Compatibility and aggregation

Hans van der Marel
ASTRON / CRAF

Outline

- What are compatibility and sharing?
- Sensitivity of radio astronomy receivers
- Propagation of radio waves
- How to perform compatibility analysis?
- Aggregation
- Simulations (Monte Carlo and epfd)
- Case studies

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Compatibility

Com`pat'i`ble *(adj.)*:

- Capable of existing or performing in harmonious, agreeable, or congenial combination with another or others

In spectrum management: when services are compatible with each other they are not interfering each other.

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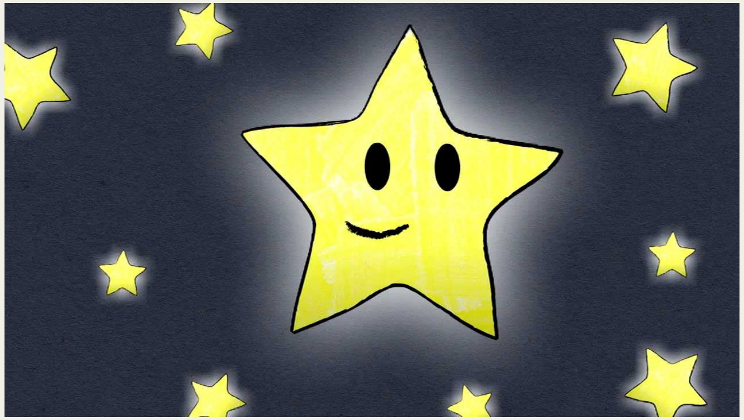
Situation 1



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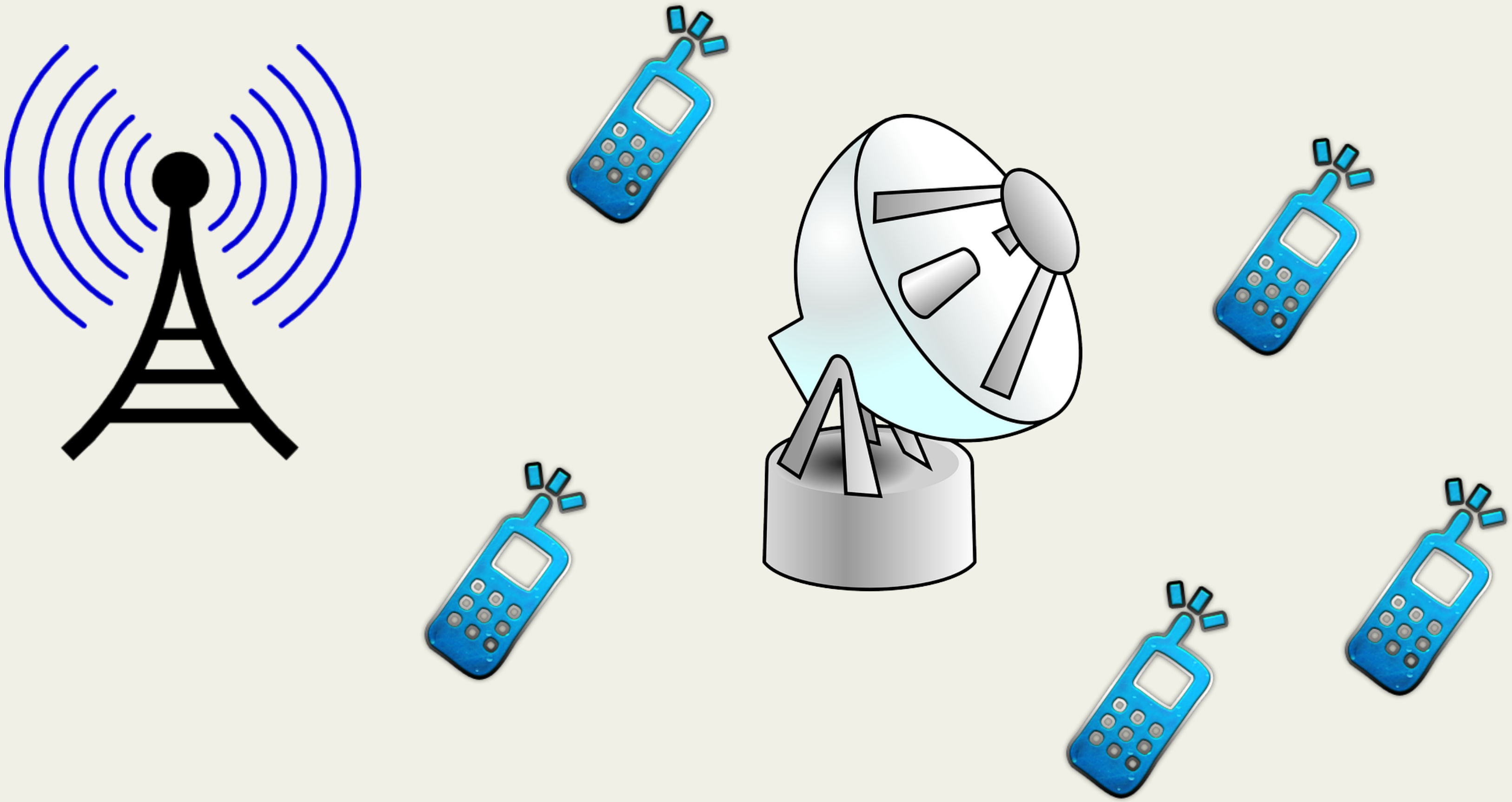
Situation 2



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General compatibility

- In-band sharing
- Adjacent band compatibility
- Nearby band compatibility

➜ Compatibility is about spectrum sharing

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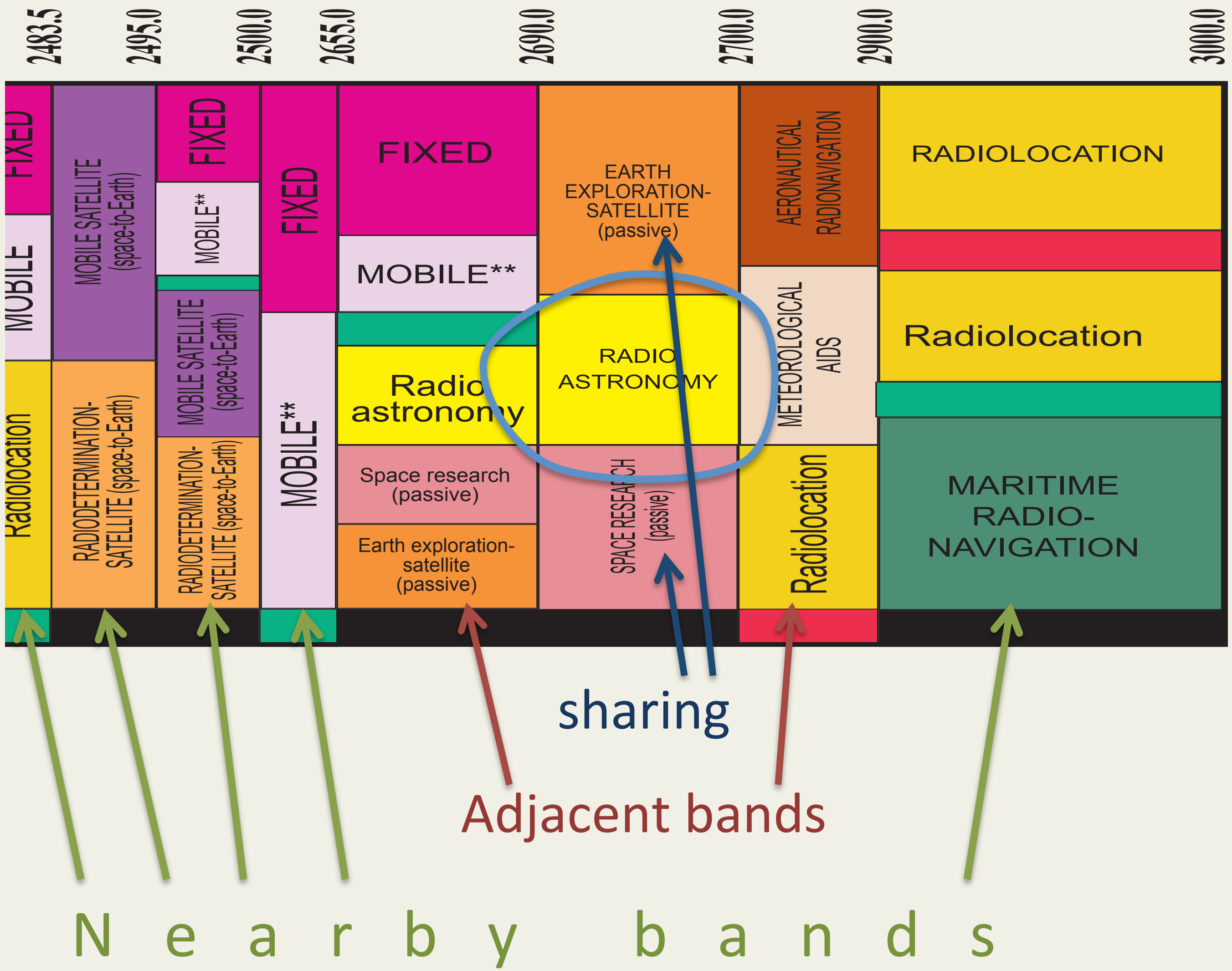
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2495.0
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FIXED
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Radiolocation
MOBILE SATELLITE (space-to-Earth)
RADIODETERMINATION-SATELLITE (space-to-Earth)
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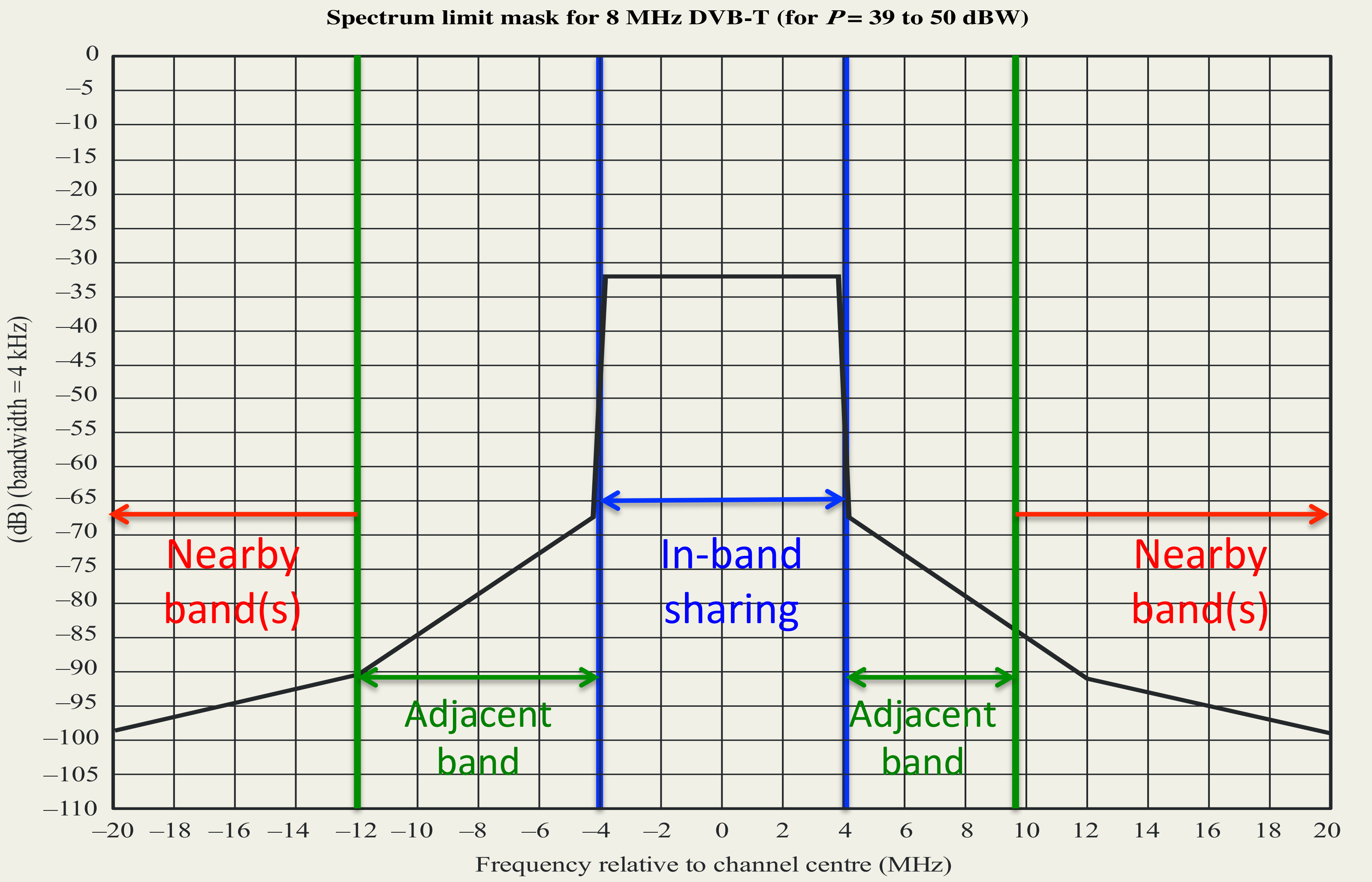
Radio astronomy
Space research (passive)
Earth exploration-satellite (passive)
EARTH EXPLORATION-SATELLITE (passive)
RADIO ASTRONOMY
SPACE RESEARCH (passive)
AERONAUTICAL RADIONAVIGATION
METEOROLOGICAL AIDS
Radiolocation
RADIOLOCATION
Radiolocation
MARITIME RADIO-NAVIGATION
sharing
Adjacent bands
Nearby bands

Spectrum mask



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Need for spectrum sharing

- There is no more “empty” spectrum
- Proposed new systems have to find way of “sharing” with some of existing systems
- Compatibility analysis:
  - To find out which existing radio systems are easiest to share with
  - Determine the “sharing rules”

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Methods for sharing

- Frequency separation
  - Band segmentation
  - Control of emission spectrum characteristics
- Spatial separation
  - Site separation and site shielding
  - Antenna characteristics (beam width, side lobes)
- Time separation
- Signal separation
  - Power/bandwidth adjustments
  - Interference rejection

See also Rec. ITU-R SM.1132

How to achieve compatibility with radio astronomy

- In-band sharing
  - Exclusion zones (Radio quiet zones)/ geographical coordination
  - Maximum transmit power
- Adjacent and nearby band compatibility
  - Exclusion zones (Radio quiet zones)/ geographical coordination
  - Guard bands
  - Requirements for unwanted emissions in standards

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Sensitivity of RAS receiver

Rec. ITU-R RA.769: protection criteria used for radio astronomical measurements

Sensitivity equation: $\frac{\Delta P}{P} = \frac{1}{\sqrt{\Delta f_0 \, t}}$

With $\Delta P = k \, \Delta T$ and $P = kT$: $\Delta T = \frac{T}{\sqrt{\Delta f_0 \, t}}$ $\left(T = T_A + T_R\right)$

Interference threshold at 10% error in *ΔP*:
$\Delta P_H = 0.1 \, \Delta P \, \Delta f$

Integration time: 2000 sec

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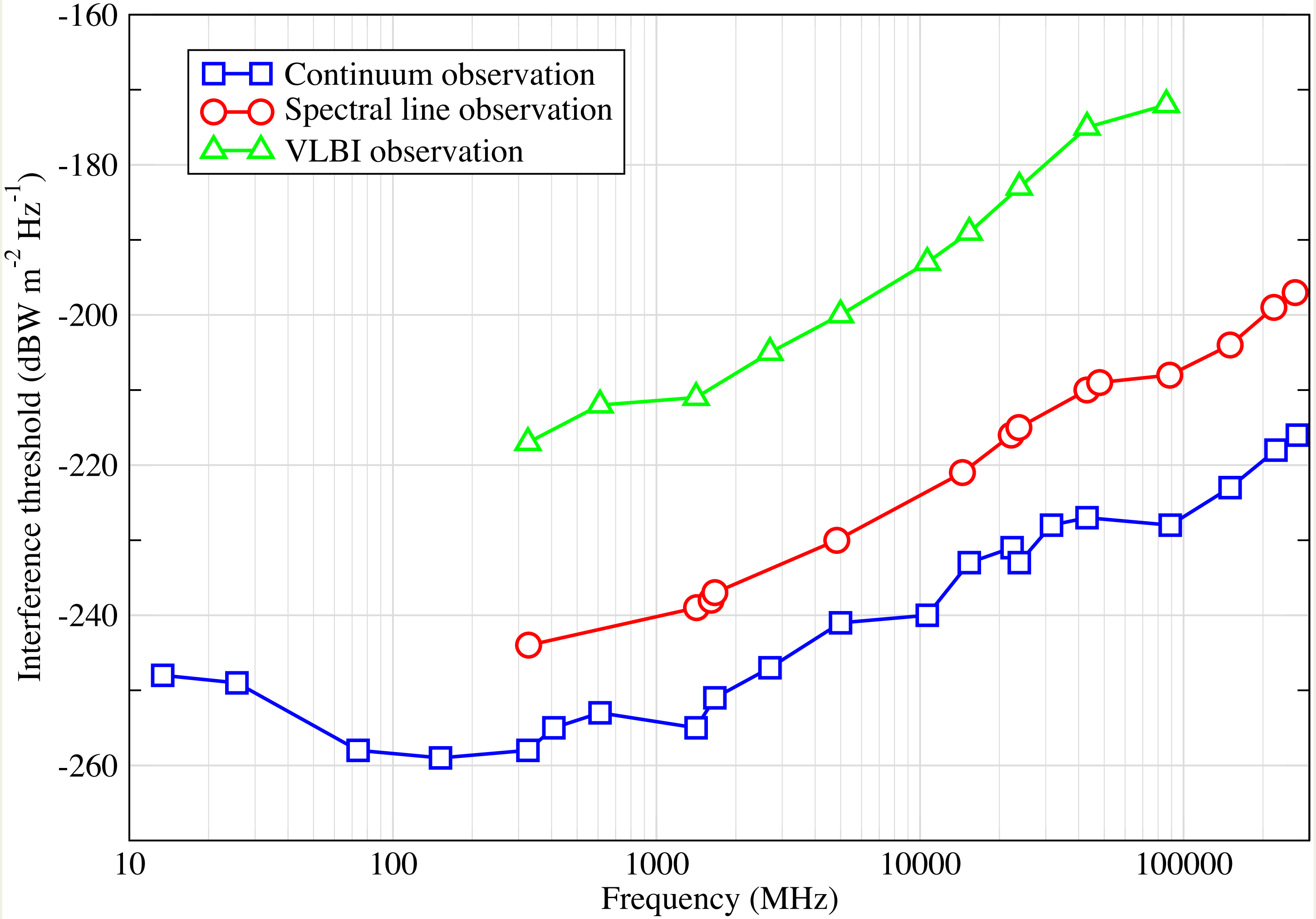
Interference threshold levels (RA.769)



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RA.769 in practice

- Threshold interference level in Spectral pfd S_H: 1 Jy = -260 dB(W m^{-2} Hz^{-1})
- Assumed bandwidths are for allocation (continuum) or typical (spectral line)
- Integration time and bandwidths can be scaled:

$$S_{H,new} = S_{H,769} - \log\left(\sqrt{\frac{2000s}{t_{\mathrm{int}}} \cdot \frac{BW_{769}}{\delta f}}\right)$$

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Rec. ITU-R RA.1513

- Max 5% data loss due to interference from all networks in primary RAS band
- Max 2% data loss due to interference from any one network in primary RAS band
- Data loss determined as percentage of 2000 s integration periods in which average spfd exceeds RA.769 levels (not valid for period interference on short time scales)

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Propagation

How do signals get from a transmitter to a receiver

Important information for:

- Quality and reliability of radio links
- Prevent overly high transmitting powers to avoid interference
- Reuse of frequencies

Propagation loss

- Free space
- Gas loss
- Refraction
- Diffraction
- Reflections
- Troposcatter
- Rain effects
- Vegetation

- General:

$$Loss = \frac{P_{rec}}{P_{transm}}$$

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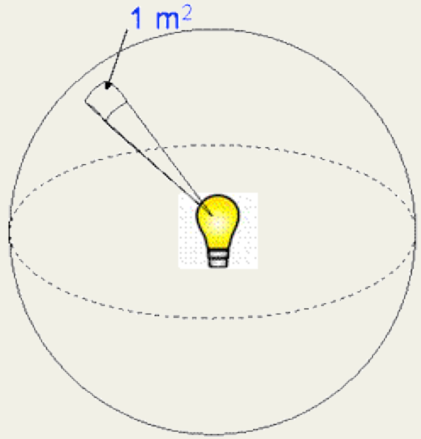
Free Space Loss



$$pfd = \frac{P_{transm}}{4\pi r^2} \quad \mathrm{W\,m^{-2}}$$

$$P_{rec} = A_e \left(\frac{P_{transm}}{4\pi r^2} \right) \quad \mathrm{W} \quad \text{with} \quad A_e = G_{rec} \frac{\lambda^2}{4\pi} \quad \mathrm{m}^2$$

Isotropic antenna: $G_{rec} = 1$: $FSL = \frac{P_{rec}}{P_{transm}} = \left(\frac{\lambda}{4\pi r} \right)^2 = \left(\frac{c}{4\pi f} \right)^2$

or:

$$FSL(\mathrm{dB}) = 32.4 + 20 \log(f(\mathrm{MHz})) + 20 \log(d(\mathrm{km}))$$

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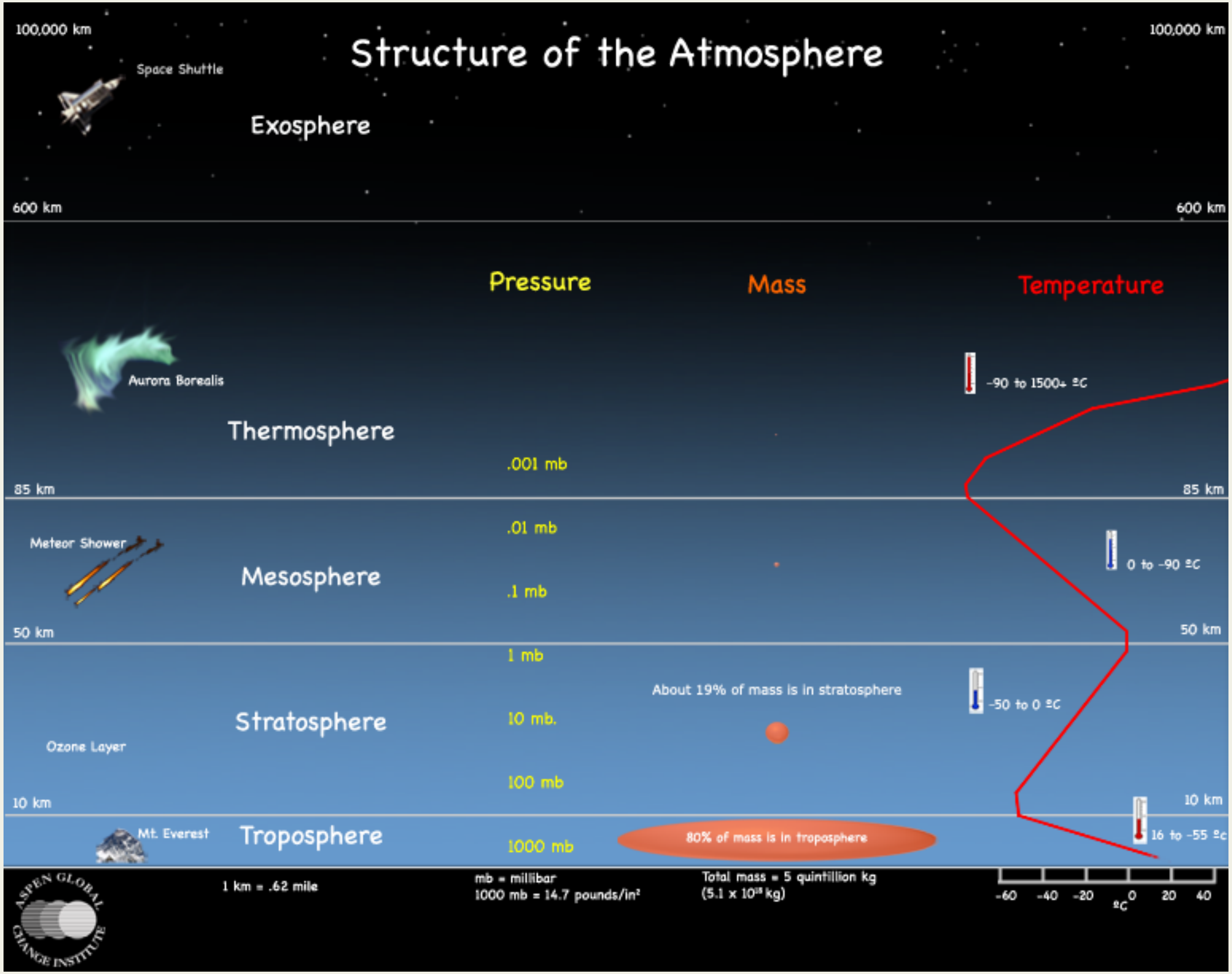

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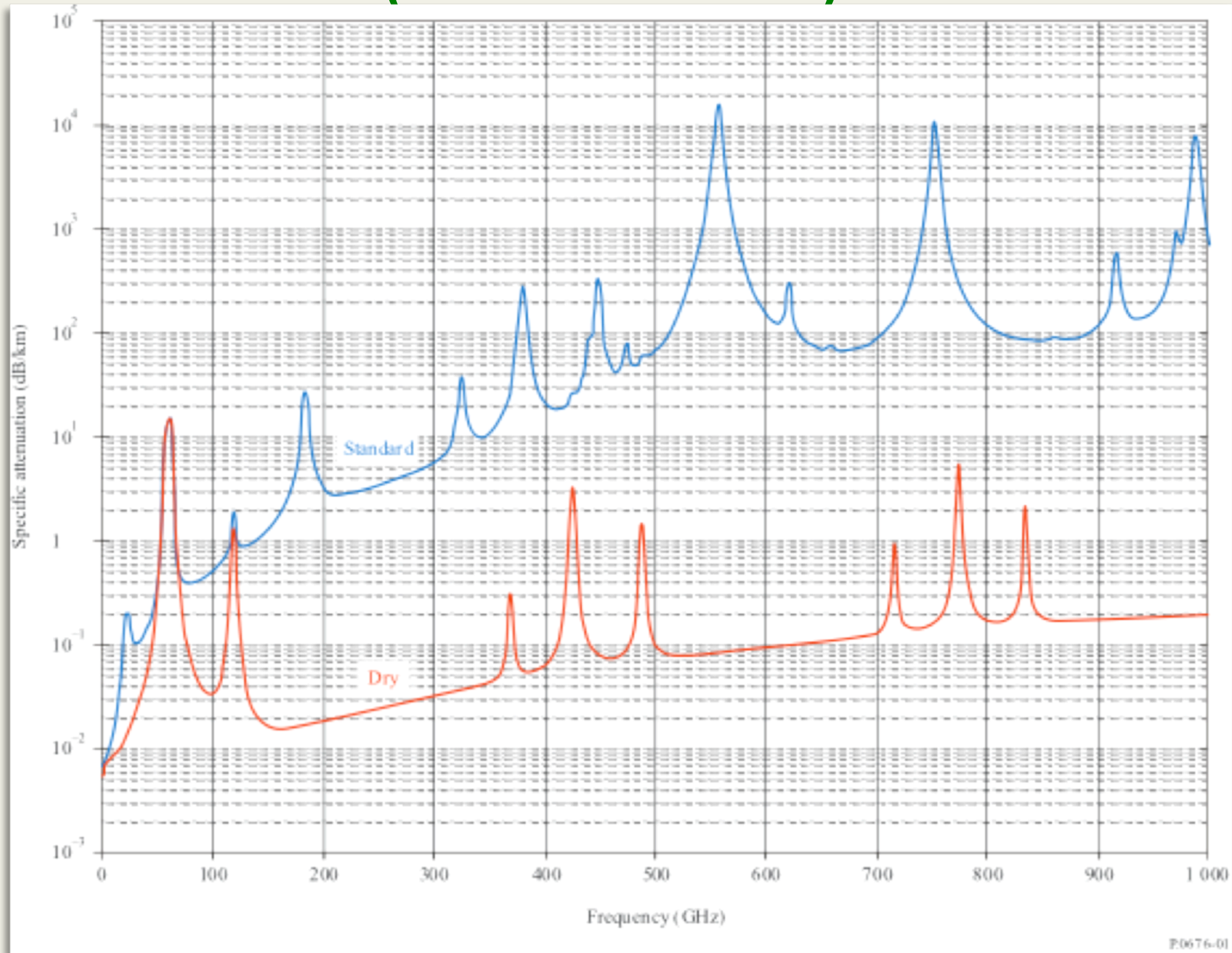
Attenuation due to atmospheric gases (ITU-R P.676)



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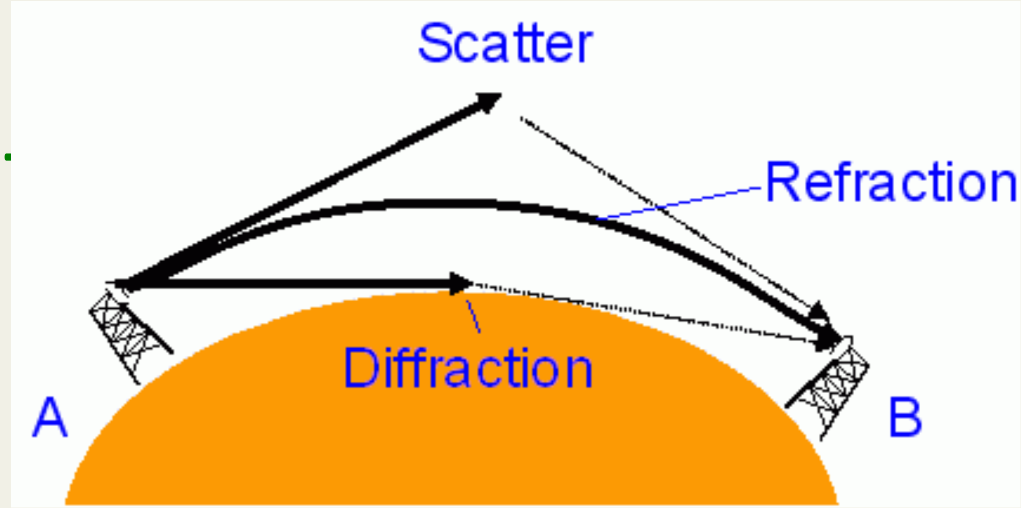
Beyond t



- Distance to horizon: $d(\text{km}) \approx 3.57\sqrt{h(\text{m})}$

Propagation beyond horizon due to:

- Refraction: bending of signals towards ground due to density variation in atmosphere
- Scattering: from eddies, particles in the air (rain, dust, comets), reflecting objects (planes, wind turbines)
- Diffraction: from terrain, buildings, vegetation

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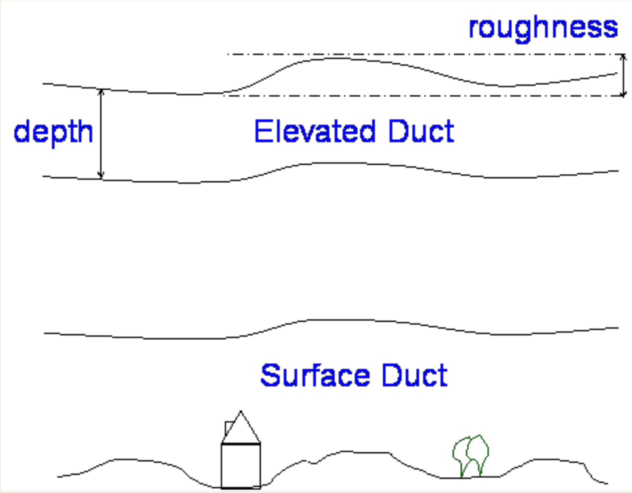
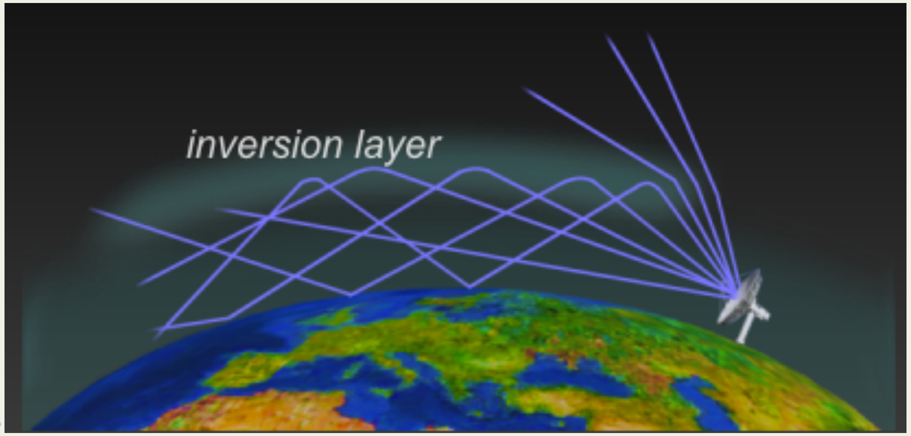
Anomalous propagation due to non-standard atmospheric conditions

Unusually rapid change of temperature increase of water vapour decrease with height:

- Evaporation ducts and temperature inversions ➜ surface ducts 6%-50% of time
- Subsidence ➜ elevated ducts 5%-40% of time





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Scattering

- Tropospheric scattering: non-uniform pressure due to eddies, turbulence etc.
- Molecular scattering (at high freqs)
- Clouds, rain, snow, hail, fog: scattering and dielectric losses
- Planes, buildings, vegetation, wind turbines etc

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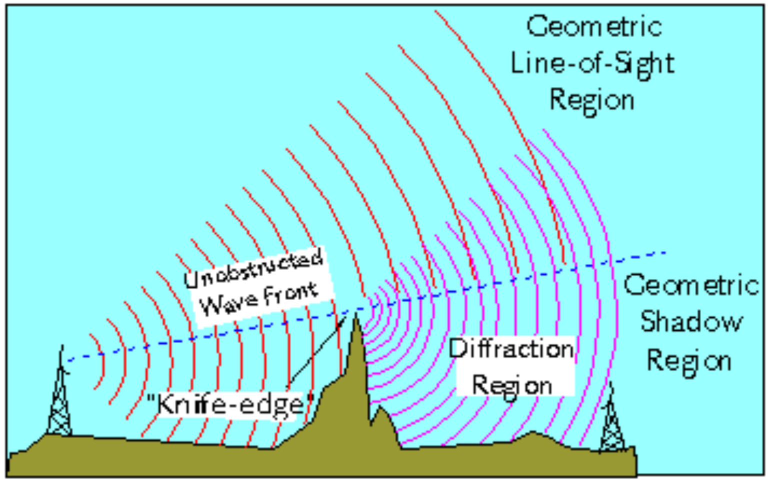
Diffraction

'Bending' of waves around obstacles (knife-edges)



knife-edge effect

Diffraction zone starts if path clearance < (60% of) 1st Fresnel zone

$$R_{1st\,Fresnel}(\mathrm{m}) = 550\left[\frac{d_1(\mathrm{km})\,d_2(\mathrm{km})}{(d_1(\mathrm{km})+d_2(\mathrm{km}))\,f(\mathrm{MHz})}\right]^{1/2}$$

Also with multiple edges

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Dominant loss mechanisms

- If Line-of-Sight (LoS) (e.g. satellites, air plane, high towers)
  ➜ Free space path loss and/or atmospheric attenuation
- If non-LoS (e.g. terrestrial transmitters)
  ➜ Diffraction losses
  - Terrain maps important
  - Surface important (sea, dry land, etc)
  - Losses much more difficult to predict due to various effects

Methods to calculate propagation loss

- Free Space Loss
- Okumura-Hata model
- Longley Rice method (e.g. Splat!)
- EBU method (broadcasting)
- ITU-R P.526
- ITU-R P.452
- ITU-R P.618
- ITU-R P.1546
- ITU-R P.1812 (e.g. pathprofile)
- ITU-R P.2001

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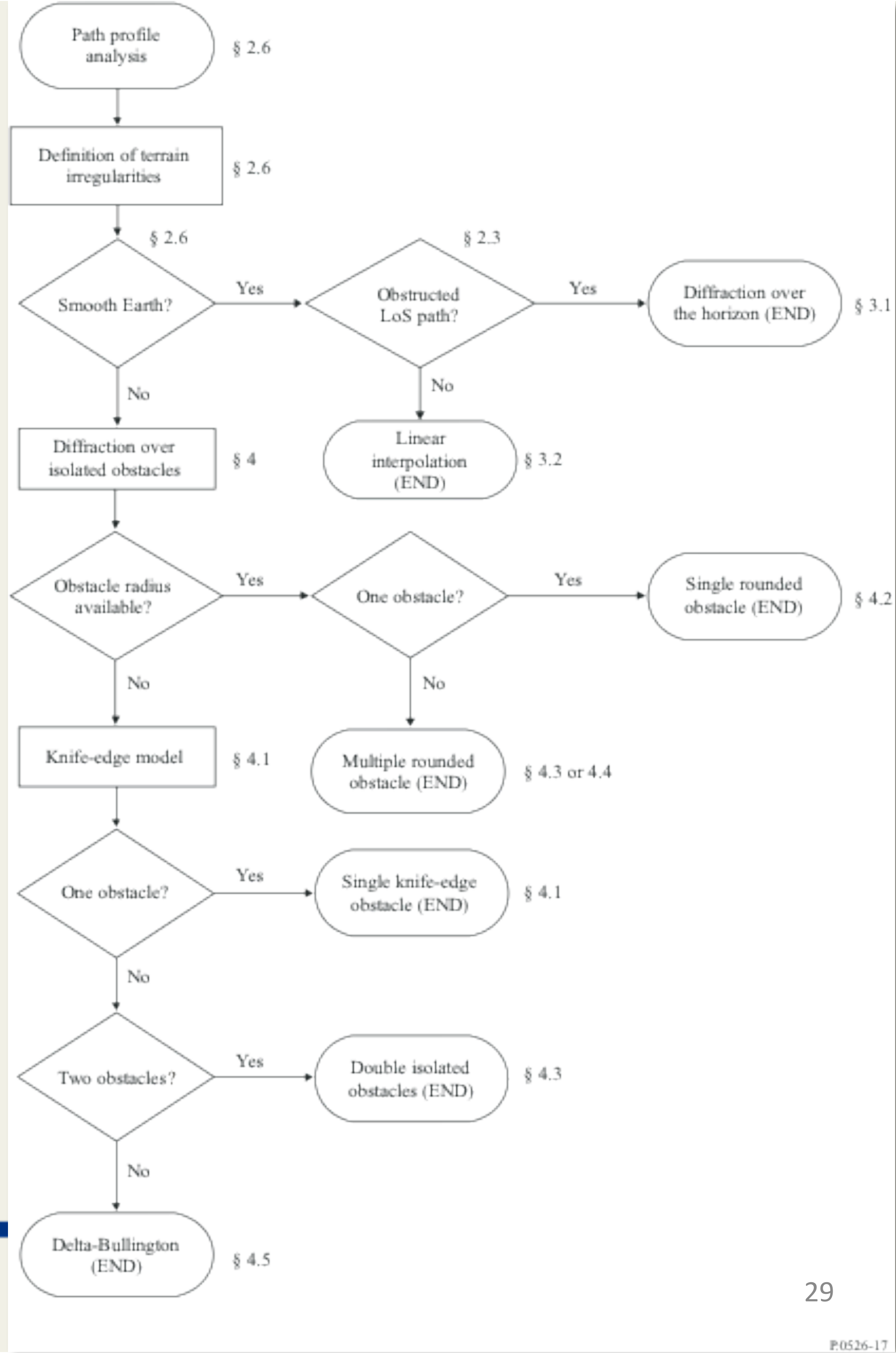
Rec. ITU-R P.526

Propagation by diffraction

➜ methodology



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AST

"Pathprofile"

- Path loss calculation program developed by Mike Willis (http://www.mike-willis.com/software.html)
- Based on Rec ITU-R P.1812 (based on P.452) works for 30 MHz - >>3 GHz
- Uses SRTM (3 arcsec, ~ 90 m) or ASTER (1 arcsec, ~ 30 m) terrain data
- Coverage maps can be exported to Google Earth
- Free software, but no warranty
- Windows software, but usable with wine

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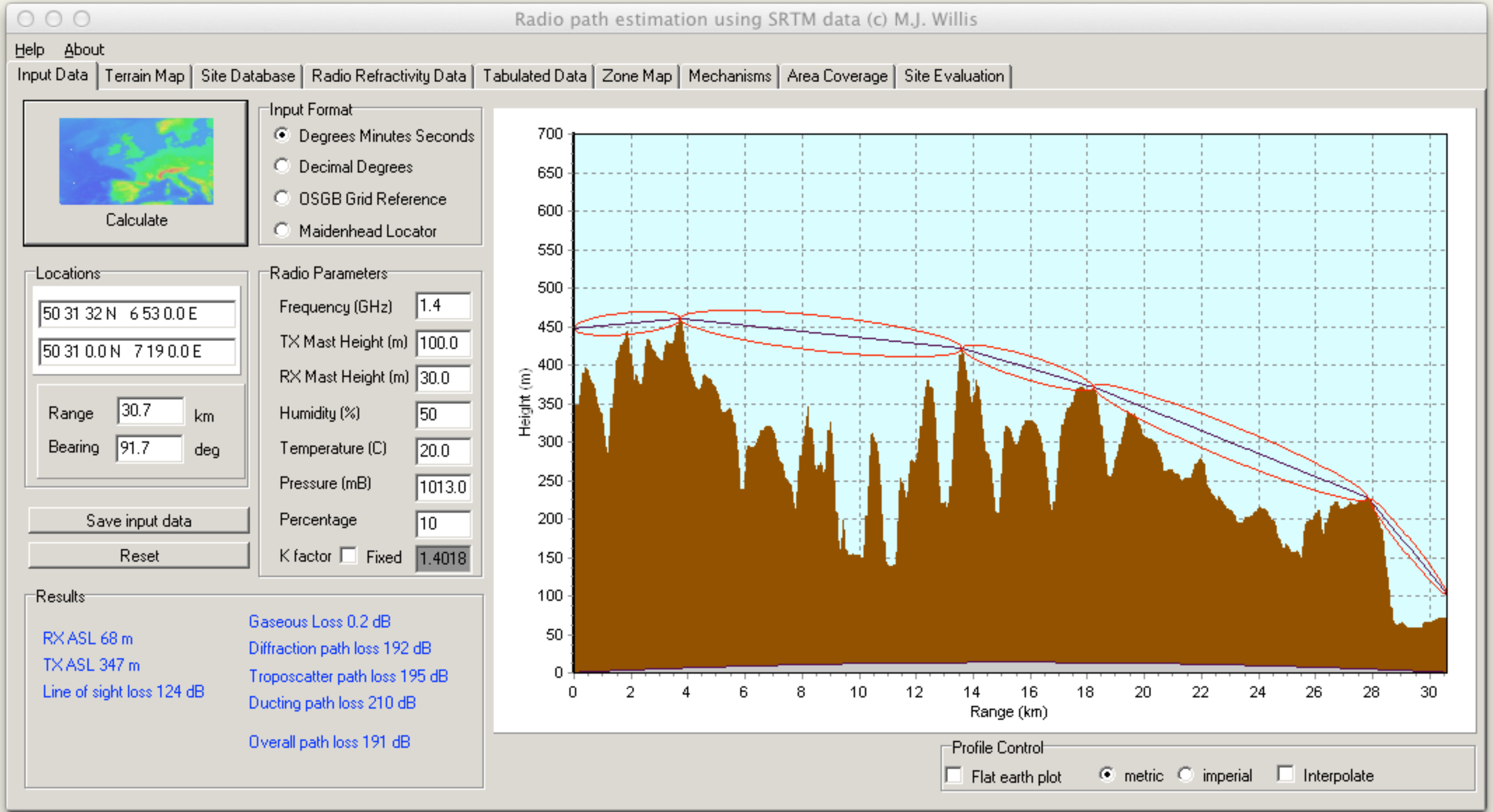
Pathprofile interface



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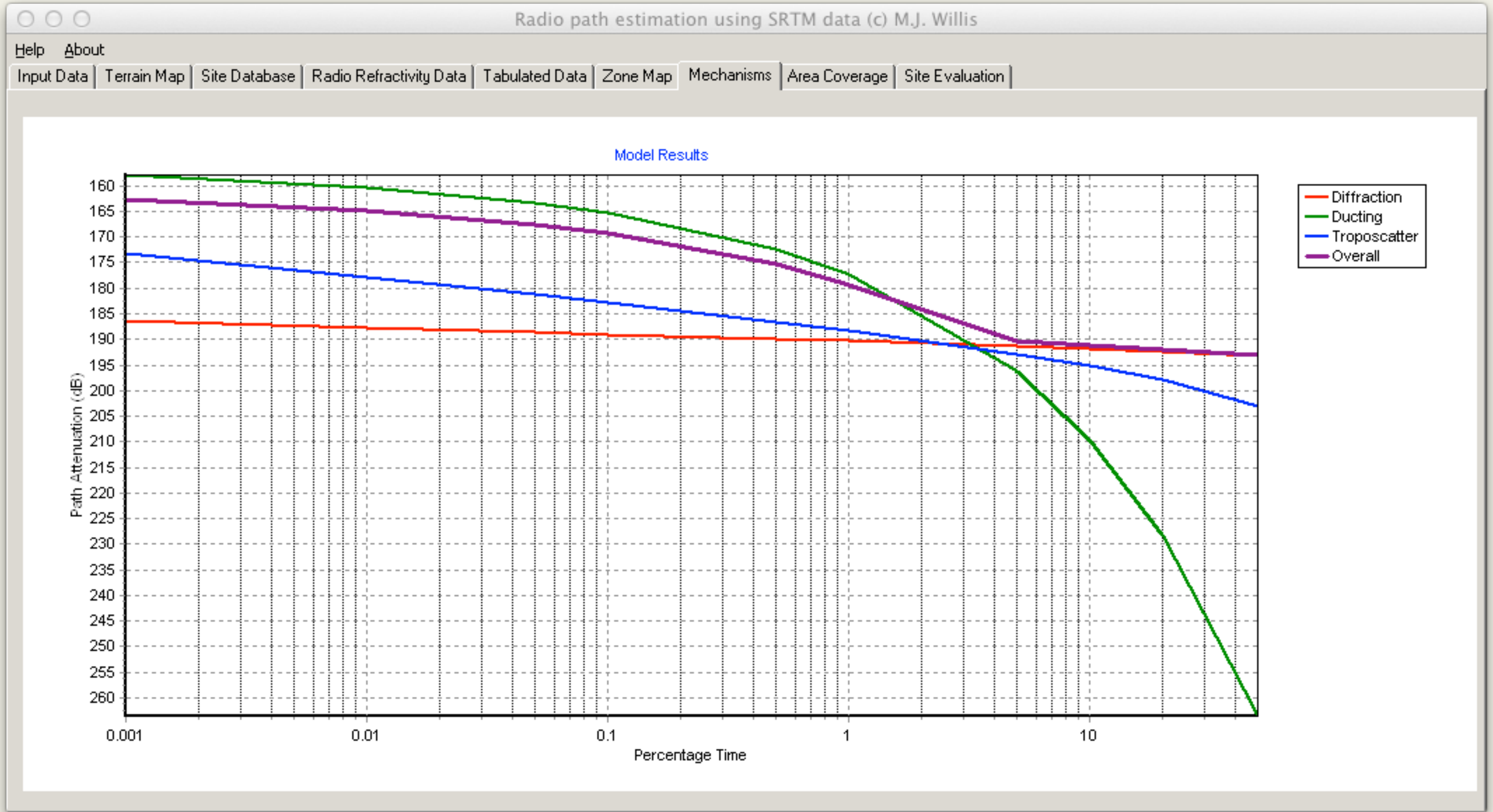
Pathprofile results



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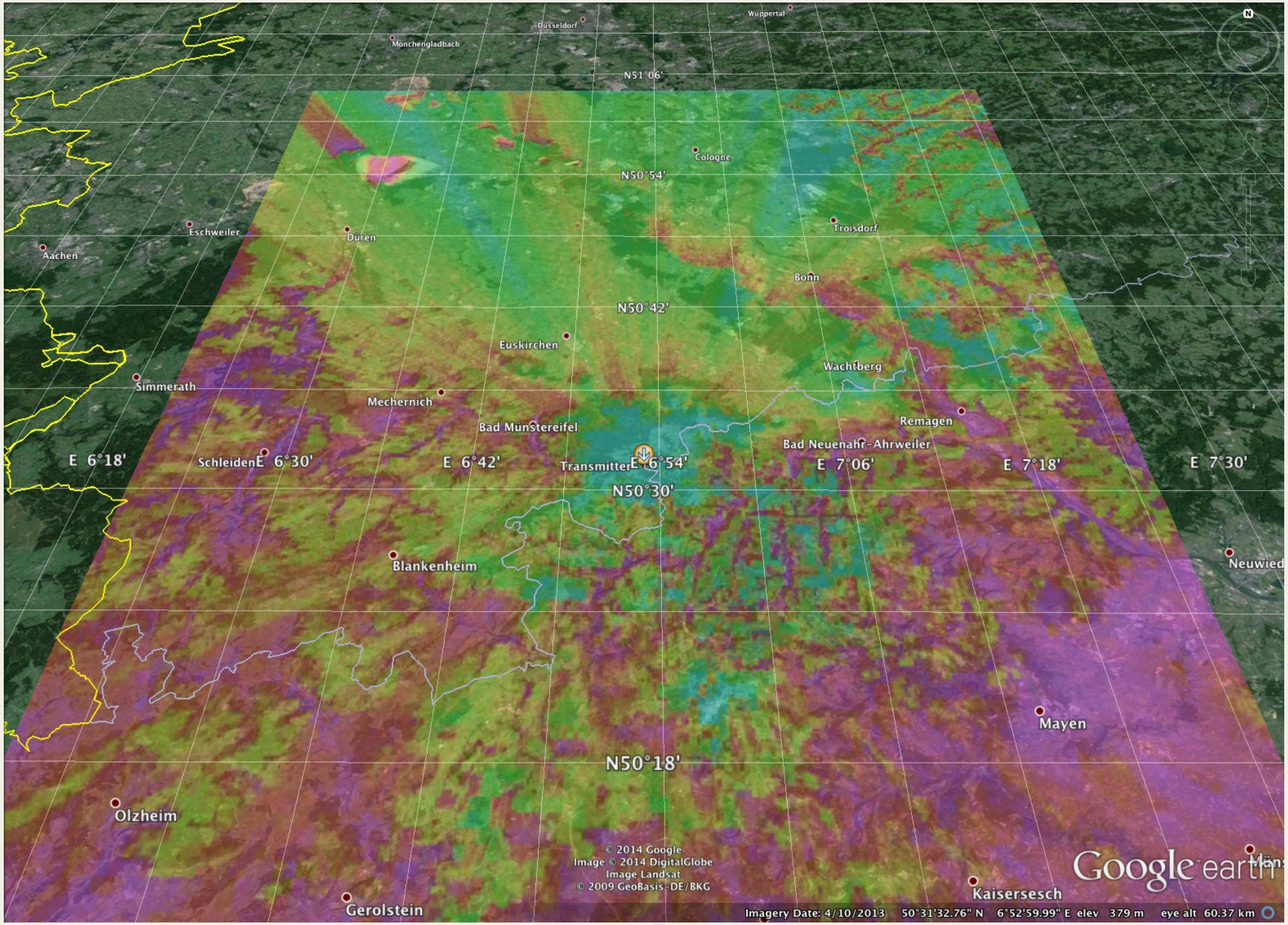
Pathprofile / Google Earth



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Recommendation ITU-R SM.1633

Compatibility analysis between a passive service and an active service allocated in adjacent and nearby bands

- Recommends methodology, but does not exclude other methodologies
- Contains results of 20 band-by-band services

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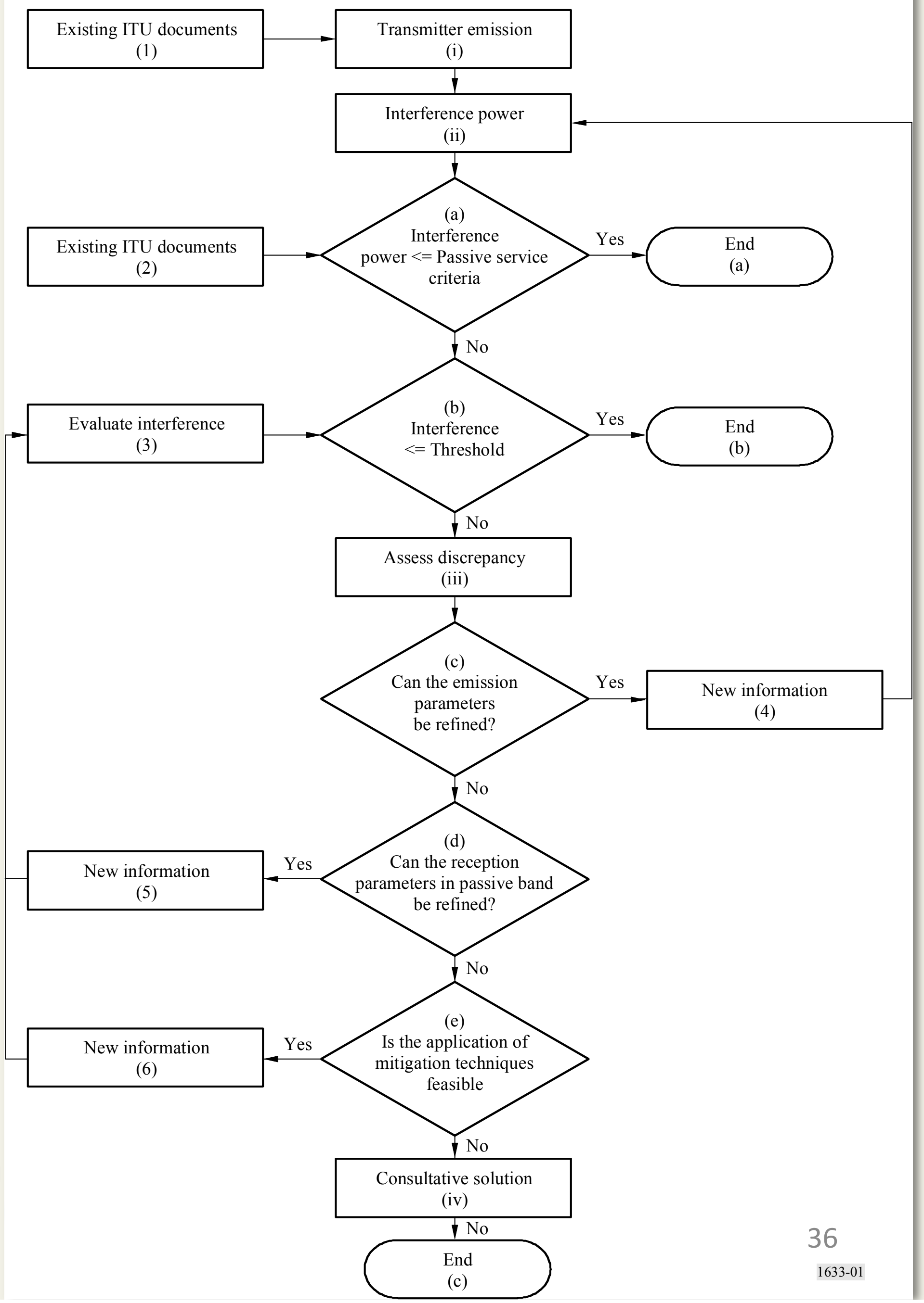
Formal methodology in SM.1633

FIGURE 1

Process for the evaluation of adjacent and nearby band operation of passive and active services



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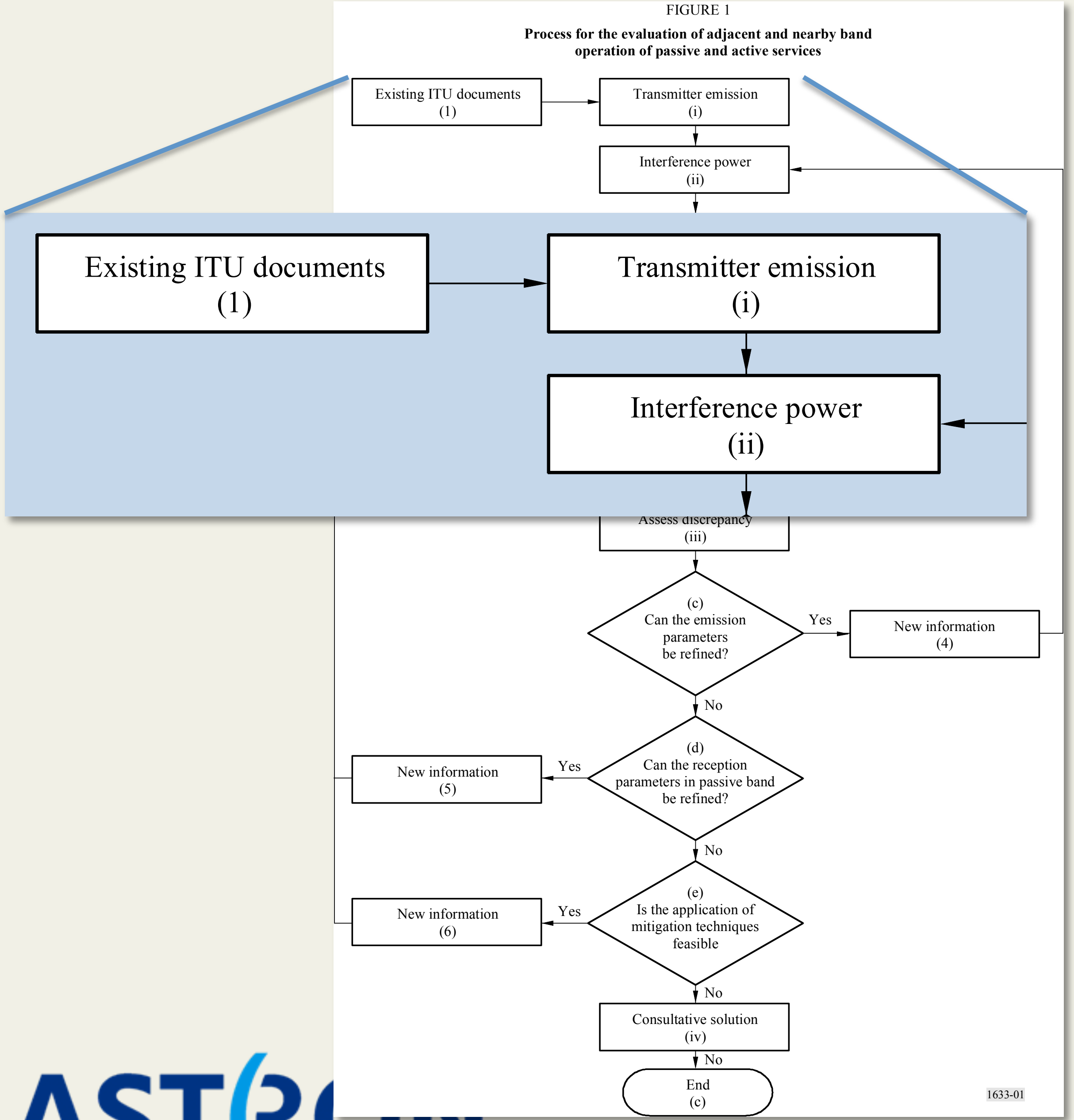
Step 1



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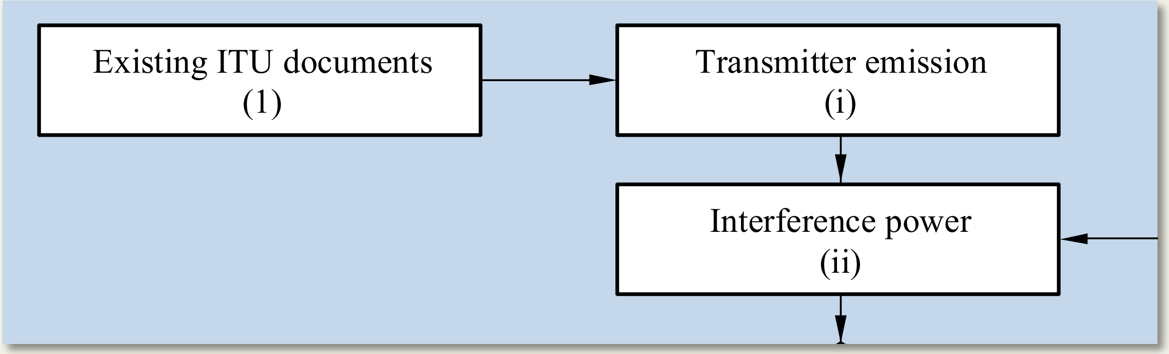
Step 1 (cont)



(i) Determine transmitter in-band power density $P_{density}$ (in dBW/Hz) at antenna flange of transmitter

Box 1: use ITU documents such as articles 1, 5, 21, 22 in RR, ITU recommendations and ITU reports as input

Also standards such as IEC, CSIPR and ETSI standards important sources of information

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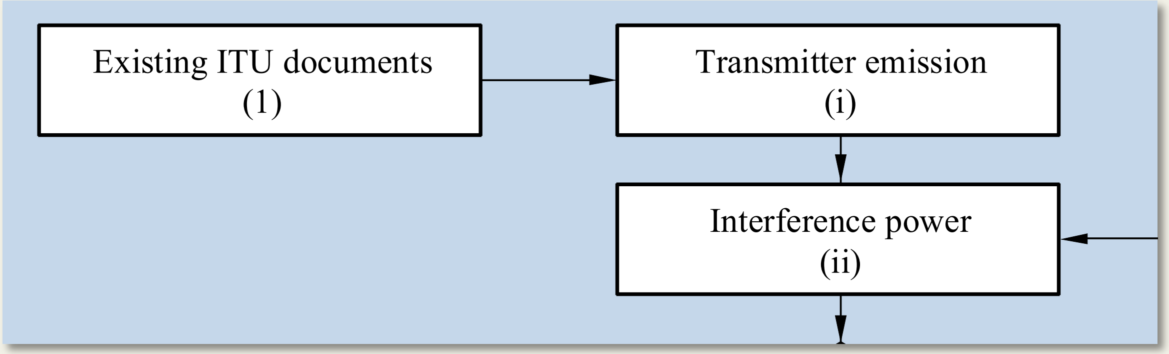
Step 1 (cont)



(ii) Determine power flux density of unwanted emission in passive band (interference power):

$$pfd_{unwanted\ emissions} = pfd_{in-band\ active} - OoB - L$$

OoB: out-of-band rejection mask e.g. DVB-T mask

L: propagation loss

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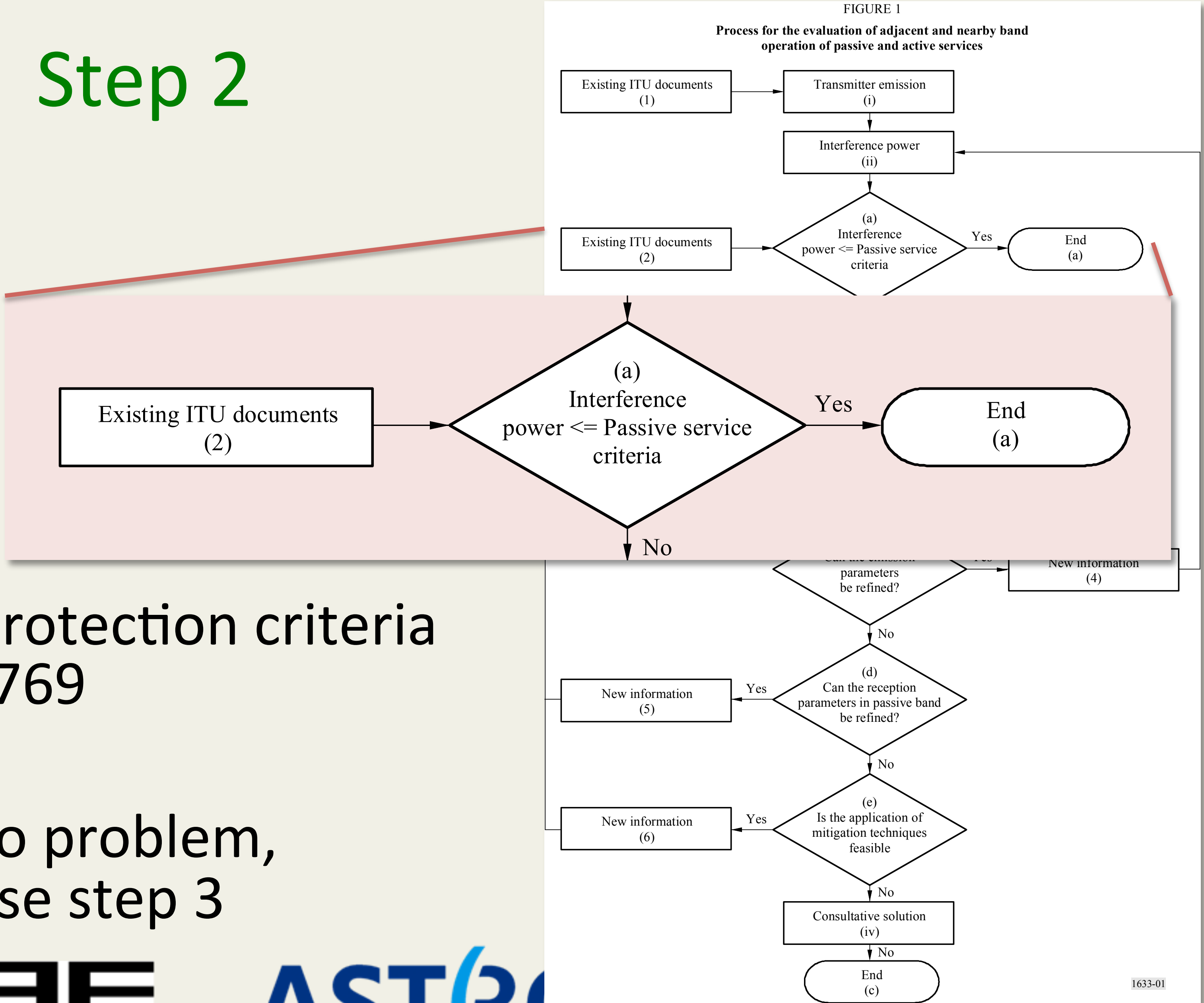
Step 2



Box 2: protection criteria e.g. RA.769

If yes: no problem, otherwise step 3

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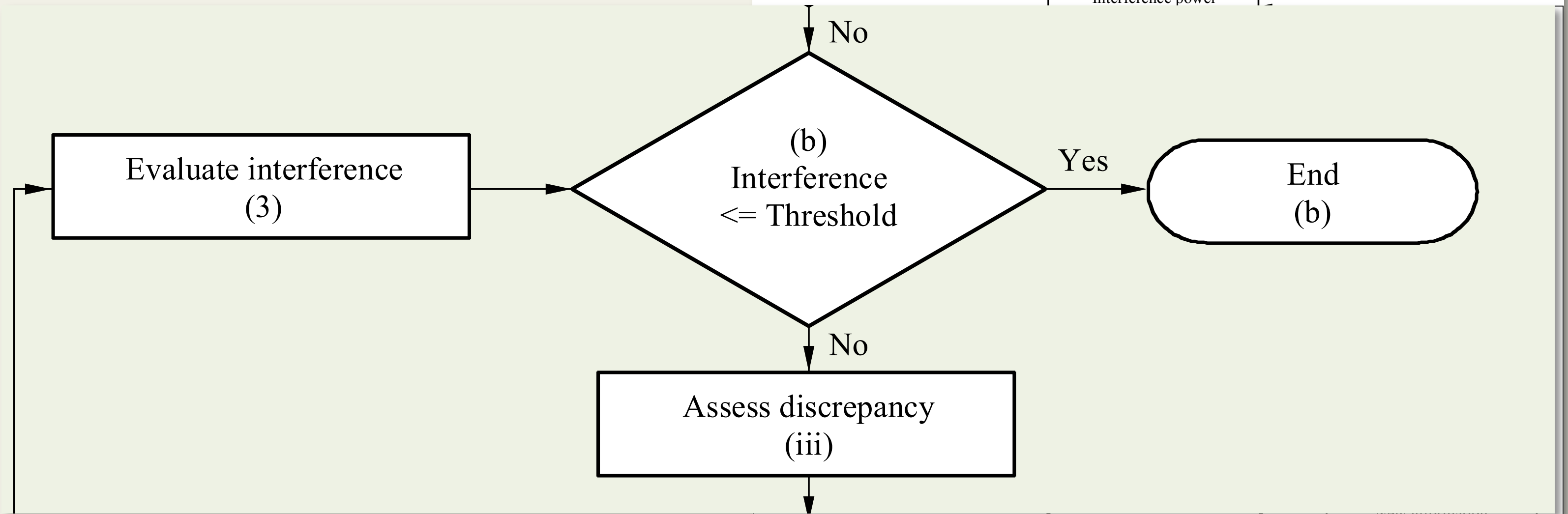
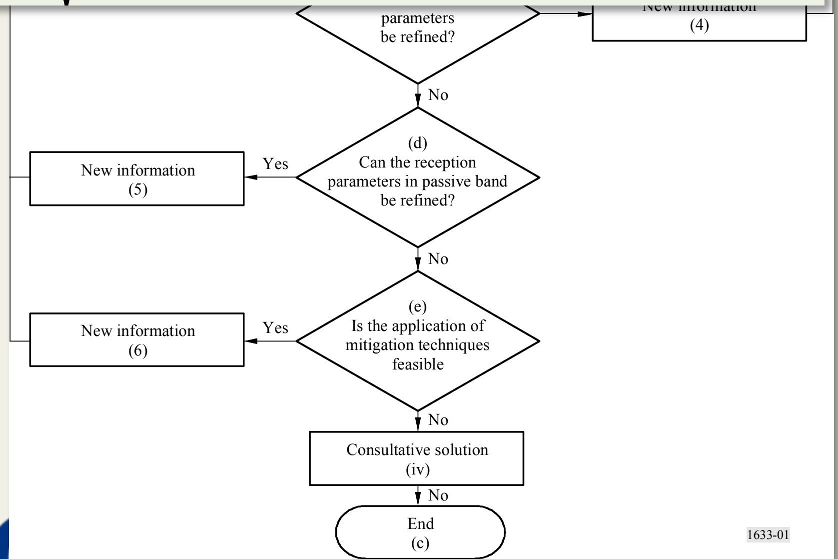
Step 3





(iii) Review input data to find cause of discrepancy

(3) and (b) Usually tested in 2nd or later iteration

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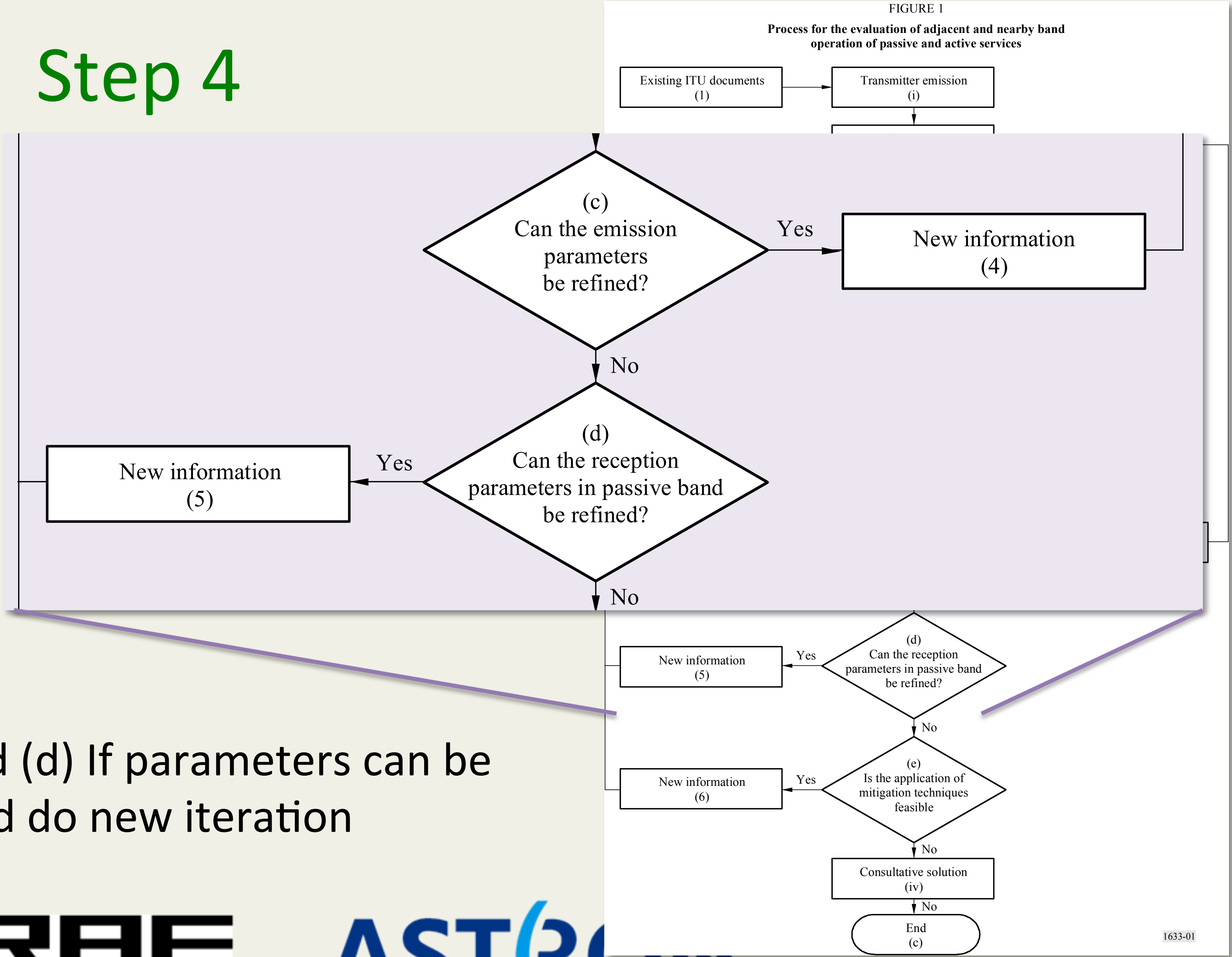
Step 4



(c) and (d) If parameters can be refined do new iteration

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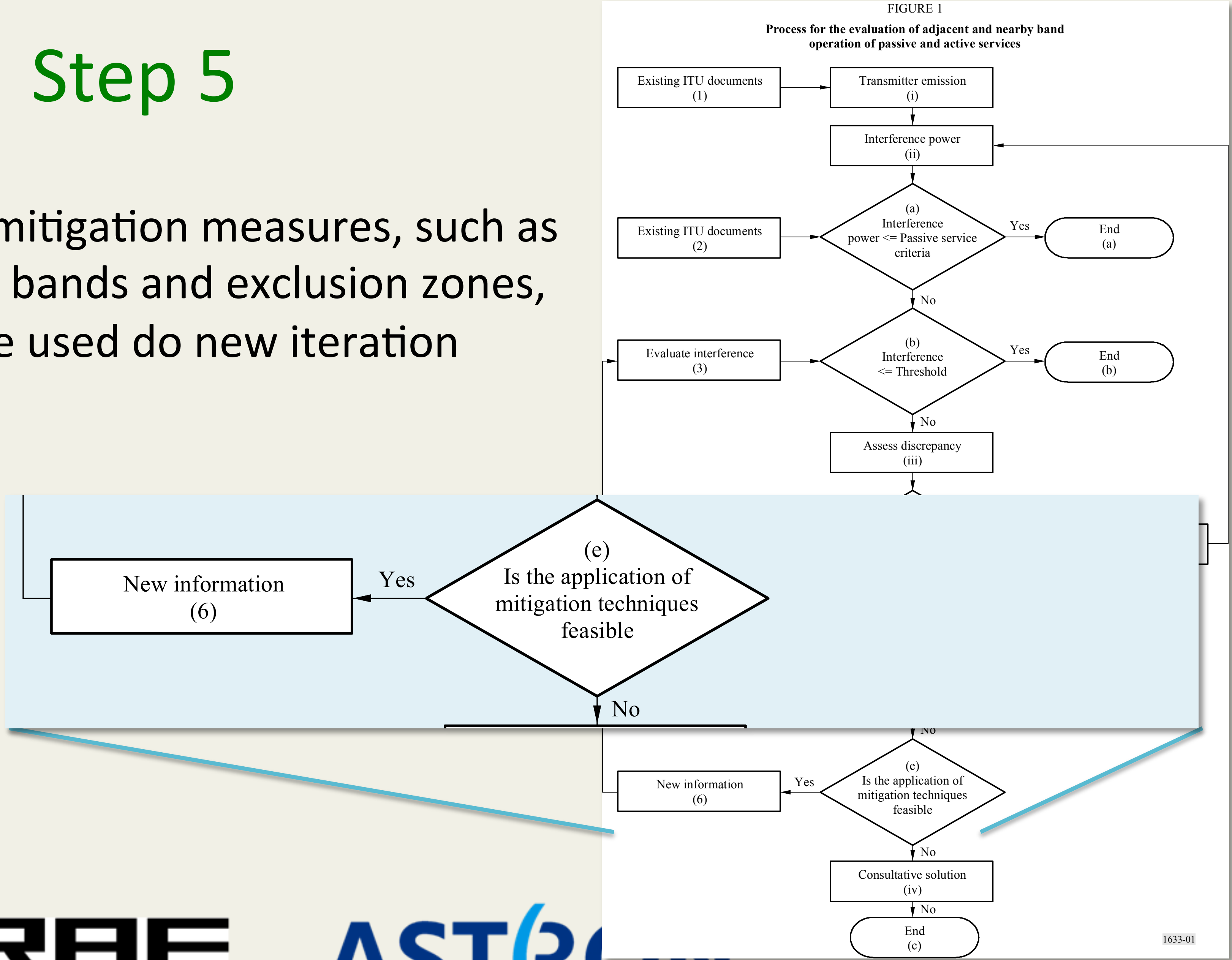
Step 5

(e) If mitigation measures, such as guard bands and exclusion zones, can be used do new iteration



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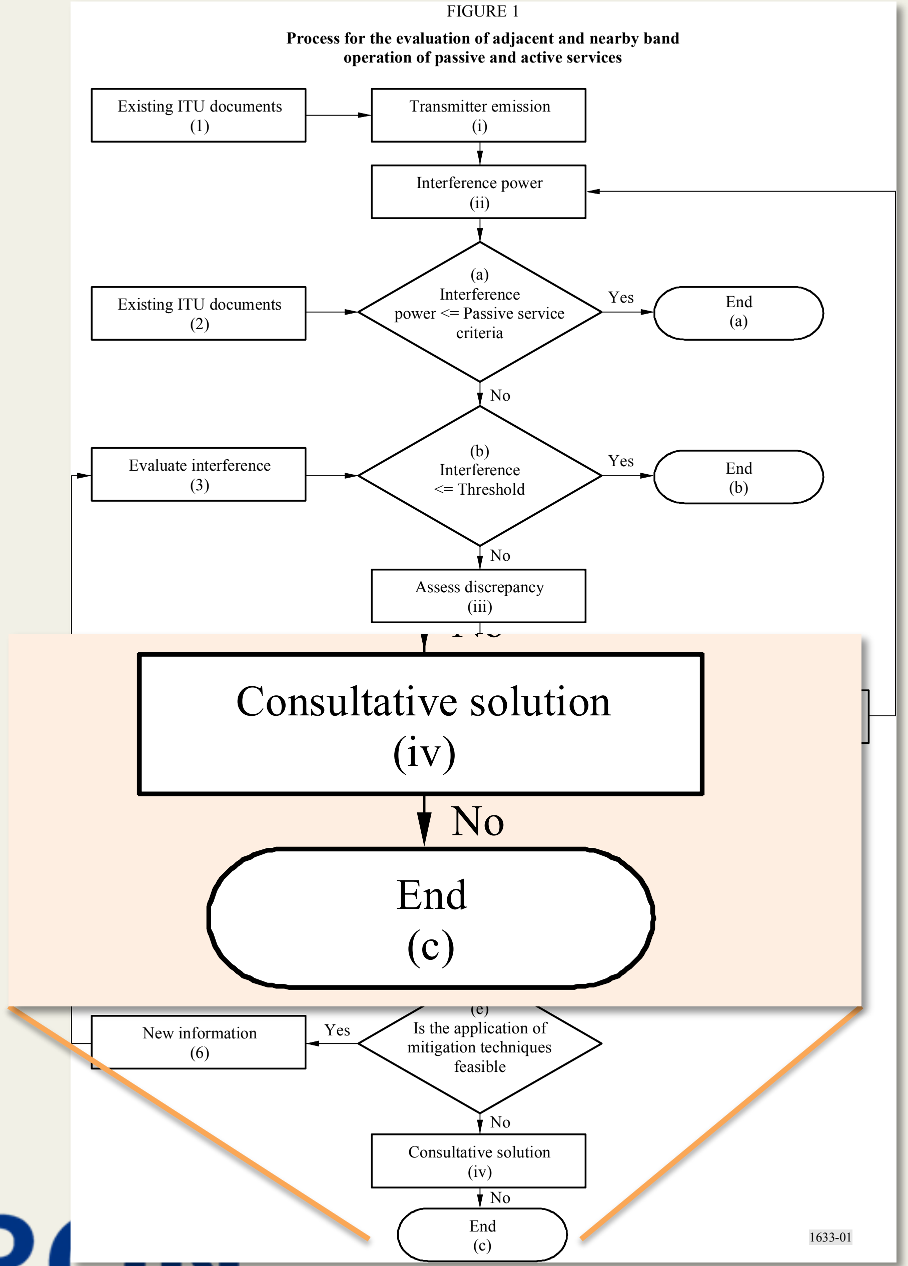
Step 6

(iv) If compatibility has not been achieved at this stage the active and passive users have to enter discussions to see whether an agreement can be reached on (parts of) the band



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Role of standards

- Valuable input information for study
  - Provides maximum 'worst' case transmit powers
  - Gives upper limits for out-of-band and spurious emissions (unwanted emissions)
    - Technically achievable limits
    - Include measurement uncertainties
- Manufacturers are enforced to be compliant
- New equipment or application ➜ new standard
  - Limitations for emissions (wanted and unwanted) from study
  - Limitations for use from study
  - Additional specifications (e.g. location sensitive)

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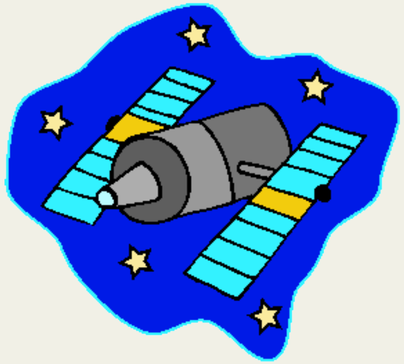
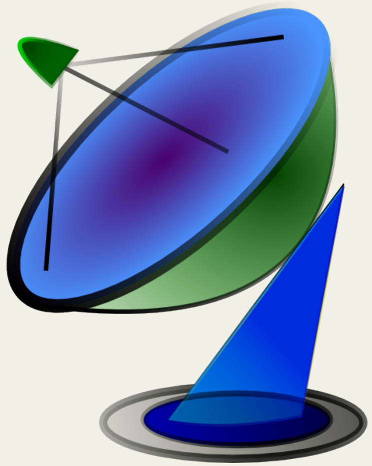


Single interferer

- From specifications determine Minimum Coupling Loss (MCL)

➜ Determine separation distance with help of propagation models

Interferer



Victim

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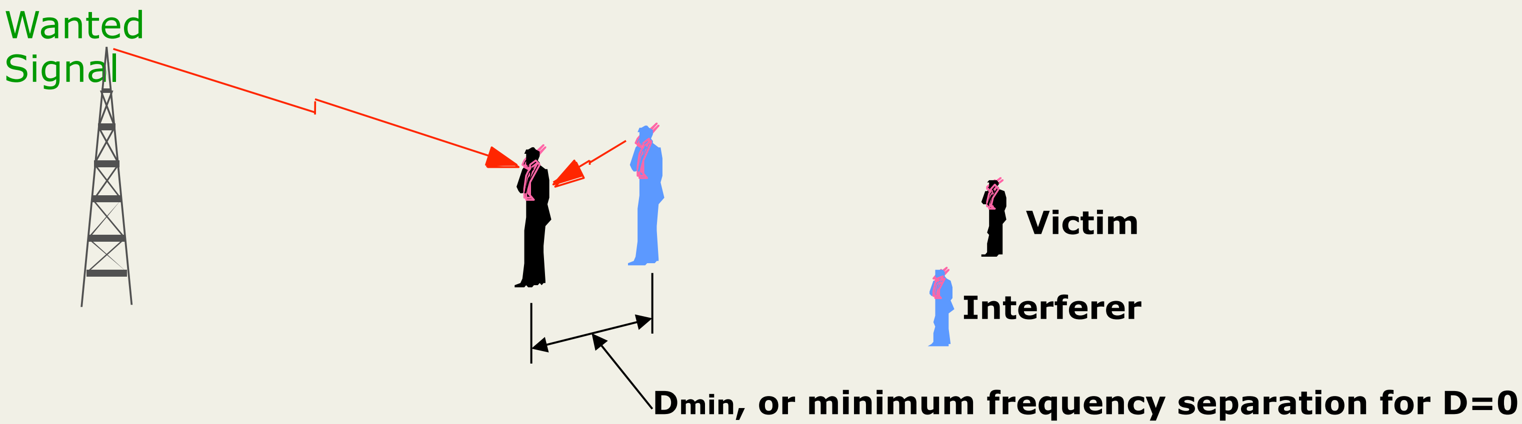
The MCL approach

- The stationary worst-case is assumed



  – However such worst-case assumption will not be permanent during normal operation and therefore sharing rules might be unnecessarily stringent – **spectrum use <u>not</u> optimal!**

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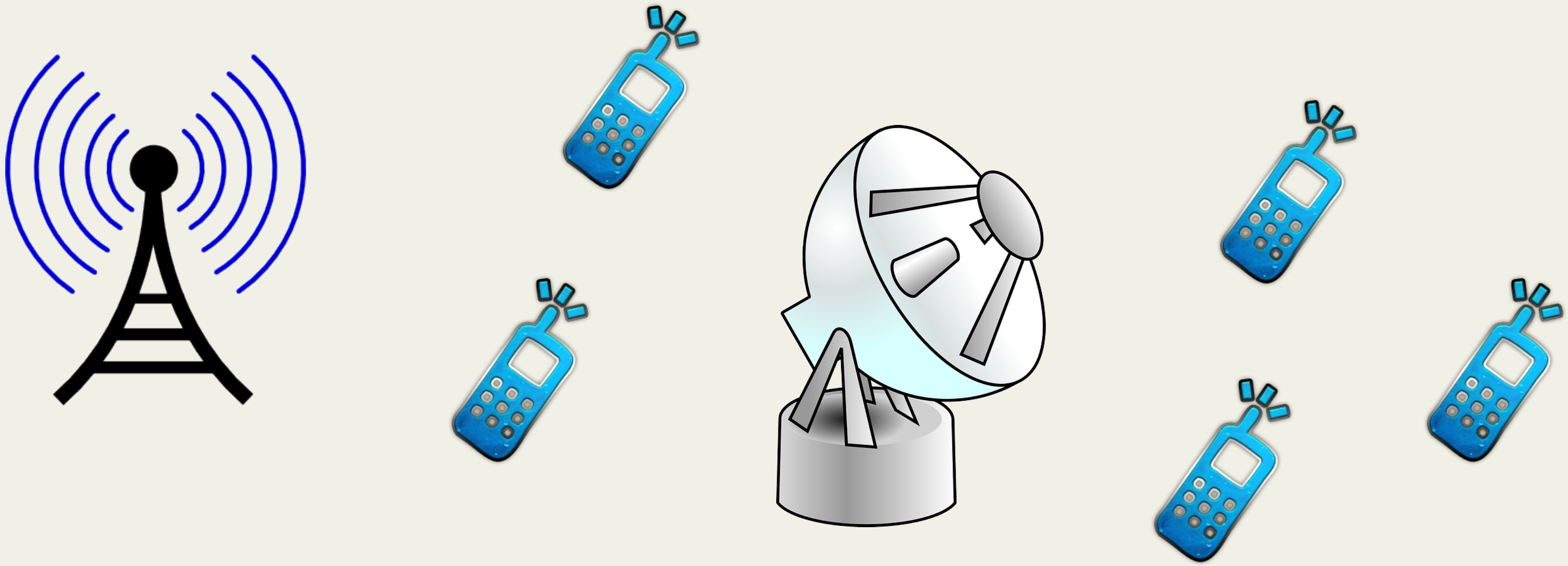
Multiple interferers ➜ Aggregate interference



- Statistical analysis of random trials:
  Monte Carlo simulations to establish probability of interference for a given deployment scenario
- 2% limit of Rec. ITU-R RA.1513

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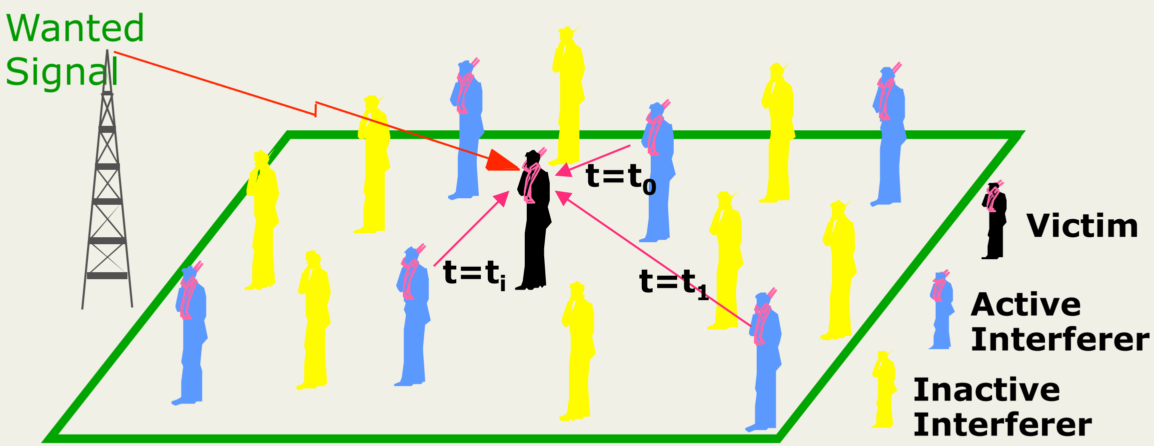
Monte-Carlo approach

- Repeated random generation of interferers and their parameters (activity, power, etc…)



– After many trials, not only unfavourable, but also favourable cases will be accounted, the resulting rules will be more "fair" – **spectrum use optimal!**

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Monte Carlo simulations

- User will need to define the distributions of various input parameters, e.g.:
  - How the power of interferer varies (Power control?)
  - How the interferer's frequency channel varies
  - How the distance between interferer and victim varies, and many others
- Number of trials has to be sufficiently high (many 1000s) for statistical reliability:
  - Not a problem with modern computers
- ECC has developed Monte Carlo simulation tool: SEAMCAT
  http://www.cept.org/eco/eco-tools-and-services/seamcat-spectrum-engineering-advanced-monte-carlo-analysis-tool

Purpose of SEAMCAT

- SEAMCAT is designed for:
  - Generic co-existence studies between different radiocommunications systems operating in same or adjacent frequency bands
  - **Not** designed for system planning purposes
- Can model any type of radio systems in terrestrial interference scenarios (mobile, broadcasting, Fixed etc..)
- Used for analysis of a variety of radio compatibility scenarios:
  - quantification of probability of interference between various radio systems (unwanted emissions, blocking/selectivity)
  - quantification of throughput and data loss for CDMA and OFDMA system
- Based on Monte-Carlo generation

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EPFD calculations

- epfd: equivalent power flux density
- Used for interference calculations by unwanted emissions between non-GSO satellites and RAS sites
- Satellites are moving wrt RAS site
- Often constellations of multiple (up to >60) satellites ➜ statistical approach
- epfd is aggregate of contributions from all satellite emissions expressed in pfd of single equivalent source on boresight of radio telescope
- Description in Rec ITU-R M.1583 and S.1586

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Definition of epfd

$$epfd = 10\log_{10}\left[\sum_{i=1}^{N_a} 10^{\frac{P_i}{10}} \cdot \frac{G_t(\theta_i)}{4\pi\, d_i^2} \cdot \frac{G_r(\phi_i)}{G_{r,max}}\right]$$

With

N_a: number of space stations visible from site

P_i: RF power of unwanted emissions at antenna

G_t: transmit antenna gain of space station

d_i: distance between space station and RAS site

G_r: receive antenna gain

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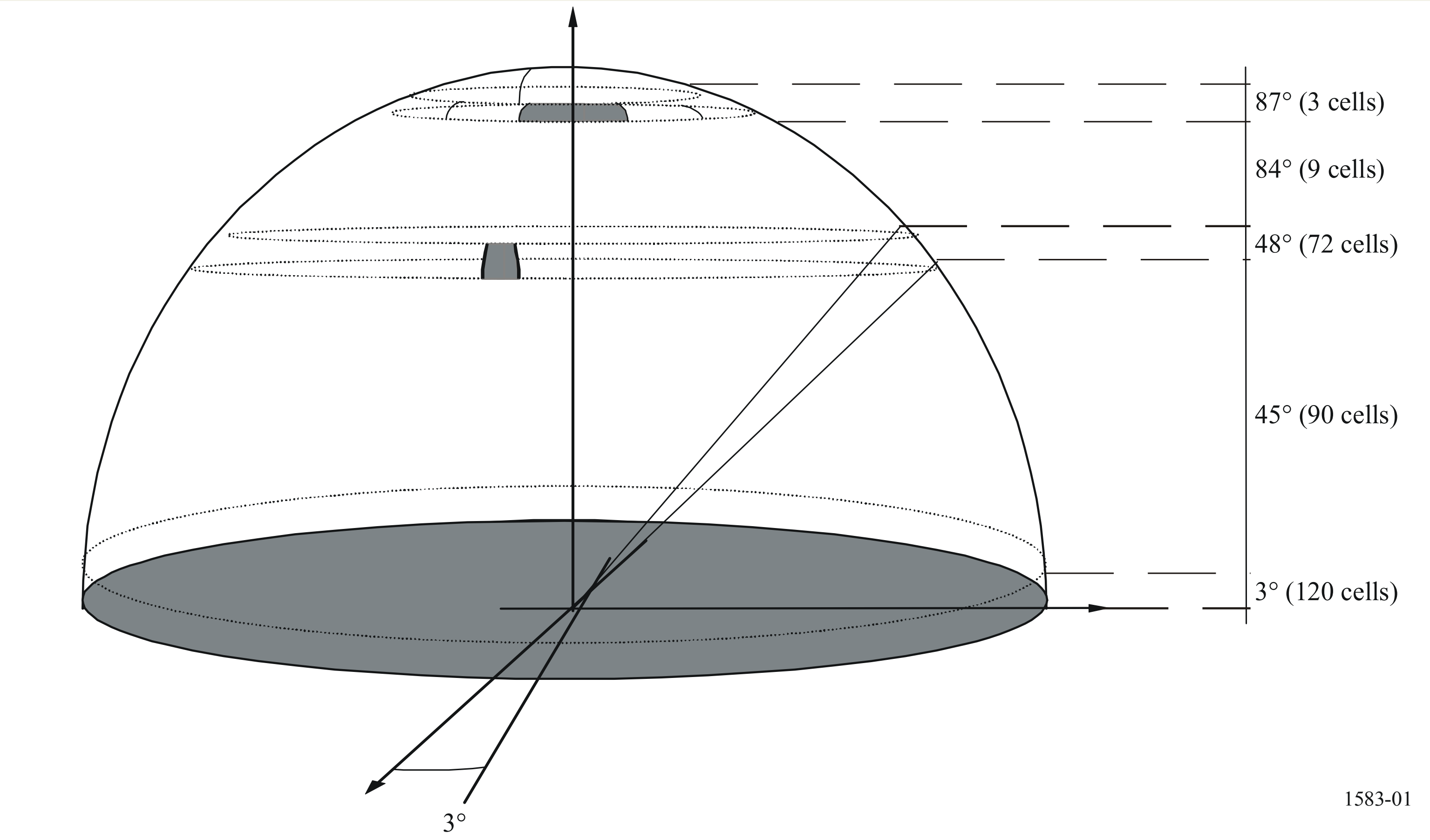
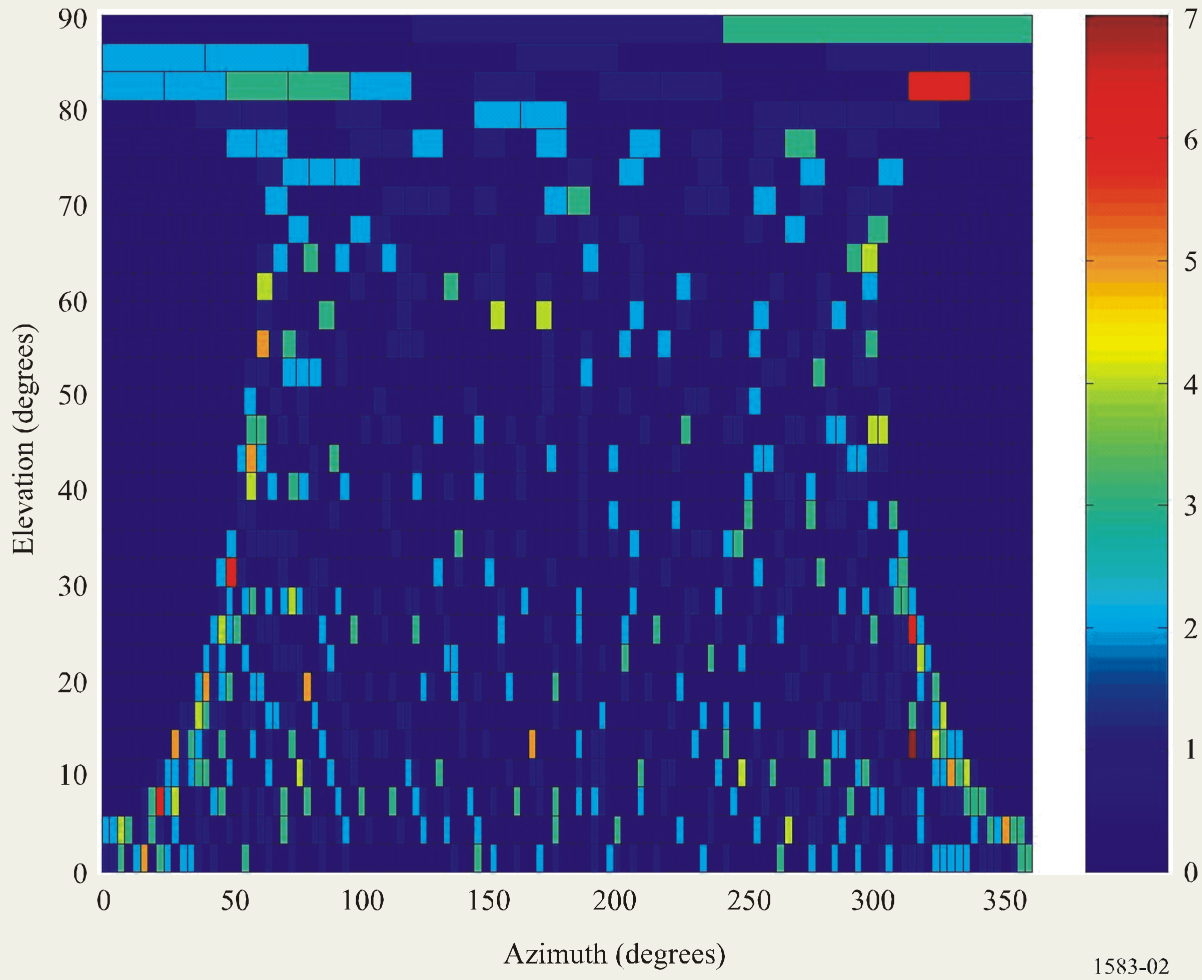
Distribution of epfd levels



Output in terms of data loss



Measurements usually do not cover all sky
➜
supplemented with simulations

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Case study: IMT

- WRC-15 AI 1.1: ***to consider additional spectrum allocations to the mobile service on a primary basis and identification of additional frequency bands for International Mobile Telecommunications (IMT) and related regulatory provisions, to facilitate the development of terrestrial mobile broadband applications, in accordance with Resolution 233 [COM6/8] (WRC-12);*** (~410 MHz - ~6GHz)

- **DRAFT NEW REPORT ITU-R RA.[RAS-IMT**]
  Compatibility and sharing studies between the radio astronomy service and IMT systems in the frequency bands 608-614 MHz, 1 330-1 400 MHz,
  1 400-1 427 MHz, 1 610.6-1 613.8 MHz, 1 660-1 670 MHz,
  2 690-2700 MHz, 4 800-4 990 MHz and 4 990-5 000 MHz
  (Doc 4-5-6-7/TEMP/106)

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Expected situation IMT

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Bands for RAS IMT studies

RAS frequency band	RAS status	RR No.	RAS use	Potential IMT proposal
608-614 MHz;	**secondary; primary in Region 2 and some countries in Regions 1 and 3**	5.149 5.304 5.305 5.306 5.307	Broadband, VLBI	In band sharing or adjacent
1 330-1 400 MHz;		5.149	Broadband, narrowband, VLBI	In band sharing
1 400-1 427 MHz;	**Primary**	**5.340**	Broadband, narrowband, VLBI (e.g. neutral hydrogen line)	Adjacent (both sides)
1 610.6-1 613.8 MHz;	**Primary**	5.149	Narrowband, VLBI (e.g. Hydroxyl line)	Nearby (below 1 525 MHz)
1 660-1 670 MHz;	**Primary**	5.149	Broadband, narrowband, VLBI (e.g. Hydroxyl lines)	Nearby (below 1 525 MHz)
2 690-2 700 MHz;	**Primary**	**5.340**	Broadband, VLBI; also, RAS techniques used by SRS	Adjacent (above 2 700 MHz)
4 800-4 950 MHz;	Secondary	5.149	Broadband, narrowband, VLBI	In band sharing or nearby (above 5 350 MHz)
4 950-4 990 MHz	secondary, **primary in some countries in Regions 2 and 3**	5.149 **5.443**	Broadband, narrowband, VLBI	In band sharing or nearby (above 5 350 MHz)
4 990-5 000 MHz	**Primary**	5.149	Broadband, narrowband, VLBI	In band sharing or nearby (above 5 350 MHz)

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RAS characteristics

- Passive (receive-only) service
- Threshold levels for interference in ITU-R RA.769 (table for continuum (broadband) and spectral-line (narrowband) observations)
- Integration time 2000 s
- Antenna gain 0 dBi
- Aggregate study: max. 2% data loss (ITU-R RA. 1513)
- (RAS antenna pattern from ITU-R SA.509)

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IMT characteristics

For RAS-IMT study only transmitter characteristics from Report ITU-R M.2292:

- User terminals
  - Transmit height: 1.5 m
  - Channel BW: 1.4, 3, 5, 10, 15 and 20 MHz
  - Transmit e.i.r.p.: 23 dBm (10 dBm/MHz for 20 MHz BW)
  - Antenna gain: -3 dBi
  - Human body absorption: 4 dB

  Other assumptions:
  - Average deployment density: 0.377 km^{-2}
  - Average activity factor: 0.5%
  - Duty cycle: 50%
  - Generic flat terrain profile (ITU-R P.452)

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IMT characteristics (cont)

- IMT base stations
  - Transmit antenna height: 45 m (macro rural)
  - Channel bandwidth: 1.4, 3, 5, 10, 15 or 20 MHz
  - Average base station power/sector e.i.r.p. taking into account 50% activity factor): 58 dBm (macro rural) (45 dBm/MHz for 20 MHz BW)

  Other assumptions:
  - Average deployment density 0.11 km^{-2}
  - Average activity factor: 100%
  - Duty cycle: 50%
  - Generic flat terrain profile (ITU-R P.452)

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Sharing in 1330 – 1400 MHz

Secondary allocation in some countries, FN 5.149 in most countries
Reference bandwidth: 70 MHz
Threshold interference level: -202 dBW (derived from ITU-R RA.769)

	User terminal	**Base station**
Single interferer MCL	175 dB	240 dB
Single interferer separation	52 km	133 km
Aggregate separation	85 km	502 km

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Compatibility with 1400-1427 MHz

Primary RAS allocation
Reference bandwidth: 27 MHz
Threshold interference level: -205 dBW (from ITU-R RA.769)

	User terminal	**Base station**
Unwanted emission level -30 dBm/MHz		
Single interferer MCL	136 dB	156 dB
Single interferer separation	20 km	69 km
Aggregate separation	25 km	89 km
Unwanted emission level -50 dBm/MHz		
Single interferer MCL	136 dB	156 dB
Single interferer separation	6 km	50 km
Aggregate separation	6 km	71 km

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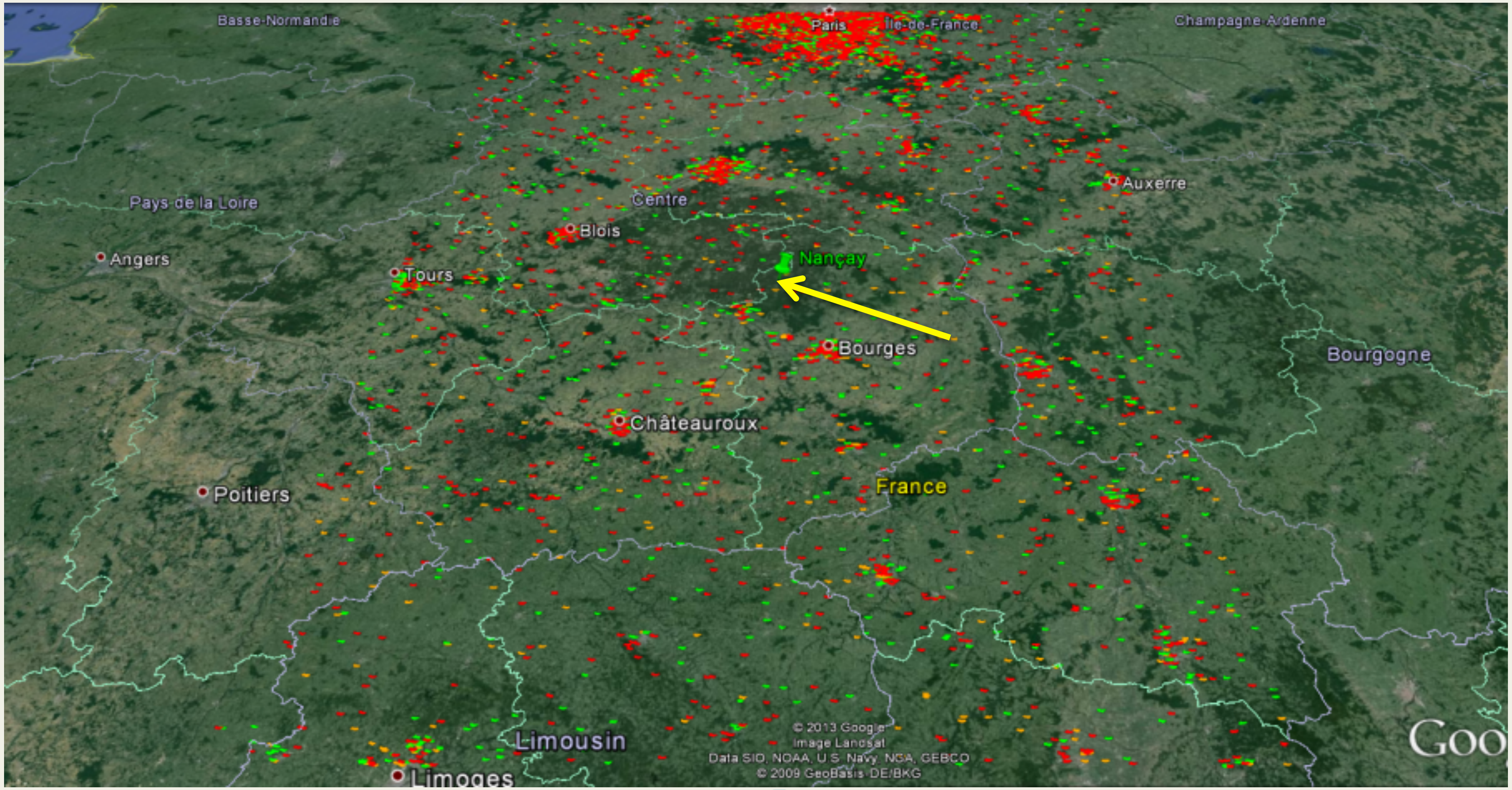
1400-1427 MHz (French study)

Base stations around Nancay, user terminals not included
Study for 1375-1400 MHz or 1427-1452 MHz
Takes real terrain into account



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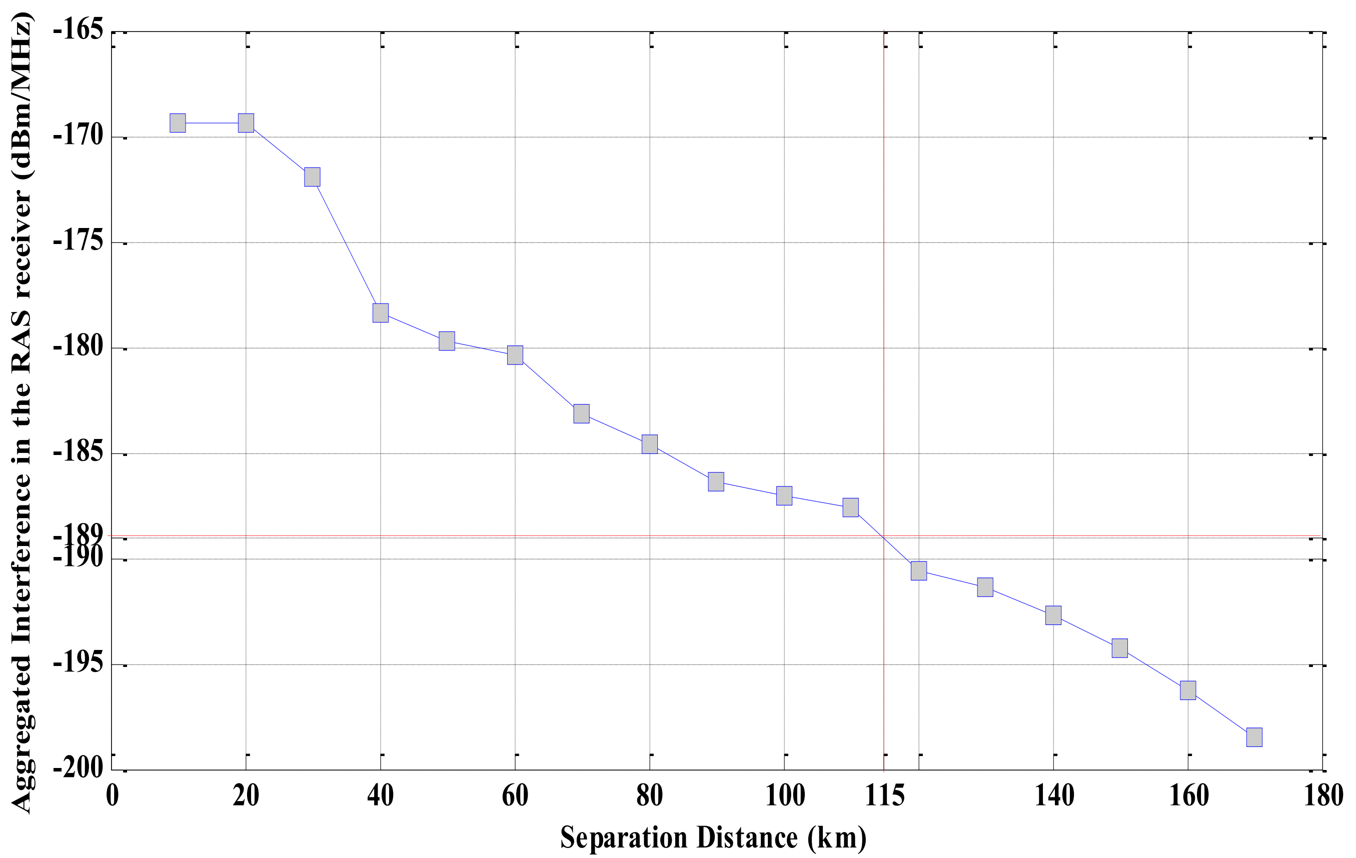
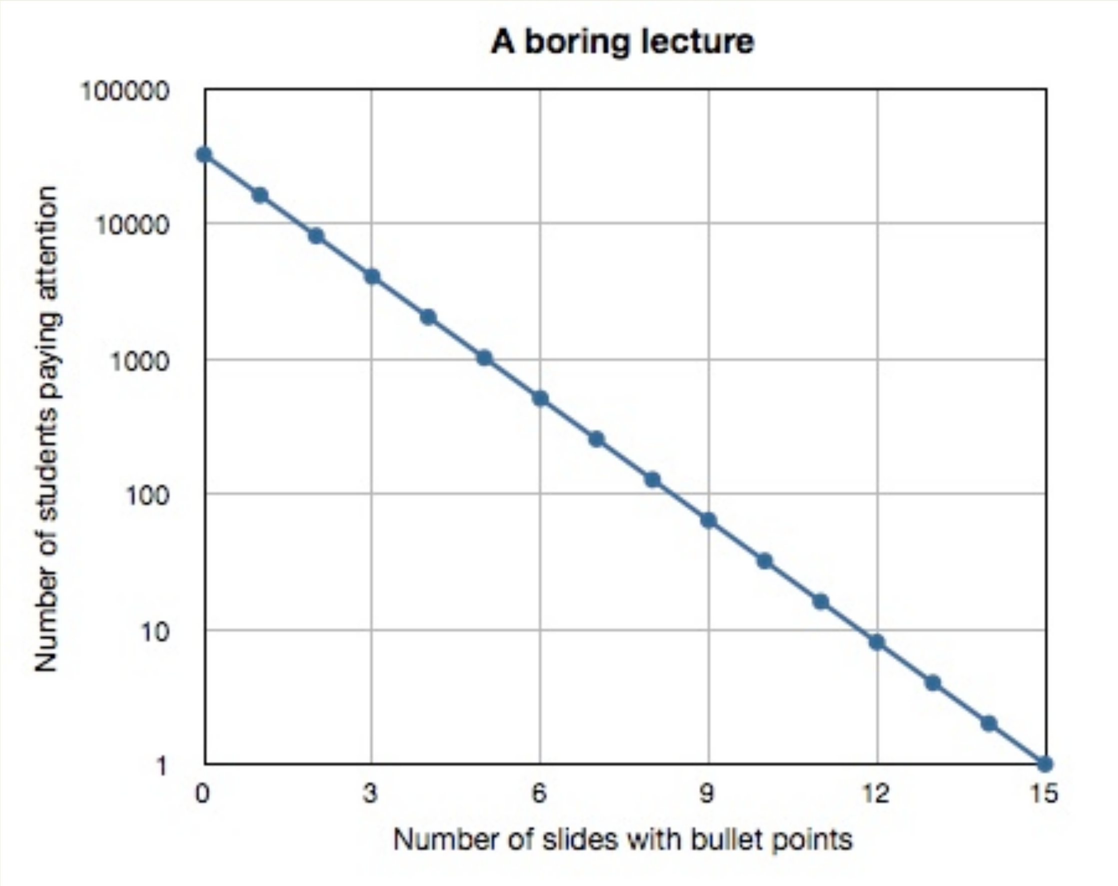
Result of French Study

Assumed unwanted emission level: -64 dBm/MHz



Thank you very much for your attention!



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