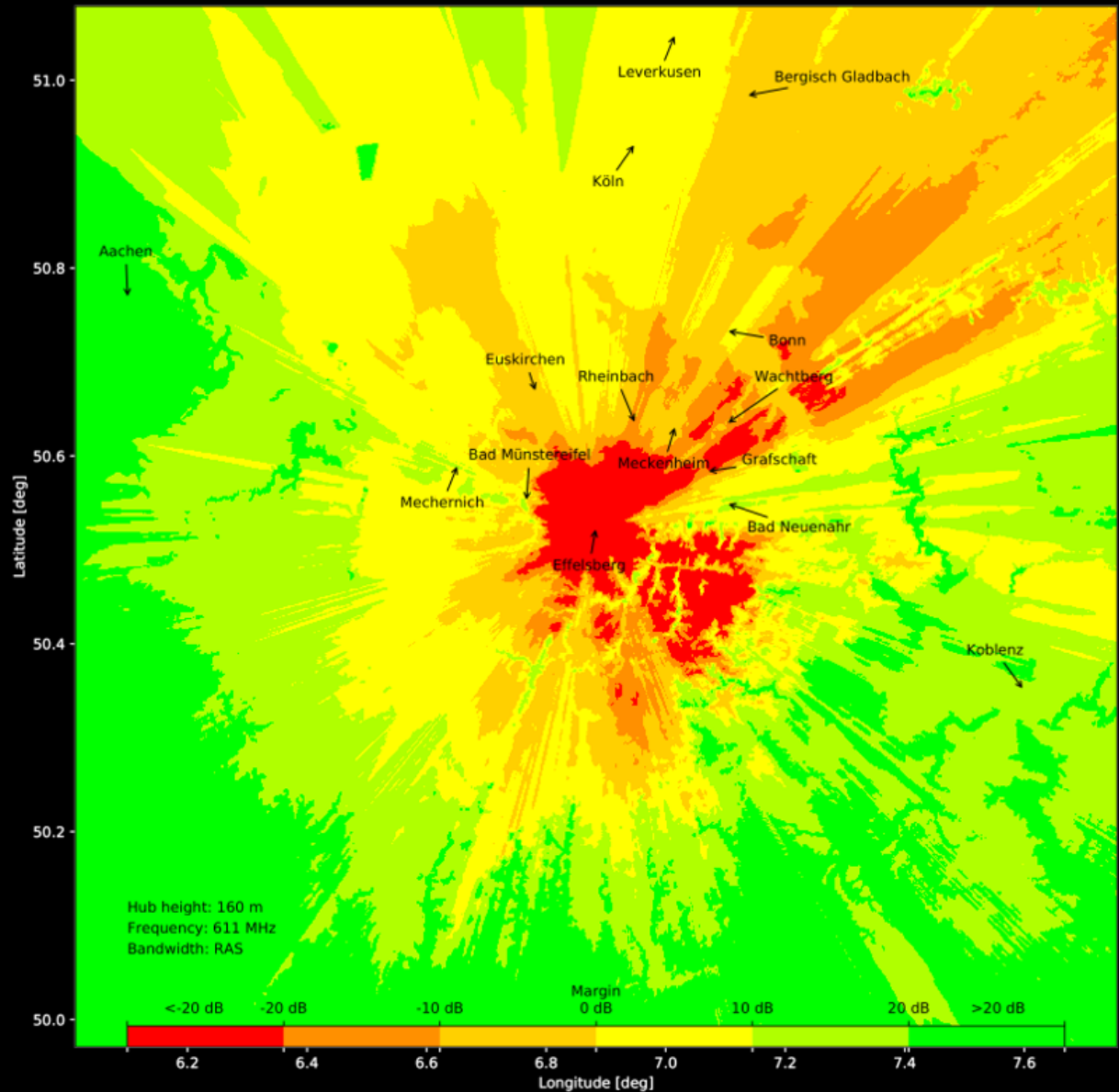


# Compatibility between Radioastronomical Observations and Wind Turbines

Benjamin Winkel  
Axel Jessner

Max-Planck-Institut  
für  
Radioastronomie



# Overview

- Introduction: radio astronomy
- Wind turbines and the 100-m telescope
  - Spectrum management
  - Compatibility calculations
- Conclusions

# Introduction – Radio astronomy



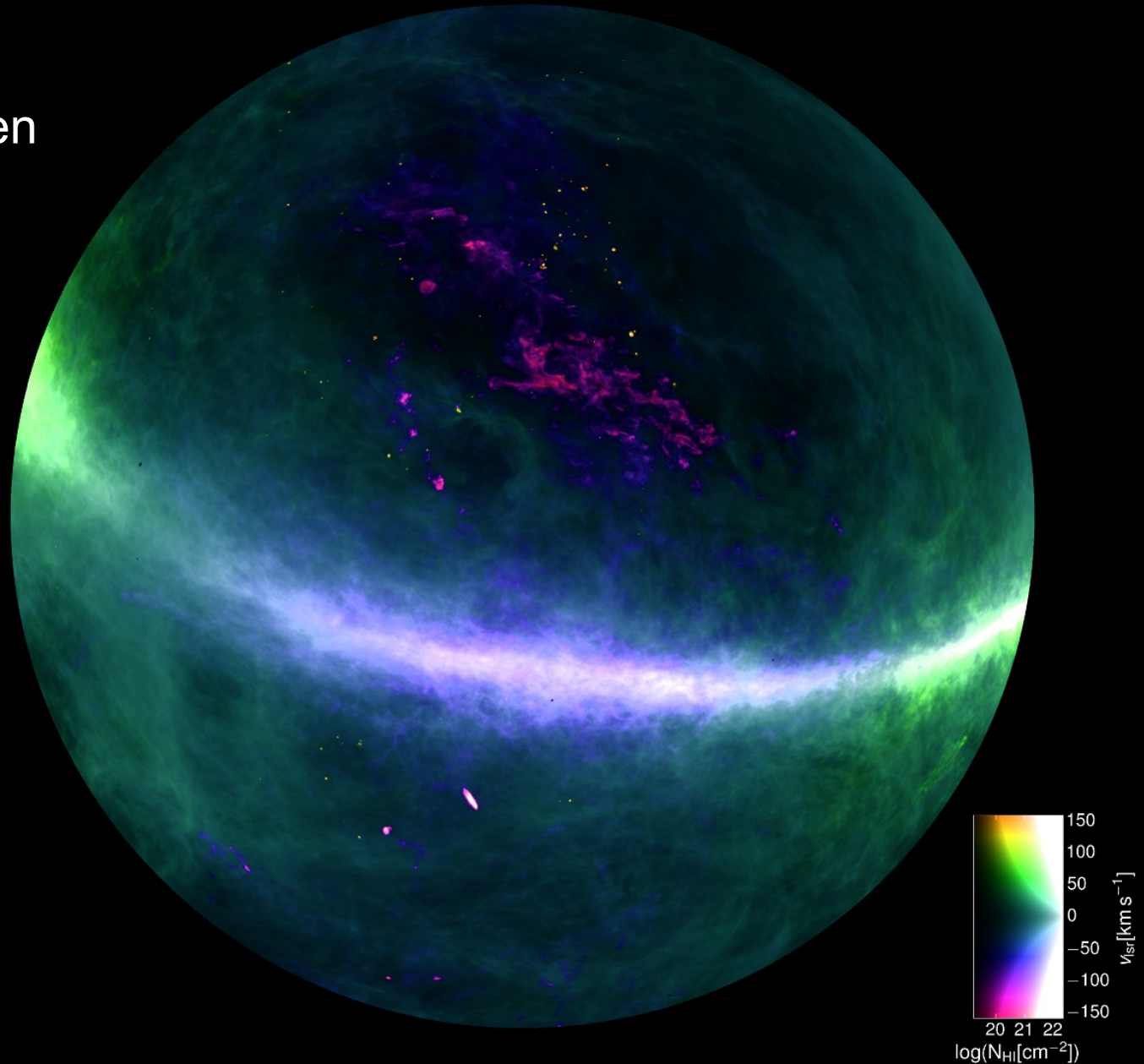
## Effelsberg 100-m telescope

- Antenna gain:  $\sim 80$  dBi
- Receivers:
  - 0.3 – 90 GHz
  - cooled to 20 K
  - $T_{\text{sys}}$ : 15 – 100 K
- Long integrations to decrease noise; up to days
- Sensitivity:  $< 10^{-29}$  W/m<sup>2</sup>/Hz

# Introduction – Radio astronomy

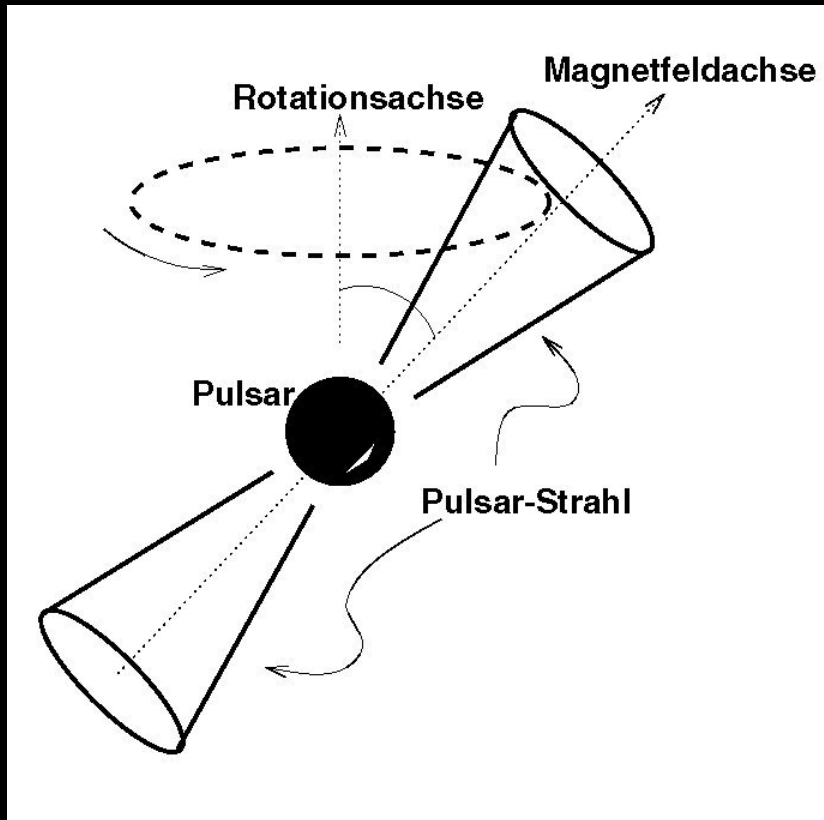
EBHIS:

Neutral hydrogen  
spectroscopy  
@ 1.4 GHz

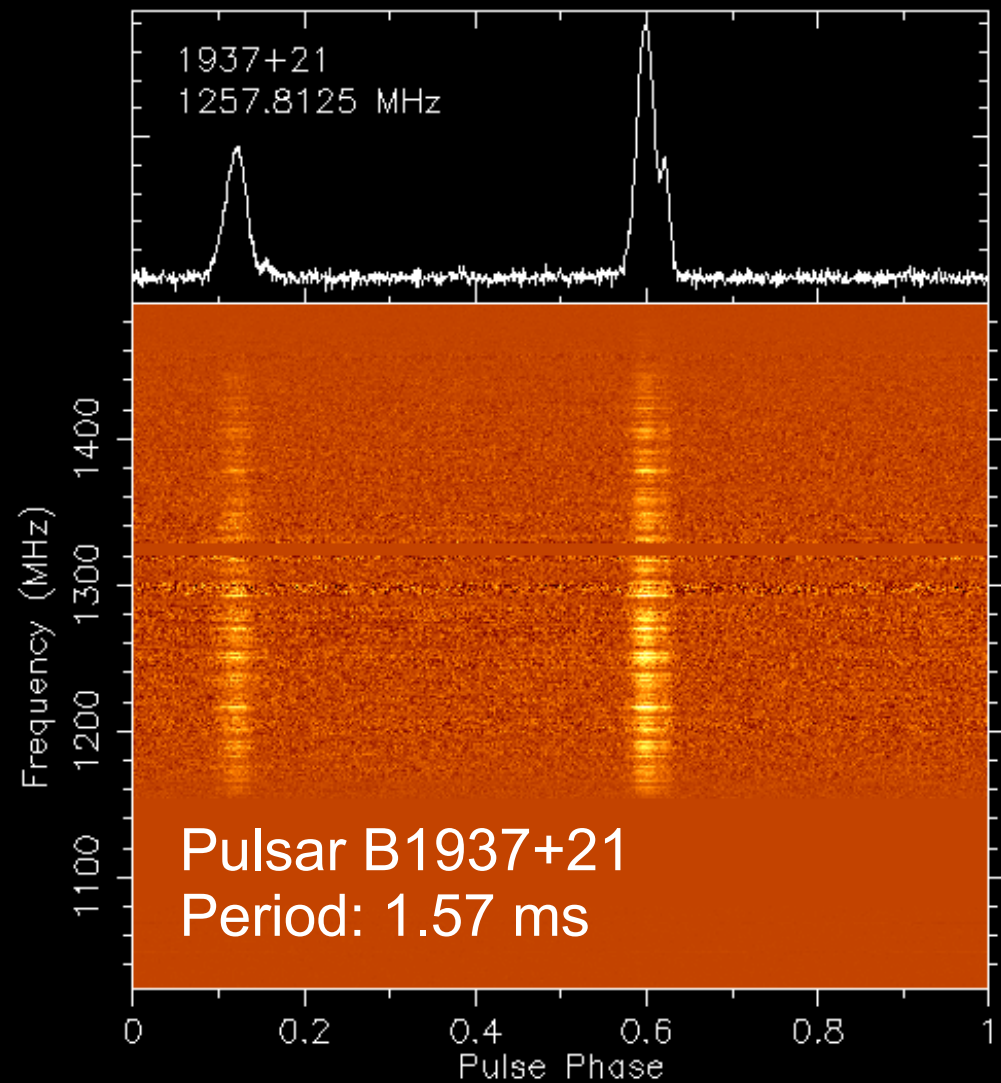




# Introduction – Radio astronomy



Magnetic field  $\sim 10^{15}$  G



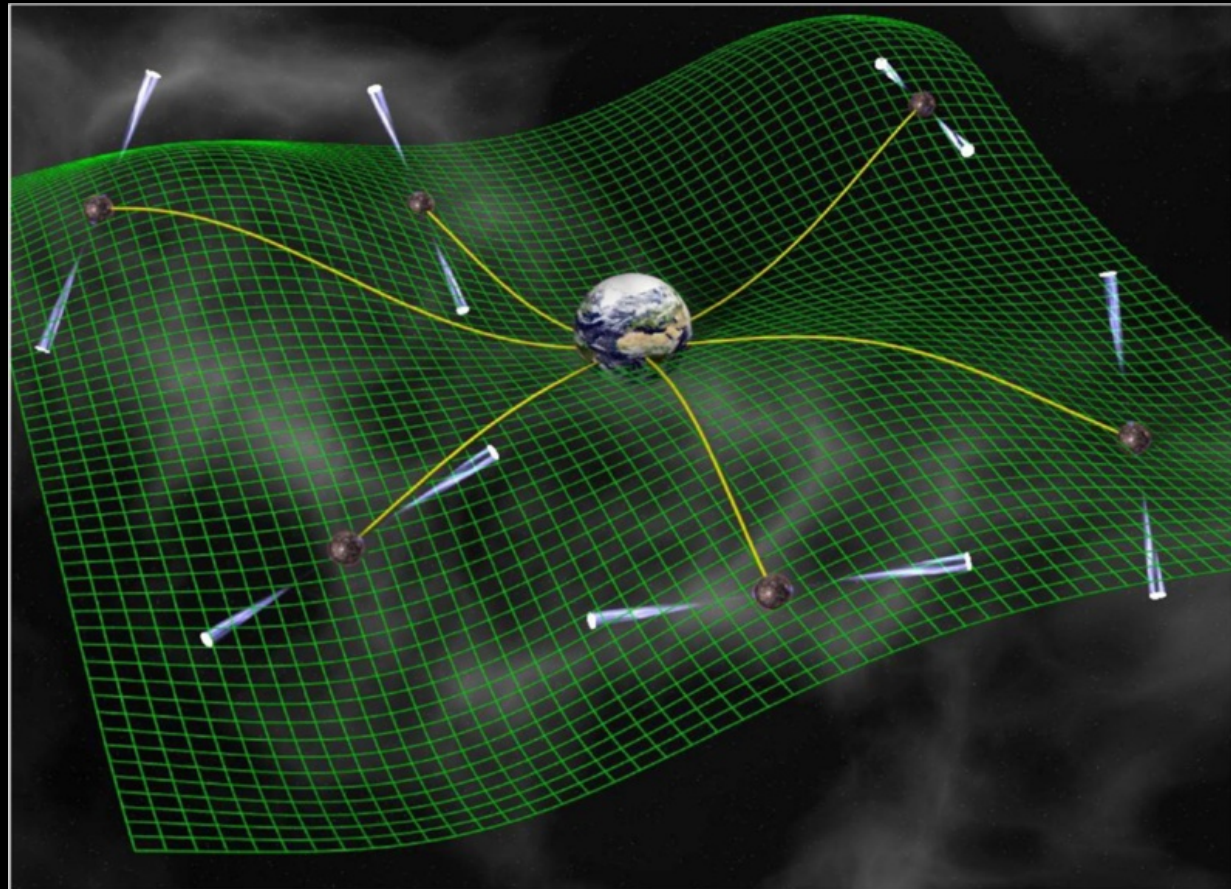
# Introduction – Radio astronomy

Some Pulsars have extremely regular periods:

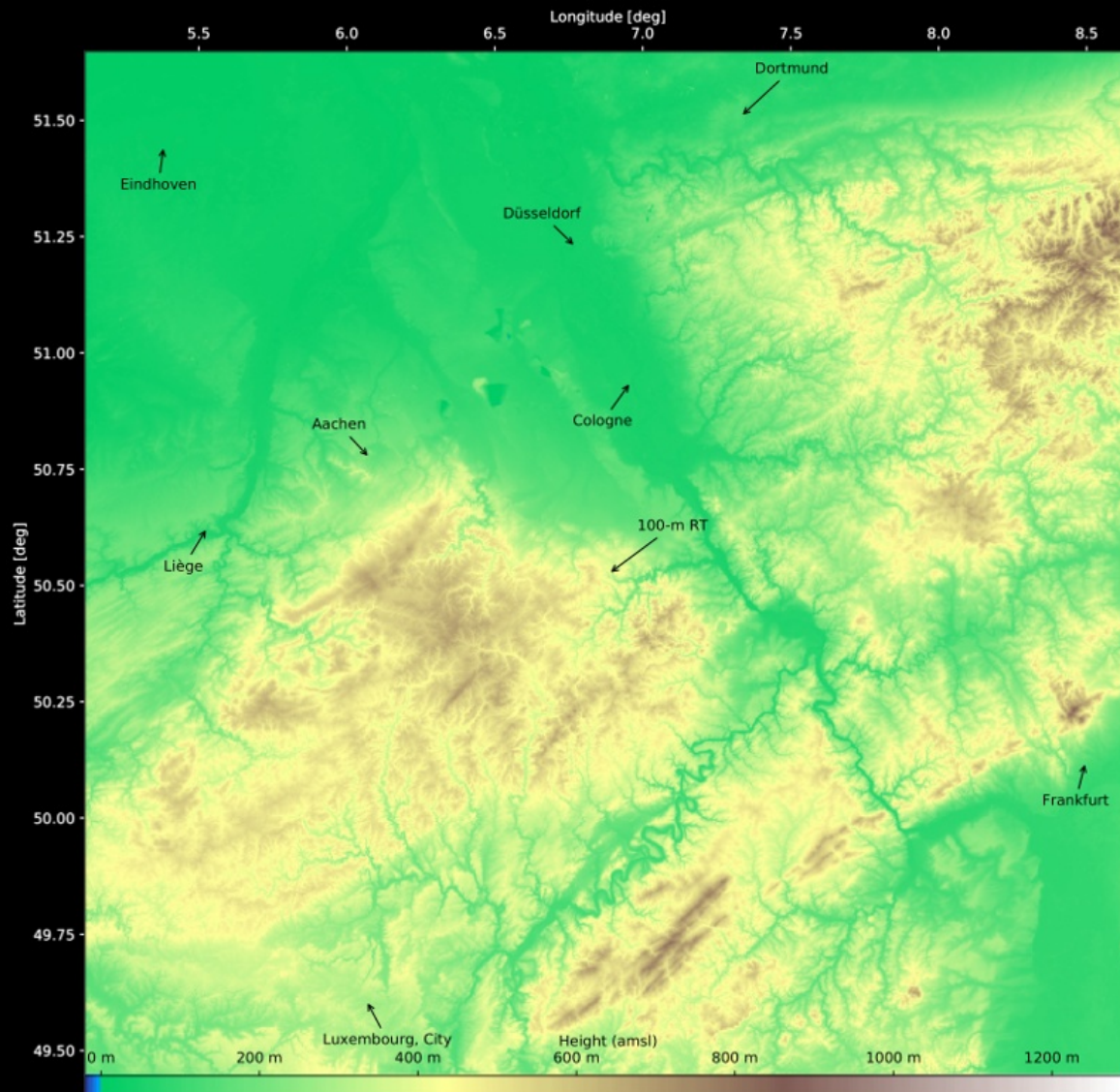
PSR J0437-4715

Period: 5.757451924362137(2) ms

→ Detect gravitational waves?



# Introduction – Radio astronomy



100-m telescope

- Located in the northern Eifel region



# Introduction – Radio astronomy

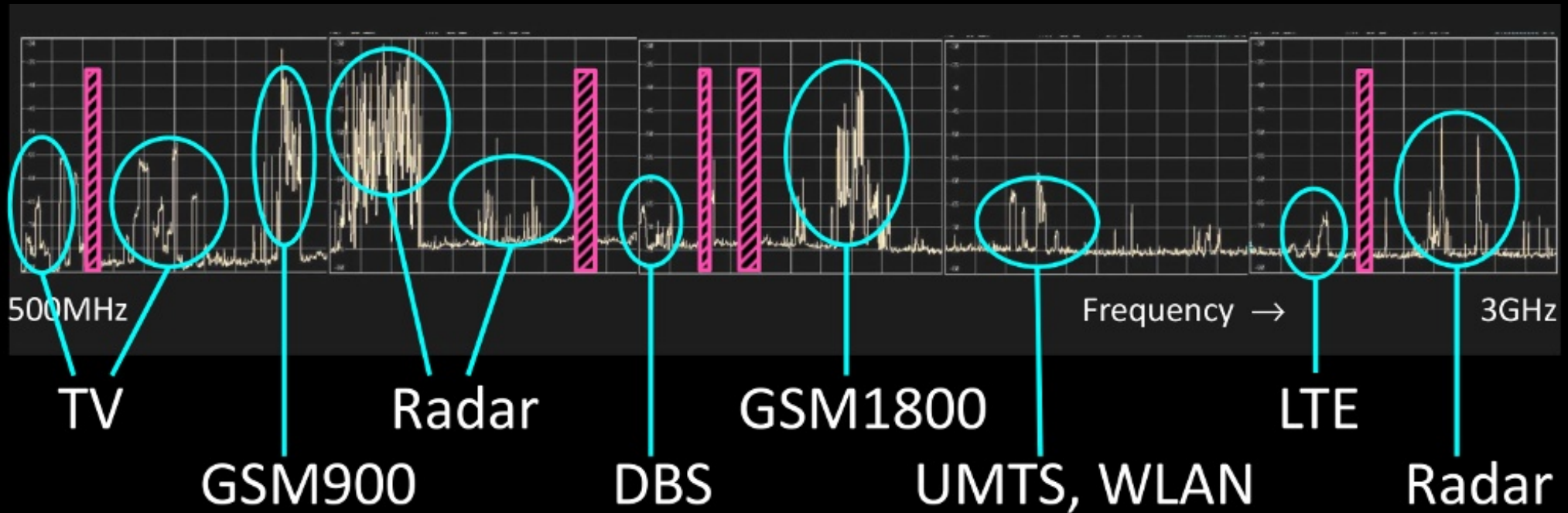


## 100-m telescope

- Located in the northern Eifel region
- Inside a valley  
→ natural shielding
- Spectrum coordination  
(via BNetzA)



# Introduction – Radio astronomy



- Still a lot of radio frequency interference

# Sources of RFI

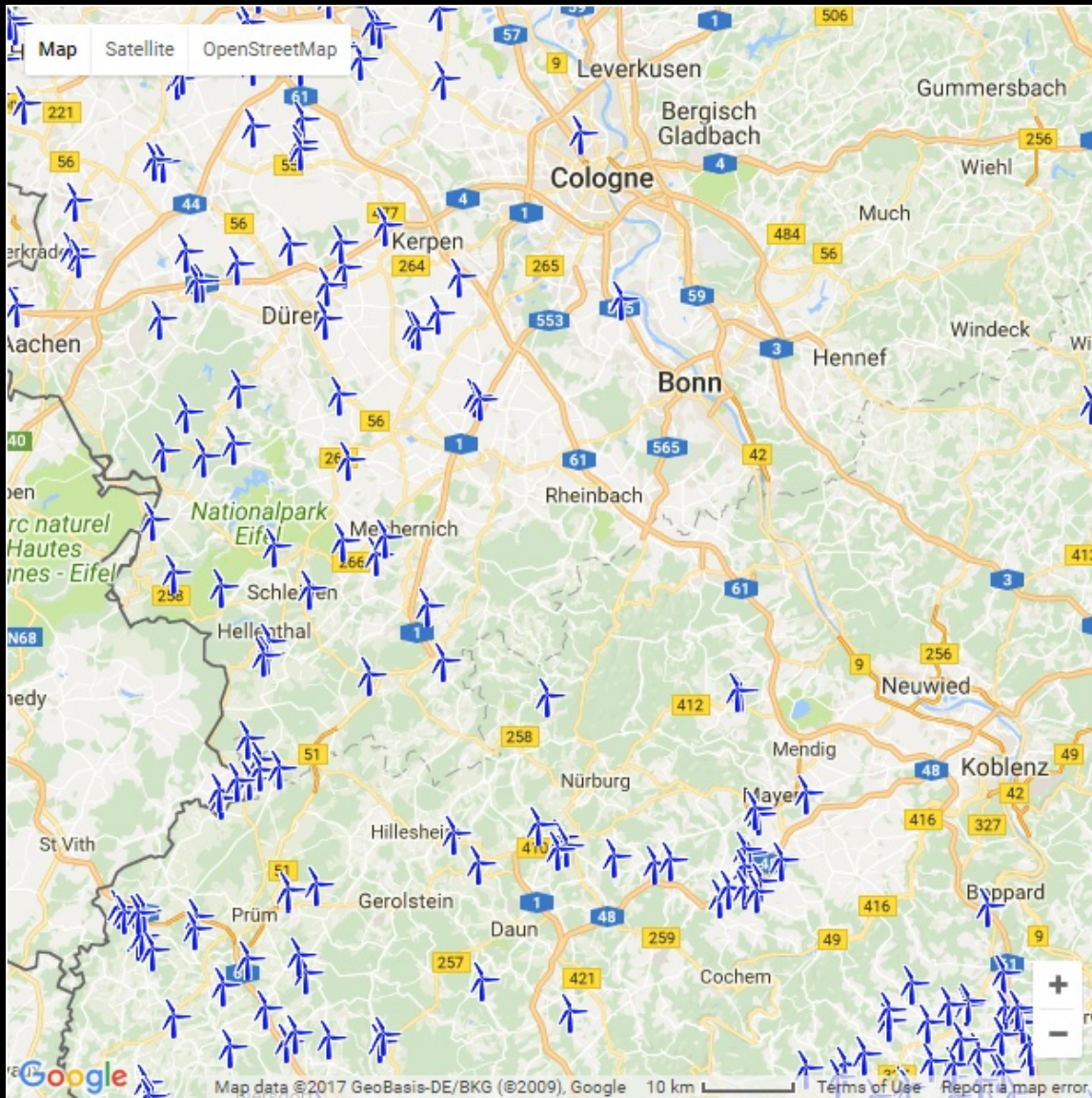
## Radiocommunication services

- Mobile service
- RADAR (civil, military)
  - Weather radar
  - Parking assistant
  - Earth sensing
- Broadcasting (radio, DVB-T)
- Navigation
- WiFi, Bluetooth, etc.
- Amateur radio
- Fixed links

## Unwanted emission (EMI)

- Out-of-band emission of radiocomm. services
- Digital electronics
- Industrial devices
  - Wind turbines
- Electrical devices

# Introduction – Radio astronomy



## 100-m telescope

- Located in the northern Eifel region
- Inside a valley  
→ natural shielding
- Spectrum coordination (via BNetzA)
- Still a lot of radio frequency interference
- Many wind turbines beyond ~30 km



# Spectrum management

## UNITED STATES FREQUENCY ALLOCATIONS

### THE RADIO SPECTRUM

#### RADIO SERVICES COLOR LEGEND


#### ACTIVITY CODE

NON-EXPERIMENTAL EXCLUSIVE  
 EXPERIMENTAL NON-EXPERIMENTAL REQUIRED

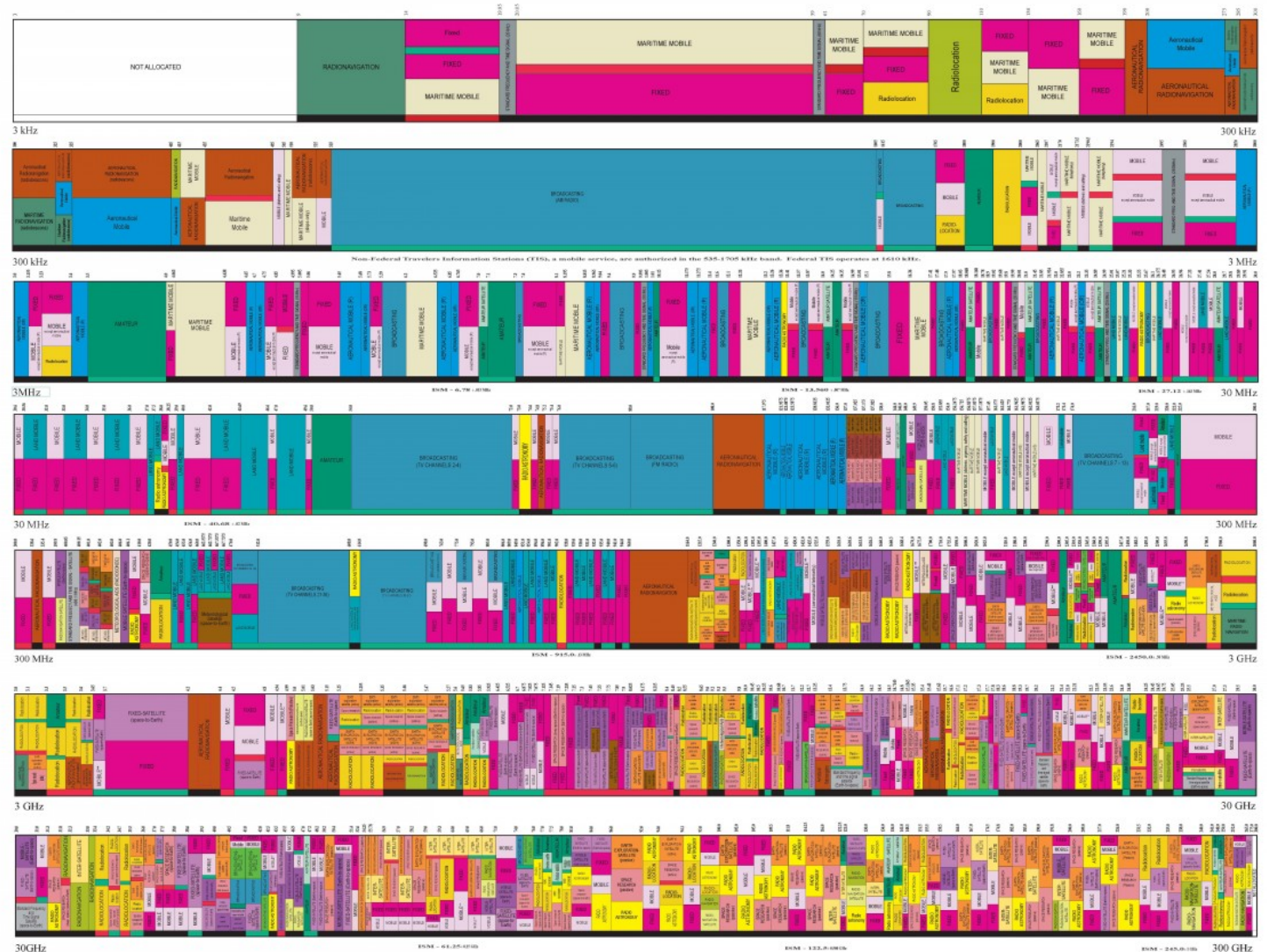
#### ALLOCATION USAGE DESIGNATION

SERVICE	EXAMPLE	DESCRIPTION
Primary	F1510	Capital Letters
Secondary	M1400	1st Capital with 1st and 2nd Letters

The United States is a party to the following agreements: International Telecommunication Union (ITU) and ITU-R, for radio frequency allocation; International Telecommunication Union (ITU) and ITU-R, for radio frequency allocation; International Telecommunication Union (ITU) and ITU-R, for radio frequency allocation.

U.S. DEPARTMENT OF COMMERCE  
National Telecommunications and Information Administration  
Office of Spectrum Management  
August 2011

For more information, visit [www.ntia.gov](http://www.ntia.gov).  
Copyright © 2011 by the U.S. Department of Commerce, National Telecommunications and Information Administration. All rights reserved.  
Printed on 100% recycled paper, 50% post-consumer waste.



PLEASE NOTE: THE CHARTING LAYOUT FOR THE 300 kHz TO 30 GHz BANDS IS BASED ON THE 2011 INTERNATIONAL TELECOMMUNICATIONS UNION (ITU) RADIO FREQUENCY ALLOCATION TABLE.

# Spectrum management

Wind turbines are no radiocomm. services

- Not subject to coordination by administration (BNetzA)
  - EMI rules apply:
    - EN 55011 (CISPR-11), Group 1, Class A
      - $f < 230 \text{ MHz}$ :  $30 \text{ dB}_{\mu\text{V/m}}$
      - $f \geq 230 \text{ MHz}$ :  $37 \text{ dB}_{\mu\text{V/m}}$
- (@ 30m, QP detector)

# Spectrum management

Rec. ITU-R RA.769-2

1

## RECOMMENDATION ITU-R RA.769-2

### **Protection criteria used for radio astronomical measurements**

(Question ITU-R 145/7)

(1992-1995-2003)

The ITU Radiocommunication Assembly,

*considering*

a) that many of the most fundamental astronomical advances made in the past five decades, (e.g. the discovery of radio galaxies, quasars, and pulsars, the direct measurement of neutral hydrogen, the direct measurement of distances of certain external galaxies, and establishment of a positional reference frame accurate to  $\sim 20$  arc  $\mu$ s) have been made through radio astronomy, and that radio astronomical observations are expected to continue making fundamental contributions to our understanding of the Universe, and that they provide the only way to investigate some cosmic phenomena;



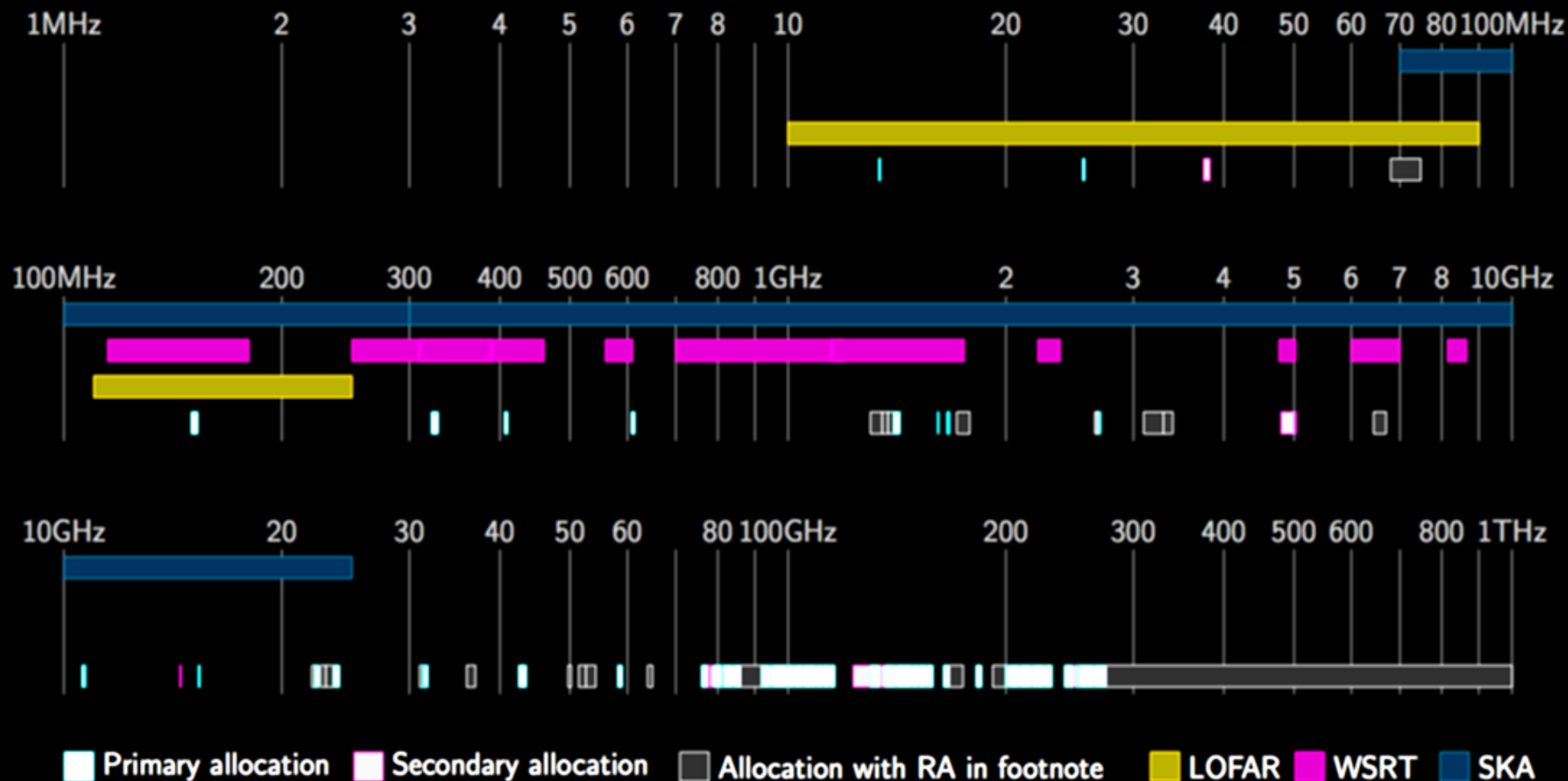
# Spectrum management

TABLE 1

Threshold levels of interference detrimental to radio astronomy continuum observations

Centre frequency <sup>(1)</sup> $f_c$ (MHz)	Assumed bandwidth $\Delta f$ (MHz)	Minimum antenna noise temperature $T_A$ (K)	Receiver noise temperature $T_R$ (K)	System sensitivity <sup>(2)</sup> (noise fluctuations)		Threshold interference levels <sup>(2) (3)</sup>		
				Temperature $\Delta T$ (mK)	Power spectral density $\Delta P$ (dB(W/Hz))	Input power $\Delta P_H$ (dBW)	pfd $S_H \Delta f$ (dB(W/m <sup>2</sup> ))	Spectral pfd $S_H$ (dB(W/(m <sup>2</sup> · Hz)))
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
13.385	0.05	50 000	60	5 000	-222	-185	-201	-248
25.610	0.12	15 000	60	972	-229	-188	-199	-249
73.8	1.6	750	60	14.3	-247	-195	-196	-258
151.525	2.95	150	60	2.73	-254	-199	-194	-259
325.3	6.6	40	60	0.87	-259	-201	-189	-258
408.05	3.9	25	60	0.96	-259	-203	-189	-255
611	6.0	20	60	0.73	-260	-202	-185	-253
1 413.5	27	12	10	0.095	-269	-205	-180	-255
1 665	10	12	10	0.16	-267	-207	-181	-251
2 695	10	12	10	0.16	-267	-207	-177	-247
4 995	10	12	10	0.16	-267	-207	-171	-241
10 650	100	12	10	0.049	-272	-202	-160	-240
15 375	50	15	15	0.095	-269	-202	-156	-233
22 355	290	35	30	0.085	-269	-195	-146	-231
23 800	400	15	30	0.050	-271	-195	-147	-233
31 550	500	18	65	0.083	-269	-192	-141	-228
43 000	1 000	25	65	0.064	-271	-191	-137	-227
89 000	8 000	12	30	0.011	-278	-189	-129	-228
150 000	8 000	14	30	0.011	-278	-189	-124	-223
224 000	8 000	20	43	0.016	-277	-188	-119	-218
270 000	8 000	25	50	0.019	-276	-187	-117	-216

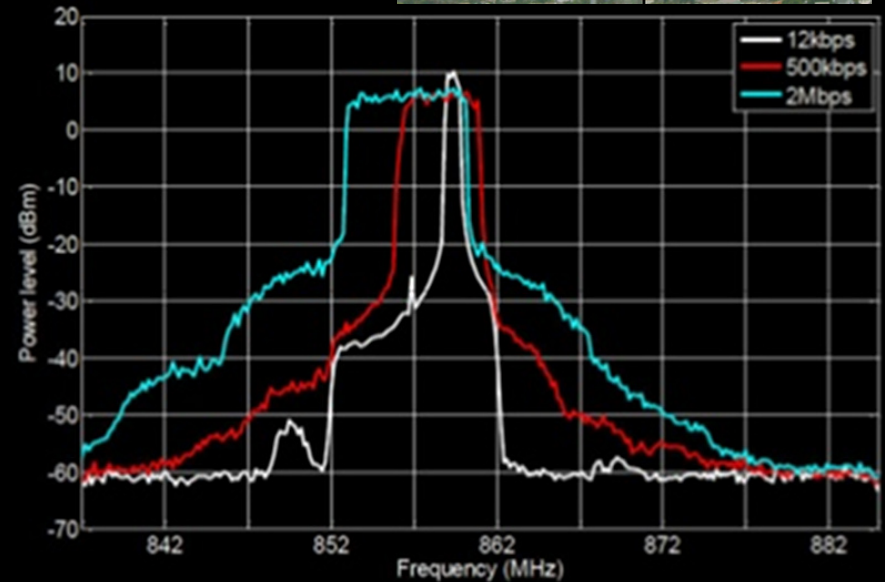
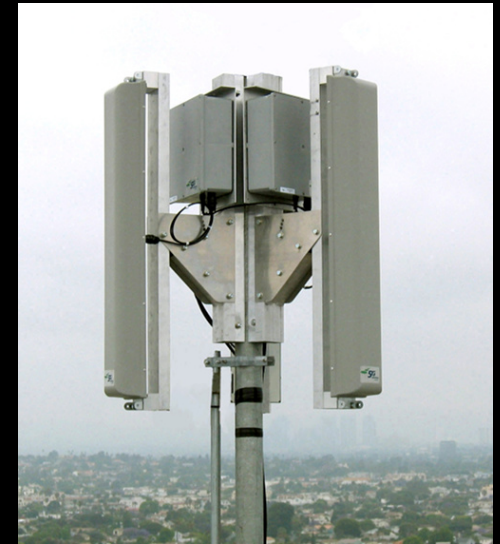
# Spectrum management



# Compatibility calculations

## Compatibility studies

- Calculate un-/wanted emission levels of interferer



Source: Ofcom (August 2012)

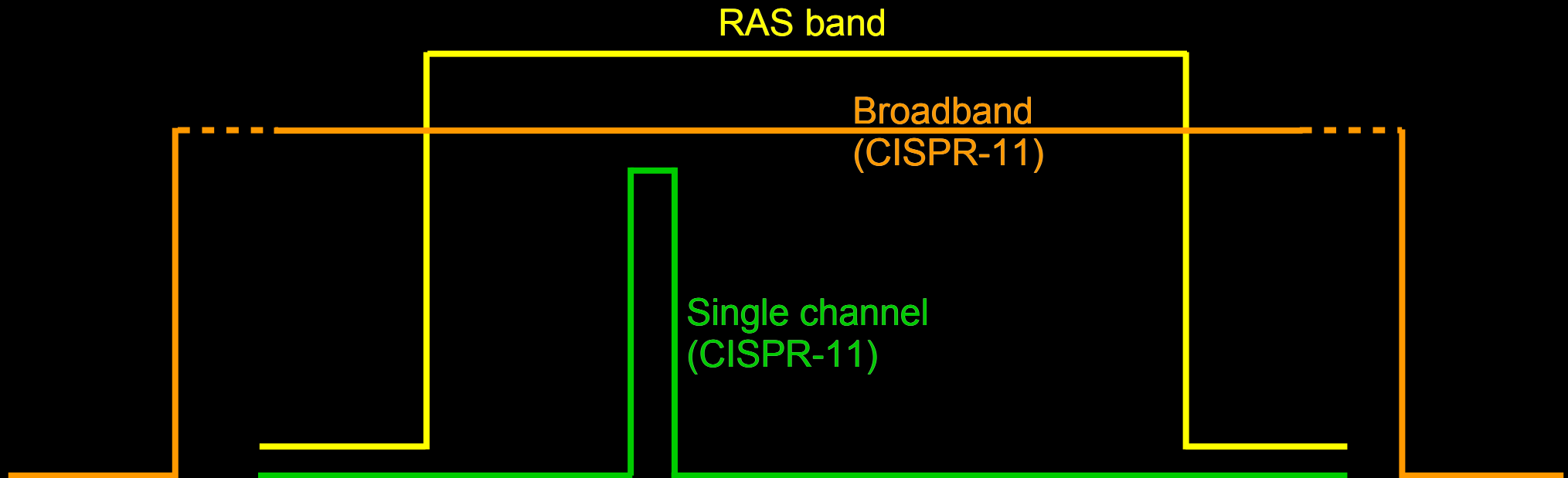


# Compatibility calculations

## Compatibility studies

- Calculate un-/wanted emission levels of interferer

Wind turbine spectrum not well known  
→ make assumptions:



# Compatibility calculations

## Compatibility studies

- Calculate un-/wanted emission levels of interferer
- Generate topographic maps (height profiles) from SRTM data

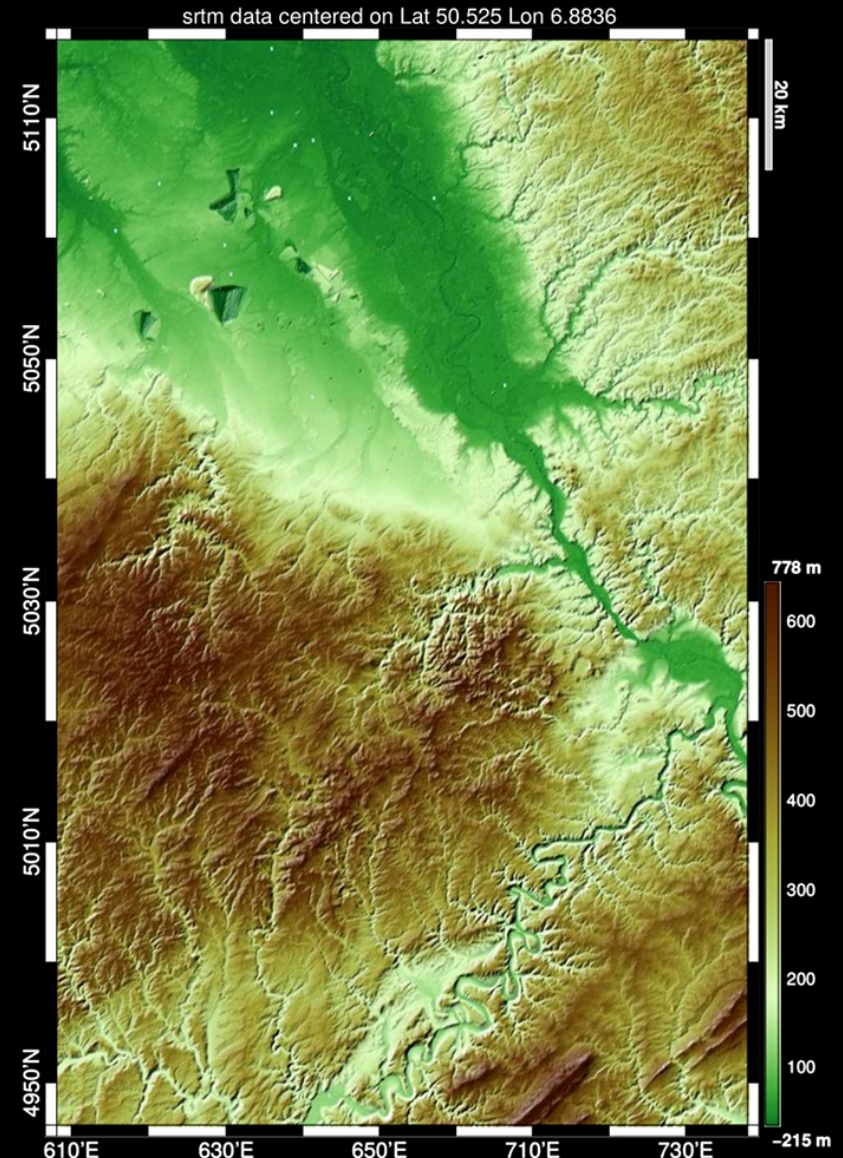
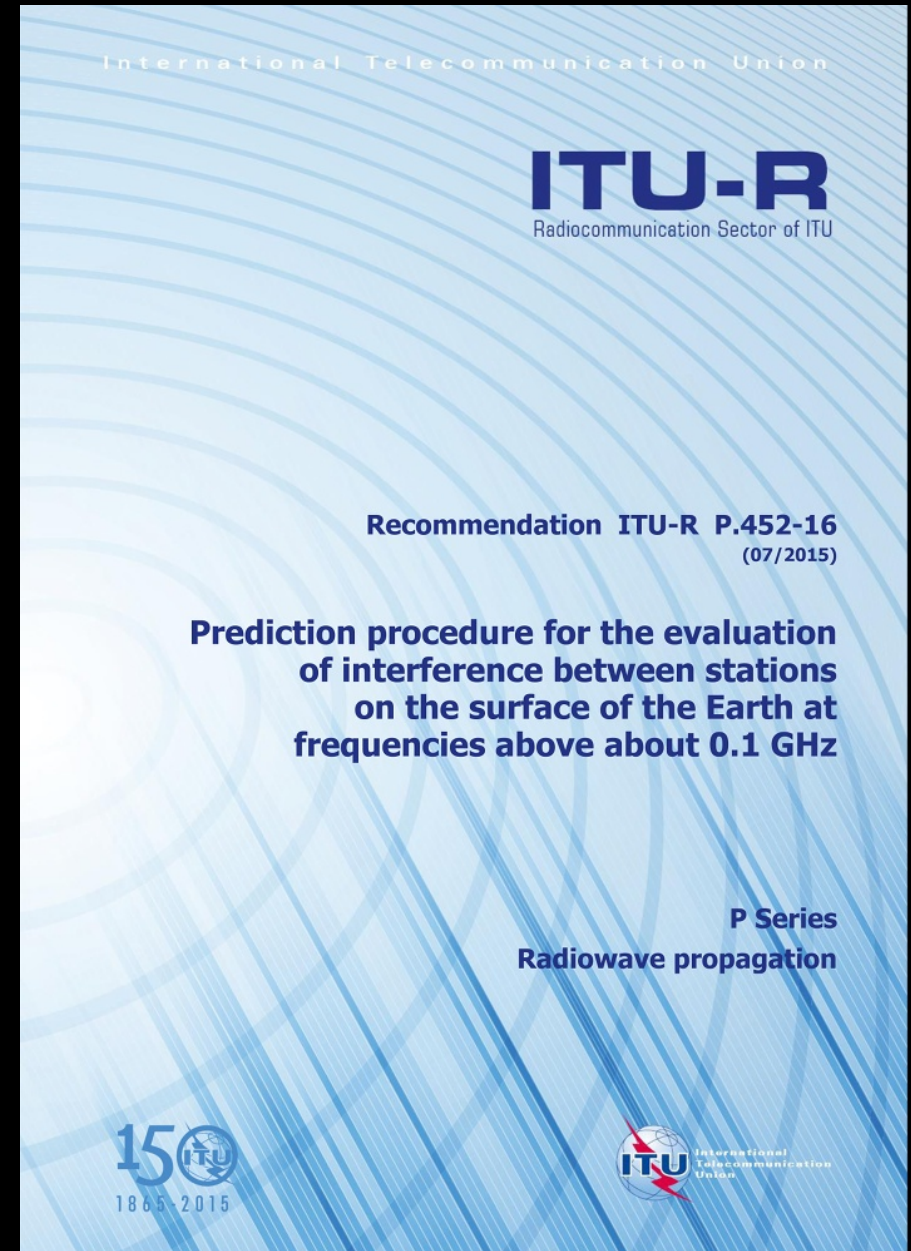


Image based on NASA/SRTM data

# Compatibility calculations

## Compatibility studies

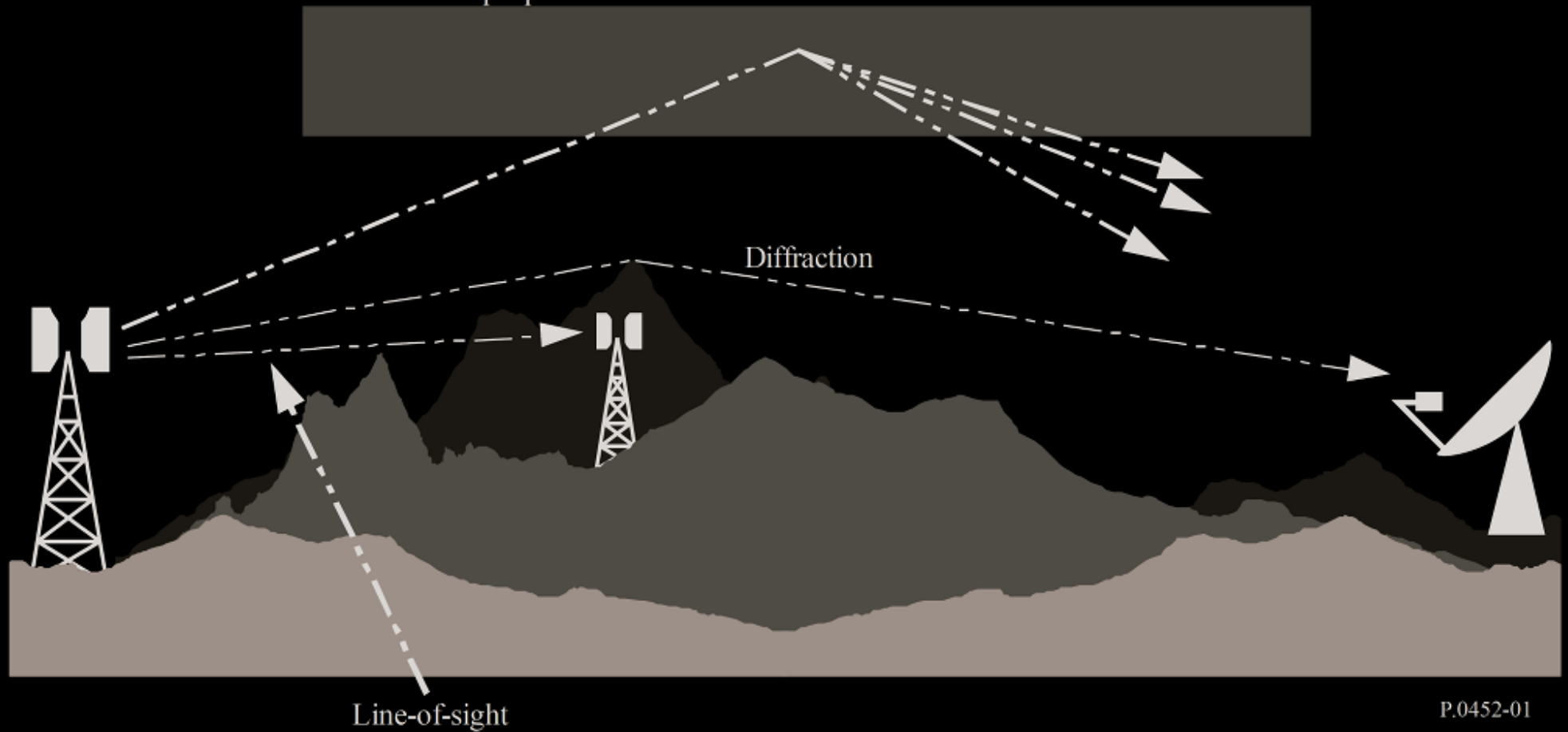
- Calculate un-/wanted emission levels of interferer
- Generate topographic maps (height profiles) from SRTM data
- Path propagation: implement ITU-R Recommendations



# Compatibility: path propagation

## Long-term interference propagation mechanisms

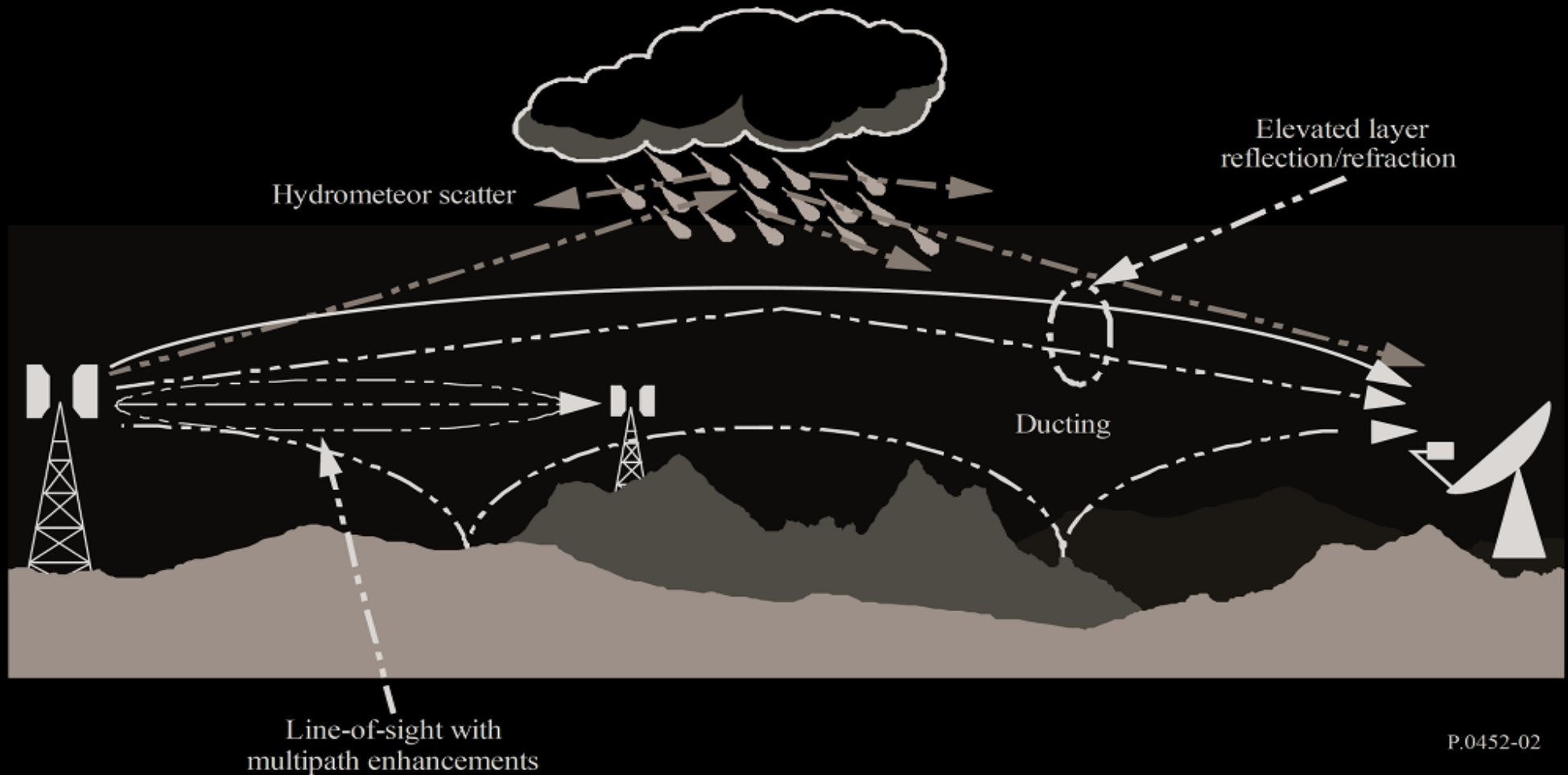
Tropospheric scatter





# Compatibility: path propagation

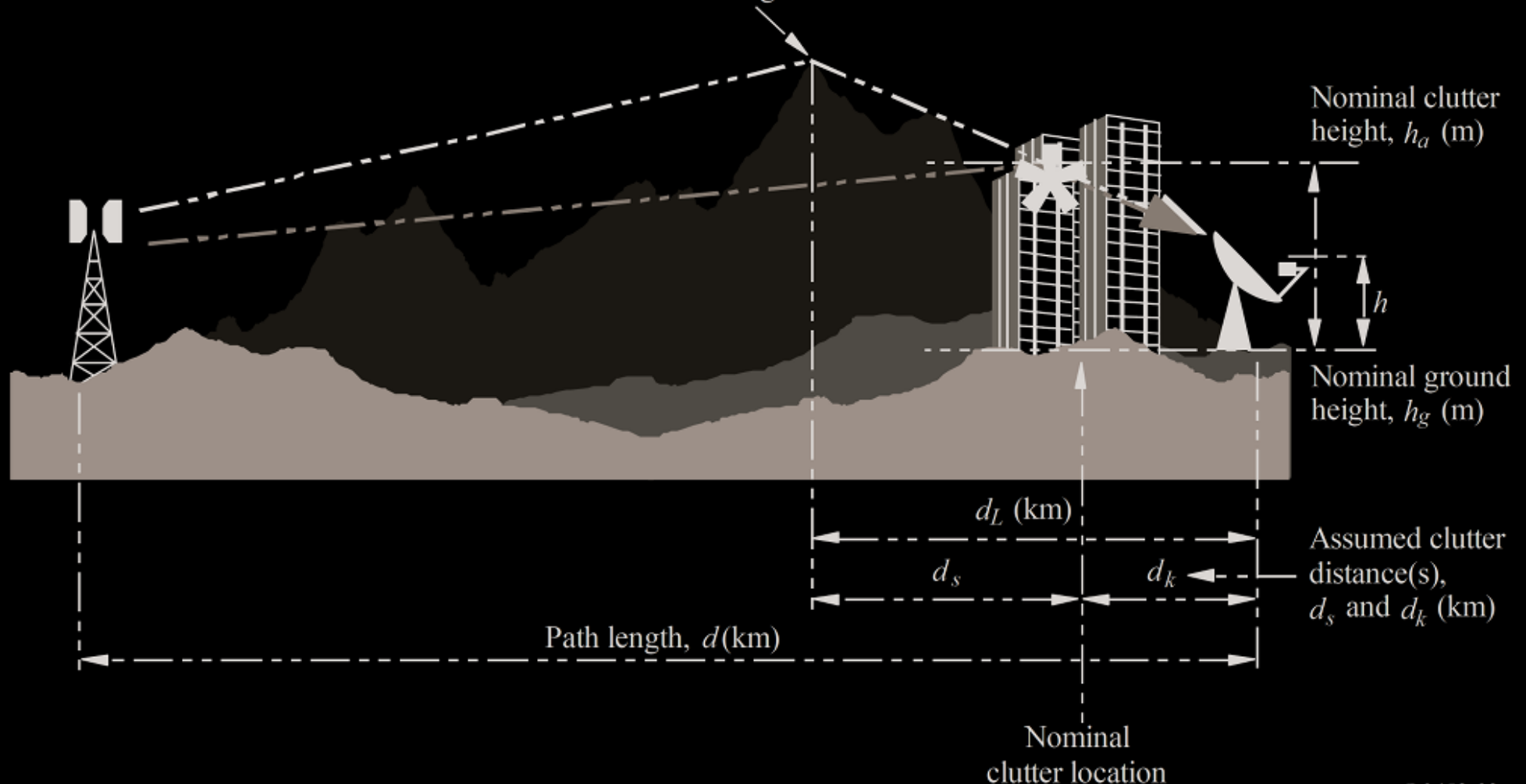
## Anomalous (short-term) interference propagation mechanisms



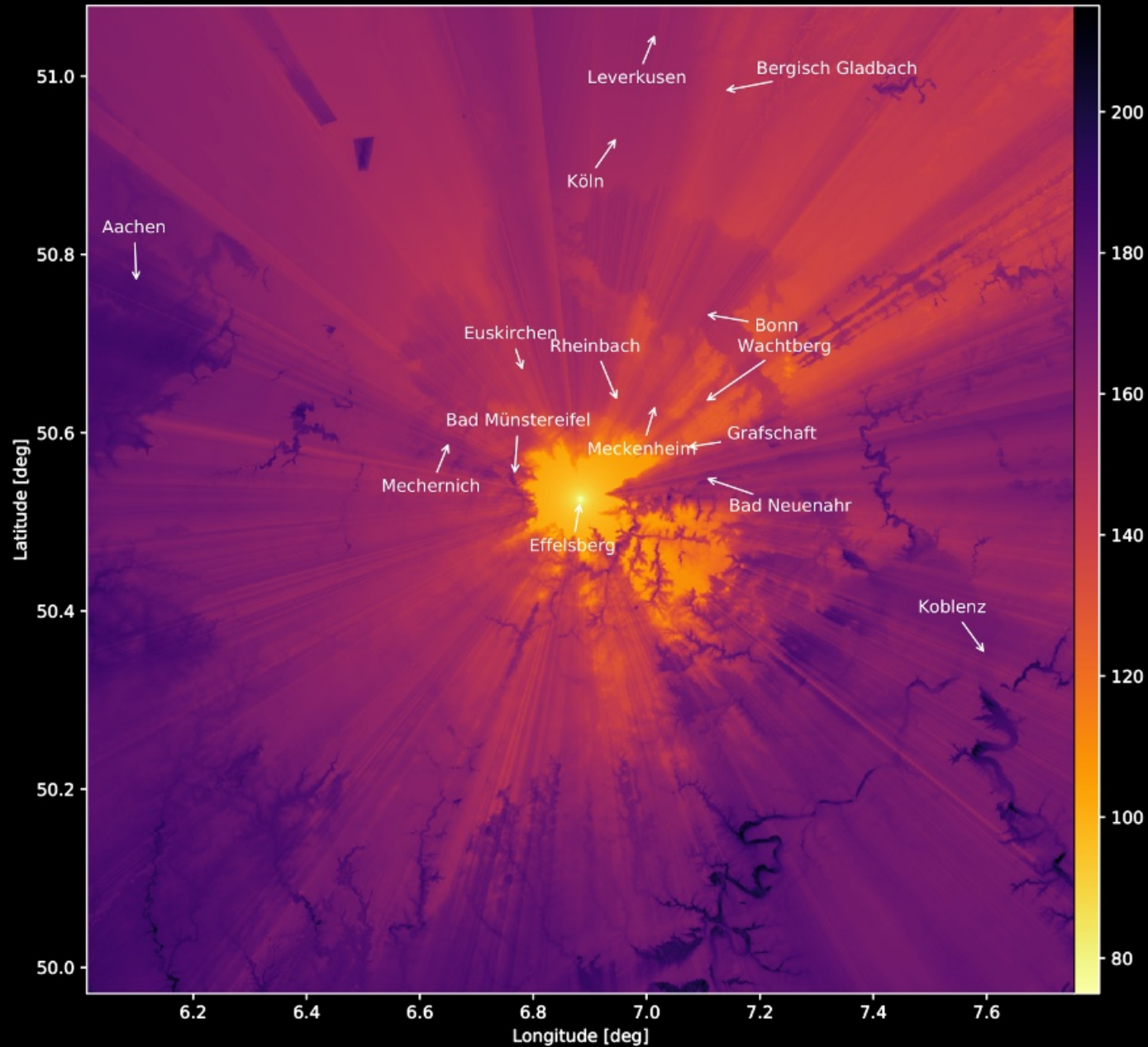
# Compatibility: path propagation

Method of applying height-gain correction,  $A_{ht}$  or  $A_{hr}$

"Site shielding" obstacle



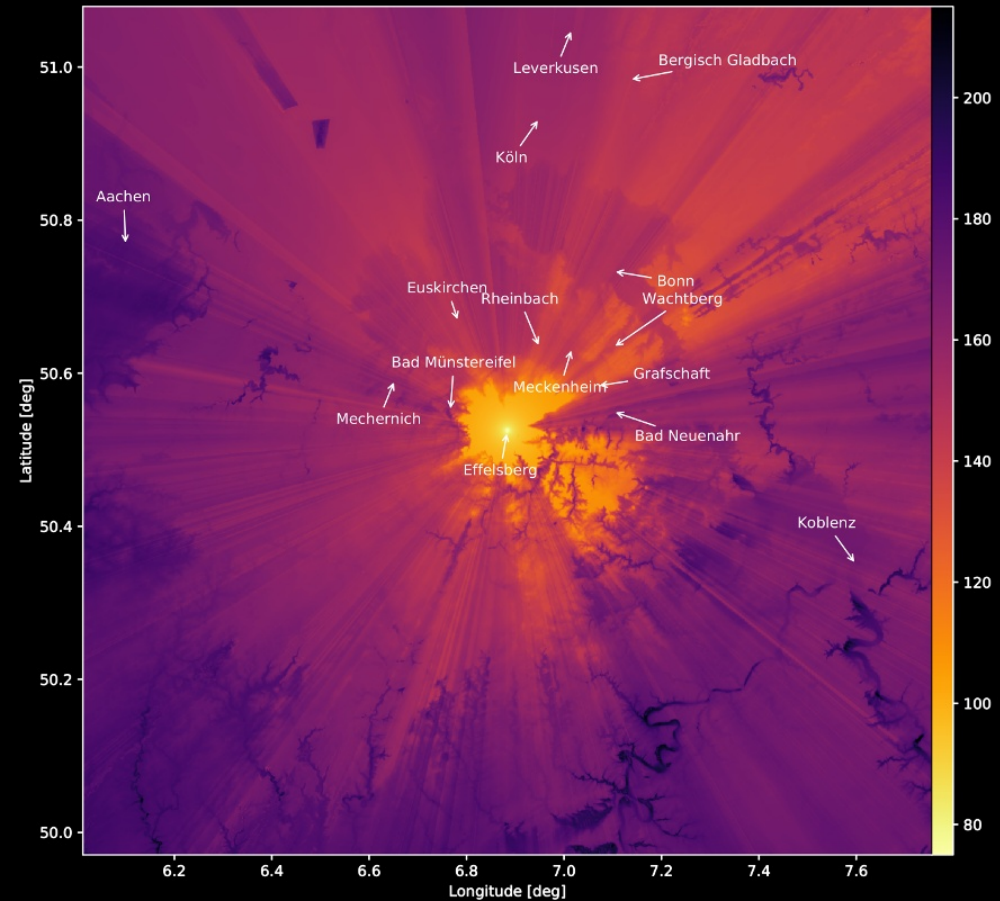
# Compatibility calculations



# Compatibility calculations

## Compatibility studies

- Calculate un-/wanted emission levels of interferer
- Generate topographic maps (height profiles) from SRTM data
- Path propagation: implement ITU-R Recommendations

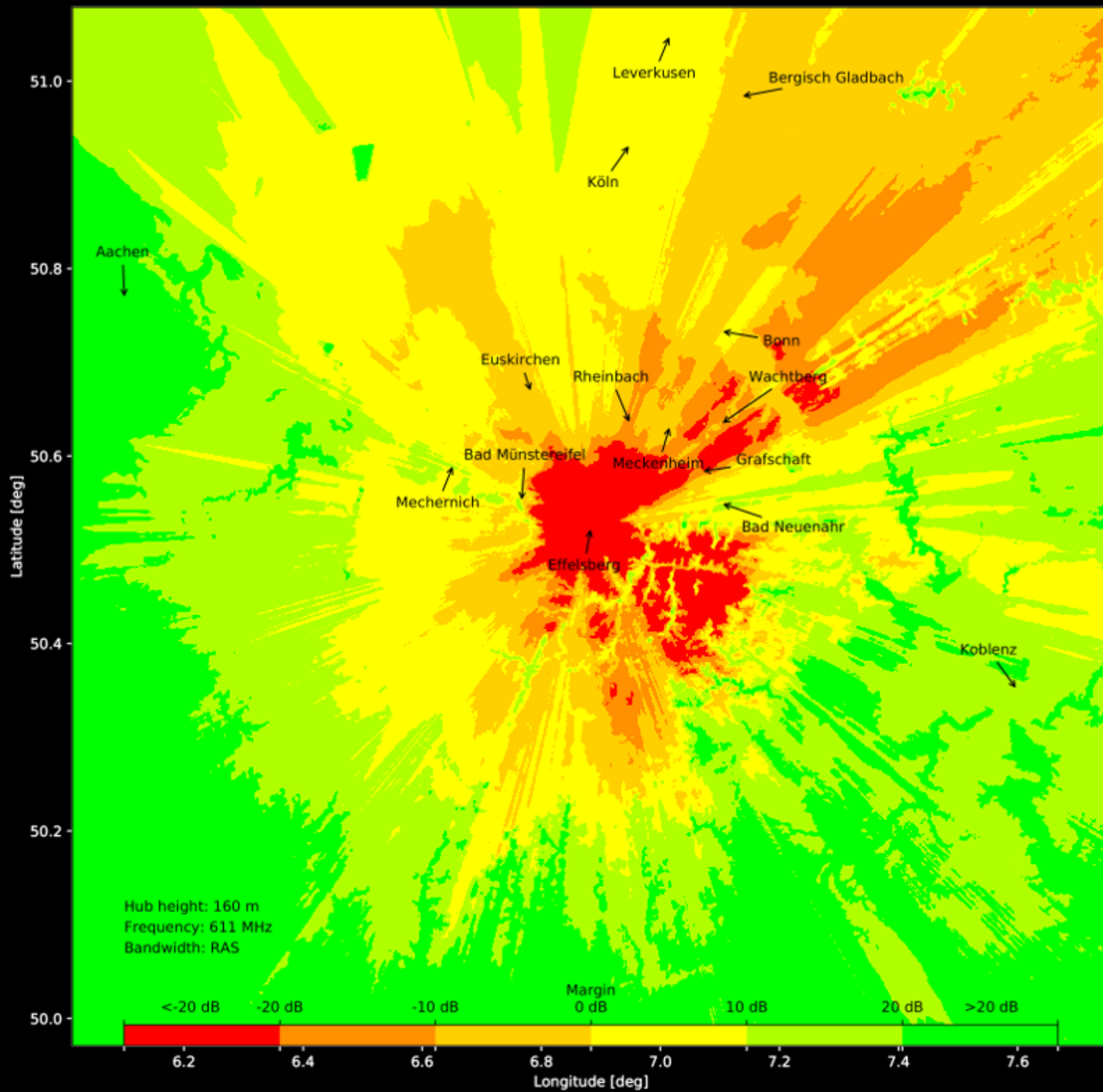




# Compatibility calculations

## Compatibility studies

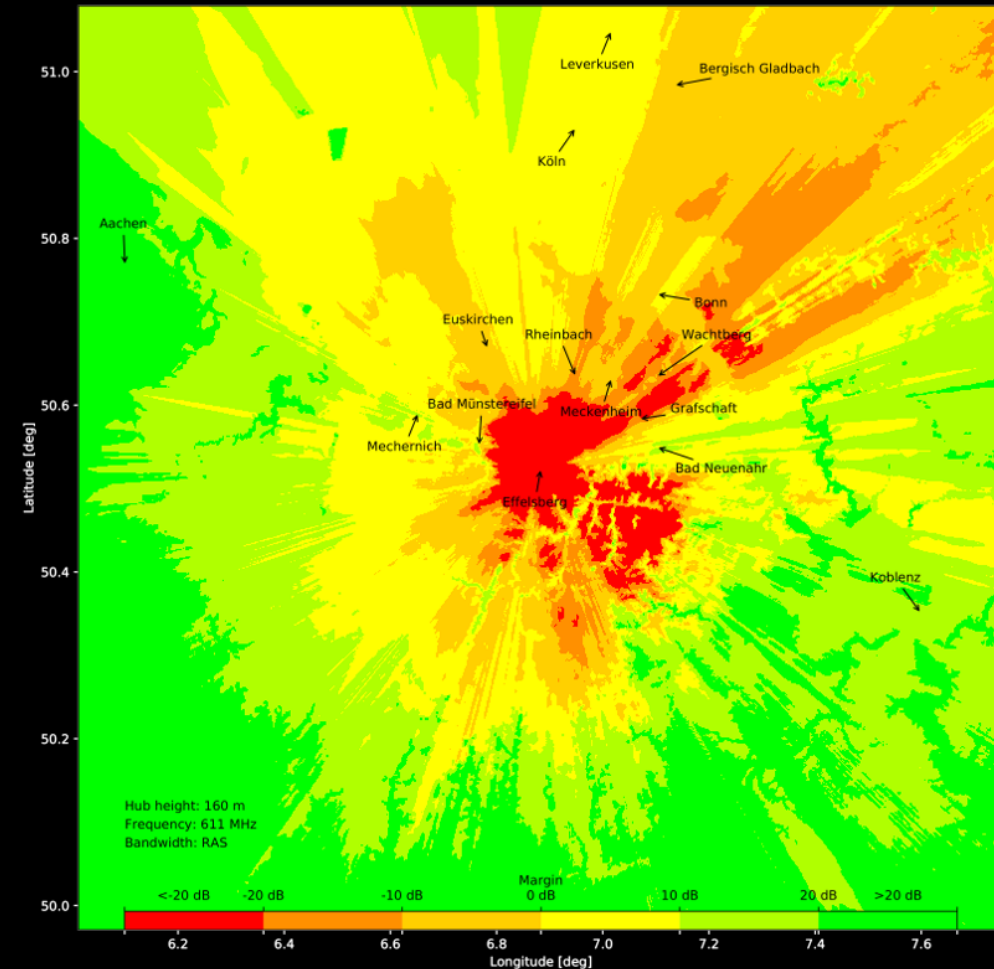
- Calculate un-/wanted emission levels of interferer
- Generate topographic maps (height profiles) from SRTM data
- Path propagation: implement ITU-R Recommendations
- Infer received power flux densities / E-field strengths at victim receiver
- Compare with permitted limits



# Compatibility calculations

## Compatibility studies

- Calculate un-/wanted emission levels of interferer
- Generate topographic maps (height profiles) from SRTM data
- Path propagation: implement ITU-R Recommendations
- Infer received power flux densities / E-field strengths at victim receiver
- Compare with permitted limits



# Measurements (by BNetzA)



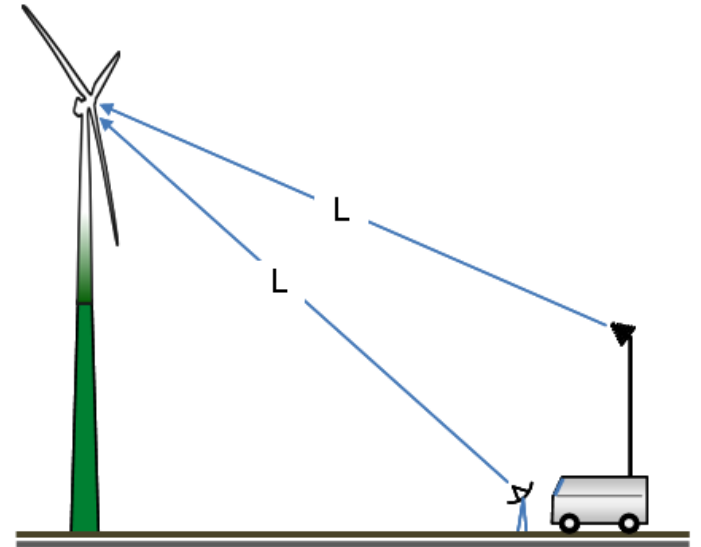
Images: Hasenpusch/Fleckenstein  
(BnetzA, 2017)



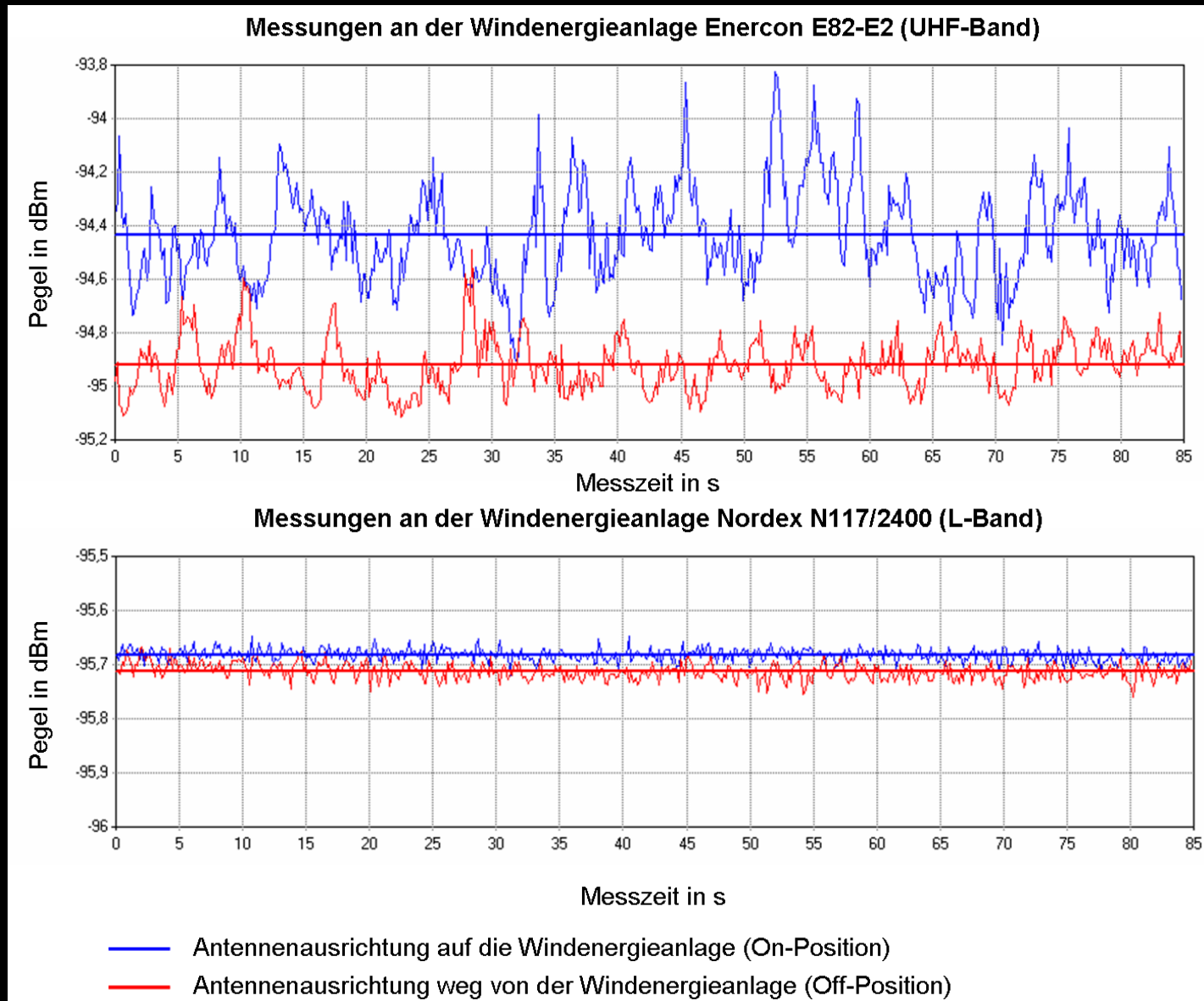
# Measurements (by BNetzA)



Images: Hasenpusch/Fleckenstein  
(BnetzA, 2017)



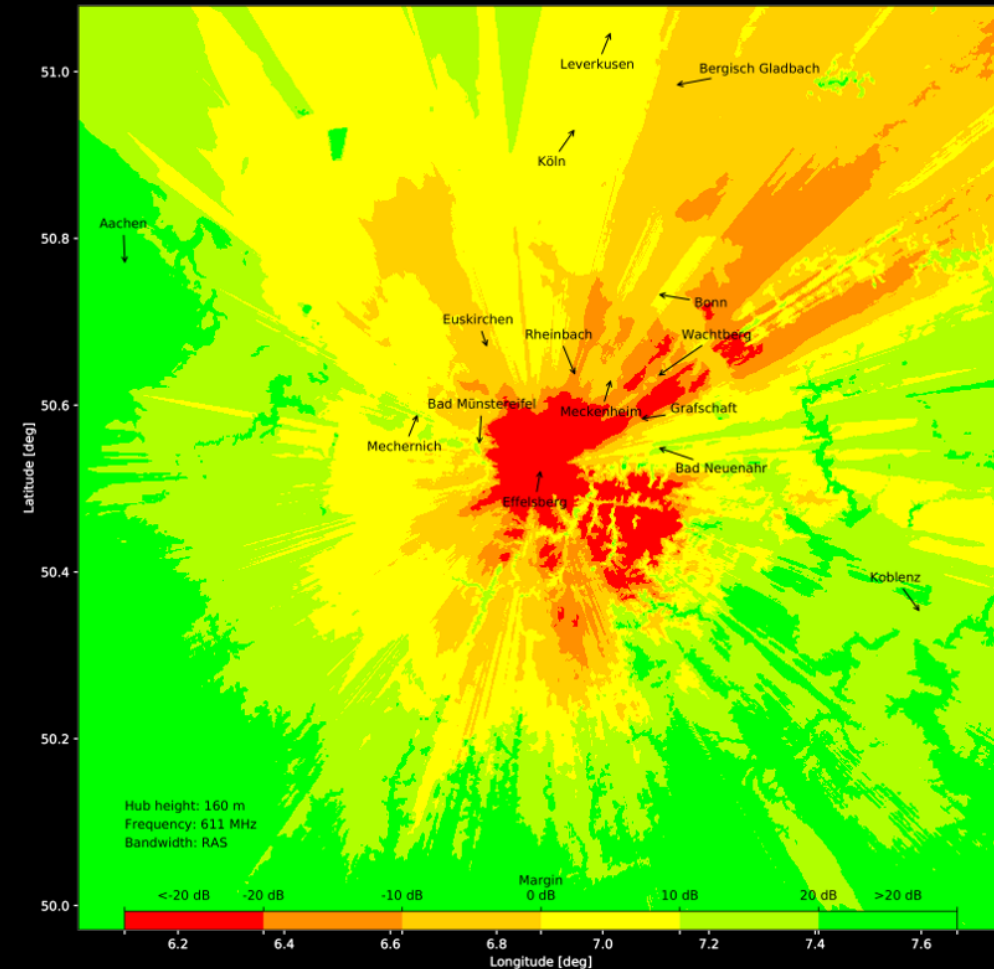
# Measurements (by BNetzA)



Images: Hasenpusch/Fleckenstein  
(BnetzA, 2017)

# Measurements (by BNetzA)

- Typically wind turbines stay 20+ dB below CISPR-11  
→ necessary distances smaller
- “Broken” equipment can lead to much larger EMI



# pycraf

## Python library pycraf

- Aid with compatibility studies
- Implements ITU-R Rec. algorithms
- Features:
  - Conversion formulas
  - Query SRTM data
  - Path propagation (P.452)
  - Atmospheric attenuation (P.676)
  - Geographical coordinates/frames
  - Some antenna models
  - Satellites (two-line elements)

```
heightprofile.py x conversions.py x cyprop.pyx x
241
242 @helpers.ranged_quantity_input(
243     Erx=(1.e-30, None, apu.V / apu.meter),
244     d=(1.e-30, None, apu.m),
245     Gtx=(1.e-30, None, dimless),
246     strip_input_units=True, output_unit=apu.W
247 )
248 def Ptx_from_Erx(Erx, d, Gtx):
249     """
250     Calculate transmitter power, Ptx, from received field strength.
251
252     Note: All quantities must be astropy Quantities
253     | (astropy.units.quantity.Quantity).
254
255     Parameters
256     -----
257     Erx - Received E-field strength [dB_uV_m, uV/m, or (uV/m)**2]
258     d - Distance to transmitter [m]
259     Gtx - Gain of transmitter [dBi, or dimless]
260
261     Returns
262     -----
263     Transmitter power, Ptx [W]
264     """
265
266     return 4. * np.pi * d ** 2 / Gtx * Erx ** 2 / RO_VALUE
267
268
269 @helpers.ranged_quantity_input(
270     Ptx=(1.e-30, None, apu.W),
271     d=(1.e-30, None, apu.m),
272     Gtx=(1.e-30, None, dimless),
273     strip_input_units=True, output_unit=apu.uV / apu.meter
274 )
275 def Erx_from_Ptx(Ptx, d, Gtx):
276     """
277     Calculate received field strength, Erx, from transmitter power.
278
279     Note: All quantities must be astropy Quantities
280     | (astropy.units.quantity.Quantity).
281
282     Parameters
283     -----
284     Ptx - Transmitter power [dB_W, W]
285     d - Distance to transmitter [m]
286     Gtx - Gain of transmitter [dBi, or dimless]
287
288     Returns
289     -----
290     Received E-field strength, Erx [uV/m]
291     """
292
293     return (Ptx * Gtx / 4. / np.pi * RO_VALUE) ** 0.5 / d * 1.e6
294
295
296 @helpers.ranged_quantity_input(
297     Ptx=(1.e-30, None, apu.W),
298     d=(1.e-30, None, apu.m),
299     Gtx=(1.e-30, None, dimless)
300 )
```

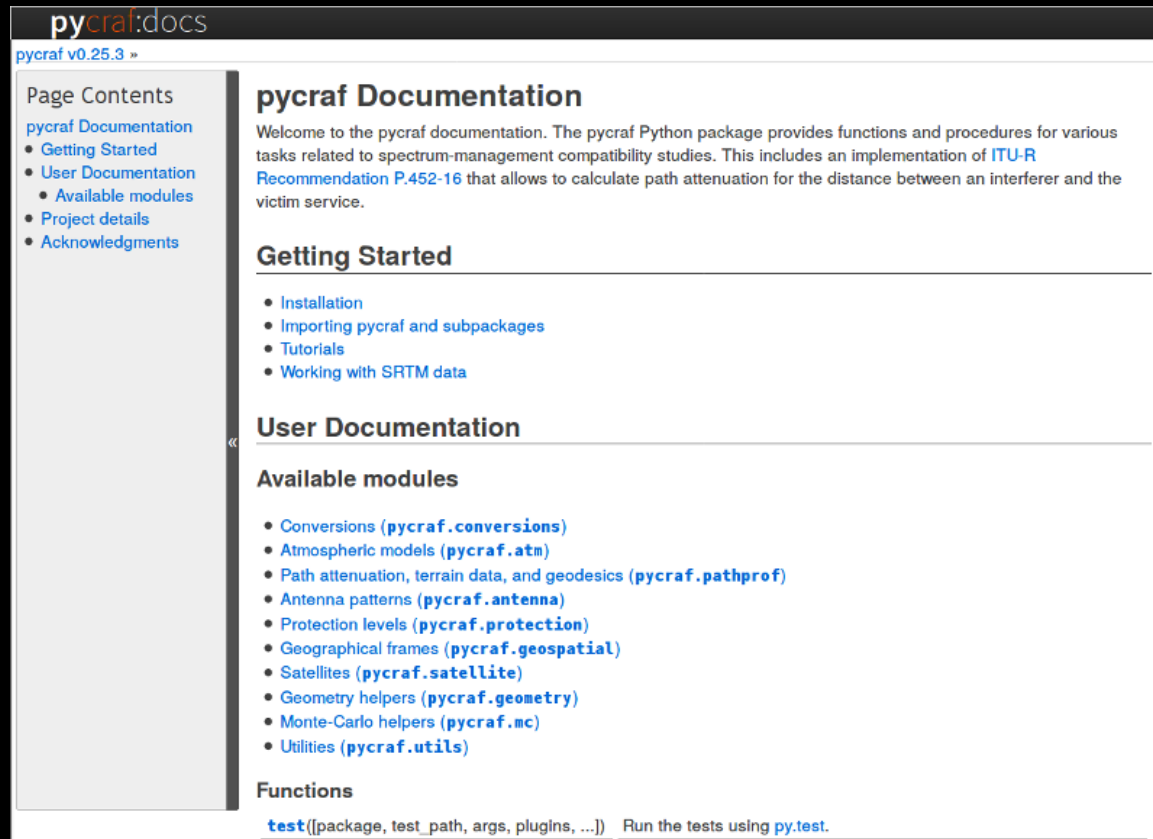
In pycraf on master. File is committed. Git branch: master. index: ✓, working: 1. Line 1. Column 1



# pycraf

## Python library pycraf

- Open-Source  
(Hosted on GitHub)
- Well-documented
- Many examples
- Contributions welcome



The screenshot shows the pycraf documentation website. The header includes the title 'pycraf:docs' and the version 'pycraf v0.25.3'. A left sidebar contains a 'Page Contents' menu with links to 'pycraf Documentation', 'Getting Started', 'User Documentation', 'Available modules', 'Project details', and 'Acknowledgments'. The main content area is titled 'pycraf Documentation' and contains a welcome message, a 'Getting Started' section with links to 'Installation', 'Importing pycraf and subpackages', 'Tutorials', and 'Working with SRTM data', a 'User Documentation' section, an 'Available modules' list including 'Conversions (pycraf.conversions)', 'Atmospheric models (pycraf.atm)', 'Path attenuation, terrain data, and geodesics (pycraf.pathprof)', 'Antenna patterns (pycraf.antenna)', 'Protection levels (pycraf.protection)', 'Geographical frames (pycraf.geospatial)', 'Satellites (pycraf.satellite)', 'Geometry helpers (pycraf.geometry)', 'Monte-Carlo helpers (pycraf.mc)', and 'Utilities (pycraf.utils)', and a 'Functions' section with a link to 'test([package, test\_path, args, plugins, ...])' and a note to 'Run the tests using py.test.'

<https://github.com/bwinkel/pycraf>

# Conclusions

Necessary separation distances: 10-30 km

→ Established procedure:

- Local administrations contact us if within 30 km
- We provide site analysis,
- Which is then considered during approval procedure

Thank you!