Radio Frequency Interference from Near-Earth Satellites

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In the near future, radio frequency interference (RFI) from a growing number of Earth-orbiting satellites may seriously degrade deep space telemetry reception. This article develops a pessimistic statistical model for predicting the extent of this interference. Based on the assumptions underlying the model, DSN S-band operations can expect one RFI interruption every 4.1 days, with the average incident lasting 24 s. This implies that 52 or more such satellites, with uncorrelated orbital trajectories, will cause in excess of 5 min of RFI per day at a DSN station (the maximum level recommended by the Consultative Committee for International Radio).

I. Introduction

Over the past 2 years, DSN operators at Goldstone, California, have logged a combined average of nearly 10 min of radio frequency interference (RFI) per day, 25 percent of which resulted in complete outages (see Fig. 1). Much of this RFI was in fact traced to ground-based and airborne sources; however, over the next decade, we can anticipate a significant RFI problem due to the ever-increasing number of Earth-orbiting satellites, whose transmissions are crowded into a limited frequency band. The RFI problem is being carefully assessed since a telemetry outage during a critical phase of a deep space mission could be disastrous (e.g., during the 2-hour lifetimes of the 1978 Pioneer Venus atmospheric probes).

From the DSN viewpoint, part of the problem is that the International Telecommunications Union (ITU) has decreed that the frequency bands used for deep space telemetry must be shared with the much higher-powered transmissions of near-Earth satellites. For example, the Tracking and Data Relay Satellite System (TDRSS, 1979 launch date) will have multiple-access, spread-spectrum operations centered at 2287.5 MHz (DSN S-band downlink telemetry uses the 2290- to 2300-MHz band); and the Geodetic Earth-Orbiting Satellite (GEOS, 1977 launch date) downlink carrier frequency is 2299.5 MHz. In addition, because of significant sidelobe gains, a DSN antenna need not be pointing directly at an Earth-orbiting satellite to experience RFI from it.

This article represents an initial attempt to project the extent of the RFI problem due to near-Earth satellites. In particular, several simplifying assumptions are made leading to the development of a pessimistic statistical model, which may be used to compute the average cumulative RFI experienced by a DSN station, the average duration of an RFI incident, and the average time between incidents, per interfering satellite. To complete the projection of the RFI problem over the near future, this model should be combined with trend data on the number of Earth-orbiting satellites within and near each of the DSN receive bands expected over this period. (The Electromagnetic Capability Analysis Center is currently gathering this information under a contract with JPL.) Furthermore, with the acquisition of more detailed data, such as distributions of satellite altitudes and transmitted power flux density levels, some of the simplifying assumptions underlying the model could be refined, resulting in a more accurate assessment of the RFI problem.

II. Analysis at S-Band

As shown in Fig. 2, consider the situation in which a DSN receiver is experiencing white noiselike (spectrally flat) in-band RFI from an Earth-orbiting satellite at an angle ϕ (deg) off the antenna boresight. Then

$$PSD = PFD + G + 10 \log_{10} \left(\frac{\lambda^2}{4\pi} \right) \tag{1}$$

where PSD (dBW/Hz) is the received power spectral density, PFD (dBW/m^2/Hz) is the received power flux density, G (dBi) is the receive antenna gain, and λ (m) is the wavelength to which the receiver is tuned. For DSN downlink operations at S-band (2295 MHz),

$$10 \log_{10} \left(\frac{\lambda^2}{4\pi} \right) = -28.67 \tag{2}$$

The 64- and 26-m DSN antenna sidelobe power gain envelopes are well approximated by

$$G = 32 - 25 \log_{10} \phi; \ 1 \leqslant \phi \leqslant 48 \tag{3}$$

Finally, the Consultative Committee for International Radio (CCIR) Recommendation 365-2 states that the interference PSD from a single RFI source, measured at the input to a DSN receiver, shall not exceed -220 dBW/Hz[1] for more than 5 min/day. From Eqs. (1-3), we conclude that PSD exceeds the CCIR recommended level whenever ϕ satisfies the constraint

$$25 \log_{10} \phi \leqslant PFD + 223.33 \tag{4}$$

We shall say that a DSN receiver is experiencing RFI from an S-band satellite transmission whenever Eq. (4) is satisfied.

We need to make some assumptions about PFD. Under Article 7 of the ITU Radio Regulations, the radio emissions from an Earth-orbiting satellite, incident on Earth's surface at an angle α (deg) above the horizon, must satisfy the restriction

$$PFD \leqslant \begin{cases} -190; \ 0 \leqslant \alpha \leqslant 5 \\ -190 + \frac{1}{2}(\alpha - 5); \ 5 \leqslant \alpha \leqslant 25 \\ -180; \ 25 \leqslant \alpha \leqslant 90 \end{cases} \tag{5}$$

We will assume that the center frequency of the interfering satellite telemetry is adjacent to the 2290- to 2300-MHz band, such that the RFI experienced by the DSN receiver is due to sidebands suppressed at least 20 dB below the maximum permissible levels of Eq. (5). Adopting a pessimistic approach, we therefore assume that the received S-band RFI from a given satellite has a PFD of -200 dBW/m^2/Hz, independent of the satellite location and transmitting antenna direction. Then Eq. (4) implies that a DSN receiver experiences RFI from an S-band satellite transmission whenever $\phi \leqslant \phi_0 \equiv 8.57$ deg.

A. Average Cumulative RFI

In the absence of any specific satellite trajectory data, we will simplify the model by assuming that an interfering satellite is in a circular Earth orbit of radius r_s, and that its instantaneous location is uniformly distributed over the sphere of that radius. As a further simplification, we assume that the DSN receiving antenna is pointing vertically; therefore, the receiver experiences RFI whenever the satellite falls within the spherical cap shown in Fig. 3. (Note that a nonvertical antenna boresight direction would yield an RFI cap of greater area and proportionally larger average cumulative RFI.)

The angle ϕ_0 subtended by the RFI cap at the DSN station translates to an angle θ at the center of the Earth:

$$\theta = \sin^{-1} \left[\left(\sqrt{1 - \gamma^2 \sin^2 \phi_0} - \gamma \cos \phi_0 \right) \sin \phi_0 \right] \tag{6}$$

[1]The conversion formula from PSD to noise temperature T (K) is $T = (1/k) 10^{PSD/10}$ where $k = 1.38 \times 10^{-23}$ W/Hz/K is Boltzmann's constant. So -220 dBW/Hz is equivalent to 7.25 K; as an example, this results in a 1.7-dB degradation in signal-to-noise ratio for a 15 K receiver.

where $\gamma \equiv r_E/r_S$ and r_E is the radius of the Earth. The area of the cap is then $2\pi r_S^2(1 - \cos\theta)$, and the instantaneous probability of RFI occurring is the ratio of this area to that of the entire satellite orbital sphere, $\frac{1}{2}(1 - \cos\theta)$. Equating ensemble and time averages, the long-term average cumulative RFI from a single satellite at altitude $(r_S - r_E)$ is 43200 $(1 - \cos\theta)$ s/day. This expression is plotted in Fig. 4 for ϕ_0 = 8.57 deg and r_E = 6357 km (polar radius of the Earth).

Based on a 1971 listing (Ref. 1) of 17 then-current and proposed nonsynchronous Earth-orbiting satellites, a histogram of their altitudes was extracted (see Fig. 5).[2] For our model, we approximate this distribution by a uniform one between 300 and 1200 km. Integrating over this simplified altitude distribution, we find that average cumulative RFI

$$= \frac{43200}{900} \int_{r_E + 300}^{r_E + 1200} dr_S \; [1 - \cos\theta\,(r_S)] \qquad (7)$$

$$= 5.86 \text{ s/day/satellite}$$

Using a Union bound argument, N such satellites with independent orbital trajectories would produce an average of $5.86N$ s/day of RFI at a DSN station. Consequently, if $N \geqslant 52$, the combined average RFI at S-band exceeds the CCIR recommended level of 5 min/day.

B. Average Duration of an RFI Incident

Using simple physical arguments, a satellite in a circular Earth orbit of radius r_S (km) has a tangential velocity v (km/s) given by

$$v = 631.3/\sqrt{r_S} \qquad (8)$$

From Fig. 3, if the satellite crosses the center of the RFI cap, the DSN receiver will experience t_{max} seconds of continuous RFI (plotted in Fig. 6), given by

$$t_{max} = \frac{2\theta}{v/r_S} = \frac{\theta r_S^{3/2}}{315.7} \qquad (9)$$

where θ is in rad. However, in general, an RFI incident occurs when the satellite crosses the RFI cap off-center; so Eq. (9) is an upper bound for the duration of the incident.

[2] For satellites with noncircular orbits, the altitude was assumed to be uniformly distributed between the apogee and perigee.

To analyze the general case, fit Fig. 3 to a Cartesian coordinate system centered at Earth's center, such that the antenna boresight is along the z-axis. As shown in Fig. 7, the boundary of the RFI cap is specified by

$$x^2 + y^2 = r_S^2 \sin^2\theta$$

$$z = r_S \cos\theta \qquad (10)$$

Now construct a new Cartesian coordinate system by rotating the x- and z-axes an angle β about the y-axis. Without loss of generality, assume the satellite trajectory is in the $y'z'$-plane, and is given by

$$x' = 0$$

$$(y')^2 + (z')^2 = r_S^2 \qquad (11)$$

But

$$x = x'\cos\beta + z'\sin\beta$$

$$z = -x'\sin\beta + z'\cos\beta \qquad (12)$$

Using Eq. (12) to specify the equation of the RFI cap boundary of Eq. (10) in the $x'y'z'$ coordinate system, we have, in part

$$x'\sin\beta = z'\cos\beta - r_S\cos\theta. \qquad (13)$$

The intersection points of the RFI cap boundary and the satellite trajectory lie in the $y'z'$-plane: setting $x' = 0$ in Eq. (13) yields

$$z' = \frac{r_s\cos\theta}{\cos\beta} = r_s\cos\zeta$$

$$\Downarrow$$

$$\zeta \equiv \cos^{-1}\left(\frac{\cos\theta}{\cos\beta}\right) \leqslant \theta \qquad (14)$$

For fixed β, the transit time $t(\beta)$ (s) of the satellite through the RFI cap is

$$t(\beta) = \frac{2\zeta}{v/r_s} = \frac{r_s^{3/2} \cos^{-1}\left(\frac{\cos\theta}{\cos\beta}\right)}{315.7} \qquad (15)$$

per crossing.

In general, we assume that β is uniformly distributed over $(0, \pi/2)$. So for fixed r_s, the average duration t_{avg} (s) of a single RFI incident, conditioned on its occurrence, is given by

$$t_{avg} = \frac{1}{\theta} \int_0^{\theta} d\beta\, t(\beta) = \frac{r_s^{3/2} f(\theta)}{315.7} \qquad (16)$$

where

$$f(\theta) \equiv \int_0^1 dx \cos^{-1}\left(\frac{\cos\theta}{\cos x\theta}\right) \leqslant \theta \qquad (17)$$

It has been determined that for $0 \leqslant \theta \leqslant \pi/2$, $f(\theta)$ is accurately approximated by

$$f(\theta) \cong 0.789\,\theta + 0.0423\,\theta^4 \qquad (18)$$

where θ is in rad. Combining Eqs. (6), (16), and (18), t_{avg} was computed as a function of satellite altitude (see Fig. 6). If we further average over the uniform satellite altitude distribution of Fig. 5, we find that the altitude-independent average S-band RFI duration is 23.95 s. Combined with the result of the previous section for N interfering satellites, this implies that the average time between RFI incidents is $23.95/5.86N = 4.09/N$ days at S-band.

III. Comparison of RFI at S- and X-Bands

DSN X-band downlink operations use the 8400- to 8500-MHz band. Extending the RFI model derived above to a DSN receiver tuned to 8450 MHz yields the following N satellite comparison between the two deep space bands:

RFI parameter	*S-band*	*X-band*
ϕ_0, deg	8.57	3.02
cumulative average, s/day	$5.86\,N$	$0.720\,N$
5 min/day	$N \geqslant 52$	$N \geqslant 417$
average incident duration, s	23.95	8.40
average time between incidents, days	$4.09/N$	$11.67/N$

IV. Review of RFI Model Assumptions

(1) Telemetry from an Earth-orbiting satellite has a center frequency adjacent to the DSN receive band of interest, and in-band RFI is caused by spectrally flat sidebands of the satellite telemetry, suppressed 20 dB below the maximum *PFD* permitted under ITU regulations ($PFD = -200$ dBW/m^2/Hz).

(2) The satellite signals cause RFI in the DSN receiver whenever $PSD > -220$ dBW/Hz.

(3) The 64- and 26-m DSN receive antenna sidelobe gains are specified by $G = 32 - 25 \log_{10} \phi$, for satellite-to-ground antenna boresight angle ϕ (deg).

(4) The interfering satellites are in uncorrelated circular orbits, and their instantaneous locations are uniformly distributed above the Earth's surface.

(5) The satellite altitudes are uniformly distributed between 300 and 1200 km.

(6) The DSN antenna is pointing vertically.

V. Conclusions

Considering how rapidly the number of Earth-orbiting satellites is increasing, and the sharing of crowded frequency bands by deep space and near-Earth satellite telemetry, the model demonstrates that the DSN could experience a significant amount of RFI outages over the next decade, particularly at S-band. The model involves several simplifying assumptions, however, which should be replaced by statistical distributions based on available trend data to make it more meaningful (this applies in particular to Assumptions 1, 4, 5, and 6 in the previous section). To control the RFI problem, and to minimize the possibility of an outage during a critical mission phase, some countermeasures are needed, such as:

(1) Frequency coordination procedures

(2) RFI monitoring equipment

(3) Frequency diversity techniques

(4) Sophisticated coding and modulation schemes to prevent mutual RFI between cooperating satellites.

Reference

1. Sudhoff, R. I., *Deep Space Research Band Occupancy – A Data Base and Analysis*, Rpt. #IITRI-E6203-F, IIT Research Institute, Aug. 3, 1971.

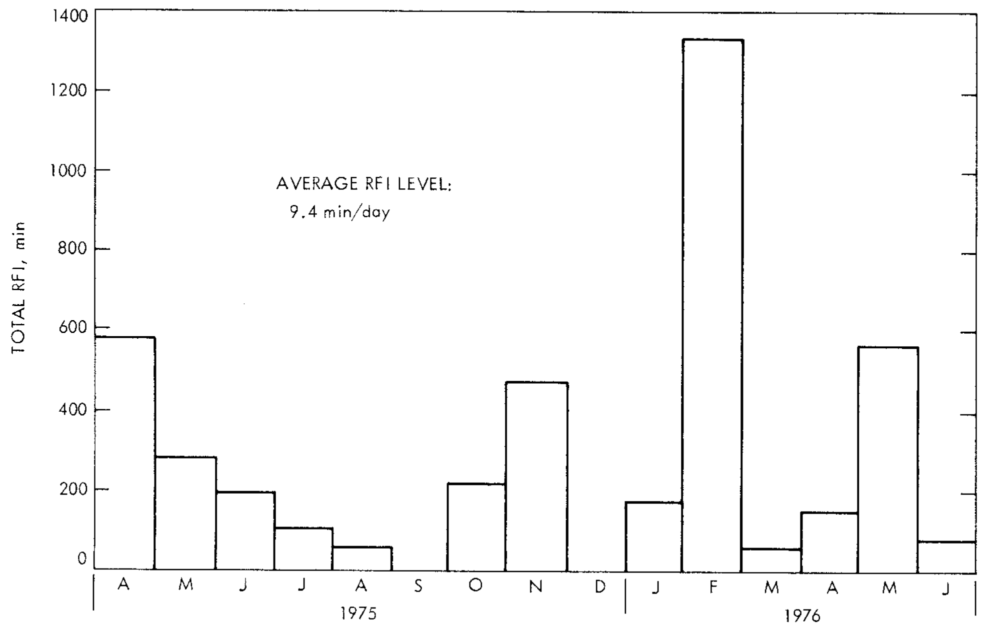

Fig. 1. History of recorded S-band RFI incidents at Goldstone DSN station

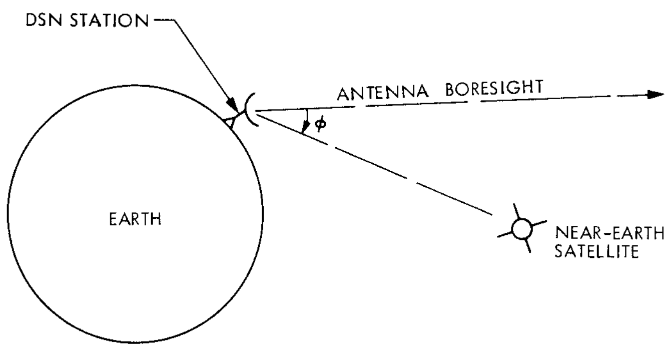

Fig. 2. Gross RFI geometry

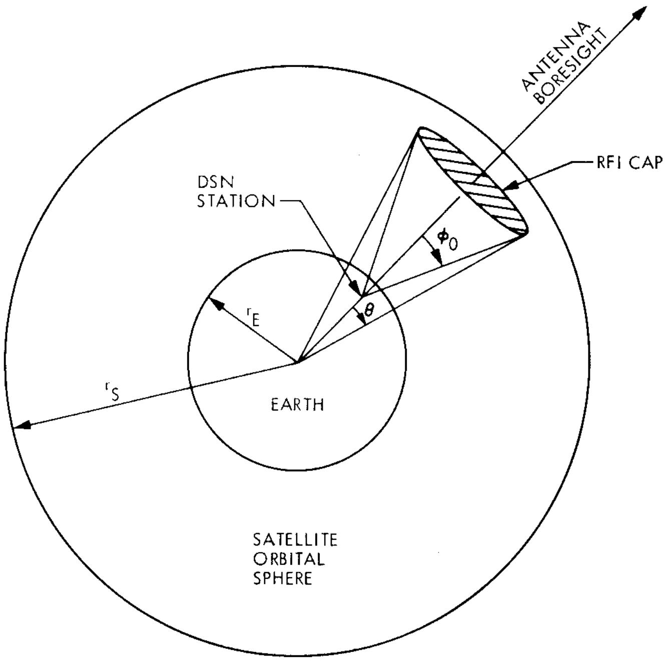

Fig. 3. Detailed RFI geometry for calculation of average cumulative RFI

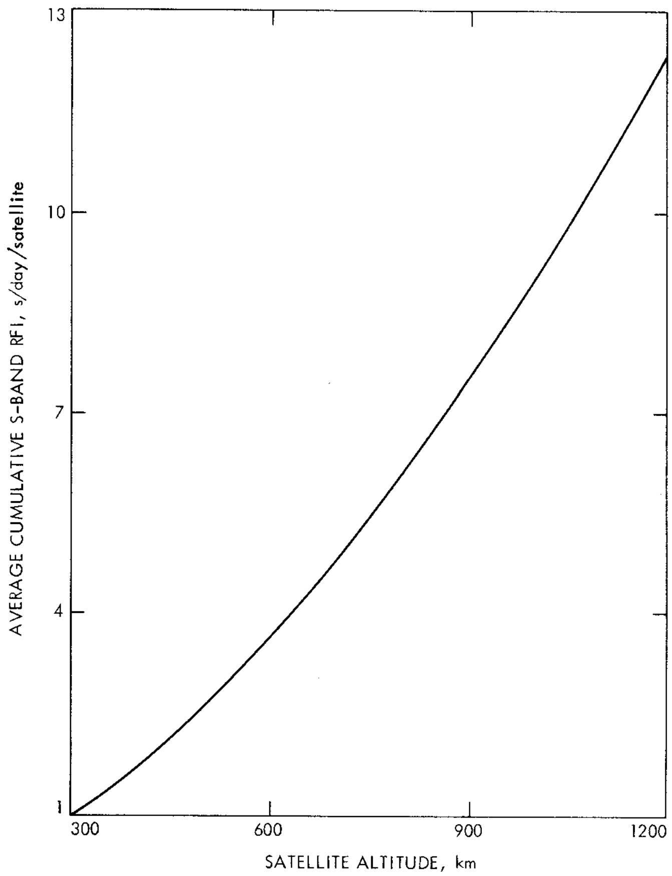

Fig. 4. Variation of amount of S-band radio frequency interference with altitude of interfering satellite

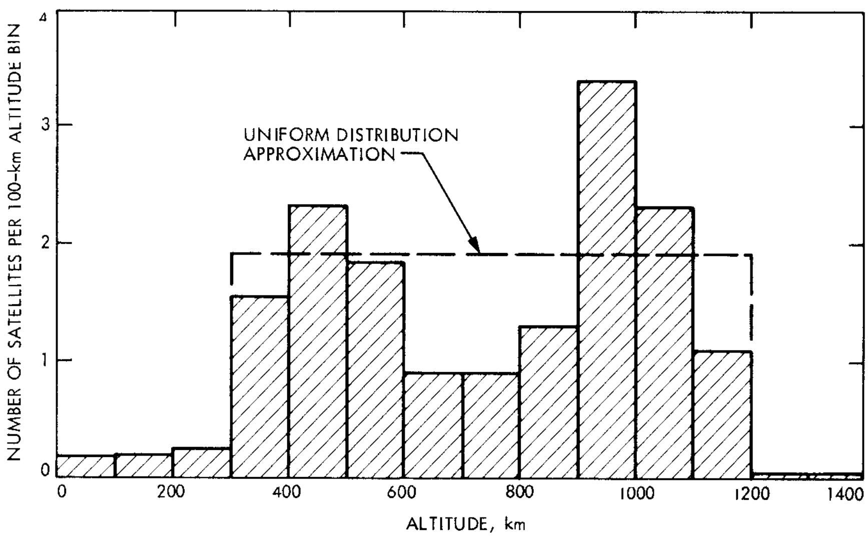

Fig. 5. Histogram of nonsynchronous, Earth-orbiting satellite altitudes (17 satellites)

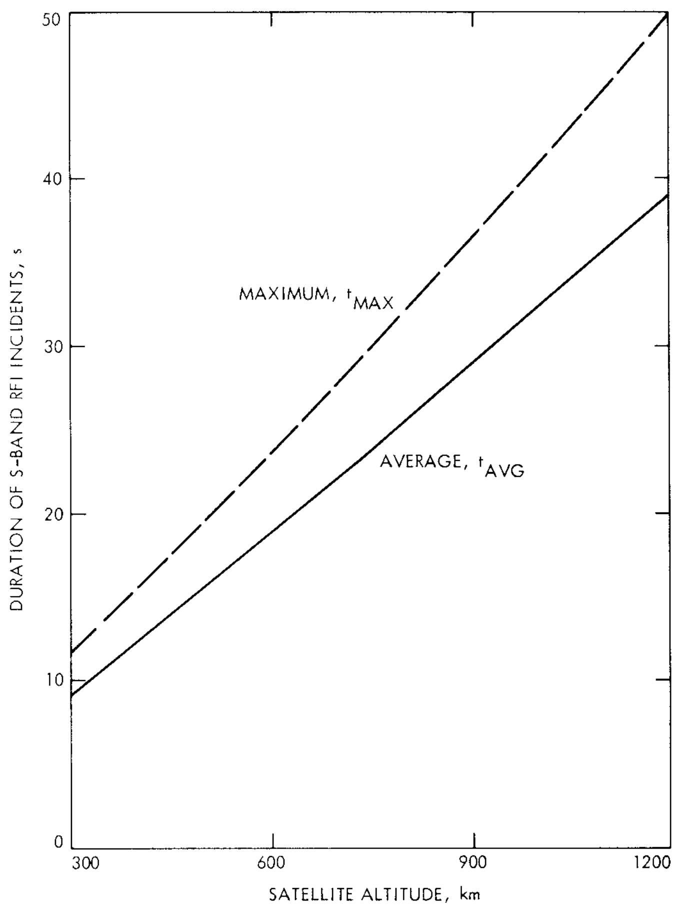

Fig. 6. Variation of average and maximum duration of S-band radio frequency interference incidents with altitude of interfering satellite

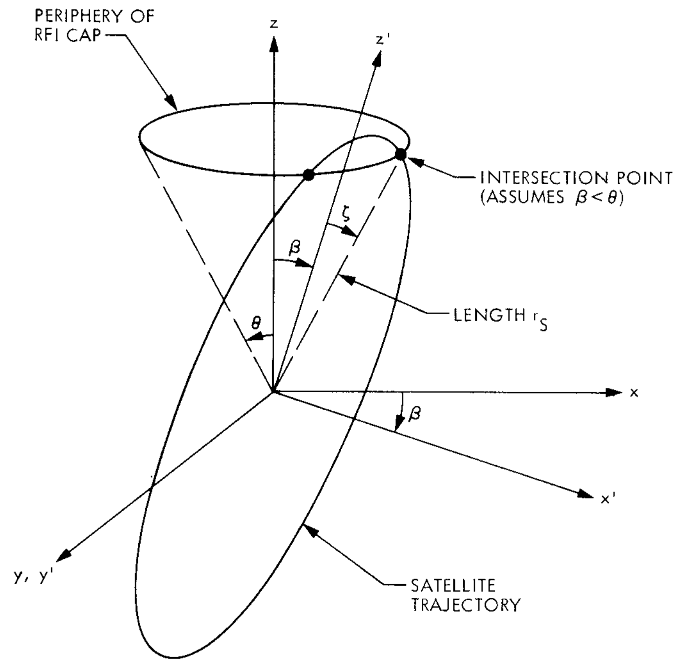

Fig. 7. Detailed RFI geometry for calculation of average RFI duration