to be higher than 1.5 degrees per second, as shown in Figure 1. As shown in Figure 4, the azimuth axis velocity becomes unacceptably high when accommodating a satellite pass through the pedestal “keyhole,” even though allowing a 6-dB loss in received signal level reduces the required peak velocity by approximately 30 percent.

<u>Specifying A Third Axis For The El/Az Pedestal</u>

The need for a high azimuth velocity is alleviated by effectively limiting elevation axis travel to +80 degrees. This is accomplished either by tilting the entire antenna pedestal ±10 degrees or by adding a third (cross-elevation) axis which has a minimum of ±10 degrees of travel. As shown in the lowest curve of Figure 4, the maximum velocity required by the azimuth axis is only 6.5 deg/sec for satellites orbiting at a 400 km altitude.

EMP has determined that the cost-effective approach is to add a servo-controlled third axis to the pedestal because it significantly reduces the required horsepower (motor and servo amplifier size) for the system, while still maintaining the mechanical stiffness of the lower pedestal. The required peak velocity of the azimuth axis servo/motor and gearbox is significantly reduced when operation of that axis is limited to LEO satellite passes that require elevation axis angle of +80 degrees or less. For higher elevation angles, the pedestal is operated in a Y over X (cross-elevation-over-elevation: X-El/El) configuration where, as shown in Figures 1 and 2, the axis velocity rates are benign.

For higher predicted elevation angles, the azimuth axis is locked at Acquisition-of-Signal (AOS) on the horizon, and the system is automatically configured as an X-El/El mount, with both axes allowed to autotrack, program track, or slave to computed ephemeris angles. The range of the X-El axis is ±11 degrees and its maximum slew rate is 0.6 degrees/second. The antenna is positioned in the program track mode from ephemeris angle coordinate pair data generated by, and stored in, the antenna control unit. Program tracking mode data, generated from ephemeris, is an azimuth and elevation angle coordinate pair, which can be read at a rate of up to 20 times per second. When the pedestal is operated in the X-El/El configuration, the antenna control unit makes the conversions:

$$\phi = \arctan(\tan El/\cos[Az - Az_{AOH}]) \quad (9)$$

$$\Psi = \arcsin(\sin[Az - Az_{AOH}])\cos El \quad (10)$$

where ϕ and El are 0º at the horizon, Ψ is positive in the clockwise direction. Az is 0º when looking north, and Az_{AOH} is the initial azimuth command to intercept the ascending satellite at the horizon.

When configured as a Y over X pedestal, and in the autotrack mode of operation, the control unit must make the following conversions to output true Az and El angles for Display and Slave commands:

$$Az_{True} = AZ_{AOH} + \arctan(\tan\Psi/\cos\phi) \quad (10)$$

$$El_{True} = \arcsin(\sin\phi s\Psi) \quad (11)$$

CONCLUSION

The comparison of the required dynamics of an El over Az pedestal with a Y over X type pedestal shows that a significant reduction in rate and acceleration is achieved by a hybrid three-axis pedestal when performing autotracking and programmed pointing of LEO satellite passes near zenith. The analysis presented shows that required pedestal dynamics increase exponentially when required to accommodate short-lived satellites in a decaying orbit below 400 Km.

All too often the supplier of antenna/pedestals is zealous to meet all specification requirements of a potential customer, even though cost and operational savings could be attained by establishing a dialogue regarding specific use and intent. It is prudent of the specifier to demand a peak acceleration and velocity no greater than that required to position the antenna at the coordinates accommodating the next satellite pass in a timely manner and in the presence of specified peak winds. Let it be incumbent on the supplier to propose an antenna/pedestal system that concerns the initial and future operating costs.

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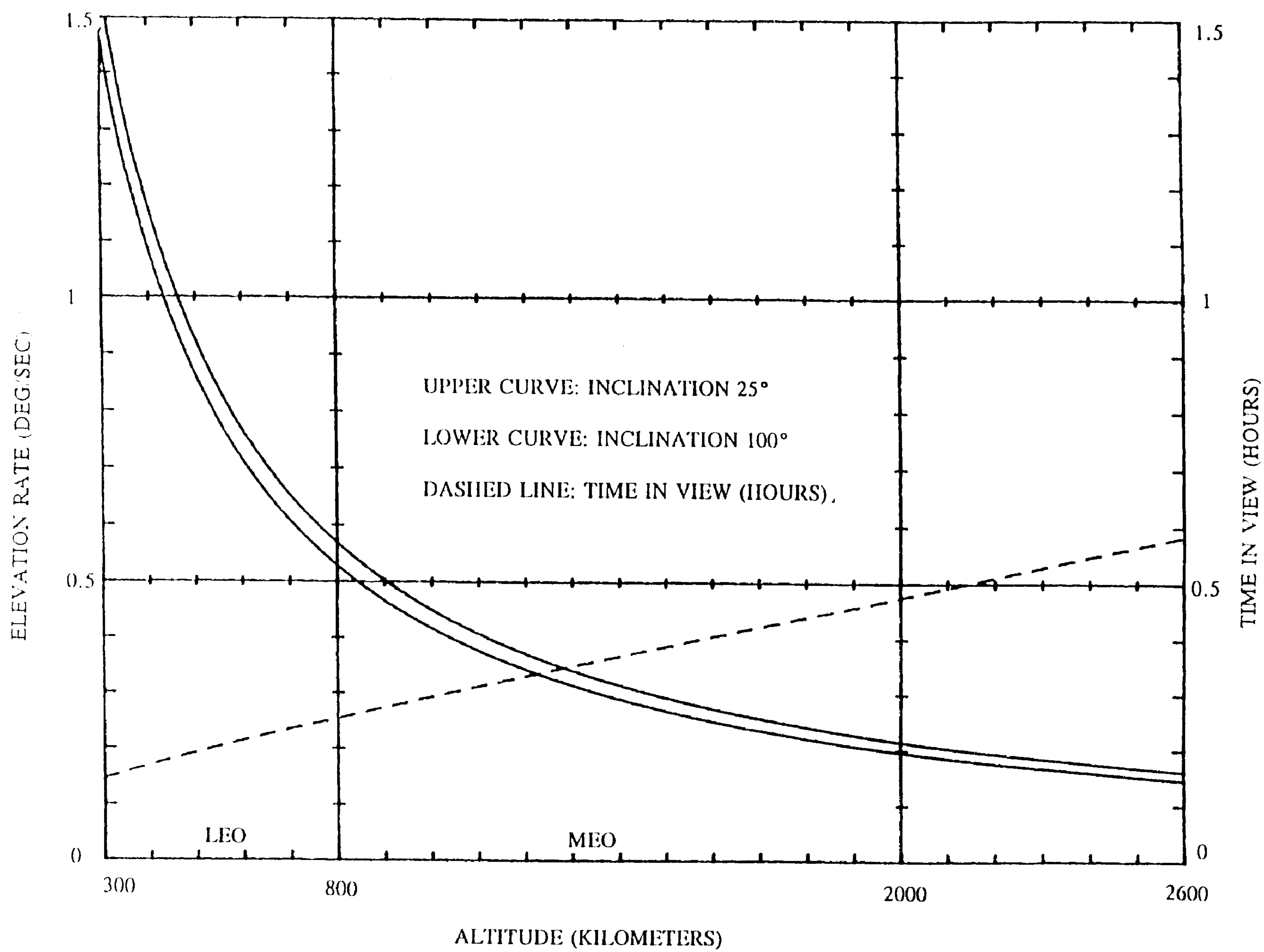

Figure 1. ELEVATION RATE AND TIME IN VIEW vs. SATELLITE ALTITUIDE

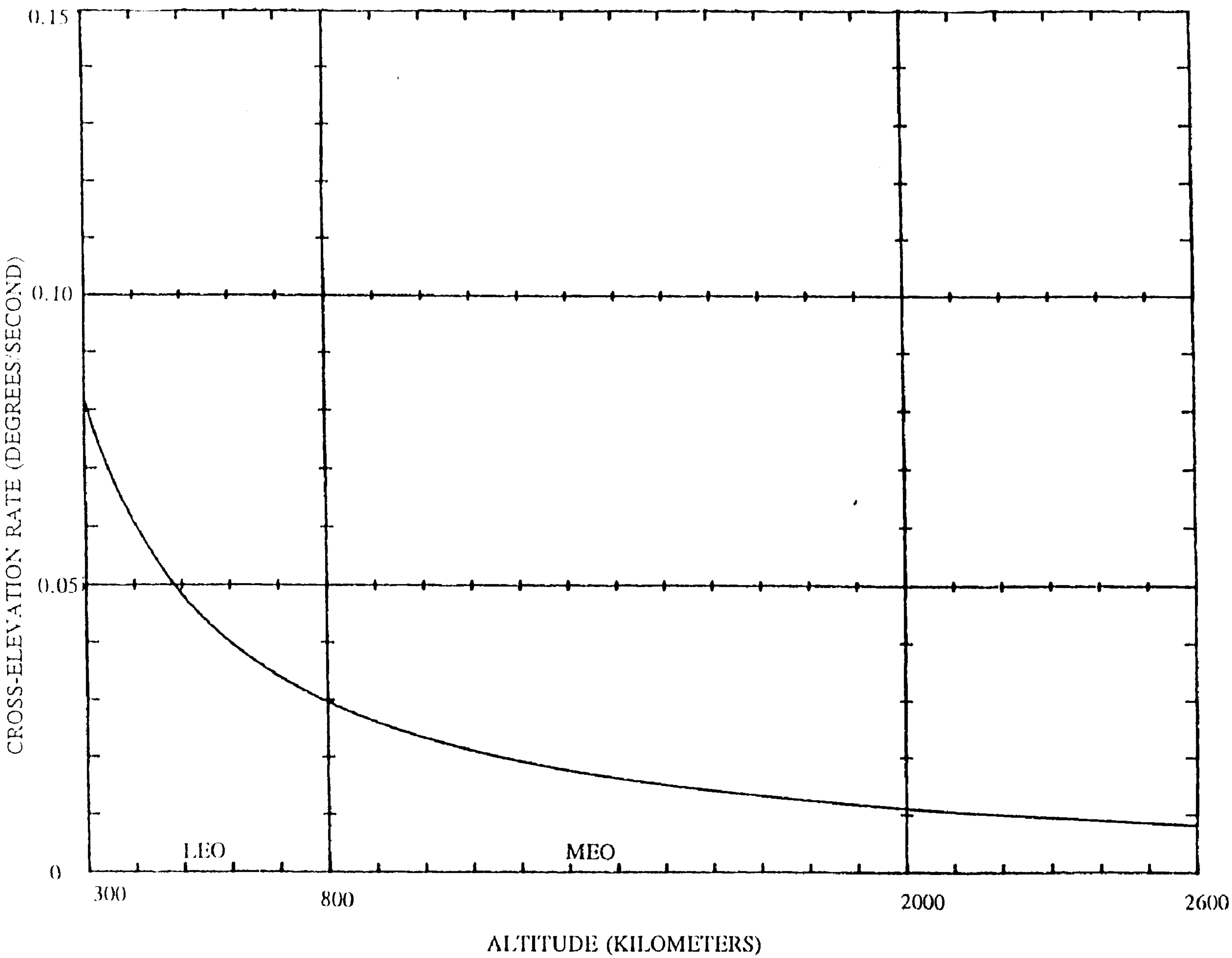

Figure 2. MAXIMUM CROSS-ELEVATION RATE vs. SATELLITE ALTITUDE

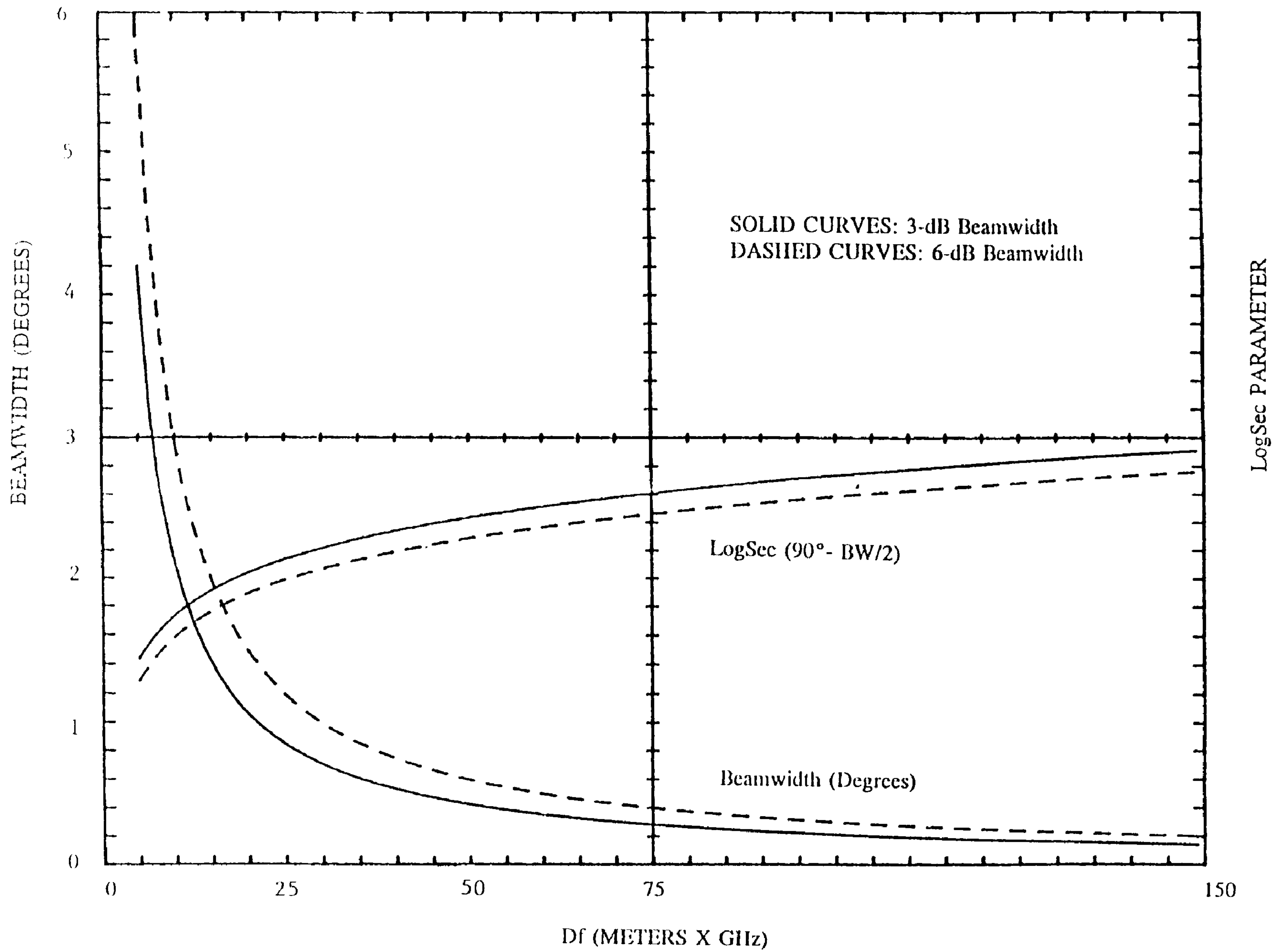

Figure 3. BEAMWIDTH & LogSec PARAMETER vs. REFLECTOR DIAMETER X FREQUENCY

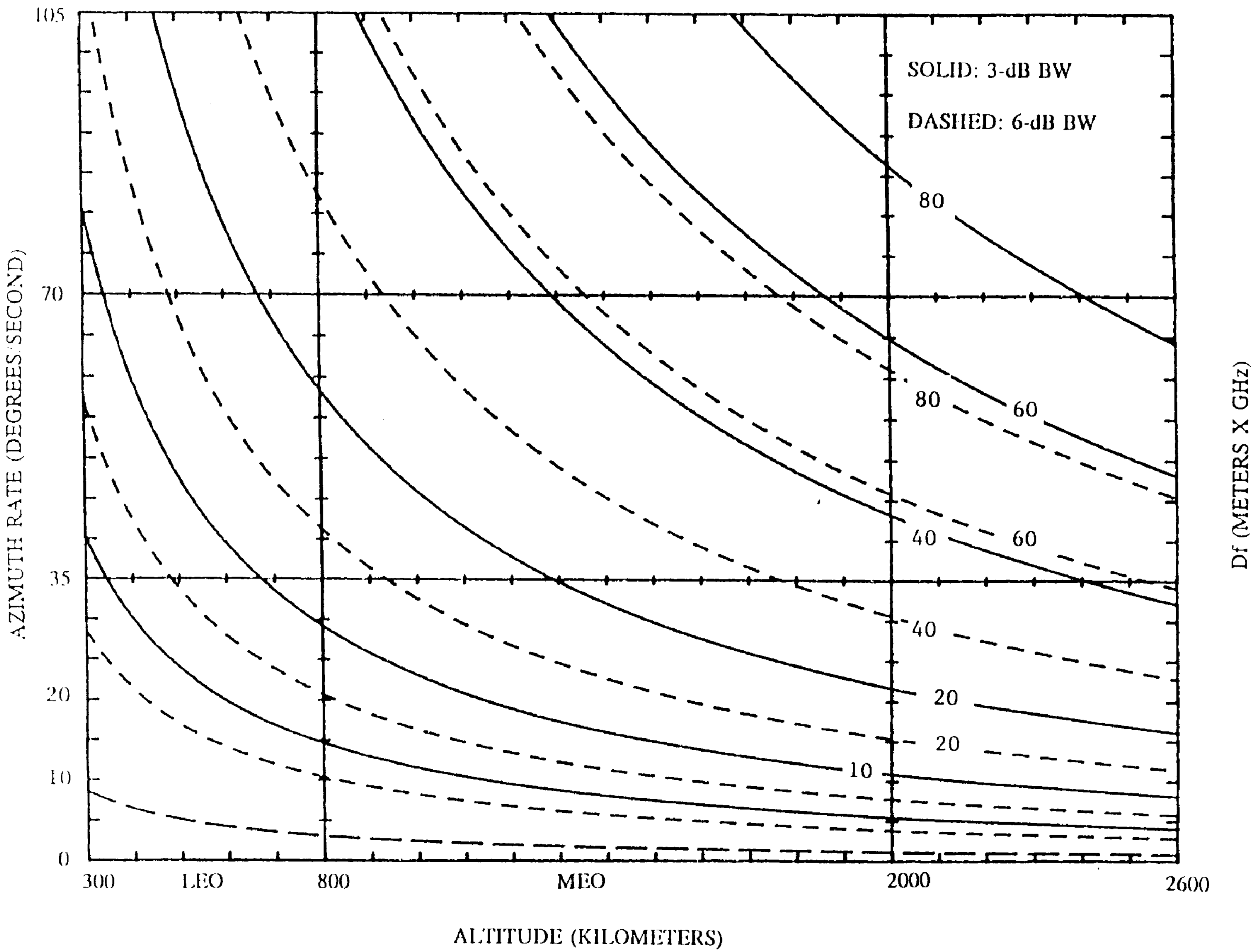

Figure 4. MAXIMUM AZIMUTH RATE vs. SATELLITE ALTITUDE (SEE TEXT)