Annexture G: Suggested Technical Rules and Regulations for the Use of TVWS and Managed Access Spectrum

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§ 1 Permissible Frequencies of Operation

a) White space devices ("WSDs") are permitted to operate on a license-exempt basis subject to the interference protection requirements set forth in these rules.[1]
b) WSDs may operate in the broadcast television frequency bands, as well as any other frequency bands designated by [Regulator].
c) WSDs shall only operate on available frequencies determined in accordance with the interference avoidance mechanisms set forth in § 2.
d) Client WSDs shall only operate on available frequencies determined by the database and provided via a master white space device in accordance with § 3(f).

§ 2 Protection of Licensed Incumbent Services

Availability of frequencies for use by WSDs may be determined based on the geolocation and database method described in § 3 or based on the spectrum sensing method described in § 6.[2]

§ 3 Geolocation and Database Access

(a) A WSD may rely on the geolocation and database access mechanism described in this section to identify available frequencies.

(b) WSD geolocation determination.

  (1) The geographic coordinates of a fixed WSD shall be determined to an accuracy of ± 50 meters by either an incorporated geolocation capability or a professional installer. The geographic coordinates of a fixed WSD shall be determined at the time of installation and first activation from a power-off condition, and this information shall be stored by the device. If the fixed WSD is moved to another location or if its stored coordinates become altered, the operator shall re-establish the device's geographic location either by means of the device's incorporated geolocation capability or through the services of a professional installer.

  (2) A personal/portable master WSD shall incorporate a geolocation capability to determine its geographic coordinates to an accuracy of ± 50 meters from the transmission. A personal/portable master device must also re-establish its position each time it is activated from a power-off condition and use its geolocation capability to check its location at least once every 60 seconds while in operation, except while in sleep mode, i.e., a mode in which the device is inactive but not powered down.

(c) Determination of available frequencies and maximum transmit power.

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[1] WAPA is also interested in exploring light-licensing regulatory frameworks as described in the discussion document.

[2] Though the Cape Town trial did not study sensing, an option of relying on sensing technology has been explored in other regulatory frameworks for TVWS. Therefore, we discuss it as a potential option to be included at the discretion of policymakers.

(1) Master WSDs shall access a geolocation database designated by [Regulator] over the Internet to determine the frequencies and maximum transmit power available at the device's geographic coordinates. A database will determine available frequencies and maximum transmit power based on the algorithm described in § 4 and Annexes A, B, and C. However, in no case shall the maximum transmit power or minimum emissions limit restrictions exceed the values provided in § 7.

(2) Master devices must provide the database with the device's geographic coordinates in WGS84 format, model number, and unique device identifier such as a serial number. Fixed master devices must also provide the database with the antenna height of the transmitting antenna specified in meters AMSL or AGL.

(3) When determining frequencies of operation and maximum transmit power, the geolocation database may also take into account additional information voluntarily provided by a master WSD about its operating parameters and indicate to the WSD that different frequencies and/or higher maximum transmit power are available based on this additional information.

(4) WSD operation in a frequency range must cease if the database indicates that the frequencies are no longer available.

(5) A personal/portable master device must access a geolocation database as described in paragraph (c)(1) to re-check the database for available frequencies and maximum operating power when (1) the device changes location by more than 100 meters from the location at which it last accessed the database or (2) the device is activated from a power-off condition.

(6) A personal/portable master WSD may load frequency availability information for multiple locations around, i.e., in the vicinity of, its current location and use that information in its operation. A personal/portable master WSD may use such available frequency information to define a geographic area within which it can operate on the same available frequencies at all locations; for example, a master WSD could calculate a bounded area in which frequencies are available at all locations within the area and operate on a mobile basis within that area. A master WSD using such frequency availability information for multiple locations must contact the database again if/when it moves beyond the boundary of the area where the frequency availability data is valid, and must access the database daily even if it has not moved beyond that range to verify that the operating frequencies continue to be available. Operation must cease immediately if the database indicates that the frequencies are no longer available.

(d) Time validity and database re-check requirements. A geolocation database shall provide master devices with a time period of validity for the frequencies of operation and maximum transmit power values described in paragraph (c).

(e) Fixed device registration.

(1) Prior to operating for the first time or after changing location, a fixed WSD must register with a database by providing the information listed in paragraph (e)(3) of this section.

(2) The party responsible for a fixed WSD must ensure that a database has the most current, up-to-date information for that device.

(3) The database shall contain the following information for fixed WSDs:

(i) A unique alphanumeric code supplied by the manufacturer that identifies the make and model of the device [in jurisdictions that require a certification ID number this ID number may be used];

(ii) Manufacturer's serial number of the device;

(iii) Device's geographic coordinates (latitude and longitude (NAD 83) accurate to ± 50 meters);

(iv) Device's antenna height above ground level (meters);

(v) Name of the individual or business that owns the device;

(vi) Name of a contact person responsible for the device's operation;

(vii) Address for the contact person;

(viii) Email address for the contact person;

(ix) Phone number for the contact person.

(f) Client device operation.

(1) A client WSD may only transmit upon receiving a list of available frequencies and power limits from a master WSD that has contacted a database. To initiate contact with a master device, a client device may transmit on available frequencies used by the master WSD or on frequencies that the master WSD indicates are available for use by a client device on a signal seeking such contacts. A client WSD may optionally provide additional information about its operating parameters to a master device that may be taken into account by the database when determining available frequencies and/or maximum transmit power for the client device. The client device must also provide the master device with a unique alphanumeric code supplied by the manufacturer that identifies the make and model of the client device, which will be supplied to a geolocation database.

(2) At least once every 60 seconds, except when in sleep mode, i.e., a mode in which the device is inactive but is not powered-down, a client device must communicate with a master device, which may include contacting the master device to re-verify/re-establish frequency availability or receiving a contact verification signal from the master device that provided its current list of available frequencies. A client device must cease operation immediately if it has not communicated with the master device as described above after more than 60 seconds. In addition, a client device must re-check/reestablish contact with a master device to obtain a list of available frequencies if the client device resumes operation from a powered-down state. If a master device loses power and obtains a new frequency list, it must signal all client devices it is serving to acquire a new frequency list.

(g) Fixed devices without a direct connection to the Internet. If a fixed WSD does not have a direct connection to the Internet and has not yet been initialized and communicated with a geolocation database consistent with this section, but can receive the transmissions of a master WSD, the fixed WSD needing initialization may transmit to the master WSD on either a frequency band on which the master WSD has transmitted or on a frequency band which the master WSD indicates is available for use to access the geolocation database to receive a list of frequencies and power levels that are available for the fixed WSD to use. Fixed devices needing initialization must transmit at the power levels specified under the technical requirements in these rules for the applicable frequency bands. After communicating with the database, the fixed WSD must then only use the frequencies and power levels that the database indicates are available for it to use.

(h) Security.

  (1) For purposes of obtaining a list of available frequencies and related matters, master WSDs shall be capable of contacting only those geolocation databases operated by administrators authorized by [Regulator].

  (2) Communications between WSDs and geolocation databases are to be transmitted using secure methods that ensure against corruption or unauthorized modification of the data; this requirement also applies to communications of frequency availability and other spectrum access information between master devices.

  (3) Communications between a client device and a master device for purposes of obtaining a list of available frequencies shall employ secure methods that ensure against corruption or unauthorized modification of the data. Contact verification signals transmitted for client devices are to be encoded with encryption to secure the identity of the transmitting device. Client devices using contact verification signals shall accept as valid for authorization only the signals of the device from which they obtained their list of available frequencies.

  (4) Geolocation database(s) shall be protected from unauthorized data input or alteration of stored data. To provide this protection, a database administrator shall establish communications authentication procedures that allow master devices to be assured that the data they receive is from an authorized source.

§ 4 Database Algorithm

(a) The input to a geolocation database will be positional information from a master WSD, the height of the transmitting antenna for fixed master devices and use by licensed incumbents in or near the geographic area of operation of the WSD. The database may, at its discretion, accept additional information about WSD operating parameters. The database will supply a list of available frequencies and associated radiated powers to WSDs pursuant to the algorithm provided in Annexes A, B, and C.

(b) Information about incumbent licensed usage typically will be provided from information contained in [Regulator's] databases.

(c) Any facilities that [Regulator] determines are entitled to protection but not contained in [Regulator's] databases shall be permitted to register with a geolocation database pursuant to § 5.

§ 5 Database Administrator

(a) Database administrator responsibilities. [Regulator] will designate one public entity or multiple private entities to administer geolocation database(s). Each geolocation database administrator designated by [Regulator] shall:

  (1) Maintain a database that contains information about incumbent licensees to be protected.

  (2) Implement propagation algorithms and interference parameters issued by [Regulator] pursuant to § 4 to calculate operating parameters for WSDs at a given location. Alternatively, a database operator may implement other

algorithms and interference parameters that can be shown to return results that provide at least the same protection to licensed incumbents as those supplied by [Regulator]. Database operators will update the algorithms or parameter values that have been supplied by [Regulator] after receiving notification from [Regulator] that they are to do so.

(3) Establish a process for acquiring and storing in the database necessary and appropriate information from the [Regulator's] databases and synchronizing the database with current [Regulator] databases at least once a week to include newly licensed facilities or any changes to licensed facilities.

(4) Establish a process for the database administrator to register fixed WSDs.

(5) Establish a process for the database administrator to include in the geolocation database any facilities that [Regulator] determines are entitled to protection but not contained in a database maintained by [Regulator].

(6) Provide accurate information regarding permissible frequencies of operation and maximum transmit power available at a master WSD's geographic coordinates based on the information provided by the device pursuant to § 3(c). Database operators may allow prospective operators of WSDs to query the database and determine whether there are vacant frequencies at a particular location.

(7) Establish protocols and procedures to ensure that all communications and interactions between the database and WSDs are accurate and secure and that unauthorized parties cannot access or alter the database or the list of available frequencies sent to a WSD.

(8) Respond in a timely manner to verify, correct and/or remove, as appropriate, data in the event that [Regulator] or a party brings a claim of inaccuracies in the database to its attention. This requirement applies only to information that [Regulator] requires to be stored in the database.

(9) Transfer its database, along with the IP addresses and URLs used to access the database and list of registered fixed WSDs, to another designated entity in the event it does not continue as the database administrator at the end of its term. It may charge a reasonable price for such conveyance.

(10) The database must have functionality such that upon request from [Regulator] it can indicate that no frequencies are available when queried by a specific WSD or model of WSDs.

(11) If more than one database is developed for a particular frequency band, the database administrators for that band shall cooperate to develop a standardized process for providing on a daily basis or more often, as appropriate, the data collected for the facilities listed in subparagraph (5) to all other WSD databases to ensure consistency in the records of protected facilities.

(b) Non-discrimination and administration fees.

(1) Geolocation databases must not discriminate between devices in providing the minimum information levels. However, they may provide additional information to certain classes of devices.

(2) A database administrator may charge a fee for provision of lists of available frequencies to fixed and personal/portable WSDs [and for registering fixed WSDs].

    (3) [Regulator], upon request, will review the fees and can require changes in those fees if they are found to be excessive.

§ 6 Spectrum Sensing in the Broadcast Television Frequency Bands

(a) Parties may submit applications for authorization of WSDs that rely on spectrum sensing to identify available frequencies in the television broadcast bands. WSDs authorized under this section must demonstrate that they will not cause harmful interference to incumbent licensees in those bands.

(b) Applications shall submit a pre-production WSD that is electrically identical to the WSD expected to be marketed, along with a full explanation of how the WSD will protect incumbent licensees against harmful interference. Applicants may request that commercially sensitive portions of an application be treated as confidential.

(c) Application process and determination of operating parameters.

    (1) Upon receipt of an application submitted under this section, [Regulator] will develop proposed test procedures and methodologies for the pre-production WSD. [Regulator] will make the application and proposed test plan available for public review, and afford the public an opportunity to comment.

    (2) [Regulator] will conduct laboratory and field tests of the pre-production WSD. This testing will be conducted to evaluate proof of performance of the WSD, including characterization of its sensing capability and its interference potential. The testing will be open to the public.

    (3) Subsequent to the completion of testing, [Regulator] will issue a test report, including recommendations for operating parameters described in subparagraph (c)(4), and afford the public an opportunity to comment.

    (4) After completion of testing and a reasonable period for public comment, [Regulator] shall determine operating parameters for the production WSD, including maximum transmit power and minimum sensing detection thresholds, that are sufficient to enable the WSD to reliably avoid interfering with incumbent services.

(d) Other sensing requirements. All WSDs that rely on spectrum sensing must implement the following additional requirements:

    (1) Frequency availability check time. A WSD may start operating on a frequency band if no incumbent licensee device signals above the detection threshold determined in subparagraph (c) are detected within a minimum time interval of 30 seconds.

    (2) In-service monitoring. A WSD must perform in-service monitoring of the frequencies used by the WSD at least once every 60 seconds. There is no minimum frequency availability check time for in-service monitoring.

    (3) Frequency move time. After an incumbent licensee device signal is detected on a frequency range used by the WSD, all transmissions by the WSD must cease within two seconds.

§ 7 Technical Requirements for WSDs Operating in the Television Broadcast Bands

(a) Maximum power levels.

(1) WSDs relying on the geolocation and database method of determining channel availability may transmit using the power levels provided by the database pursuant to § 3. However, the maximum EIRP levels for WSDs shall never exceed the following values:

   (i) The antenna attached to the WSD shall not exceed an EIRP of 10 watts[3], taking into account the transmit power of the WSD's radio, loss from cable and connectors, and diretional gain of the antenna[4].

   (ii) Personal/portable WSDs devices shall be treated the same as fixed devices, except[5]:

      a. If the personal/portable WSD does not report its height information, it will be treated like a fixed devices operating at 1.5 meters above ground.

      b. If theIf the personal/portable WSD does report its height information, and that height is more than 2 meters above ground, an additional 7 dB of power may be permitted beyond what is allowed for fixed devices.

   (iii) Fixed WSDs communicating with a master WSD for the purpose of establishing initial contact with a geolocation database pursuant to § 3 (g) may transmit using the maximum power levels in this paragraph applicable to personal/portable WSDs.

(2) WSDs relying on the spectrum sensing method of determining channel availability may transmit at 50 mW per [television channel size].

(b) Emmissions limits restrictions

(1) In the television channels immediately adjacent to the channel in which the WSD is operating, emissions from WSDs relying on the geolocation and database method of determining channel availability shall comply with the following emissions limits. Alternatively, these WSDs may provide more stringent emissions limits to the database, which the database may take into account when determining channel availability and maximum transmit power under § 3.

   (i) Fixed devices operating adjacent to occupied TV channels: -42.8 dBm conducted power per 100 kHz.

   (ii) All other fixed devices: -52.8 conducted power per 100 kHz

   (iii) Personal/portable device operating adjacent to occupied TV channels: -56.8 dBm EIRP per 100 kHz.

   (iv) All other personal/portable devices: -52.8 dBm EIRP per 100 kHz

(2) In the television channels immediately adjacent to the channel in which the WSD is operating, emissions from WSDs relying on the spectrum sensing method of determining channel availability shall not exceed -55.8 dBm EIRP per 100 kHz.

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[3] The Cape Town trial operated at 4W on an adjacent channel

[4] Channel protection using Longley-Rice calculations adaptively limits interference depending on distance to the transmitter, providing necessary protection for adjacent channels . For detailed explanation see Appenex A.

[5] According to Ofcom's proposed technical rules, portable devices located more than 2 meters above ground are presumed to be indoor. The additional power adjustment accounts for building loss.

§ 8 Definitions.

(a) *Available frequency*. A frequency range that is not being used by an authorized incumbent service at or near the same geographic location as the WSD and is acceptable for use by a license exempt device under the provisions of this subpart. Such frequencies are also known as White Space Frequencies (WSFs).

(b) *Client device*. A personal/portable WSD that does not use an automatic geolocation capability and access to a geolocation database to obtain a list of available frequencies. A client device must obtain a list of available frequencies on which it may operate from a master device. A client device may not initiate a network of fixed and/or personal/portable WSDs nor may it provide a list of available frequencies to another client device for operation by such device.

(c) *Contact verification signal*. An encoded signal broadcast by a master device for reception by client devices to which the master device has provided a list of available frequencies for operation. Such signal is for the purpose of establishing that the client device is still within the reception range of the master device for purposes of validating the list of available frequencies used by the client device and shall be encoded to ensure that the signal originates from the device that provided the list of available frequencies. A client device may respond only to a contact verification signal from the master device that provided the list of available frequencies on which it operates. A master device shall provide the information needed by a client device to decode the contact verification signal at the same time it provides the list of available frequencies.

(d) *Fixed device*. A WSD that transmits and/or receives radiocommunication signals at a specified fixed location. A fixed WSD may select frequencies for operation itself from a list of available frequencies provided by a geolocation database and initiate and operate a network by sending enabling signals to one or more fixed WSD and/or personal/portable WSDs.

(e) *Geolocation capability*. The capability of a WSD to determine its geographic coordinates in WGS84 format within the level of accuracy specified in § 3. This capability is used with a geolocation database approved by the [Regulator] to determine the availability of frequencies at a WSD’s location.

(f) *Master device*. A fixed or personal/portable WSD that uses a geolocation capability and access to a geolocation database, either through a direct connection to the Internet or through an indirect connection to the Internet by connecting to another master device, to obtain a list of available frequencies. A master device may select a frequency range from the list of available frequencies and initiate and operate as part of a network of WSDs, transmitting to and receiving from one or more WSD. A master device may also enable client devices to access available frequencies by (1) querying a database to obtain relevant information and then serving as a database proxy for the client devices with which it communicates; or (2) relaying information between a client device and a database to provide a list of available frequencies to the client device.

(g) *Network initiation*. The process by which a master device sends control signals to one or more WSDs and allows them to begin communications.

(h) *Operating frequency*. An available frequency used by a WSD for transmission and/or reception.

(i) *Personal/portable device*. A WSD that transmits and/or receives radiocommunication signals at unspecified locations that may change.

(j) *Sensing only device*. A WSD that uses spectrum sensing to determine a list of available frequencies.

(k) *Spectrum sensing*. A process whereby a WSD monitors a frequency range to detect whether frequencies are occupied by a radio signal or signals from authorized services.

(l) *White space device (WSD)*. An intentional radiator that operates on a license exempt basis on available frequencies.

(m) *Geolocation database*. A database system that maintains records of all authorized services in the frequency bands approved for WSD use, is capable of determining available frequencies at a specific geographic location, and provides lists of available frequencies to WSDs. Geolocation databases that provide lists of available frequencies to WSDs must be authorized by [Regulator].

Annex A: Generalized Description of Propagation Model

I. Introduction

The Model Rules for License-Exempt White Space Devices contemplate that available frequencies and maximum transmit power for a White Space Device at a given location may be determined based on a geolocation and database method[6]. In particular, database(s) designated by the regulator will provide this information based on the positional information from a master White Space Device, the height of the transmitting antenna (for fixed master devices), and use by licensed incumbents in or near the geographic area of operation of the White Space Device[7]. A database will supply a list of available frequencies and associated permitted transmit powers to White Space Devices pursuant to the procedures in Annexes A, B, and C[8].

These procedures rely on the Longley-Rice radio propagation model, also known as the Irregular Terrain Model ("Longley-Rice" or "ITM"), which predicts median transmission loss over irregular terrain relative to free-space transmission loss[9]. Annex A (this annex) provides a generalized description of the algorithm used by the Longley-Rice model; Annex B describes the elements to be taken into account when implementing the Longley-Rice methodology for television broadcasting service to obtain television broadcasting station field strength values at a particular geographic location; and Annex C sets forth the method by which a database operator uses the relevant inputs to indicate available frequencies and maximum power limits for White Space Devices.

II. The Longley-Rice Algorithm

The Longley-Rice model is specifically intended for computer use. The Institute for Telecommunication Sciences ("ITS"), a research and engineering laboratory of the National Telecommunications and Information Administration ("NTIA") within the United States Department of Commerce, maintains the "definitive" representation of the Longley-Rice model, which is written in the FORTRAN computing language[10]. In addition, ITS provides a detailed

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[6] *See* Model Rules for License-Exempt White Space Devices at § 3 ("Model Rules").

[7] *Id.* § 4.

[8] *Id.*

[9] *See id*

[10] S. Department of Commerce, National Telecommunications & Information Administration, Institute for Telecommunication Sciences, Irregular Terrain Model (ITM) (Longley-Rice) (20 MHz – 20 GHz), *at* http://www.its.bldrdoc.gov/resources/radio-propagation-software/itm/itm.aspx.

description of the algorithm used by the Longley-Rice model[11]. Because this document is widely referenced, this Annex reproduces much of the original text of the algorithm description provided by ITS, including the original numerical identifiers for sections and equations, immediately below.

1. Input.

The Longley-Rice model includes two modes—the *area prediction mode* and the *point-to-point mode*— which are distinguished mostly by the amount of input data required. The point-to-point mode must provide details of the terrain profile of the link that the area prediction mode will estimate using empirical medians. Since in other respects the two modes follow very similar paths, the ITS algorithm description addresses both modes in parallel.

d	Distance between the two terminals.
h_{g1}, h_{g2}	Antenna structural heights.
k	Wave number, measured in units of reciprocal lengths; see Note 1.
Δh	Terrain irregularity parameter
N_s	Minimum monthly mean surface refractivity, measured in N-units; see Note 2.
γ_e	The earth's effective curvature, measured in units of reciprocal length; see Note 3.
Z_g	Surface transfer impedance of the ground—a complex, dimensionless number; see Note 4.
radio climate	Expressed qualitatively as one of a number of discrete climate types.

1.1. General input for both modes of usage.

Note 1. The wave number is that of the carrier or central frequency. It is defined to be

$$k = 2\pi / \lambda = f / f_0 \quad \text{with } f_0 = 47.70 \text{ MHz} \cdot \text{m} \tag{1.1}$$

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[11] *See generally* George Hufford, The ITS Irregular Terrain Model, version 1.2.2, the Algorithm (1995), *available at* http://www.its.bldrdoc.gov/media/35878/itm_alg.pdf.

where λ is the wave length, f the frequency. (Here and elsewhere we have assumed the speed of light in air is 299.7 m/μs.)

Note 2. To simplify its representation, the surface refractivity is sometimes given in terms of N_0, the surface refractivity "reduced to sea level." When this is the situation, one must know the general elevation z_s of the region involved, and then

$$N_s = N_0 e^{-z_s/z_1} \qquad \text{with } z_1 = 9.46 \text{ km.} \tag{1.2}$$

Note 3. The earth's effective curvature is the reciprocal of the earth's effective radius and may be expressed as

$$\gamma_e = \gamma_a / K$$

where γ_a is the earth's actual curvature and K is the "effective earth radius factor." The value is normally determined from the surface refractivity using the empirical formula

$$\gamma_e = \gamma_a(1 - 0.04665\, e^{N_s/N_1}) \tag{1.3}$$

where

$N_1 = 179.3$ N-units, and $\gamma_a = 157 \cdot 10^{-9}\ \text{m}^{-1} = 157$ N-units/km.

Note 4. The "surface transfer impedance" is normally defined in terms of the relative permittivity εr and conductivity σ of the ground, and the polarization of the radio waves involved. In these terms, we have

$$Z_g = \begin{cases} \sqrt{\epsilon_r' - 1} & \text{horizontal polarization} \\ \sqrt{\epsilon_r' - 1}/\epsilon_r' & \text{vertical polarization} \end{cases} \tag{1.4}$$

where ε_r' is the "complex relative permittivity" defined by

$$\varepsilon_r' = \varepsilon_r + iZ_0\sigma/k, \qquad Z_0 = 376.62 \text{ ohm.} \tag{1.5}$$

The conductivity σ is normally expressed in siemens (reciprocal ohms) per meter.

1.2. Additional input for the area prediction mode.

siting criteria	Criteria describing the care taken at each terminal to assure good radio propagation conditions. This is expressed qualitatively in three steps: at random, with care, and with great care.

1.3. Additional input for the point-to-point mode.

h_{e1}, h_{e2}	Antenna effective heights.

d_{L1}, d_{L2}	Distances from each terminal to its radio horizon.
θ_{e1}, θ_{e2}	Elevation angles of the horizons from each terminal at the height of the antennas. These are measured in radians.

These quantities, together with Δh, are all geometric and should be determined from the terrain profile that lies between the two terminals. We shall not go into detail here.

The "effective height" of an antenna is its height above an "effective reflecting plane" or above the "intermediate foreground" between the antenna and its horizon. A difficulty with the model is that there is no explicit definition of this quantity, and the accuracy of the model sometimes depends on the skill of the user in estimating values for these effective heights.

In the case of a line-of-sight path there are no horizons, but the model still requires values for d_{Lj}, θ_{ej}, j = 1,2. They should be determined from the formulas used in the area prediction mode and listed in Section 3 below. Now it may happen that after these computations one discovers $d > d_L = d_{L1} + d_{L2}$, implying that the path is a beyond- horizon one. Noting that d_L is a monotone increasing function of the h_{ej} we can assume these latter have been underestimated and that they should be increased by a common factor until $d_L = d$.

2. Output.

The output from the model may take on one of several forms at the user's option. Simplest of these forms is just the *reference attenuation* A_{ref}. This is the *median* attenuation relative to a free space signal that should be observed on the set of all similar paths during times when the atmospheric conditions correspond to a standard, well-mixed, atmosphere.

The second form of output provides the two- or three-dimensional cumulative distribution of attenuation in which time, location, and situation variability are all accounted for. This is done by giving the *quantile* $A(q_T,q_L,q_S)$, the attenuation that will not be exceeded as a function of the fractions of time, locations, and situations. One says *In* q_S *of the situations there will be* at least q_L *of the locations where the attenuation* does not exceed $A(q_T,q_L,q_S)$ *for* at least q_T *of the time*.

When the point-to-point mode is used on particular, well-defined paths with definitely fixed terminals, there is no location variability, and one must use a two-dimensional description of cumulative distributions. One can now say *With probability (or confidence)* q_S *the attenuation will not exceed* $A(q_T, q_S)$ *for at least* q_T *of the time*. The same effect can be achieved by setting q_L = 0.5 in the three-dimensional formulation.

On some occasions it will be desirable to go beyond the three-dimensional quantiles and to treat directly the underlying model of variability. For example, consider the case of a communications link that is to be used once and once only. For such a "one-shot" system one is interested only in what probability or confidence an adequate signal is received that once. The three-dimensional distributions used above must now be combined into one.

3. Preparatory Calculations.

We start with some preliminary calculations of a geometric nature.

3.1. Preparatory calculations for the area prediction mode.

The parameters h_{ej}, d_{Lj}, θ_{ej}, $j = 1,2$,which are part of the input in the point-to-point mode are, in the area prediction mode, estimated using empirical formulas in which Δh plays an important role.

First, consider the effective heights. This is where the siting criteria are used. We have

$$h_{ej} = h_{gj} \qquad \text{if terminal } j \text{ is sited at random.} \tag{3.1}$$

Otherwise, let

$$B_j = \begin{cases} 5\ \mathrm{m} & \text{if terminal } j \text{ is sited with care} \\ 10\ \mathrm{m} & \text{if terminal } j \text{ is sited with great care.} \end{cases}$$

Then

$$B'_j = (B_j - H_1)\sin\big(\frac{\pi}{2}\min(h_{g1}/H_2, 1)\big) + H_1 \qquad \text{with } H_1 = 1\ \mathrm{m},\ H_2 = 5\ \mathrm{m},$$

and

$$h_{ej} = h_{gj} + B'_j e^{-2h_{gj}/\Delta h}. \tag{3.2}$$

The remaining parameters are quickly determined.

$$d_{Lsj} = \sqrt{2h_{ej}/\gamma_e}$$

$$d_{Lj} = d_{Lsj}\exp\big[-0.07\sqrt{\Delta h/\max(h_{ej}, H_3)}\big] \qquad \text{with } H_3 = 5 \tag{3.3}$$

and finally,

$$\theta_{ej} = \big[0.65\,\Delta h(d_{Lsj}/d_{Lj} - 1) - 2h_{ej}\big]/d_{Lsj}. \tag{3.4}$$

3.2. Preparatory calculations for both modes.

$$d_{Lsj} = \sqrt{2h_{ej}/\gamma_e}, \qquad j = 1,2 \tag{3.5}$$

$$d_{Ls} = d_{Ls1} + d_{Ls2} \tag{3.6}$$

$$d_L = d_{L1} + d_{L2} \tag{3.7}$$

$$\theta_e = \max(\theta_{e1} + \theta_{e2},\ -d_L\gamma_e). \tag{3.8}$$

We also note here the definitions of two functions of a distance s:

$$\Delta h(s) = (1 - 0.8\,e^{-s/D})\Delta h \qquad \text{with } D = 50 \text{ km}, \tag{3.9}$$

and

$$\sigma_h(s) = 0.78\,\Delta h(s)\exp\lfloor -(\Delta h(s)/H)^{1/4}\rfloor \qquad \text{with } H = 16 \text{ m}. \tag{3.10}$$

4. The Reference Attenuation.

The reference attenuation is determined as a function of the distance *d* from the piecewise formula

$$A_{\text{ref}} = \begin{cases} \max\left(0, A_{el} + K_1 d + K_2 \ln(d/d_{Ls})\right) & d \le d_{Ls} \\ A_{ed} + m_d d & d_{Ls} \le d \le d_x \\ A_{es} + m_s d & d_x \le d \end{cases} \tag{4.1}$$

where the coefficients A_{el}, K_1, K_2, A_{ed}, m_d, A_{es}, m_s, and the distance d_x are calculated using the algorithms below. The three intervals defined here are called the line-of-sight, diffraction, and scatter regions, respectively. The function in (4.1) is continuous so that at the two endpoints where $d = d_{Ls}$ or d_x the two formulas give the same results. It follows that instead of seven independent coefficients there are really only five.

4.1. Coefficients for the diffraction range.

Set

$$X_{ae} = (k\gamma_e^2)^{-1/3} \tag{4.2}$$

$$d_3 = \max(d_{Ls}, d_L + 1.3787\, X_{ae}) \tag{4.3}$$

$$d_4 = d_3 + 2.7574\, X_{ae} \tag{4.4}$$

$$A_3 = A_{\text{diff}}(d_3) \tag{4.5}$$

$$A_4 = A_{\text{diff}}(d_4) \tag{4.6}$$

where A_{diff} is the function defined below. The formula for A_{ref} in the diffraction range is then just the linear function having the values A_3 and A_4 at the distances d_3 and d_4, respectively. Thus

$$m_d = (A_4 - A_3)/(d_4 - d_3) \tag{4.7}$$

$$A_{ed} = A_3 - m_d d_3. \tag{4.8}$$

4.1.1. The function $A_{\mathrm{diff}}(s)$.

We first define the weighting factor

$$w = \frac{1}{1 + 0.1\sqrt{Q}} \tag{4.9}$$

with

$$Q = \min(\frac{k}{2\pi}\Delta h(s), 1000)\left(\frac{h_{e1}h_{e2} + C}{h_{g1}h_{g2} + C}\right)^{1/2} + \frac{d_L + \theta_e/\gamma_e}{s}$$

and

$$C = \begin{cases} 0 & \text{in the area prediction mode} \\ 10\ \mathrm{m}^2 & \text{in the point-to-point mode} \end{cases}$$

and where $\Delta h(s)$ is the function defined in (3.9) above. Next we define a “clutter factor”

$$A_{fo} = \min\left[15, 5\log(1 + \alpha k h_{g1} h_{g2} \sigma_h(d_{Ls}))\right] \qquad \text{with } \alpha = 4.77 \cdot 10^{-4}\ \mathrm{m}^{-2} \tag{4.10}$$

and with $\sigma_h(s)$ defined in (3.10) above.

Then

$$A_{\mathrm{diff}}(s) = (1 - w)A_k + wA_r + A_{fo} \tag{4.11}$$

where the “double knife edge attenuation” A_k and the “rounded earth attenuation” A_r

are yet to be defined. Set

$$\theta = \theta_e + s\gamma_e \tag{4.12}$$

$$v_j = \frac{\theta}{2}\left(\frac{k}{\pi}\frac{d_{Lj}(s-d_L)}{s-d_L+d_{Lj}}\right)^{1/2}, \qquad j = 1,2 \tag{4.13}$$

and then

$$A_k = \mathrm{Fn}(v_1) + \mathrm{Fn}(v_2) \tag{4.14}$$

where $\mathrm{Fn}(v)$ is the Fresnel integral defined below.

For the rounded earth attenuation we use a “three radii” method applied to Volger’s formulation of the solution to the smooth, spherical earth problem. We set

$$\gamma_0 = \theta \,/\, (s - d_L) \gamma_j = 2h_{ej} \,/\, d^2_{Lj}, \quad j = 1,2 \tag{4.15}$$

$$\alpha_j = (k/\gamma_j)^{1/3}, \quad j = 0,1,2 \tag{4.16}$$

$$K_j = \frac{1}{i\alpha_j Z_g}, \qquad j = 0,1,2. \tag{4.17}$$

Note that the K_j are complex numbers. To continue, we set

$$x_j = AB(K_j)\alpha_j\gamma_j d_{Lj}, \qquad j = 1.2 \tag{4.18}$$

$$x_0 = AB(K_0)\alpha_0\theta + x_1 + x_2 \tag{4.19}$$

and then

$$A_r = G(x_0) - F(x_1, K_1) - F(x_2, K_2) - C_1(K_0) \tag{4.20}$$

where $A = 151.03$ is a dimensionless constant and the functions $B(K)$, $G(x)$, $F(x, K)$, and $C_1(K)$ are those defined by Vogler.

In (4.14) and (4.20) we have finished the definition of A_{diff}. We should like, however, to complete the subject by defining more precisely the more or less standard functions mentioned above. The Fresnel integral, for example, may be written as

$$\mathrm{Fn}(v) = 20 \log\left|\frac{1}{\sqrt{2i}}\int_v^\infty e^{i\pi u^2/2}du\right|. \tag{4.21}$$

For Vogler’s formulation to the solution to the spherical earth problem, we first introduce the special Airy function

$$\mathrm{Wi}(z) = \mathrm{Ai}(z) + i\mathrm{Bi}(z)$$

$$= 2\mathrm{Ai}(e^{2\pi i/3}z)$$

where Ai(z) and Bi(z) are the two standard Airy functions defined in many texts. They are analytic in the entire complex plane and are particular solutions to the differential equation

$$w''(z) - zw(z) = 0.$$

First, to define the function $B(K)$ we find the smallest solution to the modal equation

$$\mathrm{Wi}(t_0) = 2^{1/3} K \mathrm{Wi}'(t_0)$$

and then

$$B = 2^{-1/3} \mathrm{Im}\{t_0\}. \tag{4.22}$$

Finally, we also have

$$G(x) = 20\ \log(x^{-1/2} e^{x/A}) \tag{4.23}$$

$$F(x, K) = 20\ \log\bigl|(\pi/(2^{1/3}AB))^{1/2}\mathrm{Wi}(t_0 - (x/(2^{1/3}AB))^2) \tag{4.24}$$

$$C_1(K) = 20\ \log\bigl|\frac{1}{2}(\pi/(2^{1/3}AB))^{1/2}(2^{2/3}K^2 t_0 - 1)\mathrm{Wi}'(t_0) \tag{4.25}$$

where A is again the constant defined above.

It is of interest to note that for large x we find $F(x, K) \sim G(x)$, and that for those values of K in which we are interested it is a good approximation to say $C_1(K) = 20$ dB.

4.2. Coefficients for the line-of-sight range.

We begin by setting

$$d_2 = d_{Ls} \tag{4.26}$$

$$A_2 = A_{ed} + m_d d_2. \tag{4.27}$$

Then there are two general cases. First, if $A_{ed} \geq 0$

$$d_0 = \min\left(\frac{1}{2}d_L, 1.908\, k h_{e1} h_{e2}\right) \tag{4.28}$$

$$d_1 = \frac{3}{4}d_0 + \frac{1}{4}d_L \tag{4.29}$$

$$A_0 = A_{\text{los}}(d_0) \tag{4.30}$$

$$A_1 = A_{\text{los}}(d_1) \tag{4.31}$$

where the function $A_{\text{los}}(s)$ is defined below. The idea, now, is to devise a curve of the form

$$A_{el} + K_1 d + K_2 \ln(d/d_{Ls})$$

that passes through the three values A_0, A_1, A_2 at d_0, d_1, d_2, respectively. In doing this, however, we require $K_1, K_2 \geq 0$, and sometimes this forces us to abandon one or both of the values A_0, A_1. We first define

$$K_2' = \max\left[0, \frac{(d_2 - d_0)(A_1 - A_0) - (d_1 - d_0)(A_2 - A_0)}{(d_2 - d_0)\ln(d_1/d_0) - (d_1 - d_0)\ln(d_2/d_0)}\right] \tag{4.32}$$

$$K'_1 = (A_2 - A_0 - K'_2 \ln(d_2/d_0)) \,/\, (d_2 - d_0) \tag{4.33}$$

which, except for the possibility that the first calculation for K'_2 results in a negative value, is simply the straightforward solution for the two corresponding coefficients. If $K'_1 \geq 0$ we then have

$$K_1 = K'_1,\ K_2 = K'_2\ . \tag{4.34}$$

If, however, $K'_1 < 0$, we define

$$K''_2 = (A_2 - A_0)/\ln(d_2/d_0) \tag{4.35}$$

and if now $K''_2 \geq 0$ then

$$K_1 = 0, \qquad K_2 = K''_2. \tag{4.36}$$

Otherwise, we abandon both A_0 and A_1 and set

$$K_1 = m_d, \qquad K_2 = 0. \tag{4.37}$$

In the second general case we have $A_{ed} < 0$. We then set

$$d_0 = 1.908 k h_{e1} h_{e2} \tag{4.38}$$

$$d_1 = \max(-A_{ed}/m_d, d_L/4). \tag{4.39}$$

If $d_0 < d_1$ we again evaluate A_0, A_1, and K'_2 as before. If $K'_2 > 0$ we also evaluate K'_1 and proceed exactly as before. If, however, we have either $d_0 \geq d_1$ or $K'_2 = 0$, we evaluate A_1 and define

$$K''_1 = (A_2 - A_1)/(d_2 - d_1). \tag{4.40}$$

If now $K''_1 > 0$ we set

$$K_1 = K''_1, \qquad K_2 = 0; \tag{4.41}$$

and otherwise we use (4.37).

At this point we will have defined the coefficients K_1 and K_2. We finally set

$$A_{el} = A_2 - K_1 d_2. \tag{4.42}$$

4.2.1. The function $A_{\text{los}}(s)$.

First we define the weighting factor

$$w = 1/\left(1 + D_1 k \Delta h / \max\left(D_2, d_{Ls}\right)\right) \quad \text{with } D_1 = 47.7 \text{ m}, D_2 = 10 \text{ km}. \tag{4.43}$$

Then

$$A_{\text{los}} = (1 - w)A_d + wA_t \tag{4.44}$$

where the “extended diffraction attenuation” A_d and the “two-ray attenuation” A_t are yet to be defined.

First, the extended diffraction attenuation is given very simply by

$$A_d = A_{ed} + m_d s. \tag{4.45}$$

For the two-ray attenuation, we set

$$\sin\psi = \frac{h_{e1} + h_{e2}}{\sqrt{s^2 + (h_{e1} + h_{e2})^2}} \tag{4.46}$$

and

$$R'_e = \frac{\sin\psi - Z_g}{\sin\psi + Z_g} \exp[-k\sigma_h(s)\sin\psi] \tag{4.47}$$

where $\sigma_h(s)$ is the function defined in (3.10) above. Note that R'_e is complex since it uses the complex surface transfer impedance Z_g. Then

$$R_e = \begin{cases} R'_e & \text{if } |R'_e| \geq \max(1/2, \sqrt{\sin\psi}) \\ (R'_e/|R'_e|)\sqrt{\sin\psi} & \text{otherwise} \end{cases} \tag{4.48}$$

We also set

$$\delta' = 2kh_{e1}h_{e2}/s \tag{4.49}$$

and

$$\delta = \begin{cases} \delta' & \text{if } \delta' \le \pi/2 \\ \pi - (\pi/2)^2/\delta' & \text{otherwise} \end{cases} \tag{4.50}$$

Then finally

$$A_t = -20 \log |1 + R_e e^{i\delta}|. \tag{4.51}$$

4.3. Coefficients for the scatter range.

Set

$$d_5 = d_L + D_S \tag{4.52}$$

$$d_6 = d_5 + D_S \text{ with } D_S = 200 \text{ km}. \tag{4.53}$$

Then define

$$A_5 = A_{\text{scat}}(d_5) \tag{4.54}$$

$$A_6 = A_{\text{scat}}(d_6), \tag{4.55}$$

where $A_{\text{scat}}(s)$ is defined below. There are, however, some sets of parameters for which A_{scat} is not defined, and it may happen that either or both A_5, A_6 is undefined. If this is so, one merely sets

$$d_x = +\infty \tag{4.56}$$

and one can let A_{es}, m_S remain undefined. In the more normal situation one has

$$m_s = (A_6 - A_5)/D_s \tag{4.57}$$

$$d_x = \max[d_{Ls}, d_L + X_{ae} \log(kHs), (A_5 - A_{ed} - m_s d_5)/(m_d - m_s)] \tag{4.58}$$

$$A_{es} = A_{ed} + (m_d - m_s)d_x \tag{4.59}$$

where D_S is the distance given above, where X_{ae} has been defined in (4.2), and where H_S= 47.7 m.

4.3.1. The function A_{scat}.

Computation of this function uses an abbreviated version of the methods described in Section 9 and Annex III.5 of NBS TN101[12]. First, set

$$\theta = \theta_e + \gamma_e s \tag{4.60}$$

$$\theta' = \theta_{e1} + \theta_{e2} + \gamma_e s \tag{4.61}$$

$$r_j = 2k\theta' h_{ej}, \qquad j = 1,2. \tag{4.62}$$

If both r_1 and r_2 are less than 0.2 the function A_{scat} is not defined (or is infinite). Otherwise we put

$$A_{\text{scat}}(s) = 10 \log(kH\theta^4) + F(\theta s, N_s) + H_0 \tag{4.63}$$

where F (θs, N_S) is the function shown in Figure 9.1 of TN101, H_0 is the "frequency gain function", and H = 47.7m.

The frequency gain function H_0 is a function of r_1, r_2, the scatter efficiency factor η_S, and the "asymmetry factor" which we shall here call s_S. A difficulty with the present model is that there is not sufficient geometric data in the input variables to determine where the crossover point is. This is resolved by assuming it to be midway between the two horizons. The asymmetry factor, for example, is found by first defining the distance between horizons

$$d_S = s - d_{L1} - d_{L2} \tag{4.64}$$

whereupon

$$s_s = \frac{d_{L2} + d_s/2}{d_{L1} + d_s/2}. \tag{4.65}$$

There then follows that the height of the crossover point is

$$z_0 = \frac{s_s d\theta'}{(1 + s_s)^2} \tag{4.66}$$

and then

$$\eta_s = \frac{z_0}{Z_0}\left[1 + (0.031 - N_s 2.32 \cdot 10^{-3} + N_s^2 5.67 \cdot 10^{-6}) e^{-(z_0/Z_1)^6}\right] \tag{4.67}$$

where

$$Z_0 = 1.756 \text{ km} \qquad Z_1 = 8.0 \text{ km}$$

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[12] See P. L. Rice, A. G. Longley, K. A. Norton, and A. P. Barsis, "Transmission loss predictions for tropospheric communication circuits," U.S. Government Printing Office, Washington, DC, NBS Tech. Note 101, issued May 1965; revised May 1966 and Jan. 1967 ("TN101").

The computation of H_0 then proceeds according to the rules in Section 9.3 and Figure 9.3 of TN101.

The model requires these results at the two distances $s = d_5, d_6$, described above. One further precaution is taken to prevent anomalous results. If, at d_5, calculations show that H_0 will exceed 15 dB, they are replaced by the value it has at d_6. This helps keep the scatter-mode slope within reasonable bounds.

5. Variability—the quantiles of attenuation.

We want now to compute the quantiles $A(q_T,q_L,q_S)$ where q_T, q_L, q_S, are the desired fractions of time, locations, and situations, respectively. In the point-to-point mode, we would want a two-fold quantile $A(q_T, q_S)$, but in the present model this is done simply by computing the three-fold quantile with q_L equal to 0.5.

Because the distributions involved are all normal, or nearly normal, it simplifies the calculations to rescale the desired fractions and to express them in terms of "standard normal deviates." We use the complementary normal distribution

$$Q(z) = \frac{1}{\sqrt{2\pi}} \int_z^\infty e^{-t^2/2} dt$$

and then the deviate is simply the inverse function

$$z(q) = Q^{-1}(q).$$

Thus if the random variable x is normally distributed with mean X_0 and standard deviation σ, its quantiles are given by

$$X(q) = X_0 + \sigma z(q).$$

Setting

$$z_T = z(q_T),\ z_L = z(q_L),\ z_S = z(q_S),$$

we now ask for the quantiles $A(z_T,z_L,z_S)$. In these rescaled variables, it is as though all probabilities are to be plotted on normal probability paper. In the case of the point-to- point mode we will simply suppose $z_L = 0$.

First we define

$$A' = A_{\text{ref}} - V_{\text{med}} - Y_T - Y_L - Y_S \tag{5.1}$$

where A_{ref} is the reference attenuation defined in Section 4, and where the adjustment V_{med}

and the deviations Y_T, Y_L, Y_S, are defined below. The values of Y_T and Y_L depend on the single variables z_T and z_L, respectively. The value of Y_S, on the other hand, depends on all three standard normal deviates.

The final quantile is a modification of A' given by

$$A(z_T, z_L, z_S) = \begin{cases} A' & \text{if } A' \geq 0 \\ A' \dfrac{29 - A'}{29 - 10A'} & \text{otherwise.} \end{cases} \tag{5.2}$$

An important quantity used below is the "effective distance." We set

$$d_{ex} = \sqrt{2a_1 h_{e1}} + \sqrt{2a_1 h_{e2}} + a_1 (kD_1)^{-1/3} \tag{5.3}$$

with

$$a_1 = 9000 \text{ km}, \ D_1 = 1266 \text{ km}.$$

Then the effective distance is given by

$$d_e = \begin{cases} D_0 d/d_{ex} & \text{for } d \leq d_{ex} \\ D_0 + d - d_{ex} & \text{for } d \geq d_{ex} \end{cases} \tag{5.4}$$

with $D_0 = 130$ km.

5.1. Time variability.

Quantiles of time variability are computed using a variation of the methods described in Section 10 and Annex III.7 of NBS TN101, and also in CCIR Report 238-3. Those methods speak of eight or nine discrete radio climates, of which seven have been documented with corresponding empirical curves. It is these empirical curves to which we refer below. They are all curves of quantiles of deviations versus the effective distance d_e.

The adjustment from the reference attenuation to the all-year median is

$$V_{\text{med}} = V_{\text{med}}(d_e, \text{clim}) \tag{5.5}$$

where the function is described in Figure 10.13 of TN101.

The deviation Y_T is piecewise linear in z_T, and may be written in the form

$$Y_T = \begin{cases} \sigma_{T-} z_T & z_T \leq 0 \\ \sigma_{T+} z_T & 0 \leq z_T \leq z_D \\ \sigma_{T+} z_D + \sigma_{TD}(z_T - z_D) & z_D \leq z_T \end{cases} \tag{5.6}$$

The slopes (or "pseudo-standard deviations")

$$\sigma_{T-} = \sigma_{T-}(d_e, \text{clim}) \tag{5.7}$$

$$\sigma_{T+} = \sigma_{T+}(d_e, \text{clim})$$

are obtained from TN101 in the following way. For σ_{T-} we use the .90 quantile and divide the corresponding ordinates by $z(.90) = -1.282$. For σ_{T+} we use the .10 quantile and divide by $z(.10) = 1.282$.

The remaining constants in (5.6) pertain to the "ducting," or low probability, case. We write

$$z_D = z_D(\text{clim}), \quad \sigma_{TD} = C_D(\text{clim})\sigma_{T+} \tag{5.8}$$

where values of z_D and C_D are given in Table 5.1. In that table we have also listed values of $q_D = Q(z_D)$.

Table 5.1. Ducting (low probability) constants

Climate	q_D	z_D	C_D
Equatorial	.10	1.282	1.224
Continental Subtropical	≈.015	2.161	.801
Maritime Subtropical	.10	1.282	1.380
Desert	0	∞	–
Continental Temperate	.10	1.282	1.224
Maritime Temperate Overland	.10	1.282	1.518
Maritime Temperate Oversea	.10	1.282	1.518

5.2. Location variability.

We set

$$Y_L = \sigma_L z_L \tag{5.9}$$

where

$$\sigma_L = 10k\Delta h(d)/(k\Delta h(d) + 13)$$

and $\Delta h(s)$ is defined in (3.9) above.

5.3. Situation variability.

Set

$$\sigma_S = 5 + 3e^{-de/\mathrm{D}} \tag{5.10}$$

where $D = 100$ km. Then

$$Y_S = \left(\sigma_S^2 + \frac{Y_T^2}{7.8 + z_S^2} + \frac{Y_L^2}{24 + z_S^2}\right)^{1/2} z_S \tag{5.11}$$

The latter is intended to reveal how the uncertainties become greater in the wings of the distributions.

6. Addenda—numerical approximations.

Part of the algorithm for the ITM consists in approximations for the standard functions that have been used. In these approximations, computational simplicity has often taken greater priority than accuracy.

The Fresnel integral is used in §4.1.1 and is defined in (4.21). We have (for $v > 0$)

$$\mathrm{Fn}(v) \approx \begin{cases} 6.02 + 9.11v - 1.27v^2 & \text{if } v \leq 2.40 \\ 12.953 + 20 \log v & \text{otherwise} \end{cases} \tag{6.1}$$

The functions $B(K)$, $G(x)$, $F(x, K)$, $C_1(K)$, which are used in diffraction around a smooth earth, are also used in §4.1.1 and are defined in (4.22)–(4.25). We have

$$B(K) \approx 1.607 - |K| \tag{6.2}$$

$$G(x) = .05751x - 10 \log x \tag{6.3}$$

$$F(x, K) \approx \begin{cases} F_2(x, K) & \text{if } 0 < x \leq 200 \\ G(x) + 0.0134xe^{-x/200}(F_1(x) - G(x)) & \text{if } 200 < x < 2000 \\ G(x) & \text{if } 2000 \leq x \end{cases} \tag{6.4}$$

where

$$F_1(x) = 40 \log(\max(x, 1)) - 117 \tag{6.5}$$

$$F_2(x, K) = \begin{cases} F_1(x) & \text{if } |K| < 10^{-5} \text{ or } x(-\log|K|)^3 > 450 \\ 2.5 \cdot 10^{-5} x^2/|K| + 20 \log|K| - 15 & \text{otherwise} \end{cases} \tag{6.6}$$

The final approximation here is

$$C_1(K) \approx 20 \tag{6.7}$$

To complete this section we have the two functions, $F(\theta d)$ and H_0, used for tropospheric scatter. First,

$$F(D, N_s) = F_0(D) - 0.1(N_s - 301)e^{-D/D_0} \tag{6.8}$$

where

$$D_0 = 40 \text{ km}$$

and (when D is given in meters)

$$F_0(D) = \begin{cases} 133.4 + 0.332 \cdot 10^{-3}D - 10 \log D & \text{for } 0 < D \leq 10 \text{ km} \\ 104.6 + 0.212 \cdot 10^{-3}D - 2.5 \log D & \text{for } 10 < D \leq 70 \text{ km} \\ 71.8 + 0.157 \cdot 10^{-3}D + 5 \log D & \text{otherwise} \end{cases} \tag{6.9}$$

The frequency gain function may be written as

$$H_0 = H_{00}\,(r_1, r_2, \eta_s) + \Delta H_0 \tag{6.10}$$

where

$$\Delta H_0 = 6(0.6 - \log\eta_s) \log s_s \log r_2 / s_s r_1 \tag{6.11}$$

and where H_{00} is obtained by linear interpolation between its values when η_s is an integer. For $\eta_s = 1, \ldots, 5$ we set

$$H_{00}(r_1, r_2, j) = \frac{1}{2}[H_{01}(r_1, j) + H_{01}(r_2, j)] \tag{6.12}$$

with

$$H_{01}(r, j) = \begin{cases} 10 \log(1 + 24r^{-2} + 25r^{-4}) & j = 1 \\ 10 \log(1 + 45r^{-2} + 80r^{-4}) & j = 2 \\ 10 \log(1 + 68r^{-2} + 177r^{-4}) & j = 3 \\ 10 \log(1 + 80r^{-2} + 395r^{-4}) & j = 4 \\ 10 \log(1 + 105r^{-2} + 705r^{-4}) & j = 5 \end{cases} \tag{6.13}$$

For $\eta_s > 5$ we use the value for $\eta_s = 5$ and for $\eta_s = 0$ we suppose

$$H_{00}(r_1, r_2, 0) = 10 \log \left[\left(1 + \frac{\sqrt{2}}{r_1}\right)^2 \left(1 + \frac{\sqrt{2}}{r_2}\right)^2 \frac{r_1 + r_2}{r_1 + r_2 + 2\sqrt{2}} \right] \tag{6.14}$$

In all of this, we truncate the values of s_s and $q = r_2/s_s r_1$ at 0.1 and 10.

Annex B: Longley-Rice Parameters for TV Broadcast Field Strength Calculations

I. Introduction

Annex B provides a description of elements to be taken into account in implementing the Longley-Rice radio propagation model—also known as the Irregular Terrain Model ("ITM")—in order to use this model to calculate the field strength of a television broadcasting station signal at a particular geographic location. As described in Annex A, implementations of the Longley-Rice model occur as programs written in a specific computer language. For example, the Institute for Telecommunication Sciences ("ITS"), a research and engineering laboratory of the National Telecommunications and Information Administration ("NTIA") within the United States Department of Commerce, maintains the "definitive" representation of the Longley-Rice model, which is written in FORTRAN[13].

These software implementations of the Longley-Rice radio propagation model will require several inputs to perform the field strength calculation for broadcast television. Although the specific inputs may depend on the particular software implementation used or developed, required parameters/data generally will fall into four categories:

a) Television Broadcasting Station Parameters
b) Planning Factors for Television Reception
c) Longley-Rice Environmental Parameters
d) Terrain Profile Data

In addition, certain path calculations—described below—will need to be taken into account in order to predict television broadcasting field strength at a given location.

II. Model Parameters

The Longley-Rice radio propagation model can be implemented in "area" mode or "point-to-point" mode. The point-to-point mode is used to evaluate the predicted strength of a particular television channel at a geographic location where a White Space Device ("WSD") is present. With the point-to-point mode, field strength at a particular geographic location is determined using path-specific parameters determined from detailed terrain profile data. In addition to the location of the WSD and the WSD antenna height (for fixed WSD deployments), software implementations of the Longley-Rice model will require the following input parameters.

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[13] *See generally* Implementation of the Irregular Terrain Model, version 1.2.2 (updated 5 Aug. 2002), *available at* http://www.its.bldrdoc.gov/media/35869/itm.pdf.

A. Television Broadcast Station Parameters

The Longley-Rice model requires the input of television broadcasting station parameters to be used in propagation calculations. For determining accurate field strength values for television stations, the relevant parameters would be those of licensed television stations of interest for each television channel to be evaluated at the WSD location. A software implementation of the Longley-Rice model thus should be designed to access a database of the following relevant licensed television broadcasting station technical characteristics:

- Frequency: The carrier frequency of the transmitted broadcast signal.
- Effective Radiated Power (ERP): i.e., W, kW, dBW, dBm
- Antenna: Absent additional information, implementations of the Longley-Rice model will assume the use of an omni-directional antenna. This is only an assumption, however, and the model will account for antenna directionality if supplied.
- Height: The height of antenna above the ground (supplied in meters or feet); the effective height for calculations should then be estimated by the software implementation of the model[14].
- Polarization: Horizontal polarization should be denoted.

B. Planning Factors for DTV Reception

The planning factors shown in Table 1 are assumed to characterize the equipment, including antenna systems, used for home reception of DTV signals[15]. They determine the minimum field strength for DTV reception as a function of frequency band and as a function of the channel in the UHF band. Implementations should assume a 10 m height above ground for the television receiving antenna[16].

Table 1: Planning Factors for DTV Reception

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[14] *See* Hufford, G. A., A. G. Longley, and W. A. Kissick (1982)280, A guide to the use of the ITS Irregular Terrain Model in the area prediction mode, NTI301A Report 82-100. (NTIS Order No. PB82-217977). *See generally* National Aeronautics and Space Administration, Shuttle Radar Topography Mission: The Mission to Map the World, at " http://www2.jpl.nasa.gov/srtm/.

[15] See Federal Communications Commission, Office of Engineering and Technology Bulletin No. 69, Longley-Rice Methodology for Evaluating TV Coverage and Interference at 3 (6 Feb. 2004), *available at* http://transition.fcc.gov/Bureaus/Engineering_Technology/Documents/bulletins/oet69/oet69.pdf("OET Bulletin No. 69").

[16] *Id.*

Planning Factor	Symbol	Low VHF	High VHF	UHF
Geometric mean frequency (MHz)	F	69	194	615
Dipole factor (dBm-dBu)	K_d	-111.8	-120.8	-130.8
Dipole factor adjustment	K_a	none	none	see below
Thermal noise (dBm)	N_t	-106.2	-106.2	-106.2
Antenna Gain (dBd)	G	4	6	10
Downlead line loss (dB)	L	1	2	4
System noise figure (dB)	N_s	10	10	7
Required Carrier to Noise ratio (dB)	C/N	15	15	15

The following dipole factor adjustment calculation, K_a = 20 log[615/(channel mid-frequency in MHz)], should be added to K_d to account for the fact that field strength requirements are greater for UHF channels above the geometric mean frequency of the UHF band and smaller for UHF channels below that frequency.

C. Longley-Rice Parameters

In addition to the technical operating characteristics for a given broadcast transmitter and planning factors for television reception, the Longley-Rice model contemplates the use of the following parameters that describe the environment in which the transmitter is operating (or, more precisely, statistics about the environment where the transmitter operates).

- Surface Refractivity: N_S.[17] This is the refractivity of the atmosphere, measured in N-Units (parts per million), which typically ranges from 250 to 400 N-units. ITS guidance on Longley-Rice model implementation[18] includes the following values:

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[17] Note that the N-Unit value for surface refractivity is a separate parameter unrelated to the symbols denoting noise in Table 1 above.

[18] *See* Hufford, G. A., A. G. Longley, and W. A. Kissick (1982)280, A guide to the use of the ITS Irregular Terrain Model in the area prediction mode, NTI301A Report 82-100. (NTIS Order No. PB82-217977).

Table 2: ITS Values for N_s

Radio Climate	N_s (N-units)
Equatorial (Congo)	360
Continental Subtropical (Sudan)	320
Maritime Subtropical (West Coast of Africa)	370
Desert (Sahara)	280
Continental Temperate	301
Maritime Temperate, over land (United Kingdom and continental west coasts)	320
Maritime Temperate, over sea	350
For average atmospheric conditions, use a Continental Temperate climate and $N_s = 301$ N-units	

- Permittivity: This is the dielectric constant of the ground. ITS guidance includes the values in Table 3 below.
- Conductivity: Soil conductivity of the ground. ITS guidance includes the values in Table 3 below.

Table 3: ITS Values for Electrical Ground Constants

	Relative Permittivity	Conductivity (Siemens per Meter)
Average ground	15	0.005
Poor ground	4	0.001
Good ground	25	0.020
Fresh water	81	0.010
Sea water	81	5.0
For most purposes, use the constants for an average ground		

- Climate Zone: This value is entered as per climate codes that correspond with the seven climate categories specified in Table 1 above. Together with N_s, the climate serves to characterize the atmosphere and its variability in time.
- Variability. The Longley-Rice model includes the following three kinds of variability:
  - Location Variability (reliability and confidence level): This value is expressed as a percentage from 0.1% to 99.9%. Location variability accounts for variations in long-term statistics that occur from path to path.
  - Time Variability: This value is expressed as percentage from 0 to 100%. Time

variability accounts for variations of median values of attenuation.

  - Situation Variability: This value is expressed as a percentage; 50% variability is considered normal for coverage estimations. Situation variability accounts for variations between systems with the same system parameters and environmental conditions.

- Variability modes: ITS guidance contemplates the following ways in which the kinds of variability listed above are treated in combination:

  - Broadcast mode: all three kinds of variability are treated separately.
  - Individual mode: situation and location variability are combined; time variability is treated separately.
  - Mobile mode: time and location variability are combined; situation variability is treated separately.
  - Single message mode: all three kinds of variability are combined.

The values listed in Table 4 below have historically been utilized when implementing the Longley-Rice model for television signal analysis,[19] and should be used to calculate the field strength of a television broadcasting station signal at a particular geographic location.

Table 4: Longley-Rice Parameter Values for Television Signal Analysis

Longley-Rice Parameter	Value
Surface refractivity in N-units (parts per million)	301.0
Relative permittivity of ground	15.0
Ground conductivity, Siemens per meter	0.005
Climate zone code	5 (continental temperate)
Mode for variability calculations	Broadcast mode

D. Terrain Profile Path Data

The Longley-Rice model may use terrain elevation values to create a detailed profile of a path for analysis by the program. The model was designed to use terrain data at equal increments along a path. Points not at equal increments are ignored. Consequently, field strength values are calculated values out to the last uniformly spaced point on a given radial.

A Longley-Rice implementation may achieve greater precision by utilizing values given by specific terrain datasets collected using empirical measurements. For example, the Shuttle Radar Topography Mission (SRTM) undertaken by the National Aeronautics and Space Administration (NASA) obtained elevation data on a near-global scale in order to create a high-resolution digital topographic database of most of the Earth, providing 3 arc-second (~ 90 m) resolution data for

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[19] *See* OET Bulletin No. 69 at 6.

most of the continents between 60 N and 60 S[20]. In many populated areas, higher resolution sources of terrain data are available.

I. Path Calculations

The Longley-Rice model uses input parameters to compute geometric parameters related to the propagation path. First, the model determines effective antenna height. Since this is an area prediction model, the radio horizons, for example, are unknown. The model uses the terrain irregularity parameter to estimate radio horizons. The model also computes a reference attenuation, using horizon distances and elevation angles to calculate transmission loss relative to free space.

The Longley-Rice model will treat the terrain that separates the television broadcast station and the white space device location as a random function characterized by Δh. The model uses a signal value Δh to represent the size of the irregularities. Roughly speaking, Δh is the interdecile range of terrain elevations—that is, the total range of elevations after the highest 10% and lowest 10% have been removed. Suggested values for Δh provided by ITS are set forth in Table 5 below.

Table 5: ITS Values for Terrain Irregularity

	Δh (meters)
Flat (or smooth water)	0
Plains	30
Hills	90
Mountains	200
Rugged Mountains	500

For an average terrain, use Δh = 90 m

II. Summary

This annex describes input parameters, terrain data, and calculations that must be taken into account in implementing software to build an application to calculate the field strength of a television broadcasting station at a particular location. Determining the field strength of relevant television broadcast stations at a specific location will be used to determine at what level and at what power level a WSD may operate at that location pursuant to the procedure outlined in Annex C.

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[20] *See generally* National Aeronautics and Space Administration, Shuttle Radar Topography Mission: The Mission to Map the World, at http://www2.jpl.nasa.gov/srtm/.

Annex C: Calculation of Available TV White Space Frequencies and Power Limits

I. Introduction

This Annex provides the detailed parameters and methodology to calculate the frequencies and maximum power limits for White Space Devices in such as way as to minimize the probability of harmful interference to other services. We are applying Longley-Rice calculations to achieve the goal of minimizing coupling loss. These calculations describe a specific application of the algorithms provided in Annexes A and B.

II. Definitions

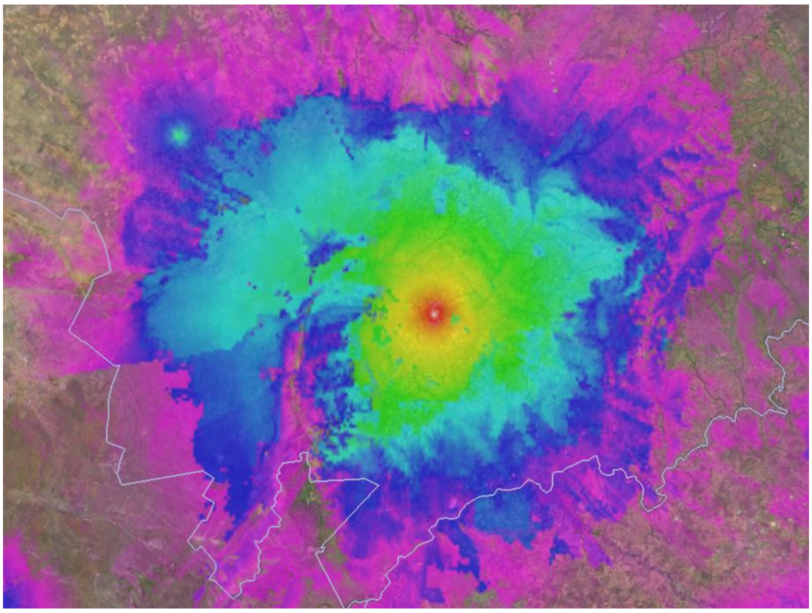
This section describe the various entities and their relationships with regard to frequency and signal strength calculations. Interference from White Space Devices (WSDs) is controlled by limiting their radiated power. The following definitions describe an approach for how those power limits can be calculated.

1. Protected services

1.1. Analog terrestrial television(ATT): PAL-I standard

The service area of an analog TV broadcast includes any locations where the signal to noise ratio of its signal is greater than or equal to 17.0 dB plus a link margin of 13 dB.[21]

Figure 1: Example coverage map showing "in service" areas extending out to blue areas, purple = "too weak" ("out of service")



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[21] A service's signal to noise ratio (SNR) limit is the minimum theoretical operating level for a service to be functional, while the link margin accounts for the extra signal power that is typically required to cope with real-world environments. The link margin provides a buffer so that the service is somewhat robust against common signal impairments like multi-path, fading, and interference.

1.2. Digital terrestrial television (DTT): DVB-T2 standard

The service area of a digital TV broadcast includes any locations where the signal to noise ratio of its signal is greater than or equal to 17.0 dB plus a link margin of 13 dB. Given that the proposed methodology analyzes transmitters individually, Single Frequency Networks (SFNs) and Multi-Frequency Networks (MFNs) can be treated the same.

1.3. Radio astronomy sites (RASs)

The protected area of radio astronomy sites (RASs) particularly the Square Kilometer Array (SKA) project sites are designated as Radio Quite Zones (RQZs). However, this designation also extends to some other SKA sites that are not located within the RQZs. The prescribed minimum received Power Spectral Density (PSD) around each site must be not exceed - xx dBWHz^{-1}. These methodology for calculating the protections from White Spaces is still to be determined.

1.4. Other

Radio astronomy frequencies, Lower band edge, Upper band edge, Wireless microphones, Studio to transmitter links, Cable TV receive sites and Gap Filter terrestrial television stations may require additional protections. Further analysis and industry consultation is required.

2. Receiver characteristics

2.1. Analog television (PAL-I)

An analog TV receiver's sensitivity to White Space Device interference is a function of its adjacent channel rejection ratio (ACR). If a receiver is tuned to channel "N", it can tolerate signals on adjacent channels without harmful interference if the relative signal strength are less than the values given in Table 1.[22]

Table 1: Analog TV adjacent channel rejection ratios

Channel offset	Relative signal strength (dB)
N-10 or lower	62
N-9	60
N-8	58
N-4	55

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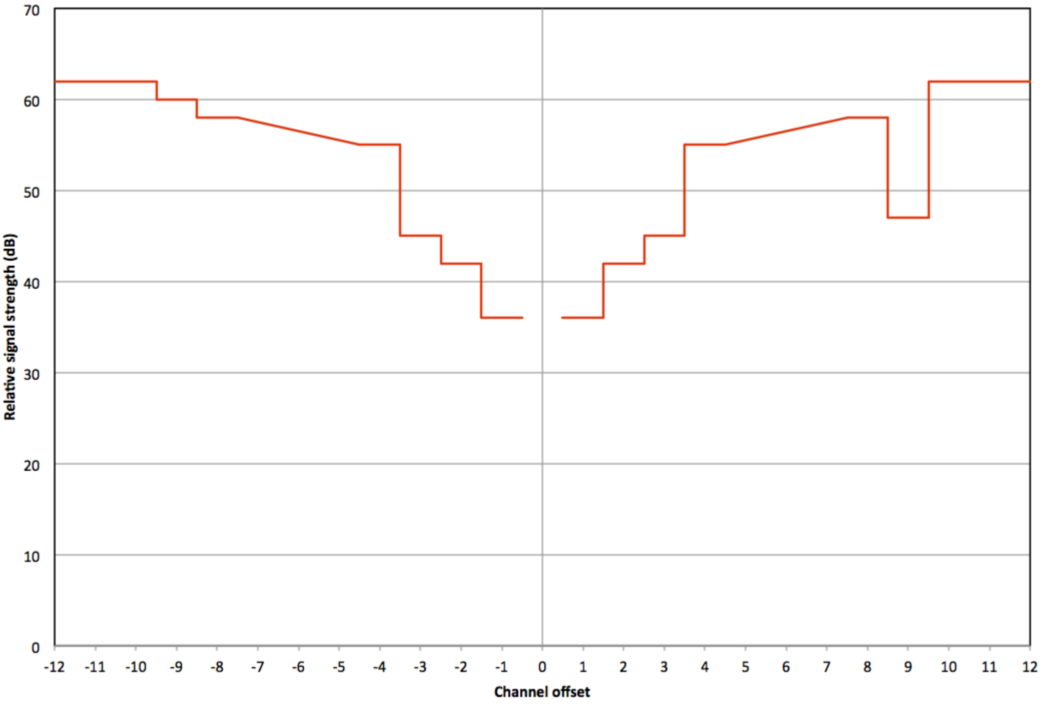
[22] The ACR performance values are based on an Ofcom analysis of 50 commercially available receivers currently on the market. See Ofcom technical-report.pdf - TV white space: approach to coexistence.

N-3	45
N-2	42
N-1	36
N+1	36
N+2	42
N+3	45
N+4	55
N+8[23]	58
N+9	47[24]
N+10 or higher	62

Figure 2: Plot of analog TV adjacent channel rejection ratios



2.2. Digital television (DVB-T2)

A digital TV receiver's sensitivity to White Space Device interference is a function of its adjacent channel rejection ratio (ACR). If a receiver is tuned to channel "N", it can

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[23] Values between N±4 and N±8 should be linearly interpolated.

[24] The ACR performance on channel N+9 is different than N-9 due to internal tuner design limitations.

tolerate signals on adjacent channels without harmful interference if the relative signal strength are less than the values given in Table 2.[25]

2.3. Mobile digital terrestrial television (MDDT): DVB-H standard

The reference minimum media field strength values of DVB-H reception for band IV and band V are prescribed in table 11.14 and 11.15 in the DVB blue book.

Table 2: Digital TV adjacent channel rejection ratios

Channel offset	Relative signal strength (dB)
N-10 or lower	62
N-9	60
N-8	58
N-4	55
N-3	45
N-2	42
N-1	36
N+1	36
N+2	42
N+3	45
N+4	55
N+8[26]	58
N+9	47[27]
N+10 or higher	62

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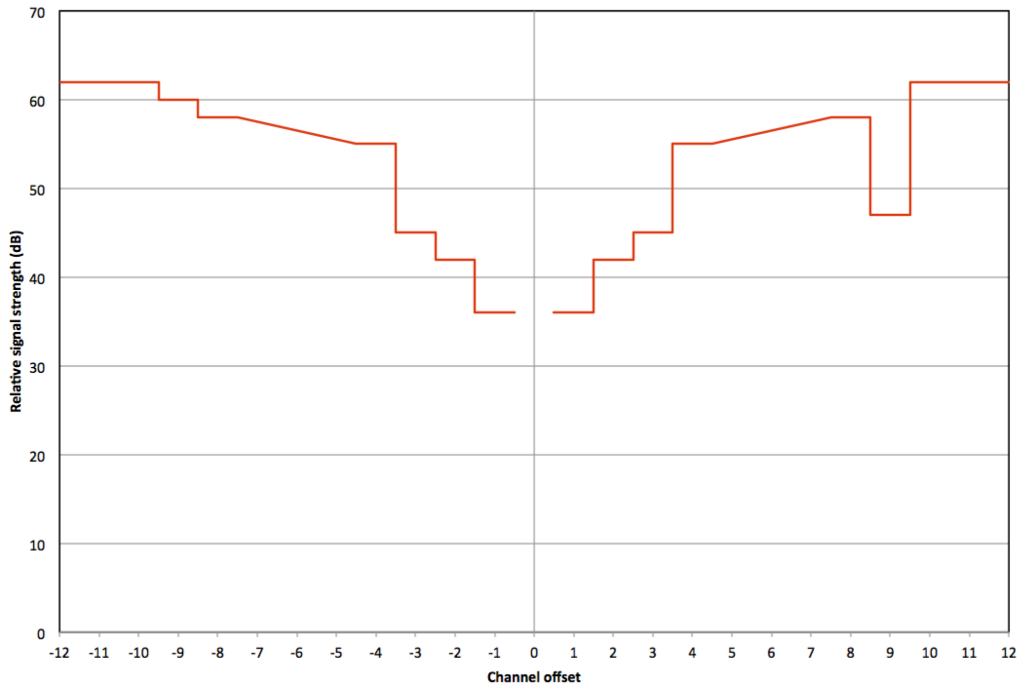
[25] The ACR performance values are based on an Ofcom analysis of 50 commercially available receivers currently on the market. See Ofcom technical-report.pdf - TV white space: approach to coexistence.

[26] Values between N±4 and N±8 should be linearly interpolated.

[27] The ACS performance on channel N+9 is different than N-9 due to internal tuner design limitations.

Figure 3: Plot of digital TV adjacent channel rejection ratios



3. WSD coupling loss

The coupling loss between a White Space Device and other types of receivers is assumed to be 60 dB.[28]

4. Resolving Terrain Overlap

Terrain data files are generally organized in "tiles" (rectangular rasters aligned to latitude and longitude bins) that include overlapping data along each of its edges. When overlapping tiles contain non-identical data in their overlapping zones, there is the potential for elevation ambiguity in those areas.

To resolve this ambiguity, the following tile selection methodology shall be used. For any given point, exactly one terrain tile will be selected as the authoritative source of elevation data.

1. For any given point (lat and lon), determine the set of tiles that include the requested lat and lon coordinates. The number of matching tile candidates is expected to be between 0 and 4.

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[28] The coupling loss accounts for a multitude of factors, including the separation distance between devices, antenna discrimination, polarization discrimination, building attenuation, physical obstructions, etc.

    a. If the number of matching tiles is 0 (point does not fall within any terrain tile), then treat the elevation as 0 meters and return.
    b. If the number of matching tiles is 1, then the point does not have any data overlap issues. Use bilinear interpolation to compute the terrain elevation using the selected tile.

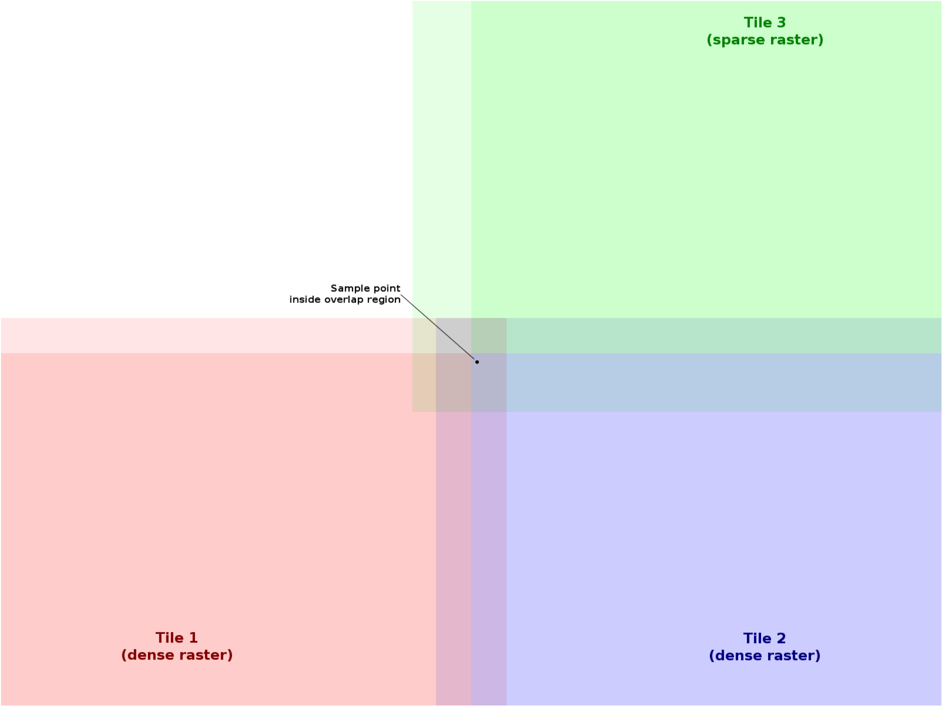
2. If 2 or more tile candidates are found, use the following criteria to select which tile to use.
    a. Compute the latitude distance from `lat` to each candidate tile. The tile(s) with the smallest latitudinal distance (`lat_distance`) wins.
    b. In case of a tie, compute the longitude distance from `lon` to each candidate tile. The tile(s) with the smallest longitude distance (`lon_distance`) wins.
    c. In case of a tie, select the tile with the lowest latitude and lowest longitude coverage (i.e., lowest numerical values).
    d. Use bilinear interpolation to compute the terrain elevation using the selected tile.

Hint: This is effectively the same as sorting the candidate tiles according to multiple keys. The primary key is the `lat_distance`$_i$, followed by `lon_distance`$_i$, `center_lat`$_i$, and `center_lon`$_i$ to resolve any ties when necessary.

Illustrated Example

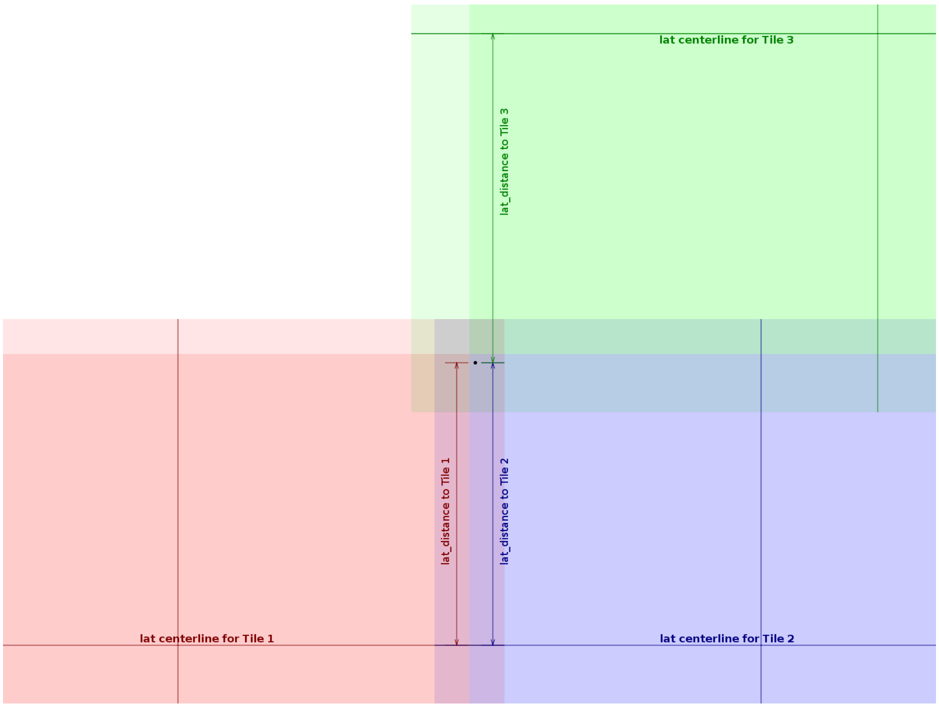
Consider a sample point that lies in the overlap zone between three tiles.

Note that the tiles do not necessarily have the same raster density or coverage range.



Since there are 2 or more candidate tiles to consider, they need to be ranked according to `lat_distance`$_i$.

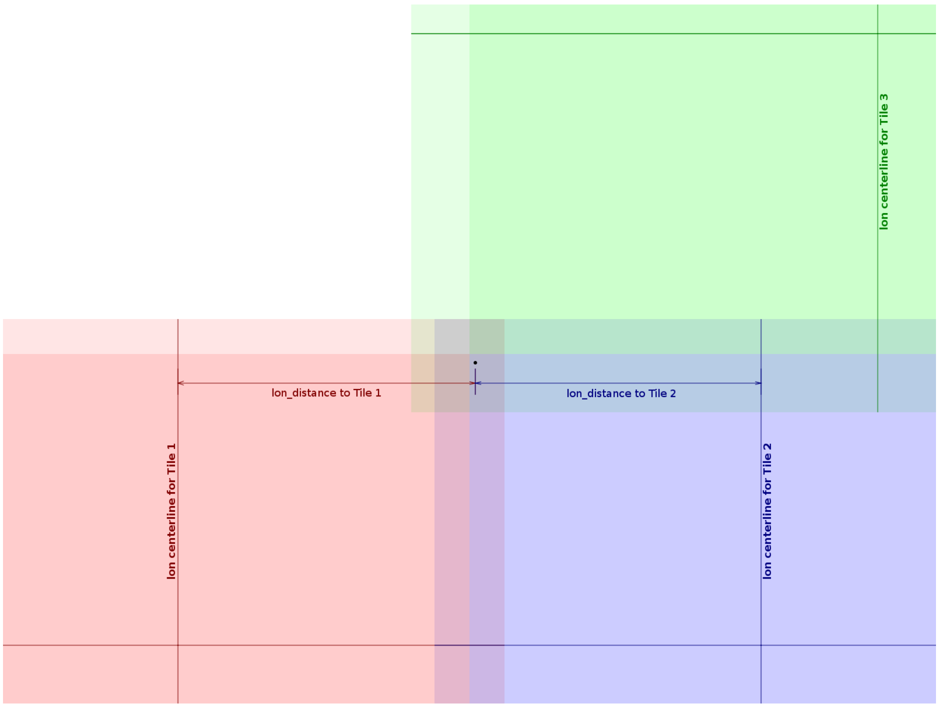
In this example, Tile 1 and Tile 2 have the same `lat_distance`. Both tiles are closer to the sample point than Tile 3.



Since the `lat_distance` for Tile 1 and Tile 2 is the same, the `lon_distance` needs to be checked.

In this example, Tile 2 is closer than Tile 1.

Tile 2 is selected as the authoritative tile to use.



5. Terrain Profile

The terrain profile between a transmit and receive point is constructed by taking the terrain elevation at equally spaced points along the shortest path between the transmitter and receiver. The shortest path is computed using the Vincenty algorithm[29]. The nominal spacing of the bins in the terrain profile is 50 meters.

II. Calculations

White space spectrum availability calculations are location-specific. For the purpose of discussion in this section, the WSD is assumed to be at a point W_0, which has a latitude of $W_{0,lat}$, a longitude of $W_{0,lon}$, and a height of $W_{0,h}$ (optional).

1. Compute frequencies that are "in use" by protected services
    a. Identify all of the protected entities that are within 300 km of point W_0.
    b. If the height of W_0 is not available, then assume that $W_{0,h}$ = 10 meters above ground.
    c. For each protected entity, apply the point-to-point propagation model prescribed in Annexes A and B to predict the residual power level of each entity at point W_0.

        Example
        i. For a TV transmitter T_i, compute the effective radiated power ($P_{i,radiated}$) of T_i in the direction of W_0, including any antenna pattern adjustments.
        ii. Use propagation modeling to compute the path loss (L_{Ti}) between T_i and W_0.
        iii. Compute the effective ambient signal power at point W_0 as $P_{i,eff} = P_{i,radiated} - L_{Ti}$
        iv. If $P_{i,eff}$ is greater than the SNR limit plus link margin for TV transmitters, then this channel is considered to be "in use" by T_i, otherwise the signal is too weak and this channel is considered to be "not in use" by T_i.

2. For each "in use" protected service, use the adjacent channel rejection ratios relative to $P_{i,eff}$ to compute the power constraints that should be applied to White Space Devices.
    a. Television example

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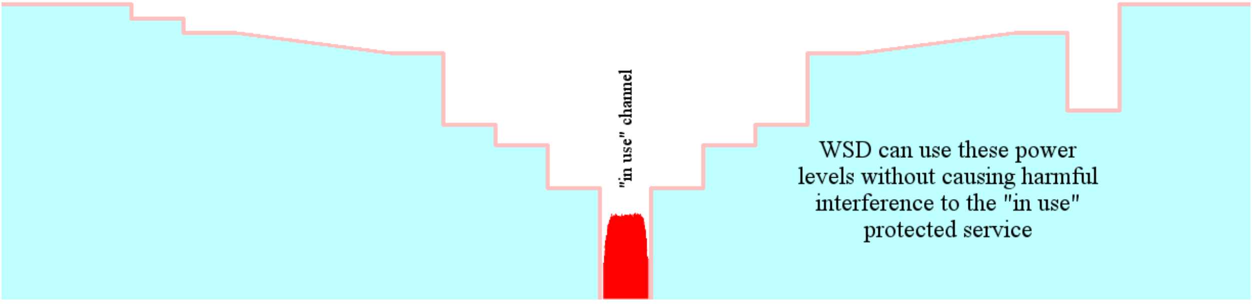
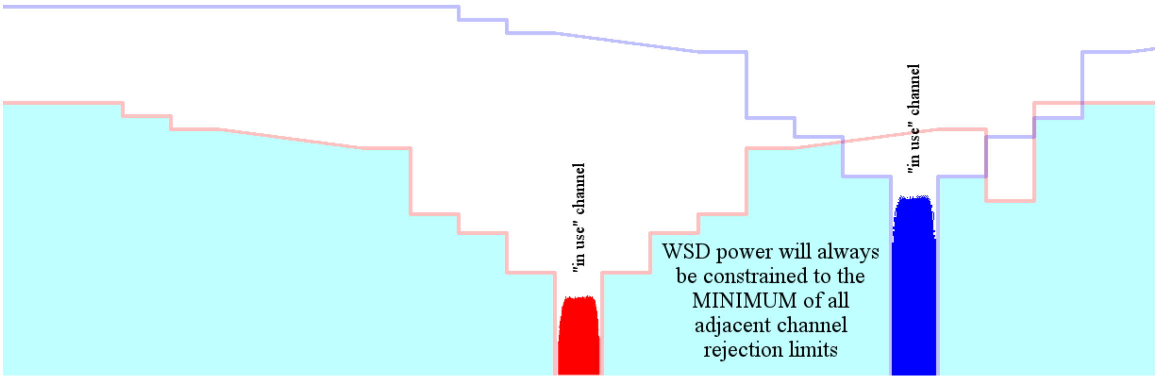
[29] The Vincenty inverse algorithm (http://www.ngs.noaa.gov/PUBS_LIB/inverse.pdf) computes the shortest ellipsoidal path between two points on an oblate spheroid (like the WGS84 reference model of the Earth).



When multiple channels are "in use", their relative adjacent channel rejection ratios can overlap. The adjacent channel restriction with the LOWEST power level is used to determine the power limit for WSD use since this prevents the WSD from causing interference on any of the active services.



After all protected services have been processed, the remaining power envelope defines the maximum permitted power levels for WSD use.

b. [Need example of channel 38?]

c. [Need example of band edges?]

3. WSD Emission mask considerations
When the WSD gets a response from the spectrum database, it must take into consideration its own out-of-band emissions mask to ensure that it will not violate the limits specified in the spectrum response.

A device might have different out-of-band emission characteristics depending on its class of device (e.g., high-end vs. low-end components), or it may use a technology that supports multiple modulation types (e.g., Wi-Fi supports up to 76 different modulation coding schemes), or there might be other factors that cause the emissions profile to change depending on current operating conditions. In each of these situations, it is up to the WSD to ensure that it's emissions profile is compliant with the database's spectrum response.

Figure 3: Example of WSD emissions profile being considered in conjunction with the power envelope provided by the spectrum database.