A Monte Carlo Simulation Study of Interference Effect from Multiple HDFS Transmitters above 30 GHz

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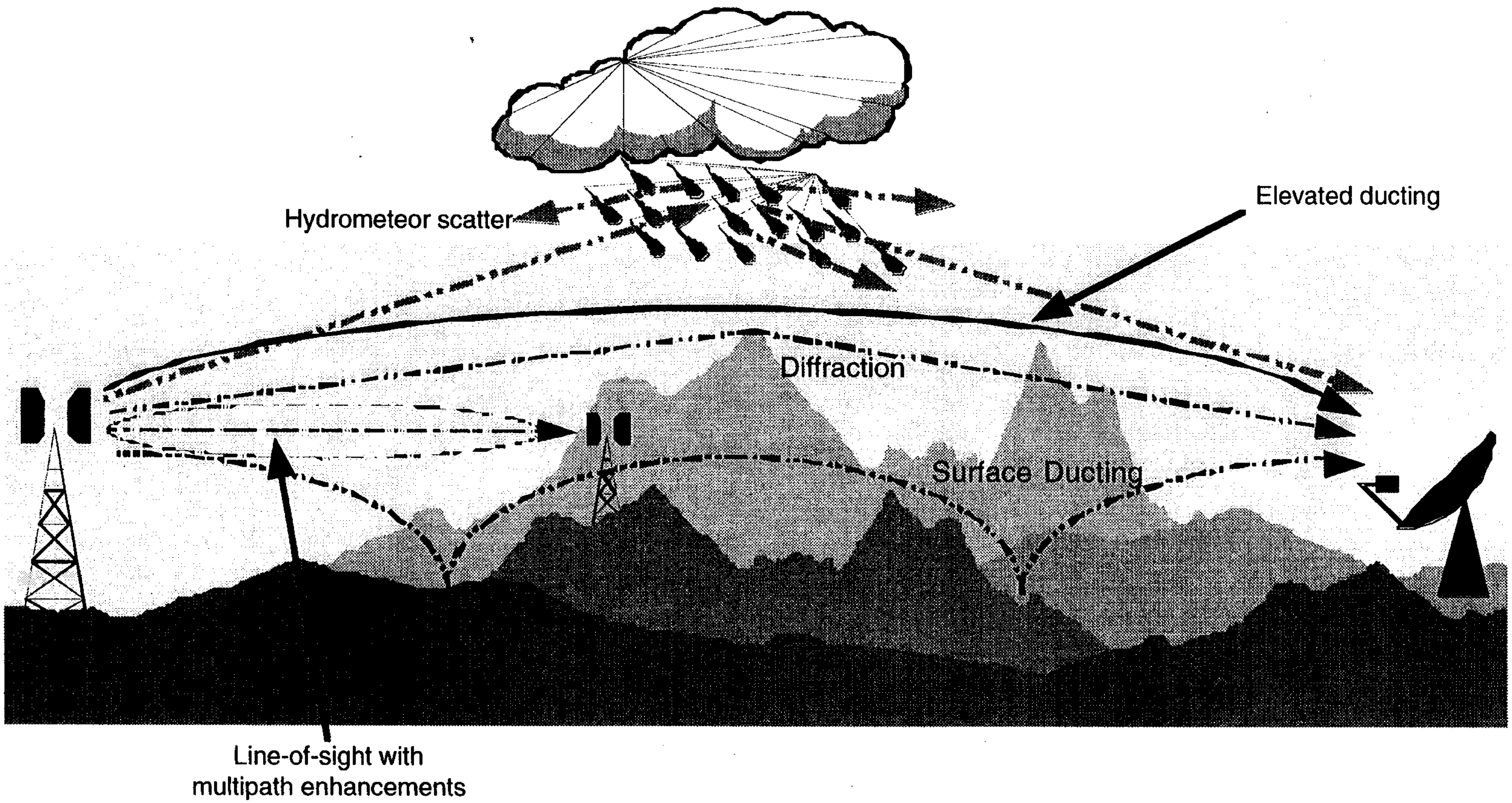
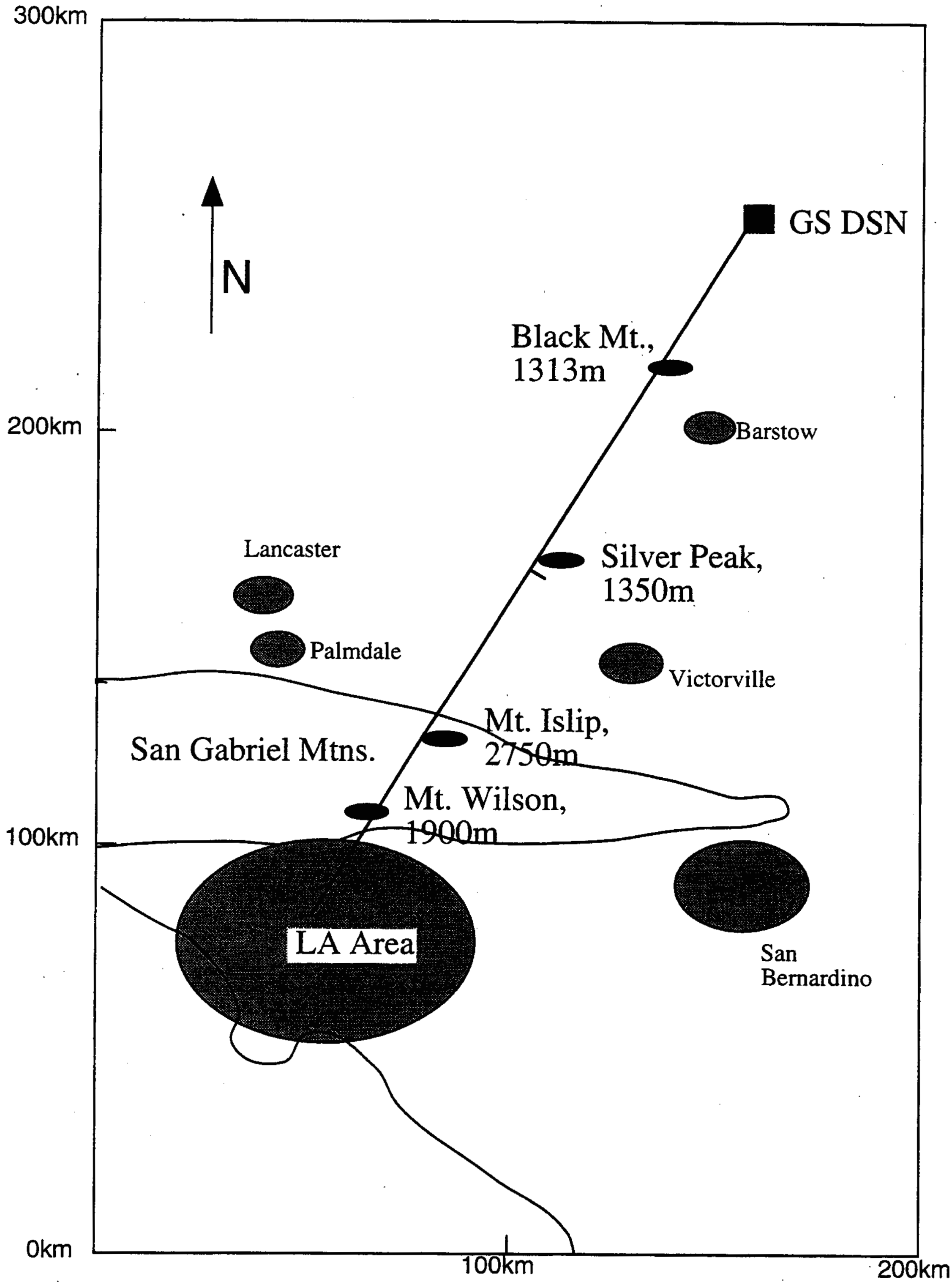
Background

- Commercial operators are now proposing to install thousands of High Density Fixed Services (HDFS) microwave transmitters in large urban centers, such as Los Angeles.
- These transmitters will share the same frequencies in the Ka band (32 GHz and 37-38 GHz) as some Space Research Service (SRS) receiving Earth stations.
- To face this challenge, Resolution 126 (WRC-97) has requested the ITU-R to conduct, as a matter of urgency and in time for WRC-99, appropriate studies to determine sharing criteria between stations in the fixed service and stations in other services.
- The three DSN tracking stations worldwide utilize this frequency band and may become vulnerable to interference from the planned deployments of HDFS transmitters.
- These HDFS transmitters operate at a relatively strong signal power (up to -60 dBW/Hz). Thus, they will seriously interfere with the sensitive DSN receivers.
- It has become imperative to accurately predict the impact of HDFS transmitters on NASA's DSN receivers in the Ka band.

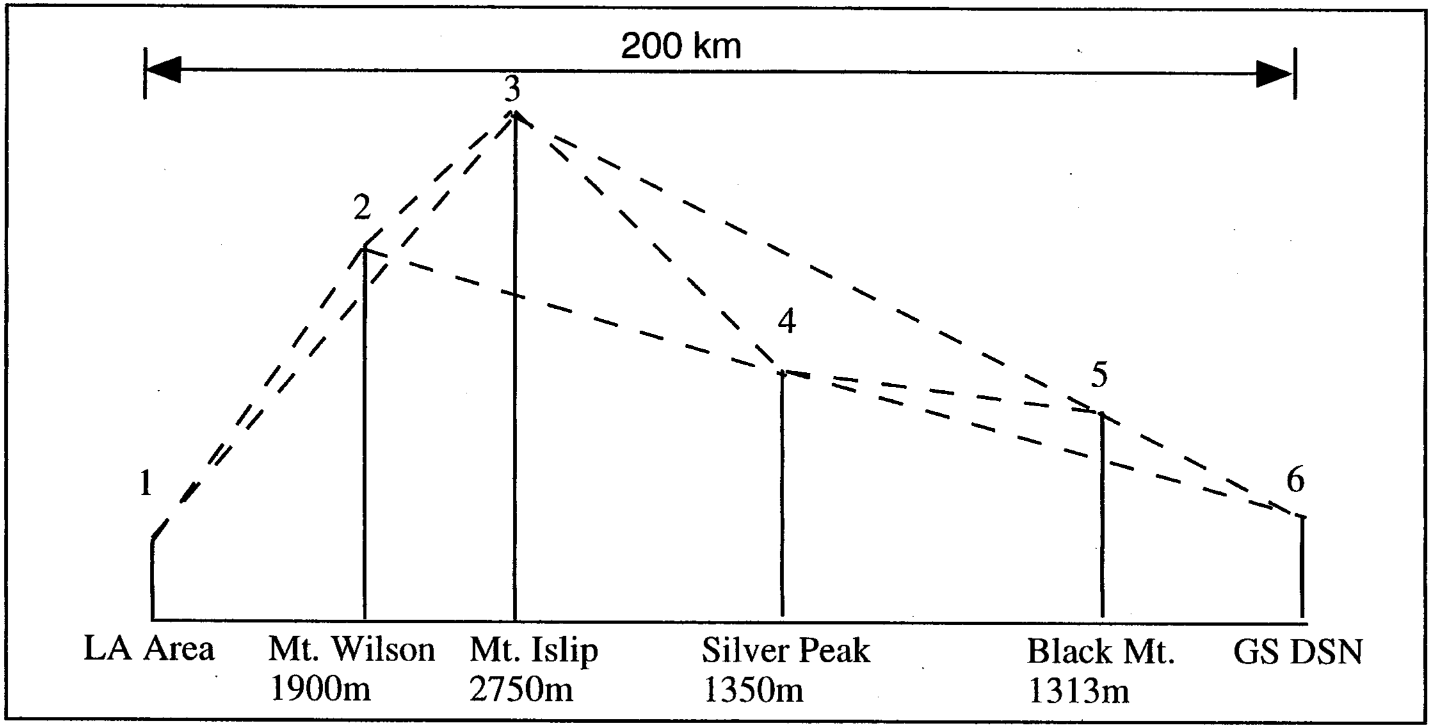
Interference Propagation Mechanisms



Los Angeles - Goldstone Topographic Profile



Path Profile Analysis

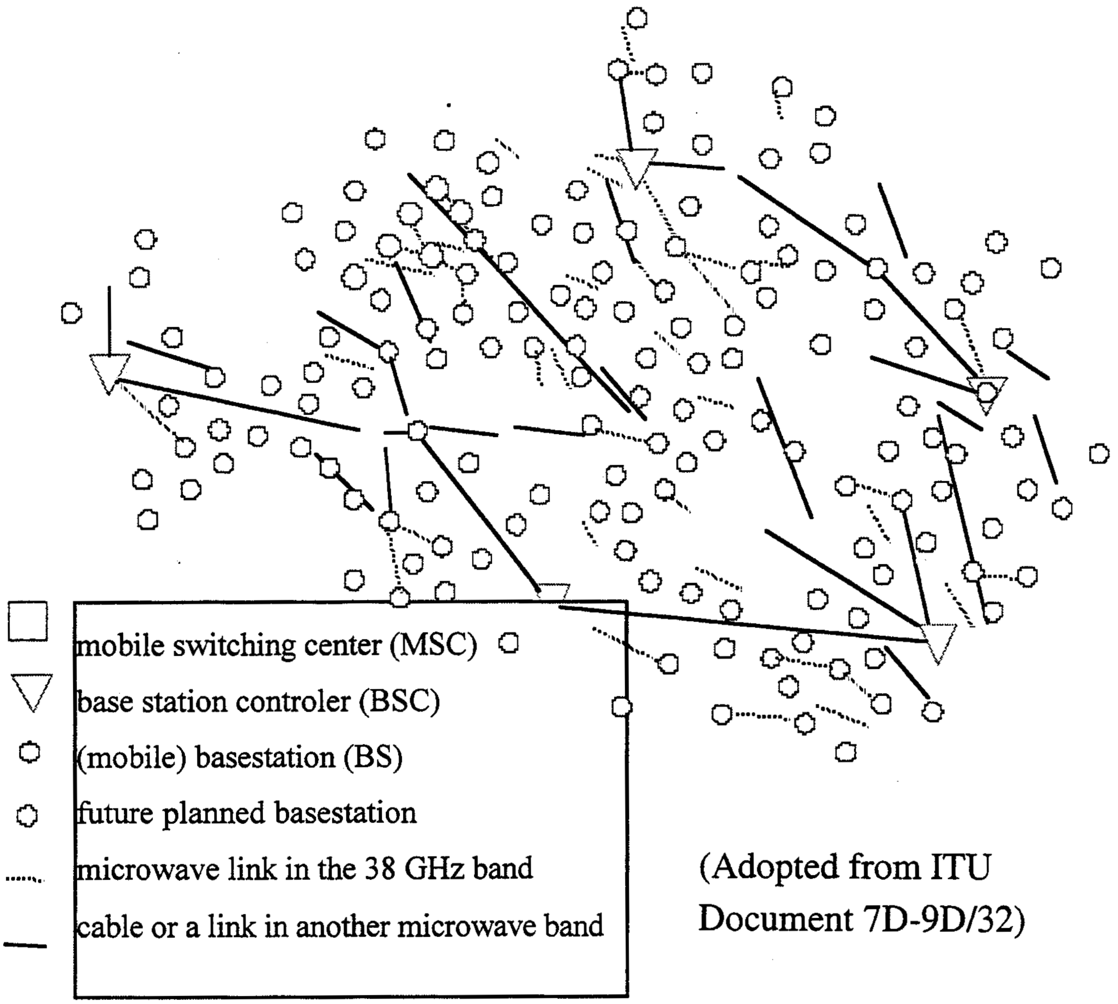


Loss (Due to Diffraction) = Loss (Free Space Spread) + Loss (Diffraction at 4 Mts.)
= 188 dB + 33 dB = 221 dB

There are three types of transmission losses:

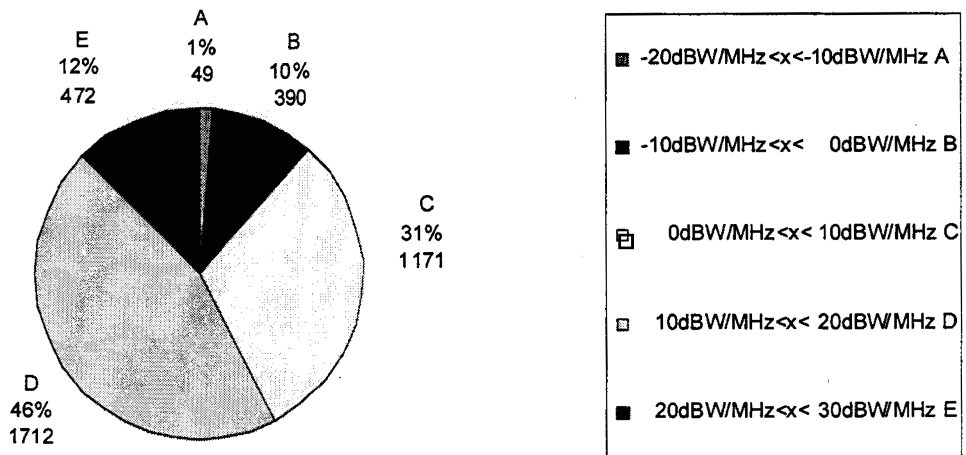
Diffraction Effect (<200 km)
Rain Scattering Effect (<300 km)
Ducting Effect (Transhorizen)

A Typical Point-Point System in Dense Urban Areas and its EIRP Distribution



(Adopted from ITU Document 7D-9D/32)

EIRP - Classes (dBW/MHz) for 38 GHz microwave on the base of 3794 terminals
EIRPmax. = 26,9 dBW/MHz; EIRPmin. = -21,2 dBW/MHz



Characteristics of Point-to-Point Fixed Systems**

Characteristic	For Systems in the 37-39.5 GHz Band				
Modulation	4-FSK	4-FSK	4-FSK	4-FSK	16-QAM
Capacity	2x2 Mbit/s	8 Mbit/s	2x8 Mbit/s	34 Mbit/s	155 Mbit/s
Channel Spacing, MHz	3,5	7	14	28	56
Max. Antenna Gain, dBi	47 *	47 *	47 *	47 *	47 *
Min. Multiplexer Loss, dB	0	0	0	0	0
Antenna Type	Dish	Dish	Dish	Dish	Dish
Max. Tx Power, dBW	0	0	0	0	0
EIRP (max) dBW	47	47	47	47	47
Rx IF Bandwidth, MHz	2	4	8	17	40
Rx Noise Figure, dB	11	11	11	11	8
Rx Thermal Noise, dBW	-130	-127	-124	-121	-120
Nominal Rx Input Power, dBW	-112 +M	-109+M	- 106+M	- 103+M	- 99+M
Rx Input Power, dBW for $1x10^{-3}$ BER	-115	-112	-109	-106	102
Nominal short-term Int., dBW	-	-	-	-	-
Nominal long-term Int., dBW	-140	-137	-134	-131	-130
Equivalent power, dB(W/MHz)	-	-	-	-	-
Spectral Density, dB(W/MHz)	-143	-143	-143	-143	-146
Applicable Notes	**1 and 2**	**1 and 2**	**1 and 2**	**1 and 2**	**1 and 2**

* 0.9 m dish assumed

** Extracted from Table 15 of Recommendation ITU-R F.758 & more.

Note 1: Specified interference will reduce system C/N by 0.5 dB. (Interference level is 6 dB below receiver noise floor.)

Note 2: The specified interference level is total power within the receiver bandwidth.

Representative Characteristics of Point-to-Multipoint Systems*

System No.	Hub No. 1	Remote No. 1	Hub No. 2	Remote No. 2	Hub No. 3	Remote No. 3
Capacity/data rate	DS-3 45 Mbit/s	DS-3 45 Mbit/s	OC-3 155 Mbit/s	OC-3 155 Mbit/s	OC-6 310 Mbit/s	OC-6 310 Mbit/s
Modulation type	OQPSK	OQPSK	16-QAM	16-QAM	256-QAM	256-QAM
Necessary bandwidth (MHz)	50	50	50	50	50	50
Tx power (dBW)	0	–13	5	–10	7	–4
Antenna gain (dBi)	16	29	18	33	28	39
Transmit e.i.r.p. (dBW)	16	16	23	23	35	35
Antenna beamwidth (degrees)	45 or 90	1.9	45 or 90	1.7	45 or 90	1.7
Antenna polarization	H/V	H/V	H/V	H/V	H/V	H/V
Rx noise figure (dB)	7	7	5	6	5	5
Rx noise temperature (K)	1 740	1 740	1 160	1 450	1 160	1 160
Rx sensitivity, (1×10^{-6} BER) (dBW)	–110	–110	–102	–101	–90	–90
Maximum interference (dB(W/MHz))	–146.2	–146.2	–148.0	–147.0	–148.0	–148.0

* reproduced from TABLE 16 of Recommendation F.758

HDFS Transmitter Antenna Model

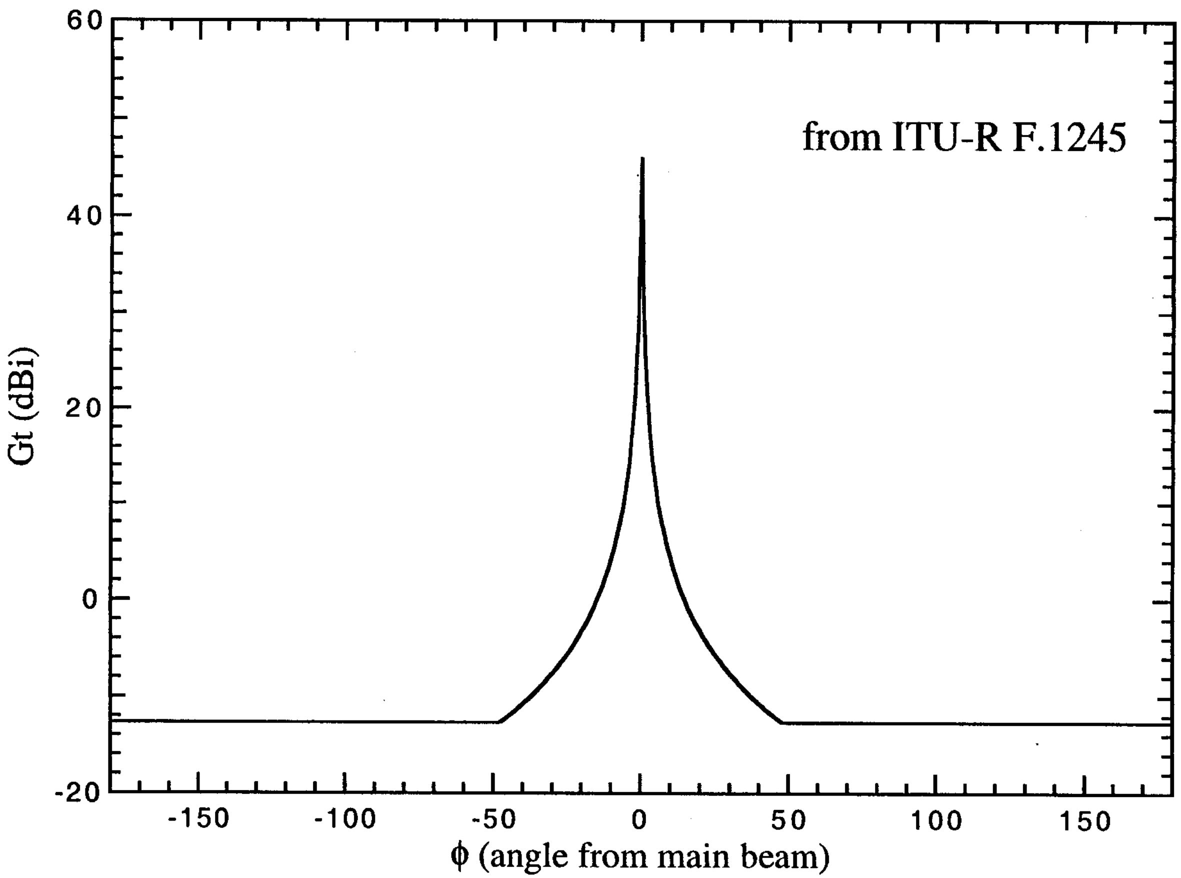
Based on Document ITU-R F.1245, transmitter gain G_t as a function of azimuthal angle (φ):

$$
\begin{aligned}
G_t(\varphi) &= 46 - 2.5 \times 10^{-3} \left(\frac{D}{\lambda}\varphi\right)^2 && \text{for } 0^\circ \le \varphi < \varphi_m \\
G_t(\varphi) &= 29 - 25\log\varphi && \text{for } \varphi_m \le \varphi < 48^\circ \qquad (1) \\
G_t(\varphi) &= -13 && \text{for } 48^\circ \le \varphi \le 180^\circ
\end{aligned}
$$

where D is antenna diameter (0.8 m), λ is wavelength for 32 GHz wave (0.0094 m), and φ_m (first sidelobe angle) is 1.4°.

Thus, for a transmitter with main lobe gain of 46 dB, the maximum $EIRP = P_t + G_t$ = -60 dBW/Hz + 46 dB = -14 dBW/Hz.

HDFS Microwave Transmitter (Point to Point) Model



Transmission Loss Models

1. Line of Sight (Free Space Loss)

For a line of sight propagation, the received power P_r is defined as

$$P_r = \frac{P_t G_t G_r}{L_b} = \frac{P_t G_t G_r}{L_{fs} L} \qquad (2)$$

where $L_b = L_{fs} L = \frac{P_t G_t G_r}{P_r}$ is basic transmission loss

$L_{fs} = (\frac{4\pi df}{c})^2$ is free space loss,

d is the distance between the receiver and transmitter,

c is speed of light, P_t is the transmitter power

G_r is the receiver antenna gain.

Thus, there is a general relation in logarithm

$$P_r = EIRP + G_r - L_b \qquad \text{in dB} \qquad (3)$$

Furthermore,

$$L_{fs} = 20[\log(4\pi / c) + \log f + \log d] \quad \text{in dB} \qquad (4)$$

Changing units of frequency *f* from Hz to GHz, and *d* from meter to km, we have

$$L_{fs} = 92.45 + 20\log f + 20\log d \qquad \text{in dB} \qquad (5)$$

In equation (2), *L* is the correction term for loss:

$$L = A_g + A_d \qquad \text{in dB} \qquad (6)$$

where A_g is gaseous attenuation [23], A_d is defocus factor due to the Earth curvature, and

$$A_g = (\gamma_0 + \gamma_w)d = 0.2d \qquad (8)$$

where γ_o is loss from oxygen and γ_w is from water vapor (in dB/km). Thus,

$$L_b = L_{fs} + L = L_{fs} + A_g + A_d \qquad \text{in dB} \qquad (7)$$

When $f = 32$ GHz, and $d = 200$ km, we have $L_b = 188$ dB

2. Diffraction over Mountains

Diffraction loss L_d is defined as

$$L_d = L_b + L_{ds} = L_b + \sum_i J_i(v) \qquad \text{in dB} \qquad (9)$$

where $L_{ds} = \sum_i J_i(v)$ is all sub-path diffraction over edges and troughs in the path profiles $J(v)$ is a diffraction function. For a 200-km path profile between Los Angeles and Goldstone, there are 4 major mountain peaks. The total sub-path diffraction loss is

$$\sum_i J_i(v) = 33dB$$

Thus, total loss due to diffraction is 221 dB over a 200 km path from Los Angeles to Goldstone.

3. Transhorizon Ducting (mode 1)

For a transhorizon ducting propagation along the great circle of the Earth, the transmission loss L_1 is a function of p, the percentage of time of weather condition

$$L_1(p) = 92.5 + 20\log f + 10\log d_1 + A_h + [\gamma_d(p) + \gamma_o + \gamma_w]d_1 \quad \text{dB} \quad (10)$$

Ducting propagation has a one-dimensional loss (10 log d_1) due to tropospheric layer trapment. Taking $\gamma(p) = 0.01 + \gamma_d(p) + \gamma_o + \gamma_w$,

$$L_1(p) = 120 + 20\log f + \gamma(p)d_1 + A_h \quad \text{dB} \quad (11)$$

When $p = 0.001$, $d_1 = 200$ km, $\gamma_d\, d_1 = 38$ dB. Thus

$$L_1(0.001) = 208 \text{ dB}$$

Corresponding to a larger p, there is a larger loss L_1, or smaller interference. Similar to Equation (3), the received interference power is given by

$$P_r(p) \doteq EIRP + G_r - L_1(p) \quad \text{dB} \quad (12)$$

4. Rain Scattering (mode 2)

For the rain scattering transmission loss L_2, the received interference power is independent of receiver antenna gain.

$$L_2(p) = \frac{P_t}{P_r} \qquad (13)$$

From the radar equation, we have

$$P_r = \frac{P_t G_r \eta V A_r}{(4\pi)^2 (R_1)^2 (R_2)^2} \qquad (14)$$

$$L_2(p) = 168 + 20\log d_2 - 20\log f - 13.2\log R - G_t + 10\log A_b - 10\log C + \Gamma + \gamma_g d_2 \quad \text{dB} \quad (15)$$

where R is the rain rate, and A_b, C, and Γ are other correction factors.

For $p = 0.001$ in Rain zone E, 200 km distance, and a transmitter gain $G_t = 46$ dB, we have $L_2 = 160$ dB. $L_2^*(p) = L_2(p) + G_t = 206$ dB.

Summary of Transmission Losses

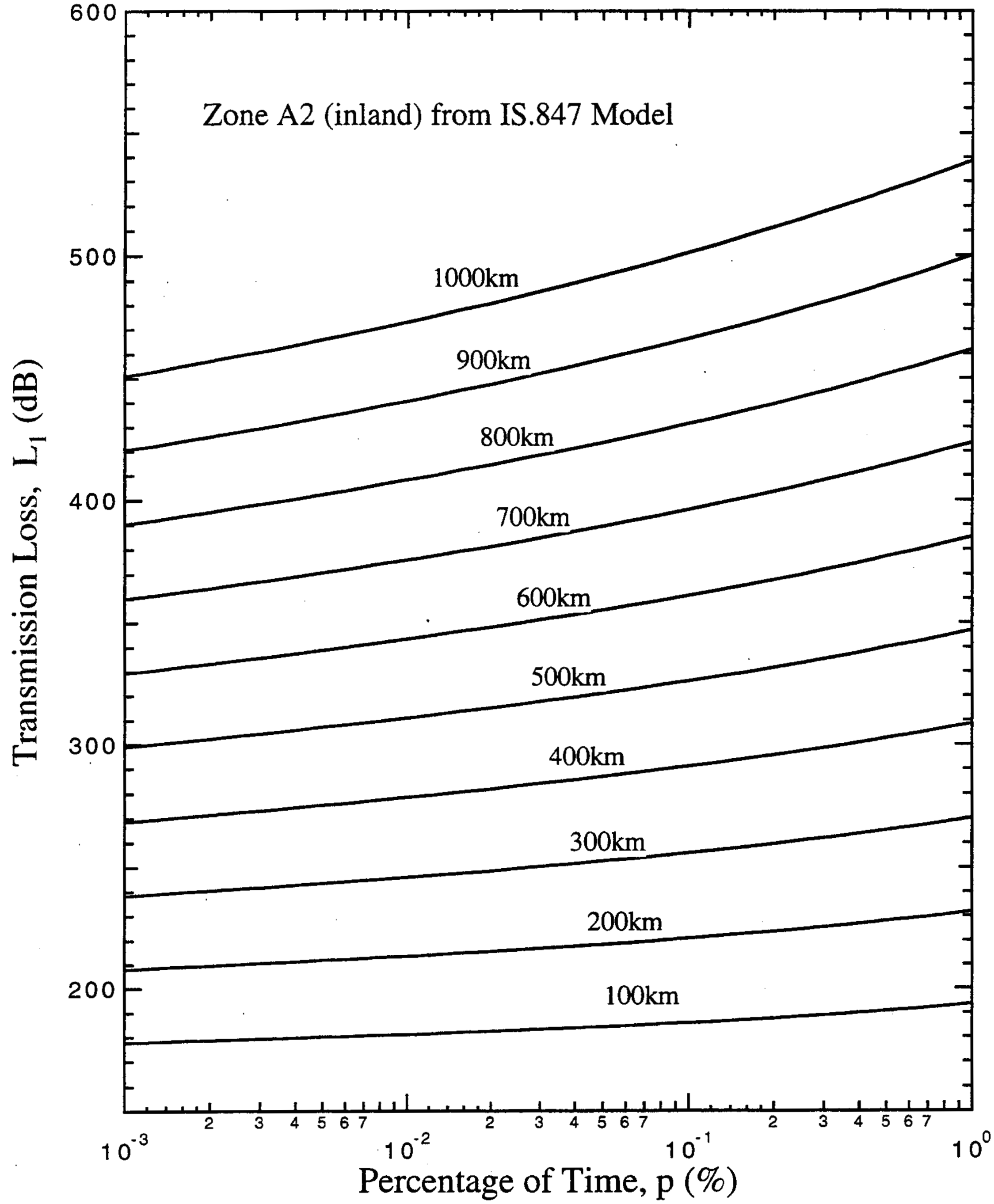
For a single transmitter with

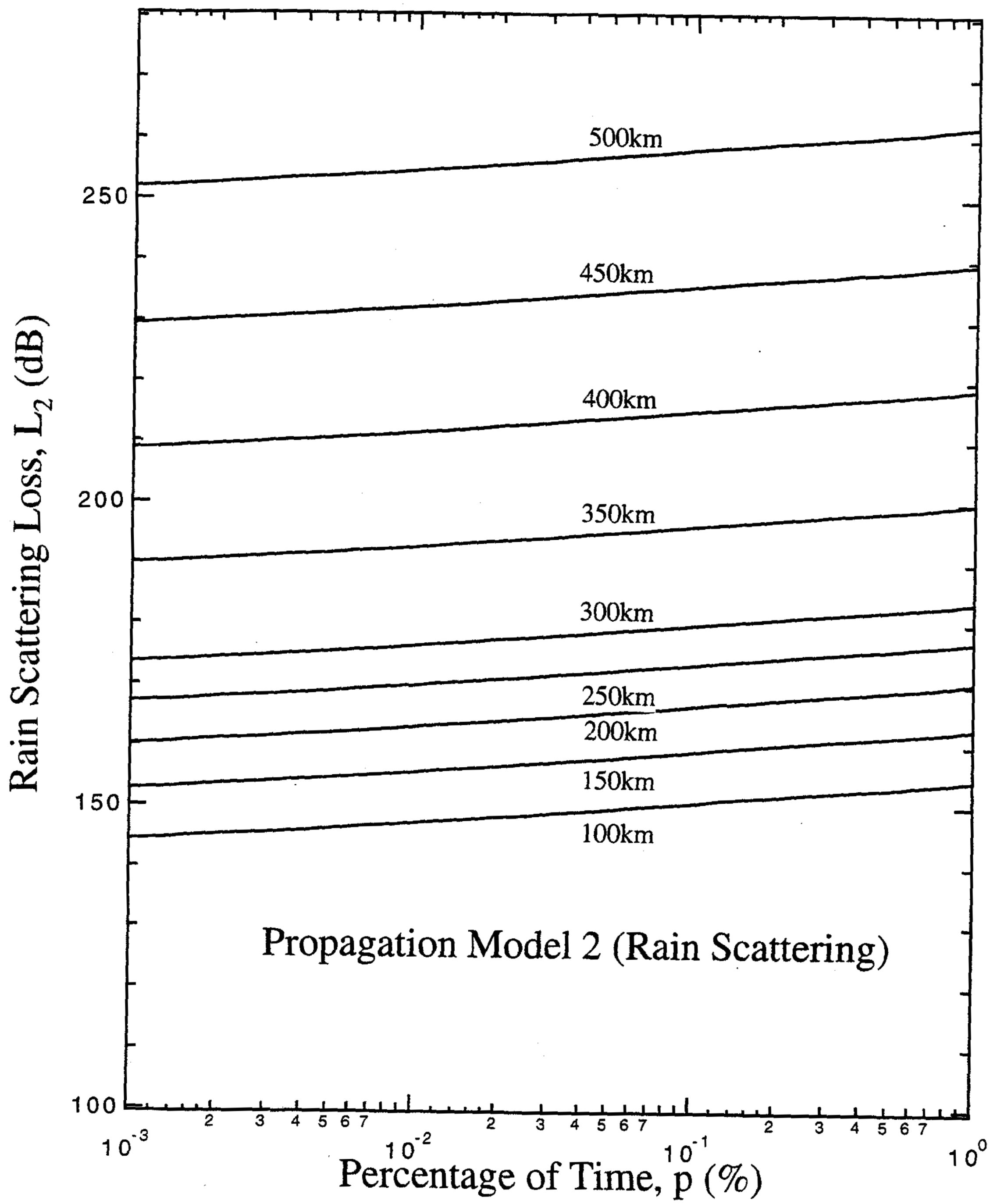
- Distance (d) = 200 km;
- Frequency (f) = 32 GHz;
- Time percent (p) = 0.001%,

we have:

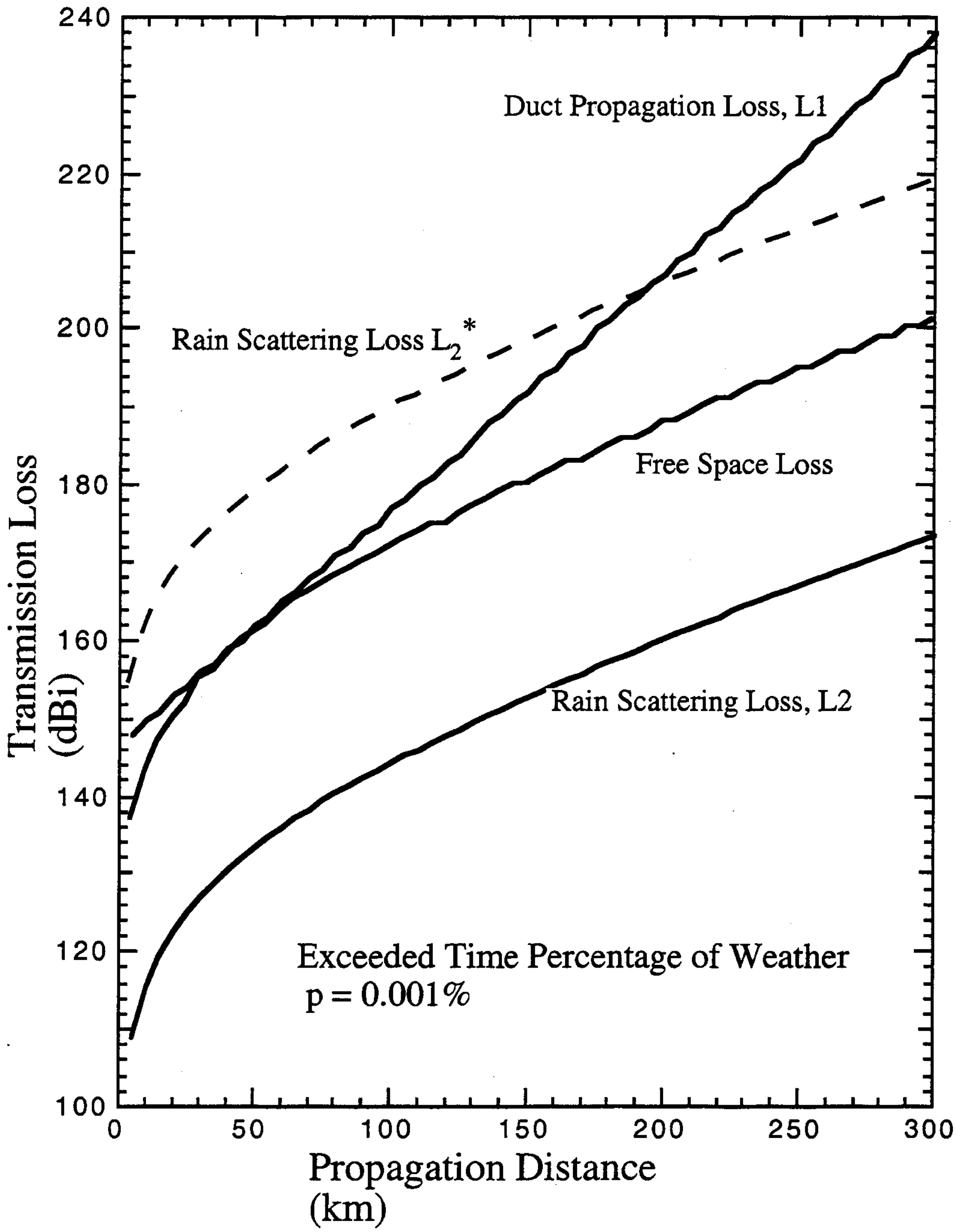
- Line of sight Loss (including gaseous attenuation): L_b = 188 dB
- Diffraction loss over mountains: L_d = 221 dB
- Ducting transmission loss (0.001 percentage time): L_1 = 208 dB
- Rain scattering loss (0.001 percent time): L_2^* = 206 dB.

Transmission Loss for Propagation Mode 1




500km
450km
400km
350km
300km
250km
200km
150km
100km
Propagation Model 2 (Rain Scattering)
Rain Scattering Loss, L2 (dB)
250
200
150
100
Percentage of Time, p (%)
10-3
10-2
10-1
100
2 3 4 5 6 7

Transmission Losses as a Function of Distance



DSN Receiver Model

The model was documented in ITU Radio Regulations for the DSN antenna pattern with the following parameters:

- DSN antenna with a diameter $D = 70$ m;
- threshold power spectral flux density $p_d = -251$ dBW/m^{2}Hz at Ka band;
- threshold power spectral density $P_{th} = \zeta\pi(D/2)^2 p_d = -217$ dBW/Hz,

  where antenna efficiency $\zeta = 52\%$,

  main lobe gain at boresite is 85 dB,

  back lobe gain is -10 dB.

Worst-Case Estimate of HDFS Interference Effects on DSN Receiver at 32 GHz for Single Transmitter

- HDFS Transmitter Model:

  Transmitter power: P_t = 0 dBW/MHz = -60 dBW/Hz (strongest case)

  Frequency: 32 GHz

  Elevation angle: 0° horizontal

  Main lobe (Maximum Gain): 46 dBi

  Back lobe gain: -12.5 dB

  EIRP: $P_t + G_t$ = -60 dBW/Hz + 46 dBi = -14 dBW/Hz

- Transmission Loss Model:

  Distance, d = 200 km; Frequency, f = 32 GHz, Time percent, p = 0.001%

  Line of sight Loss: L_b = 188 dBi

  Diffraction Loss: L_d = 221 dBi

  Ducting Loss: L_l = 208 dBi

  Rain Scattering Loss: L_2*= 206 dBi

- DSN Receiver Antenna Model:

  Size: D = 70 m

  Threshold Power Density: p_d= -251 dBW/m^2Hz

  Threshold Receive Power $P_r = \eta\pi (D/2)^2 p_d$ = -217 dBW/Hz,

  where η = 52%

  Main lobe gain: 85 dBi

  Back lobe gain: -10 dBi

Worst Case Estimate of Interference Effect for Single Transmitter from Los Angeles on Goldstone DSN Receiver

Transmitter P_t = -60 dBW/Hz, G_t = 46 dBi (main-lobe), -12.5 dB (back-lobe), EIRP = -14 dBW/Hz

Distance d = 200 km, probability p = 0.001%

Receiver G_r = 85 dB (main-lobe), -10 dB (back-lobe), threshold P_{th} = -217 dBW/Hz

				P_r (dBW/Hz)		Margin	$(P_{th} - P_r)$*
	EIRP	Loss	EIRP-Loss	back-lobe	Main-lobe	back-lobe	Main-lobe
Line of Sight	-14	188	-202	-212	-117	-5	-100
Diffraction	-14	221	-235	-245	-160	**28**	-57
Ducting	-14	208	-222	-232	-147	**15**	-70
Rain Scattering	-14	206	-220	-220	-220	**3**	**3**

* A negative margin indicates that the protection level criterion is exceeded.

Worst Case Estimate of Interference Effect from Nearby City

Single Transmitter on Goldstone DSN Receiver

Transmitter P_t = -60 dBW/Hz, G_t = 46 dBi (main-lobe), -12.5 dB (back-lobe), EIRP = -14 dBW/Hz

Probability p = 0.001% for ducting, rain scattering losses

Receiver G_r = 85 dB (main-lobe), -10 dB (backlobe), threshold P_{th} = -217 dBW/Hz

							P_r (dB W/Hz) Rain Scattering		P_r (dB W/Hz) Ducting		Margin (P_{th}-P_r)*	
	Distance from GS	EIRP dBW/Hz	LOS dBi	Diffraction dBi	Ducting dBi	Rain Scattering	backlobe	mainlobe	backlobe	mainlobe	backlobe (Rain)	mainlobe (Ducting)
Barstow	50 km	-14	161	163	162	133	***-148***	-148	-186	***-91***	**-69**	**-126**
Victorville	65 km	-14	165	169	166	137	***-151***	-151	-190	***-95***	**-66**	**-122**
Lancaster	150 km	-14	180	193	192	153	***-167***	-167	-216	***-121***	**-50**	**-96**
Palmdale	160 km	-14	183	198	197	154	***-168***	-168	-221	***-126***	**-49**	**-91**

* A negative margin indicates that the protection level criterion is exceeded.

Monte Carlo Simulation Procedure

- **There are three independent random variables representing HDFS 2D transmitter location and antenna orientation**

  For transmitter location with ranges:

  radial distance: $0 \le \rho_i \le \rho_0$ (=1, 10, 30 and 50 km)

  azimuthal angle for mainbeam: $-180° \le \phi_i \le 180°$

  For transmitter antenna mainlobe azimuthal angle (φ):

  $$-180° \le \varphi_i \le 180°$$

  Assuming Los Angeles City Center has a geographic coordinate (x_c, y_c) the *ith* transmitter's location is

  $$X = x_i + x_c$$

  $$Y = y_i + y_c$$

  where

  $$x_i = \rho_i \cos \phi_i,$$

  $$y_i = \rho_i \sin \phi_i$$

- **Ducting propagation only is assumed**

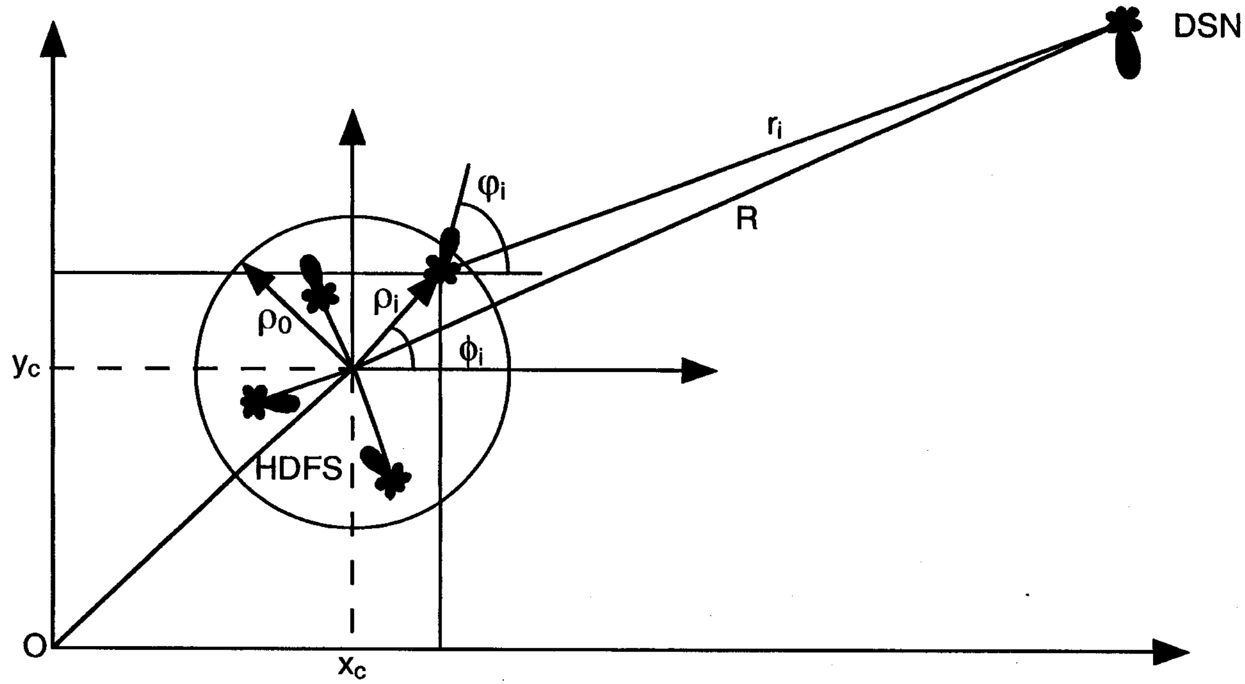
  At a Distance, d = 200 km; Time percent, p = 0.001%, ducting Loss: L_1 = 208 dBi

- **The total interference power spectral flux density P_{SFD} is obtained by linearly superposing all transmitted powers**

$$P_{SFD} = \sum_i^n (P_t + G_t(\varphi_i) - L_1(\rho_i, \phi_i))$$

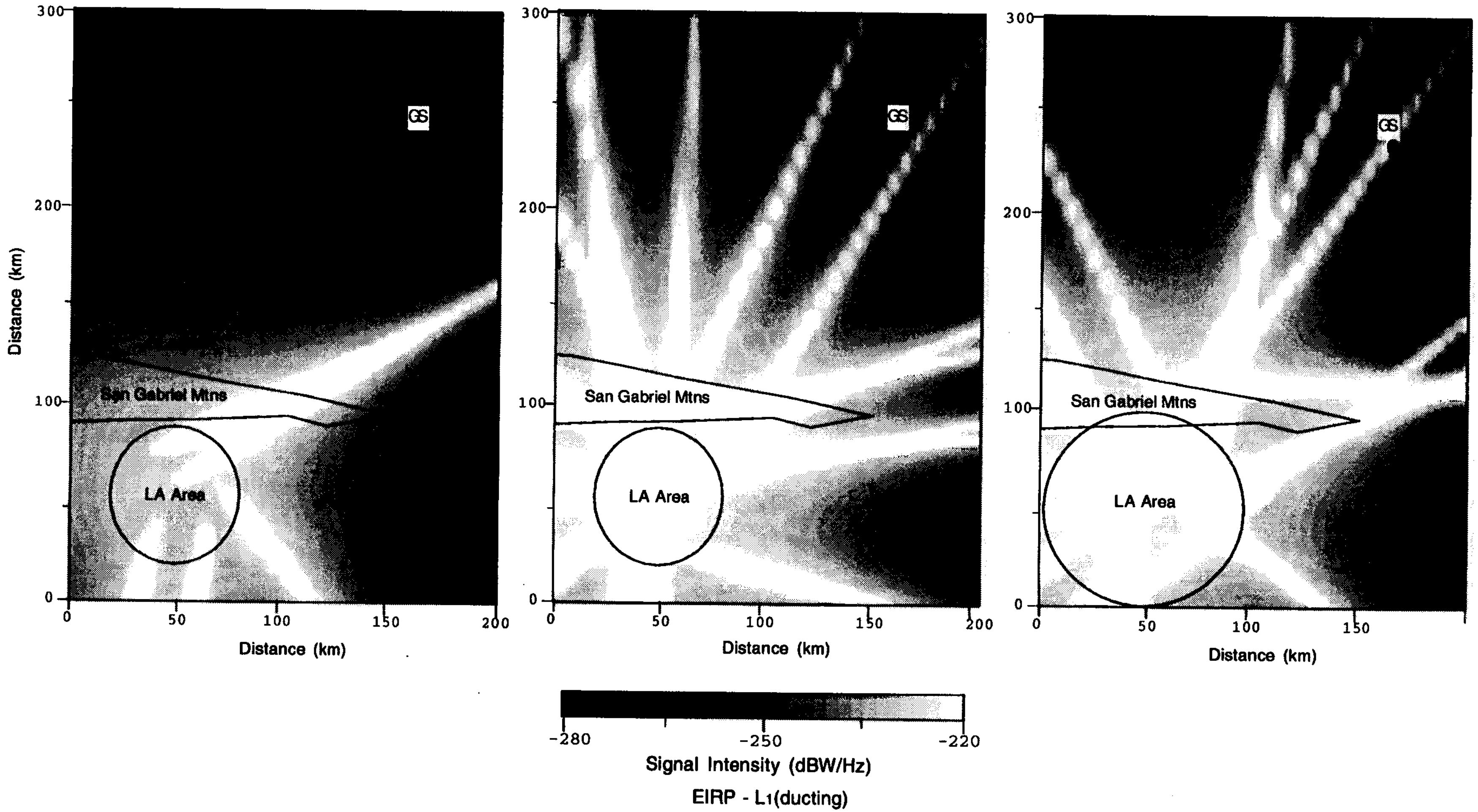
- **We have made 1,200 trials using 3,000 transmitters. Each trial run has a different transmitter pattern (in location and orientation)**

HDFS Spatial Distribution Configuration and Simulation Variables



Transmitters are deployed in a circular area with a maximum radius ρ_0 around the center of Los Angles. Each transmitter has a random location (ρ_i,ϕ_i) and a mainbeam orientation φ_i. Goldstone DSN receiver has a distance r_i from the receiver and a 200 km distance from the city center.

Interference Signal Intensity for Various Numbers of Transmitters and Extended Radii in the Los Angeles Area



Left panel: 5 transmitters with 30 km radius; middle panel: 20 transmitters with 30 km radius; right panel: 20 transmitters with 50 km radius. The Goldstone DSN receiver is at the upper-right corner.

Monte Carlo Simulation of Interference Effect from Los Angeles Area HDFS on Goldstone DSN Receiver

A total of 1,200 runs. Each run (or pattern) uses 3,000 transmitters.

Each Transmitter P_t = -60 dBW/Hz, G_t = 46 dBi (main-lobe), -12.5 dB (backlobe), EIRP = -14 dBW/Hz

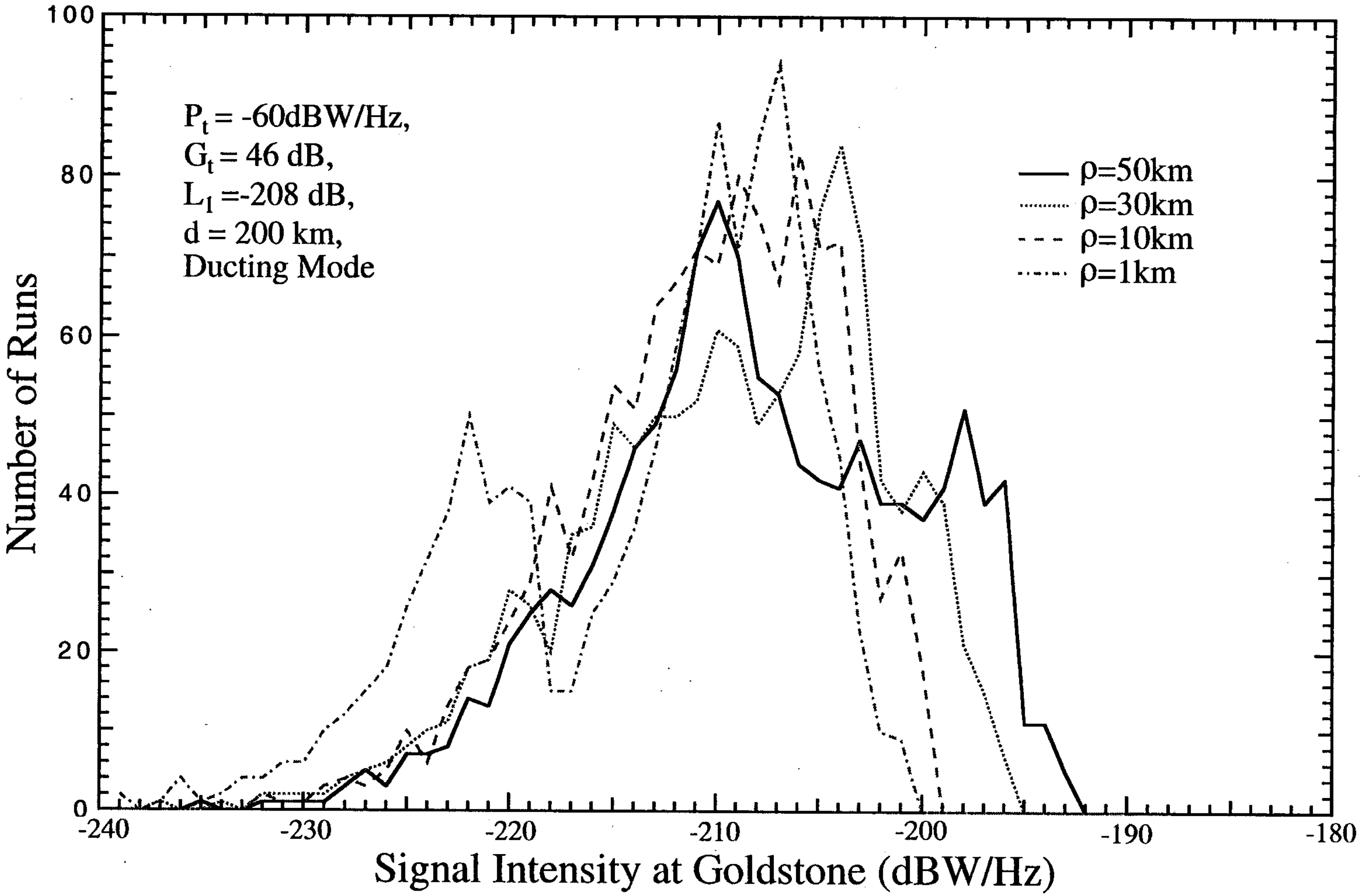
Probability p = 0.001% for ducting transmission only, L_l = 208 dBi at distance d = 200 km

Receiver G_r = 85 dB (main-lobe), -10 dB (backlobe), threshold P_{th} = -217 dBW/Hz

Maximum radial Distance (km)	Average Power Flux P_{SFD} at GS dBW/Hz	Aggregate EIRP (dBW/Hz) $P_{SFD} + L_l$	Equivalent Antenna Gain G_0 EIRP - P_t	P_r (dBW/Hz)		Margin (P_{th}-P_r)*	
				backlobe	mainlobe	backlobe	mainlobe
1 km	-212.5	-4.5	55.5	-222.5	-127.5	5.5	-89.5
10 km	-211.5	-3.5	56.5	-221.5	-126.5	4.5	-90.5
30 km	-209.0	-1.0	59.0	-218	-124	2.0	-93.0
50 km	-205.0	-3.0	63.0	-215	-120	-2.0	-97.0

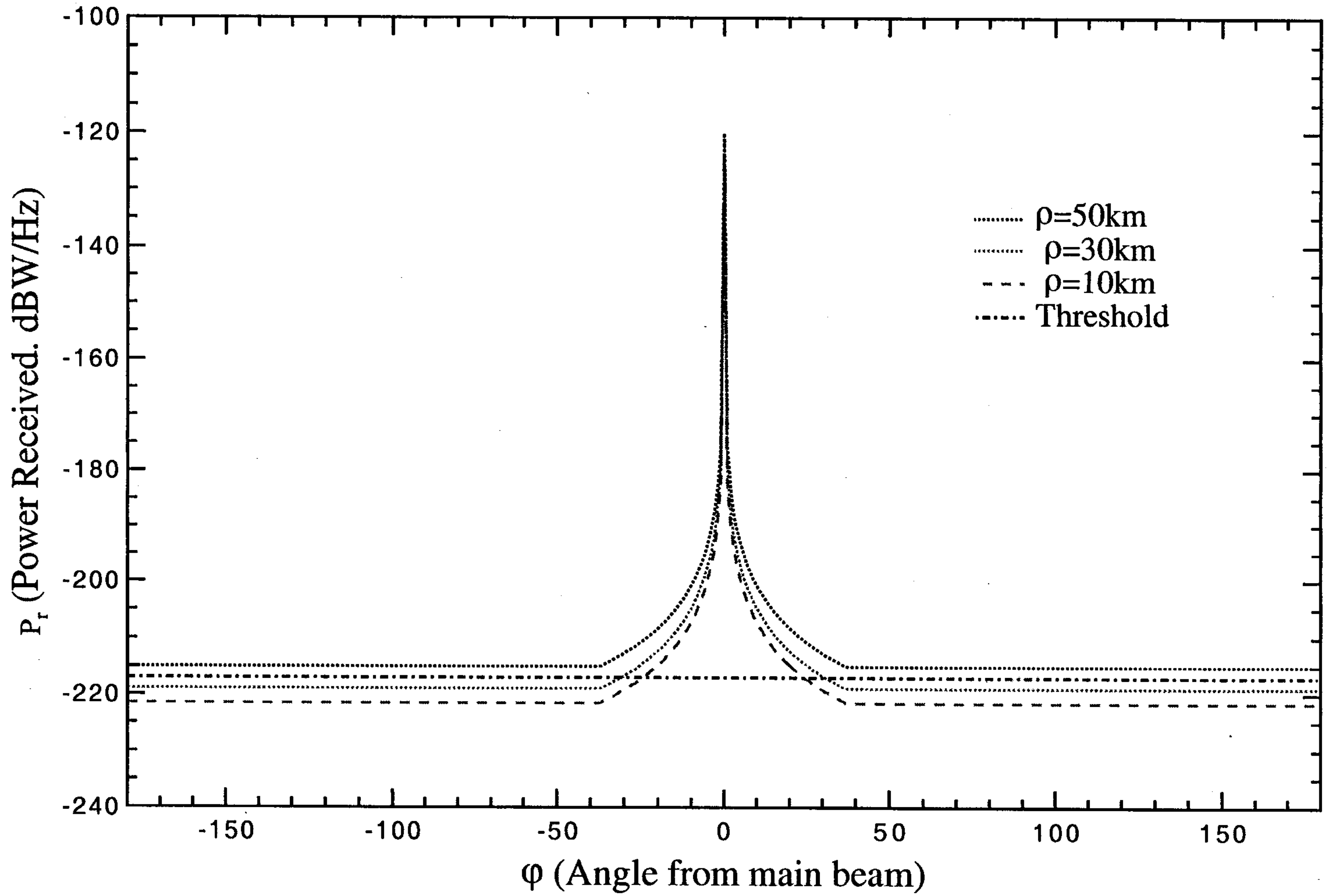
* A negative margin indicates that the protection level criterion is exceeded.

Interference signal intensities at Goldstone for different HDFS extended radii



Each curve shows the signal intensity distribution from 1,200 HDFS deployment patterns. Only ducting transmission loss over a 200 km distance is considered here. In general, when the HDFS extended radius increases, the signal intensities shift to higher values.

Received Interference Powers at Goldstone after the DSN Receiver Antenna Gain in All Azimuthal Angles



Three curves correspond to signals from transmitters with different extended radii. As a reference, the DSN receiver threshold level is also shown. When the radius is greater than 30 km, the threshold is exceeded.

Summary

1. A thorough literature search was conducted for all ITU documents related to transhorizon propagation interference effects and all HDFS operating parameters. Interference from a single transmitter through ducting, rain scattering, and diffraction have been fully investigated. For the first time, aggregated interference effects from HDFS transmitter spatial distributions have been assessed using a simulation technique.

2. Worst-case estimates were performed for a single transmitter with the highest power level in the Los Angeles area and the cities near Goldstone. At a 200 km separation distance, when the transmitter's mainbeam is exactly pointed to the DSN antenna, only small positive margins can be expected relative to the backlobe of the receiver antenna for 0.001% of the time (weather condition). For some cities with distances smaller than 200 km, interference signals will largely exceed the threshold of the receiver.

3. Monte Carlo simulations were conducted to examine the interference effects on Goldstone tracking station using 3,000 HDFS transmitters in the Los Angeles area. The impact of HDFS EIRP levels, spatial distributions and maximum radial distances have been examined. Preliminary statistical results for aggregated power distributions from 1,200 trials with different maximum radial distances of the HDFS distributions were obtained. The results show that when the HDFS transmitter spatial distributions have large radial distances, aggregated transmitter antenna gains and interference power received at Goldstone are much greater than those calculated from a Normal distribution. When the radial distance is 50 km, the DSN receiver interference threshold will be exceeded.

4. We have developed an approach to quantitatively study the interference effect of HDFS transmitters with various orientations and distributions on the DSN, using a Monte Carlo simulation. As a future study, actual HDFS distributions can be simulated more realistically, and any proposed HDFS deployment patterns to mitigate the interference effects, such as coordinated (planned) antenna pointing, can be examined using this simulation tool. This tool can be also used to estimate potential interference to the DSN from other transhorizon terrestrial services.