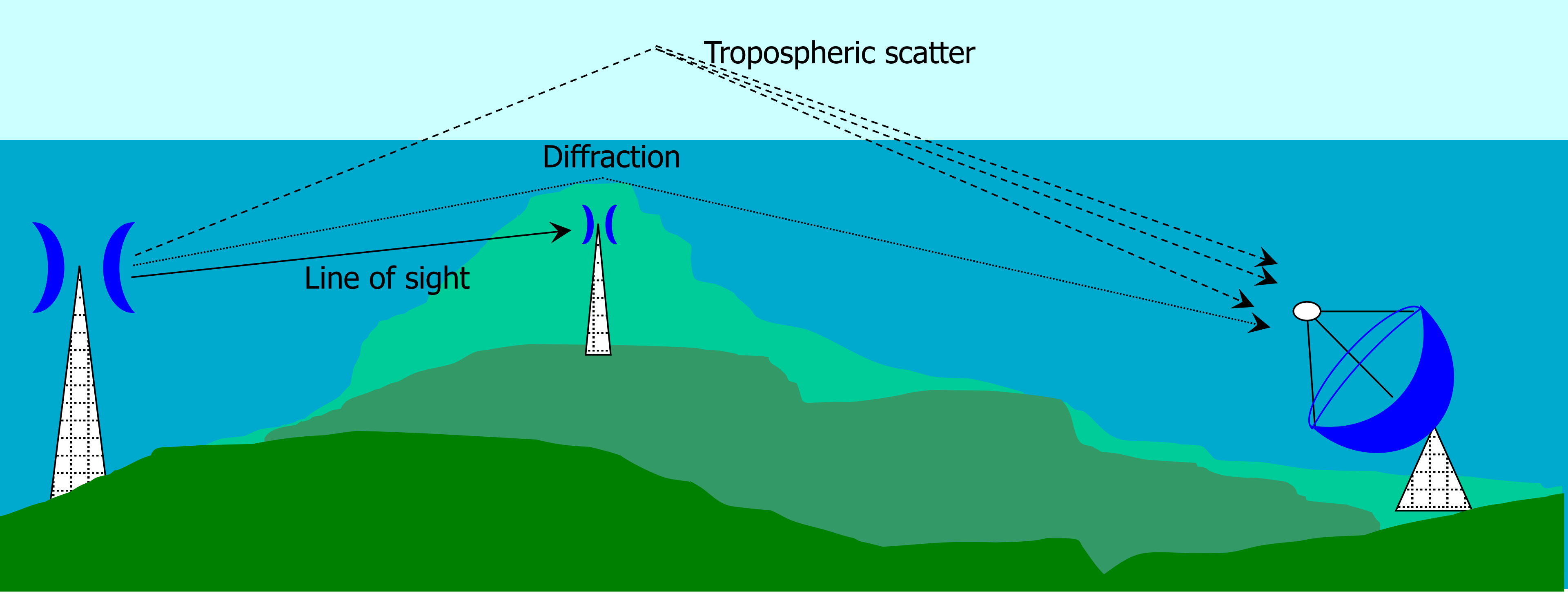


Propagation: fundamentals and models

Carol Wilson, CSIRO

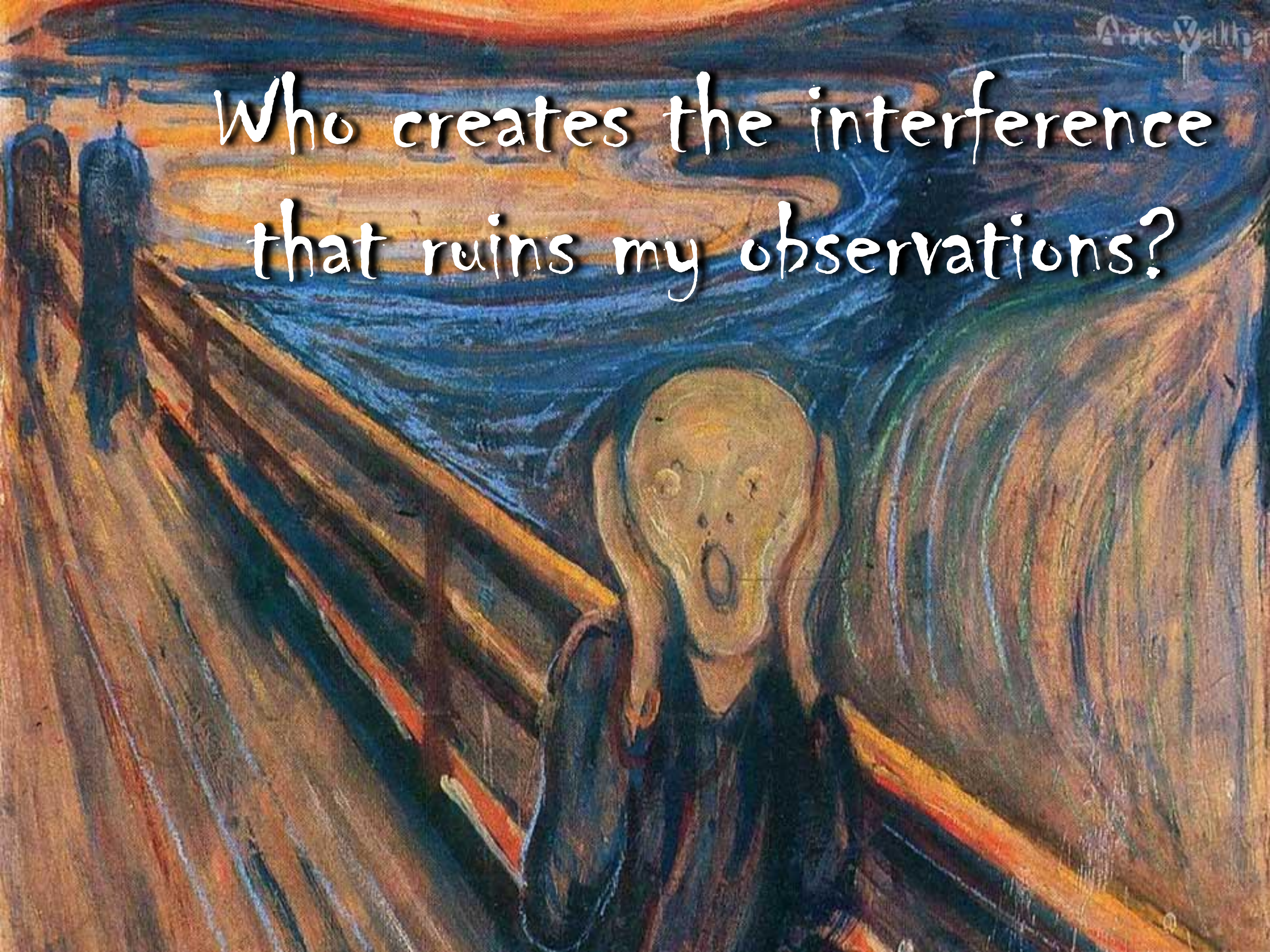
Chairman ITU-R Study Group 3 (Radiowave Propagation)

5th Summer School in Spectrum Management for Radio Astronomy

2 – 6 March 2020, Stellenbosch

Outline of presentation

- Introduction – Who creates RFI?
- Why propagation is important
- Mechanisms of radiowave propagation and prediction methods
- Types of models
- Software
- Conclusion


Who creates the interference
that ruins my observations?

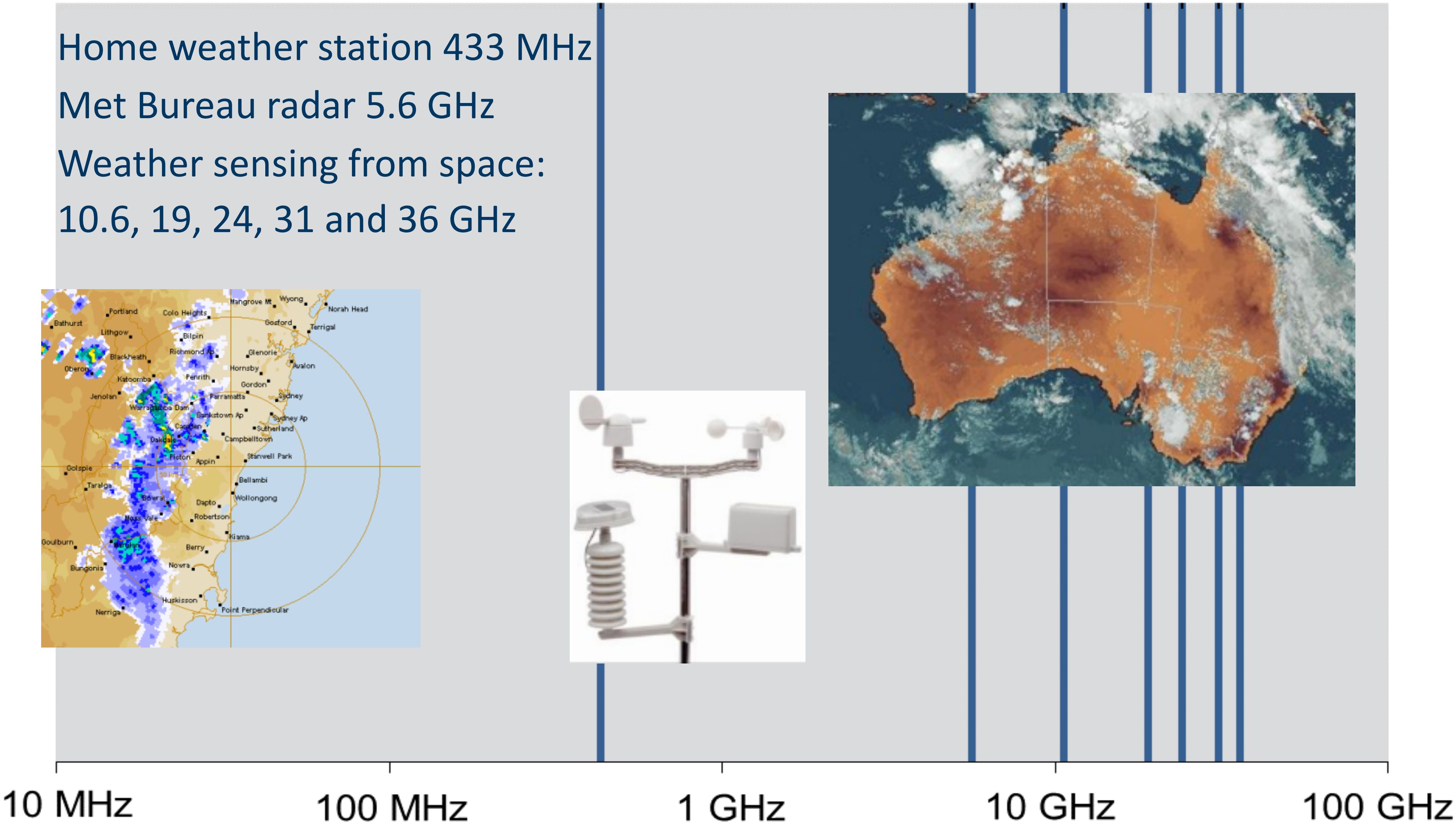
RFI from meteorological systems

Home weather station 433 MHz

Met Bureau radar 5.6 GHz

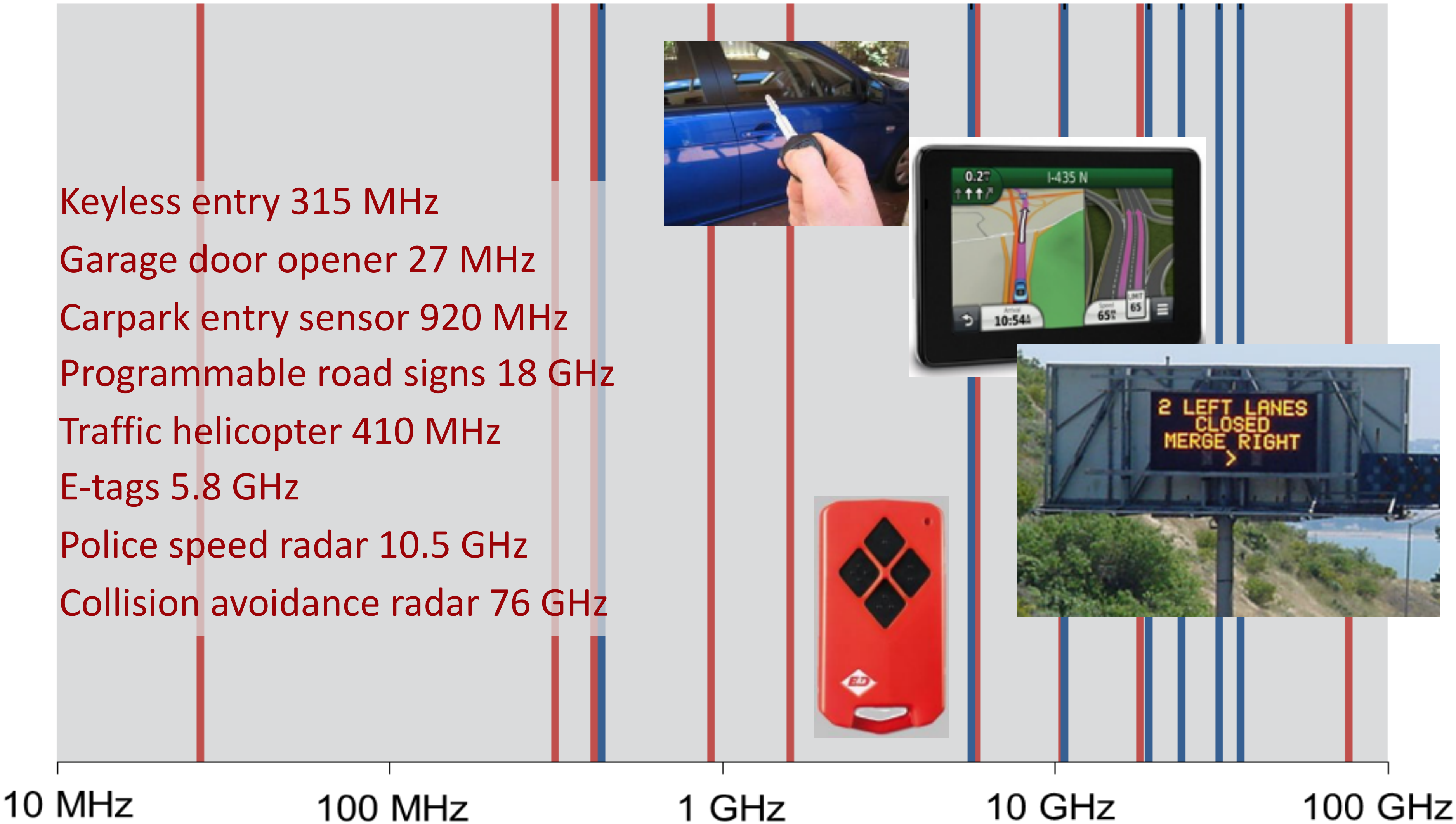
Weather sensing from space:

10.6, 19, 24, 31 and 36 GHz



RFI from transportation

- Keyless entry 315 MHz
- Garage door opener 27 MHz
- Carpark entry sensor 920 MHz
- Programmable road signs 18 GHz
- Traffic helicopter 410 MHz
- E-tags 5.8 GHz
- Police speed radar 10.5 GHz
- Collision avoidance radar 76 GHz



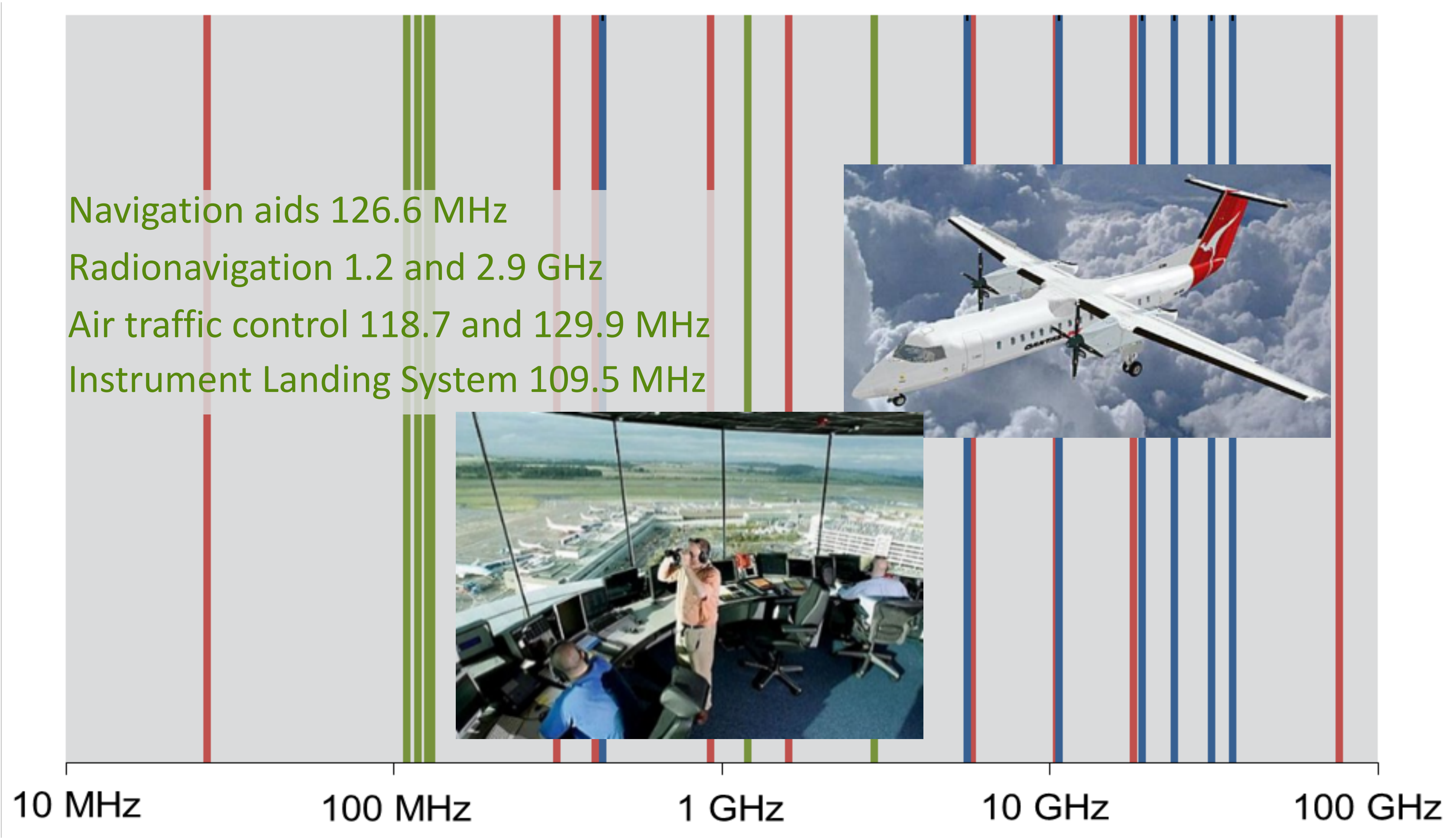
RFI from aircraft systems

Navigation aids 126.6 MHz

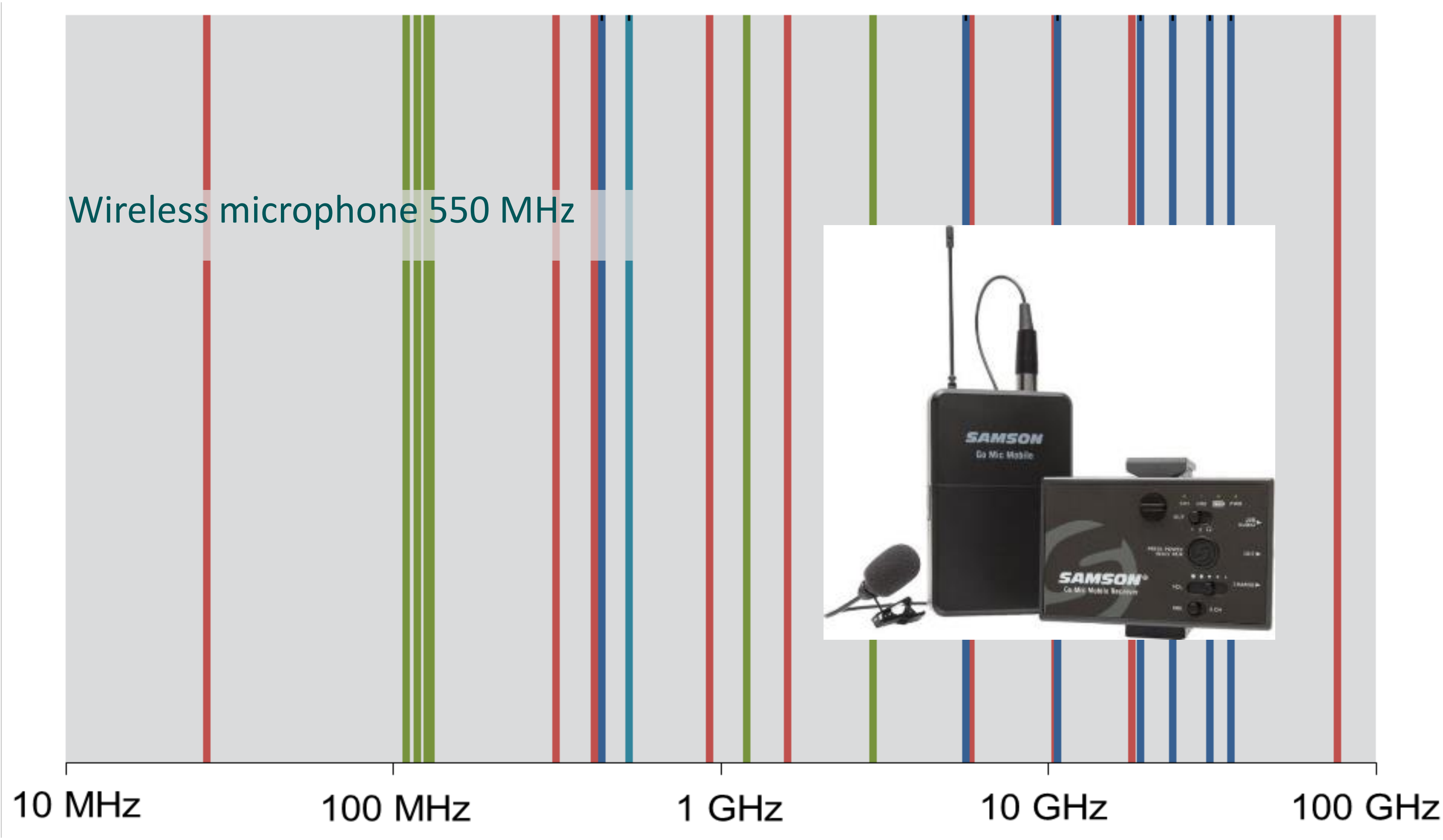
Radionavigation 1.2 and 2.9 GHz

Air traffic control 118.7 and 129.9 MHz

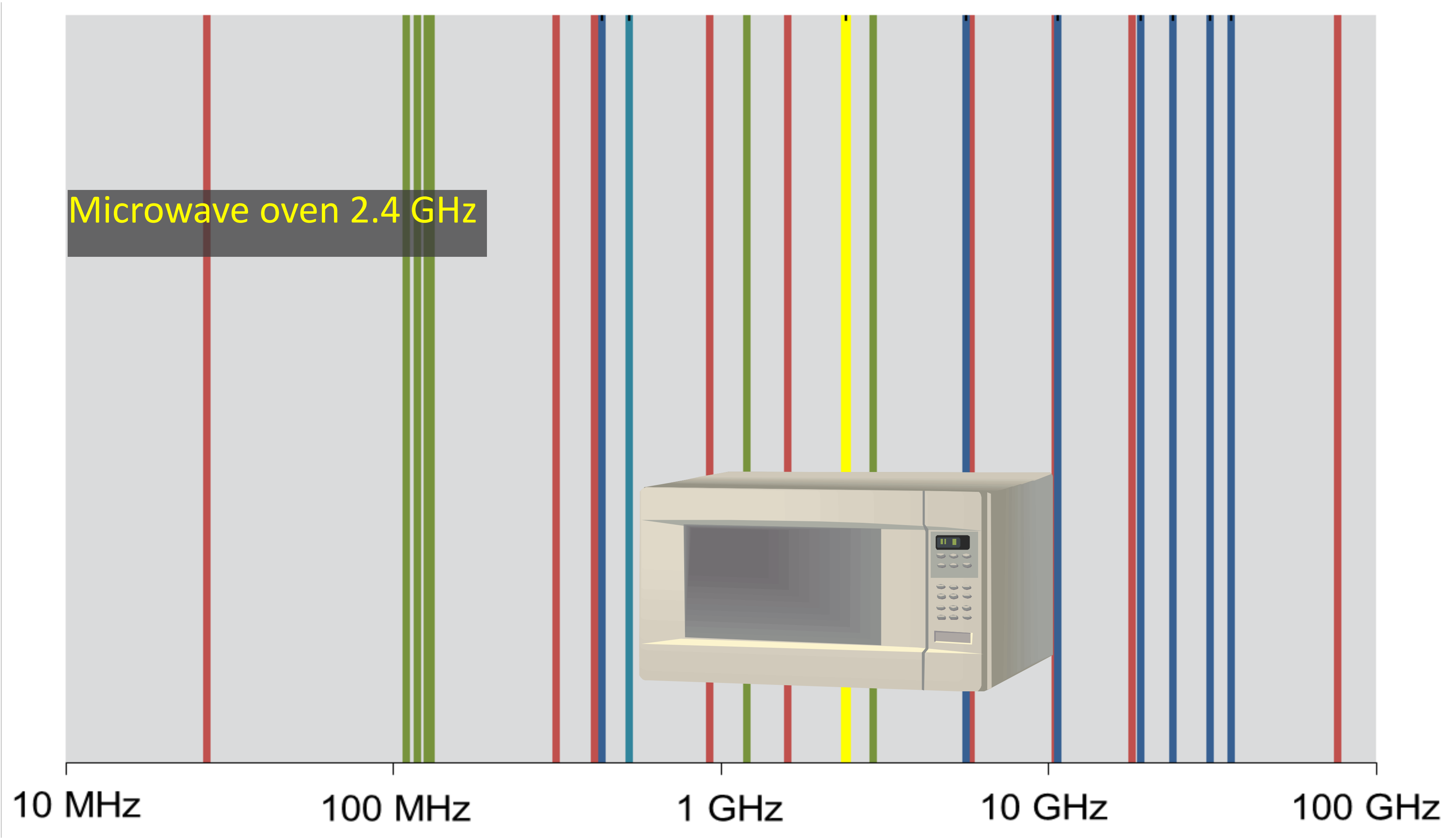
Instrument Landing System 109.5 MHz



RFI from giving a talk at a conference



Lunchtime!!



RFI from consumer communications

3G phone 2.1 GHz*

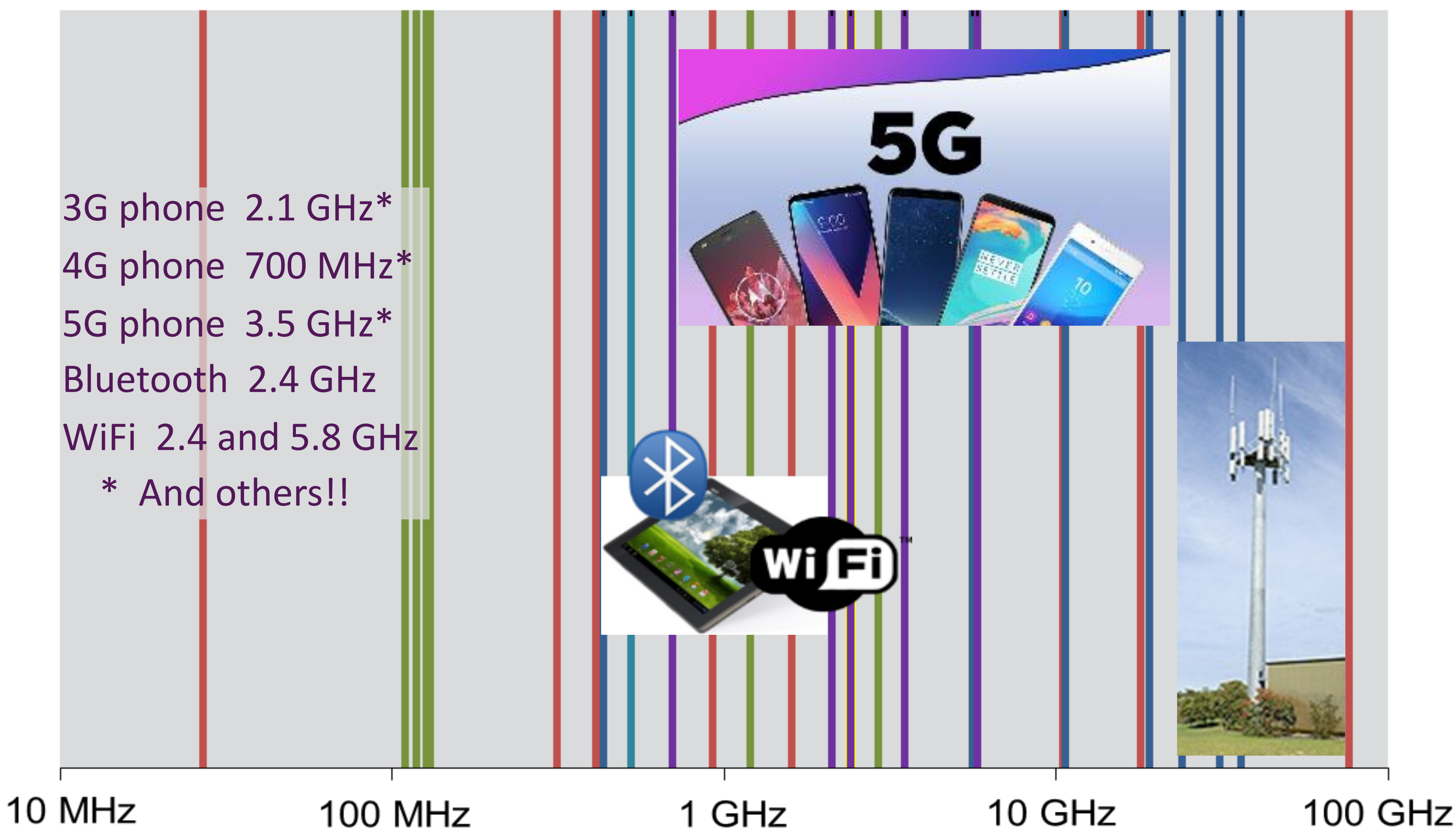
4G phone 700 MHz*

5G phone 3.5 GHz*

Bluetooth 2.4 GHz

WiFi 2.4 and 5.8 GHz

* And others!!



RFI from broadcasting

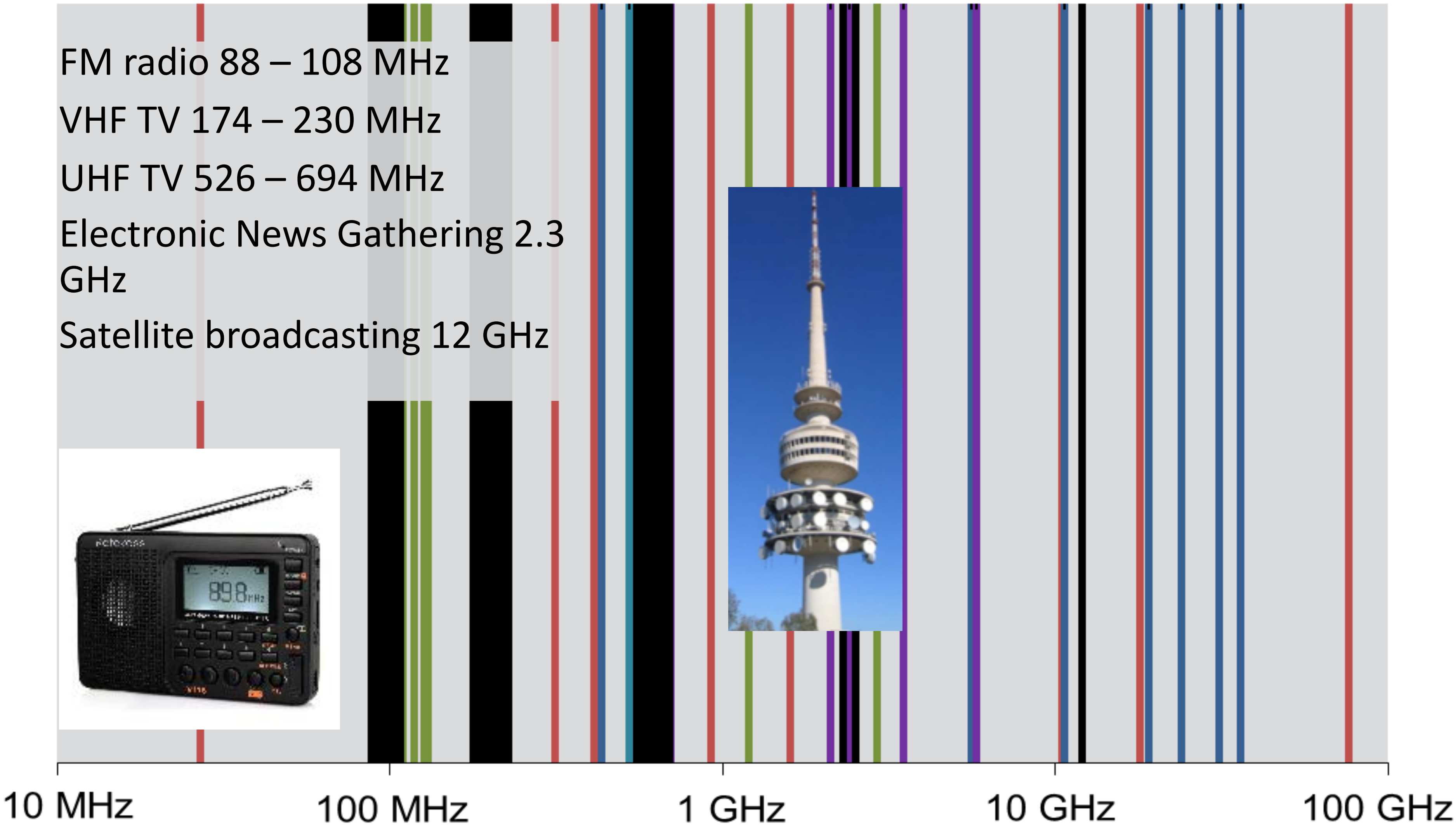
FM radio 88 – 108 MHz

VHF TV 174 – 230 MHz

UHF TV 526 – 694 MHz

Electronic News Gathering 2.3 GHz

Satellite broadcasting 12 GHz



We are the "other users of spectrum"

Urban, suburban and small towns have an increasing amount of radio system usage and electrical appliances.

The other users of the radio spectrum aren't going away. We all use spectrum for communication, entertainment, navigation and safety.

Other radio services are legally entitled to use their own spectrum.

Why does
an understanding of propagation
matter for radio astronomers?

With some knowledge of propagation you can:

- Predict levels of interference from other radio sources
- Understand variability of interference
- Assess possible interference mitigation methods

Basic definitions

- Propagation – what happens to an radio signal as it travels.
  - Enough signal where you want it to be? (System design)
  - Too much signal where you don’t want it to be? (Interference)
- Attenuation – loss due to:
  - Distance
  - Ground
  - Obstacles (terrain, buildings…)
  - Tropospheric and ionospheric variations (weather, etc)
- Occasionally gain due to constructive interference, focussing.
- Loss = $10*\log(P_{tx}/P_{rx})$ (expressed as positive number in dB)
- Does not (generally) include antenna gain or other equipment effects (cable loss, etc)

Diversion - Decibels

$X_{dB} = 10*\log_{10}(x)$ $x = 10^{(X_{dB}/10)}$

0 dB = 1 (error 0%)

1 dB = 1.25 (error 0.7%)

2 dB = $\pi/2$ (error 0.9%)

3 dB = 2 (error -0.2%)

4 dB = 2.5 (error 0.5%)

5 dB = π (error 0.7%)

6 dB = 4 (error -0.5%)

7 dB = 5 (error 0.2%)

8 dB = 2π (error 0.4%)

9 dB = 8 (error -0.7%)

10 dB = 10 (error 0%)

11 dB = 4π

12 dB = 16

...

20 dB = 100

30 dB = 1000

40 dB = 10000

-20 dB = 0.01

...

23 dB = 200

37 dB = 5000

44 dB = 25000

-16 dB = -20 dB + 4 dB = 0.025

...

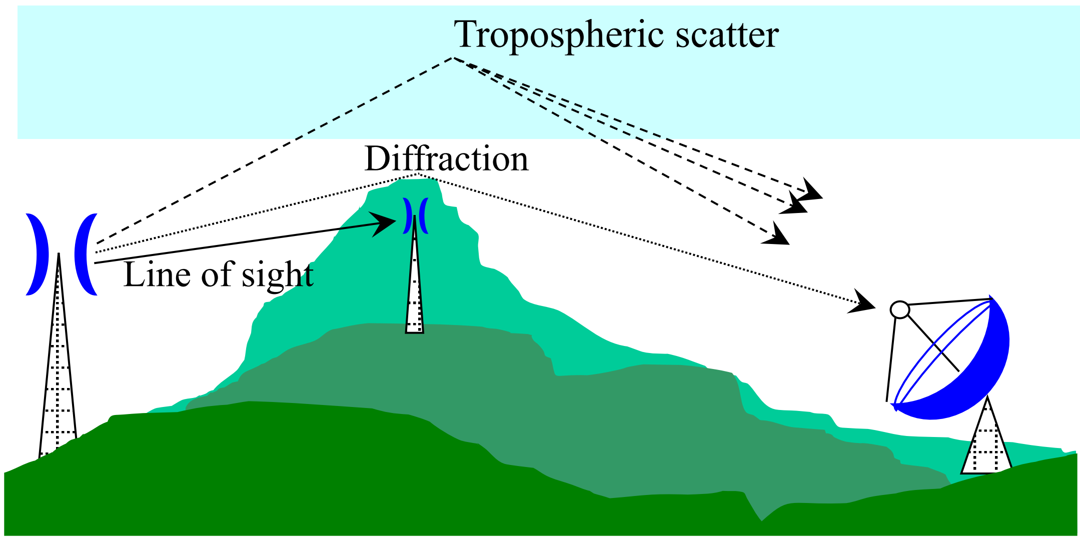
Mechanisms of propagation

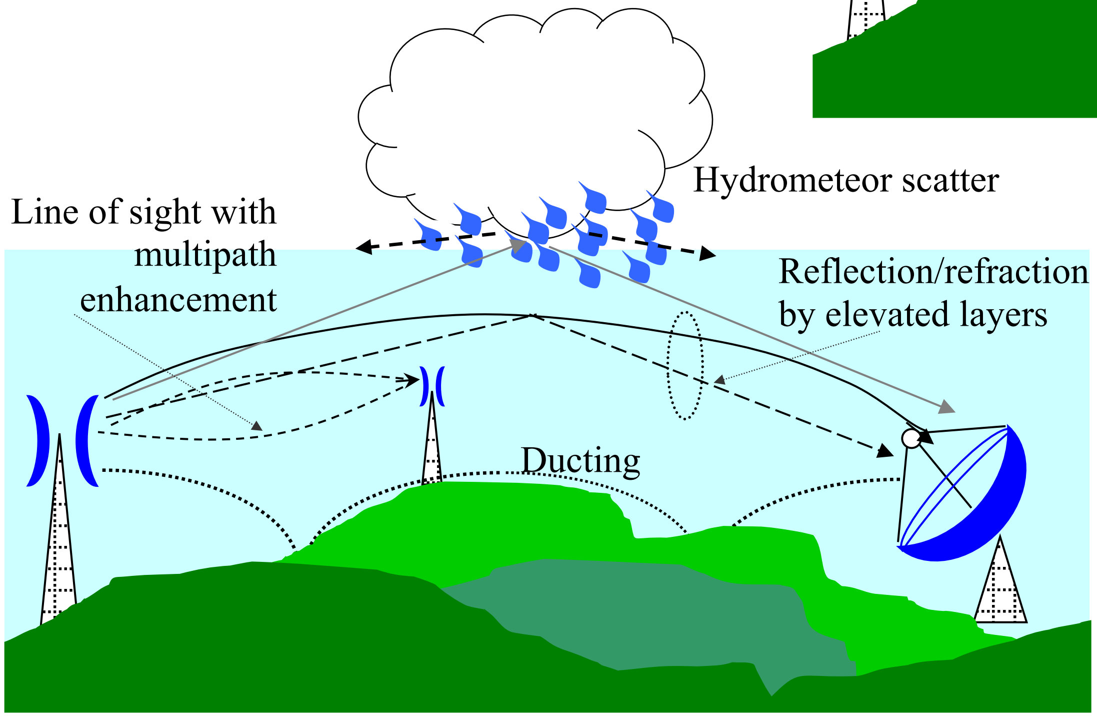
Mechanisms of propagation

- Free space – loss due simply to distance
  - Generally sets the lower bound on the loss (= upper bound on interference level)
- Mechanisms that add more loss (decrease interference)
  - Diffraction (including sub-path diffraction)
  - Attenuation by rain (snow, etc) and atmospheric gases
- Mechanisms that decrease loss (increase interference)
  - Reflection/refraction (ground or atmospheric layers)
  - Multipath in cluttered environments
  - Atmospheric ducting
  - Ionospheric sporadic-E propagation (VHF/HF)
  - Rain scatter
- Environment is complex and difficult (or impossible) to define in detail ⇨ uncertainty in prediction. (c.f. weather forecasting)

Interference mechanisms

Long-term effects ⇨





⇦ Short-term effects

ITU-R Study Group 3 Resources

Study Group 3 webpage:

https://www.itu.int/en/ITU-R/study-groups/rsg3/Pages/default.aspx

Recommendations:

https://www.itu.int/rec/R-REC-P/en

Note: these are updated when better methods or information is available. Use most recent version. (Rec P.526-15 rather than P.526-14)

Software and digital files:

- Essential software/data is with Recommendation (see above)
- Helpful software/data is at
  https://www.itu.int/en/ITU-R/study-groups/rsg3/Pages/iono-tropo-spheric.aspx

Relation between propagation values

Field strength for a given isotropically transmitted power:

$$E = P_t - 20 \log d + 74.8$$

Isotropically received power for a given field strength:

$$P_r = E - 20 \log f - 167.2$$

Free-space basic transmission loss for a given isotropically transmitted power and field strength:

$$L_{bf} = P_t - E + 20 \log f + 167.2$$

Power flux-density for a given field strength:

$$S = E - 145.8$$

where:

P_t :	isotropically transmitted power (dB(W))
P_r :	isotropically received power (dB(W))
E :	electric field strength (dB(μV/m))
f :	frequency (GHz)
d :	radio path length (km)
L_{bf} :	free-space basic transmission loss (dB)
S :	power flux-density (dB(W/m^2)).

From ITU-R Recommendation P.525

Free space loss

Attenuation of signal due to distance alone (spreading of energy on spherical wavefront).

$$L_{bf} = 20 \log (4\pi d / \lambda) \qquad \text{dB}$$

or in practical units

$$L_{bf} = 32.4 + 20 \log(f) + 20 \log (d) \qquad \text{dB}$$

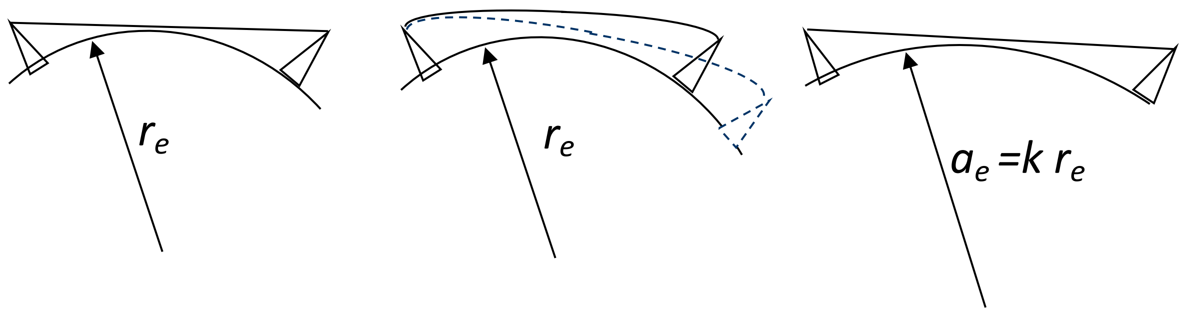
where f is in MHz and d is in km.

- For most practical situations, free space loss is the minimum loss ⇨ worst case interference.
- Applicable to interference from aircraft, satellites.
- Apparent “line-of-sight” paths not necessarily free space loss only!

ITU-R Recommendation P.525

Refraction through atmospheric layers

Ordinary atmospheric conditions create ray bending so that the radio horizon is greater than the geometric horizon.



Modelled by use of *k*-factor multiplied by physical earth radius. Median global value of *k* is 4/3.

Physical earth radius is ~6370 km. a_e = 6370*(4/3) = ~8500 km

For antenna heights h_1 and h_2, line of sight distance is:

$$d_{los} = \sqrt{2a_e}\left(\sqrt{h_1} + \sqrt{h_2}\right)$$ (consistent units)

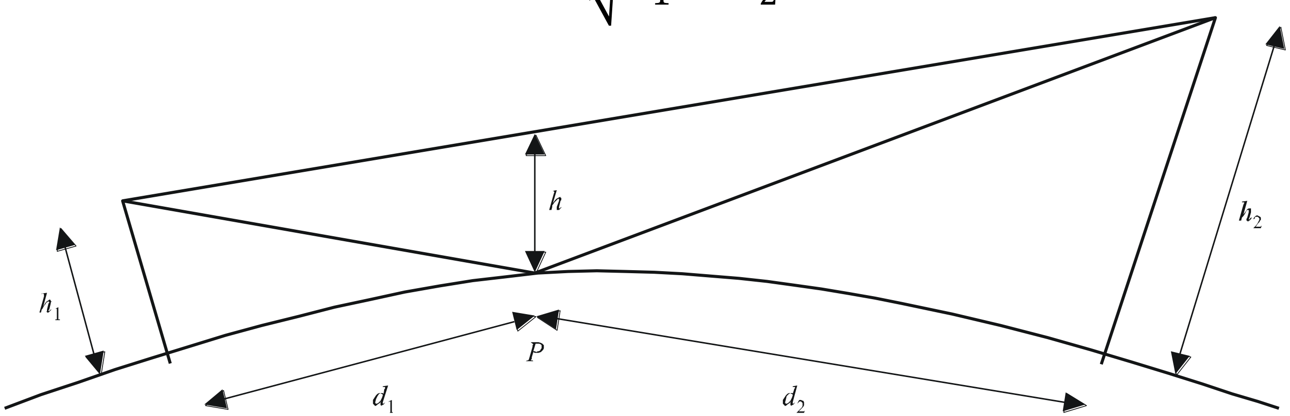
Recommendation ITU-R P.834

Diffraction – within line-of-sight

Diffraction can occur even when direct line between transmitter and receiver is not obstructed.

Subpath diffraction – due to Earth bulge on paths within line-of-sight distance if clearance is less than

$$h_{req} = 0.552 \sqrt{\frac{d_1 \ d_2 \ \lambda}{d_1 + d_2}}$$ (in self-consistent units)

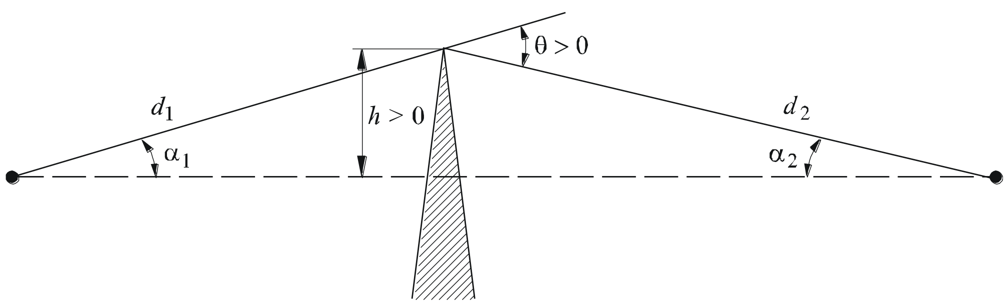


Recommendation ITU-R P.526

Diffraction – simple obstructions

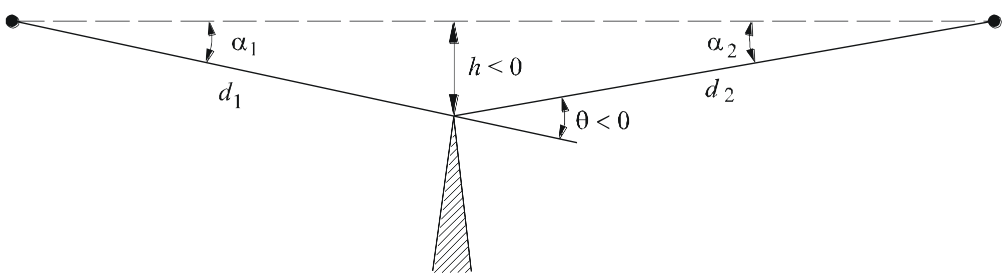
Smooth earth diffraction – curvature of the Earth itself on a transhorizon path. (Rec P.526; below 10 MHz, use Rec P.368.)

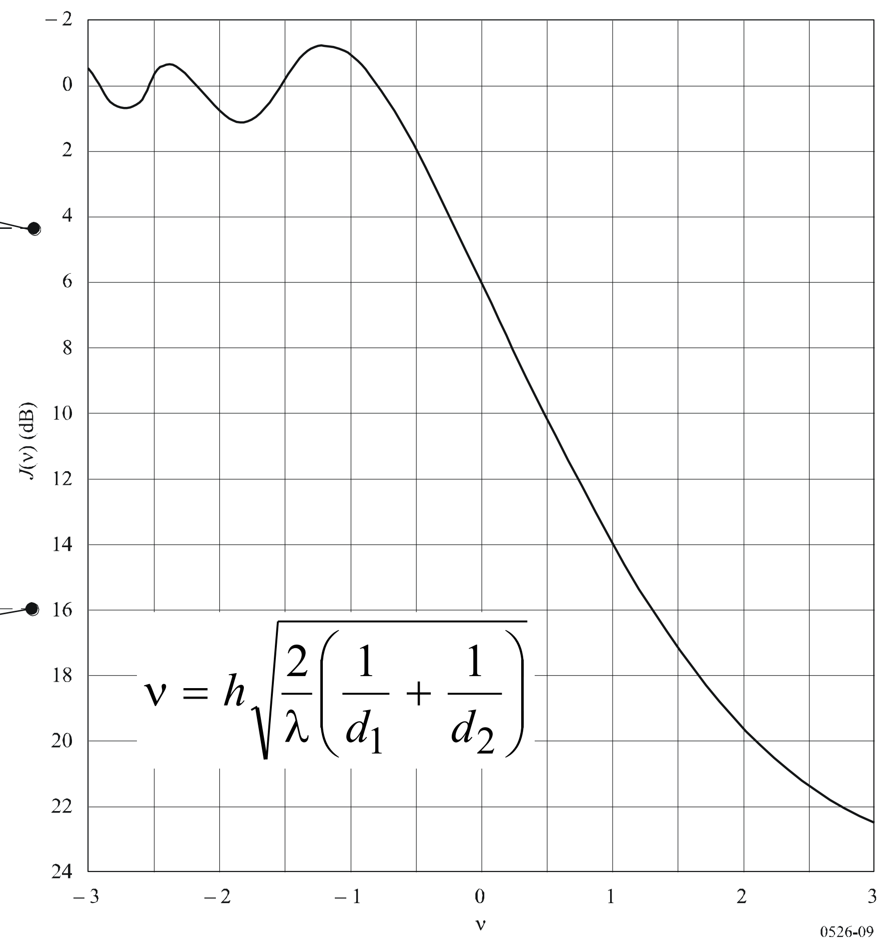
Single obstacles. Approximated as ideal knife-edge or rounded cylinders. Methods in Rec. P.526.



a)

$$\nu = \sqrt{\frac{2 h \theta}{\lambda}} \quad (\nu \text{ has the sign of } h \text{ and } \theta)$$



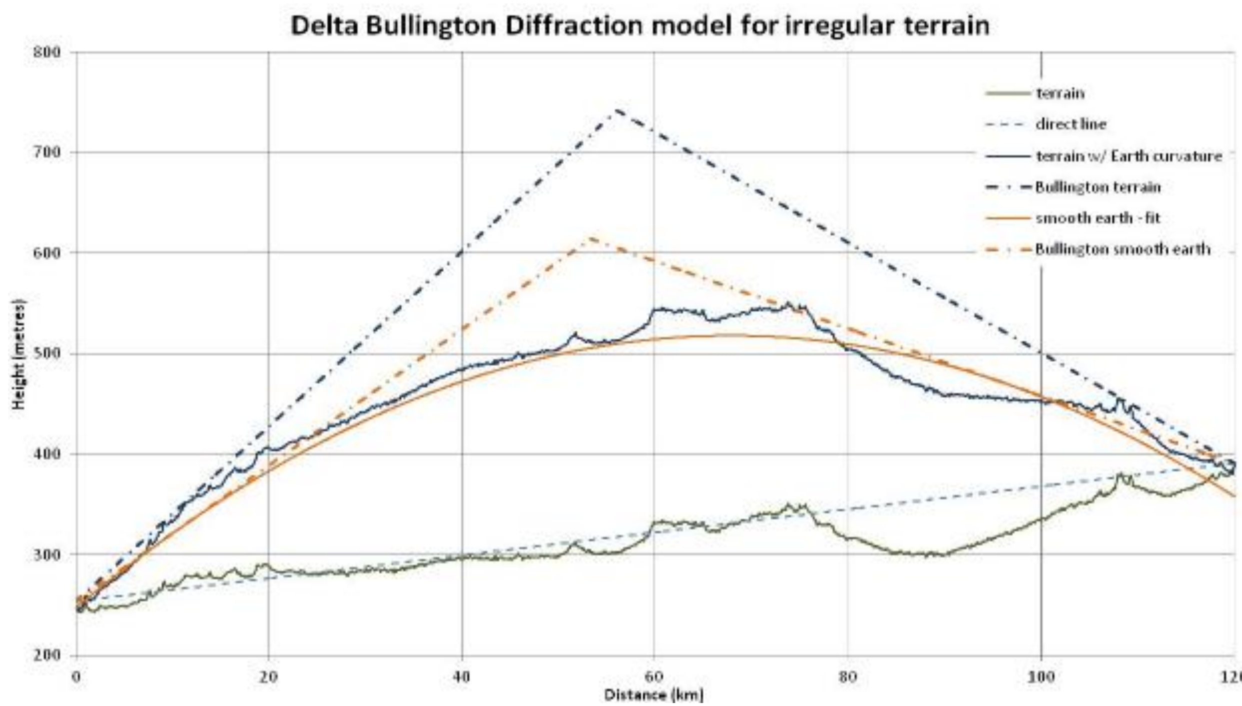


$$\nu = h\sqrt{\frac{2}{\lambda}\left(\frac{1}{d_1}+\frac{1}{d_2}\right)}$$

Diffraction – more complicated terrain

Generic diffraction model:

- Used for prediction of signal level over long distances or wide areas
- Uses digital terrain map
- Simple to implement but surprisingly accurate compared to measurements
- Used by ITU-R for prediction of both wanted and interfering signals



Delta Bullington model components

- Find terrain points with highest slope from tx and rx end.
- Construct lines from tx and rx through these points, find intercept.
- Calculate knife edge diffraction on equivalent edge at intercept.
- Apply taper: $L_{ba} = L_{knife} + [1 - \exp(-L_{knife}/6)](10 + 0.02\,d)$

- Fit a smooth profile to the terrain points and repeat above process.
- L_{bs} = diffraction loss for smooth profile

- Calculate diffraction over a spherical earth = L_{sph}
- Diffraction loss = $L_{ba} + \max\{L_{sph} - L_{bs}, 0\}$

Example Calculation

d = 120 km, f_{tx} = 165 MHz, P_{tx} = 5W, G_{tx} =2.2dBi, h_{tx} =5 m, BW= 10 kHz

⇨ PSD = -1 dBm/Hz

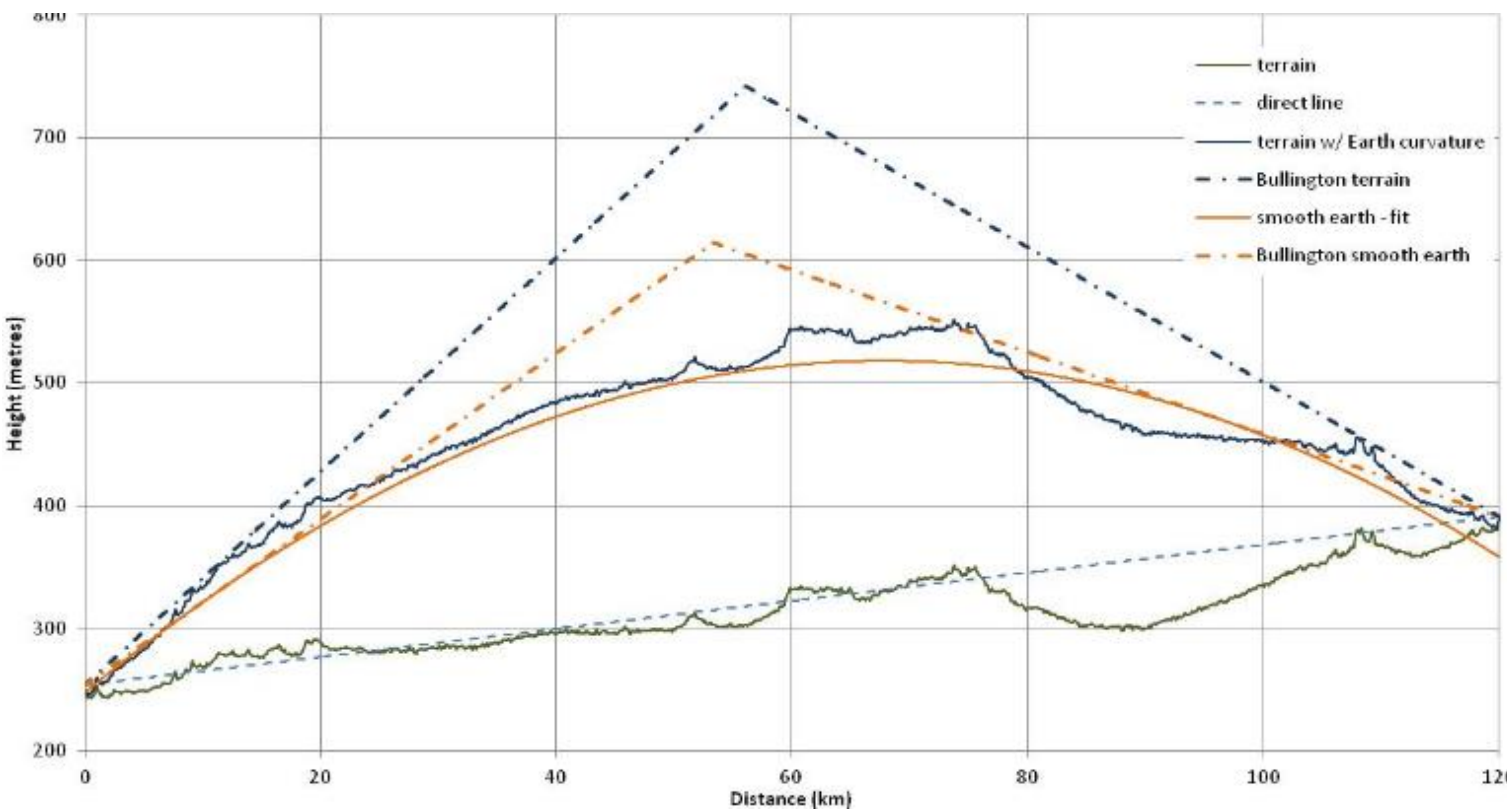
Interference threshold at MRO is -214 dBm/Hz

⇨ Loss required = 213 dB

Free space loss = 118 dB

L_{ba}= 33 dB; L_{sph}= 72 dB; L_{bs}= 30 dB   Diffraction loss = 75 dB

Total loss = 193 dB ⇨ **signal will exceed threshold by 20 dB**



Tropospheric scatter and ducting

- Scattering from inhomogeneities (troposcatter) is the main long-term effect on long paths (more than ~100 km) when diffraction loss becomes high.
- Ducting may occur for short periods of time due to atmospheric layers near the surface (over water or flat coastal areas) or elevated layers in the atmosphere. May be significant for very long distances (100s to 1000s of km).
- Recommendation ITU-R P.452 gives an empirical calculation method for troposcatter, ducting and reflection from atmospheric layers.
- Scatter from rain can also calculated using Recommendation ITU-R P.452. (May be significant above ~ 5 GHz)

Mechanisms affecting HF and VHF

- Small but intense ionization layers in the E-region of the ionosphere (Sporadic-E) can cause abnormal VHF propagation for periods lasting several hours. Effect decreases with increasing frequency but can be significant up to ~135 MHz.

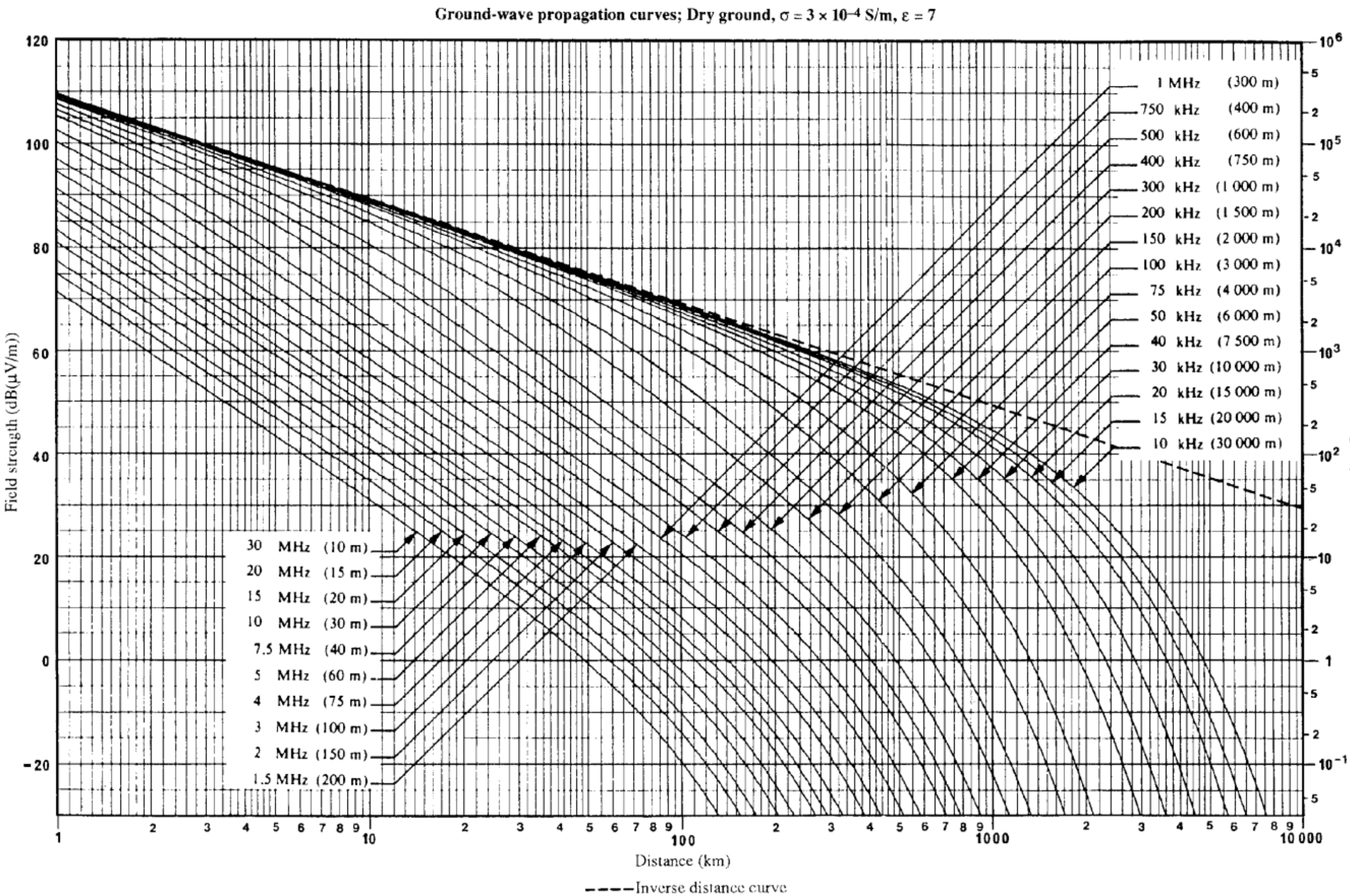
- Recommendation P.534 gives a method for predicting field strength and probability of occurrence.

- At frequencies to ~30 MHz, ground wave propagation is the major propagation mechanism.

- Recommendation P.368 gives a method for predicting ground wave field strength, based on curves.

- Properties of the ground or sea surface (conductivity and permittivity) are important at these frequencies).

Ground wave 10 kHz to 30 MHz



Ionospheric characterisation

- Astronomers, particularly using low-frequency arrays, need to characterise the ionosphere to remove its effects from observations.
- This information can be useful to propagation researchers to better understand and model ionospheric structure and behaviour.
- Better models of the ionosphere can, in term, help astronomers correct their observation.

⇨ This is a useful area for joint research between astronomy and propagation community.

⇨ Joint session on this topic at URSI GASS in Rome later this year.

Other propagation mechanisms

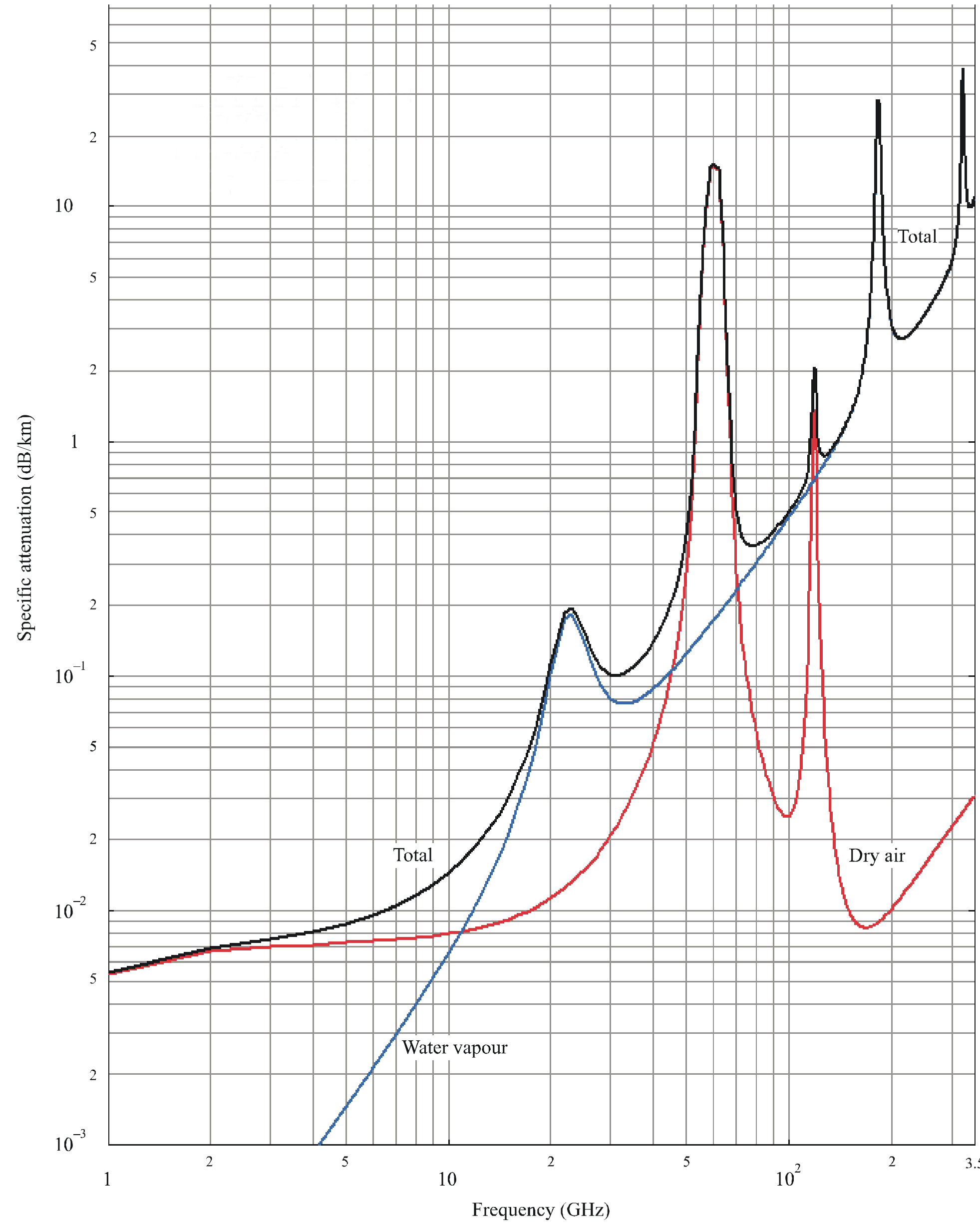
- Multipath – reflections from objects may cause distortion of wanted signal. In some specific scenarios, may increase interference power.
- Attenuation due to rain, clouds, fog, snow, etc. Noticeable above about 5 GHz. Decreases wanted signal (and interference signal). Also raises noise temperature of the sky.
- Atmospheric attenuation noticeable with increasing frequency and at specific molecular resonance frequencies. Provides good isolation between active transmitters and passive services in frequency bands above ~ 200 GHz.

Specific attenuation due to atmosphere

- Chart shows specific attenuation at 1013 hPa, 15°C, water vapour density 7.5 g/m^3

- At frequencies above 100 GHz, loss becomes significant.

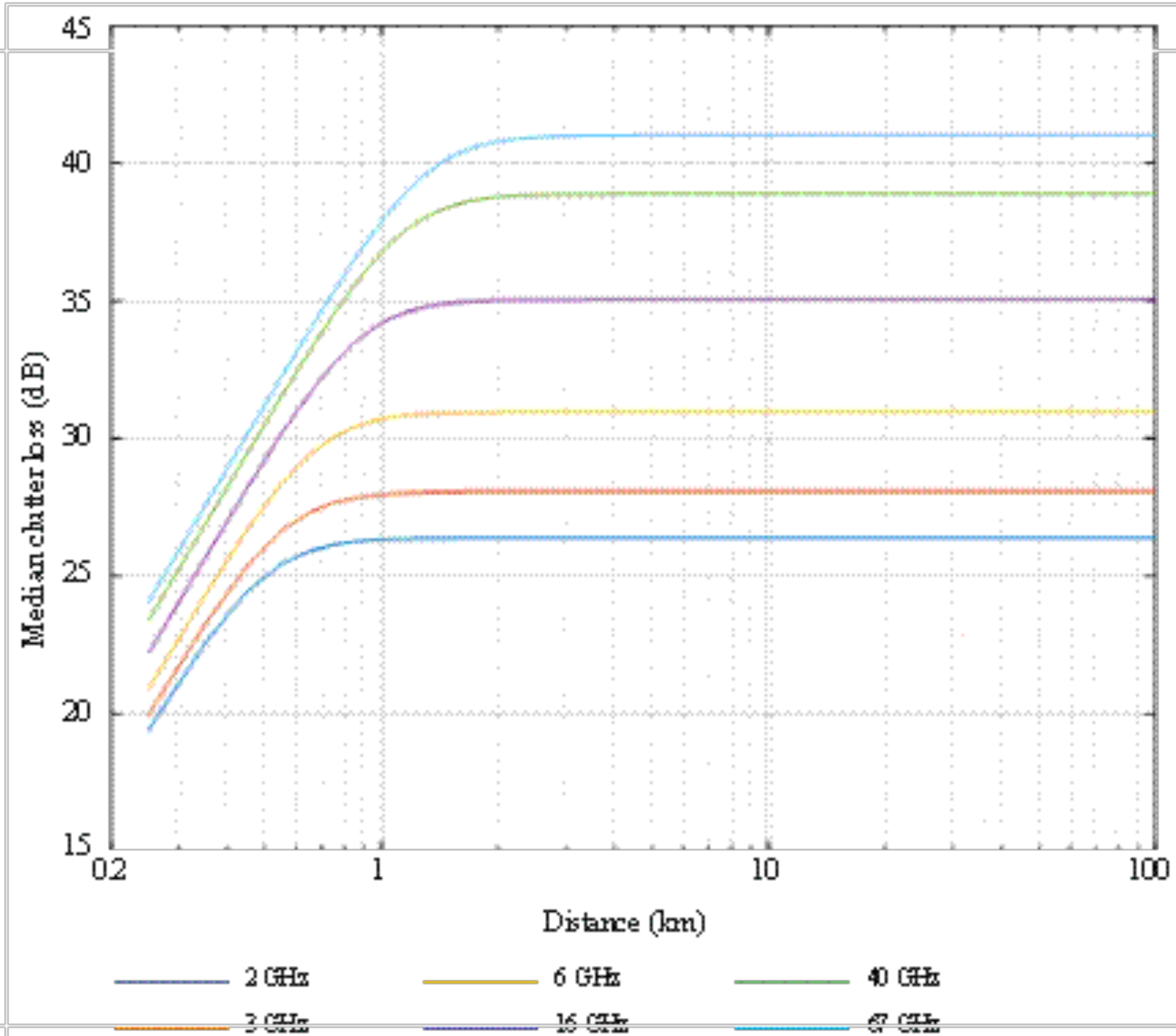
- Helpful in protecting passive services as very high bands.



Recent developments: Local clutter loss

- Recommendation P.2108 – "Prediction of clutter loss" (2017) has three models:
  - 300 MHz – 3 GHz with one end (or both) of path below average height of local clutter. End correction for one end (or both) of path to account for building clutter effects.
  - 2 – 67 GHz for terrestrial paths – gives probability curve for a terminal within local clutter; can be applied to one or both ends of path. Requires frequency and path length.
  - 10 – 100 GHz for slant paths (to satellite, aircraft) – gives probability curve for one terminal within local clutter. Requires frequency and elevation angle.

Median clutter loss (from P.2108)

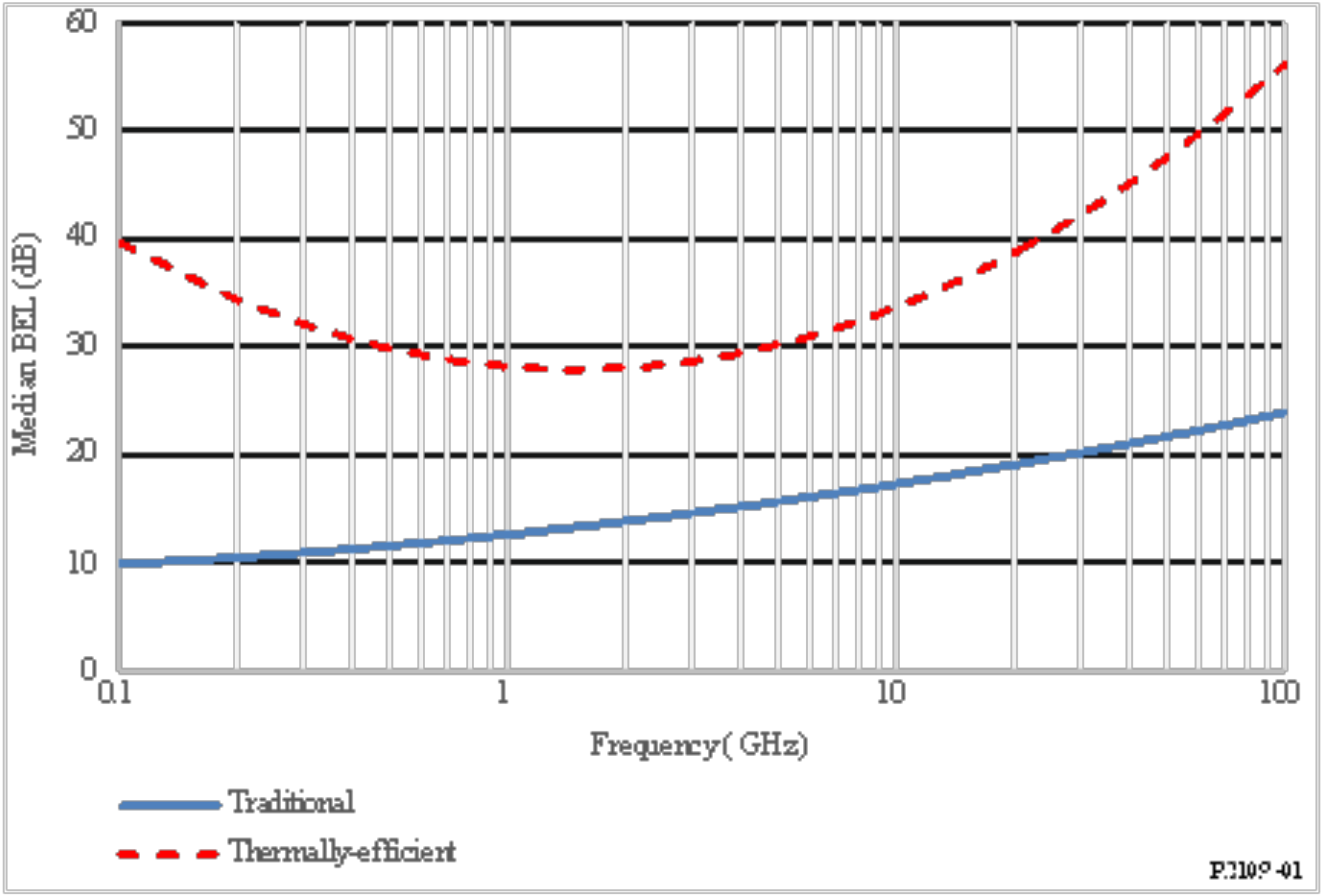


Recent developments: Building entry loss

- Recommendation P.2109 – “Prediction of building entry loss” (2017) gives statistical prediction of loss going through an external building wall. Inputs required are:
  - frequency (80 MHz to 100 GHz);
  - building class (‘traditional’ or ‘thermally-efficient’);
  - elevation angle of the path at the building façade (degrees above the horizontal)

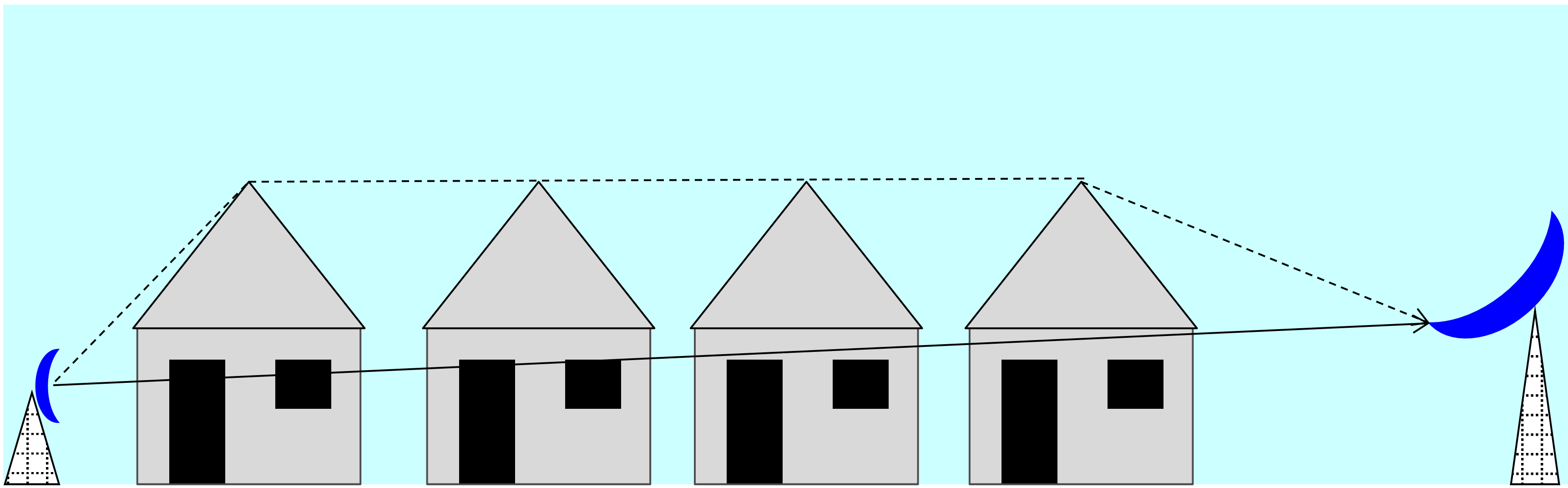
  - Gives loss <u>not</u> exceeded for probability *p*%.

Median building entry loss (from P.2109) for horizontal incidence

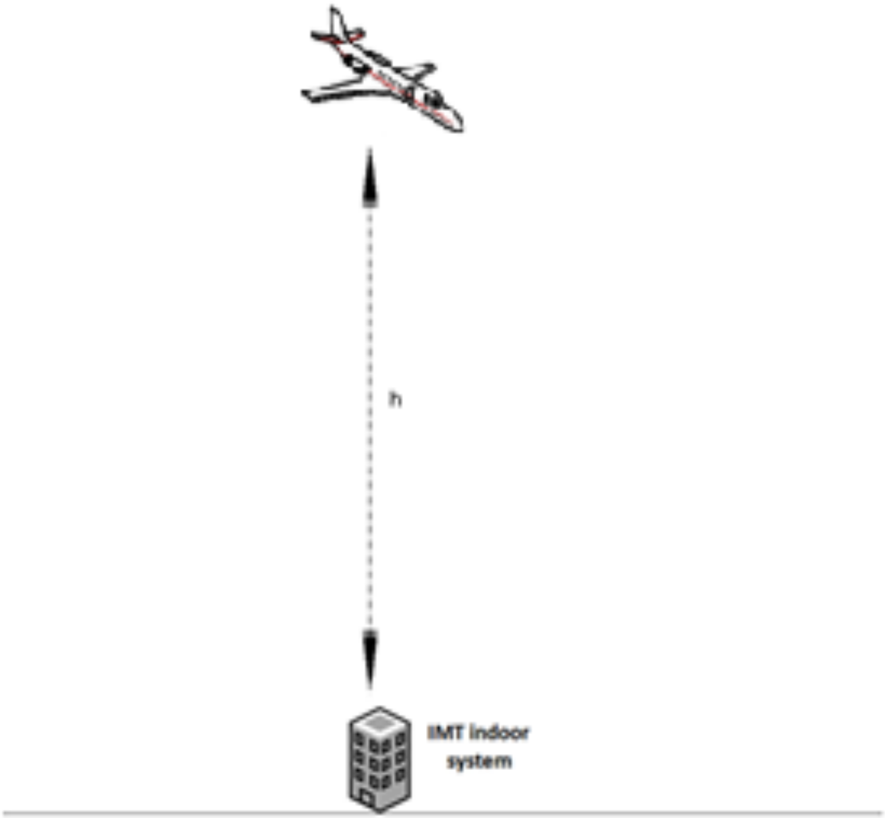


Chapter 4:
wherein things go terribly, terribly wrong.

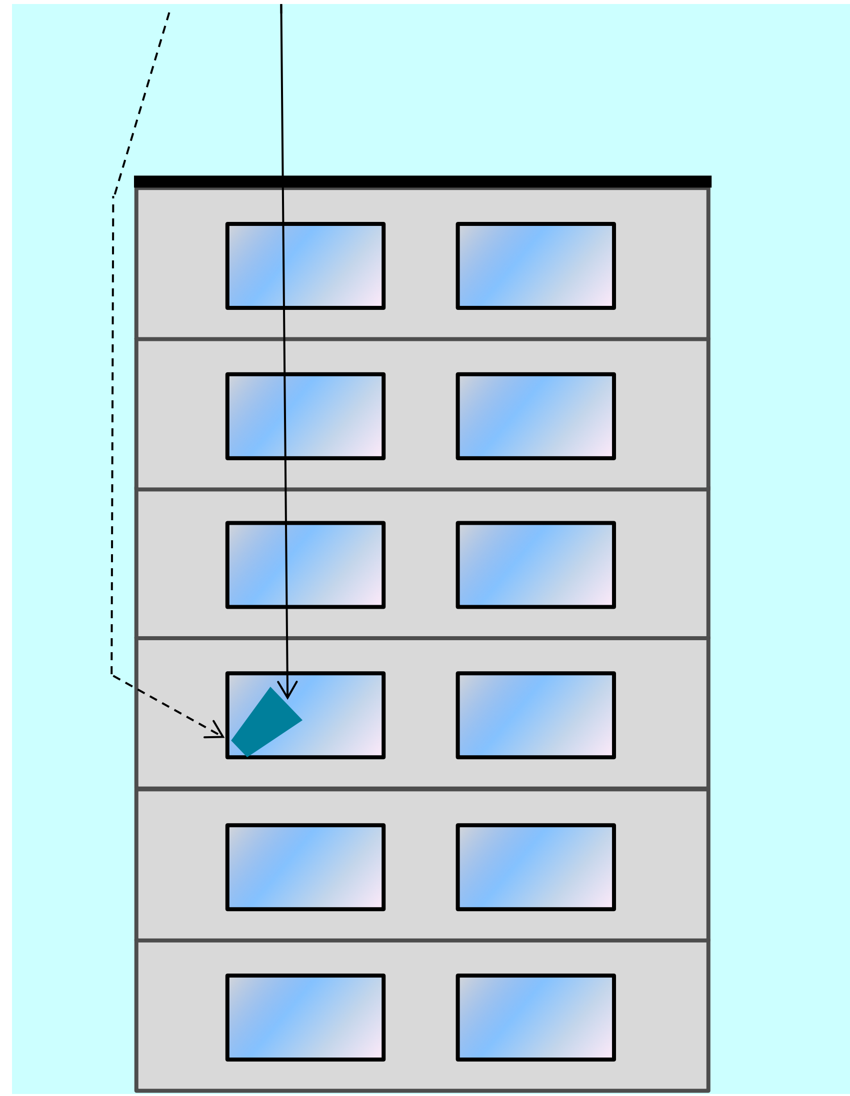
What are the possible propagation paths?



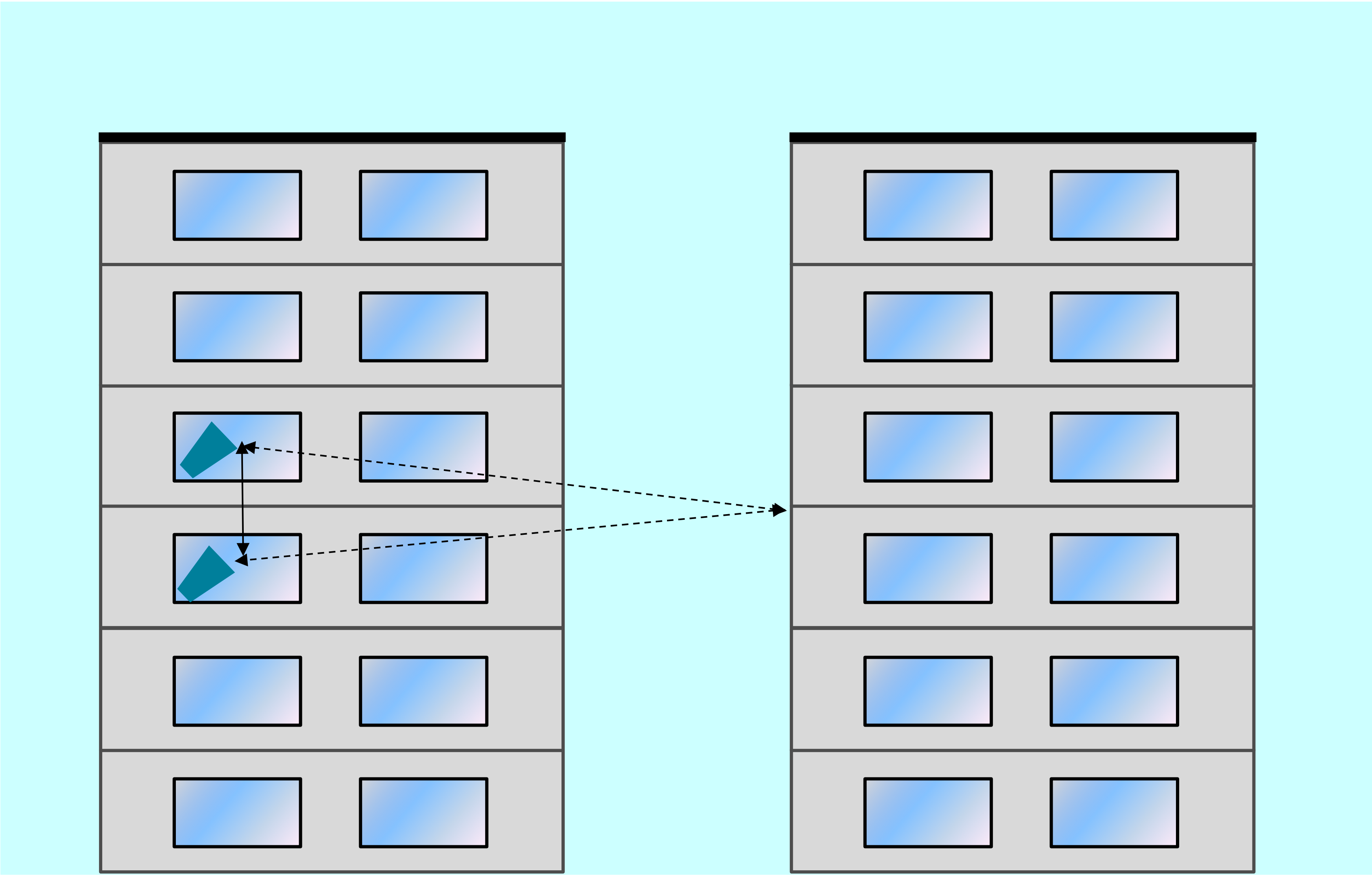
Interference from aircraft to indoor IMT



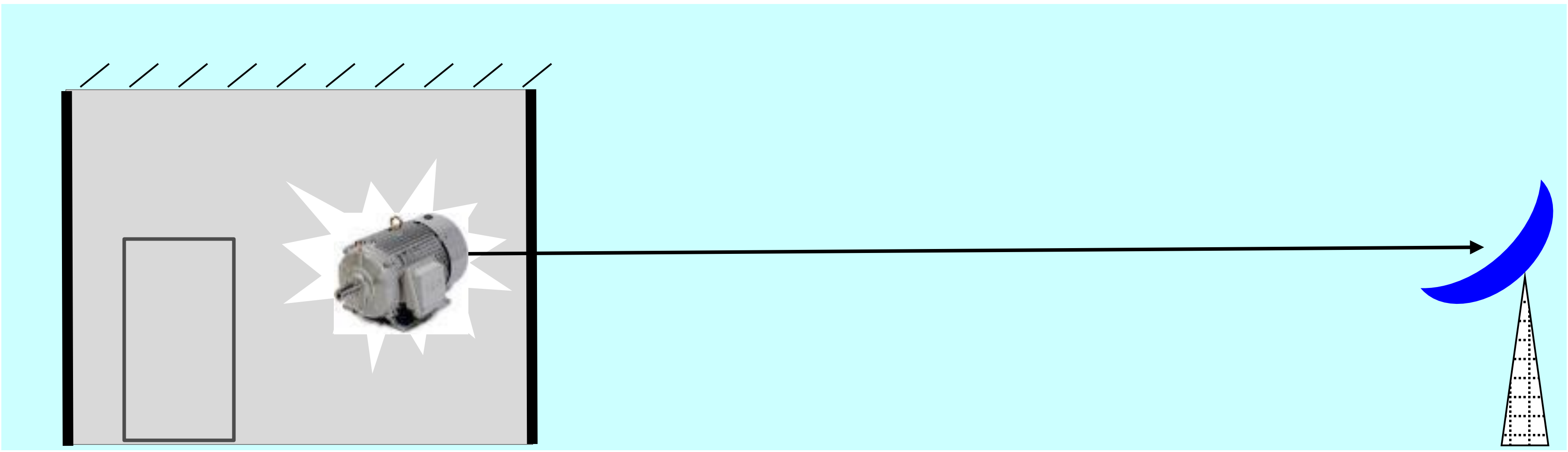
Interference scenario between airborne radar and IMT small cell indoor deployment

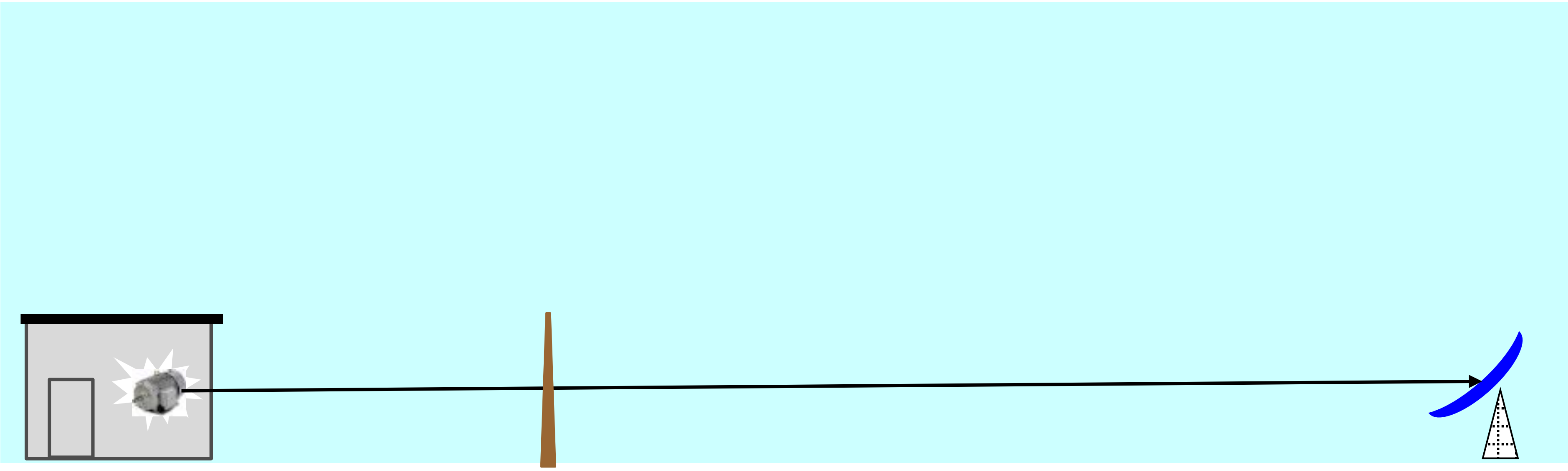


In building interference (WiFi, IMT)



Building or site shielding





Types of propagation models

Types of models

- Propagation models typically used to define worst case scenario for the intended purpose.
- Interference varies with changing conditions, leading to statistical descriptions.
- Models for system <u>design</u> focus on <u>high attenuation</u> scenarios.
- Models for <u>interference</u> focus on <u>low attenuation</u> scenarios.
- Be cautious about applying system design propagation models for interference analysis.

- Model accuracy depends on quality of information available.
- Generic models useful when specific sites not known.
- Site-specific models useful when terrain information is available.

Key ITU-R Recommendations

Recommendation ITU-R P.452 (Prediction of interference between stations on the surface of the Earth at frequencies above 0.1 GHz)

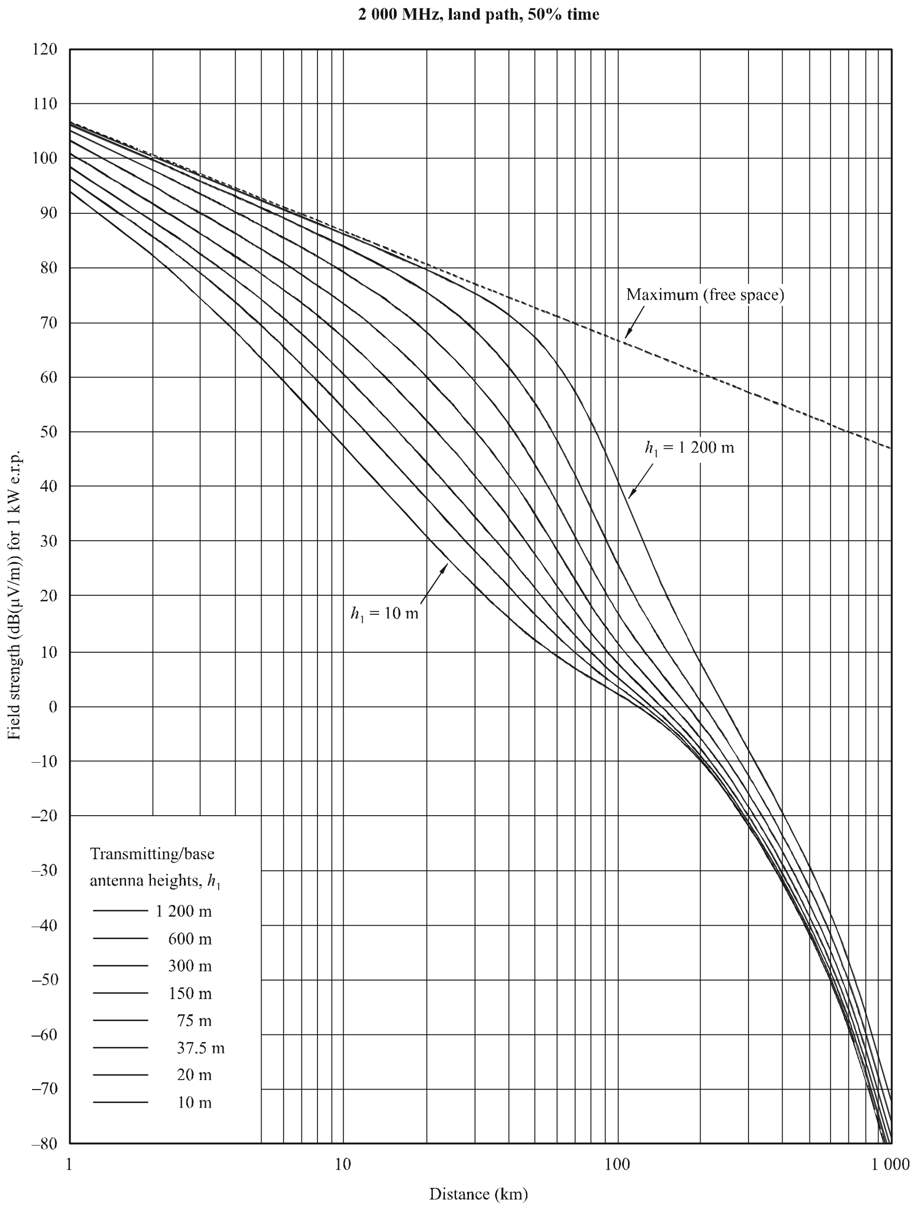
- Uses delta-Bullington diffraction model for specific terrain, and troposcatter, ducting, etc.

Recommendation ITU-R P.1546 (Point-to-area predictions for terrestrial services 30 MHz to 3 000 MHz). Generic terrain assumptions.

- Based on curves of measured data over a number of land paths.
- Used in 2006 by ITU as technical basis to replan broadcasting across Europe, Africa and the Middle East.

Recommendation P.1546 for 30 MHz to 3 GHz

- Curves represent field strength exceeded at 50% of locations for 1kW ERP transmission as function of:
  - Frequency: 100, 600, 2000 MHz
  - Time: 50%, 10%, 1%
  - Tx antenna height: 10 to 1200 m; Rx antenna height: local clutter height (minimum 10 m)
  - Path type: land, warm sea, cold sea
  - Distance: 1 to 1000 km
  - Interpolation method for all of above.
- Curves are based on extensive measurement campaigns in Europe, North America, the North Sea and Mediterranean.



A word about software packages

- Many commercial software packages available and useful, but:

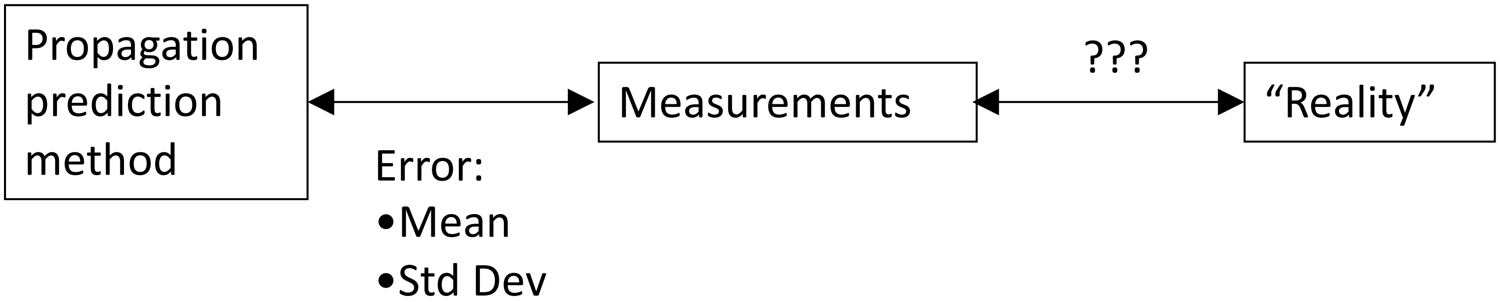
- Be aware of purpose (system design vs interference analysis)
- Sometimes mistakes in coding go unnoticed.
- Often out-of-date with respect to ITU-R Recommendations.
- Understand the underlying mechanisms being modelled and look for anomalies.

- ITU Study Group 3 website has some free software available on “as is” basis, Including Rec P.452, curves for P.1546, etc and “validation examples” to help test your own code.

Study Group 3 databases

- ITU-R Study Group 3 collects data from propagation measurements to test and improve models. More data from different environments leads to better prediction methods.
- Recommendation P.311 describes how the databanks work and how data should be formatted (https://www.itu.int/rec/R-REC-P.311/en)
- Databanks are at: https://www.itu.int/en/ITU-R/study-groups/rsg3/Pages/dtbank-dbsg3.aspx
- Separate database of radio noise at: https://www.itu.int/oth/R0A04000004/en
- Formatted templates for submitting new data are at: https://www.itu.int/en/ITU-R/study-groups/rsg3/Pages/dtbank-form-tables.aspx

Expectations



- Prediction method development – aim to minimize mean error
- Site specific models – std deviation of several dB
- SG 3 goals: 1) accuracy, 2) clarity, 3) simplicity, 4) physical representation.
- On all but shortest paths, propagation loss varies with time.
- Models useful for comparison of different options, for overall statistics.
- An accepted, transparent model often useful in regulatory situations.

Conclusions

- Propagation prediction methods necessary to estimate, understand interference to radioastronomy.
- Prediction methods available from ITU (and other sources) to model various propagation mechanisms.
- Statistics of interference and system design are different.
- General knowledge of propagation phenomena useful in radioastronomy design and operation.

- See you at the Study Group 3 website!

https://www.itu.int/en/ITU-R/study-groups/rsg3/Pages/default.aspx

Thank you!

Questions?

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Annex – additional information about ITU-R Study Group 3

Science for better spectrum usage

ITU-R Study Group 3 – developing international radio propagation prediction methods.

Propagation – understanding behaviour of radio in complex environments. Critical for new technology developments.

- Getting more out of systems requires performance prediction.
- Balance between efficiency and reliability in spectrum management relies on prediction of interference.

Propagation prediction in ITU-R Study Group 3

Prediction of wanted signal for system design.

- Fixed terrestrial systems
- Satellite systems – fixed and mobile-satellite
- Indoor and short-range outdoor systems
- Broadcasting and land-mobile systems

Prediction of unwanted signal level for interference analysis.

- Between terrestrial systems
- Between terrestrial and space systems
- Coordination distance for regulatory application

Structure of ITU-R Study Group 3

- Working Party 3J: Propagation fundamentals
- Working Party 3K: Point-to-area propagation
- Working Party 3L: Ionospheric propagation and radio noise
- Working Party 3M: Fixed, satellite and interference propagation prediction

- Meetings about once a year, for two weeks
- Revising and improving Recommendations
- 70 to 100 experts representing 25 to 30 countries

Study Group 3 Recommendations

- Developed over many decades in response to:
  - ITU spectrum management requirements (WRC agenda items)
  - User requirements
  - Research interests of SG 3 participants
- Based on:
  - Physical understanding of mechanisms
  - Empirical fit to measurements

Why get involved?

- Your propagation research could be shaping international decisions about the use of the radio spectrum for coming decades
- Opportunity to meet and work with leading propagation researchers from around the world
- Increase your exposure to new technology developments in a wide range of radio services

How to get involved?

You need to be associated with an ITU “Member”

- Through your government’s national regulator (department of communications or similar) as part of national delegation
- Become an “Academia” member through your university
- Investigate “Sector” (business) members in your country

- Please feel free to contact me if you want to make links!

Conclusion – working together