Workshop “Frontiers in Propagation and Wireless Channel Modeling”

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POLITECNICO DI MILANO

Accurate and reliable atmospheric channel modeling

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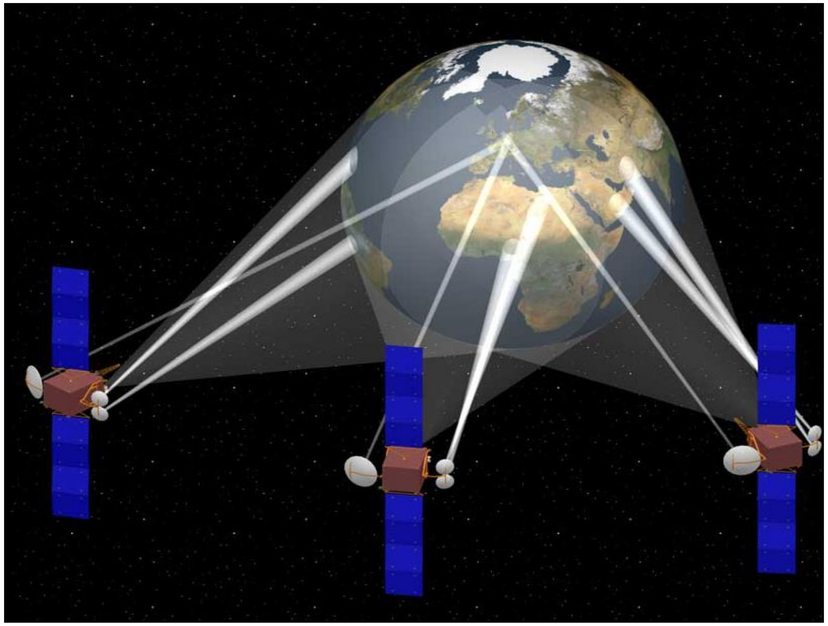
Agenda

- Brief introduction
- Evolution and trends of atmospheric channel modeling:
  - ✓ Models: from empirical to physically-based
  - ✓ Models: from yearly to seasonal/monthly basis
  - ✓ Data: the role of Numerical Weather Predictions
  - ✓ Experiments: always a key resource
- Conclusions

GEO SatCom systems

- Advanced satellite-based systems
- Broadcast services with improved quality (HDTV)
- Interactive systems (e.g. Internet) – multi beam services
- Larger bandwidth → increase from Ku to Ka, Q and V (W? Optical?)



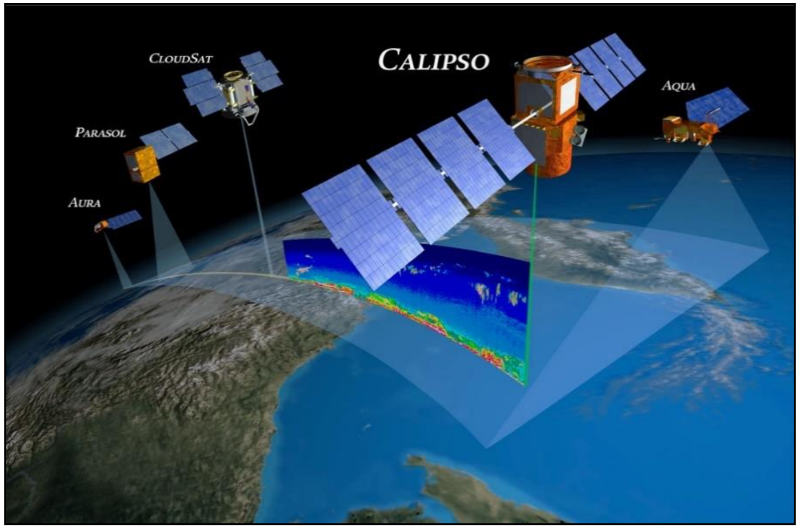
Deep space missions

- More and more interest in deep space mission (e.g. Mars exploration)
- Scientific instruments with higher and higher resolution
- Links with high data rate and reliability
- Shift from X to Ka band

Introduction

Earth Observation

- High number of Earth Observation satellites in orbit and planned for the near future (e.g. MSG)
- Scientific instruments with higher and higher resolution
- Links with high data rate and reliability
- Shift from X to Ka band



Non-GEO SatCom

- Increasing interest in SatCom systems using MEO (e.g. current O3b fleet) and LEO satellites (e.g. planned by SpaceX and OneWeb)
- Scientific instruments with higher and higher resolution
- Links with high data rate
- Target band → Ka band

Introduction

Earth Observation

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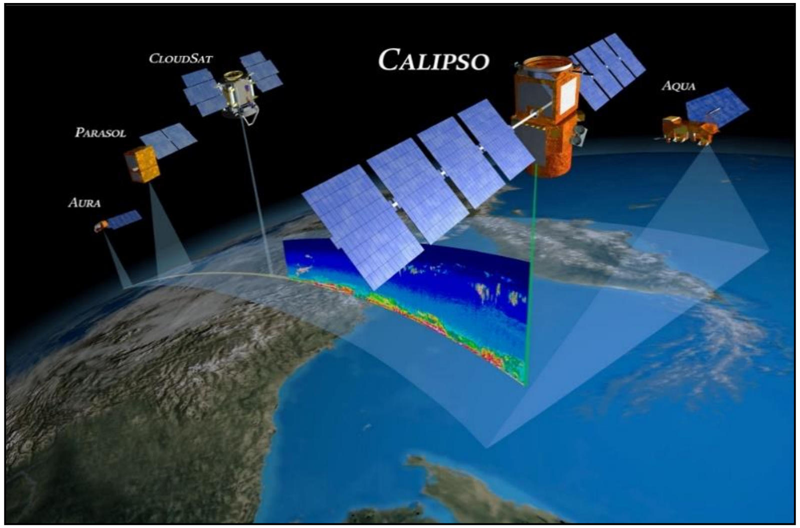

Non-GEO SatCom

- Increasing interest in SatCom systems
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  d
- Links with high data rate
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Overall, there is a need for more and more accurate design of Earth-space links at high frequency and with high reliability

Reliable and accurate channel modeling: how?

How to achieve reliable and accurate prediction of the atmospheric channel?

What is the main trend of atmospheric channel modeling?

What are the key points to be considered?

Models: from empirical to physically-based

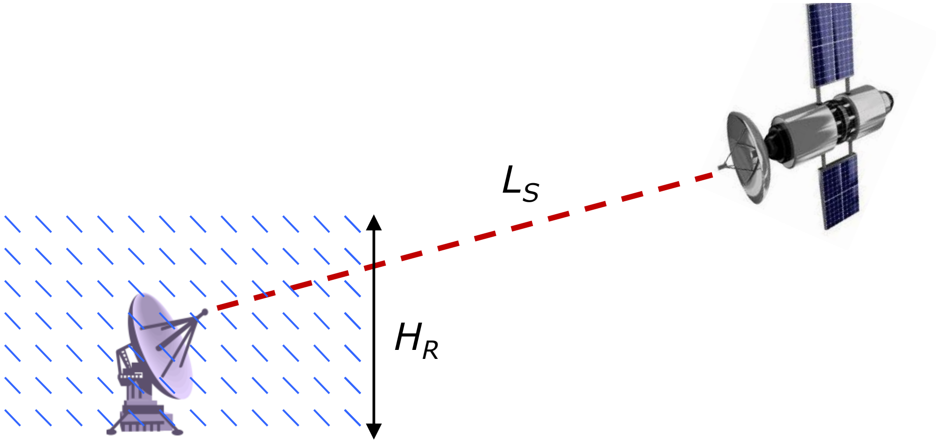
Empirical/semi-empirical models → start from local data to devise models:

- Advantages: simple, quick to develop and to apply
- Disadvantages: typically valid locally, for specific ranges of the input values (e.g. frequency, ground station height, …), limited field of applicability

Physically-based models → exploit global data to develop models that have a sound physical basis:

- Advantages: global, valid for extended ranges of the input values, flexible applicability (different scenarios and different output quantities)
- Disadvantages: more complex to develop, implement and apply, higher computation time

Prediction of rain attenuation on Earth-space links: ITU-R P.618-12 model (semi-empirical) [1]



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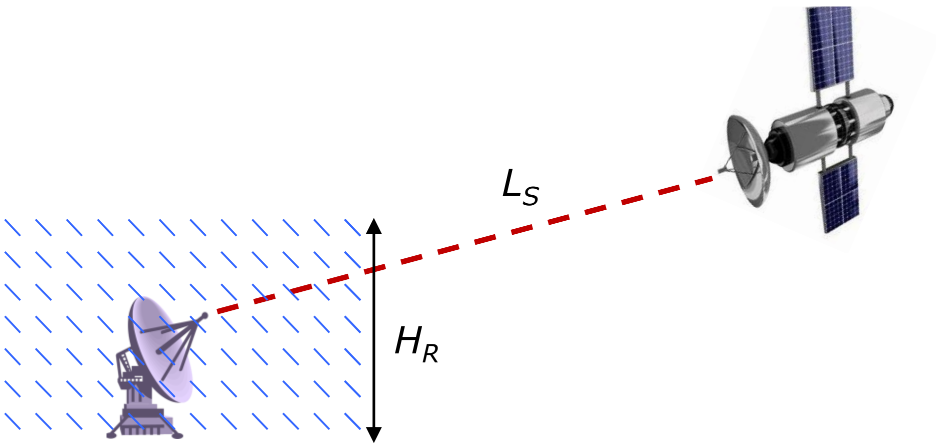

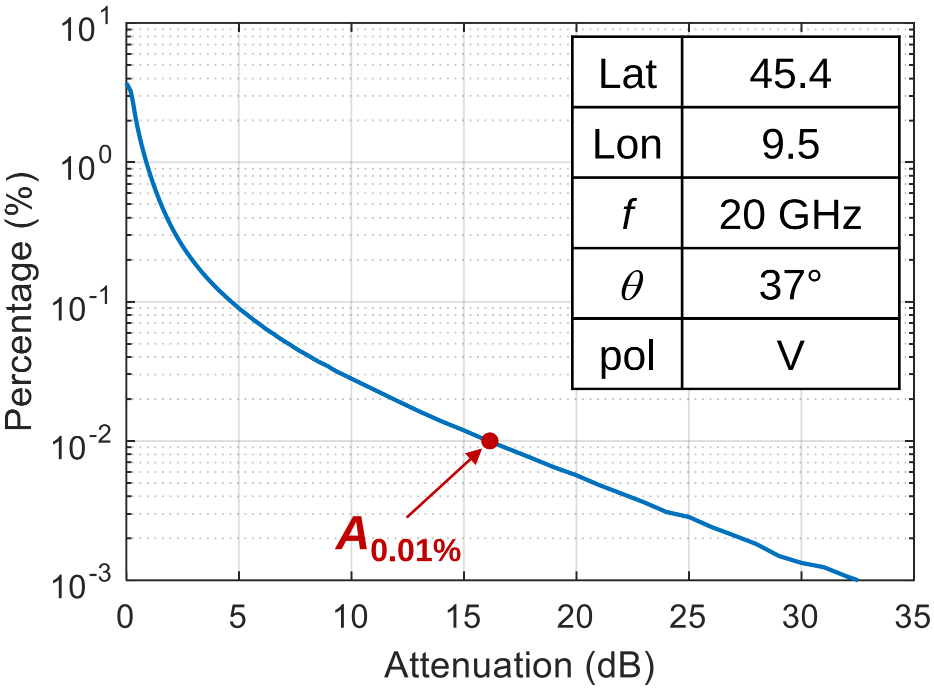

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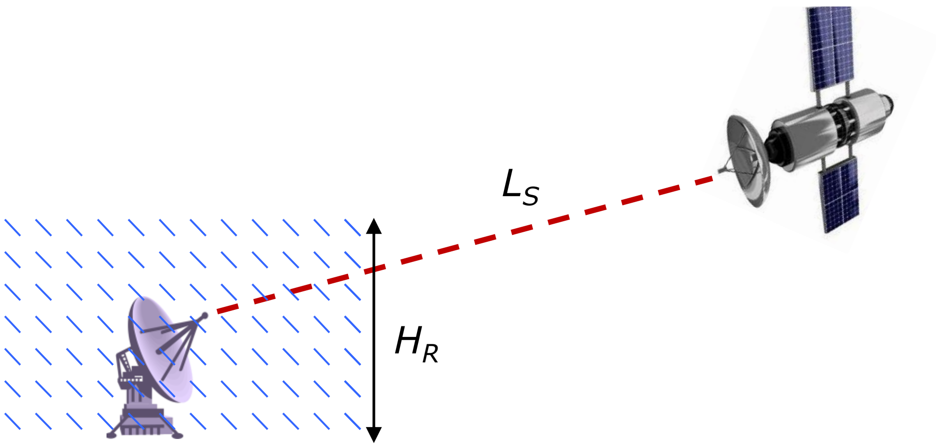

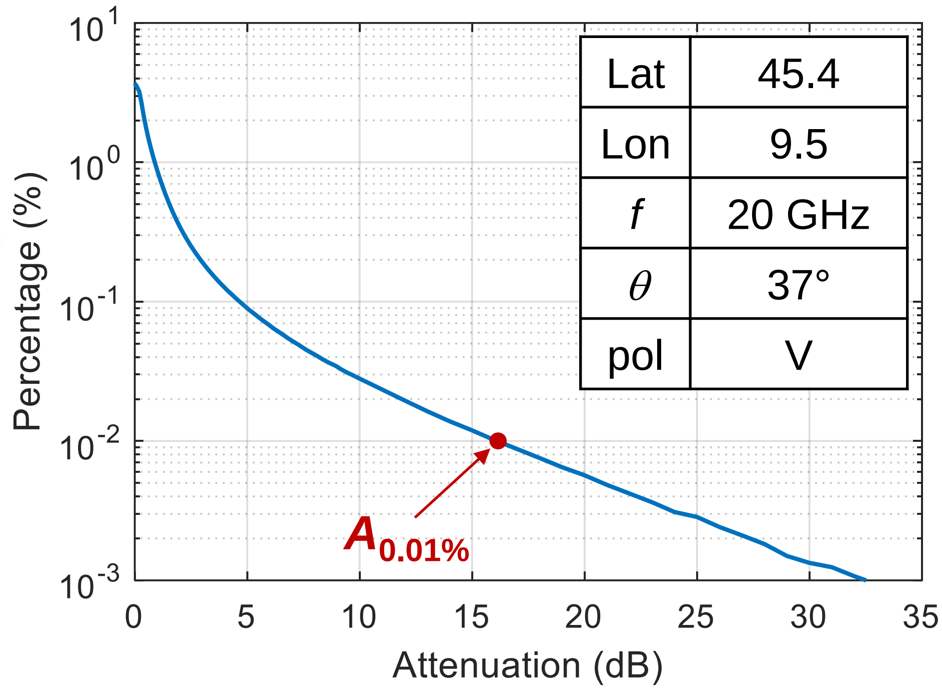

Lat	45.4
Lon	9.5
f	20 GHz
θ	37°
pol	V

$$A_{0.01\%} = k\left(R_{0.01\%}\right)^{\alpha} L_S \, AF(0.01\%, f)$$

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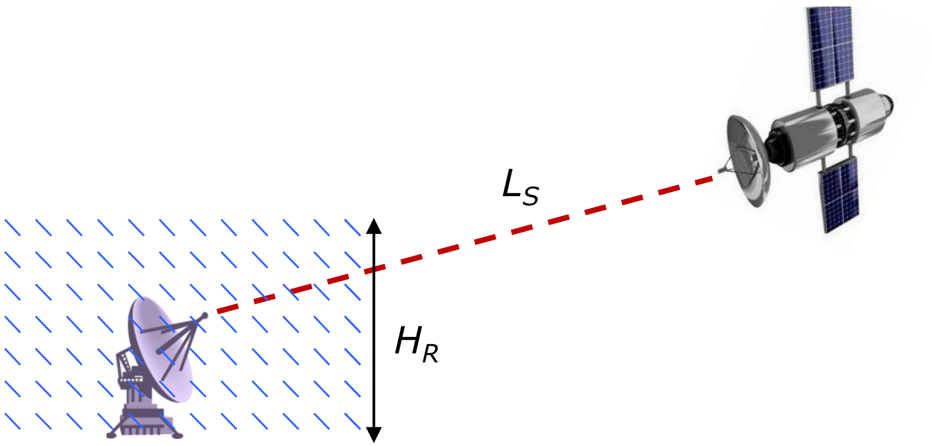

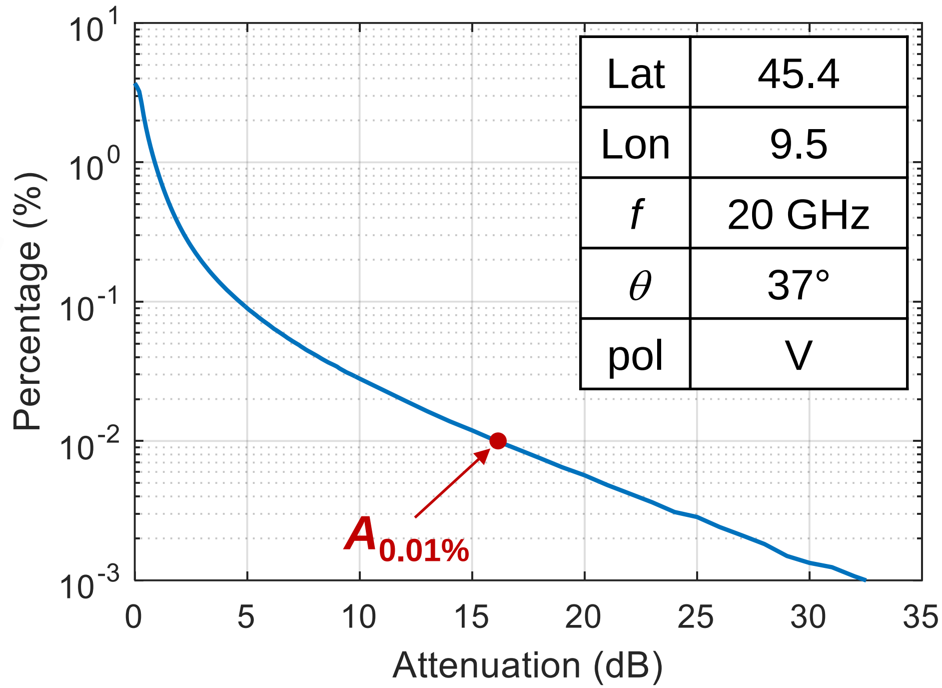

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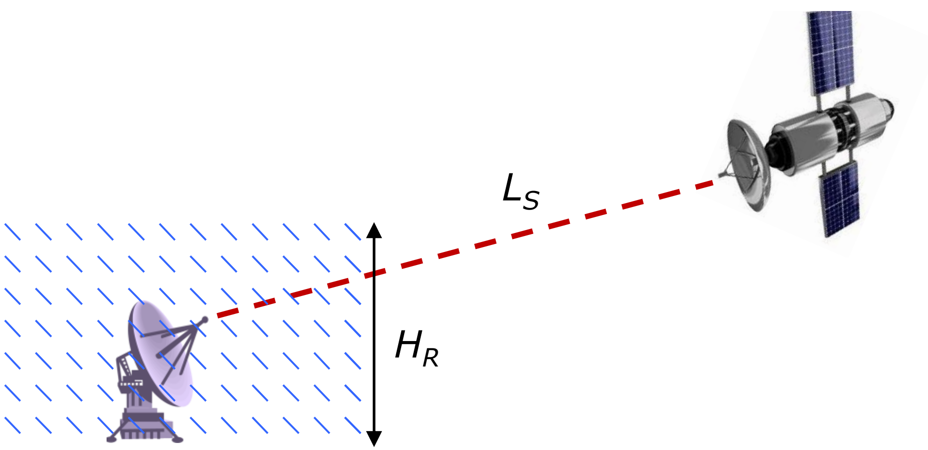

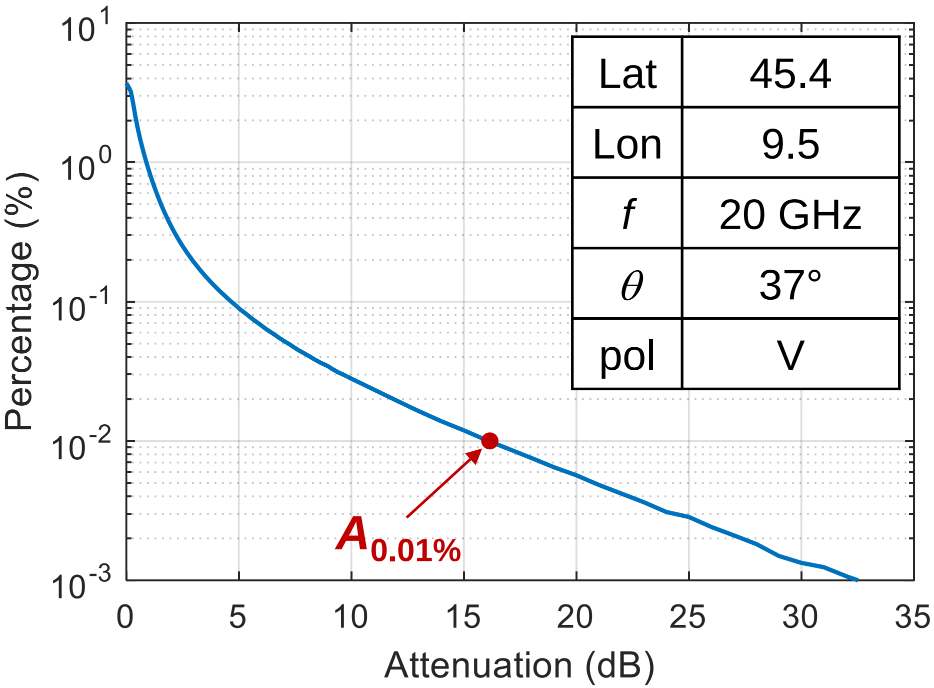

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$$v_{0.01} = \frac{1}{1+\sqrt{\sin\theta}\left(31\left(1-e^{-(\theta/(1+\chi))}\right)\frac{\sqrt{L_R\,\gamma_R}}{f^2}-0.45\right)}$$

$$r_{0.01} = \frac{1}{1+0.78\sqrt{\frac{L_G\,\gamma_R}{f}}-0.38\left(1-e^{-2L_G}\right)}$$

Rainfall path reduction factors

Models: from empirical to physically-based

Prediction of rain attenuation on Earth-space links: ITU-R P.61… (semi-empirical…

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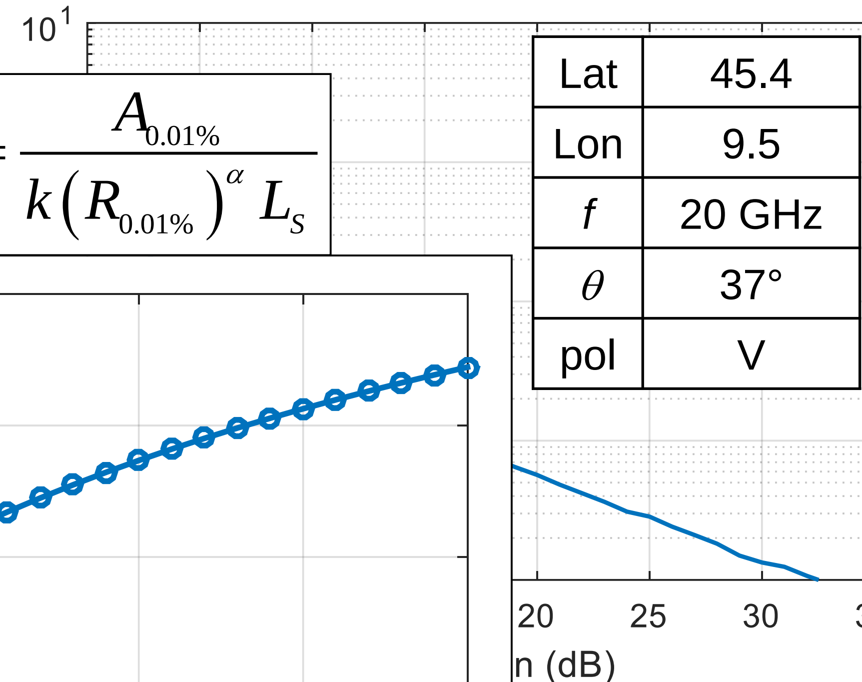

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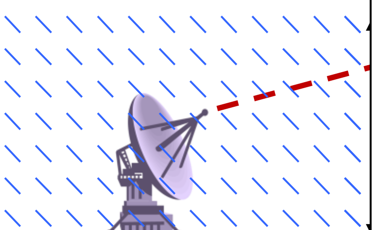

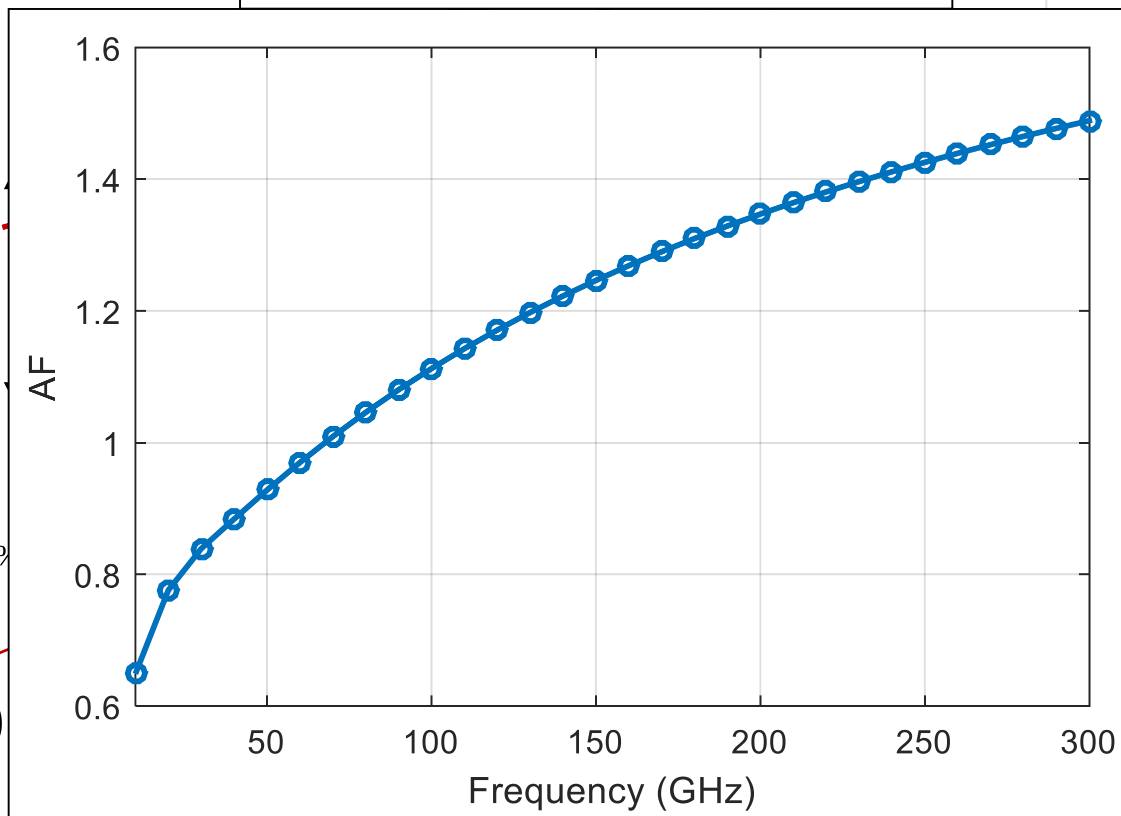

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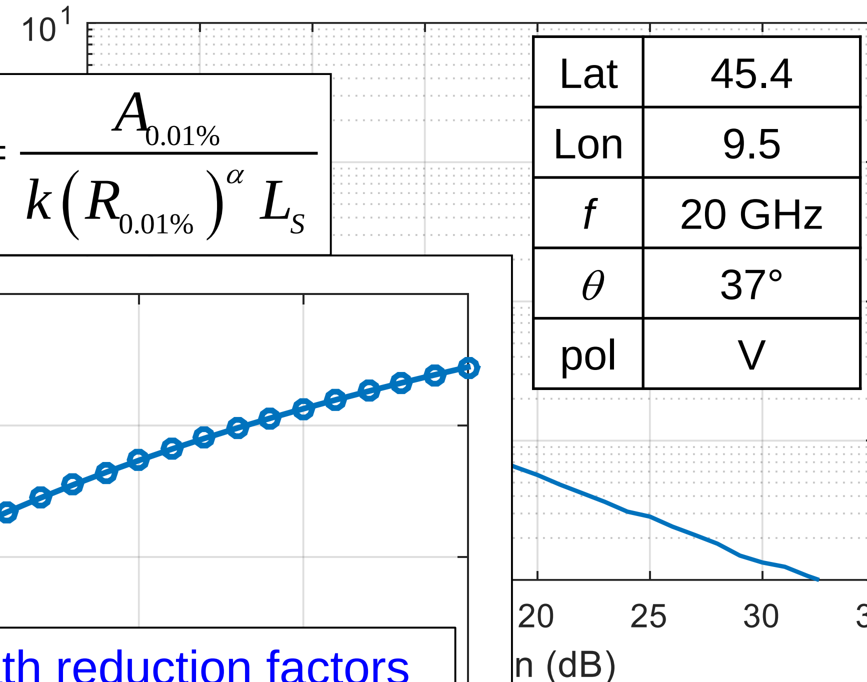

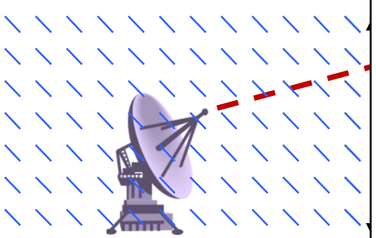

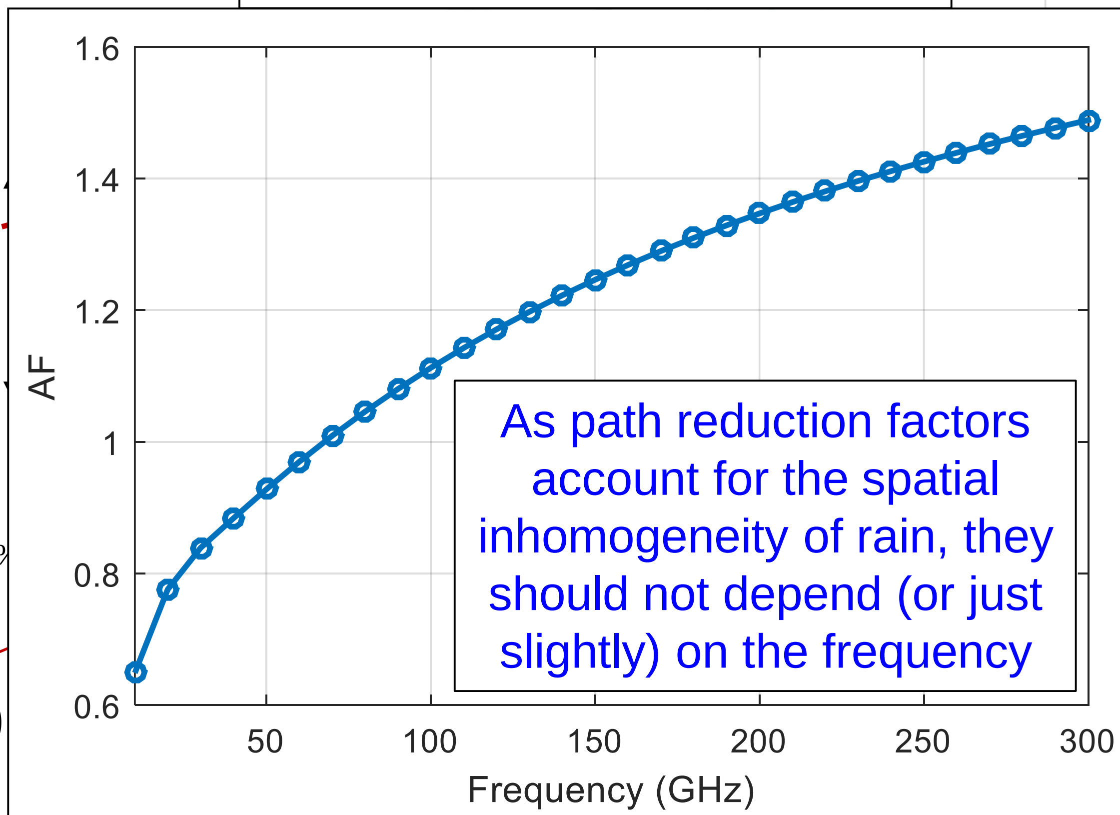

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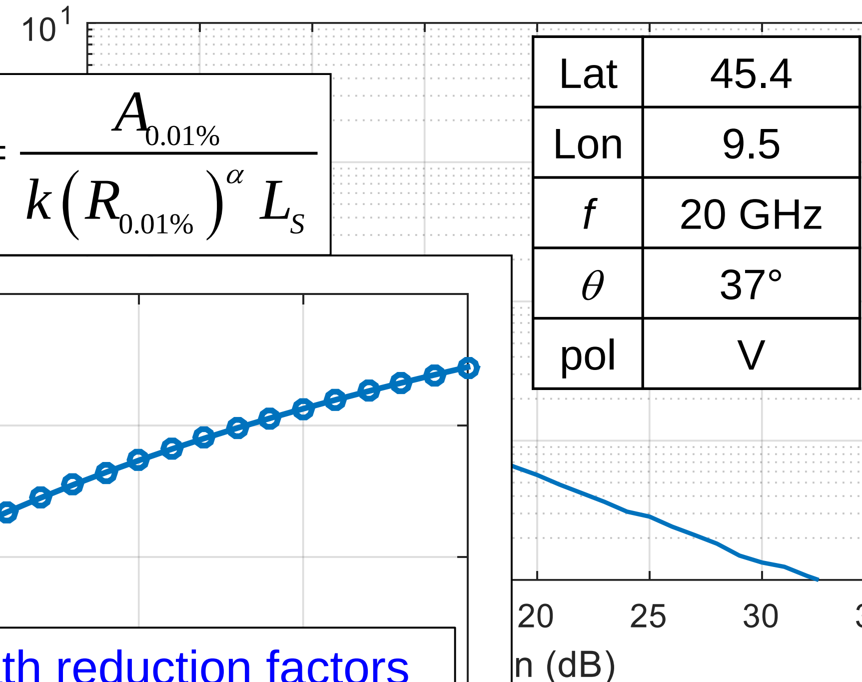

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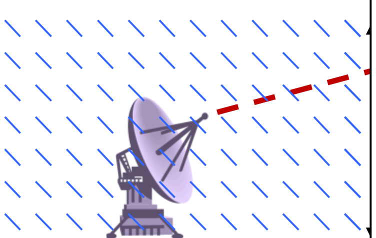

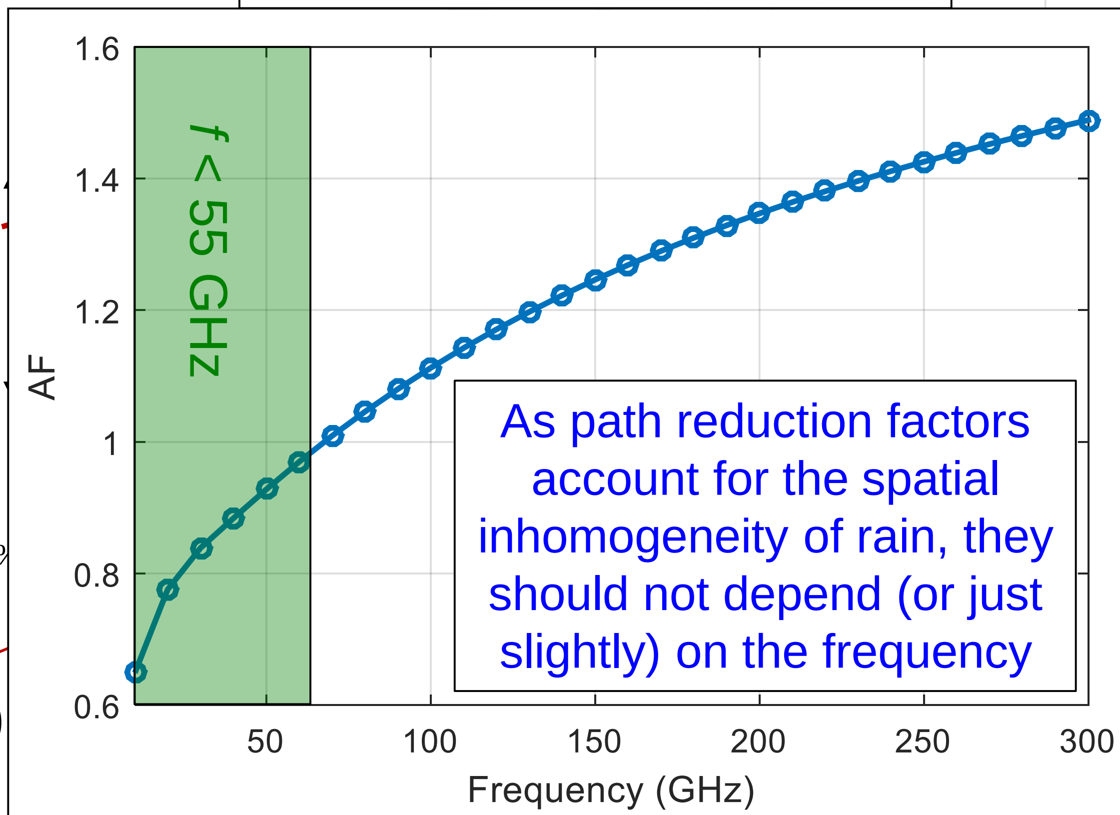

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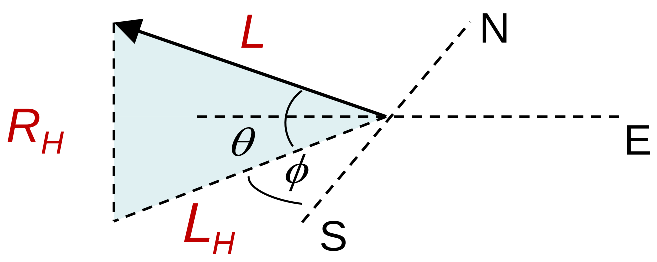
Rainfall path reduction factors

Models: from empirical to physically-based

Prediction of rain attenuation on Earth-space links: weather radar rainfall maps

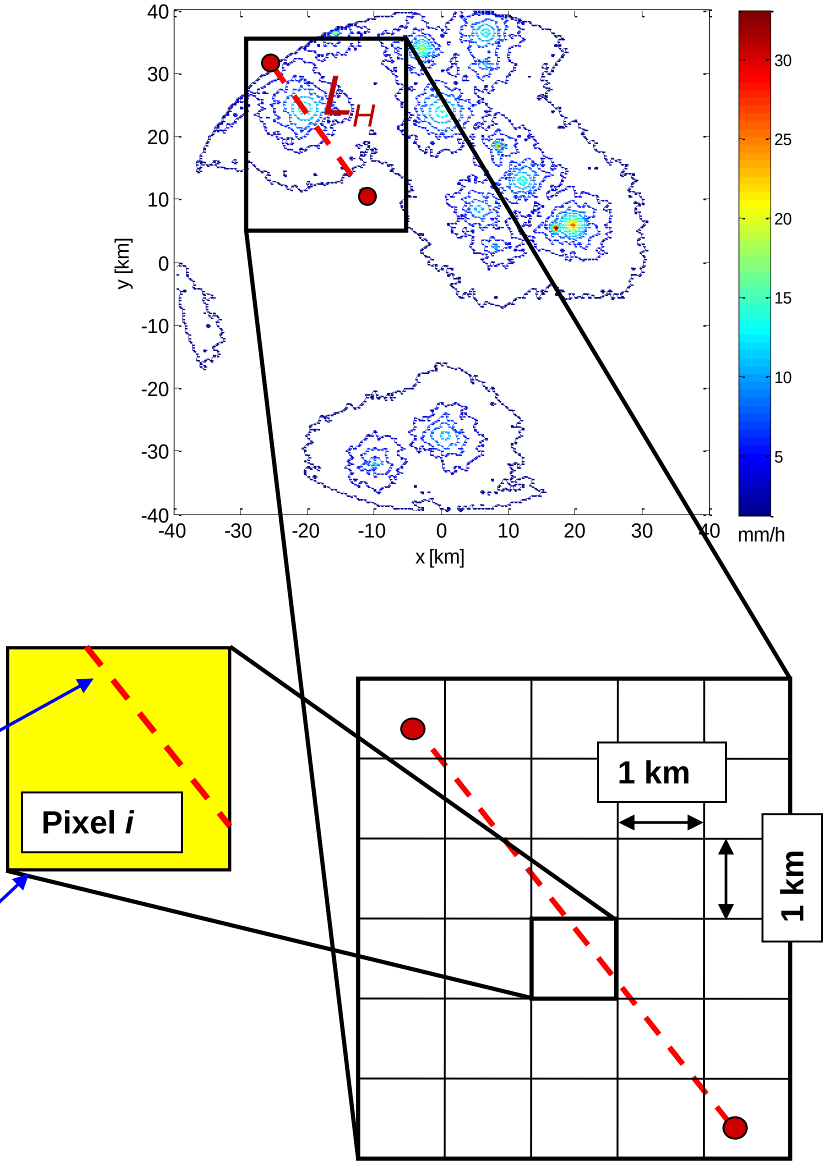
- Define the radio link geometry for a given position on the map



- Extract the k and α coefficients from ITU-R rec. P.838-3 (frequency, polarization) to calculate specific attenuation γ from rain rate R → $\gamma = kR^{\alpha}$
- Calculate the total rain attenuation affecting the radio link for a given position on the map as:

$$A = \int_L k\, R(l)^{\alpha}\, dl = \sum_{i=1}^{N} k (R_i)^{\alpha} \frac{\Delta l_i}{\cos(\theta)}$$

- Move the radio link geometry across the whole rain map to consider the interaction with the whole rain field → attenuation map



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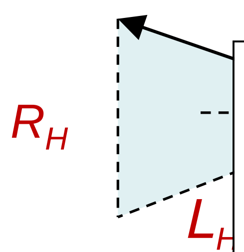

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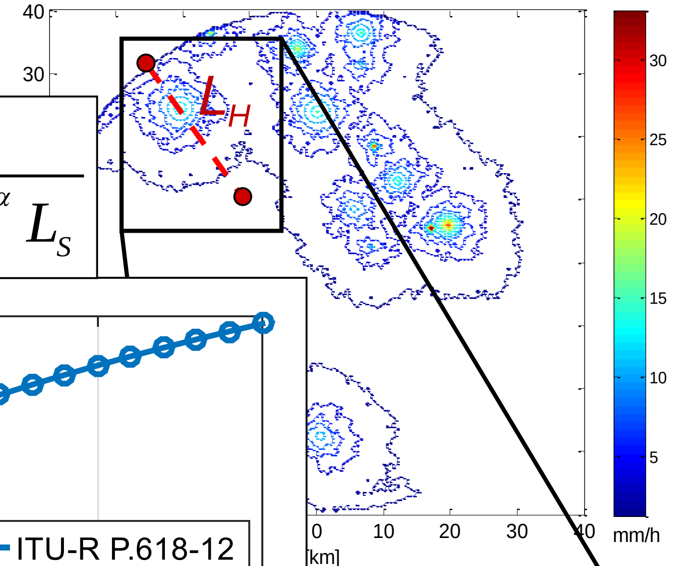

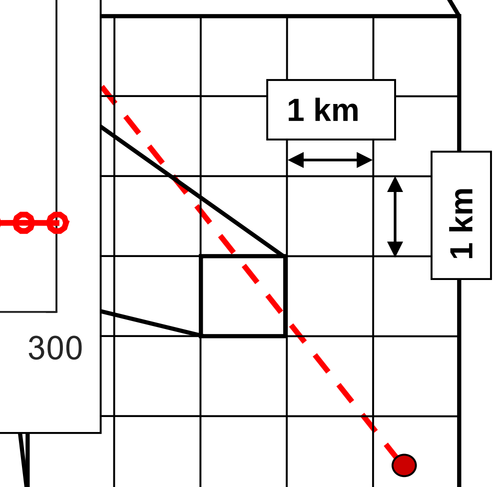

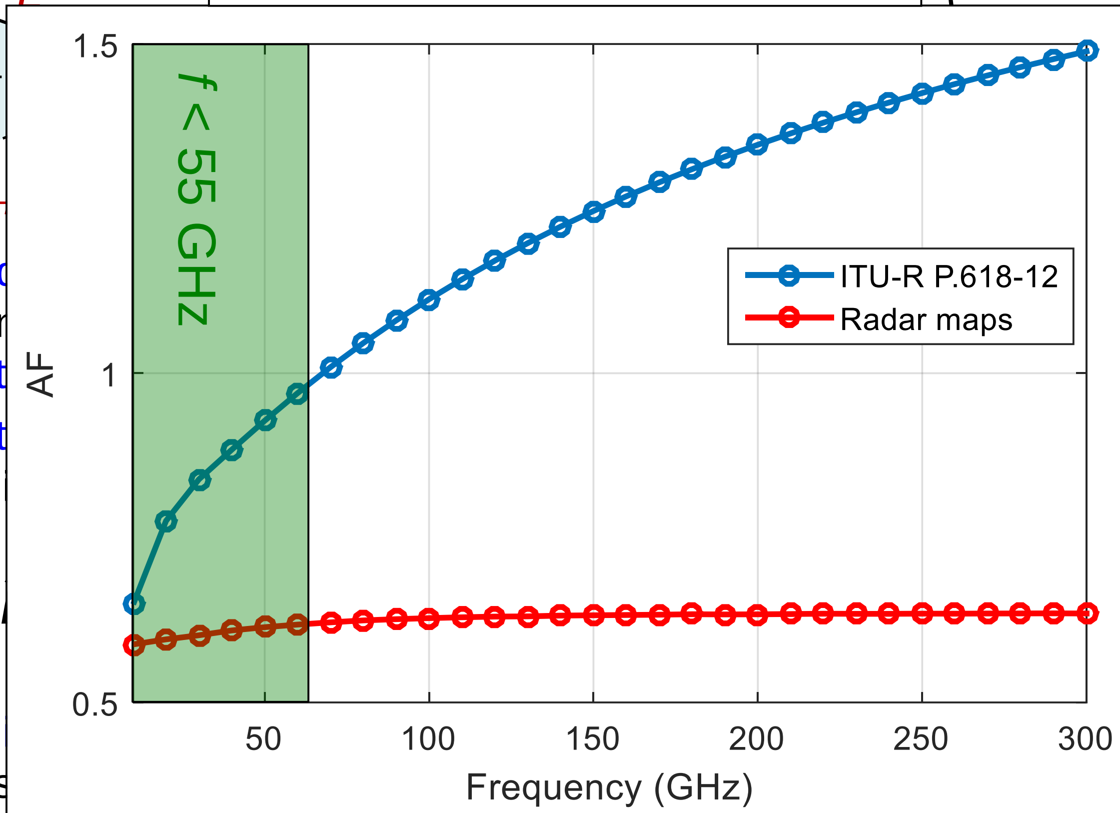

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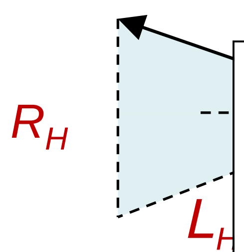

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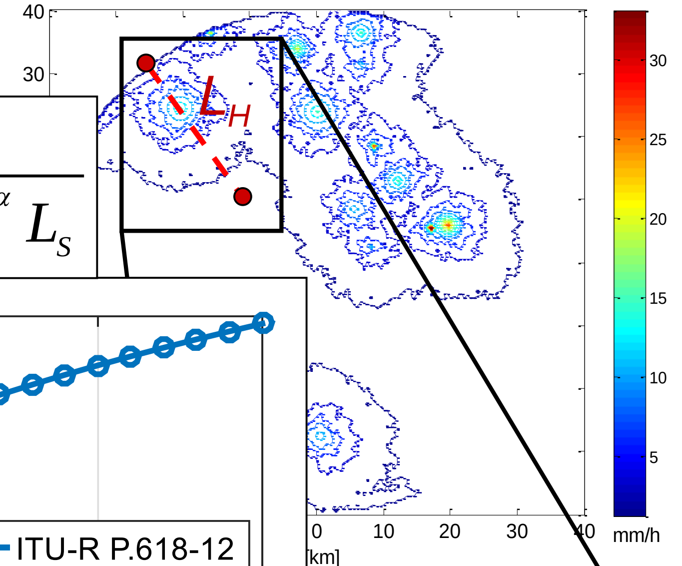
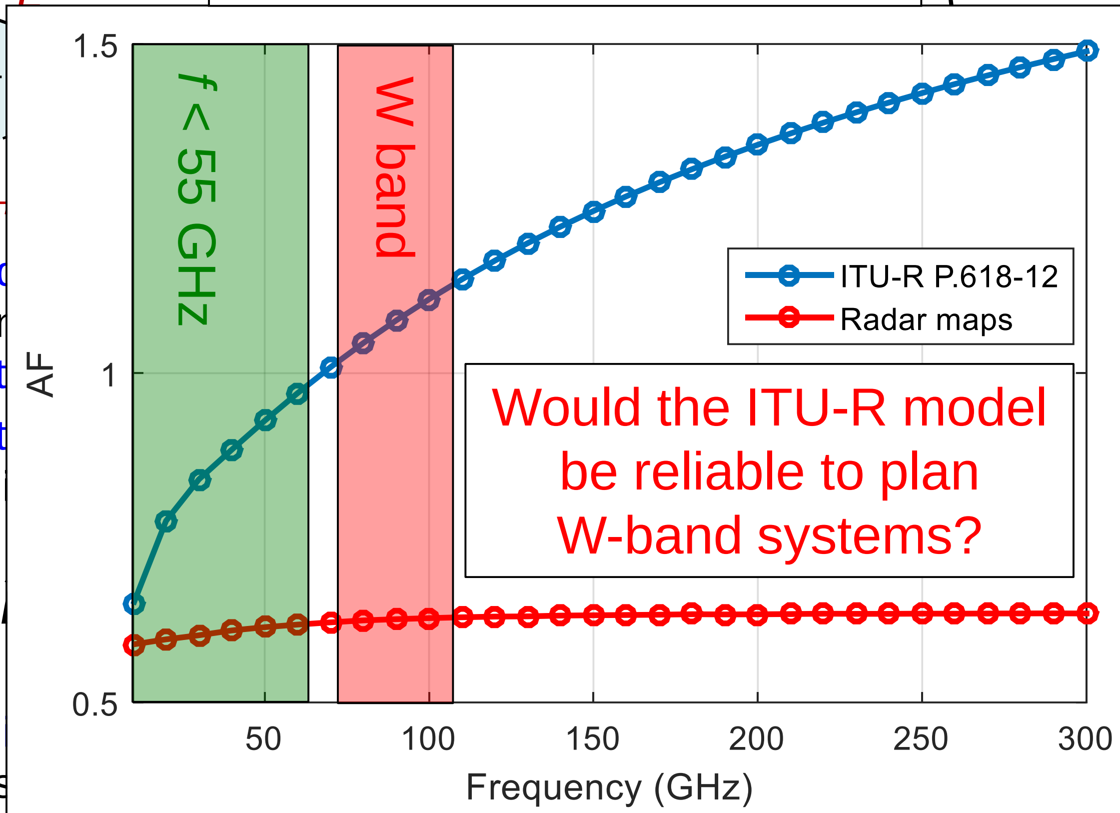
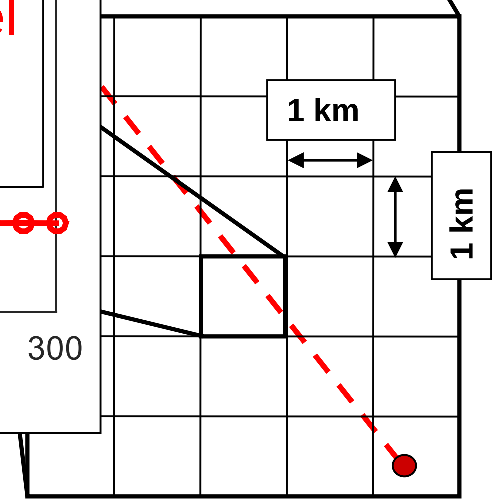
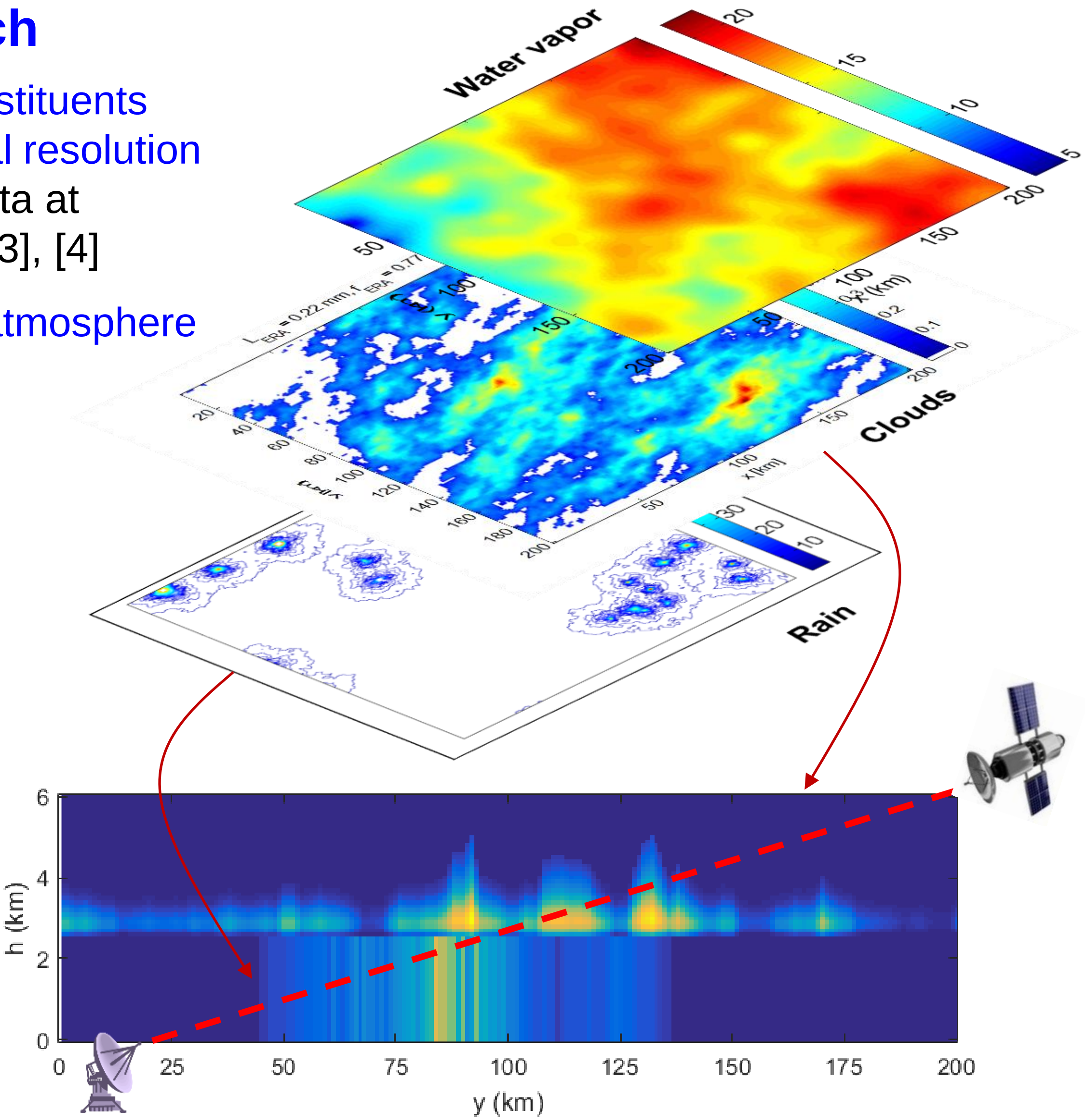






Physically-based approach

- Example: synthesize atmospheric constituents that impair EM waves, with high spatial resolution (both time and space) starting from data at coarser resolution (e.g. ECMWF) [2], [3], [4]
- Simulate the interaction between the atmosphere and any wireless system



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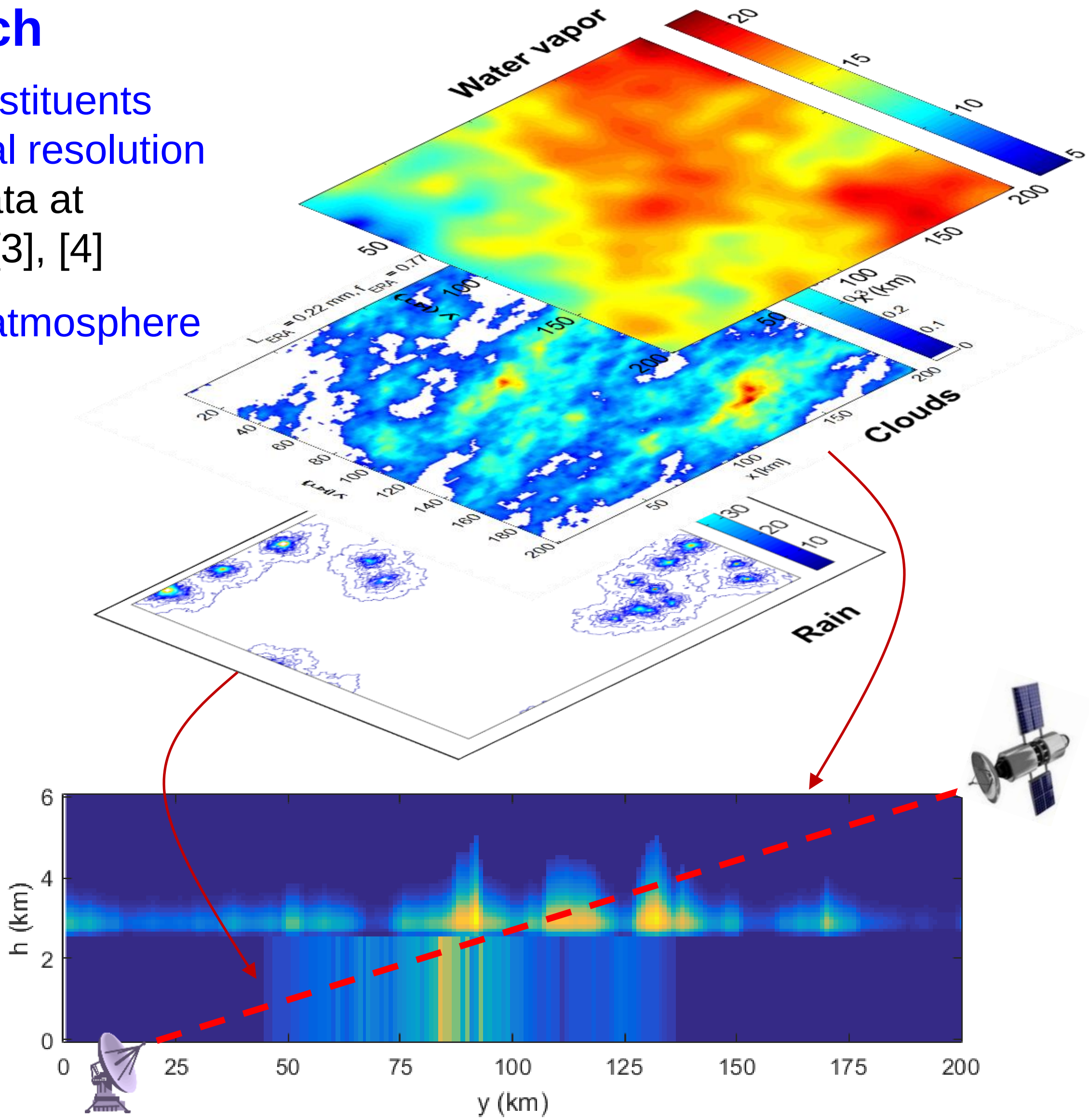
- Simulate the interaction between the atmosphere and any wireless system
- Main advantages:
  - ✓ Any geometrical/electrical characteristics of the link
  - ✓ Different propagation quantities can be calculated (attenuation, delay, depolarization, …)
  - ✓ Seamless summation of all attenuation contributions
  - ✓ Different scenarios, same model for consistent results (e.g. site diversity, GEO/LEO/MEO systems, …)



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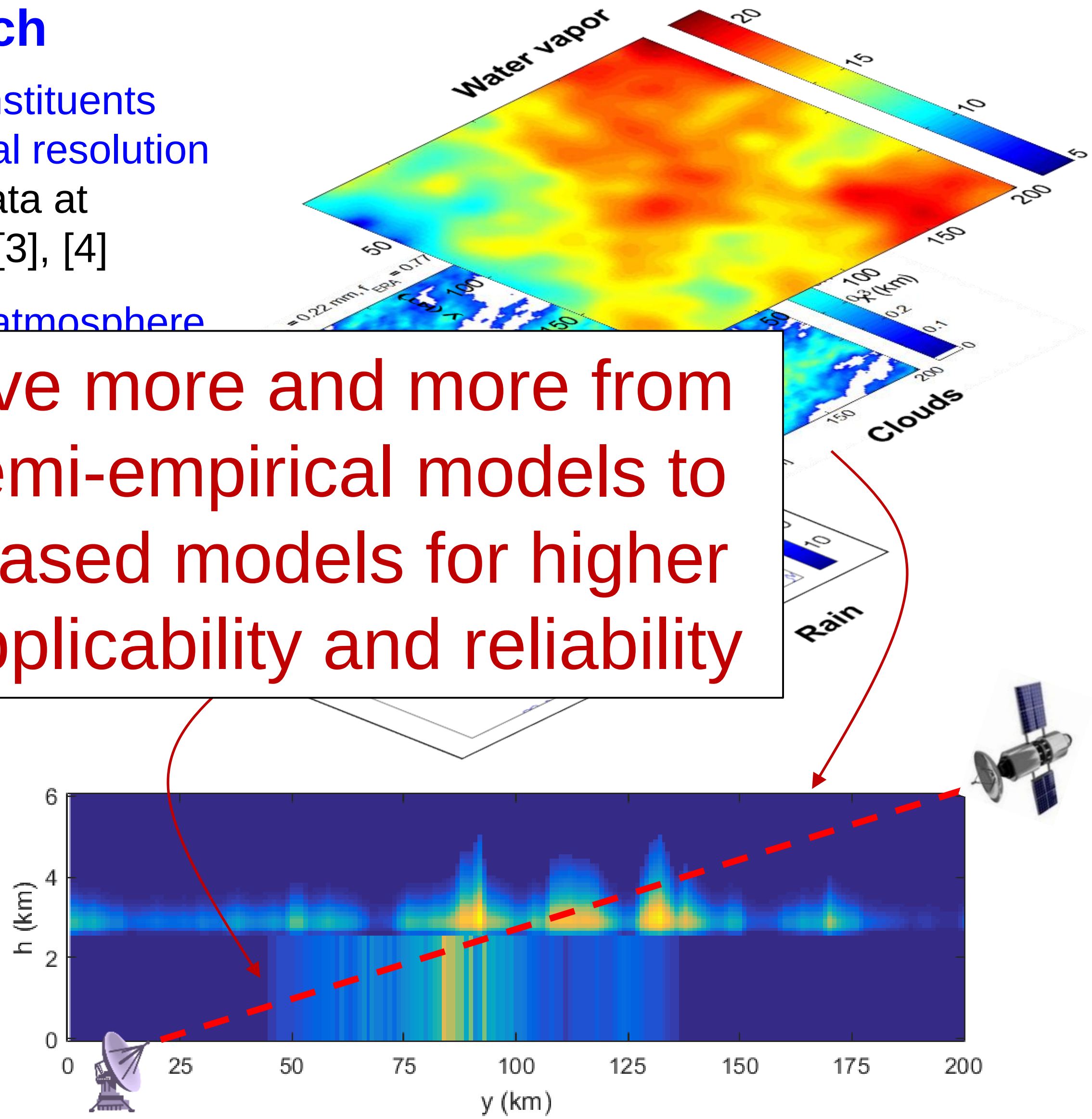

Need to move more and more from empirical/semi-empirical models to physically-based models for higher accuracy, applicability and reliability

Models: from yearly to seasonal/monthly basis

- Propagation prediction models work mainly on yearly basis → e.g. power margin predicted to guarantee that the system is available for 99.99% of the time in a year
- But what happens on monthly basis? In other words, is that goal achieved for each month or are there months with significantly worse propagation conditions?

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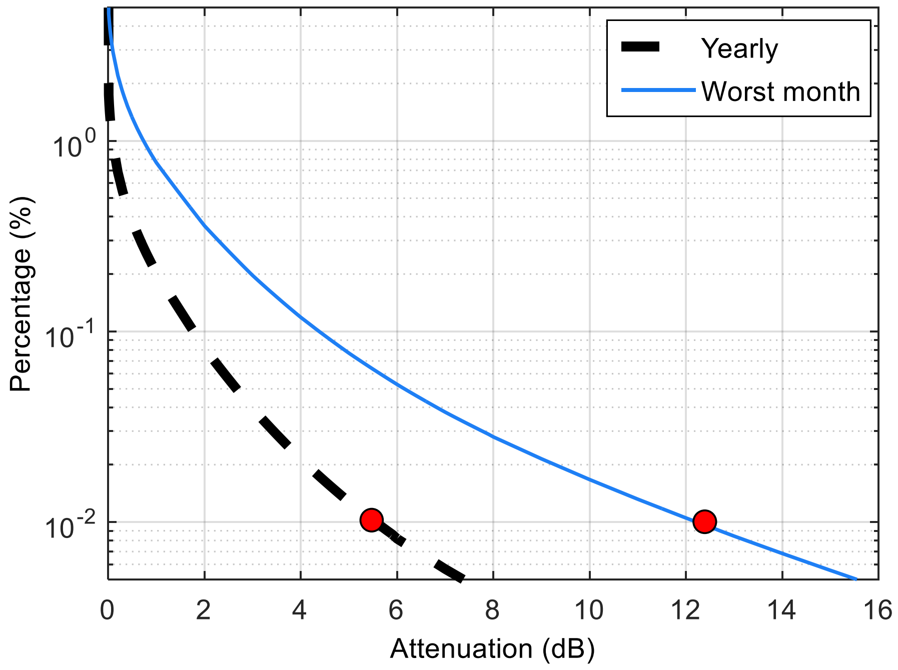

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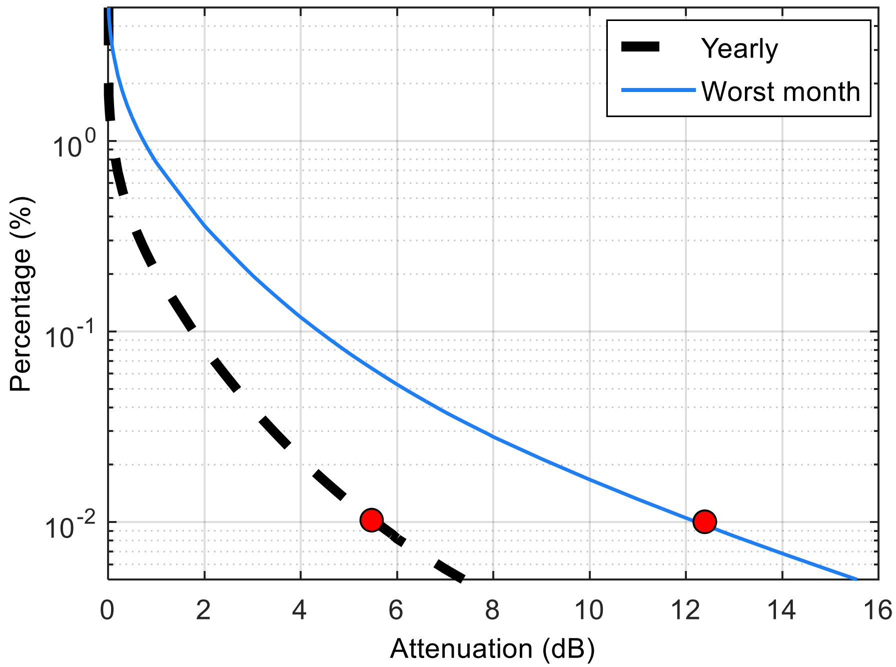
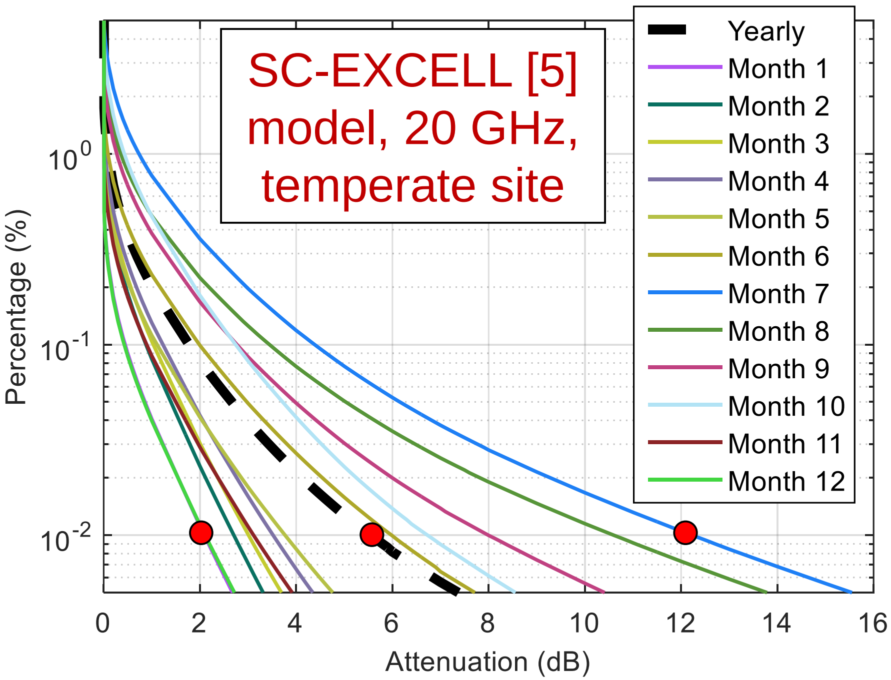
- To provide a more conservative design, the concept of "worst month" was introduced
- A step further is to develop/modify existing models to provide predictions on monthly basis



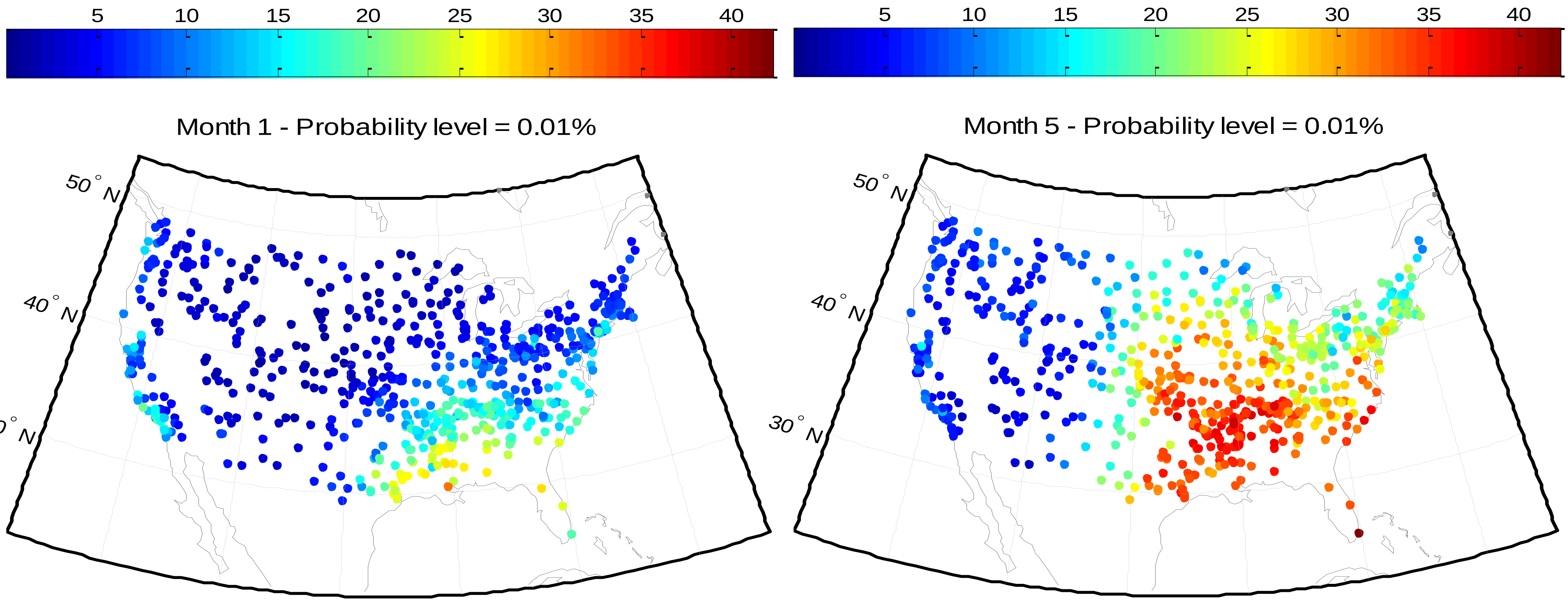


Models: from yearly to seasonal/monthly basis

Usefulness of monthly attenuation statistics

- Additional information on the availability/QoS that can be provided to users → variability of the service level through the year

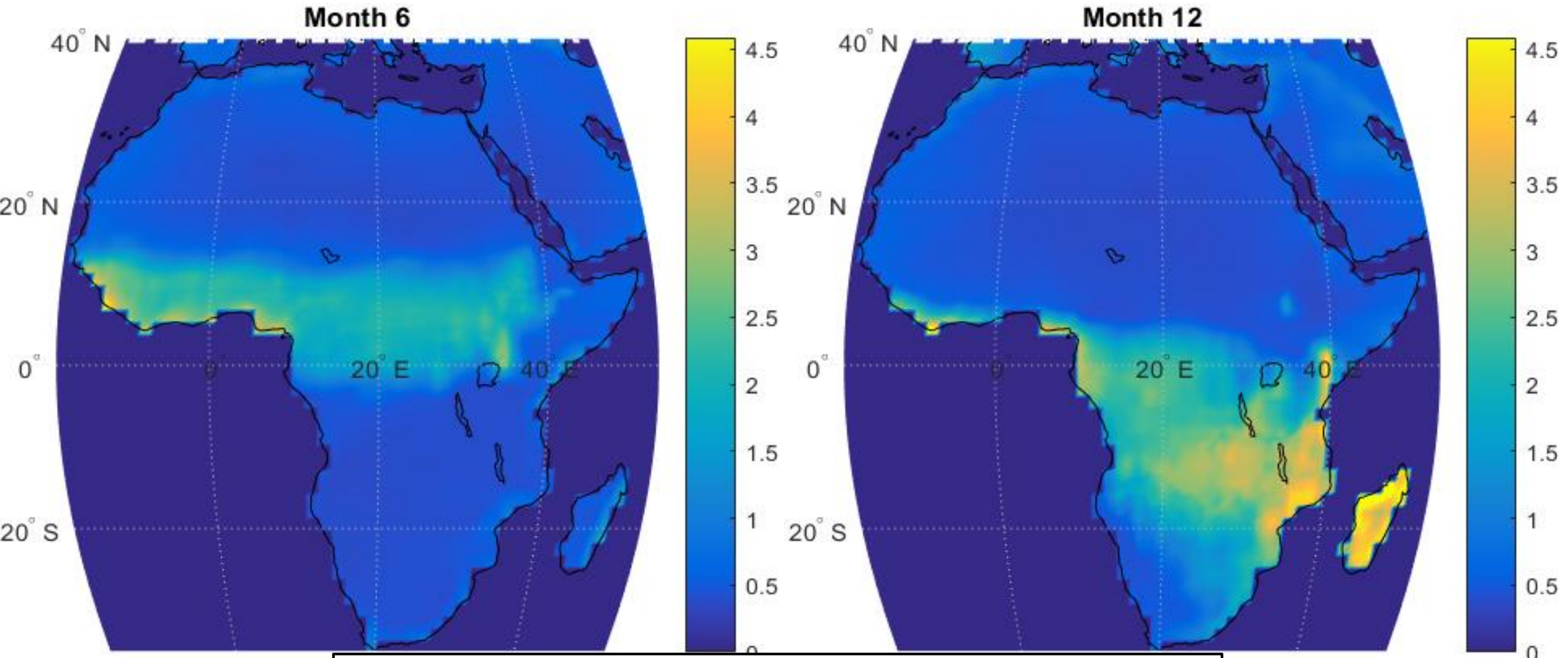
f = 18.5 GHz, satellite position = 100° W



Models: from yearly to seasonal/monthly basis

Usefulness of monthly attenuation statistics [6]

- Overall power available on board can be reallocated unevenly over the region (on monthly/seasonal basis) so as to provide more power where more adverse conditions are expected: save costs in the planning phase and improve system performance in the operative phase



f = 12.1 GHz, satellite position = 19.2° E

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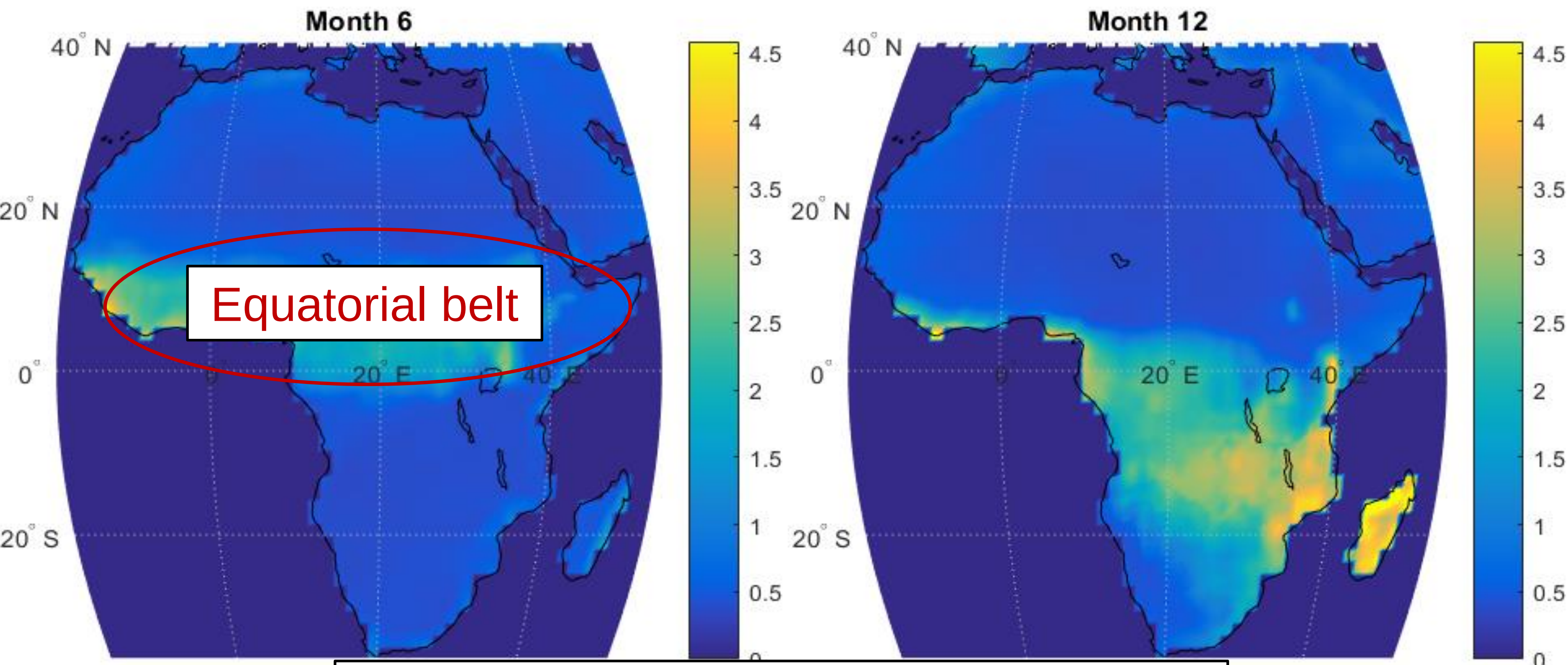

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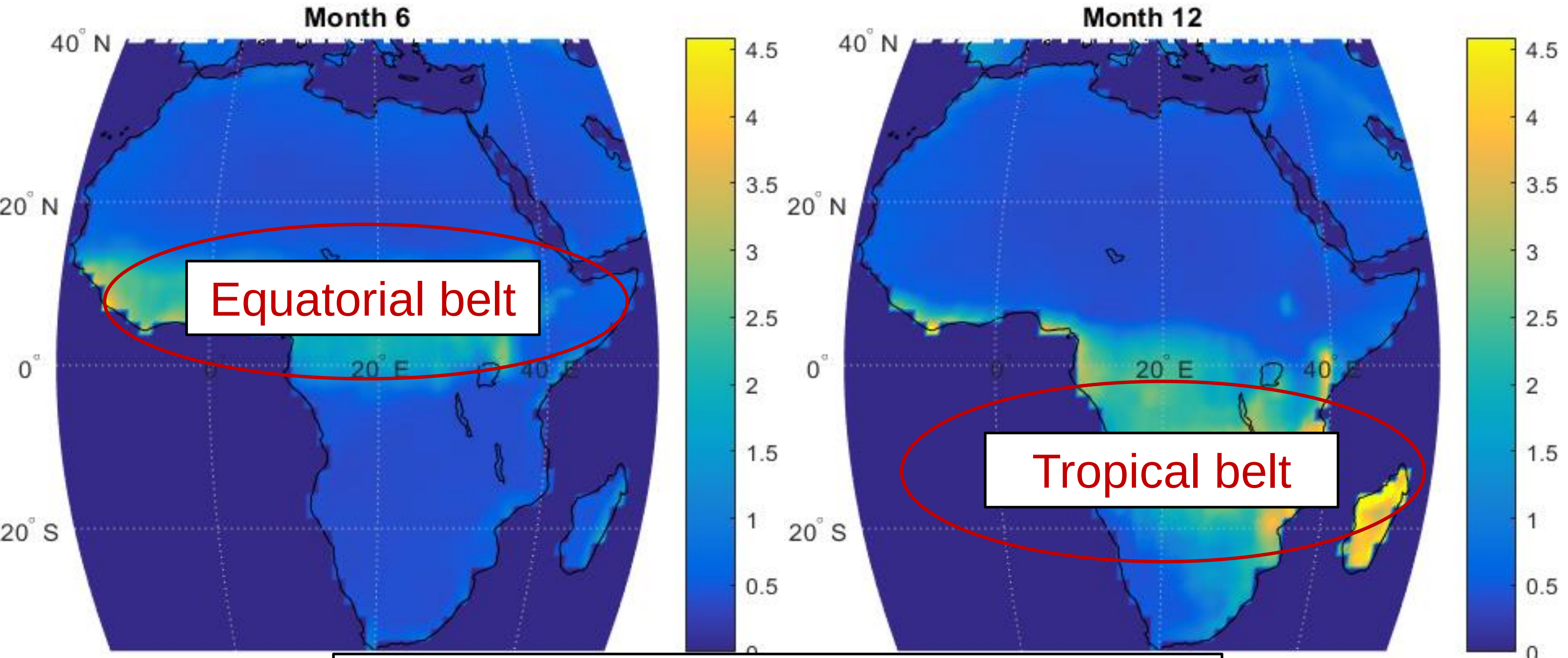

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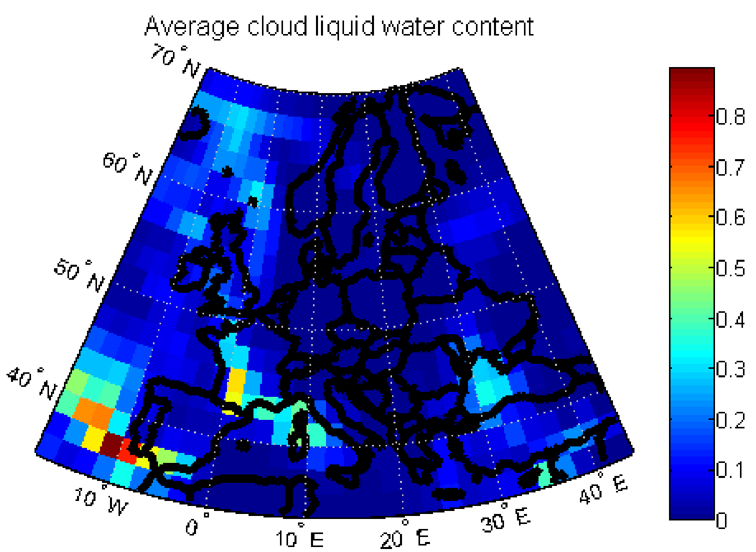
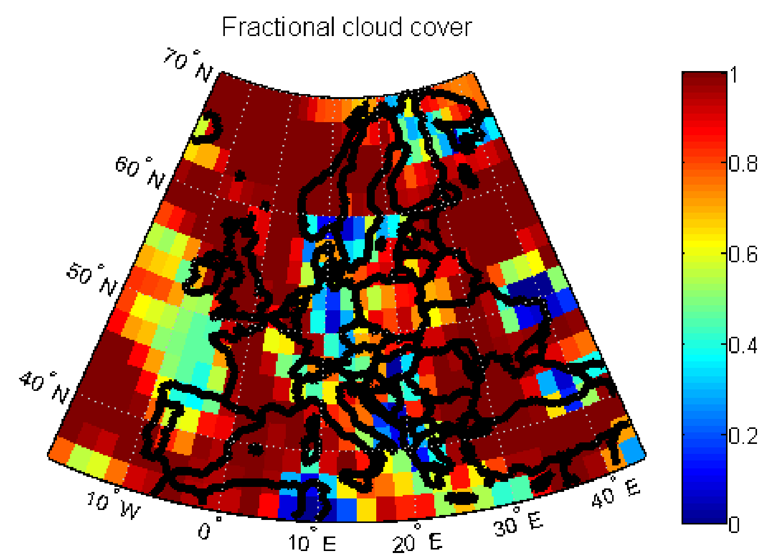
Data: the role of Numerical Weather Predictions

- Main input to propagation prediction models → local meteorological data (e.g. integrated water vapor content for gaseous attenuation prediction)
- When no local data are available, Numerical Weather Prediction data (e.g. ECMWF) are the fundamental source of information to be used (e.g. ITU-R models)
- Advantages → long-term, gridded, global, multisource (ground-based + space-borne instruments), checked for errors/consistency/biases, homogeneous, …
- Disadvantages → mixture of measurements and modeling (accuracy), typically coarse temporal and spatial resolution





Data: the role of Numerical Weather Predictions

- In the last decade NWP data have been evolving considerably:
  - ✓ Accessibility: direct download from websites, such as ECMWF and NOAA
  - ✓ Availability: more and more meteorological quantities made available
  - ✓ Accuracy: constant improvement of atmospheric models over time
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ERA-40	1957-2001	6 hours	1.125°×1.125°	60 levels
ERA-Interim	1979-present	6 hours	0.75°x0.75°	60 levels
ERA-5	1979-present	1 hour	≈ 0.28°x0.28°	137 levels
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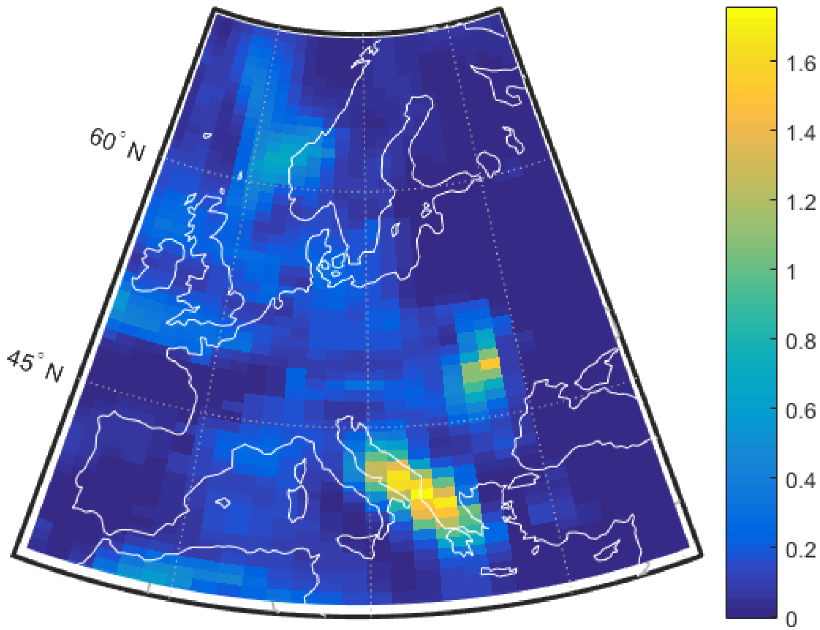

Integrated liquid water content in clouds

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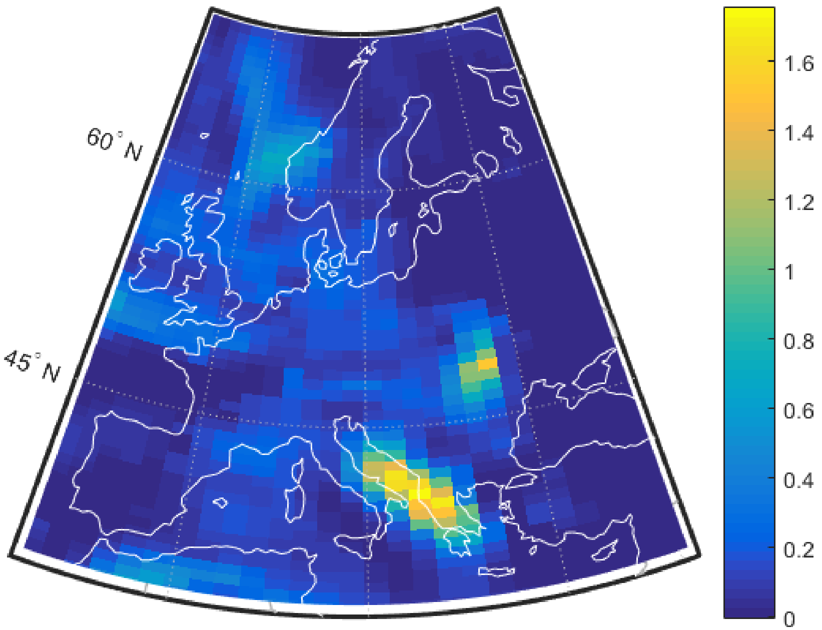

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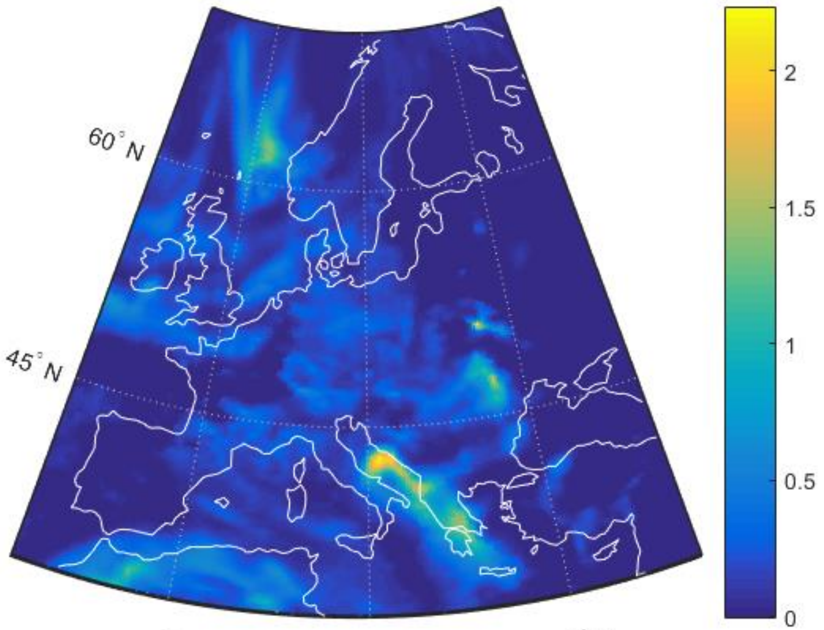
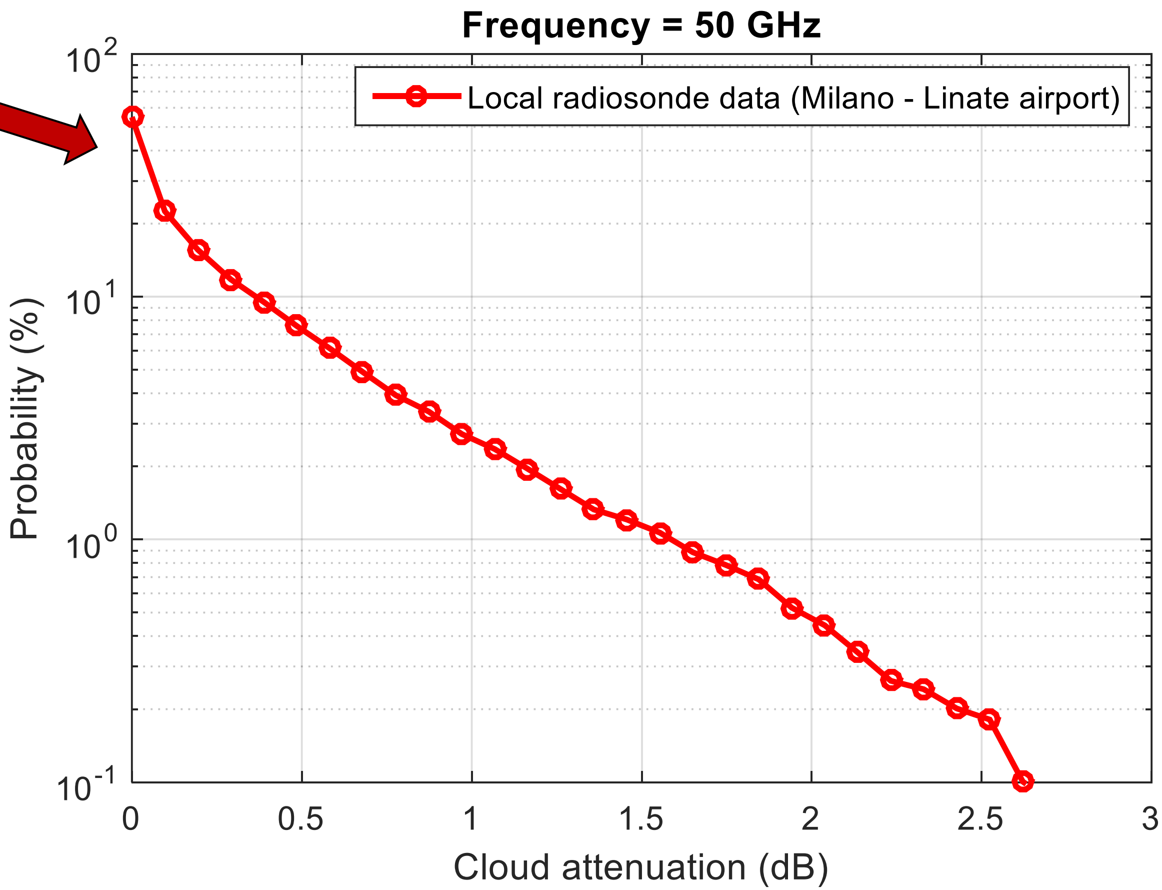


Integrated liquid water content in clouds

Example: cloud attenuation prediction



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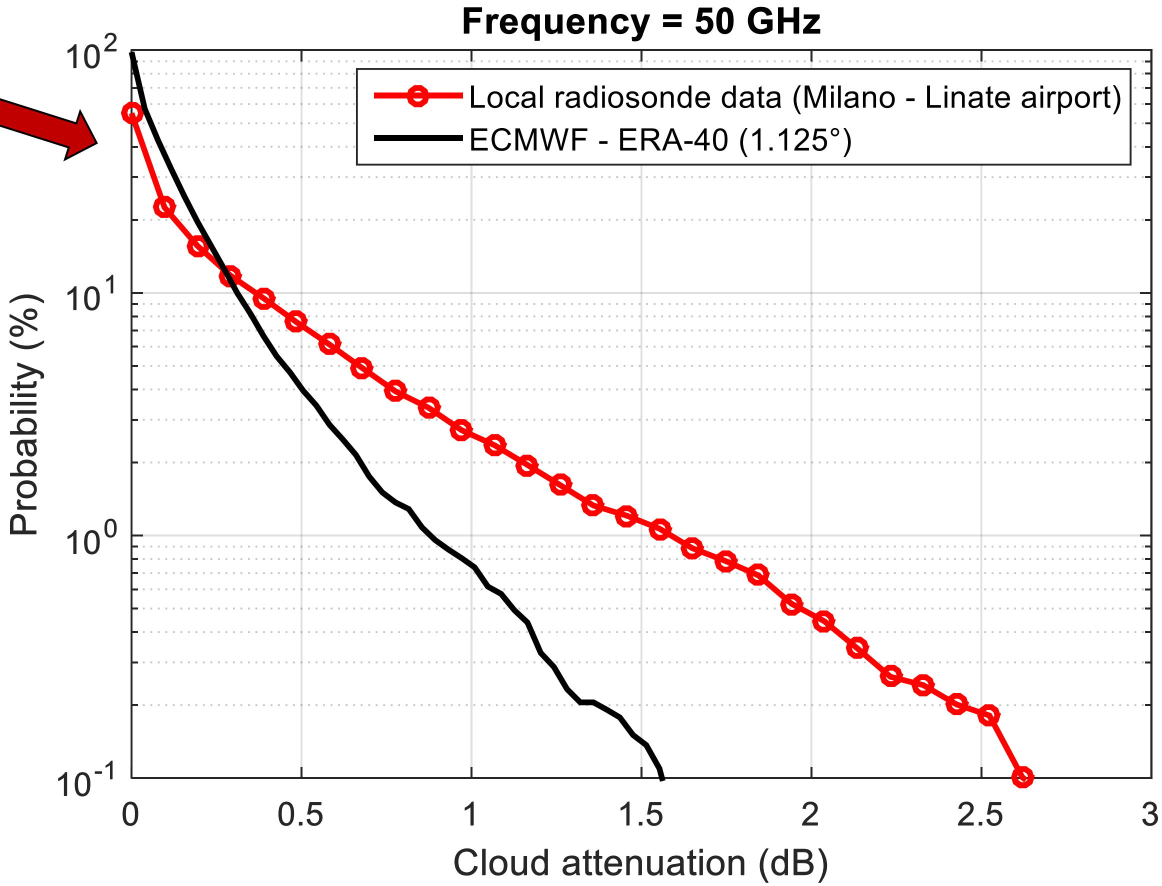

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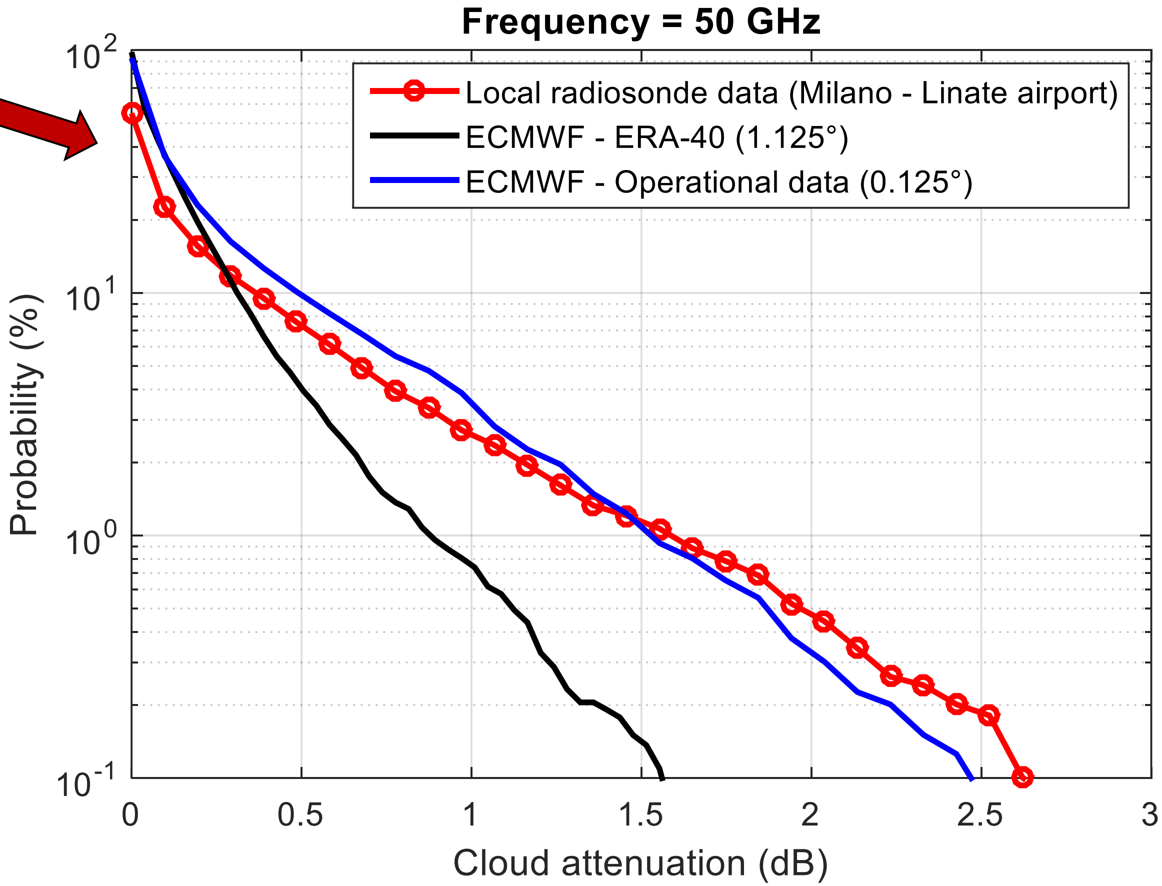

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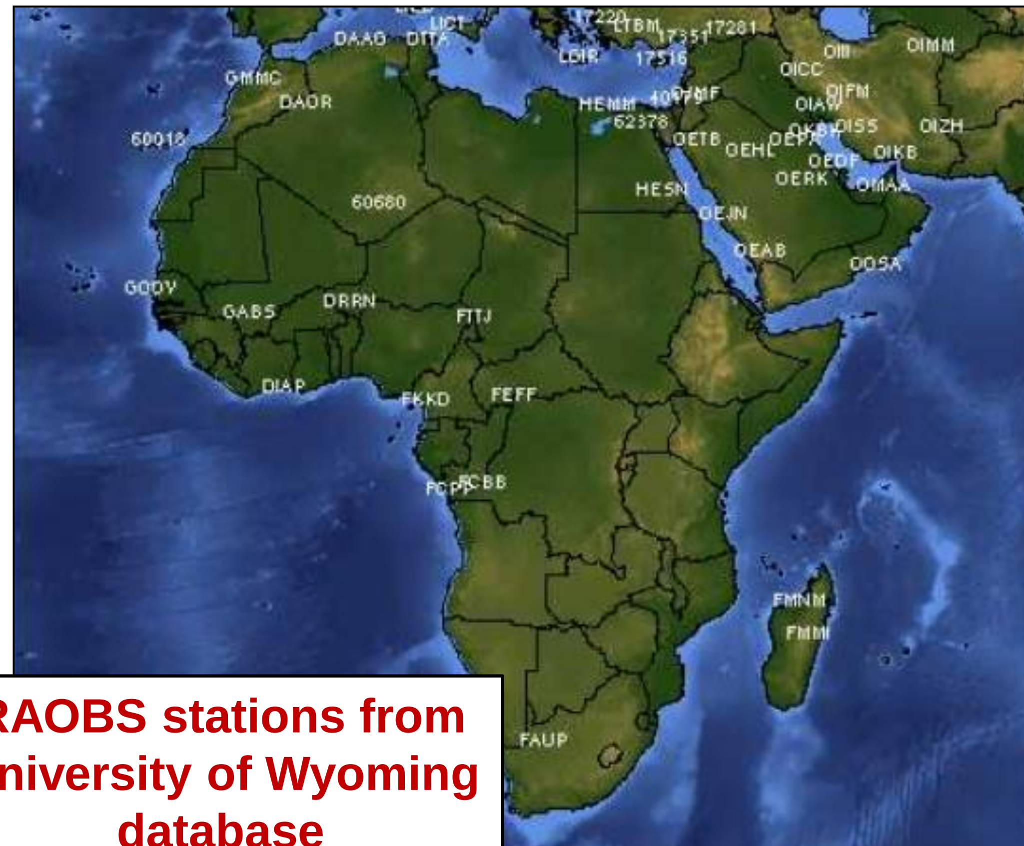
Data: the role of Numerical Weather Predictions

- The accuracy of NWP data strongly depends on local input meteorological information (e.g. RAOBS, raingauges, ground meteorological sensors), besides space-borne observations → need of more data in some developing Countries



RAOBS stations from University of Wyoming database

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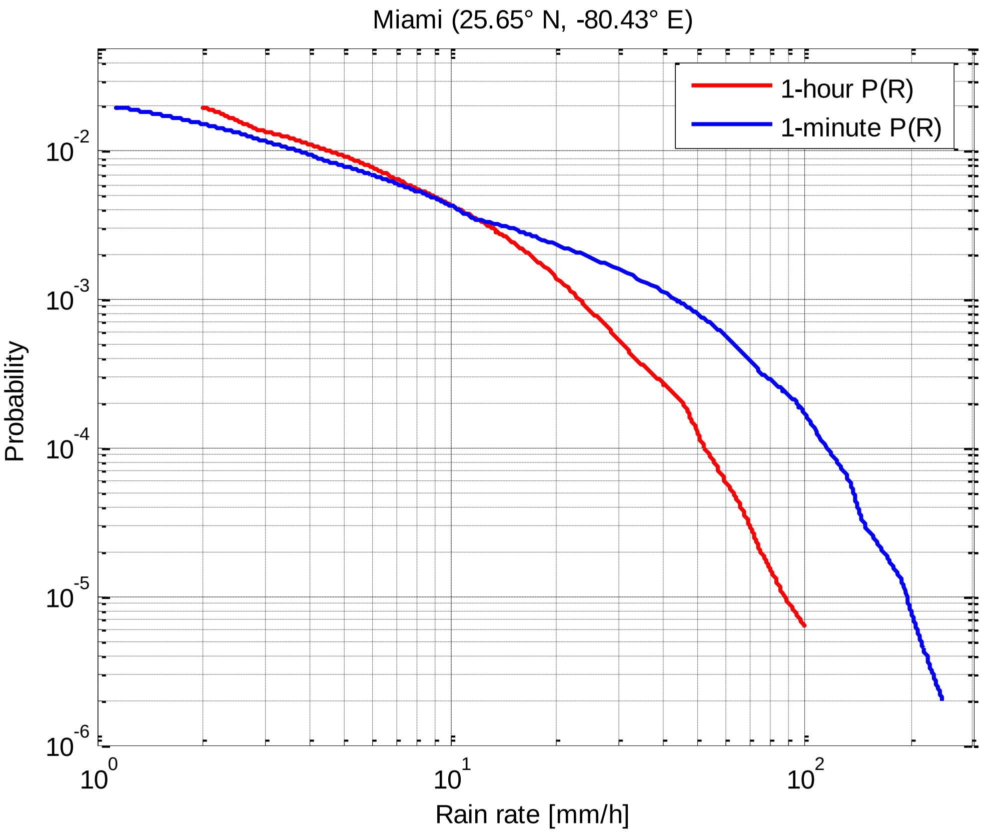

- NWP data are quickly evolving to providing the full atmospheric environment on global basis, with proper spatial and temporal resolutions, with higher accuracy and with very detailed information (e.g. convectivity degree of a precipitation event, Drop Size Distribution, …)
- True both for re-analysis products (mainly system design) and forecast products (both system design and operation)

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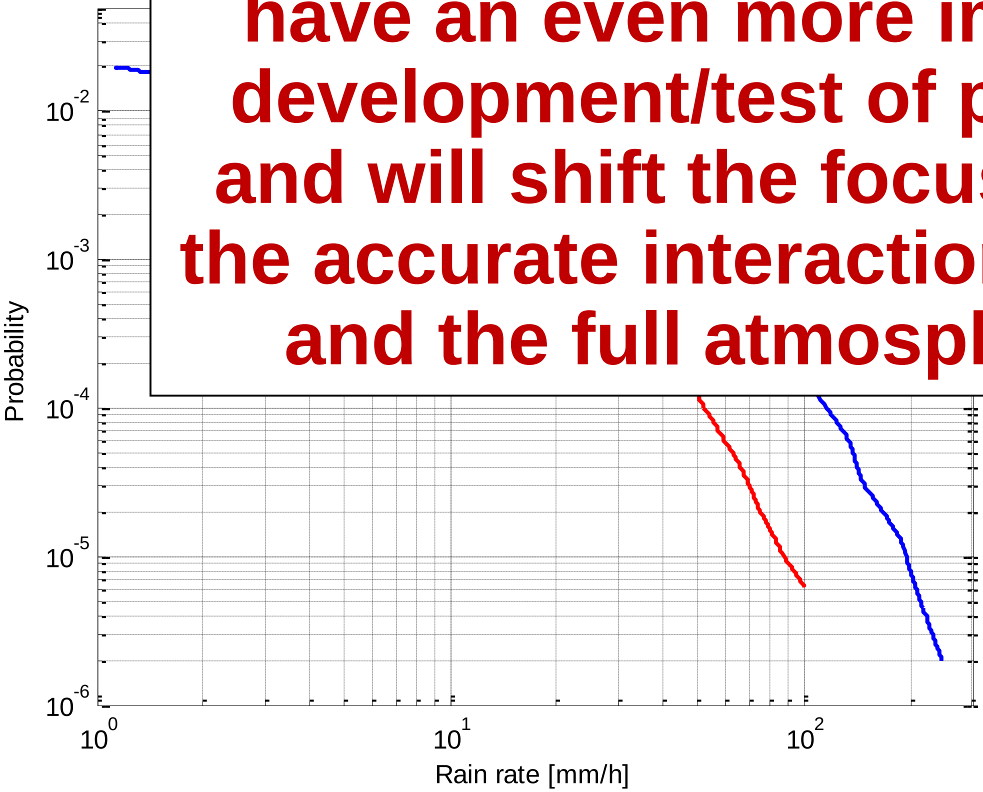
Numerical Weather Prediction data will have an even more important role in the development/test of propagation models and will shift the focus more on modeling the accurate interaction between EM waves and the full atmospheric environment



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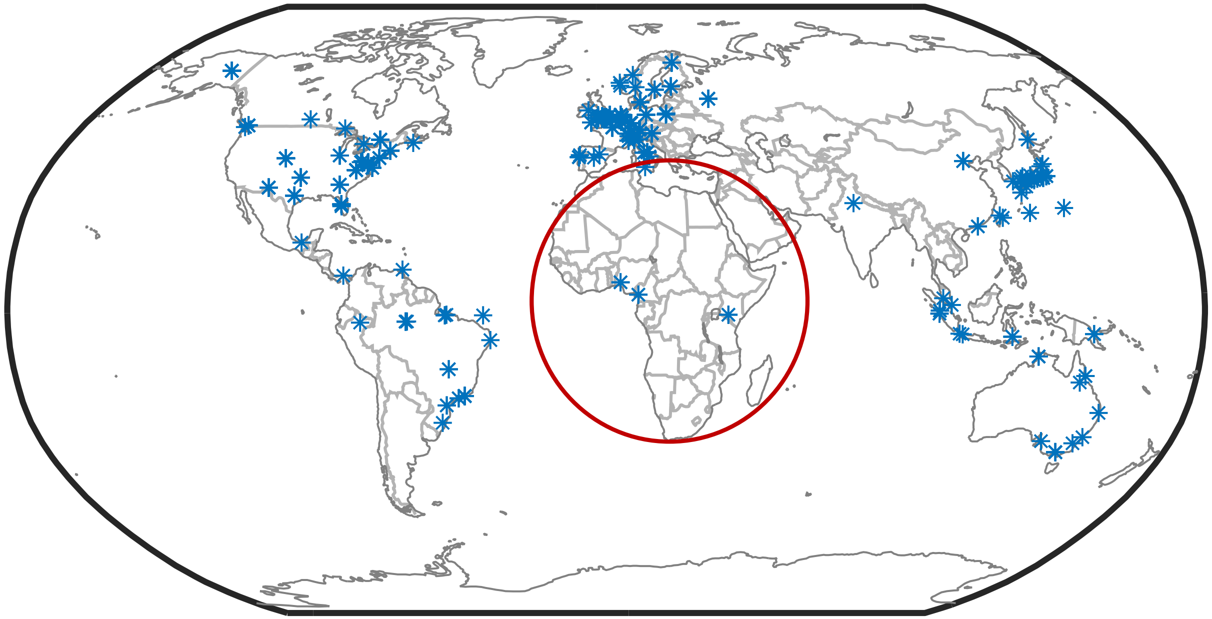

ITU-R DBSG3 for rain attenuation experiments

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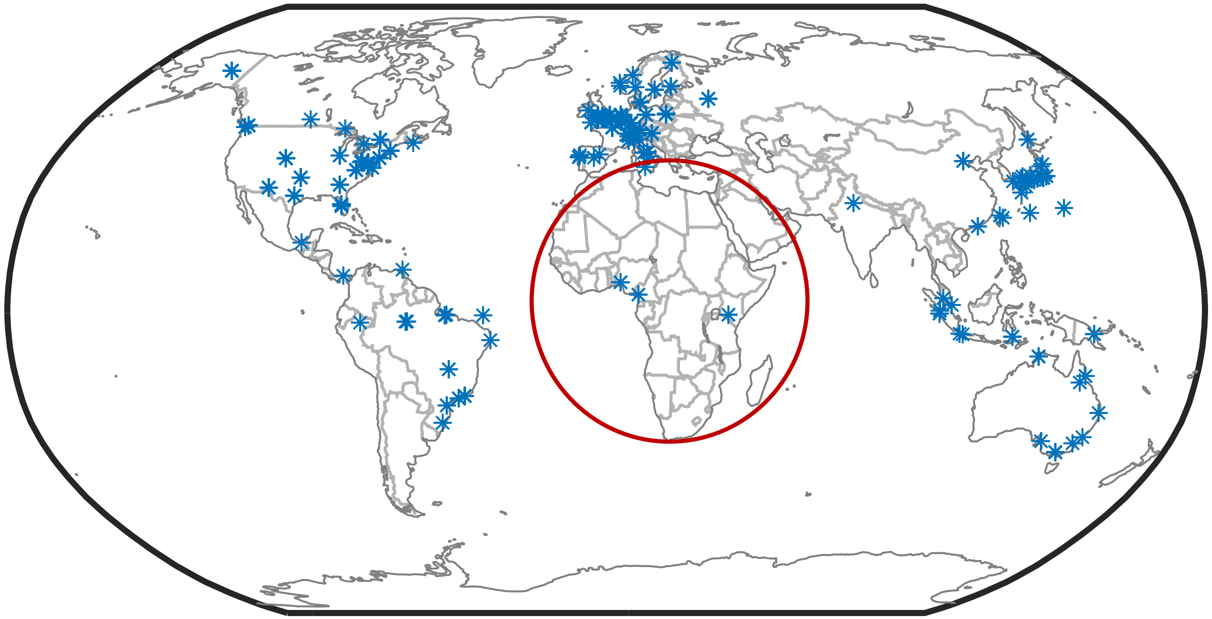


ITU-R DBSG3 for rain attenuation experiments

- Need of new experiments at higher frequency bands (e.g. V and W bands), and not only with GEO systems → LEO, MEO satellites
- Many critical aspects to be studied (e.g. depolarization and scintillations at very low elevation angles, rain and cloud attenuation scaling with elevation angle, …)

Conclusions and hints on other topics

Conclusions

- Reliable and accurate prediction of atmospheric channel modeling is more and more required by the current evolution of Earth-space communication systems
- Research efforts should shift more and more from empirical to physically-based models to enhance modeling accuracy, applicability and reliability
- Models allowing predictions also on seasonal/monthly basis will provided additional useful information to characterize the atmospheric channel
- Global Numerical Weather Predictions are gaining more and more a key role in atmospheric channel modeling thanks to the constant increase in their accuracy, availability and space-time resolution
- Propagation experiments, especially in developing Countries and also with non-GEO systems, remain a key resource for the progress of atmospheric channel modeling

Other topics

- Models and data for the operation of reconfigurable systems
- Free Space Optics for Earth-space links and associated modeling challenges
- The importance of accurate frequency scaling models for predictions in very high bands (W band)

References

[1] Recommendation ITU-R P.618-12, “Propagation data and prediction methods required for the design of Earth-space telecommunication systems”, Geneva, 2015.

[2] L. Luini, C. Capsoni, “MultiEXCELL: a new rain field model for propagation applications”, IEEE Transactions on Antennas and Propagation, vol. 59, no. 11, Page(s): 4286 - 4300, November 2011.

[3] L. Luini, C. Capsoni, “Modeling High Resolution 3-D Cloud Fields for Earth-space Communication Systems”, IEEE Transactions on Antennas and Propagation, vol. 62, no. 10, Page(s): 5190 - 5199, October 2014.

[4] L. Luini, “Modeling and Synthesis of 3-D Water Vapor Fields for EM Wave Propagation Applications”, IEEE Transactions on Antennas and Propagation, vol. 64, no. 9, Page(s): 3972 - 3980, September 2016.

[5] C. Capsoni, L. Luini, “The SC EXCELL Model for the Prediction of Monthly Rain Attenuation Statistics”, pp. 1382-1385, EuCAP 2013, 8-12 April 2013, Goteborg, Sweden.

[6] L. Luini, L. Emiliani, C. Capsoni, “Worst-Month Tropospheric Attenuation Prediction: Application of a New Approach”, EuCAP 2016, 10-15 April 2016, pp. 1-5, Davos, Switzerland.

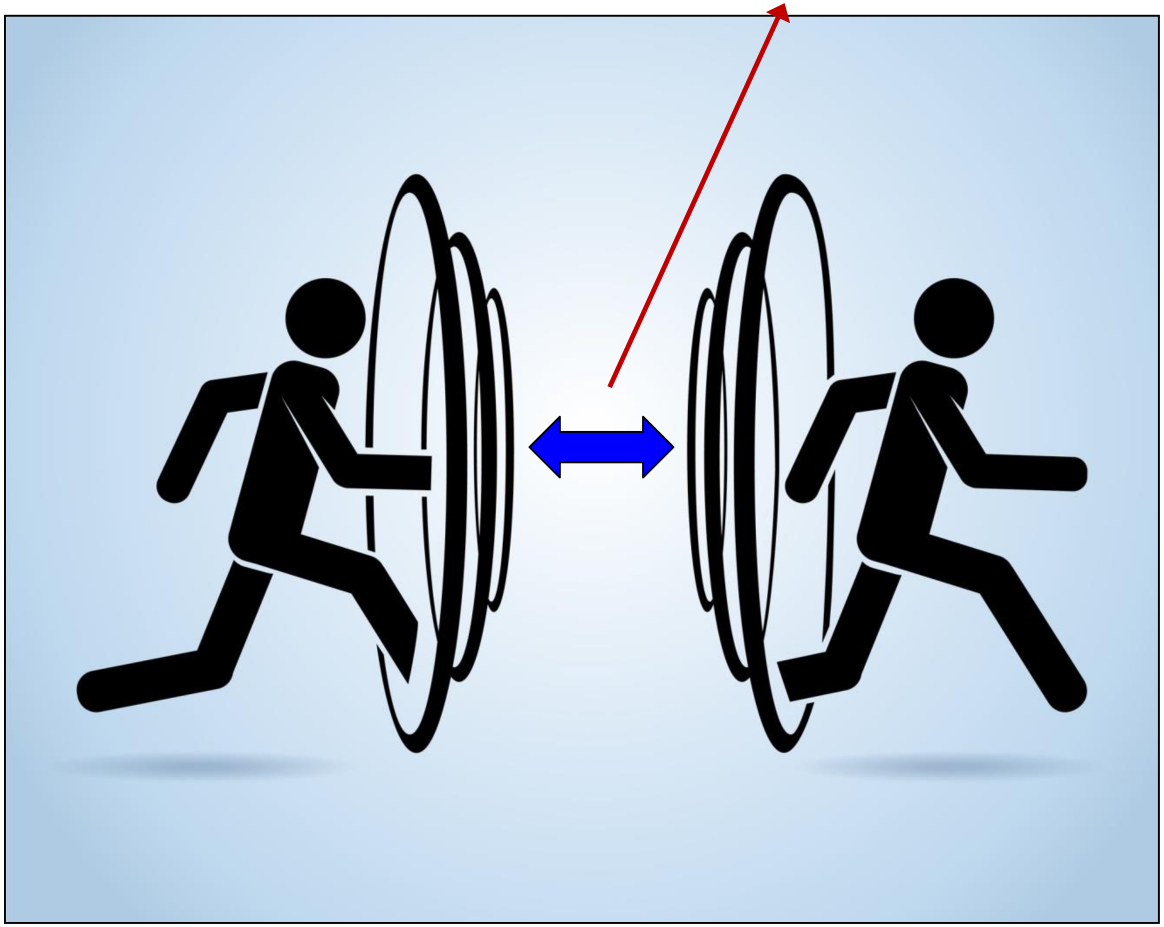
[7] E. Salonen and S. Uppala, “New prediction method of cloud attenuation”, Electron. Lett., vol. 27, no. 12, pp. 1106–1108, Jun. 1991.

[8] H. J. Liebe, G. A. Hufford, andM.G. Cotton, “Propagationmodeling of moist air and suspended water/ice particles at frequencies below 1000 GHz,” in Proc. AGARD 52nd Spec. Meeting EM Wave Propag., Palma de Mallorca, Spain, May 17–20, 1993, Paper 3/1-10.

[9] L. Luini, C. Capsoni, “Efficient Calculation of Cloud Attenuation for Earth-space Applications”, IEEE Antennas and Wireless Propagation Letters, vol. 13, Page(s): 1136 - 1139, doi: 10.1109/LAWP.2014.2329953, 2014.

[10] C. Capsoni, L. Luini, “A physically based method for the conversion of rainfall statistics from long to short integration time”, IEEE Transactions on Antennas and Propagation, vol. 57, no. 11, Page(s): 3692 – 3696, November 2009.

Beware of unreliable wireless links!!!



Thank you for your attention. Questions?

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