UNITED STATES DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Washington, D.C. 20230

JUL 22 2013

Mr. Julius P. Knapp
Chief, Office of Engineering and Technology
Federal Communications Commission
445 12th Street, SW
Washington, DC 20554

Dear Mr. Knapp:

The National Telecommunications and Information Administration (NTIA) greatly appreciates that the Federal Communications Commission (FCC) will soon commence a rulemaking proceeding to address the proposed repurposing of the 1695-1710 MHz and 1755-1850 MHz bands, among others, for Advanced Wireless Services (AWS-3). As you know, for more than a year, NTIA and the federal agencies that use spectrum in these bands have been collaborating with FCC staff and industry stakeholders, through NTIA's Commerce Spectrum Management Advisory Committee (CSMAC) in an effort to make the entire 1755-1850 MHz band available for commercial broadband use while protecting the vital federal systems and missions that rely on that band. As the CSMAC process begins to wrap up, it is becoming apparent that a combination of relocation and sharing approaches are going to be required to enable commercial access and assure such protection, especially in the 1755-1780 MHz portion of the 1755-1850 MHz band.

In anticipation of some of the CSMAC's likely recommendations and the FCC's forthcoming rulemaking, enclosed please find recent correspondence to NTIA from the Chief Information Officer of the Department of Defense (DoD) that outlines a proposal for making 1755-1780 MHz available for auction and licensing in the near-term, while protecting critical DoD capabilities and preserving the necessary flexibility to address the long-term status of the 1780-1850 MHz portion of the band. It also would, according to DoD, reduce estimated costs and eliminate the need to displace any non-federal incumbents. NTIA has only recently received this proposal and is not in a position to endorse it at this time, but is very encouraged by the ongoing commitment of DoD to finding a viable path forward with respect to this valuable spectrum. Accordingly, in the interest of obtaining input from all interested stakeholders on this proposal, NTIA respectfully requests that the FCC include this correspondence in the record and seek public comment on it as part of the AWS-3 rulemaking.[1]

Also enclosed, please find a Feasibility Assessment for accommodation of mobile broadband Long Term Evolution (LTE) systems in the 2025-2110 MHz band prepared by the National Aeronautics and Space Administration (NASA) and recently submitted by the United

[1] DoD has requested that NTIA not forward at this time for inclusion in the public record the two enclosures referenced in the DoD letter inasmuch as they have not been approved for public release. They will, however, be provided to FCC staff and submitted into the record after such approval is received.

States to International Telecommunication Union-Radiocommunication Sector Joint Task Group 4-5-6-7. Recognizing the interest in the potential for use of the band for wireless broadband, NASA performed a compatibility study examining the potential for commercial broadband systems employing LTE technology on a shared basis with forward link transmissions from NASA's geostationary Tracking and Data Relay Satellite System (TDRSS) satellites to some typical satellite users, which are in Low Earth Orbit. The results of the study show that high-density terrestrial base stations or user equipment operating co-frequency in the 2025-2110 MHz band will exceed established protection criteria for the TDRSS spaceborne receivers by an average of 16.4 dB to 40.7 dB. Analysis of sharing with satellite systems of other administrations will likely show similar results. Accordingly, NTIA likewise requests that the FCC include this assessment in the record of the AWS-3 rulemaking and seek comment on it.

NTIA looks forward to participating in the FCC's rulemaking and our further collaborative efforts to maintain federal capabilities, minimize costs and promote efficient resource allocation. If you have any questions, please contact me or Edward Davison from my staff (edavison@ntia.doc.gov and 202-482-5526).

Sincerely,

Karl B. Nebbia
Associate Administrator
Office of Spectrum Management

Enclosures (2)

DEPARTMENT OF DEFENSE
6000 DEFENSE PENTAGON
WASHINGTON, D.C. 20301-6000

Enclosure 1

CHIEF INFORMATION OFFICER

JUL 17 2013

The Honorable Lawrence E. Strickling
Assistant Secretary for Communications and Information
National Telecommunications and Information Administration
United States Department of Commerce
1401 Constitution Avenue, NW
Washington DC, 20230

Dear Mr. Strickling,

The Department of Defense (DoD) proposes an alternative solution based upon shared access to the 2025 – 2110 MHz band to make the 1755 – 1780 MHz band available for auction in the near-term, while protecting critical capabilities. This solution has been developed after considering the myriad of technical, statutory, and other factors involved. This includes results of the 2012 National Telecommunications and Information Administration (NTIA) 1755 – 1850 MHz Feasibility Assessment, the Commerce Spectrum Management Advisory Committee (CSMAC) working groups, DoD/Industry Spectrum Monitoring, internal compression studies, and requirements of the Commercial Spectrum Enhancement Act and Fiscal Year 2000 National Defense Authorization Act.

The Department believes this alternative proposal constitutes a workable balance to provide access to the 1755-1780 MHz band most desired by the commercial wireless industry while ensuring no loss of critical DoD capabilities and preserving the necessary flexibility to address the long-term status of the 1780-1850 MHz band. Further, the significantly reduced estimated costs will be a key factor to enabling a successful auction that can generate the required 110% of estimated federal relocation and sharing costs. Key provisions of the alternative proposal are provided below and explained in more depth in the attached slides:

1. DoD retains access to the 1780-1850 MHz band
2. DoD is provided shared access to 2025 – 2110 MHz band, removing the need to relocate broadcasters
3. DoD is not provided access to 5150 – 5250 MHz for telemetry, leaving the band available for Wi-Fi consideration
4. DoD will modify selected systems to operate at both 1780 – 1850 MHz & 2025 – 2110 MHz. These include Small Unmanned Aerial Systems, Tactical Targeting Network Technology, Tactical Radio Relay, and High Resolution Video systems
5. DoD will modify selected systems to operate in other existing Federal bands as identified: Precision Guided Munitions to 1435 - 1525 MHz, Point-to-Point Microwave Links to 7125 – 8500 MHz, and DoD Video Surveillance/Robotics to 4400 – 4940 MHz
6. DoD systems will share spectrum with commercial users in the 1755-1780 MHz band as follows: Satellite Operations (SATOPS), Electronic Warfare (EW), Air Combat Training System (ACTS) (where required), and Joint Tactical Radio System (JTRS) at 6 sites.
7. DoD will compress remaining operations into 1780 – 1850 MHz
8. Estimate of DoD costs is * $3.5B for 25 MHz

* $3.5B includes $272M implementation cost, $400M for Unmanned Aerial Systems growth, and $100M to compress Airborne Mobile Telemetry, ACTS, JTRS and share SATOPS/EW

Even though the above proposal addresses only those systems that might be required to relocate from the 1755-1850 MHz band based on the CSMAC process, the intent is that future DoD systems would also be allowed access to the 2025-2110 MHz band in accordance with Government footnote G xxx as described in Annex 1.

The Department believes the actions we are proposing are entirely consistent with the President's June 14, 2013 Executive Memorandum on expanding U.S. leadership in wireless innovation and recent Congressional direction to expedite availability of spectrum, specifically the 1755-1780 MHz band, to support commercial broadband operations. In order to implement this alternative, it will require actions on the part of DoD, NTIA and the Federal Communications Commission to ensure the 1755-1780 MHz band is available for wireless services.

Please feel free to contact me directly if I can be of further assistance in this matter. I look forward to further discussions on this important issue.

Sincerely,

Teresa M. Takai

Enclosures:
As stated

cc:
Deputy Chief Technology Officer, Telecommunications, OSTP
Senior Director for Defense Policy, National Security Staff

Radiocommunication Study Groups

International Telecommunication Union

Received: 12 July 2013

Subject: WRC-15 agenda items 1.1

Document 4-5-6-7/170-E
16 July 2013
English only

United States of America

FEASIBILITY ASSESSMENT FOR ACCOMODATION OF MOBILE BROADBAND LONG TERM EVOLUTION (LTE) SYSTEMS IN THE 2 025-2 110 MHz BAND

1 Introduction

WRC-15 agenda item 1.1 calls for conducting sharing and compatibility studies with services already having allocations in candidate bands for potential accommodation of International Mobile Telecommunication (IMT) systems. The band 2 025-2 110 MHz has been identified by Working Party 5D as a suitable frequency range for accommodation of IMT systems (Document JTG 4-5-6-7/46).

Incumbent primary services in the band 2 025-2 110 MHz include Space Operation (earth-to-space and space-space), Earth Exploration-Satellite (earth-to-space and space-space), Fixed, Mobile, and Space Research (earth-to-space and space-to-space). The allocation to the mobile service in this band is under the limitation of RR **No. 5.391:**

5.391 *In making assignments to the mobile service in the bands 2 025-2 110 MHz and 2 200-2 290 MHz, administrations shall not introduce high-density mobile systems, as described in Recommendation ITU-R SA.1154, and shall take that Recommendation into account for the introduction of any other type of mobile system. (WRC-97)*

This study considers the feasibility the Long Term Evolution (LTE) type of IMT systems sharing the 2 025-2 110 MHz band with incumbent primary services of the Space Operation, Earth Exploration-Satellite and Space Research services in the space-to-space direction. In particular, this study examines the sharing potential of commercial broadband systems with forward link transmissions from NASA geostationary Tracking and Data Relay Satellite System (TDRSS) satellites in the band 2 025-2 110 MHz to some typical satellite users, which are in Low Earth Orbit (LEO). These are typical of the many forward link systems of various Data Relay Satellite (DRS) satellites and user spacecraft. The protection of DRS forward links is critical to U.S. and other administrations' Earth science and space exploration programs as well as cooperative programs involving space agencies from around the world and authorized non-governmental user satellite operators.

This report does not include analysis of LTE sharing with other incumbent services and systems in the 2 025-2 110 MHz band, such as proximity links with the International Space Station, satellite earth-to-space links, and launch vehicles telecommand or other low-density mobile systems. As a result of the findings of this sharing analysis, namely that sharing between commercial broadband systems and data relay satellite (DRS) systems space-to-space links precludes the accommodation of LTE systems, it is considered unnecessary to study other incumbent services in the band 2 025-2 110 MHz.

An overview of the technical parameters used for this study is presented in section 3. Detailed technical characteristics, including calculation steps and analysis procedures, are presented in Appendix 1-4. The technical parameters for LTE systems in section 3 and the Appendices of this study are consistent with the agreed upon characteristics provided to WP 5D by 3GPP in Attachment 4.16 to Doc. 5D/300, the Working Document Towards a Preliminary Draft New Report ITU-R M. [IMT. ADV. PARAM]. Where certain LTE system parameters were not yet agreed by WP5D, the study utilized parameters developed by a joint U.S. government advisory committee, which included participation by wireless industry representatives, as well as other federal and non-federal spectrum users, to provide advice on a broad range of spectrum policy including expediting the introduction of wireless broadband services in the United States.

As indicated in the JTG work plan contained in Annex 1 of Document 4-5-6-7/113, the third meeting of the JTG 4-5-6-7 is intended to look at initial sharing and compatibility studies on potential candidate frequency bands with a goal of finalizing studies by the fourth meeting of the JTG 4-5-6-7. To facilitate the work of the JTG in finalizing studies during its next meeting, this initial sharing study is presented using the best available agreed upon information on LTE systems. When an updated set of LTE parameters is available from Working Party 5D, the United States will update the analysis presented in this document with any updated technical parameters.

2 Background

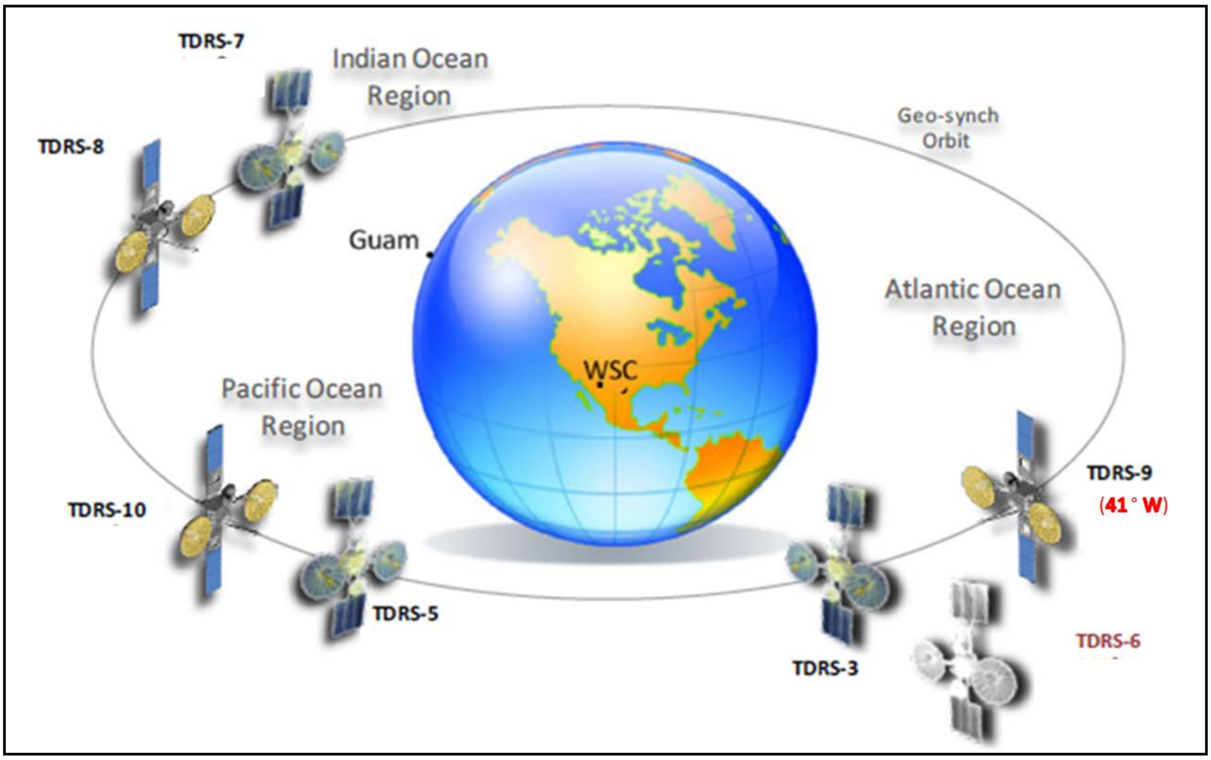
This section provides background on the systems and parameters that were used for the sharing analysis between commercial broadband systems and DRS forward links in the band 2 025-2 110 MHz.

2.1 TDRSS

The Tracking Data and Relay Satellite System (TDRSS) comprises six on-orbit Tracking and Data Relay Satellites (TDRS) located in geosynchronous orbit. Multiple additional TDRSs are available as backups for operational support at any given time. The TDRSS is a relay system which provides continuous, highly reliable, worldwide tracking and data relay services between low earth orbiting spacecraft and earth stations that are interconnected with command centres and data processing facilities. Figure 1 presents an overview of the TDRSS constellation operating at locations around the world. Several other DRS satellites not shown in Figure 1 are operated by other administrations.

FIGURE 1

Overview of the TDRSS constellation

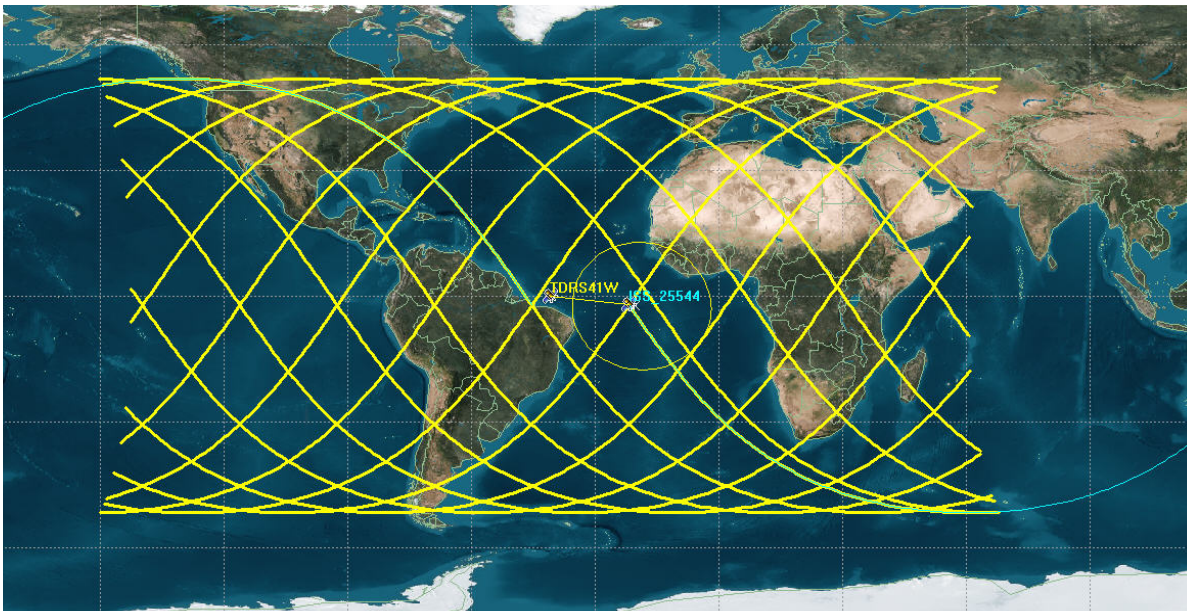


The geostationary location of TDRSS provides capability for satellites in lower orbits to have seamless communications with their control centre. This is a critical requirement for space science missions and space exploration programs as telecommand from the control centre can be transmitted via TDRSS in real-time to low earth orbiting satellites observing the Earth.

The sharing study presented in this document focuses exclusively on the forward links from the TDRS located at 41° West longitude to a few of NASA's satellites in Low Earth Orbit (LEO) as a typical data relay operation. These forward links are critical because it is used for command and control of LEO satellites that collect data for weather prediction and science research. For example, the International Space Station (ISS) forward link must be available for uninterrupted communication because it is used exclusively by astronauts for communications with Earth stations and command centres. As can be seen in Figure 2, the orbit of the ISS, while in communication with the TDRS at 41°West, places it above a variety of locations around the Earth which is typical of many of the satellites considered in this analysis.

FIGURE 2

Overview of ISS ground track over a 24 hour period



This study focuses on one orbital location of the TDRS; however similar results would be obtained for other TDRS orbital locations because each TDRS has similar parameters. Further, other DRSs operated by China (CTDRS), ESA (ARTEMIS), Japan (DRTS), and Russia (CSDRN-M/ VSSRD-2M/ WSDRN-M) have notified frequency assignments across the 2 025-2 110 MHz band. These DRS systems can also be expected to have similar results as those presented for TDRS 41° West because their forward links have characteristics similar to those of TDRS, as can be seen in Rec. ITU-R SA.1414. Recommendation ITU-R SA.1275 specifies orbital locations for DRS systems in the 2 200-2 290 MHz band. Recommends 1 from ITU-R SA.1275 states: "that receivers on-board DRS that operate in the 2 200-2 290 MHz band which should be protected in accordance with Recommendation ITU-R F.1247 are located in the following geostationary orbital positions (given in the East direction): 10.6°, 16.4°, 16.8°, 21.5°, 47°, 59°, 77°, 80°, 85°, 89°, 90.75°, 95°, 113°, 121°, 133°, 160°, 171°, 176.8°, 177.5°, 186°, 189°, 190°, 200°, 221°, 281°, 298°, 311°, 314°, 316°, 319°, 328°, 344°, 348°." (Note that 319°E = 41°W). These DRS locations are the same for the 2 025-2 110 MHz band since it is a companion band to the 2 200-2 290 MHz band.

2.1.1 TDRSS protection criteria and applicable ITU-R Recommendations

The protection criteria used in the analysis considered in this document, as specified in Recommendation ITU-R SA.1154, is an aggregate interfering signal power density from mobile systems in the band 2 025-2 110 MHz of -184 dB (W/kHz) at the DRS receiving antenna port, not to be exceeded for more than 0.1% of the time. Applicable recommendations listing orbital locations and characteristics of data relay satellites include:

- ITU-R SA.1414 - Characteristics of data relay satellite systems;
- ITU-R SA.1275 - Orbital locations of data relay satellites to be protected from the emissions of fixed service systems operating in the band 2 200-2 290 MHz and hence the 2 110-2 025 MHz since it is a companion band to the 2 200-2 290 MHz band;
- ITU-R SA.1155 - Protection criteria related to the operation of data relay satellite systems .

2.2 Commercial broadband LTE systems

The wireless broadband technologies systems at 2 025-2 110 MHz were assumed to implement Long Term Evolution (LTE) technology with parameters that were provided by U.S. industry for use in U.S. frequency sharing studies in the 1 695-1 710 MHz and 1 755-1 850 MHz bands. These parameters were used in this analysis without any frequency-scaling adjustments that may be appropriate for LTE operation at 2 025-2 110 MHz (e.g., increases in LTE transmitter power or reductions in cell coverage areas). Although this analysis assumes wireless broadband characteristics based on the LTE technology standard, the results would also apply to other types of wireless broadband technology with similar characteristics. It should be noted that these are preliminary parameters and this study may be updated with additional parameters produced by Working Party 5D, as appropriate.

3 Technical characteristics

This section provides the technical characteristics of the space-to-space forward links and the commercial broadband systems that were used for this sharing study. Section 3.1 provides the technical characteristics of the space-to-space links from the TDRS located at 41° West to some of NASA typical user satellites. Section 3.2 provides the technical characteristics for the commercial mobile broadband base stations and user equipment (UE) terminals. Additional technical characteristics used for this sharing analysis can be found in the Appendices.

3.1 Space-to-space forward links

The forward links considered in this analysis is from TDRS 41° West to the systems listed in Table 1. When calculating the interference into the forward links, it was assumed that:

- The receiver technical characteristics listed in Table 1;
- The receiver antenna pattern used is Recommendation ITU-R S.672 (first sidelobe is 25 dB down from the peak);
- The polarization discrimination is 3 dB on and off-axis (Circular polarized forward links vs. LTE linear polarization);
- The ITU-R recommended threshold is threshold for Interference from Mobile System Transmitters: Io = -184 dBW/kHz to be exceeded no more than 0.1% of the time per Recommendation ITU-R SA.1154, recommends 1.2.

TABLE 1

TDRS user satellite teceiver technical characteristics

Receiver	Altitude (km)	Inclination (degrees)	Eccentricity	Min. Frequency (MHz)	Max. Frequency (MHz)	Antenna Gain (dBi)	System Noise Temp. (K)
AURA	705	98.2	0.000	2103.33	2109.49	7.0	240
CONNECT - HGA	400	51.6	0.000	2103.33	2109.49	12.0	600
Cygnus	460	51.6	0.000	2037.49	2043.65	1.6	1849
GPM	407	65.0	0.000	2103.33	2109.49	23.0	226
ISS - HGA	400	51.6	0.000	2082.61	2088.77	12.9	588
ISS - LGA	400	51.6	0.000	2082.61	2088.77	1.1	479
SWIFT	600	22.0	0.000	2103.33	2109.49	3.5	139
TERRA	705	98.2	0.000	2103.33	2109.49	25.8	410
TRMM - HGA	403	35.0	0.001	2073.86	2080.02	23.0	513
WISE	500	97.3	0.000	2067.41	2073.57	6.0	437

3.2 Commercial broadband LTE ;parameters

As discussed in section 2.2, the U.S. LTE industry provided technical parameters for commercial broadband LTE systems for use in sharing studies made within the United States. The technical parameters used in this analysis were varied to test a range of assumptions. The assumptions regarding base station resource loading, power distributions, and clutter and other propagation losses, were varied as to encompass a range of assumptions that are associated with worst-case and best-case frequency sharing scenarios. Section 3.2.1 provides an overview of technical characteristics for LTE base stations and section 3.2.2 provides an overview of technical characteristics for LTE user equipment (UE). Further, more detailed parameters such as aggregate base station and user equipment e.i.r.p. calculation methods, deployment models, antenna patterns, and a listing of cities used in this analysis can be found in the appendices.

3.2.1 Overview of LTE base station technical parameters

The LTE base station technical parameters are presented in Table 2 and an overview of the deployment model is presented in Table 3, Figure 3 and Figure 4. The transmit power values shown in Table 2 are levels emanating from LTE ground transmissions. Note that two antenna patterns were used for the base stations in this analysis, an ITU-R generic antenna pattern given by Recommendation ITU-R F. 1336-3, and a real Andrew antenna pattern (see Appendix 1).

TABLE 2

LTE base station technical characteristics

LTE base station parameter	Parameter
Antenna Pattern	Sector antenna (Rec. ITU-R F.1336-3 Recommends 3.5, see Appendix 1 for Andrew antenna pattern)
Sector antenna pointing azimuth	120° spacing on the same tower; randomly oriented among towers (relative to true north)
Sector antenna pointing elevation	3° down tilt for each sector antenna
Sector antenna height	10 meters (AGL)
Sector antenna gain	17 dBi (Andrew antenna) / 18 dBi (ITU-R antenna)
Sector transmit power (Andrew antenna)	Peak power of 40W/10MHz[1] with 50% and 10% time resource loading
Sector transmit power (Rec. ITU-R F.1336-3 antenna)	Peak power of 40W/10 MHz with 100%, 50%, 10% time resource loading
Net Power per city with population > 250k	78.6 dBm (see Appendix 2)
Net Power per city with population < 250k	74.0 dBm (see Appendix 2)
LTE channel bandwidth	10 MHz
Elevation mask for Andrew antenna cases	Three cases: hypothetical complete clutter blockage of signals on paths having elevation angles below 0°, 20°, 45°
Elevation mask for Rec. ITU-R F.1336-3	For elevation angles of 5˚ and below, hypothetical clutter attenuation increases 2 dB per decreasing degree to a maximum of 16 dB at -3˚

[1] Report ITU-R M.2039-2, “Characteristics of terrestrial IMT-2000 systems for frequency sharing/interference analyses,” shows 46 dBm (40 Watt) maximum output power for several types of base stations that operate with 10 MHz overall signal bandwidths. In the analyses herein, the base station transmitter output power is varied in proportion to the assumed base station loading. Output power levels as low as 4 Watts were assumed (10% loading).

TABLE 3

LTE base station deployment model

Deployment scenario	Value
Analysis city deployment	349 world cities including 249 cities in the USA with a population greater than 100,000 and the largest cities worldwide outside the USA with a population greater than 250,000 visible to TDRS orbital position at 41° West
LTE Base Station deployment for larger cities with populations >= 250,000 (1201 cells total)	• Urban/suburban zone extends out 30 km from city centre and contains 1075 cells (1.732 km ISD) • Rural zone extends from 30-50 km from city centre and contains 126 cells (7 km ISD)
LTE Base Station deployment for smaller cities with population < 250,000 (420 cells total)	• Urban zone extends out 10 km from city centre and contains 154 cells (1.5 km ISD) • Suburban zone extends 10-30 km from city centre and contains 140 cells (4.6 km ISD) • Rural zone extends from 30-50 km from city centre and contains 126 cells (7 km ISD)

FIGURE 3

LTE base station deployment in larger cities (Population >= 250,000)

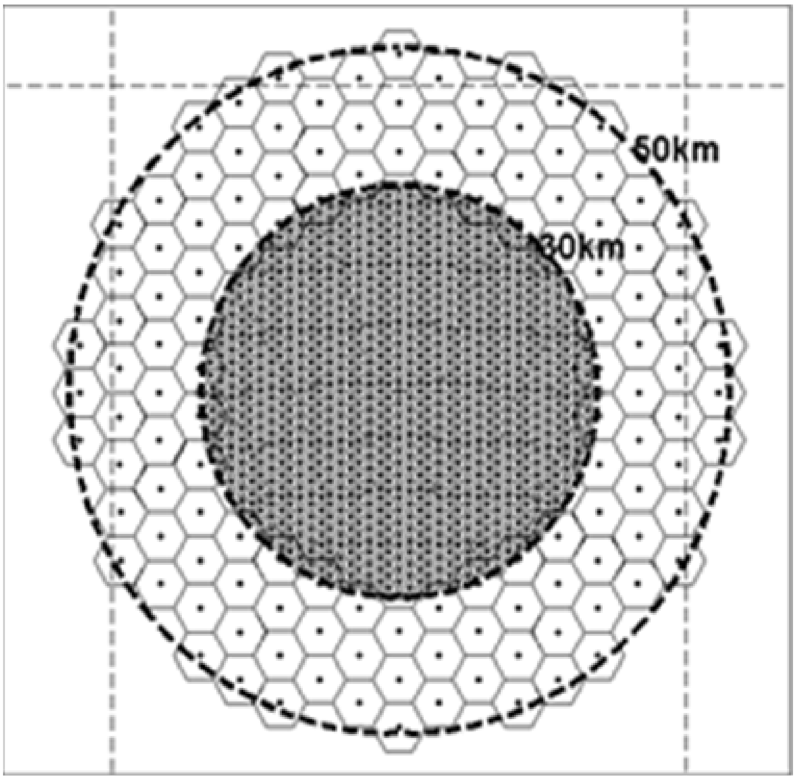
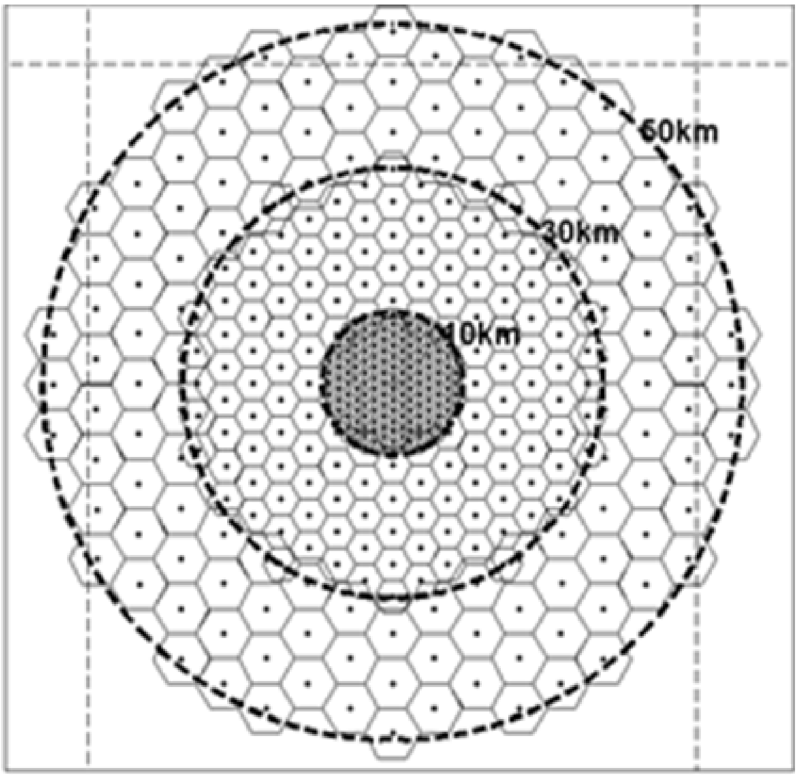


FIGURE 4

LTE base station deployment in smaller cities (Population < 250,000)



3.2.2 Overview of LTE user equipment (UE) technical parameters

The UE technical characteristics are presented in Table 4. Please refer to Appendix 3 for the derivations of the aggregate total e.i.r.p. for cities. The aggregate, per-city e.i.r.p. level is the total e.i.r.p. from all UE located in the city (Figure 3 or 4) which is assumed to be emanating from the center of the city, as further explained in Section 4 and Appendix 3.

TABLE 4

LTE user equipment technical characteristics

Technical characteristic	Value
Aggregate total UE e.i.r.p for cities with population < 250,000	-53.12 dBW/Hz
Average individual UE e.i.r.p for cities with population < 250,000	8.08 dBm/10 MHz
Aggregate total UE e.i.r.p. for cities with population >= 250,000	-50.78 dBW/Hz
Average individual UE e.i.r.p. for cities with population >= 250,000	5.87 dBm/10 MHz
Antenna Pattern	Omni Directional
Cellular Deployment Scenario	Same as LTE Base Stations presented in section 3.2.1

4 Analysis

This section presents the results of the sharing feasibility assessment conducted between the TDRSS forward links and commercial broadband LTE operations in the band 2 025-2 110 MHz. For this analysis, software was used to dynamically model the interference scenario. The TDRS 41° West location was selected as a representative DRS location. Interference from the LTE system was simulated using a cellular distribution around selected worldwide cities using technical parameters as discussed in Section 3.2. The analysis considered potential interference from base station to user equipments and user equipments to base station emissions. At each time sample, which was selected randomly, potential interference into the TDRS user is calculated from the aggregate of LTE interferers.

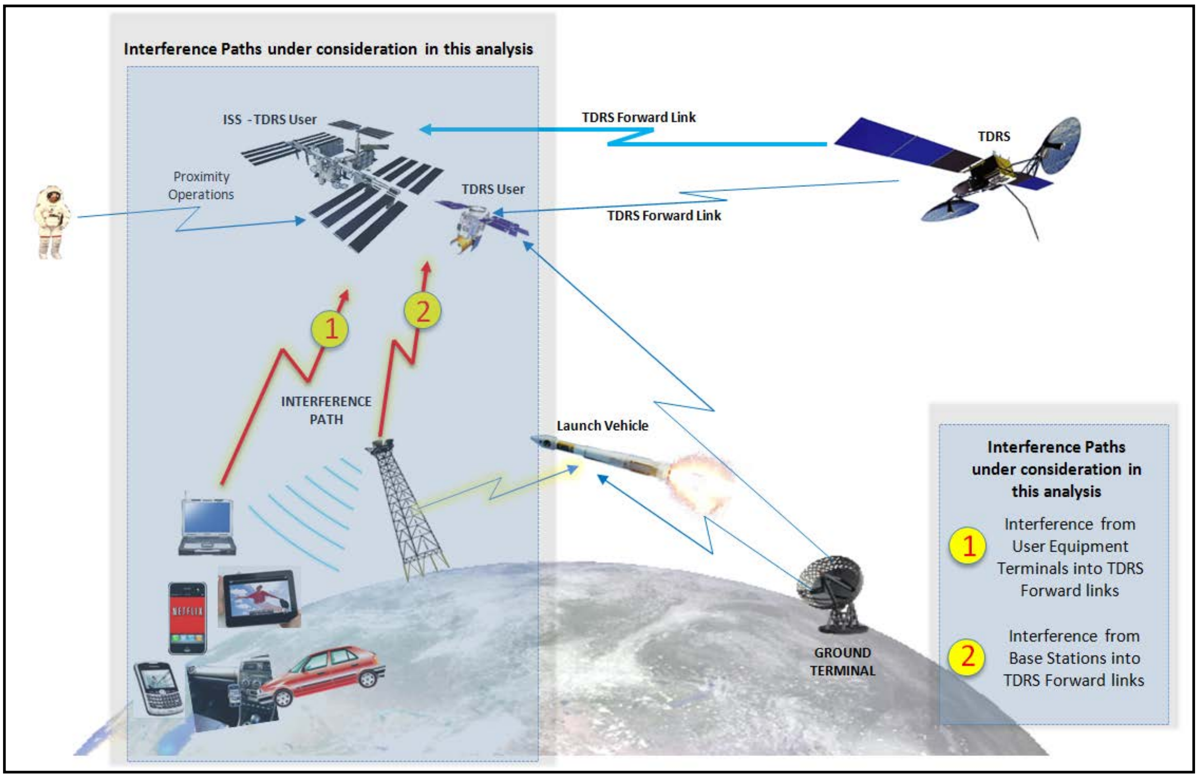
For the purposes of reduced computational complexity, the power from each base station or UE was aggregated at the centre of each city in the simulation. The method for calculating the aggregate per city power for base stations and UEs are presented in Appendix 2 and Appendix 3, respectively. A validation for the aggregation method is also presented in Appendix 3. The respective simulation for both base stations and UE interference was then run and the interference was recorded at each time step to produce the tables and curves in this section.

Figure 5 presents an overview of TDRSS operations and the potential for interference as studied in this analysis. The analysis presented in this document considers interference paths to the TDRSS forward links as shown in Figure 5.

Section 4.1 presents results of potential interference to TDRSS forward links from LTE Base Stations. Section 4.2 presents results of potential interference to TDRSS forward links from LTE user terminals.

FIGURE 5

Overview of interference analysis into TDRS system in the 2 025-2 110 MHz



The LTE deployment model considered in this analysis assumed no base stations more than 50 km from the centre of each city. In large metropolitan areas, it is likely that there will be deployments outside of the 50 km cut off considered in this analysis. The LTE base stations in this analysis assumed a peak power value of 40 W/10 MHz. However, the LTE base station standards contain no power limits. Some other assumptions favouring sharing were a base station sector down tilt angle of 3°, low base station resource loading, and blockage of interfering signal paths due to clutter. Lastly, the analysis considered LTE deployment in only 349 worldwide cities, whereas a full deployment of LTE systems will involve many more cities that will be in view of the TDRS antenna beam.

The analysis approach used herein can be generalized to consider other sharing scenarios. The cumulative probability distributions (CDFs) of aggregate interfering signal power levels presented below in this document (Figures 6-9) can in many cases be shifted upward or downward to estimate the effects of alternative assumptions that have not been addressed in this study. For example, the aggregate UE and base station e.i.r.p. per-city values are key intermediate results that encompass the effects of several assumed IMT equipment operating parameters. If alternate assumed IMT equipment parameters would shift the aggregate per-city EIRP levels by X dB, the resulting CDF curves for the corresponding baseline case would also shift by X dB. The effects of alternative assumptions regarding propagation losses, if applied as averages over all interfering signal paths, could be estimated in the same manner.

4.1 Potential interference from LTE base stations

Table 1 Table 5, Table 6, and Table 7 present the results of analysis considering the potential for sharing with LTE base stations. This analysis considered base station transmitters using the antenna pattern of Reccommendation ITU-R F.1336-3 or an Andrew antenna pattern for the base station sector antennas. In each case, several loading scenarios were modelled. Further, for the ITU-R recommended antenna pattern, a clutter factor was considered where clutter attenuation increases 2 dB per decreasing elevation degree to a maximum of 16 dB at -3˚. For the Andrew antenna pattern case, the clutter model assumed full signal blockage at elevation angles below 0°, 20°, and 45° between the base station and the TDRS user in order to consider hypothetical best- and worst-case scenarios (e.g. a 20° elevation mask means that only LTE base stations which “see” the TDRS user satellite above 20° contribute to the aggregate interference at a given time sample). From each table of results, one forward link was chosen - International Space Station High Gain Antenna (ISS-HGA) Forward Link - to show the Cumulative Density Function (CDF) curve (Figure 6, Figure 7, and Figure 8) which demonstrated even at high percentage of the time (approaching or exceeding 10%) the ITU Io/No threshold criterion will not be met for most cases.

TABLE 5

Potential interference from the base stations (ITU-R 1336 Antenna) into typical NASA TDRS forward links

Forward Links from TDRS 41° West into	Min. Frequency (MHz)	Max. Frequency (MHz)	Io/No (dB) at 0.1% of the time			System Noise Temp. (K)	Io/No ITU Threshold	ITU Threshold Exceedance (dB)		
			100% Load	50% Load	10% Load			100% Load	50% Load	10% Load
AURA	2103.33	2109.49	37.8	34.8	27.8	240.0	-9.2	47.0	44.0	37.0
CONNECT - HGA	2103.33	2109.49	41.0	38.0	31.0	600.0	-13.2	54.2	51.2	44.2
Cygnus	2037.49	2043.65	30.7	27.7	20.7	1849.0	-18.1	48.8	45.8	38.8
GPM	2103.33	2109.49	43.0	40.0	33.0	226.0	-8.9	51.9	48.9	41.9
ISS - HGA	2082.61	2088.77	41.4	38.4	31.4	588.0	-13.1	54.5	51.5	44.5
ISS - LGA	2082.61	2088.77	36.9	33.9	26.9	479.0	-12.2	49.1	46.1	39.1
SWIFT	2103.33	2109.49	36.9	33.9	26.9	139.0	-6.8	43.7	40.7	33.7
TERRA	2103.33	2109.49	38.5	35.5	28.5	410.0	-11.5	50.0	47.0	40.0
TRMM - HGA	2073.86	2080.02	47.0	44.0	37.0	513.0	-12.5	59.5	56.5	49.5
WISE	2067.41	2073.57	36.4	33.4	26.4	437.0	-11.8	48.2	45.2	38.2

FIGURE 6

Potential interference from the base stations (ITU-R 1336 Antenna) into ISS-HGA forward link

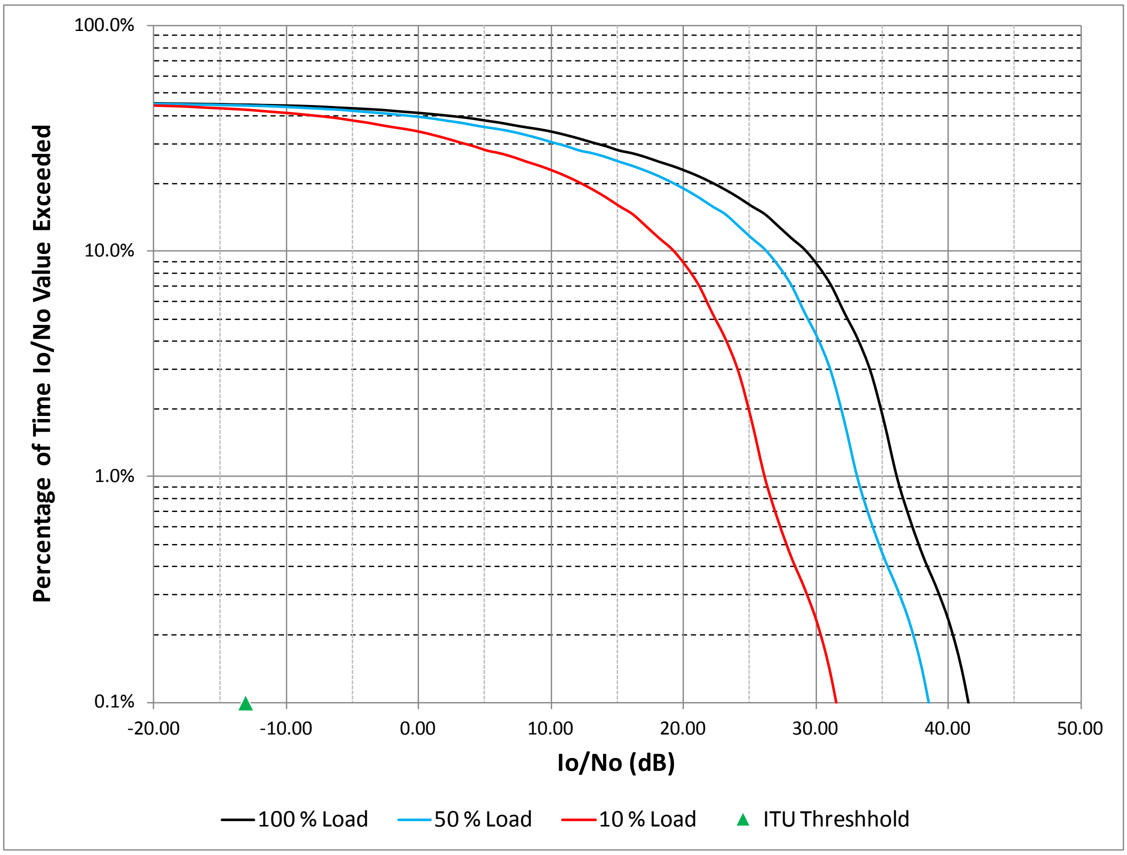


TABLE 6

Potential interference from the base stations (Andrew Antenna, 50% Load) into typical NASA TDRS forward links

Forward Links from TDRS 41° West into	Min. Frequency (MHz)	Max. Frequency (MHz)	Io/No (dB) at 0.1% of the time			System Noise Temp. (K)	Io/No ITU Threshold	ITU Threshold Exceedance (dB)		
			0° Elev. Mask	20° Elev. Mask	45° Elev. Mask			0° Elev. Mask	20° Elev. Mask	45° Elev. Mask
AURA	2103.33	2109.49	36.1	21.8	14.6	240.0	-9.2	45.3	31.0	23.8
CONNECT - HGA	2103.33	2109.49	39.6	19.8	12.8	600.0	-13.2	52.8	33.0	26.0
Cygnus	2037.49	2043.65	27.3	15.6	8.9	1849.0	-18.1	45.4	33.7	27.0
GPM	2103.33	2109.49	46.5	26.8	20.6	226.0	-8.9	55.4	35.7	29.5
ISS - HGA	2082.61	2088.77	40.2	20.3	13.6	588.0	-13.1	53.3	33.4	26.7
ISS - LGA	2082.61	2088.77	33.5	22.1	15.8	479.0	-12.2	45.7	34.3	28.0
SWIFT	2103.33	2109.49	35.7	18.1	11.3	139.0	-6.8	42.5	24.9	18.1
TERRA	2103.33	2109.49	42.2	21.9	16.0	410.0	-11.5	53.7	33.4	27.5
TRMM - HGA	2073.86	2080.02	50.6	23.0	18.4	513.0	-12.5	63.1	35.5	30.9
WISE	2067.41	2073.57	35.2	19.9	12.3	437.0	-11.8	47.0	31.7	24.1

FIGURE 7

Potential interference from the base stations (Andrew Antenna, 50% Load) into ISS-HGA forward link

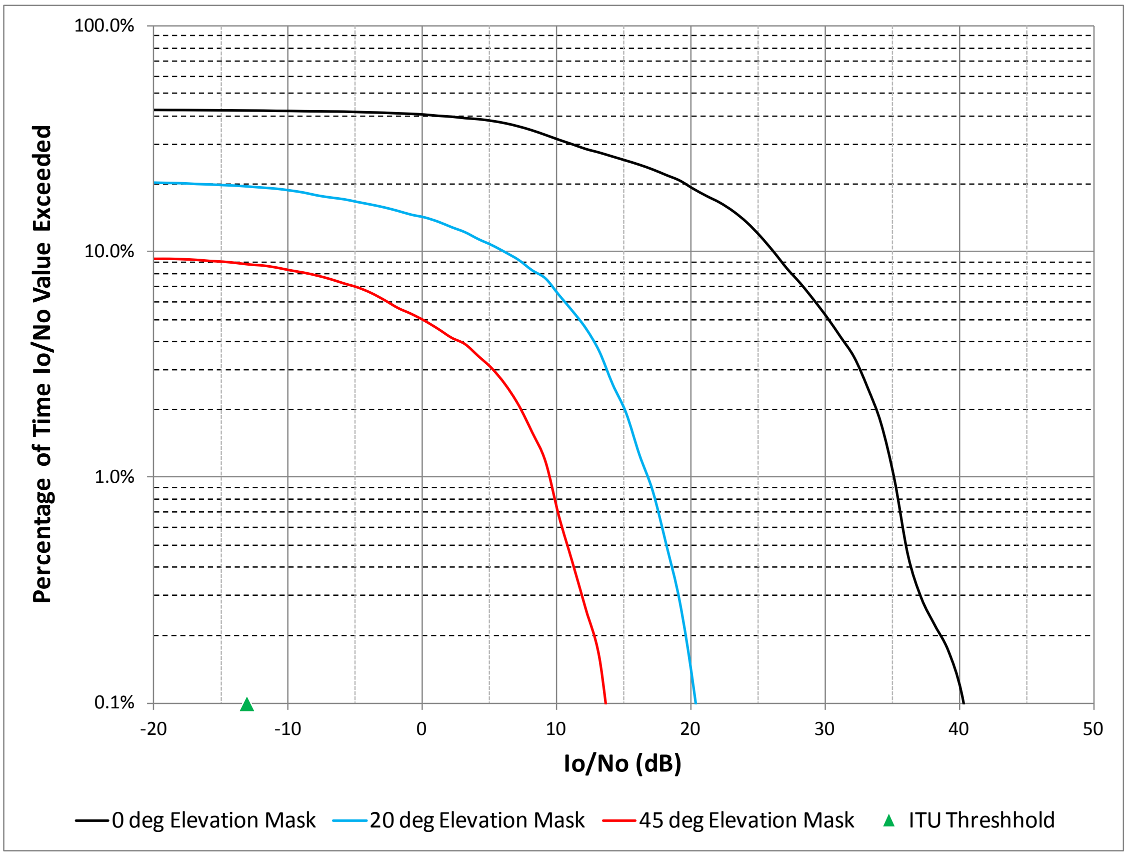


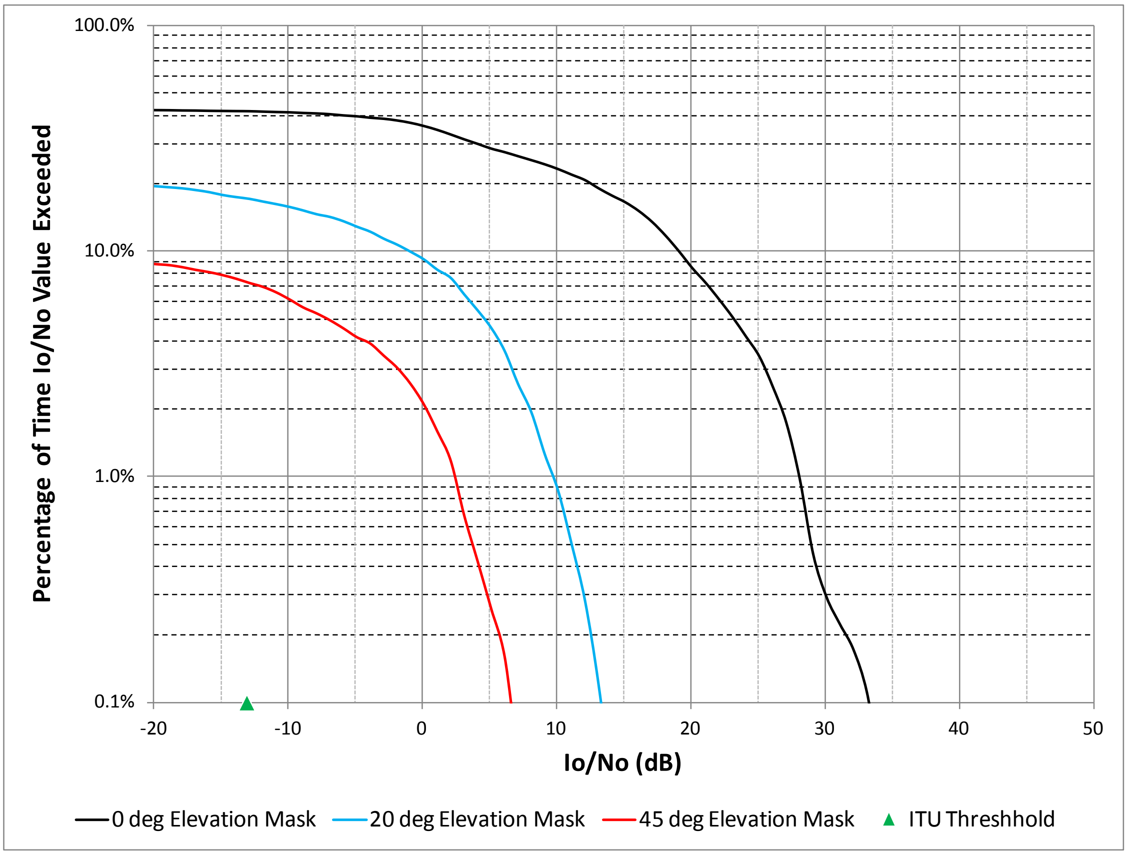
TABLE 7

Potential interference from the base stations (Andrew Antenna, 10% Load) into typical NASA TDRS forward links

Forward Links from TDRS 41° West into	Min. Frequency (MHz)	Max. Frequency (MHz)	Io/No (dB) at 0.1% of the time			System Noise Temp. (K)	Io/No ITU Threshold	ITU Threshold Exceedance (dB)		
			0° Elev. Mask	20° Elev. Mask	45° Elev. Mask			0° Elev. Mask	20° Elev. Mask	45° Elev. Mask
AURA	2103.33	2109.49	29.1	14.8	7.6	240.0	-9.2	38.3	24.0	16.8
CONNECT - HGA	2103.33	2109.49	32.6	12.8	5.8	600.0	-13.2	45.8	26.0	19.0
Cygnus	2037.49	2043.65	20.3	8.6	1.9	1849.0	-18.1	38.4	26.7	20.0
GPM	2103.33	2109.49	39.5	19.8	13.6	226.0	-8.9	48.4	28.7	22.5
ISS - HGA	2082.61	2088.77	33.2	13.3	6.6	588.0	-13.1	46.3	26.4	19.7
ISS - LGA	2082.61	2088.77	26.5	15.1	8.8	479.0	-12.2	38.7	27.3	21.0
SWIFT	2103.33	2109.49	28.7	11.1	4.3	139.0	-6.8	35.5	17.9	11.1
TERRA	2103.33	2109.49	35.2	14.9	9.0	410.0	-11.5	46.7	26.4	20.5
TRMM - HGA	2073.86	2080.02	43.6	16.0	11.4	513.0	-12.5	56.1	28.5	23.9
WISE	2067.41	2073.57	28.2	12.9	5.3	437.0	-11.8	40.0	24.7	17.1

FIGURE 8

Potential interference from the base stations (Andrew Antenna, 10% Load) into ISS-HGA forward link



4.2 Potential interference from LTE user equipment

Table 8 presents the results of analysis considering the potential of sharing LTE user equipment distributed over cities worldwide with TDRS 41° West forward link transmissions to some typical NASA TDRS users. For this case, a hypothetical clutter mask was analysed for angles below 0°, 20°, and 45° in relation to the TDRS users (e.g. a 20° elevation mask means that only LTE UE location which “see” the TDRS user satellite above 20° contribute to the aggregate interference at a given time sample). Again, one forward link was chosen (ISS-HGA) to show the Cumulative Density Function (CDF) curve (Figure 9).

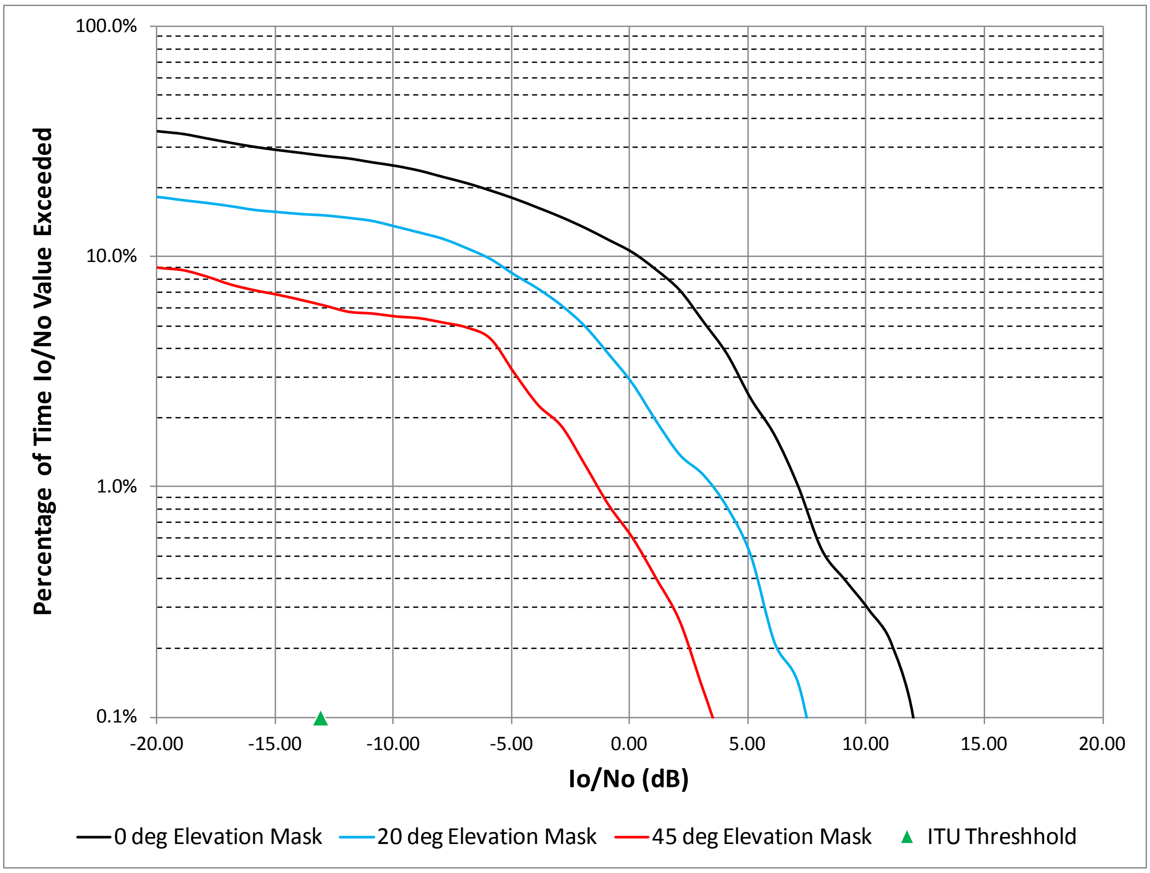
TABLE 8

Potential interference from the user equipment terminals into typical NASA TDRS forward links

Forward Links from TDRS 41° West into	Min. Frequency (MHz)	Max. Frequency (MHz)	Io/No (dB) at 0.1% of the time			System Noise Temp. (K)	Io/No ITU Threshold	ITU Threshold Exceedance (dB)		
			0° Elev. Mask	20° Elev. Mask	45° Elev. Mask			0° Elev. Mask	20° Elev. Mask	45° Elev. Mask
AURA	2103.33	2109.49	9.9	8.3	6.2	240.0	-9.2	19.1	17.5	15.4
CONNECT - HGA	2103.33	2109.49	11.1	6.5	2.4	600.0	-13.2	24.3	19.7	15.6
Cygnus	2037.49	2043.65	3.2	2.2	-0.6	1849.0	-18.1	21.3	20.3	17.5
GPM	2103.33	2109.49	15.0	13.6	11.3	226.0	-8.9	23.9	22.5	20.2
ISS - HGA	2082.61	2088.77	11.8	7.4	3.5	588.0	-13.1	24.9	20.5	16.6
ISS - LGA	2082.61	2088.77	9.9	9.0	6.0	479.0	-12.2	22.1	21.2	18.2
SWIFT	2103.33	2109.49	7.0	3.2	-1.2	139.0	-6.8	13.8	10.0	5.6
TERRA	2103.33	2109.49	9.9	9.0	7.0	410.0	-11.5	21.4	20.5	18.5
TRMM - HGA	2073.86	2080.02	17.8	11.0	10.1	513.0	-12.5	30.3	23.5	22.6
WISE	2067.41	2073.57	8.7	6.9	2.0	437.0	-11.8	20.5	18.7	13.8

FIGURE 9

Potential interference from the user equipment terminals into ISS-HGA forward link



5 Summary

This document presents study results on the feasibility of sharing with DRS (space-to-space) forward link operations between the TDRSS and typical NASA TDRS users the band 2 025-2 110 MHz. Interference scenarios were considered between the DRS forward link operations and a worldwide LTE deployment in 349 highly populated world cities (see Appendix 4 for a list of cities). LTE uplink and downlinks operations that were considered included either transmitting base station or transmitting user equipment, but not both simultaneously. The assumptions and parameters used in the analysis such as LTE deployment models, transmit power, clutter attenuation, and propagation conditions were varied in order to analyze the best- and worst-case scenarios. Although this analysis assumes wireless broadband characteristics based on the LTE technology standard, the results would also apply to other types of wireless broadband technology with similar characteristics.

The parameters used in the analysis were varied to test a range of assumptions. However, even with the wide range of parameters and very favourable sharing assumptions used for the analysis in this document, it can be seen that the amount of interference is so excessive that additional interference mitigations cannot sufficiently reduce interfering signal levels to enable sharing. In particular, interference from LTE base stations using an ITU-R recommended antenna pattern and assuming 10% loading and up to 16 dB of clutter attenuation, was found to exceed the interference threshold by an average of 40.7 dB. Potential interference from LTE base stations using an Andrew antenna pattern, only 10% loading, and full signal blockage within a 45° elevation mask, was found to exceed the interference criterion by an average of 19.2 dB. Potential interference from LTE user equipment with a full blockage elevation mask of 45° was found to exceed the interference criterion by an average of 16.4 dB. Table 9 below summarize analysis results.

Based on the results presented by the analysis in this document, it is found that interference mitigation techniques cannot sufficiently reduce interfering signal levels to enable sharing between LTE systems and incumbent services in the band 2 025-2 110 MHz. Further, any DRS system in the 2 025-2 110 MHz band, other than TDRSS, would be impacted in a manner similar to the TDRS located 41° West addressed in the analysis presented in this document.

TABLE 9

Analysis result summary

Analysis scenario	**Assumptions**	**Average Interference Exceedence (dB)**
Interference from LTE base stations using ITU-R recommended antenna pattern with up to 16 dB of clutter attenuation	100% loading	50.7
	50% loading	47.7
	10% loading	40.7
Interference from LTE base stations using Andrew antenna and 50% loading	0° elevation mask	50.4
	20° elevation mask	32.7
	45° elevation mask	26.2
Interference from LTE base stations using Andrew antenna and 10% loading	0° elevation mask	43.4
	20° elevation mask	25.7
	45° elevation mask	19.2
Interference from LTE user terminals	0° elevation mask	22.2
	20° elevation mask	19.4
	45° elevation mask	16.4

6 Recommendations

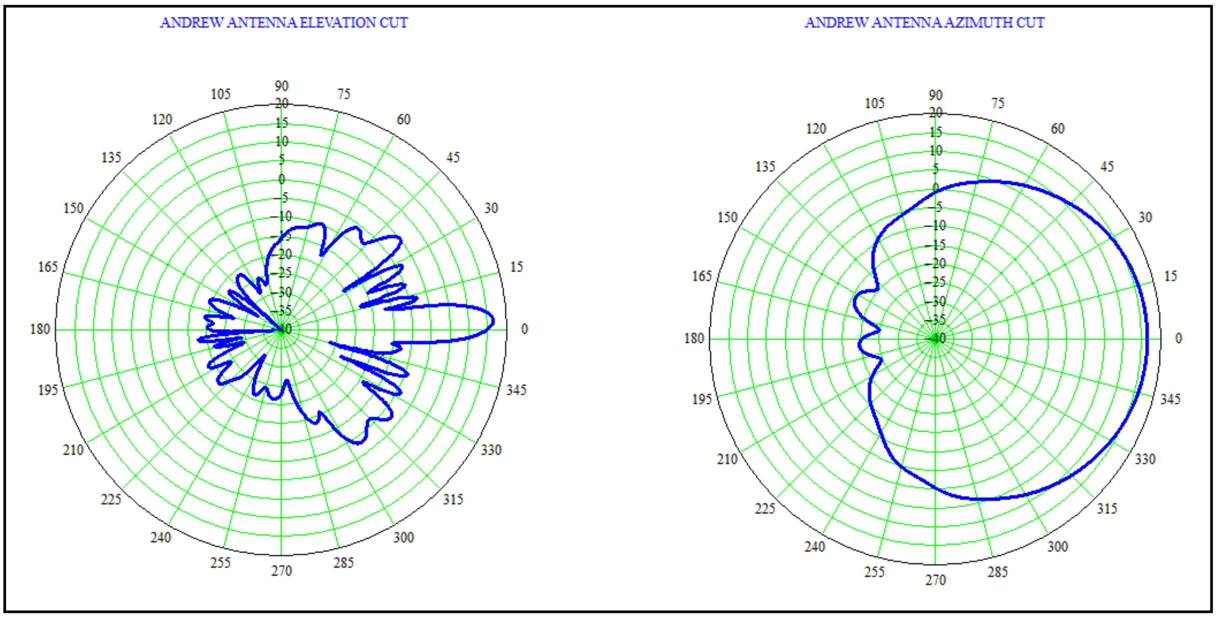
As can be seen from the analysis results, based on assumptions that will be refined and updated, it is found that sharing is not feasible between LTE systems and incumbent DRS forward links operating in the 2 025-2 110 MHz band in the Space Research (space-to-space), Earth Exploration-Satellite (space-to-space) and Space Operations (space-to-space) services. The United States recommends that the JTG 4-5-6-7 exclude the band 2 025-2 110 MHz from consideration as a candidate band under WRC-15 agenda item 1.1 at this time, and that JTG 4-5-6-7 revisit this matter after WP 5D provides updated IMT parameters. The United States also recommends that a Working Document towards a Preliminary Draft New Report ITU-R SA.[2 025 MHz] be developed based on this study.

APPENDIX 1

Antenna Patterns

FIGURE 1-1

ANDREW Antenna Pattern



Note: In this polar diagram the 90° angle is pointed toward the ground.

APPENDIX 2

Aggregate LTE Base Station Power for Cities

Method for calculating aggregate LTE base station power for worldwide cities

1 Large cities (population > 250,000) assumed to have 1075 urban/suburban + 126 rural = 1201 Cells

2 Small cities (population < 250,000) assumed to have 294 urban/suburban + 126 rural = 420 Cells

3 With 3 sectors per cell, 3x1201 = 3603 Base Station Transmitters for large cities and 3x420 = 1260 Base Station Transmitters for small cities

4 Estimate probability distribution of aggregate Base Station power per city by performing Monte Carlo simulations (100,000 trials)

5 For the i-th Monte Carlo trial perform the following steps

a) Generate N random samples of Base Station time-frequency loading according to truncated Gaussian probability Density Function (PDF) shown in Figures 2-1 and 2-2. (N=3603 for large city and N=1260 for small city)

b) Assume maximum Base Station transmit power of 40W and that Base Station transmit power is proportional to resource loading (e.g. alpha = 0.5 = 50% resource loading corresponds to 20W Base Station transmit power). Compute N samples of Base Station transmitter power from the N samples of resource loading (i.e. Power = % loading x 40W)

c) Sum up the N samples of power (in watts) to get the aggregate effective Base Station transmitter power and convert to dBm

d) The result is the aggregate Base Station transmitter power per city value (in dBm) for the i-th trial

6 After 100,000 trials we have a [100000 x 1] vector of aggregate power values from which we can calculate the minimum, maximum, mean, and standard deviation of the aggregate power distribution

7 the [minimum, maximum, mean standard deviation] of the aggregate power per city from the various cases are as follows

a) 1201 cells/3603 Base Station transmitters for large cities: [78.43; 78.71; 78.57; 0.03] dBm

b) 420 cells/1260 Base Station transmitters for small cities: [73.76; 74.23; 74.01; 0.06] dBm

8 Note that the standard deviations/variances of these aggregate power distributions are very small (<0.1 dBm). Therefore we use the mean values, which are 78.6 dBm for large cities and 74.0 dBm for small cities; these same numbers are arrived at if we assume all Base Station Transmitters are at 20W (i.e. 50% of maximum 40W) (i.e. 10xlog(20x3603) = 48.6 dBW = 78.6 dBm and 10xlog(20x1260) = 44 dBW = 74 dBm)

9 Assuming 10 MHz LTE channel bandwidth the corresponding power densities are -21.4 dBW/Hz and -26 dBW/Hz

10 Note that net power values above are the aggregate over all Base Station sectors in the city (with 3 sectors per Base Station). Therefore, the effective Base Station which is assumed to represent all these individual Base Stations is assumed to have these power values (sum of all 3 of its sectors). So for effective Base Station, the power for each of its 3 individual sectors is 10log(3) = 4.8 dB less than the values above (i.e. the power into each of the effective BS sectors is 73.8 dBm/-26.2 dBW/Hz (large city) and 69.2 dBm /-30.8 dBW/Hz (small city).

11 the Andrew and Rec. ITU-R 1336-3 sectoral antenna patterns are then applied to these power values to compute interference from the effective Base Station.

FIGURE 2-1

Assumed LTE base station resource block loading/transmit power distribution

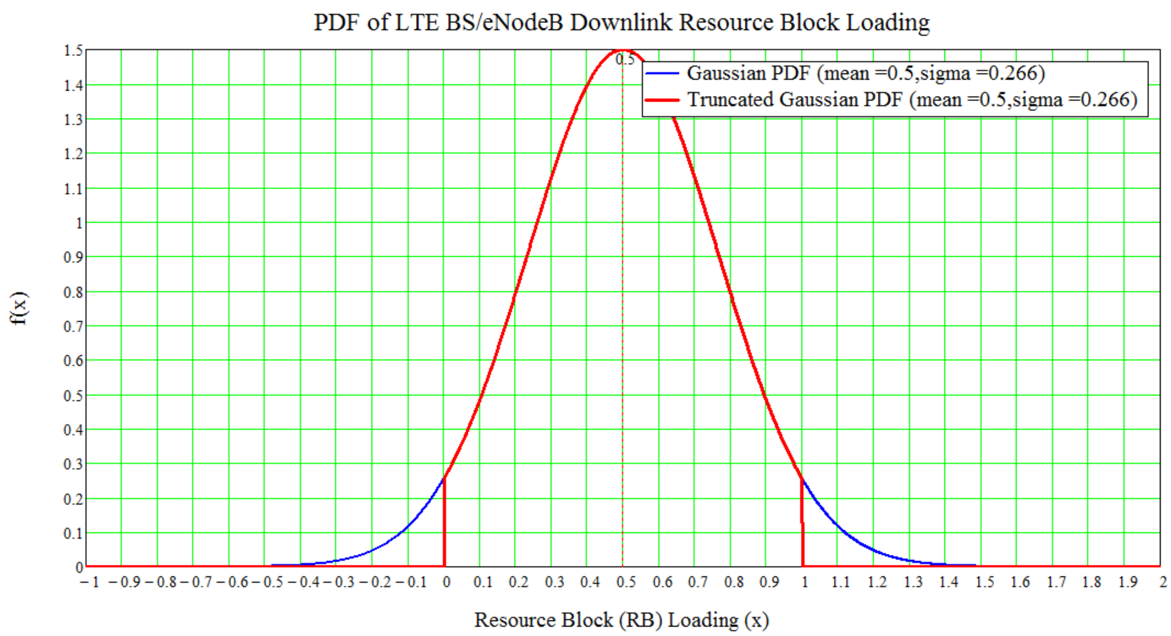
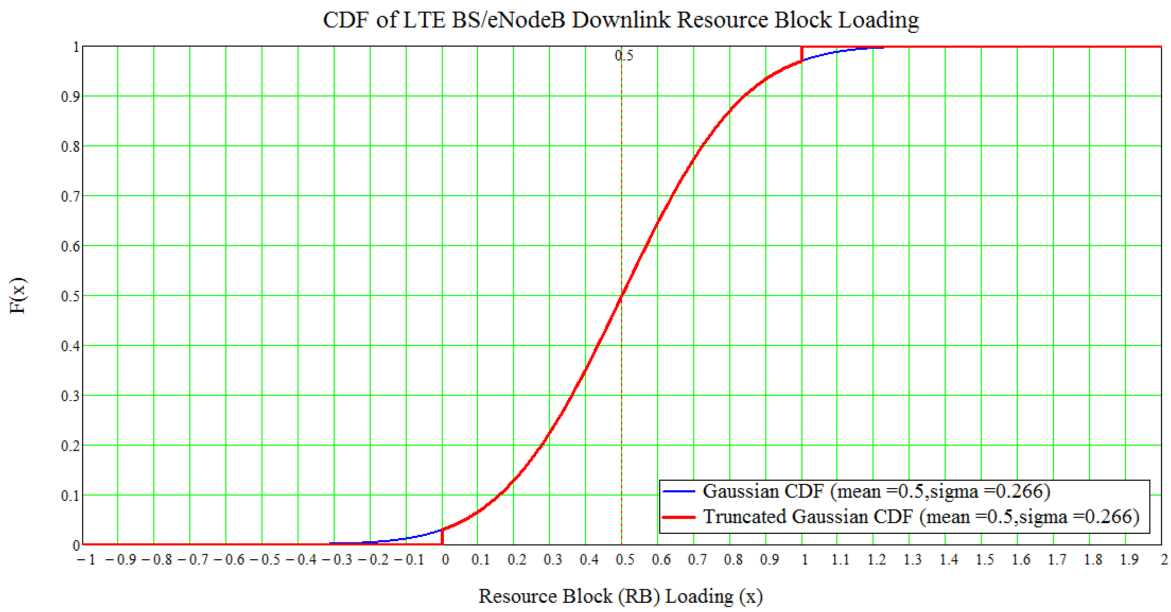


FIGURE 2-2

CDF curve for base station/eNodeB downlink resource block loading



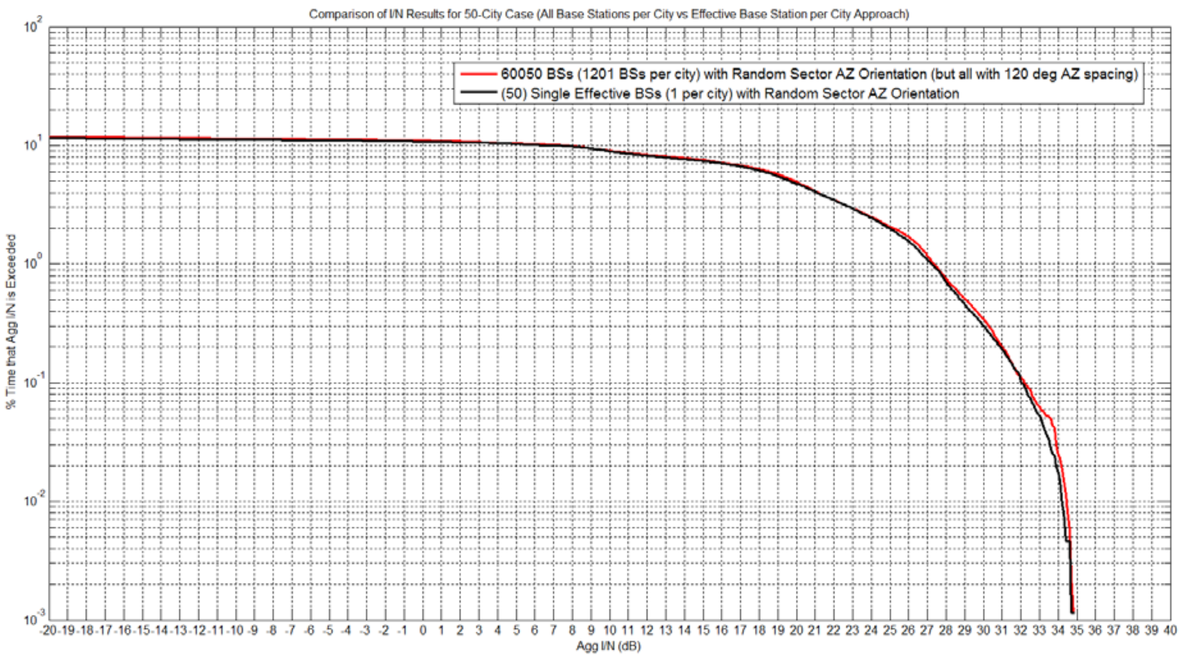
Validation for using single effective base station per city approach

The calculation method presented above for calculating a single aggregate Base Station power for each city used in the analysis was used to reduce simulation execution time. A validation of the approach to use an aggregate city Base Station EIRP was performed by running a simulation for 2 cases using the top 50 cities in the United States. The results of the simulation can be seen in Figure 2-3. The following simulation parameters were used for the curves in Figure 2-3:

1) Case 1 (red curve): model Base Station transmitter in each cell is at 50% loading (20W per Base Station sector); assuming 1201 cells per city, this is a total of 50 x 1201 = 60050 cells; in additional all Base Stations have random sector azimuth antenna pointing (but with 120° azimuth spacing for each Base Station)
2) Case 2 (black curve): replace the 1201 Base Station transmitters per city with a single "effective" Base Station at city centre with power per sector = 20W x 1201 cells = 24020 W (43.8 dBW); also randomize the azimuth sector antenna pointing of the 50 effective Base Stations
3) Figure 2-3 below shows that effective transmitter approach (the black curve) which was used in this analysis is valid approximation to modelling all cells (red curve) and greatly reduces simulation time
4) Further note that uniform sector azimuth pointing of the Base Station sector antennas gives slightly worse/higher interference

FIGURE 2-3

Validation of using single effective base station per city approach



APPENDIX 3

Method for calculating aggregate user equipment (UE) EIRP for cities

1 Large cities (population > 250,000) assumed to have 1075 urban/suburban + 126 rural = 1201 Cells

2 Small cities (population < 250,000) assumed to have 294 urban/suburban + 126 rural = 420 Cells per U.S. LTE industry provided data and Cumulative Distribution Functions (CDF) assume 10 MHz LTE channel with PDCCH capacity = 6 (i.e. 6 simultaneous transmit UE per subframe sector)

3 Assume 3 sectors per cell to give 6x3x1075 = 19350 urban UEs and 6x3x126 = 2268 rural UEs for large cities and 6x3x294 = 5292 urban UEs and 6x3x126 = 2268 rural UEs for small cities

4 Estimate probability distribution of aggregate UE EIRP per city by performing Monte Carlo simulation (100,000 trials)

5 For the i-th Monte Carlo trial perform the following steps:

a) generate N random samples of probability p that are uniformly distributed between 0 and 1 (N = 19350 for large city urban UEs; N = 5292 for small city UEs; N = 2268 for rural UEs)

b) Using the inverse CDFs of the CDF plots of (single UE EIRP) provided by the U.S. LTE industry (see figures 3-1, 3-2, and 3-3) calculate N corresponding random samples of (single) UE EIRP (dBm). (Note that there are two CDF curves in Figure 3-1 one for suburban/urban and one for rural areas)

c) Convert the UE EIRP values from dBm to Watts; sum them up; and convert back to dBm

d) The result is the aggregate UE EIRP per city value (in dBm) for the i-th trial

6 After 100,000 trials we have a [100000 x 1] vector of aggregate EIRP values from which we can calculate the minimum, maximum, mean, and standard deviation of the aggregate EIRP distribution

7 the [minimum, maximum, mean std deviation] of the aggregate power per city from the various cases are as follows

a) 1075 urban cells for large cities (using urban/suburban CDF): [46.47; 47.15; 46.82; 0.08] dBm

b) 294 urban cells for small cities (using urban/suburban CDF): [40.58; 41.71; 41.19; 0.15] dBm

c) 126 rural cells for large and small cities (using rural CDF): [45.02; 45.93; 45.51; 0.12] dBm

8 Note that the standard deviations/variances of all these aggregate EIRP distributions are very small (< 0.2 dBm). Therefore, we use the mean values for all cities.

9 The combined (urban + rural) aggregate UE EIRPs and EIRP spectral densities (assuming 10 MHz LTE BW) are:

a) For large cities (population > 250,000): aggregate UE EIRP per city = 49.22 dBm (EIRPo = -50.78 dBW/Hz)

b) For small cities (population < 250,000): aggregate UE EIRP per city = 46.87 dBm (EIRPo = -53.12 dBW/Hz).

FIGURE 3-1

U.S. LTE industry provided CDF of LTE UE transmitter EIRP

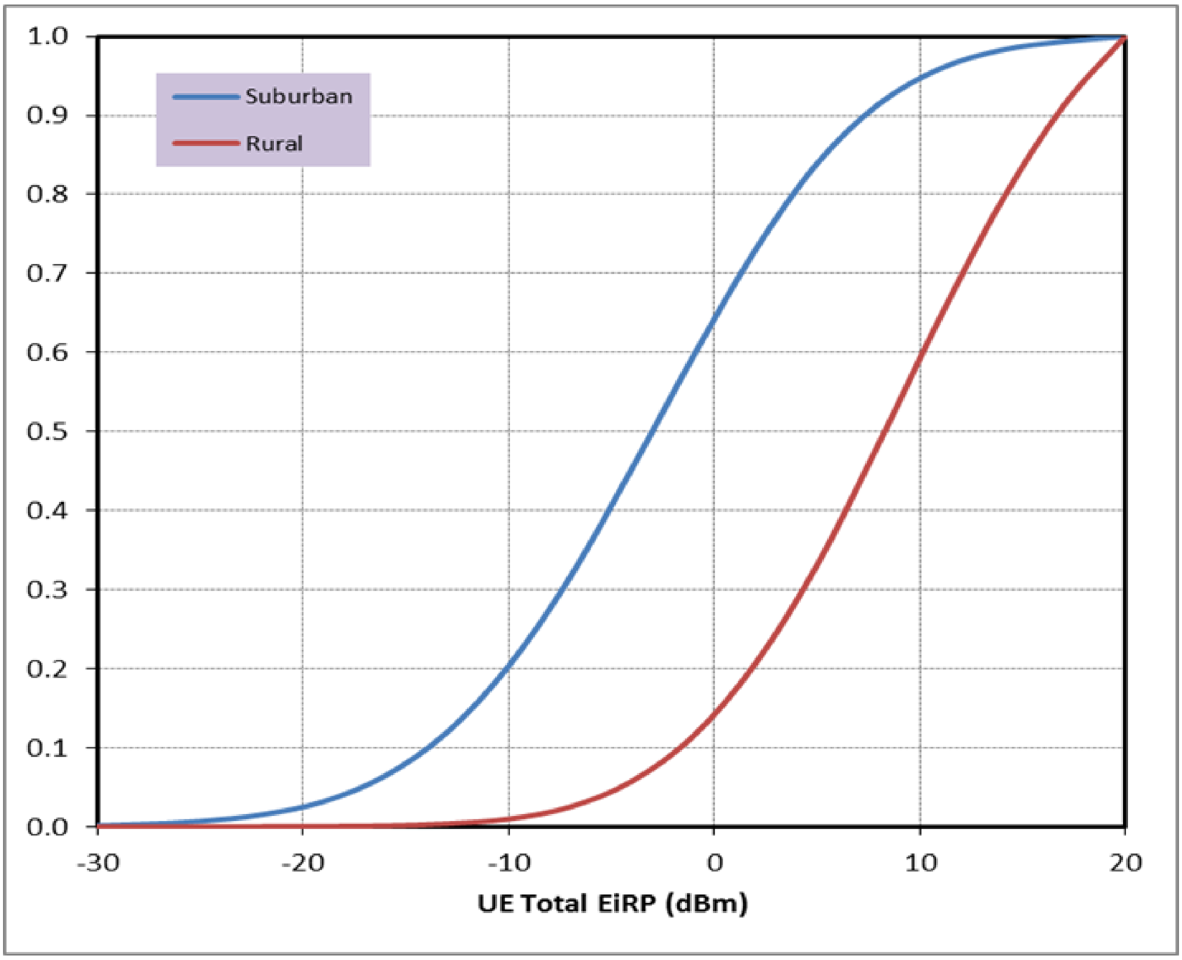


FIGURE 3-2

Curve fit for LTE UE Uplink EIRP (urban/suburban)

Generating Random Sample Values of UE EIRP

Curve Fit Equation for CDF:

$$y = f(x) = \frac{C_0}{\left(1 + C_1 \cdot \exp(-C_2 \cdot x)\right)}$$

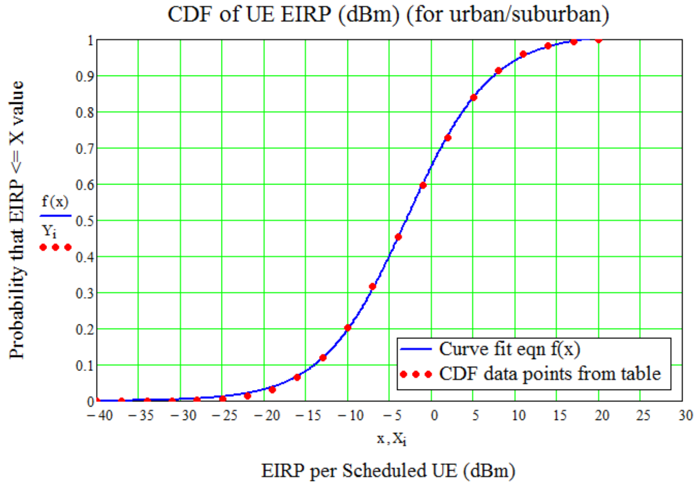
where: $C_0 = 1.014575$

$C_1 = 0.563958$

$C_2 = 0.199101$

Inverse CDF equation:

$$x = g(y) = -\frac{\ln\left(\frac{\frac{C_0}{y} - 1}{C_1}\right)}{C_2}$$



Therefore, by the inverse sampling method, we can generate N random samples of x (UE EIRP) with the above CDF by generating N uniformly distributed random values of p = y in the interval (0,1) and substituting these sample p values into the above inverse CDF equation g(p) = g(y) to get the corresponding UE EIRP values.

FIGURE 3-3

Curve fit for LTE UE Uplink EIRP (rural case)

Generating Random Sample Values of UE EIRP from rural case CDF

Curve Fit Equation for CDF:

$$y = f(x) = \frac{C_0}{\left(1 + C_1 \cdot \exp(-C_2 \cdot x)\right)}$$

where: $C_0 = 1.098653$

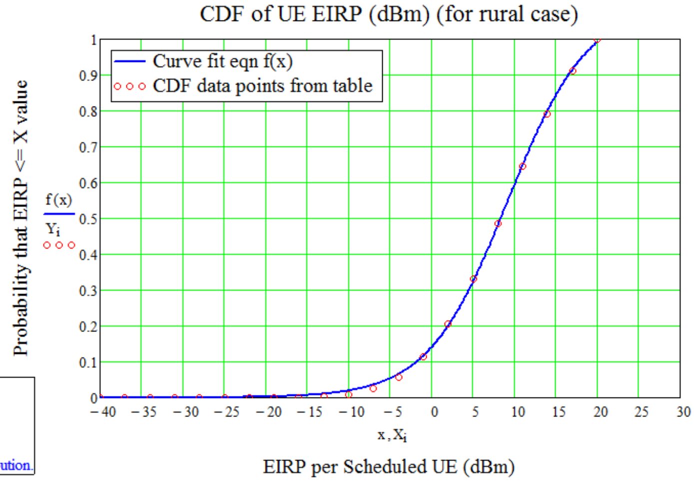
$C_1 = 6.784309$

$C_2 = 0.207312$

Inverse CDF equation:

$$x = g(y) = -\frac{\ln\left(\frac{\frac{C_0}{y} - 1}{C_1}\right)}{C_2}$$

So if I put in a sample probability value p=y between 0 and 1 in this inverse CDF eqn, I get the corresponding UE EIRP value. By generating N uniformly distributed samples of p between 0 and 1 and substituting them into the inverse CDF eqn, I get N random samples of UE EIRP with the correct CDF distribution.



Therefore, by the inverse sampling method, we can generate N random samples of x (UE EIRP) with the above CDF by generating N uniformly distributed random values of p = y in the interval (0,1) and substituting these sample p values into the above inverse CDF equation g(p) = g(y) to get the corresponding UE EIRP values.

APPENDIX 4

List of worldwide cities used

TABLE 4-1

List of cities with populations greater than 250,000 used in simulation

City	Latitude (N)	Lonitude (E)	Population	City	Latitude (N)	Lonitude (E)	Population
Adana	37.06135	35.38944	1849473	Birmingham	52.50402	-2.26071	2310000
Albuquerque	35.1107	-106.61	448607	Bogota	4.592056	-74.083	7440000
Alexandria	31.30443	30.40976	4150000	Bordeaux	44.84955	-0.61961	1105000
Algiers	36.78699	3.039669	3390000	Boston	42.40962	-71.13	4750000
Amman	31.74443	35.92138	2530000	Brasilia	-15.7225	-47.761	2383784
Amsterdam	52.36986	4.889227	743079	Bucharest	44.4449	26.1119	2000000
Anaheim	33.83617	-117.89	328014	Budapest	47.49966	19.13126	1697117
Ankara	39.78313	32.94958	3810000	Buenos Aires	-34.5996	-58.483	12390000
Arequipa	-16.3867	-71.4434	783000	Buffalo	42.67592	-78.908	1135509
Arlington CDP	38.88034	-77.1083	332969	Cairo	30.08823	31.28507	16750000
Asuncion	-25.1162	-57.5113	513399	Cali	3.723131	-75.2438	2500000
Athens	38.01645	23.51829	3730000	Cape Town	-33.9614	18.48409	2900000
Atlanta	33.76575	-84.3489	4160000	Caracas	10.46815	-66.6214	2670000
Aurora	41.75988	-88.2985	276393	Casablanca	33.59868	-7.61908	2930000
Austin	30.30047	-97.7472	656562	Charlotte	35.20719	-80.8292	540828
Bahia Blanca	-38.7281	-62.2566	301572	Chicago	41.97176	-87.7972	9030000
Baltimore	39.30796	-76.617	651154	Cincinnati	39.15437	-84.4642	2896016
Bamako	12.6593	-8.02561	1016296	Cleveland	41.50485	-81.6102	478403
Barcelona	41.40138	2.1647	4040000	Colorado Springs	38.86344	-104.792	360890
Beirut	34.03627	35.63599	1303129	Columbus	39.98978	-82.9915	711470
Belem	-1.24344	-48.3176	1407737	Conakry	9.563742	-13.5561	1091500
Belgrade	44.79918	20.50254	1306168	Copenhagen	55.70934	12.45732	1167569
Belo Horizonte	-19.8892	-43.9543	4640000	Cordoba	-31.3102	-64.3433	1428214
Berlin	52.42574	13.08021	3690000	Corpus Christi	27.74286	-97.4019	277454

List of cities with populations greater than 250,000 used in simulation (2)

City	Latitude (N)	Lonitude (E)	Population	City	Latitude (N)	Lonitude (E)	Population
Cracov	50.10295	20.06691	755050	Helsinki	60.05525	23.98195	562713
Curitiba	-25.4455	-49.2624	2900000	Houston	29.70693	-95.3861	4550000
Dakar	14.74519	-17.377	2650000	Indianapolis	39.79094	-86.1477	781870
Dallas	32.77915	-96.7962	5160000	Istanbul	41.06546	29.00315	11220000
Damaskus	33.64004	36.69902	2240000	Izmir	38.42448	27.11023	2480000
Denver	39.68884	-104.943	2180000	Jacksonville	30.31941	-81.66	735617
Detroit	42.46457	-83.0549	3860000	Jerusalem	31.72489	34.9707	726638
Dublin	53.29546	-6.23001	495781	Johannesburg	-26.1482	28.04991	6470000
Durban	-29.8492	30.9601	3070000	Khartoum	15.62369	32.54114	700887
Edinburgh	55.88857	-2.8378	448624	Kingston	17.99779	-76.8056	579137
Edmonton	53.54763	-113.52	817498	La Paz	-16.4943	-67.8974	835167
El Paso	31.79021	-106.423	563662	Las Vegas	36.19417	-115.222	478434
Fort Worth	32.73888	-97.3338	534694	Lexington-Fayette	38.02963	-84.4946	260512
Fortaleza	-3.58074	-38.9576	3160000	Lisbon	38.77132	-9.36554	2340000
Frankfurt	50.10822	8.673213	2320000	London	51.51877	-0.13	8320000
Fresno	36.78155	-119.792	427652	Long Beach	33.80413	-118.158	461522
Gdansk	54.24599	18.68616	461865	Los Angeles	33.9987	-118.204	14730000
Glasgow	55.8812	-4.25398	577670	Louisville	38.22887	-85.7495	3694820
Guadalajara	20.68225	-103.357	4090000	Madrid	40.43124	-3.67883	5130000
Guatemala	14.63043	-90.5531	1022001	Manaus	-3.06457	-60.0691	1688524
Guayaquil	-2.20131	-79.9024	2530000	Maracaibo	10.64939	-71.6385	1706547
Hamburg	53.56897	10.0839	1704735	Marseille	43.46702	5.172716	796525
Harare	-17.9783	30.86291	1435784	Medellin	6.436432	-75.7473	3080000
Havana	23.08934	-82.3779	2190000	Memphis	35.10905	-90.0355	672277

List of cities with populations greater than 250,000 used in simulation (3)

City	Latitude (N)	Lonitude (E)	Population	City	Latitude (N)	Lonitude (E)	Population
Mesa	33.4112	-111.746	396375	Omaha	41.26048	-96.0130	390007
Mexico City	19.41059	-99.0973	8851080	Oslo	59.95307	10.75376	586860
Miami	25.8327	-80.242	5220000	Ottawa	45.32252	-76.1855	812135
Milan	45.47238	9.183953	4190000	Palermo	38.05041	13.41269	668686
Milwaukee	43.06206	-87.9704	578887	Paris	48.87084	2.413063	10430000
Minneapolis	44.90396	-93.3569	2570000	Philadelphia	40.00577	-75.1173	5270000
Minsk	53.88294	27.58782	1789098	Phoenix	33.45952	-112.071	3540000
Monterrey	25.81271	-100.51	3650000	Pittsburgh	40.46667	-79.8665	1753136
Montevideo	-34.8935	-56.1222	1345010	Porto Alegre	-30.1022	-51.2678	3440000
Montreal	45.52253	-73.6121	3360000	Prague	50.07801	14.41574	1176116
Munich	48.18552	11.22672	1326807	Quebec	46.64567	-71.2349	7903000
Naples	40.84728	14.26327	3010000	Quito	-0.17425	-78.4889	1482447
Nashville-Davidson (balance)	36.15484	-86.7621	545524	Rabat	33.95733	-6.76569	673000
New Orleans	29.95897	-90.1162	343829	Raleigh	35.81884	-78.6446	276093
New York	40.69746	-73.9301	20090000	Recife	-8.09434	-34.9191	3490000
Newark	40.7352	-74.1849	273546	Rio de Janeiro	-22.8842	-43.3882	11160000
Nouakchott	17.91428	-15.959	558195	Riverside	33.94807	-117.396	255166
Odessa	46.52228	30.61018	989468	Rome	41.92599	12.49507	2761477
Oklahoma City	35.48231	-97.535	506132				

TABLE 4-2

List of cities with populations less than 250,000 used in simulation

City	Latitude (N)	Lonitude (E)	Population	City	Latitude (N)	Lonitude (E)	Population
Abilene	32.44643	-99.7455	115930	Cayenne	4.936513	-52.3299	97300
Akron	41.07316	-81.5179	217074	Cedar Rapids	41.9831	-91.6685	120758
Alexandria	38.81624	-77.0713	128283	Chandler	33.29776	-111.864	176581
Allentown	40.6017	-75.4773	106632	Chattanooga	35.04547	-85.2673	155554
Amarillo	35.19925	-101.845	173627	Chesapeake	36.7674	-76.2874	199184
Ann Arbor	42.27449	-83.7393	114024	Chula Vista	32.62791	-117.048	173556
Arlington	32.70503	-97.1228	189453	Clarksville	36.55938	-87.3583	103455
Arvada	39.81996	-105.111	102153	Clearwater	27.97364	-82.7643	108787
Athens-Clarke County (balance)	33.95546	-83.3832	100266	Columbia	34.01711	-81.0108	116278
Augusta-Richmond County (balance)	33.43327	-82.022	195182	Columbus city (balance)	32.48961	-84.9404	185781
Aurora	39.69589	-104.808	142990	Coral Springs	26.27066	-80.2592	117549
Bakersfield	35.35728	-119.032	247057	Corona	33.87	-117.568	124966
Baton Rouge	30.45809	-91.1402	227818	Costa Mesa	33.66497	-117.912	108724
Bayamón zona urbana	18.38243	-66.1657	203499	Dayton	39.76271	-84.1967	166179
Beaumont	30.07991	-94.1267	113866	Des Moines	41.59094	-93.6209	198682
Birmingham	33.52476	-86.8127	242820	Downey	33.93816	-118.131	107323
Boise City	43.61374	-116.238	185787	Durham	35.98864	-78.9072	187035
Bridgeport	41.1886	-73.1959	139529	East Los Angeles CDP	34.03146	-118.169	124283
Brownsville	25.93031	-97.4844	139722	El Monte	34.07328	-118.027	115965
Burbank	34.18017	-118.328	100316	Elizabeth	40.66215	-74.2091	120568
Cambridge	42.37375	-71.1106	101355	Erie	42.11451	-80.0762	103717
Cape Coral	26.6396	-81.9825	102286	Escondido	33.12479	-117.081	133559
Carolina zona urbana	18.40196	-65.9744	168164	Evansville	37.97717	-87.5506	121582
Carrollton	32.99009	-96.8933	109576	Fayetteville	35.06666	-78.9176	121015

List of cities with populations less than 250,000 used in simulation (2)

City	Latitude (N)	Lonitude (E)	Population	City	Latitude (N)	Lonitude (E)	Population
Flint	43.02758	-83.694	124943	Independence	39.07981	-94.4066	113288
Fontana	34.09774	-117.458	128929	Inglewood	33.95751	-118.346	112580
Fort Collins	40.55924	-105.078	118652	Iquitos	-3.77837	-73.3531	100000
Fort Lauderdale	26.13576	-80.1418	152397	Irvine	33.68407	-117.793	143072
Fort Wayne	41.07835	-85.1265	205727	Irving	32.84713	-96.9663	191615
Fullerton	33.87991	-117.929	126003	Jackson	32.32045	-90.2044	184256
Garden Grove	33.77877	-117.96	165196	Jersey City	40.7221	-74.0654	240055
Garland	32.90733	-96.6352	215768	Joliet	41.53303	-88.1089	106221
Gary	41.58079	-87.3454	102746	Kansas City	39.03459	-94.6307	100000
Gilbert town	33.34444	-111.762	109697	Kiev	50.44737	30.45478	100000
Glendale	34.17094	-118.25	194973	Knoxville	35.97288	-83.9422	173890
Glendale	33.58073	-112.199	218812	Koln	50.82123	7.084478	100000
Goteborg	57.70274	11.99116	100000	Lafayette	30.2139	-92.0294	110257
Grand Prairie	32.71527	-97.0169	127427	Lakewood	39.70634	-105.103	144126
Grand Rapids	42.96048	-85.6583	197800	Lancaster	34.68698	-118.154	118718
Green Bay	44.51344	-88.0158	102313	Lansing	42.71759	-84.5549	119128
Greensboro	36.07987	-79.8194	223891	Laredo	27.52445	-99.4906	176576
Hampton	37.03495	-76.3601	146437	Leningrad	60.02766	30.33562	100000
Hartford	41.76255	-72.6886	121578	Lima	-12.2254	-76.7792	100000
Henderson	36.02925	-115.025	175381	Lincoln	40.80987	-96.6753	225581
Hialeah	25.86047	-80.294	226419	Little Rock	34.73601	-92.3311	183133
Hollywood	26.02147	-80.1749	139357	Livonia	42.39509	-83.3656	100545
Huntington Beach	33.69289	-118	189594	Lowell	42.63952	-71.3146	105167
Huntsville	34.71234	-86.5963	158216	Lubbock	33.56474	-101.878	199564

List of cities with populations less than 250,000 used in simulation (3)

City	Latitude (N)	Lonitude (E)	Population	City	Latitude (N)	Lonitude (E)	Population
Lvov	49.44856	23.95921	100000	Orange	33.80295	-117.833	128821
Lyon	45.97598	4.686924	100000	Orlando	28.53351	-81.3758	185951
Madison	43.07461	-89.3948	208054	Overland Park	38.94007	-94.6807	149080
Managua	12.14589	-86.2717	100000	Oxnard	34.19129	-119.182	170358
Manchester	42.98628	-71.4516	107006	Palmdale	34.58101	-118.101	116670
McAllen	26.21626	-98.2364	106414	Panama	9.000792	-79.5061	100000
Merida	20.95199	-89.5403	100000	Paradise CDP	36.08207	-115.125	186070
Mesquite	32.78288	-96.6099	124523	Paramaribo	5.884146	-55.439	100000
Metairie CDP	29.9978	-90.1775	146136	Pasadena	34.1561	-118.132	133936
Mobile	30.67952	-88.1033	198915	Pasadena	29.6762	-95.1738	141674
Monrovia	6.551656	-10.8119	100000	Paterson	40.9155	-74.1629	149222
Montgomery	32.36154	-86.2791	201568	Pembroke Pines	26.01291	-80.3137	137427
Moreno Valley	33.92627	-117.228	142381	Peoria	33.64974	-112.252	108364
Nantes	47.29709	-1.894	100000	Peoria	40.72074	-89.6094	112936
Naperville	41.74983	-88.1557	128358	Plano	33.05037	-96.7459	222030
New Haven	41.31115	-72.9232	123626	Pomona	34.06076	-117.756	149473
Newport News	37.07105	-76.4846	180150	Ponce zona urbana	18.01123	-66.6174	155038
Norfolk	36.88575	-76.2599	234403	Portsmouth	36.8313	-76.3456	100565
North Las Vegas	36.22851	-115.147	115488	Providence	41.82355	-71.4221	173618
Norwalk	33.90691	-118.083	103298	Provo	40.24442	-111.661	105166
Oaxaca	16.86952	-97.0411	100000	Pueblo	38.26693	-104.62	102121
Oceanside	33.21157	-117.326	161029	Rancho Cucamonga	34.12335	-117.579	127743
Ontario	34.05281	-117.628	158007	Reykjavik	64.29883	-21.8323	117980
Oran	35.76765	-0.55038	100000	Richmond	37.53835	-77.4615	197790

List of cities with populations less than 250,000 used in simulation (4)

City	Latitude (N)	Lonitude (E)	Population
Riga	56.94335	24.05717	100000
Rochester	43.1655	-77.6115	219773
Rockford	42.26977	-89.0698	150115
San Bernardino	34.12951	-117.293	185401
San Buenaventura (Ventura)	34.27524	-119.228	100916
Santa Clarita	34.41656	-118.506	151088
Savannah	32.05071	-81.1038	131510
Scottsdale	33.59071	-111.896	202705
Shreveport	32.468	-93.7711	200145
Simi Valley	34.27108	-118.739	111351
Sioux Falls	43.53629	-96.7318	123975
South Bend	41.6726	-86.2552	107789
Spokane	47.67334	-117.41	195629
Spring Valley CDP	36.11252	-115.25	117390
Springfield	37.1951	-93.2862	111454
Springfield	39.78325	-89.6504	151580
Springfield	42.11241	-72.5475	152082
St. Petersburg	27.78225	-82.6676	248232
Stamford	41.07445	-73.5413	117083
Sterling Heights	42.57982	-83.0281	124471
Sunrise Manor CDP	36.17545	-115.06	156120
Syracuse	43.0469	-76.1444	147306
Tallahassee	30.4518	-84.2728	150624
Tallinn	59.40613	24.7336	100000
Tampico	22.37766	-97.8684	100000
Tempe	33.3887	-111.929	158625
Thousand Oaks	34.18949	-118.875	117005
Topeka	39.0392	-95.6895	122377
Torrance	33.83482	-118.341	137946
Waco	31.55152	-97.1559	113726
Warren	42.49199	-83.024	138247
Waterbury	41.55604	-73.0383	107271
West Covina	34.05666	-117.919	105080
West Valley City	40.68918	-111.994	108896
Westminster	39.87342	-105.057	100940
Wichita Falls	33.89705	-98.5149	104197
Winston-Salem	36.10276	-80.2605	185776
Worcester	42.26884	-71.8038	172648
Yonkers	40.94148	-73.8644	196086

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