APPENDIX C

INTERFERENCE ANALYSIS

PREPARED BY WIRELESS FACILITIES, INC.

Appendix C:
Interference Protection Analyses; Coexistence of i-BURST with the incumbents of the 1670-1675 MHz Band

1. Methodology

The i-BURST system will coexist with a variety of wireless systems, which are either adjacent to or partially overlay the band 1670-1675 MHz. These incumbents, namely, Radio Astronomy stations, Meteorological Satellite stations (MetSats), and Radiosondes operated by institutions such as National Weather Services, would operate on a protected status basis. The effects of interference on the protected sites were analyzed in several ways.

First, the interference levels at the location of a given protected site due to an i-BURST transmitter at various distances were calculated and compared to the required values. Section 2 explains the methodology, the formulas and the results used in the process of deterministically relating the required levels to the operational distances. Due to the random nature of the location of the i-BURST transmitters and their orientation relative to the protected systems, statistical analyses were also performed to reveal the likelihood and severity of interference into each of the incumbents. The results of these analyses can be found in sections 3 and 4. While Section 3 analytically formulates the problem, Section 4 uses simulation to reveal the statistical characteristics of the potential interference. Finally, case studies were taken place using deployment scenarios in cities near actual sites. Two Radio Astronomy sites near cities likely of having i-BURST deployment were chosen; Hat Creek site near Redding, CA and Los Alamos site near Santa Fe, NM. Section 5 discusses the methodology and results for this study.

Protection requirements for all systems are taken from ITU and NTIA specifications created by the operators of those systems, and described in detail elsewhere in this filing.

The analyses described below are conservative in that they generally assume the i-BURST base stations to be simultaneously operating on all available carriers at a relatively high EIRP of 52 dBm, and also that all subscriber units operate at the relatively high EIRP of 27.5 dBm. This should be viewed as an extreme operating point of the system given its power control capabilities and high capacity. In the single case of the MetSat interference analyses, it is assumed for the purposes of this document that the i-BURST carrier immediately adjacent to the MetSat band has been reserved as an internal guard band.

2. PSFD Calculations

The Power Spectral Flux Density (*PSFD*) from an interfering station into a victim receiver in free space conditions is given by the following equation.

$$PSFD_{victim} = P_{TX} + G_{TX} - 10\log(4\pi) - 20\log(R)$$ **Equation 1**

If P_{TX} is the Power Spectral Density (PSD) of the interfering transmitter in dBm/MHz, G_{TX} is the antenna gain of the interfering transmitter in the direction of the victim receiver in dBi, and R is the distance between the interfering transmitter and victim receiver in meters, then the above formula gives *PSFD* in dBm/MHz-m^2. This equation assumes no atmospheric losses and free-space conditions. In order to include the effect of terrain at the frequencies of interest to this document, the calculations were complemented by the COST 231 – Hata empirical model. COST 231 – Hata is a well-known extension of the Hata equation on the propagation modeling curves originally created by Okumura. It is the best-suited model for the general terrain-independent analyses at 1670 MHz provided in Sections 2 through 4. The general format of this model is as follows.

$$A + B\log(R) - C$$ **Equation 2**

In the above expression, A, B, and C are given in the Table 1 below, R is the distance between the transmitter and the receiver in meters, and C is the log-normal fading standard deviation. The inclusion of the "-C" term in the model is highly conservative in that it yields the 80th-percentile worst-case (minimum) propagation loss between an i-BURST transmitter and a receiving site. The sample separation distances quoted below should therefore be viewed as pessimistic (overly large) estimates of the distances that would be required in practice to meet the PSFD interference requirements at a protected receiver site.

Therefore, with P_{TX} defined as PSD of the transmitting station, the *PSD* at victim including the effect of terrain is calculated using the following formula.

$$PSD_{victim} = P_{TX} + G_{TX} - A - B\log(R) + C$$ **Equation 3**

COST-231-Hata does have a limiting assumption that one antenna is positioned between 1 and 10 m above the terrain with the other being situated between 30 and 200 m above the terrain. Violating these parameter assumptions leads to poor predictive capability for the model. Consistent with those limitations and, to the extent possible, with deployment practices, the selected heights and resulting A, B and C values are as shown in Table 1.

Scenario	**Antenna 1 height**	**Antenna 2 height**	**A**	**B**	**C**
i-BURST BS to RA	30 m	10 m	5.2 dB	35.2 dB	13.3 dB
i-BURST BS to MetSat	30	10	5.2	35.2	13.3
i-BURST BS to radiosonde	30	5	19.5	35.2	13.3
i-BURST terminal to RA	30	1.5	29.4	35.2	13.3
i-BURST terminal to MetSat	30	1.5	29.4	35.2	13.3
i-BURST terminal to radiosonde	30	1.5	29.4	35.2	13.3

Table 1: COST-231-Hata input parameters

At the victim antenna, the required protection, in terms of received power spectral density, is related to the *PSFD* level through the following formula.

$$PSFD = P_r - 20\log(\lambda) - G + 10\log(4\pi)$$ **Equation 4**

In the above equation, P_r is the received power density in dBm/MHz, λ is the wavelength in meters, and G is the receiver antenna gain in dBi. The combination of the above two equations was used to analyze the *PSFD* levels at various distances against the required values.

It is often necessary to convert from Power, Power Spectral Density (*PSD*) or Power Flux Density (*PFD*) to Power Spectral Flux Density (*PSFD*). The following set of formulas can be used for the conversions. If P represents the power in Watts, B the bandwidth in Hz, A_e the effective aperture of a receiving antenna in m^2, and G the antenna gain (dimensionless), then:

$$PSD = \frac{P}{B} \qquad (W/Hz)$$

$$PFD = \frac{P}{A_e} = \frac{P}{G\frac{\lambda^2}{4\pi}} = \frac{4\pi P}{G\lambda^2} \qquad (W/m^2)$$ **Equations 5a, 5b, 5c**

$$PSFD = \frac{PSD}{A_e} = \frac{4\pi \cdot PSD}{G\lambda^2} \qquad (W/Hz\text{-}m^2)$$

It must be noted that although the above parameters are often expressed in decibels (dB), the conversion from one to another needs to be done in linear scale using the above formulas. For example, in order to convert from PSD in *dBW/MHz* to *dBm/Hz-m*^{2} the following calculation should be performed.

$$PSFD_{(dBm/Hz\text{-}m^2)} = 10\log\left[\frac{4\pi[(10^{\frac{PSD_{dBW/MHz}}{10}})_{W/MHz}\frac{10^3}{10^6}]_{mW/Hz}}{G\lambda^2}\right]$$ **Equation 6**

A series of feasibility analyses were performed to determine the effect of an i-BURST transmitter on the co- and adjacent-channel incumbents. The interference levels (in terms of *PSFD*) generated by the i-BURST transmitter were then compared to the maximum tolerable interference levels required by the incumbents for protection purposes. The outcome of this point-to-point link analysis process was the distance required to guarantee the compliance with the protection levels. Table 2 summarizes these distances for various incumbents.

	MetSat- 1	MetSat- 1K	Radio Astronomy - VLBI	Radio Astronomy - non-VLBI	Radiosonde-1	Radiosonde-2
Distance (km)	8.913	17.136	7.47	124.184	13.373	5.017
Requirement dBm/MHz-m^2	-96	-106	-118	-161	-121	-106

Table 2. Protection requirements and safe operational distances under worst case conditions

Notes for Table 2
1) MetSat-1: interference power over 1 Hz
2) MetSat-1K: interference power over 1 kHz
3) Radiosonde-1: interference power less than 0.24% of the time
4) Radiosonde-2: interference power less than 0.03% of the time

It should be noted that although the above analyses are done with one i-BURST transmitter, the transmitter is in a worst case situation; i.e., directing its maximum in-band energy at the protected site at all times. While multiple i-BURST transmitters will operate in any given area, the likelihood of all the transmitters directing their maximum energy at the protected site at the same time is extremely low. Therefore, in order to get a better picture of the situation in the real world, a series of statistical analyses were performed, which are explained in Section 3.

3. Statistical Analysis – I

It was assumed that i-BURST base stations are surrounding a protected site at distance *R* as depicted in Figure 1. Each base station is assumed to have a coverage radius of *r*, determined from the i-BURST link budget and the COST-231-HATA propagation model. The base stations utilize adaptive antennas, whose effective patterns change in response to the environment including subscriber locations. The parameters of the base stations' radiated energy are summarized in Table 3. Also, subscribers are randomly distributed within the coverage areas of the base stations and produce interference by radiating energy in all directions. Given these assumptions, the goal is to calculate the interference level at the location of the protected site due to base stations and subscribers.

It must be noted that in real world deployments, it is highly unlikely for the i-BURST transmitters to surround a protected site as assumed in this analysis. Therefore, the results of this analysis present a highly pessimistic scenario.

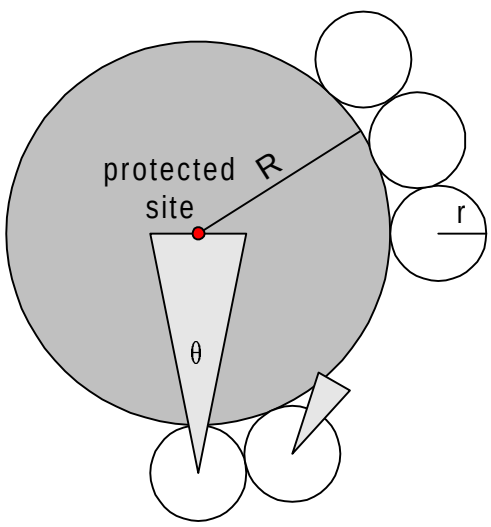


Figure 1. Problem layout for statistical analysis I

3.1. Interference Due to Base Stations

We can estimate how many base stations surround the protected site by equating the circumference of the great circle passing through all of the base stations to the sum of the diameters of the base stations' coverage areas.

$$2\pi(R+r) = 2rN \qquad \textbf{Equation 7}$$

N is the number of base stations that surround the protected site. Therefore,

$$N = \left\lceil \frac{\pi(R+r)}{r} \right\rceil \qquad \textbf{Equation 8}$$

in which $\lceil . \rceil$ denotes the Ceiling function.

Parameter	Value
Beamwidth (°)	θ
Main lobe EIRP (dBW)	W
Sidelobe EIRP (dBW)	W – a
Azimuth (°)	ϕ

Table 3. System parameters

It is assumed that the azimuth of a given base station beam is a random variable that is uniformly distributed from 0° to 360°. In the calculations, the beamwidth, θ, is taken to be ten degrees, consistent with the typical 5λ (0.9 m at 1670 MHz) horizontal aperture of an i-BURST antenna array.

Therefore, the probability that the protected site falls within a single base station's main lobe is given by:

$$P(Hit) = \frac{\left(\phi + \frac{\theta}{2}\right) - \left(\phi - \frac{\theta}{2}\right)}{360} = \frac{\theta}{360}$$ **Equation 9**

Let us designate this probability as *p*. Therefore, the probability that the center of the exclusion zone falls outside one given base station's main lobe can be designated *q*=1-*p* or P(Miss). A Bernoulli random variable (r.v.) describes this probability.

The total number of hits and misses, H, for the entire base stations therefore consists of N independent identically distributed (i.i.d.) Bernoulli random variables (or N trials of a Bernoulli r.v.) where the probability of success (hit) is *p* and the probability of failure (miss) is 1-*p*. The summation of all hits and misses is a r.v. with Binomial distribution, $P_n(k)$.

$$P_n(k) = \binom{n}{k} p^k (1-p)^{n-k}$$ **Equation 10**

Which describes the probability of *k* successes in *n* trials.

The statistics for H are as follows:

$$\mu = Np = \frac{N\theta}{360} \qquad \text{(mean)}$$ **Equation 11**

$$\sigma = \sqrt{Np(1-p)} = \frac{\sqrt{N\theta(360-\theta)}}{360} \qquad \text{(standard deviation)}$$ **Equation 12**

The total interference at the center of the protected site can be determined using the above results.

The average power level due to all the hits is given by

$$PSFD_{Total_hits} = \mu \cdot PSFD_{Hit} = Np \cdot PSFD_{Hit}$$ **Equation 13**

The average power level due to all the misses is given by

$$PSFD_{Total_misses} = N(1-p) \cdot PSFD_{Miss}$$ **Equation 14**

Therefore, the total power level due to all the hits and the misses is as follows.

$$PSFD_{Total} = Np \cdot PSFD_{Hit} + N(1-p) \cdot PSFD_{Miss}$$ **Equation 15**

in which $PSFD_{Hit}$ and $PSFD_{Miss}$ are the interference levels due to a single base station.

The following formula is being used to calculate *PSFD* level generated by a base station given free space conditions.

$$PSFD_{BS} = 10\log\left(10^{\frac{EIRP_{BS} - ACR - 10\log 4\pi - 20\log(R+r)}{10}}\right)$$ **Equation 16**

In the above equation *ACR* is the Adjacent Channel Rejection due to filters (This factor is not present if co-channel effects are analyzed).

In order to consider the effects of intervening terrain through widely used COST231-HATA empirical model, the following method has been used in calculating the *PSFD* levels.

For a general case of a transmitter and a receiver separated by distance R, the received *PSD* at the receiver is given by

$$P_r = \frac{P_t G_t G_r}{L(R)}$$ **Equation 17**

in which P_t is the transmitter *PSD*, G_t is the transmitter antenna gain in the direction of the receiver, G_r is the receiver antenna gain in the direction of the transmitter, and *L(R)* is the distance-dependent path loss. On the other hand, the receiving antenna captures the incoming electromagnetic flux through its effective area, A_e. Therefore, the spectral density of the received power is given by

$$P_r = PSFD \cdot A_e$$ **Equation 18**

in which *PSFD* is the Power Spectral Flux Density of the incoming wave. Substituting Equation 17 into Equation 18 and solving for *PSFD*, we obtain,

$$PSFD = \frac{4\pi P_t G_t}{\lambda^2 L(R)}.$$ **Equation 19**

L(R) used in the analyses was obtained from COST231-HATA empirical model as described in section 2 of this appendix.

3.2. Interference Due to Subscribers

Figure 2 depicts a simple system layout for the analysis of subscriber effects. The protected site is located at the center of the concentric circles. It can be assumed that the subscribers are uniformly distributed in the shaded annular region between the two circles.

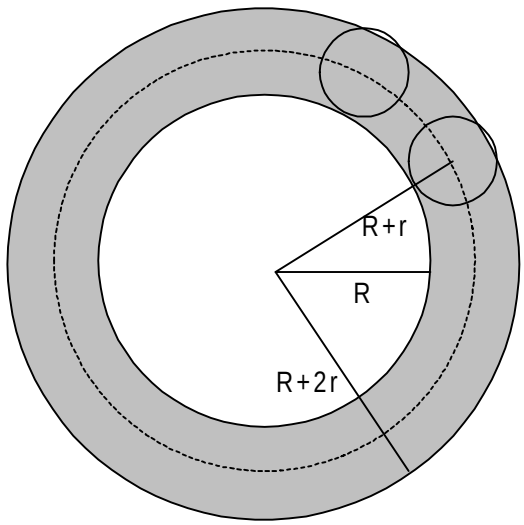


Figure 2. System layout for subscribers

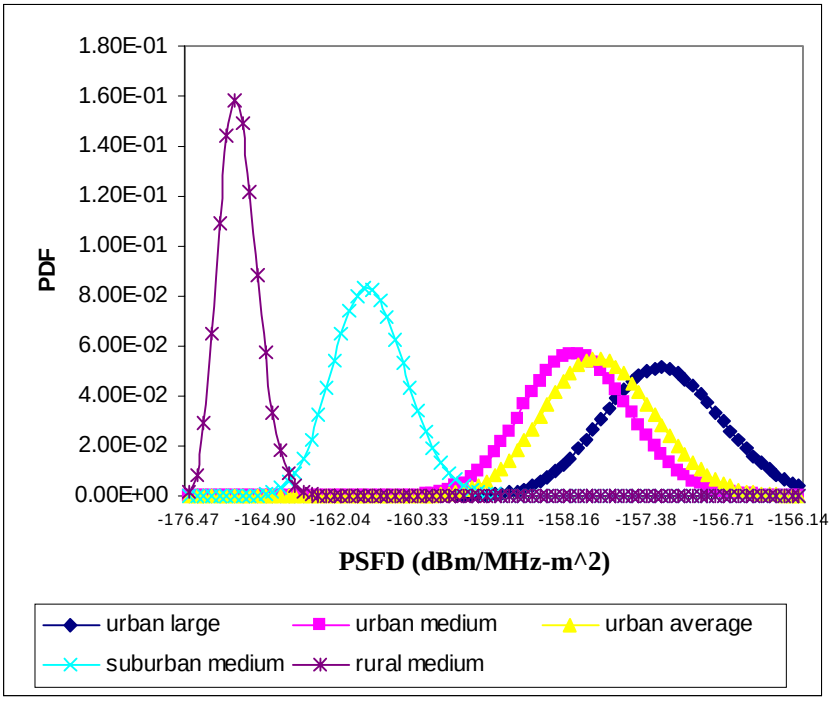
The distance of the subscribers, which determines the *PSFD* generated by them, is therefore uniformly distributed in [*R*, *R+2r*]. On the average, one could conclude that the subscribers are at a distance *R+r* from the center of the exclusion zone, thus creating the following *PSFD* level in dB in free space conditions

$$PSFD_{total_subscribers} = 10\log\left[N_s\left(10^{\frac{EIRP_{sub}-ACR-10\log 4\pi-20\log(R+r)}{10}}\right)\right] \qquad \textbf{Equation 20}$$

in which, N_s is the total number of subscribers in the shaded region obtained from i-BURST specifications and *ACR* is the Adjacent Channel Rejection due to filters (This factor is not present in the co-channel case). Equation 19 multiplied by N_s can be used to calculate the total *PSFD* effect of subscribers in the presence of intervening terrain provided that transmit power and antenna gain of the subscriber unit is used. The same path loss model as the base stations can be used for subscriber units since the propagation channel does not differ significantly between transmit and receive times.

i-BURST uses Time Division Duplex. This means that there is no time at which both base stations and subscribers are transmitting. Therefore, the *PSFD* generated by subscribers must not be added to the *PSFD* generated by base stations.

The results of the Statistical Analysis –I are presented in Figure 3 through Figure 7. The figures provide the probability density function (PDF) and cumulative distribution function (CDF) of PSFD at the receiver sites of each incumbent system. The separation distances, R, are selected to meet the various incumbents' PSFD criteria (cf. Table 2) in essentially 100% of the cases. The one exception here is in the case of non-VLBI radio astronomy which is discussed in more detail below. Also, the notations *Urban Large, Urban Medium, Suburban Medium*, etc., indicate morphology assumptions used in calculating i-BURST cell radii based on the i-BURST link budget. Generally speaking, as the building density increases, i-BURST cell sizes shrink leading to a larger number of base stations surrounding the incumbent site and hence to more interference.



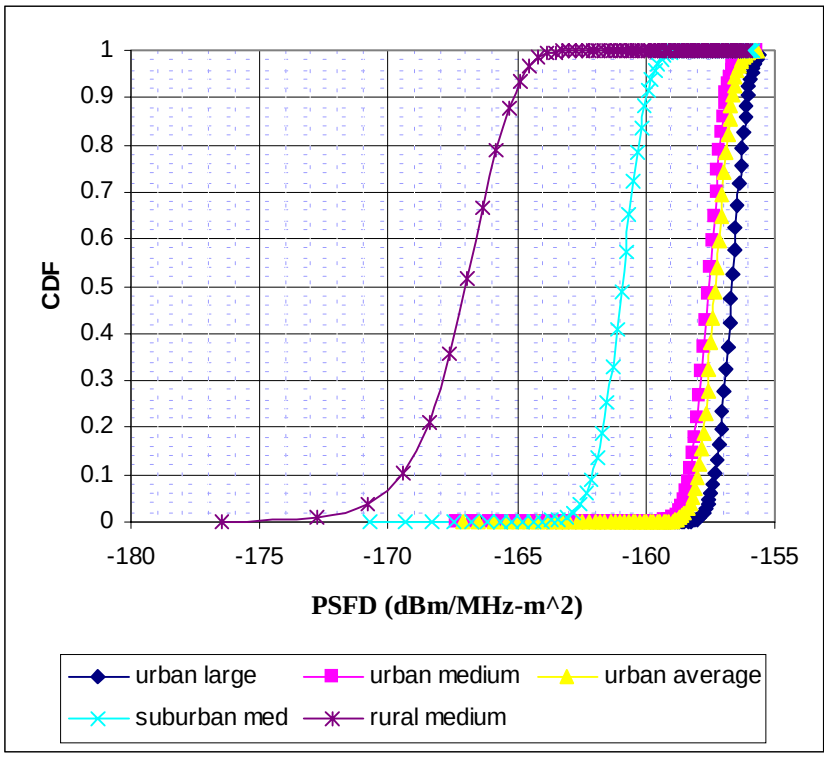
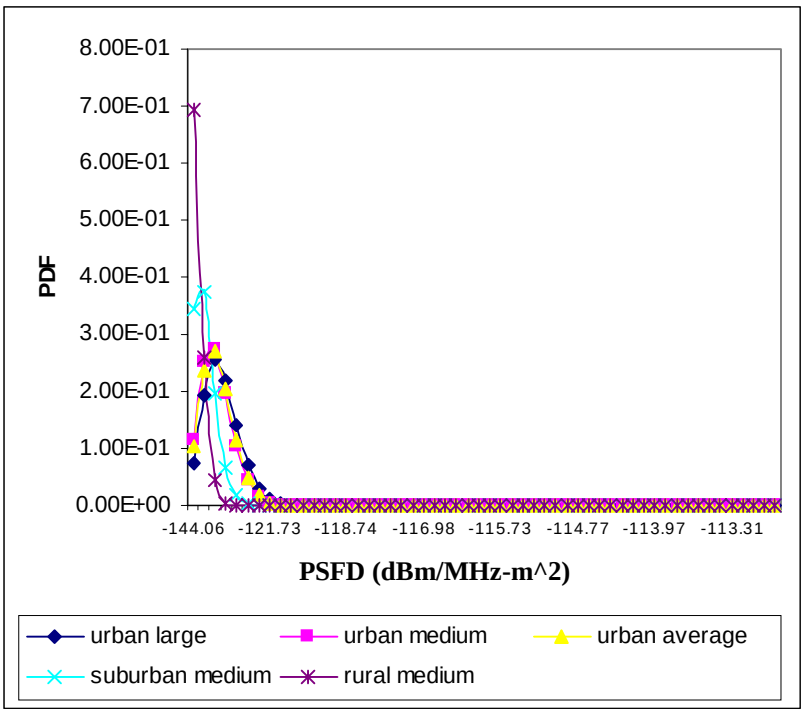


Figure 3. Sample PDF and CDF plots for estimating the likelihood of interference PSFD in dBm/MHz-m^2 from i-BURST to non-VLBI RA incumbents. R = 300km, PSFD limit = -161 dBm/MHz-m^2



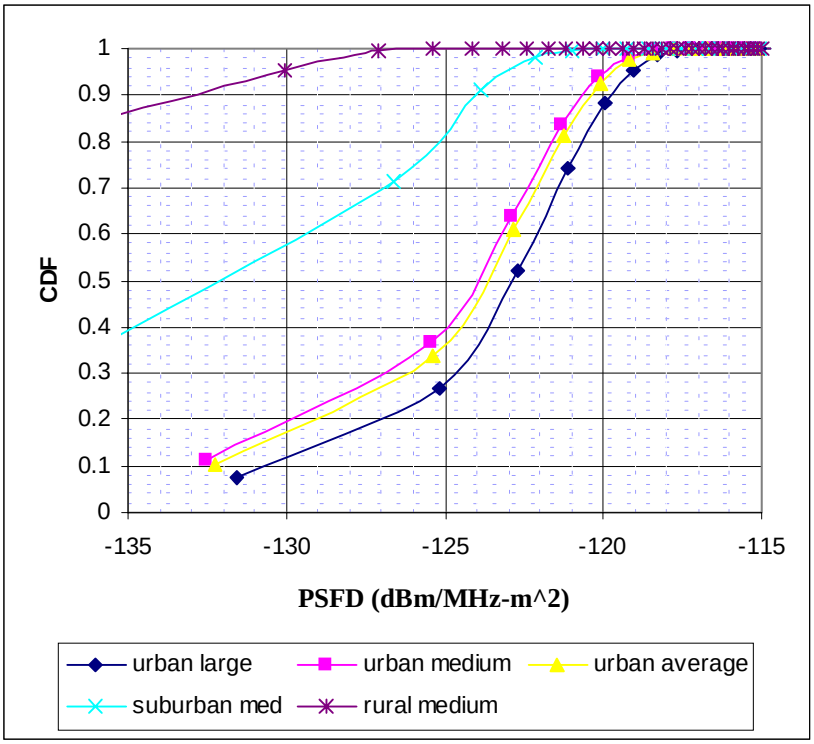
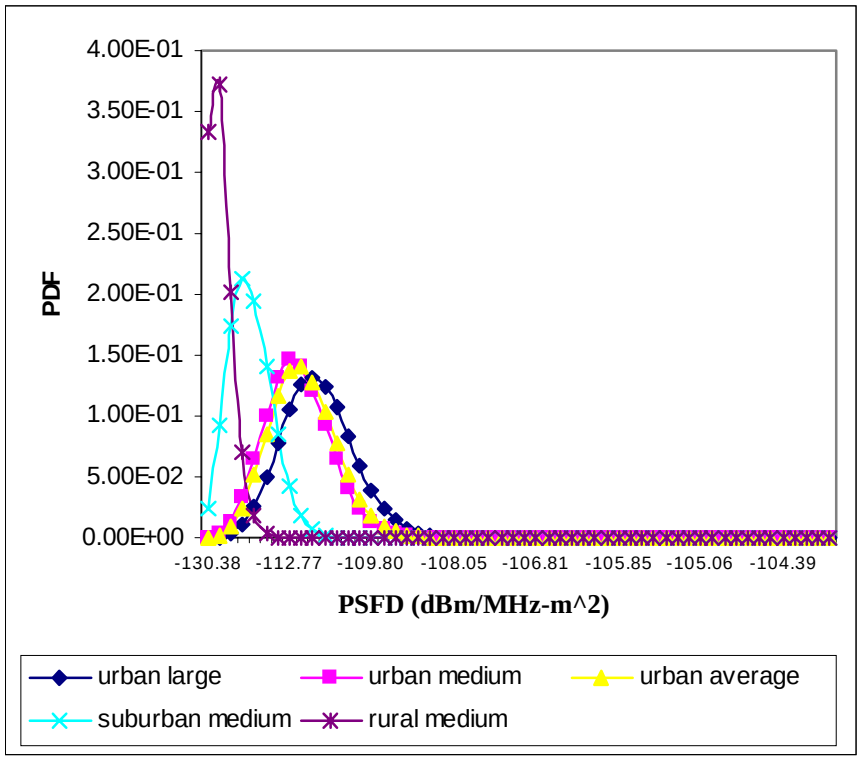


Figure 4. Sample PDF and CDF plots for estimating the likelihood of interference PSFD in dBm/MHz-m^2 from i-BURST to VLBI RA incumbents. R= 12 km, PSFD limit = -118 dBm/MHz-m^2



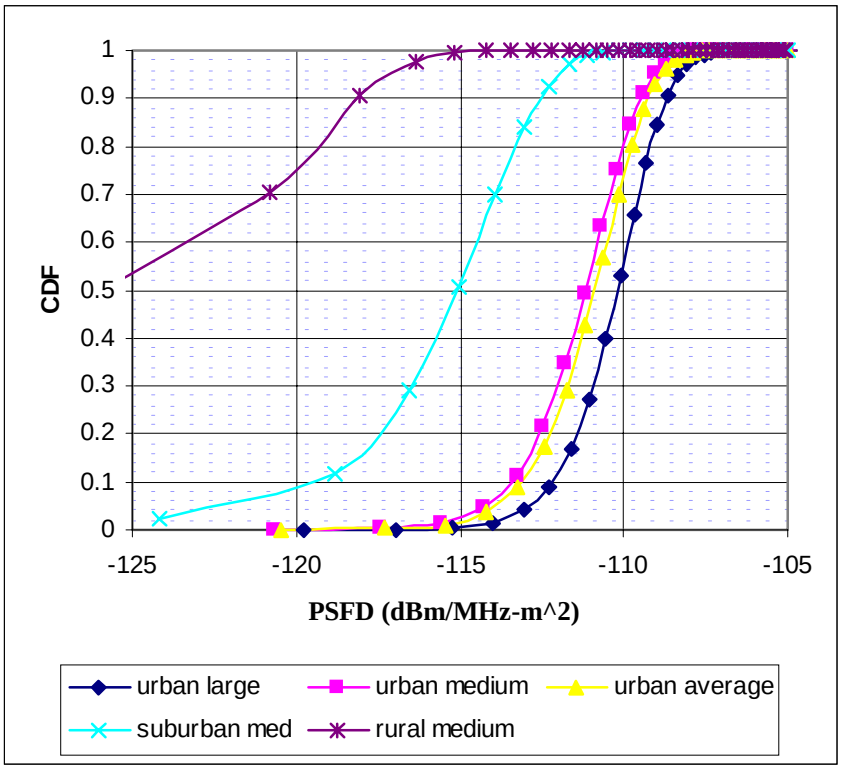
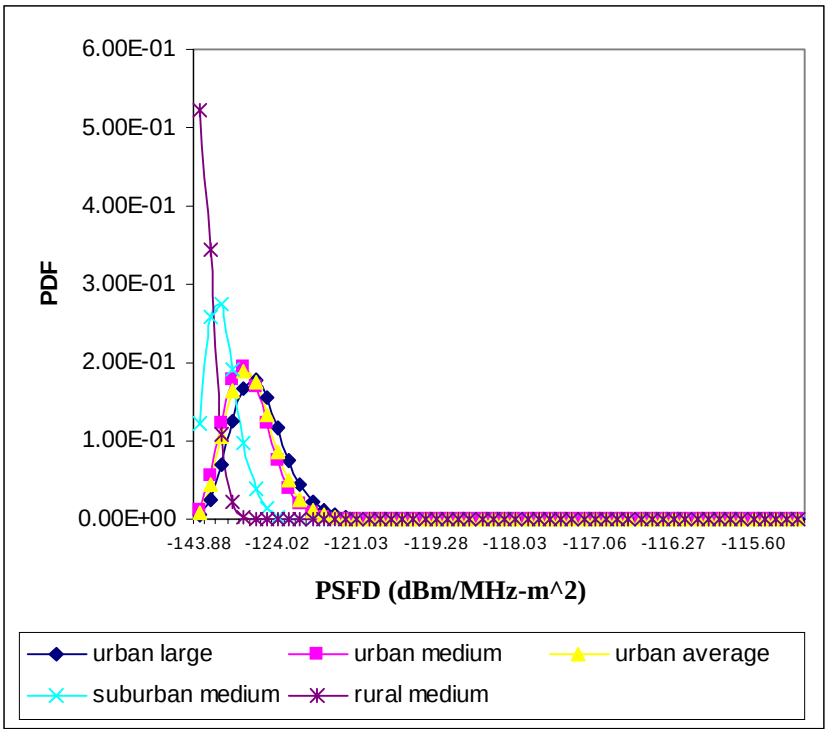


Figure 5. Sample PDF and CDF plots for estimating the likelihood of interference PSFD in dBm/MHz-m^2 from i-BURST to METSAT incumbents. R = 45 km, PSFD limit = -106 dBm/MHz-m^2



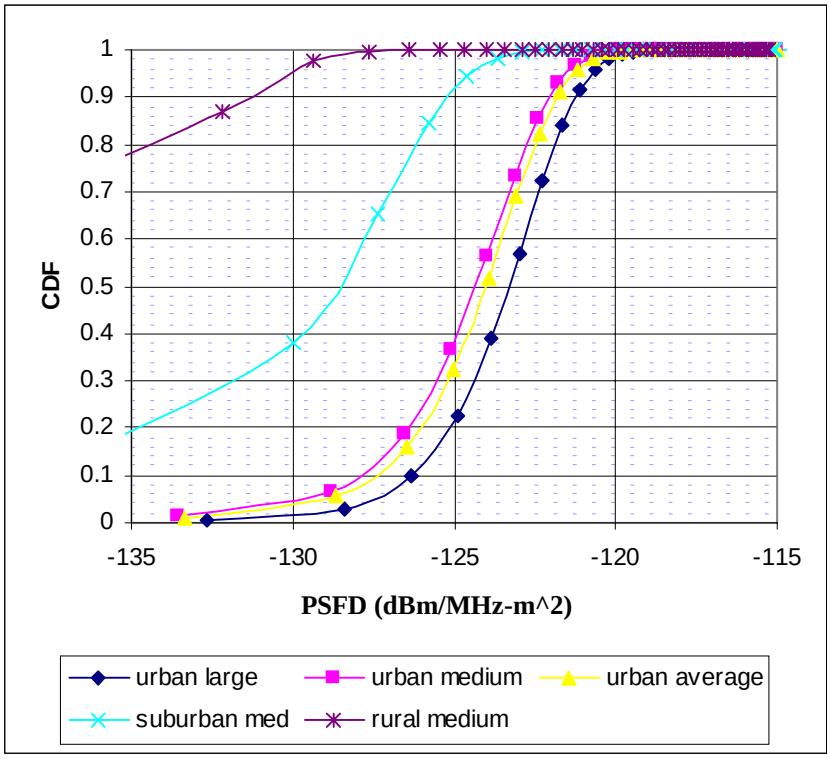


Figure 6. Sample PDF and CDF plots for estimating the likelihood of interference PSFD in dBm/MHz-m^2 from i-BURST to Radiosonde incumbents. R = 25 km, PSFD limit = -121 dBm/MHz-m^2

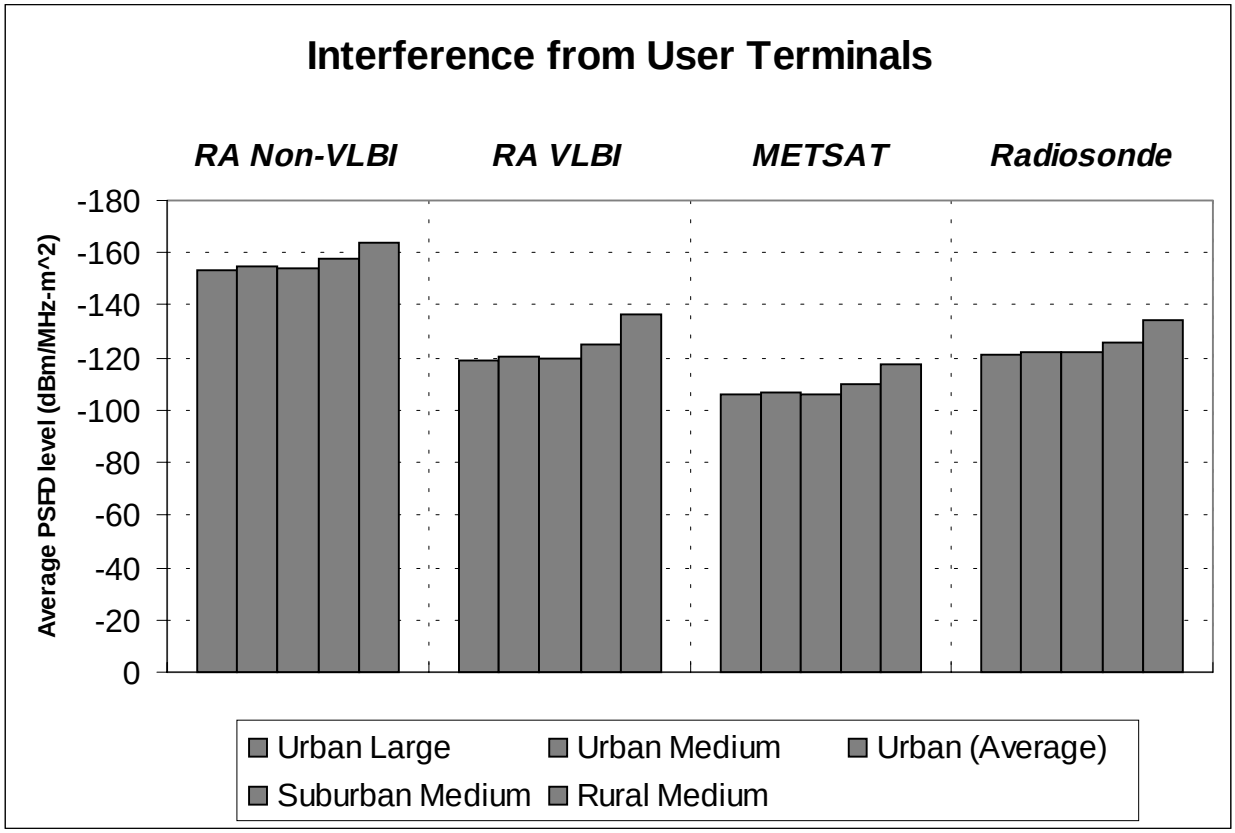


Figure 7. Average interference PSFD in dBm/MHz-m^2 from User Terminals to incumbents. Separation distances 80 km for RA Non-VLBI, 3 km for RA VLBI, 20 km for MetSat, 10 km for radiosonde. Same protection criteria as in Figures 3-6.

As it is shown in the results, compliance with the required PSFD values for protecting the incumbents is easily achieved in most cases even under the pessimistic model where the protected system is completely ringed by i-BURST systems. The case of the non-VLBI Radio Astronomy sites needs more attention due to its very stringent requirement. In the case of coexistence with these systems within distances shorter than the numbers presented in Table 2, special protection measures should be taken. One of the most effective options available is the utilization of some guard-band or additional filtering between the two systems, thus increasing the isolation between the two systems in frequency domain. The other point to be made regarding non-VLBI systems is that these systems tend to be located in remote areas, far from population centers, and hence that large separation distances, should they be required, are reasonably realized.

4. Statistical Analysis – II

The second statistical analysis follows the more practical case of i-BURST base stations deployed in an area at some distance to a protected site and not surrounding it. The protected sites of interest are typically located in remote areas and are far from large cities. Occasionally, there is a small city nearby, which could potentially be a deployment target for i-BURST. To capture this scenario the model in Figure 8 was adopted.

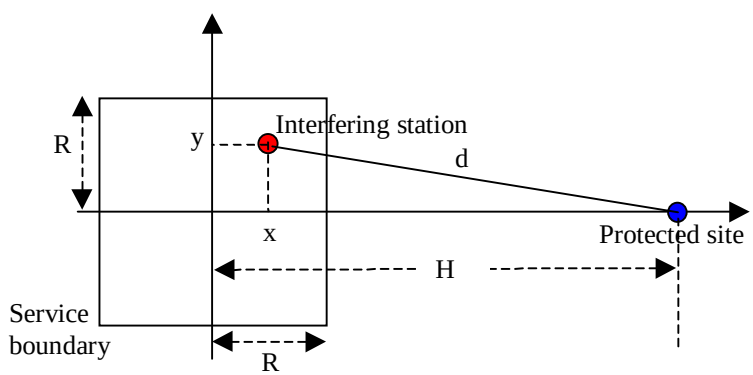


Figure 8. Problem layout for statistical analysis II

It is assumed that the protected site is located at distance *H* from the center of the service area and the interfering stations are randomly distributed inside the area. For the sake of simplicity, it is assumed that service area takes the form of a square of side *2R*. We can always choose the coordinate system in a way that the origin is at the centroid of a square circumscribing the city, and that the protected site lies on the x-axis.

The coordinates of the interfering stations, *(x,y)* satisfy the following.

$$-R \le x \le R$$
$$-R \le y \le R$$

A MATLAB program was written to generate pairs of random variables *(X,Y)* with *X* and *Y* uniformly and independently distributed on [-R,R].

Based on the location of the interfering station, distance *d* to the protected site is given by the following equation through simple geometry.

$$d = \sqrt{Y^2 + (H - X)^2}$$ **Equation 21**

The distance *d* is then used to calculate the *PSFD* generated by the interfering stations at the location of the protected site. COST231-Hata model was used to calculate the propagation path loss *L(R)* in the *PSFD* calculations.

The program was run for 1,000 rounds for various *R*, *H*, and the number of stations, *N*, and the mean and standard deviation of the *PSFD* values were extracted. Figure 9 through Figure 12 depict the results of the analysis.

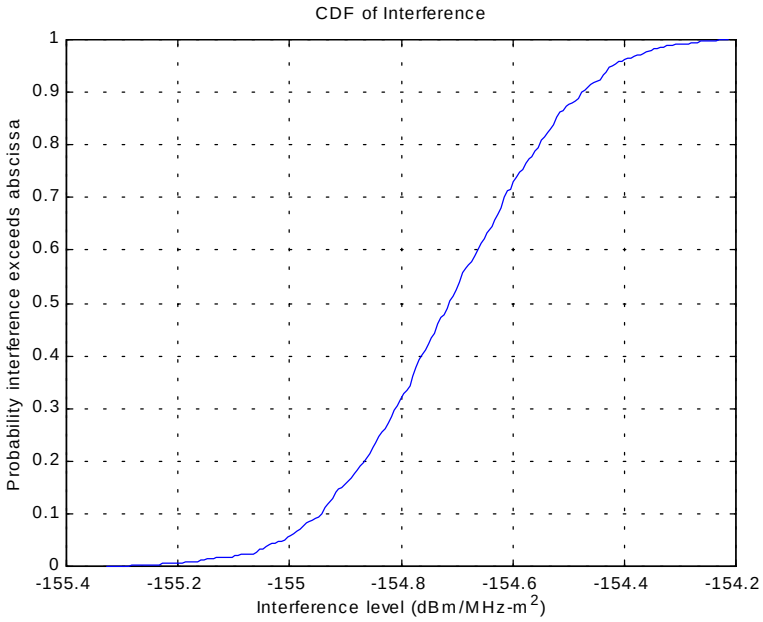


Figure 9. A sample CDF for estimating the likelihood of interference from a deployment area to a protected site location (R=5 km, N=9, EIRP=54 dBm/MHz, H=80 km)

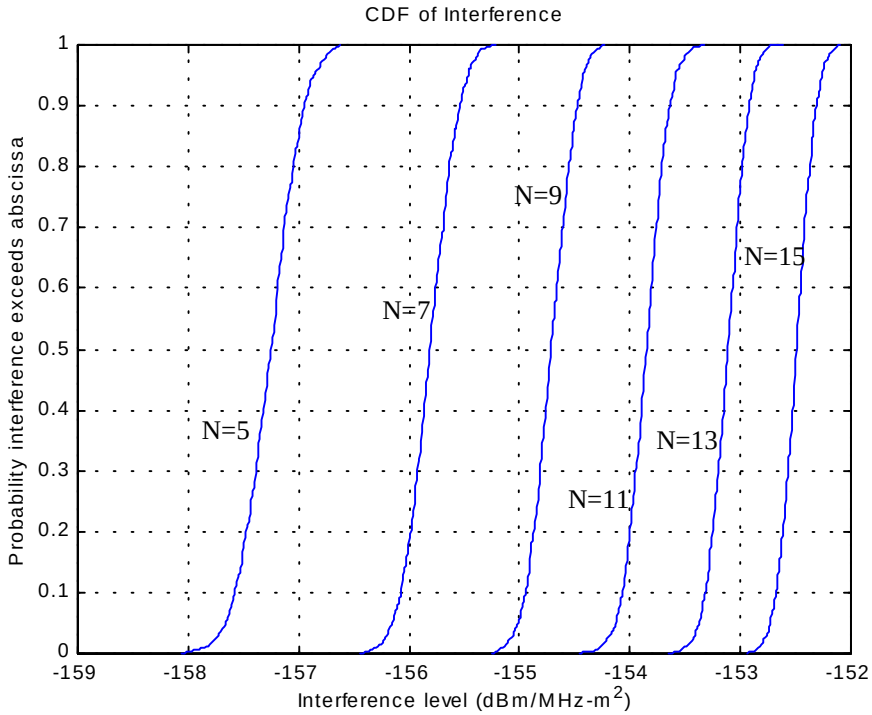


Figure 10. Interference likelihood plots for various N (R=5 km, EIRP=54 dBm/MHz, H=80 km)

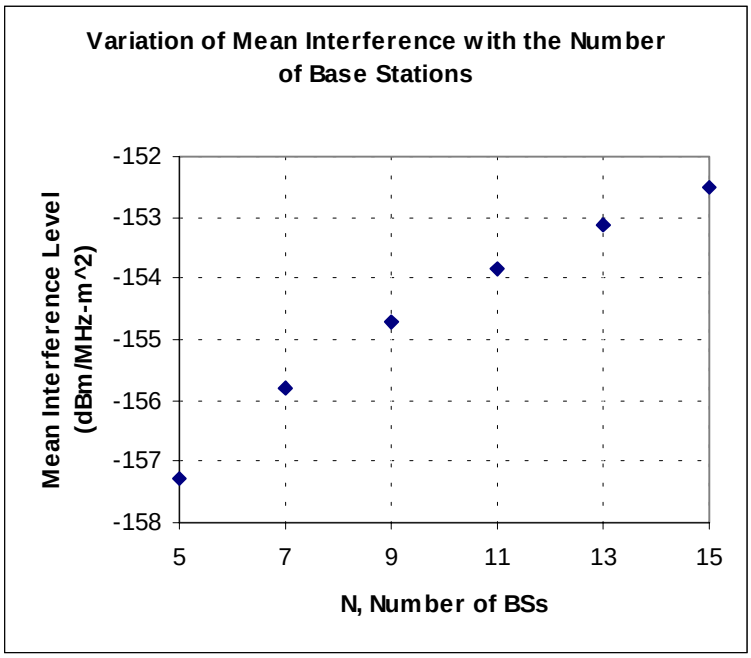


Figure 11. Variation of mean PSFD interference with the number of interfering sources (R=5 km, EIRP=54 dBm/MHz, H=80 km)

Figure 11 depicts the PSFD levels created at a protected site due to various number of base stations in a typical i-BURST deployment.

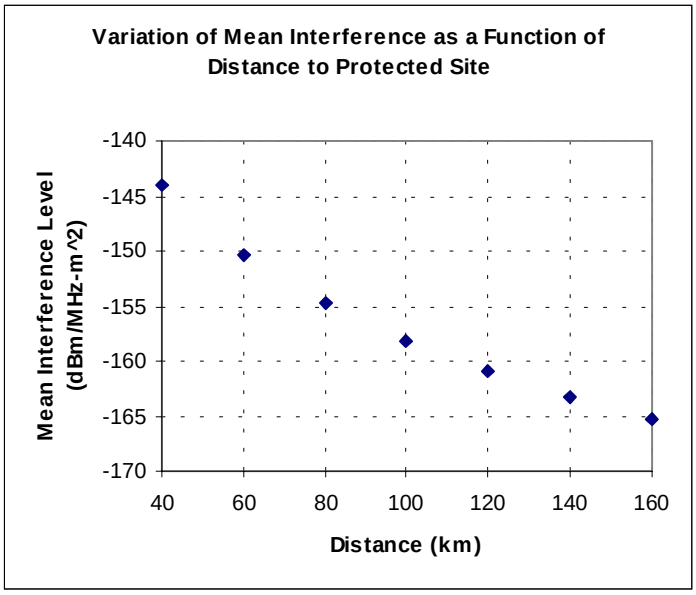


Figure 12. Variation of mean interference as a function of distance to the protected site (R=5 km, N=9, EIRP=54 dBm/MHz)

Figure 12 depicts a situation in which 9 base stations each with 2-km coverage area cover a 100 km^2 deployment with some required cell overlap.

The results of the Statistical Analysis – II agree with the previous analyses. Note that with a 120 km separation distance (cf. Figure 12) the protection requirement for the most sensitive system, non-VLBI Radio Astronomy is met. Again, it is likely that coexistence with non-VLBI Radio Astronomy in some cases requires some special remedies such as guard-bands or additional filtering.

5. Simulation Using A Propagation Tool

In order to address the actual deployment scenarios, case studies were performed using widely accepted propagation models and EDX SignalPro propagation modeling software. Most of the protected sites are tens of miles away from large cities and many of them are quite distant from cities likely to be targets of i-BURST deployment. As a result, two Radio Astronomy sites near cities likely of having i-BURST deployment were chosen; Hat Creek site near Redding, CA and Los Alamos site near Santa Fe, NM. Depending on the size of the city, a typical deployment scenario comprising of smaller cells in the city center and larger cells in the outskirts was implemented in each case.

Figure 13 and Figure 14 depict the terrain variation around the Radio Astronomy sites and i-BURST network planing in the nearby city.

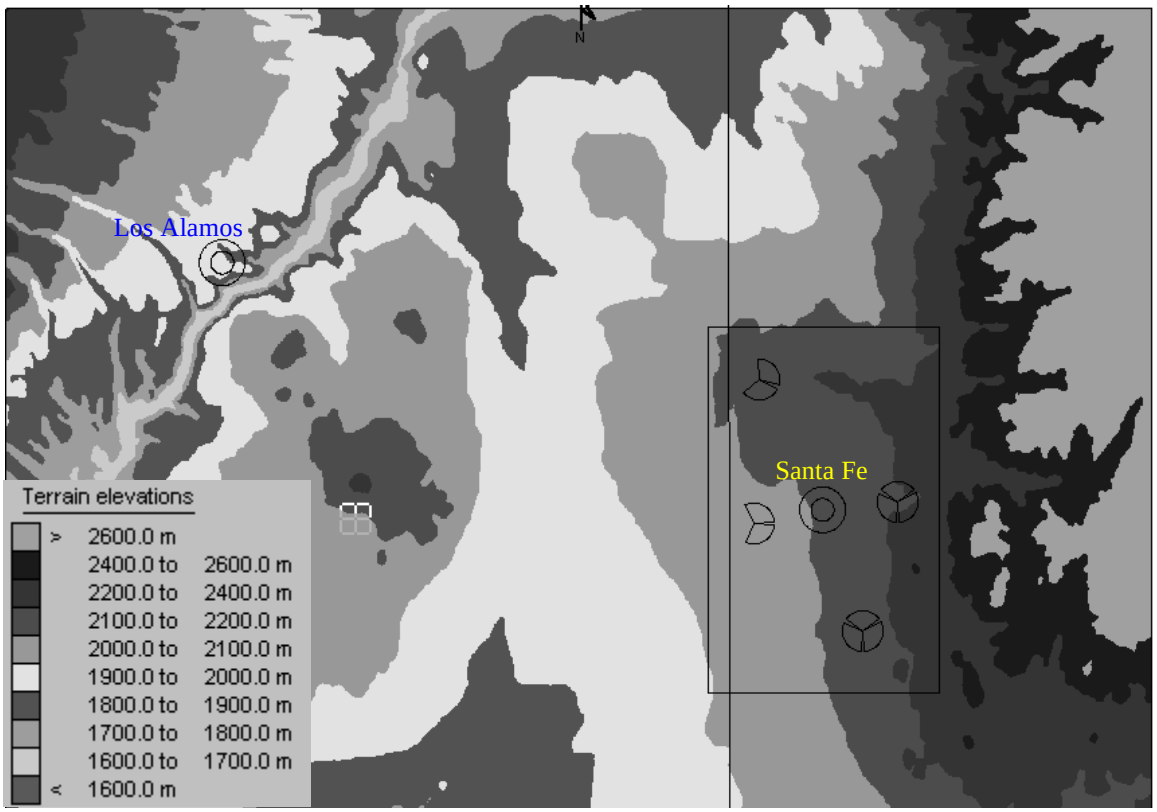


Figure 13. Terrain variation near Los Alamos site

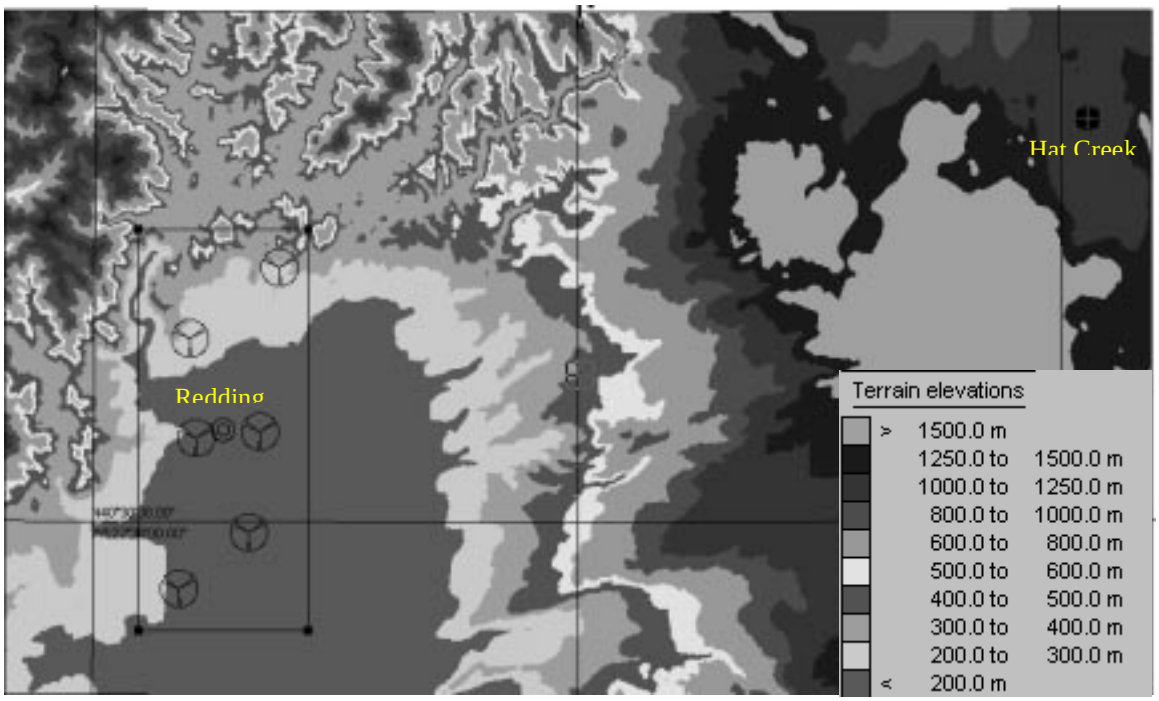


Figure 14. Terrain variation near Hat Creek site

As it can be seen from the terrain variation plots, Hat Creek and Los Alamos present two very different environments. While Hat Creek is more typical of the locations of the Radio Astronomy sites (surrounded by higher elevation terrain), The site at Los Alamos is uniquely challenging in the sense that the near-by city is located at a much higher elevation than the Radio Astronomy site. This is certainly not a typical case. Selection of these two sites almost covers the range of all actual Radio Astronomy locations and provides us a sample representative of all cases.

Table 4 summarizes the i-BURST base station parameters used in the analysis.

Parameter	Value	Unit
EIRP sector	54	dBm/MHz
BW	0.625	MHz
Downtilt	2	degrees
Sector Width	120	degrees

Table 4. i-BURST base station parameters

Three widely accepted propagation models were used; COST231-Hata, Longley-Rice, and Free Space + RMD (Reflection, Multiple-Diffraction). The latter two models take detailed account of the intervening terrain between transmitter and receiver sites. The Received Signal Level (RSL) from each base station sector at the location of the protected site was recorded and then the cumulative effect of all the stations was calculated. The results of this analysis are summarized in Table 5 and Figure 15. The analysis assumes that the protected site is in adjacent band to i-BURST stations and therefore enjoys the extra protection created by i-BURST filters' out-of-band suppression.

		Free Space + RMD	COST231-Hata	Longly-Rice	
Hat Creek, CA	Cumulative	-226.0786027	-194.2927419	-240.2739545	dBm/MHz
		-200.1745895	-168.3887288	-214.3699414	dBm/MHz-m2
	Average	-239.259236	-208.0948543	-253.4545879	dBm/channel
		-213.3552229	-182.1908412	-227.5505747	dBm/MHz-m2
Los Alamos, NM	Cumulative	-176.7165179	-172.0649438	-200.4667129	dBm/MHz
		-150.8125047	-146.1609307	-174.5626998	dBm/MHz-m2
	Average	-189.8971512	-185.8670563	-213.6473463	dBm/channel
		-163.9931381	-159.9630431	-187.7433331	dBm/MHz-m2

Table 5. Cumulative and average interference levels created by simulating an i-BURST network deployment near two radio Astronomy sites.

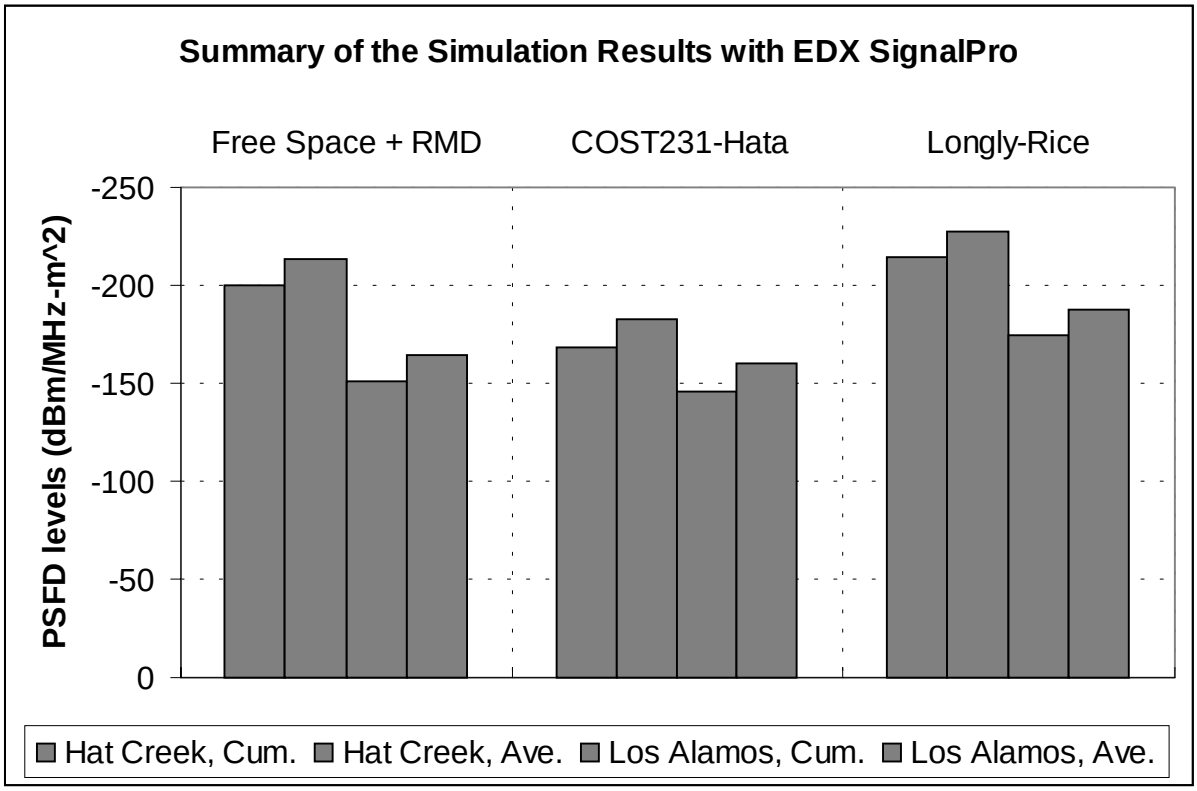


Figure 15. Summary of the simulation results with EDX SignalPro using three different propagation models.

Three general observations can be made from these results. First, the conservatism of the terrain-independent COST-231-Hata model employed in the other analyses is confirmed by the relatively larger losses calculated using the terrain-dependent Longley-Rice and Free Space + RMD models as demonstrated by Table 5. Actual separation distances required between i-BURST systems and protected systems should therefore be substantially less than those predicted in the earlier sections. Second, notwithstanding the first point, the terrain-independent analyses, in particular that of Section 4, do have useful predictive capability. A 120 km separation distance was predicted there as necessary to protect non-VLBI Radio Astronomy sites. In the Hat Creek case considered in the current section, the 120 km separation distance was in fact (much more than) adequate to

provide the requisite protection at the 80 km distance between Redding and Hat Creek and taking full account of intervening terrain. Finally, we note that the Los Alamos site is part of the VLBI, and hence that the interference calculated in this section from a nearby i-BURST deployment is many orders of magnitude below the corresponding interference threshold.

6. Conclusion

Several types of analyses were done so that the problem could be looked at from various angles; deterministic point-to-point calculations, probabilistic formulations, and simulation using a propagation tool. The results of all the analyses collectively agree that with Radiosondes moving out of the 1670-1675 MHz band, coexistence with all incumbents can be readily achieved with modest losses in coverage area. In special cases where the operational distances are extremely short or interference requirements are extremely stringent, i-BURST possesses additional flexibility to meet coexistence requirements through special measures such as guard-bands, re-orientation of the base station antennas, better filters, etc.