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Future Satellite TLC systems: the challenge of using very high frequency bands

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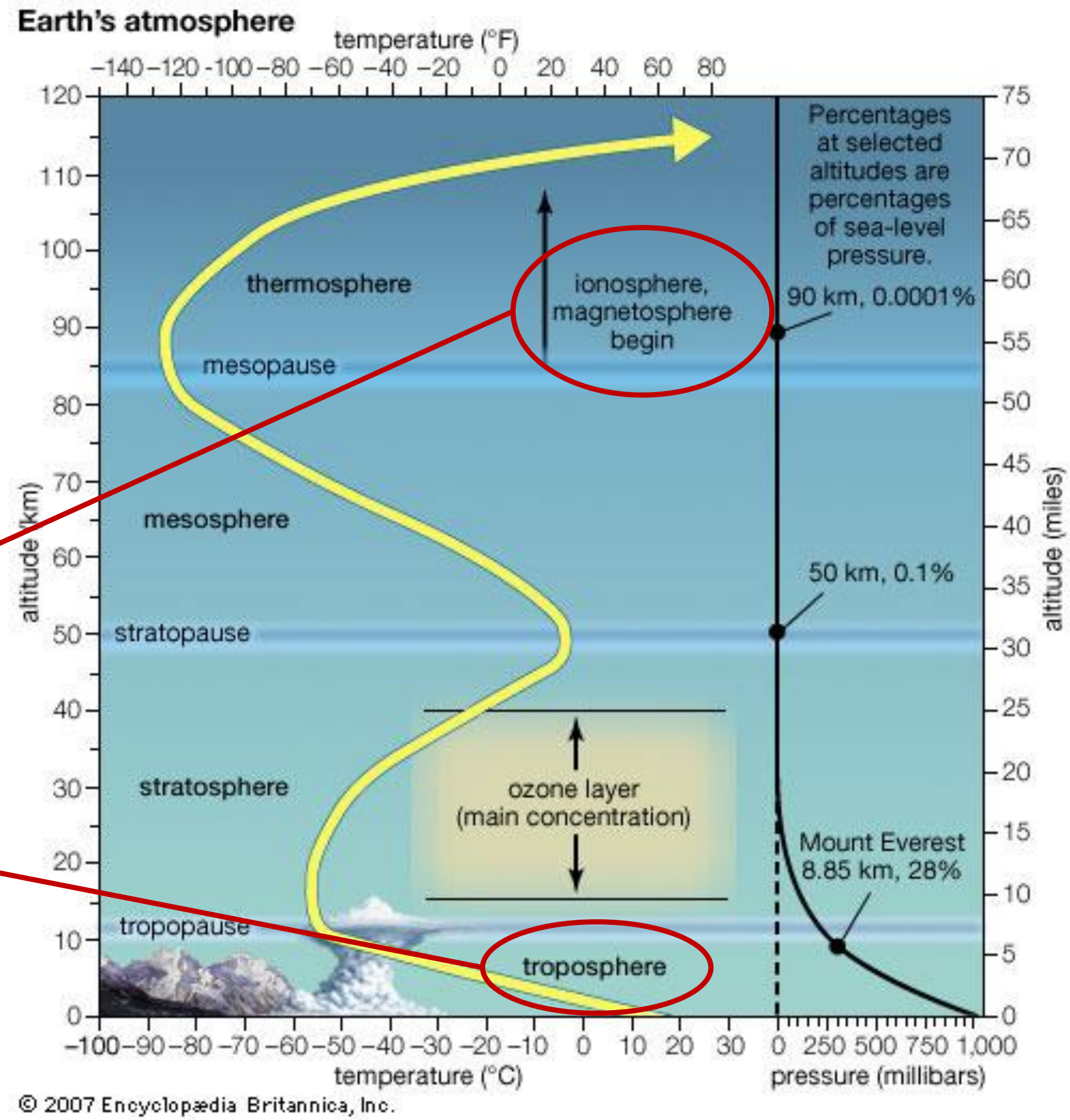
Agenda

- EM wave propagation through the atmosphere
  - ✓ Ionospheric propagation
  - ✓ Tropospheric propagation
- Earth-space communication systems
  - ✓ First satellites
  - ✓ Modern systems
  - ✓ Near future systems
- Design of Earth-space communication systems
  - ✓ EM wave propagation prediction models
  - ✓ The role of Numerical Weather Predictions
  - ✓ EM wave propagation experiments
- Conclusion

EM wave propagation through the atmosphere

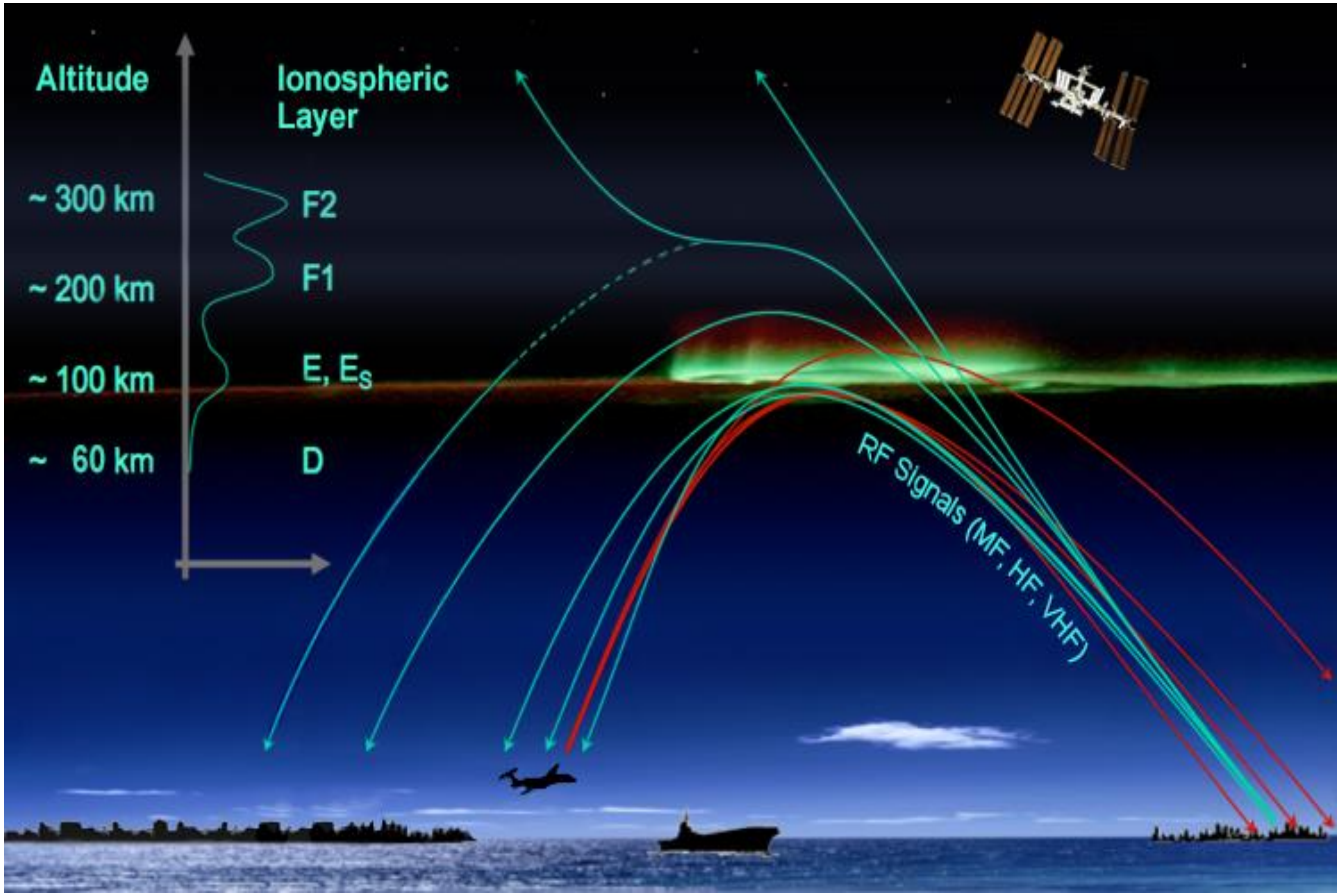
The ionosphere
(≈ 90 km → 450 km)

The troposphere
(≈ ground → 10/15 km)



Atmospheric propagation: the ionosphere

- Ionosphere: free to move charges → plasma medium
- Strong interaction with EM waves
- For *f* < 100 MHz (approx.) → EM wave likely to be totally reflected
- For *f* > 100 MHz, the main effect is signal delay (mostly affecting global navigation satellite systems – GNSS)



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Earth-space communication systems operating at frequencies higher than 1 GHz

Atmospheric propagation: the troposphere

Troposphere:
- The layer where weather events take place

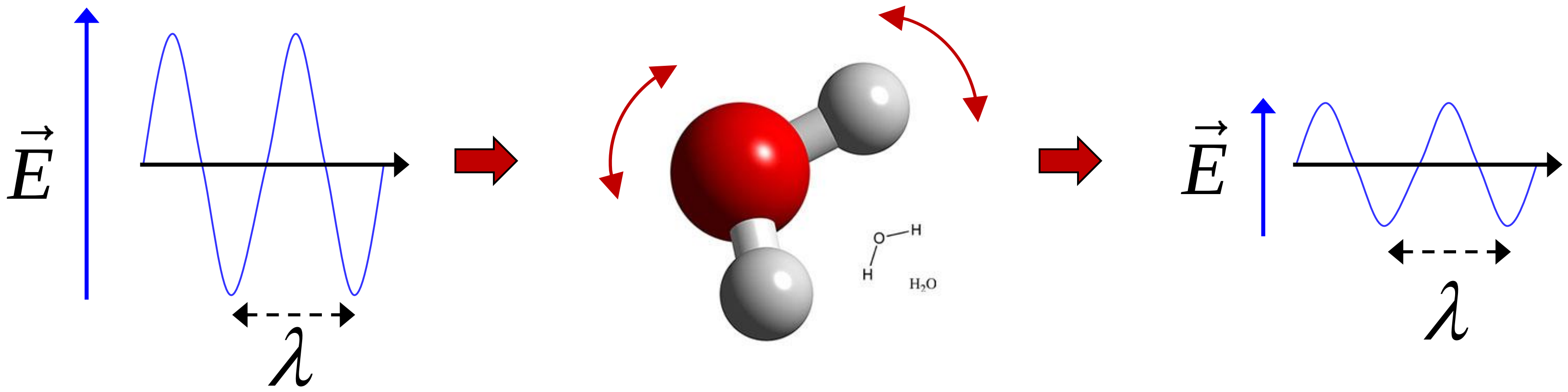
Constituents affecting EM waves:
- Gases
- Clouds
- Hydrometeors

Effects on EM waves:
- Refraction
- Scintillations due to turbulence
- Absorption
- Scattering
- Depolarization
- Noise

Tropospheric effects on EM waves

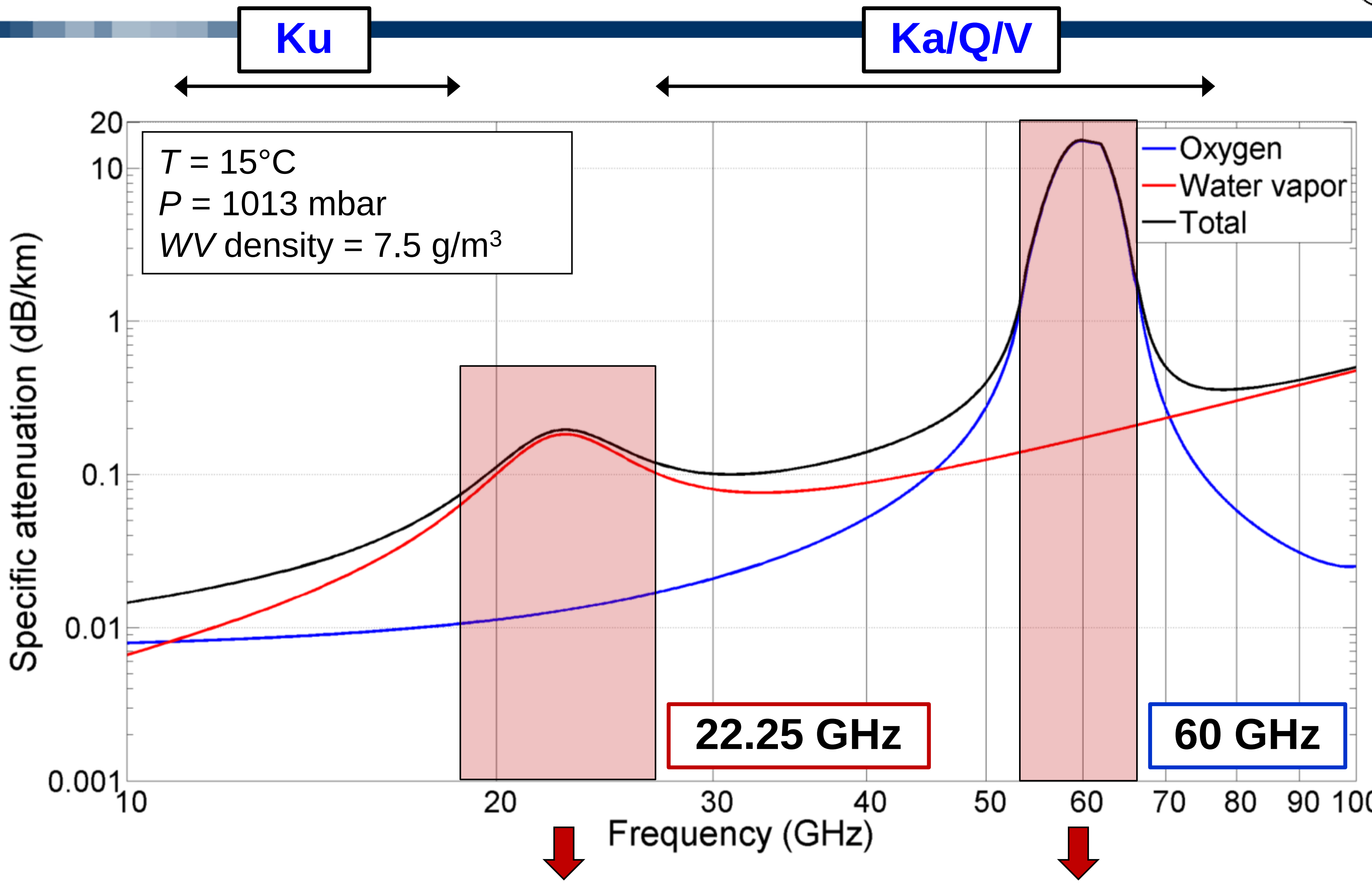
Signal fades caused by atmospheric gases (1–100 GHz)

- Gaseous components affecting EM propagation in this frequency range → oxygen and water vapor
- Absorption → due to the rotation of oxygen (magnetic dipole) and water vapor (electric dipole) molecules induced by EM waves



- Significant absorption levels only around specific frequencies → resonance
- Oxygen and water vapor absorption depends on temperature, pressure and relative humidity
- Both always present in the atmosphere, but low variability in space and time

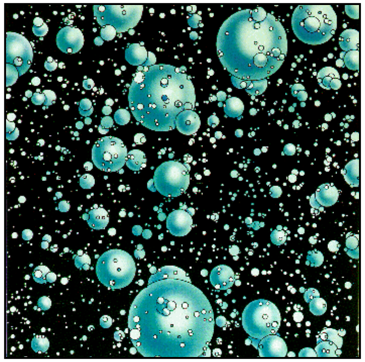
Atmospheric effects on E.M. waves: gaseous absorption



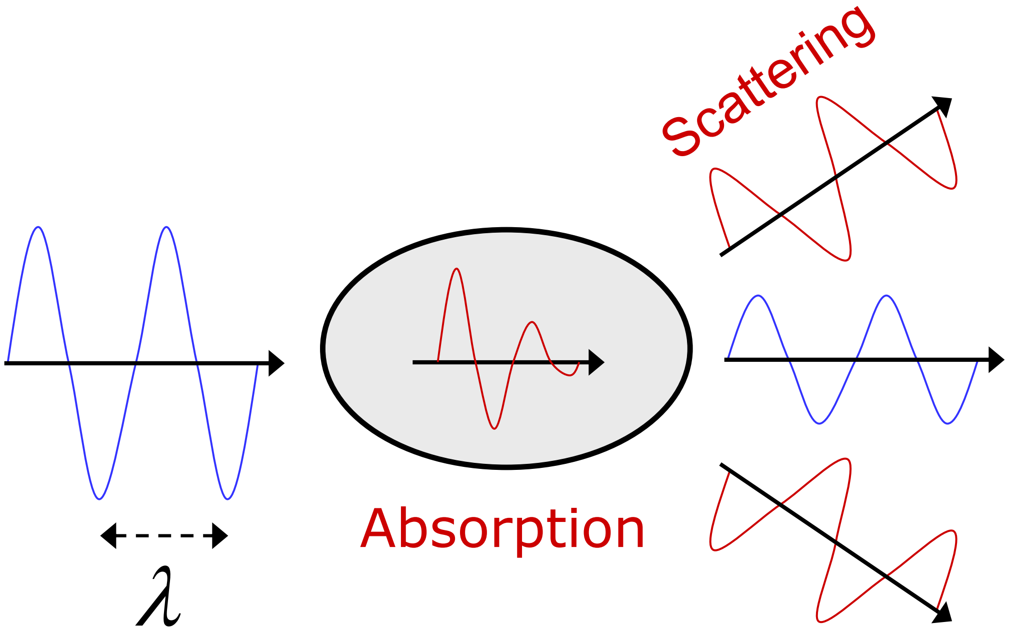
Water vapor absorption peak

Oxygen absorption peak

Effects caused by ice and water particles (rain, clouds, hail, …)



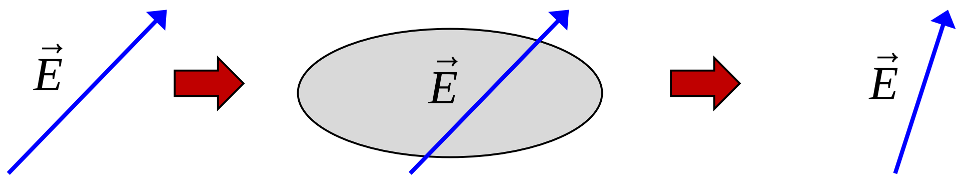
- Signal attenuation → both scattering and absorption due to the ice and water particles
- Effects for $f > 10$ GHz → dimensions of particles (e.g. few mm for rain) comparable with the wavelength
- Different physical mechanism → unlike for gases, induced fade continuously increasing with frequency (10-100 GHz range) and concentration of the particles (e.g. rain rate)
- Different phenomena due to different size, concentration and physical state of the particles
  RAIN → tens of dBs
  CLOUDS → some dBs



Tropospheric effects on EM waves: secondary effects

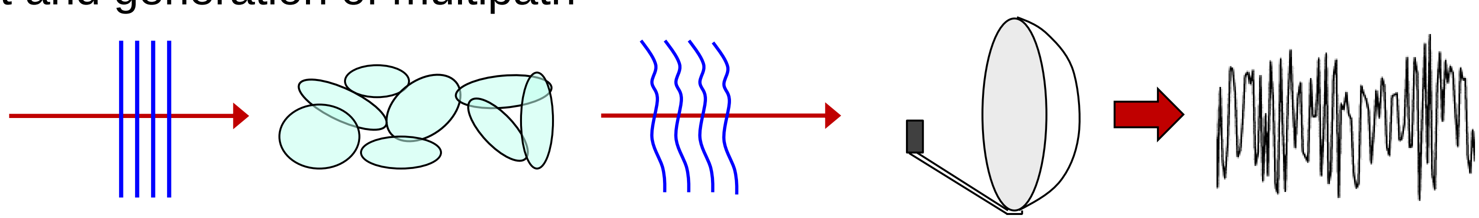
Depolarization

- Change of the wave polarization due to the anisotropic shapes of ice/water particles



Scintillations

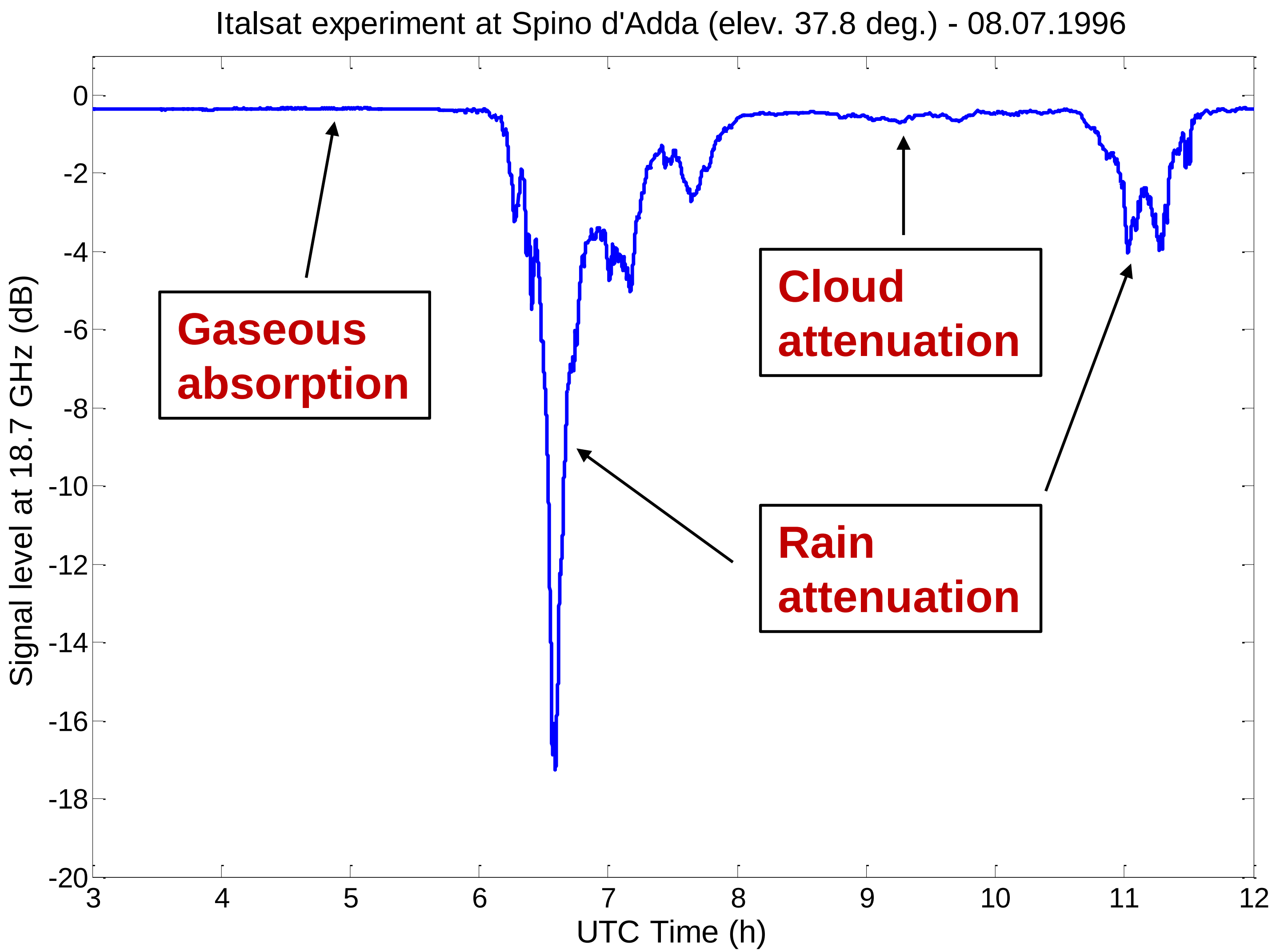
- Very fast oscillations of the received signal due to turbulence in the atmosphere (humidity/temperature variations, clouds, winds, rain drops …) → distortion of the wave front and generation of multipath



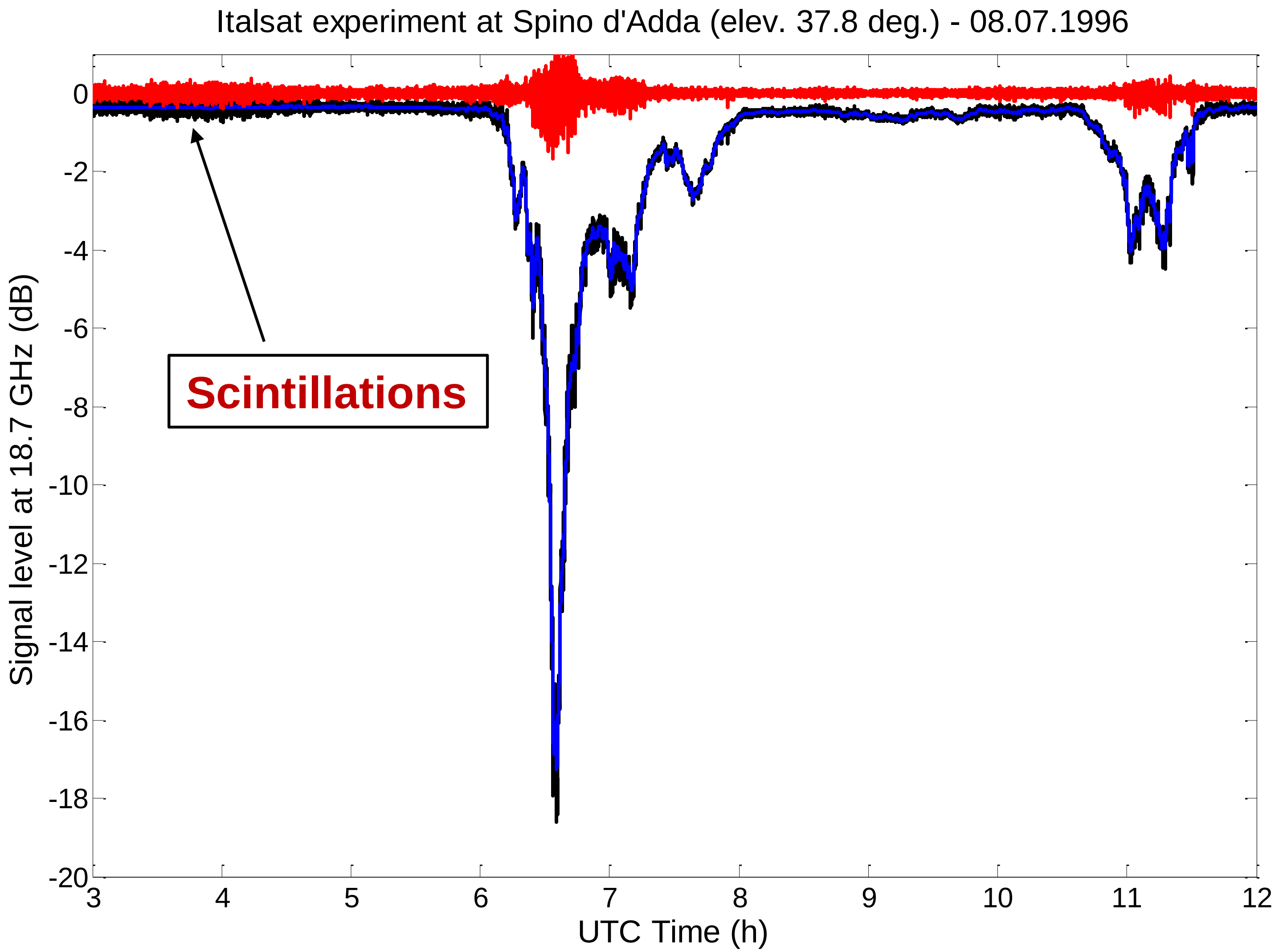
Snow/ice particles

- Negligible attenuation up to 100 GHz
- Ice particle are anisotropic → depolarization issues (e.g. cirrus clouds)

Beacon signal measurement in Spino d'Adda (Italsat experiment)

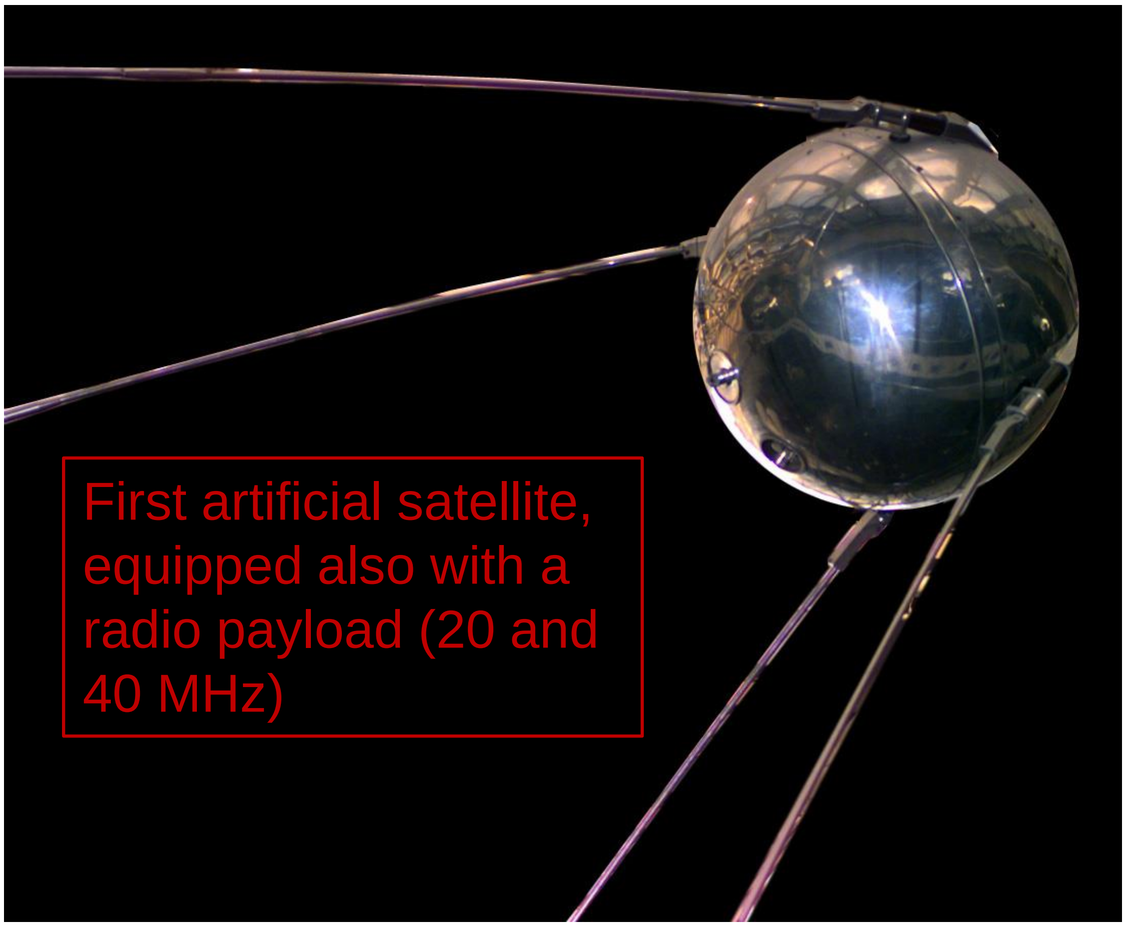


Tropospheric effects on EM waves: measured signal



First artificial satellites

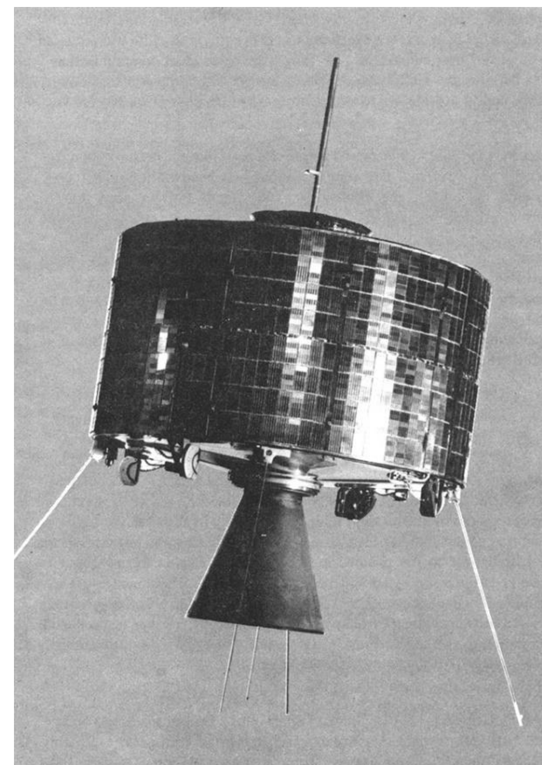
Sputnik 1 – 1957 (Soviet Union)



First artificial satellite, equipped also with a radio payload (20 and 40 MHz)

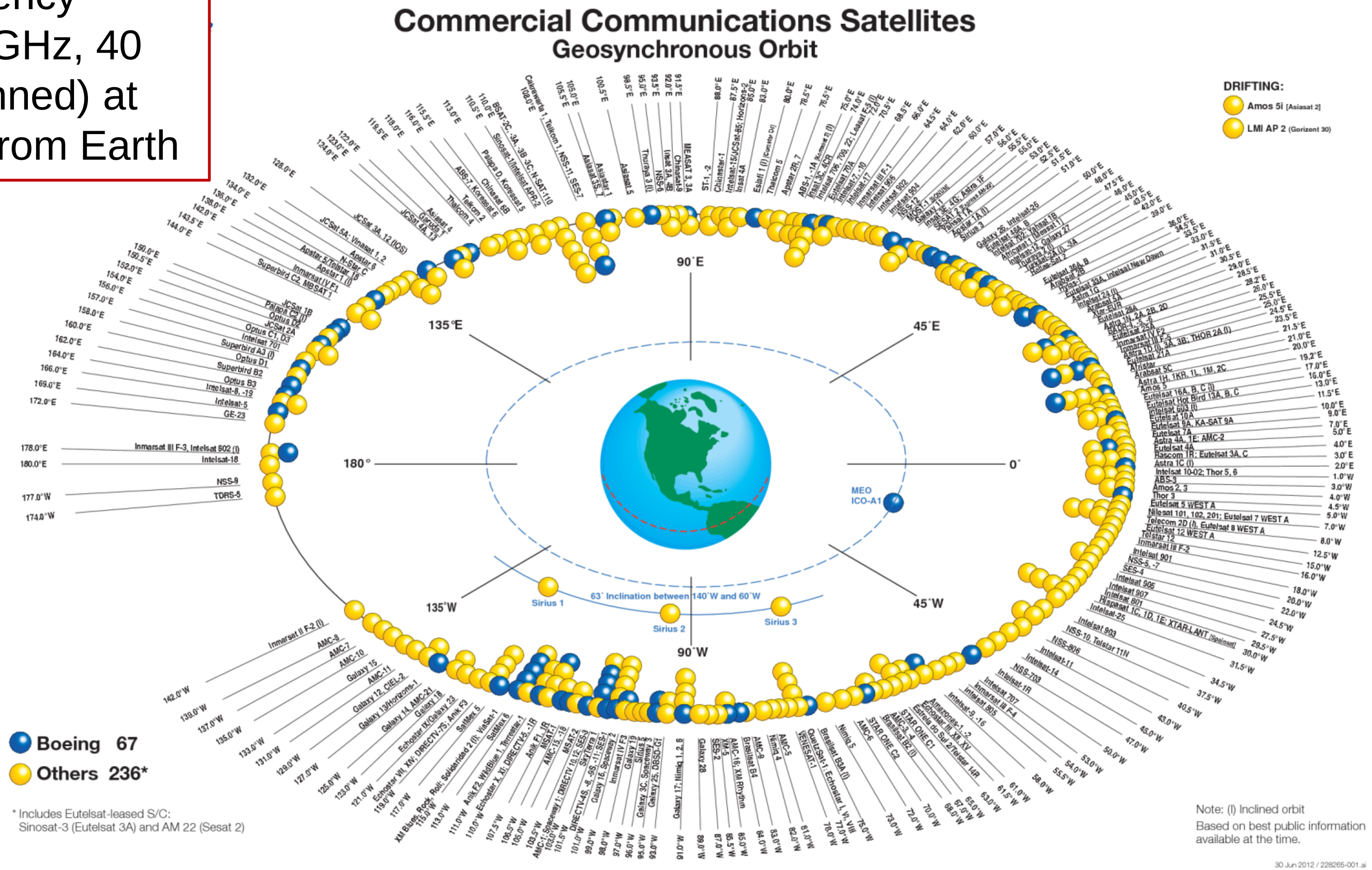
Syncom 3 – 1964 (USA)

First GEO satellite (1.8 and 7.6 GHz)



Many GEO satellites (max frequency around 30 GHz, 40 and 50 planned) at 36000 km from Earth

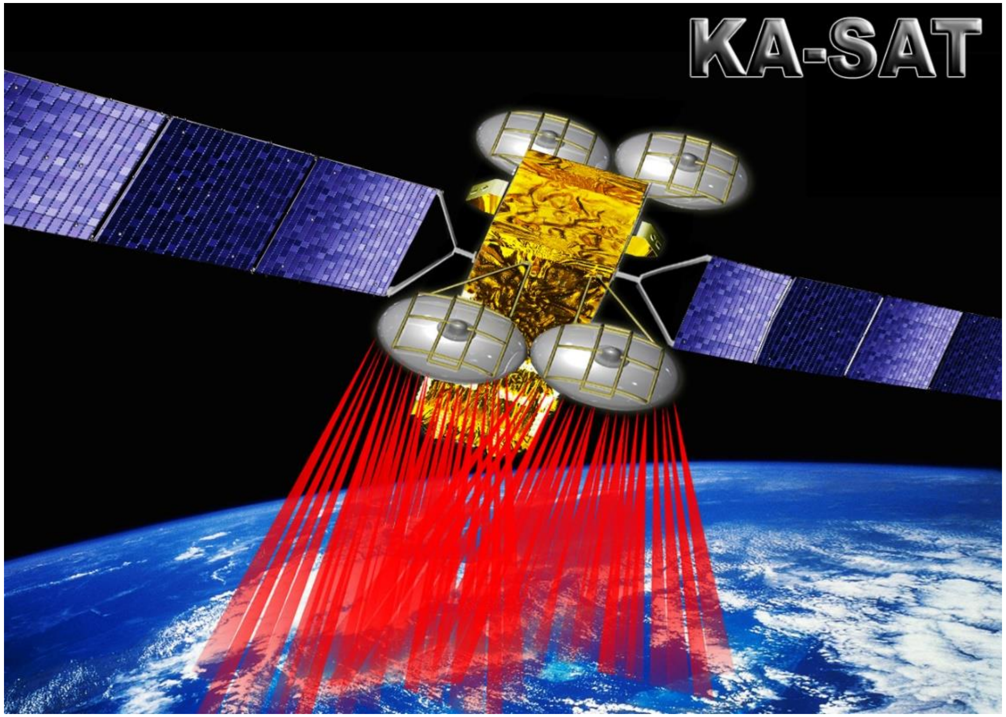
Modern Earth-space systems

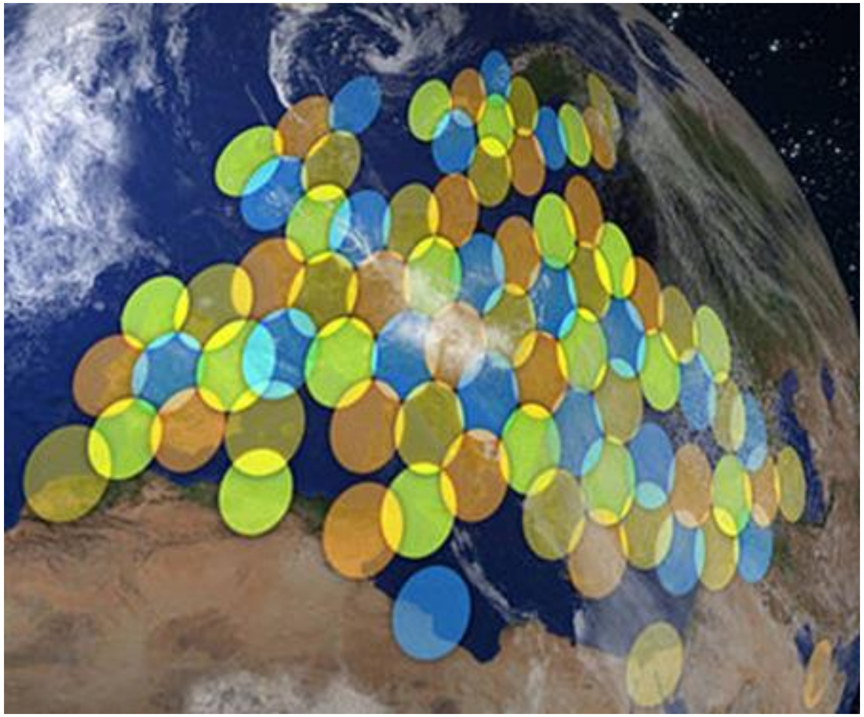


Modern Earth-space systems: GEO satellites

From broadcast to interactive (e.g. Internet via satellite) → KA-SAT by EUTELSAT

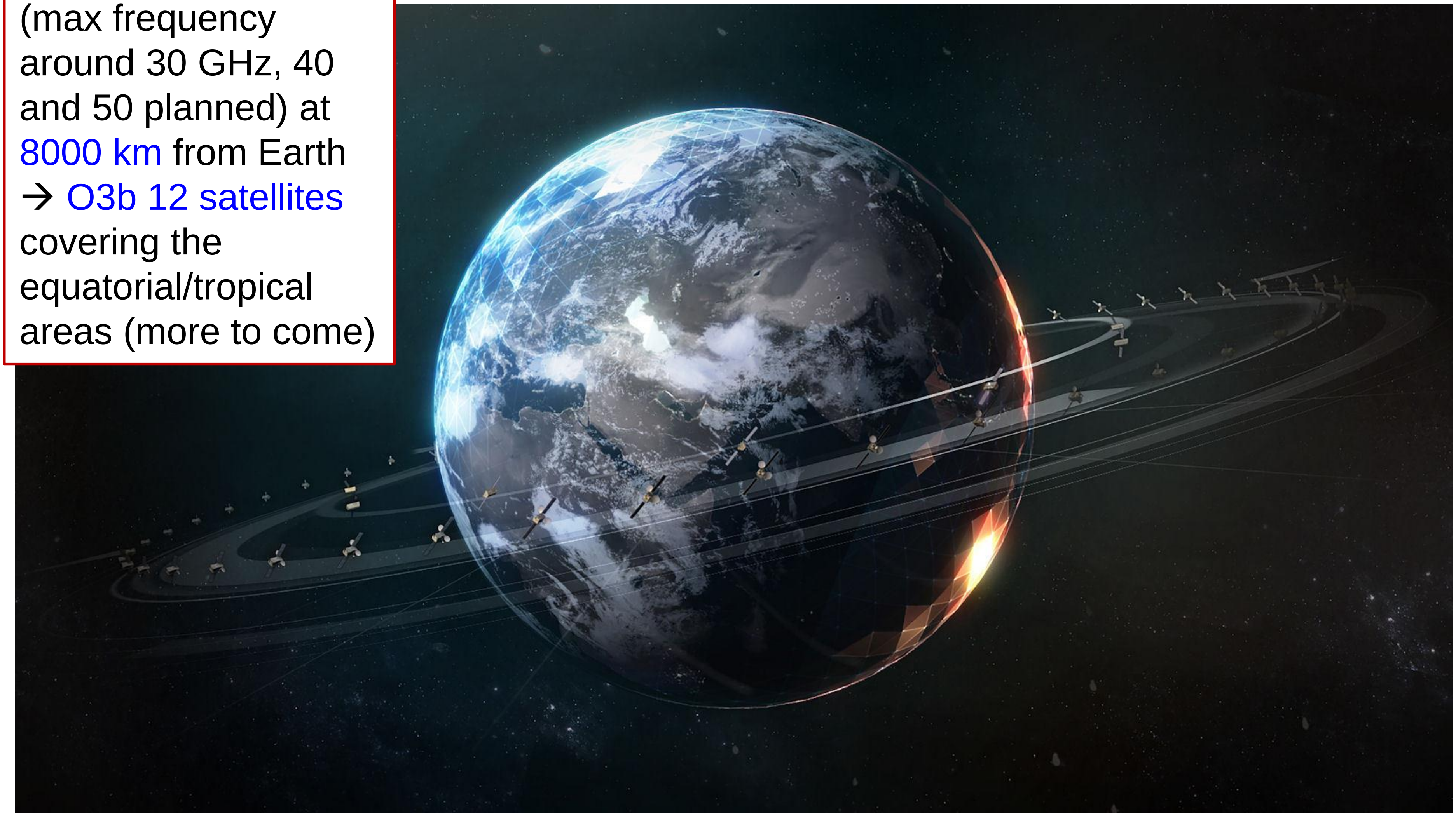
- 82 beams covering the whole Europe
- Spots are arranged so as to reuse frequency channels (3 color scheme → increase capacity)
- Dual polarization system
- Total capacity → 70 Gbps (up to 475 Mbps per beam in 250 MHz bandwidth)





Modern Earth-space systems: MEO satellites

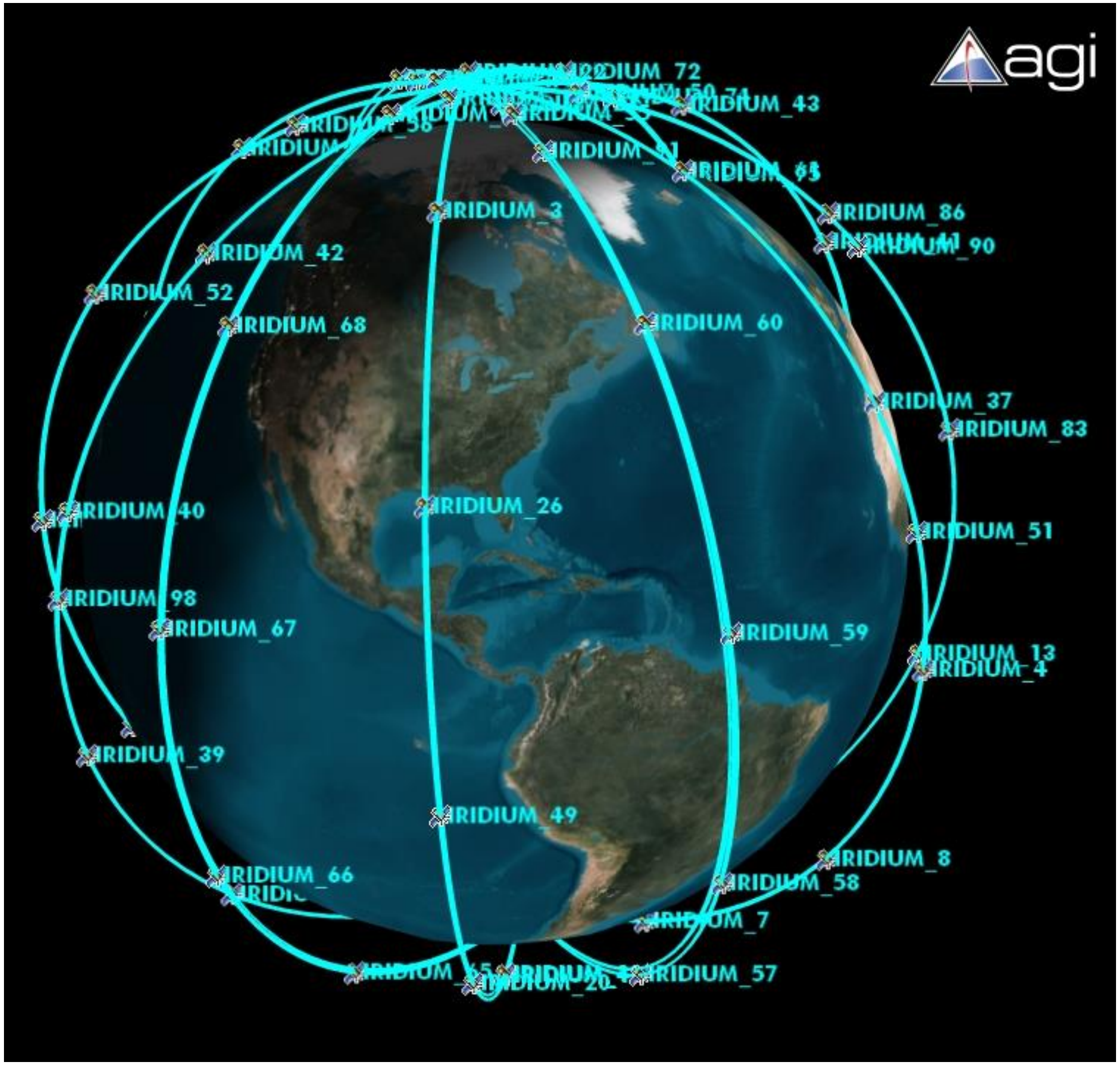
Some MEO satellites (max frequency around 30 GHz, 40 and 50 planned) at 8000 km from Earth → O3b 12 satellites covering the equatorial/tropical areas (more to come)



Modern Earth-space systems: LEO satellites

- LEO satellites (e.g. 160-2000 km) from Earth → Iridium constellation (95) already in place for communication (satellite telephone) and upgrade expected soon

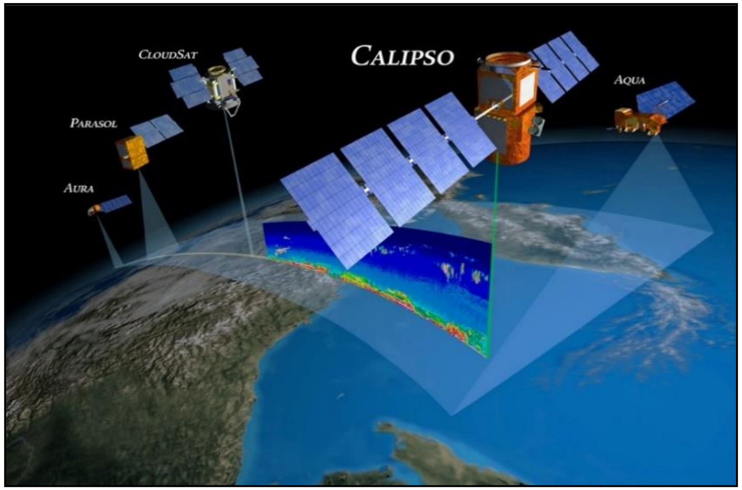
- SpaceX and OneWeb to implement global broadband internet connectivity using other LEO constellations



Modern Earth-space systems: EO and deep space

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 (below 10 GHz) to Ka band (20/30 GHz)



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
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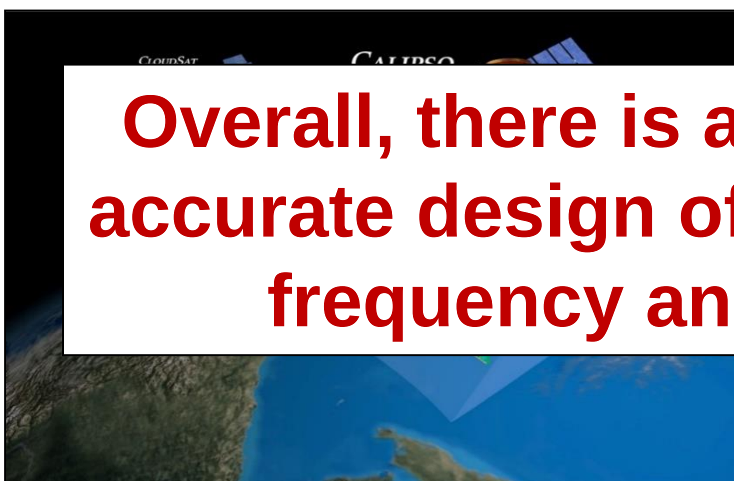

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Overall, there is a need for more and more accurate design of Earth-space links at high frequency and with high reliability

Reliable and accurate Earth-space link design: 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 [1] → 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

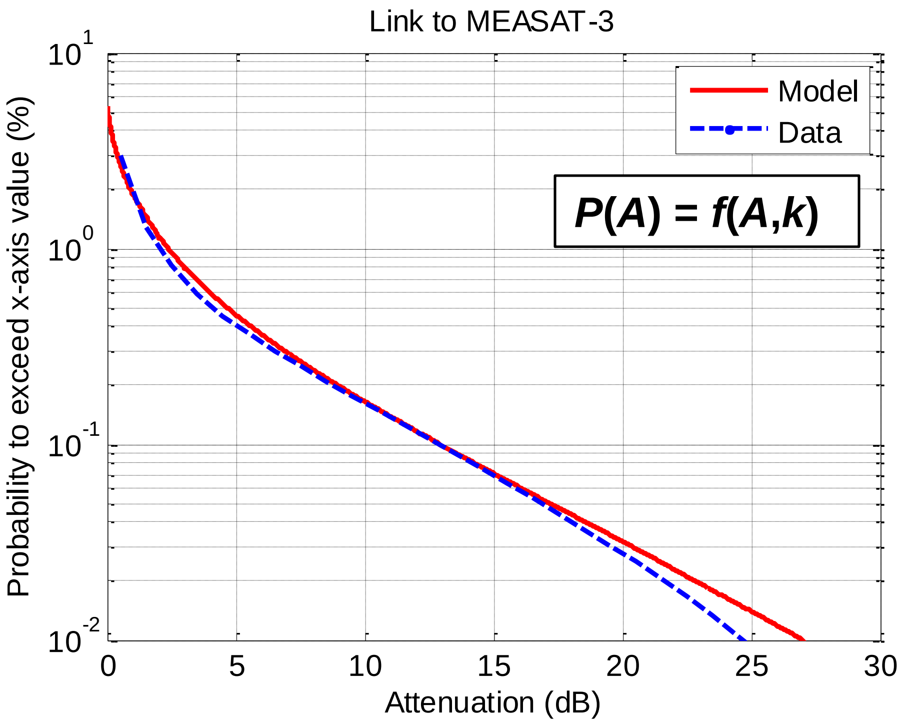
Physically-based models → exploit global data to develop models that have a sound physical basis:

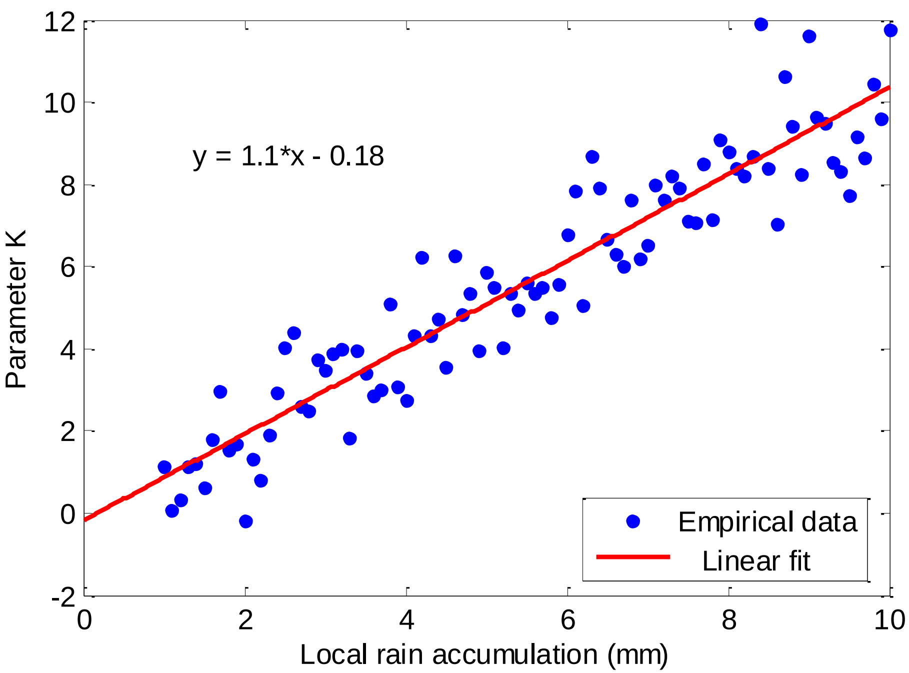
- Advantages: global, valid for extended ranges of the input values, flexible applicability (different scenarios and different output quantities)
- Disadvantages: more complex to develop, implement and apply, higher computation time

Models: from empirical to physically-based

Empirical models

- Typical approach: definition of simple models based on local data
- Well-established models available but with clear limitations: accuracy, reliability (based on available data) and applicability (e.g. complex systems with more stations)

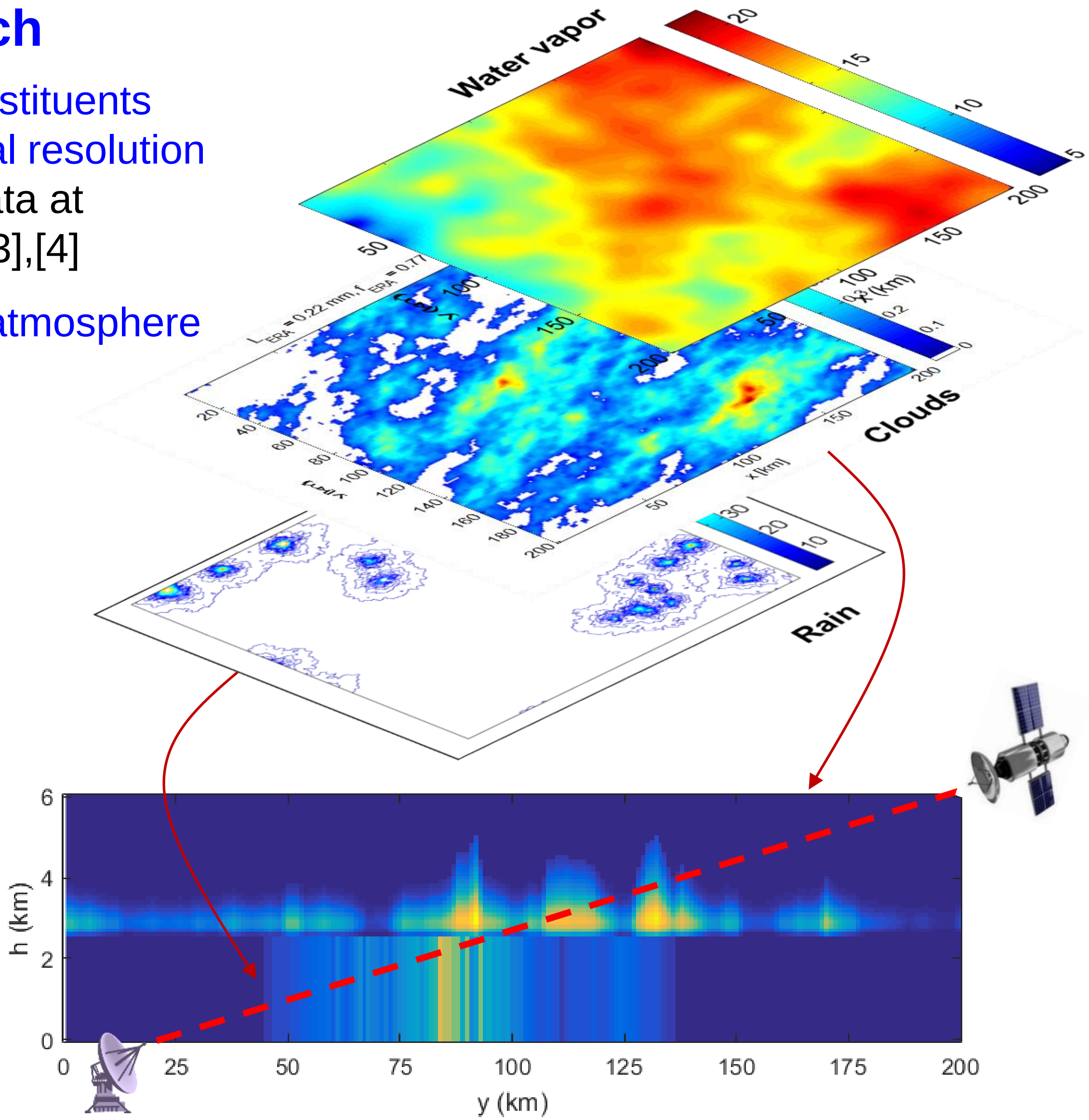




Models: from empirical to physically-based

Physically-based approach

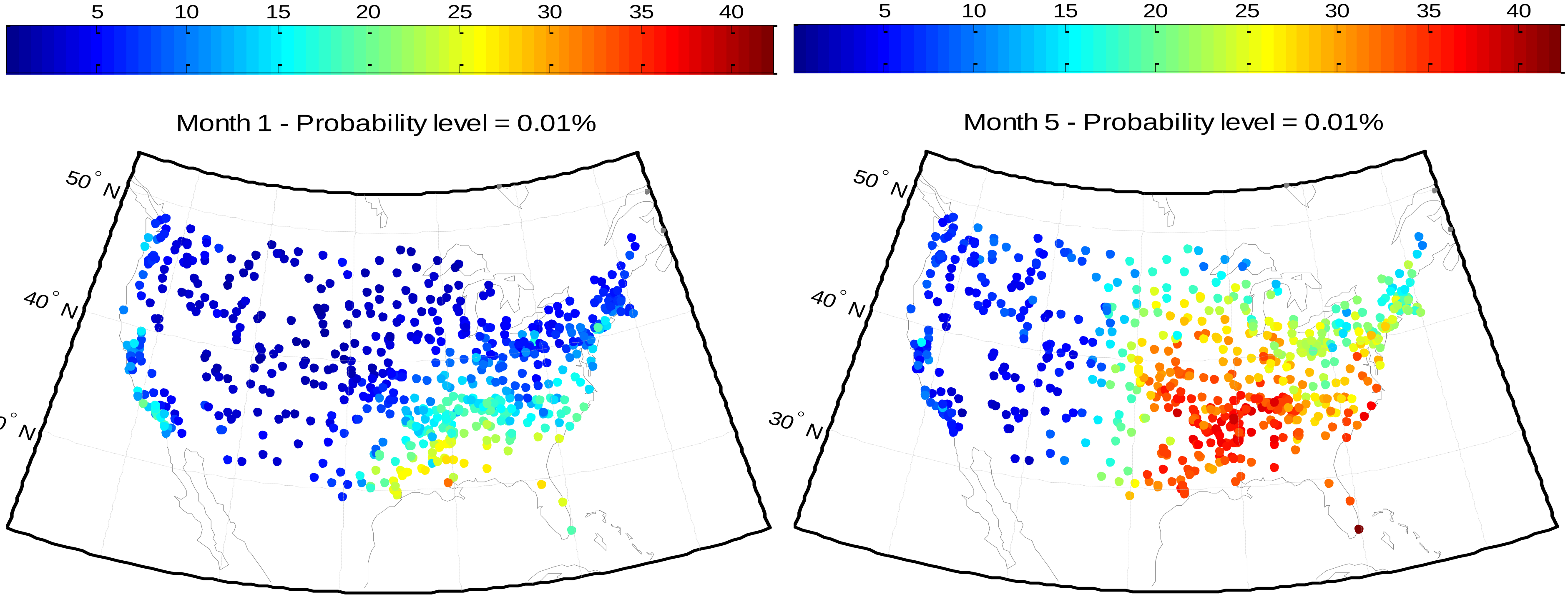
- Example: synthesize atmospheric constituents that impair EM waves, with high spatial resolution (both time and space) starting from data at coarser resolution (e.g. ECMWF) [2],[3],[4]
- Simulate the interaction between the atmosphere and any wireless system
- Main advantages:
  - ✓ Any geometrical/electrical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



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?

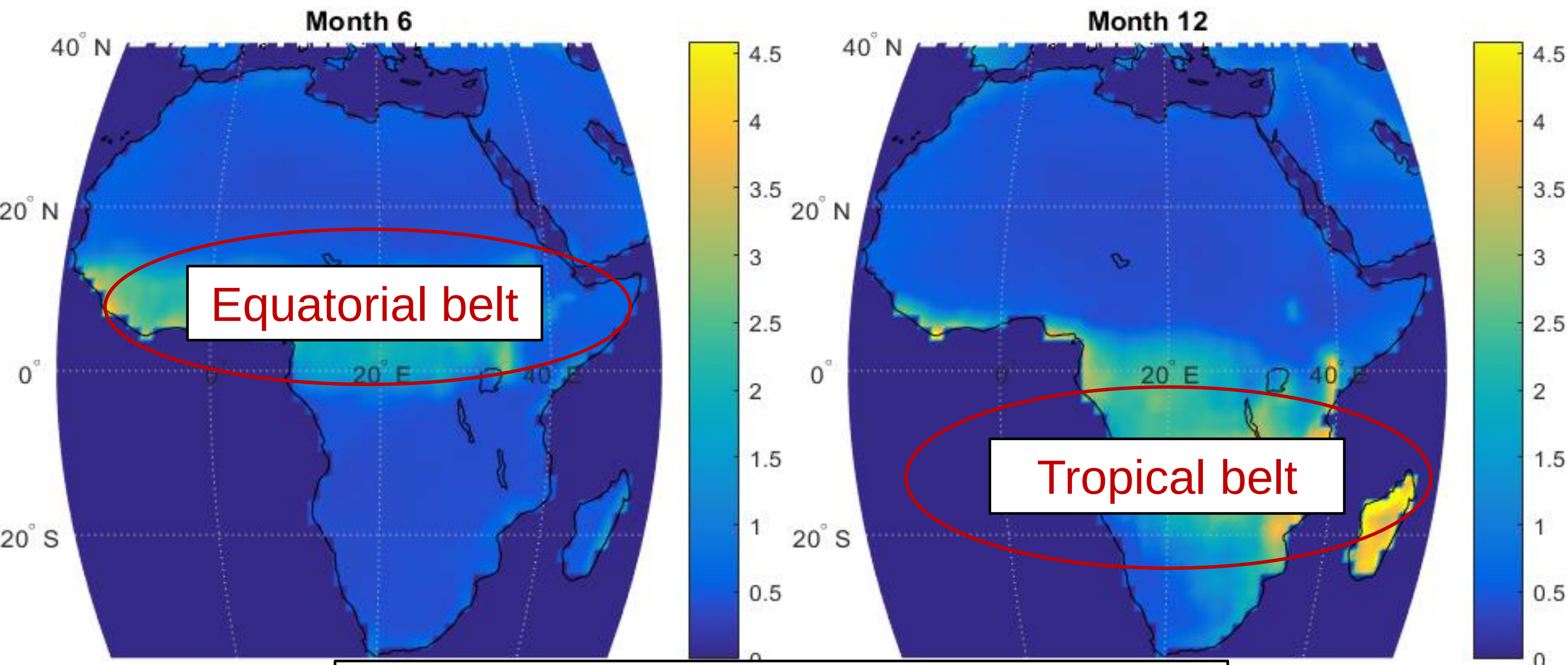
f = 18.5 GHz, satellite position = 100° W



Models: from yearly to seasonal/monthly basis

Usefulness of monthly attenuation statistics [5],[6]

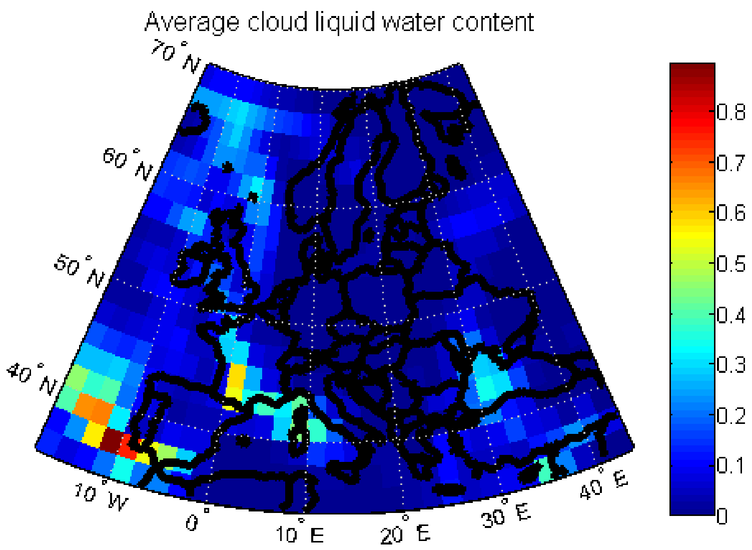
- Overall power available on board can be reallocated unevenly over the region (on monthly/seasonal basis) so as to provide more power where more adverse conditions are expected: save costs in the planning phase and improve system performance in the operative phase

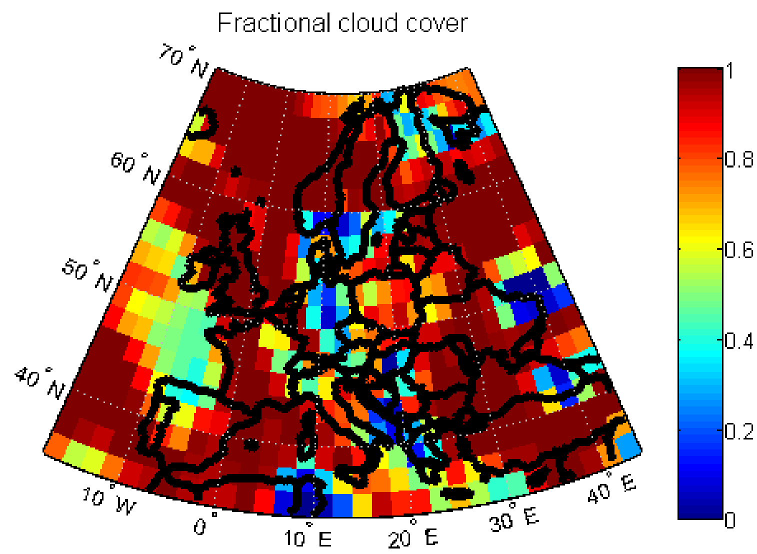


f = 12.1 GHz, satellite position = 19.2° E

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

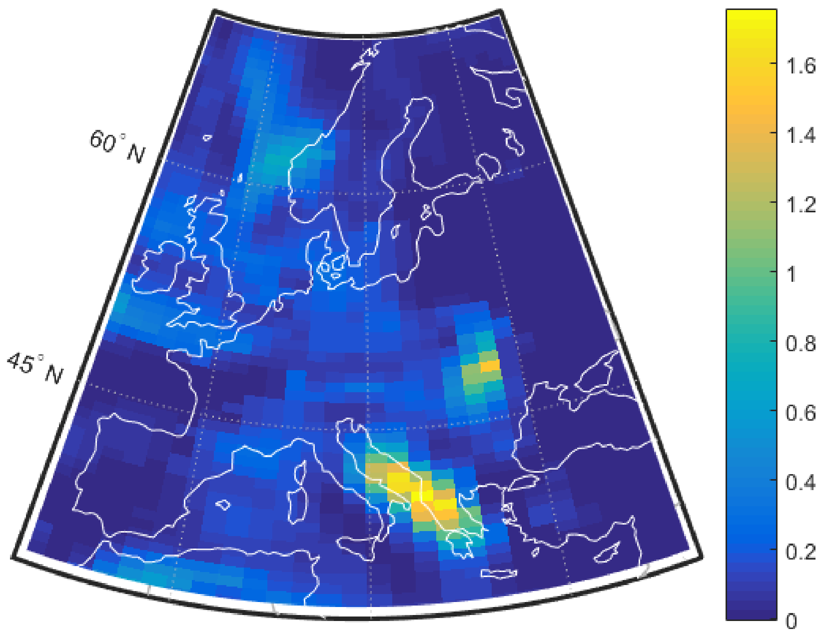
- In the last decade NWP data have been evolving considerably:
  - ✓Accessibility: direct download from websites, such as ECMWF [7] and NOAA
  - ✓Availability: more and more meteorological quantities made available
  - ✓Accuracy: constant improvement of atmospheric models over time
  - ✓Resolution: finer in time, even more, in space

Name	Data period	Temporal resolution	Horizontal resolution	Vertical resolution
ERA-15	1979-1993	6 hours	1.5°×1.5°	31 levels
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
ERA-6 (2020?)	?	?	?	?

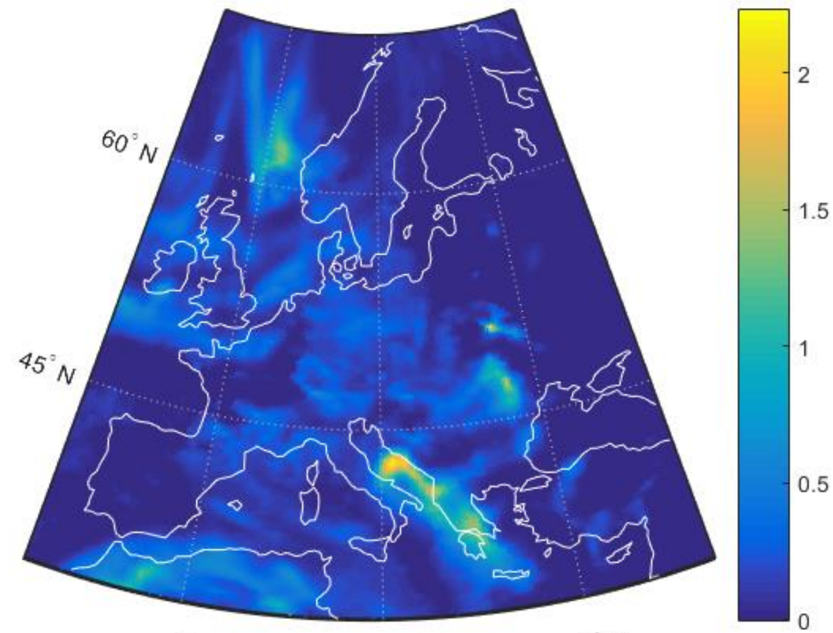
Data: the role of Numerical Weather Predictions

Name	Data period	Temporal resolution	Horizontal resolution	Vertical resolution
Operational	1982-present	1 hour	0.1°×0.1°	137 levels

ERA-40 (1.125°×1.125°)



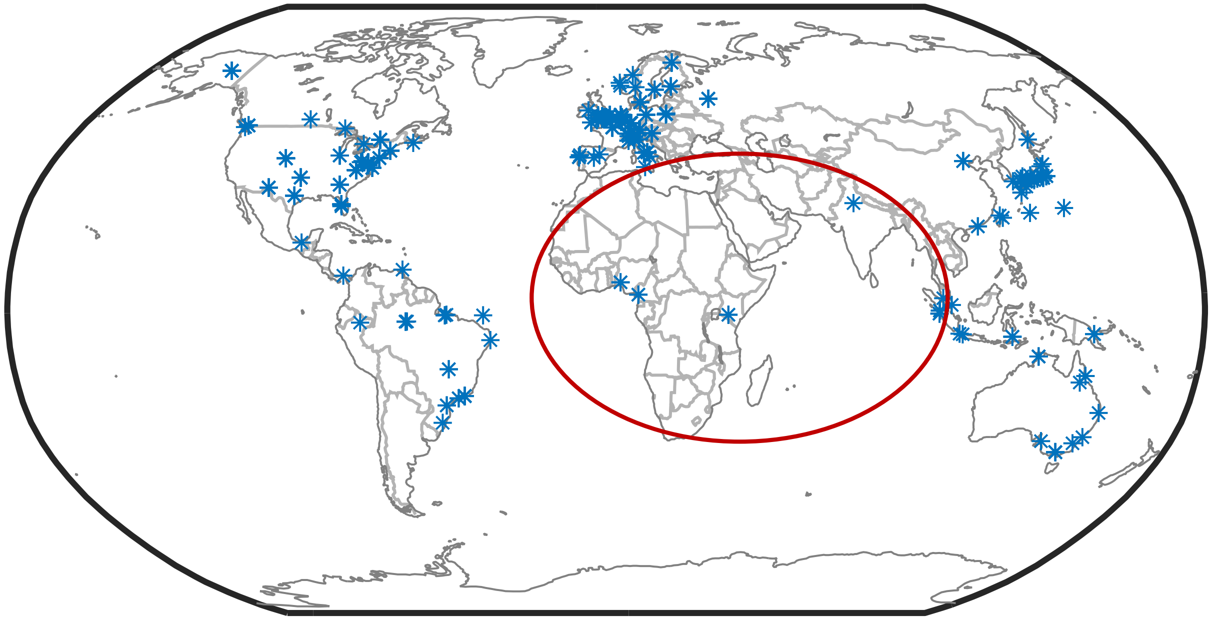
Operational (0.125°×0.125°)



Attenuation due to clouds at 50 GHz [7],[8]

Experiments: always a key resource

- Test of EM wave propagation models → against experimental data collected during propagation campaigns (e.g. Olympus, ACTS, ITALSAT, Alphasat, …)
- Need of more experiments in tropical and equatorial areas, and specifically in some Countries



ITU-R DBSG3 for rain attenuation experiments

- Need of new experiments at higher frequency bands (e.g. beyond 50 GHz), 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 provide 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.

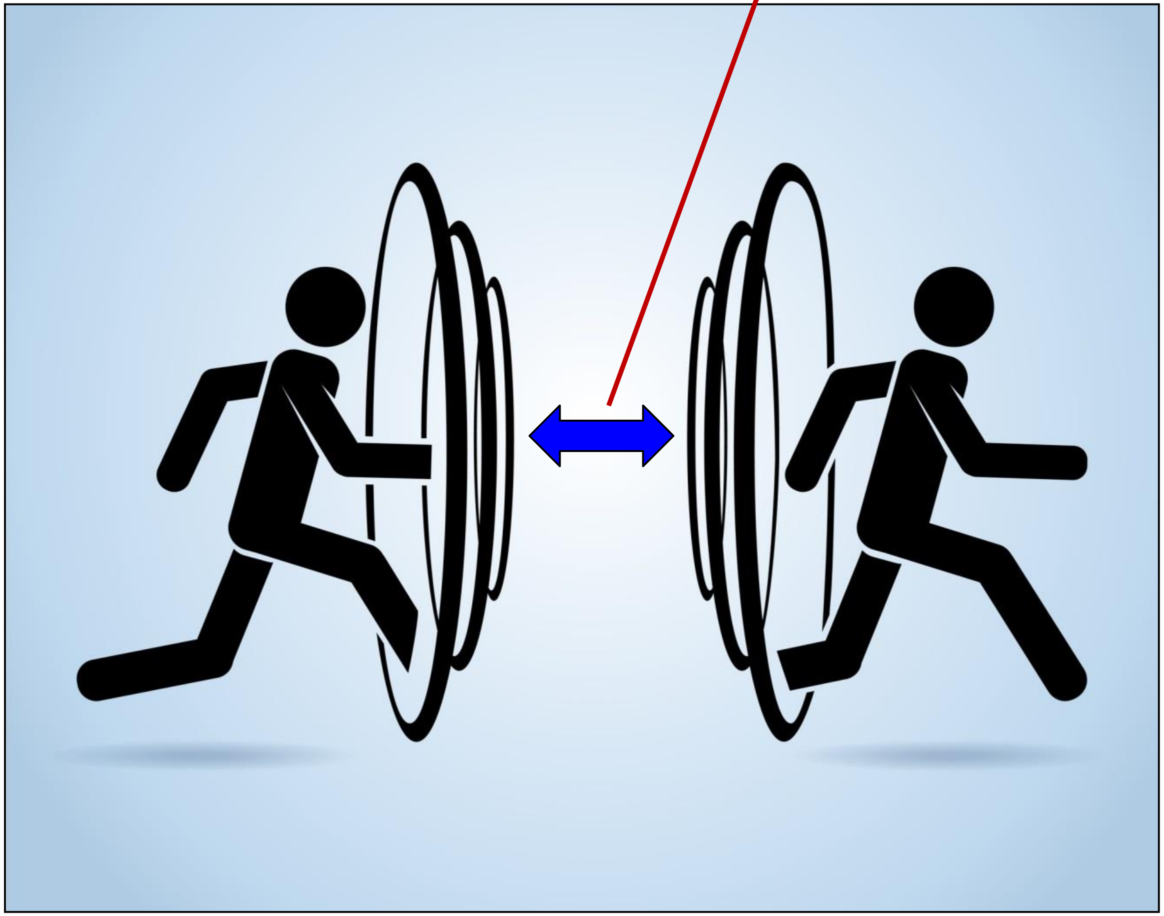
[5] C. Capsoni, L. Luini, “The SC EXCELL Model for the Prediction of Monthly Rain Attenuation Statistics”, pp. 1382-1385, EuCAP 2013, 8-12 April 2013, Goteborg, Sweden.

[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] www.ecmwf.int

[8] 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, 2014.

Beware of unreliable wireless links!



Thank you for your attention. Questions?

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