Autonomous Profiling Radiometer

BOULDER ENVIRONMENTAL SCIENCES & TECHNOLOGY

Marian Klein
marian.klein@boulderest.com
+1 303 532-1198, x111
www.boulderest.com

Robust & Autonomous – APR – TRL 5-6

Continuously scanning radiometer

Rate of scanning is 120 rpm, or 2 rps

Sampling at Nyquist rate

Motion power is less than 30 Watts

Two radiometers 18-27 and 50-75 GHz

Dual polarization observations

4 receivers + data acquisition + motion=~100 W

Many more radiometric bands can be added

The enclosure is sealed, IP67

Precipitation protection & observation

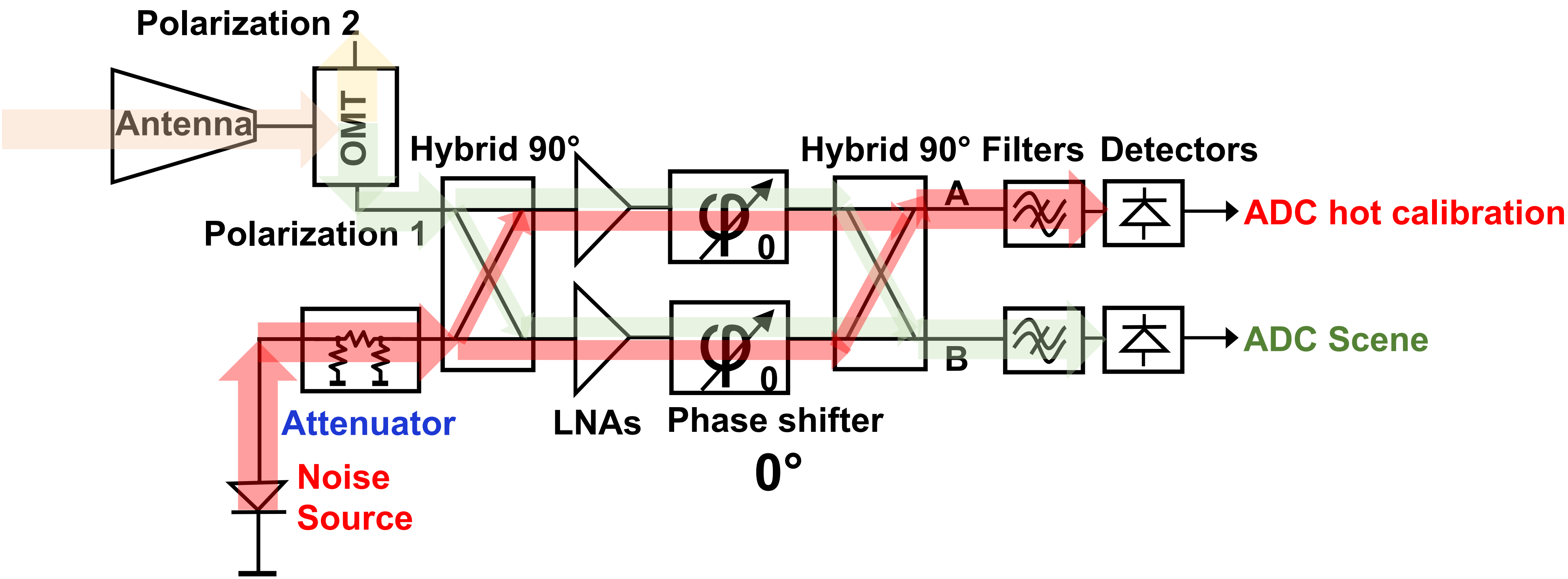
Autonomous calibration

No LN2 targets are needed

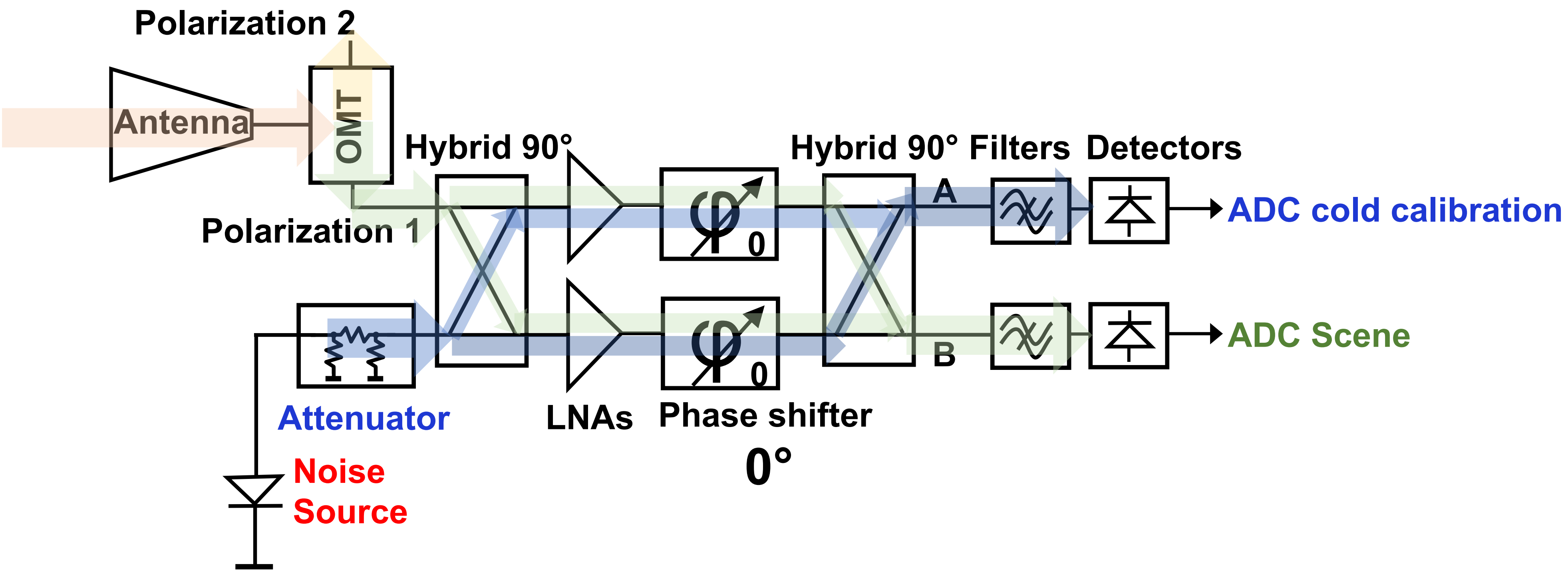
No thermal stabilization, no platform stabilization

Pending US Patent, No: 2022/0205930 A1

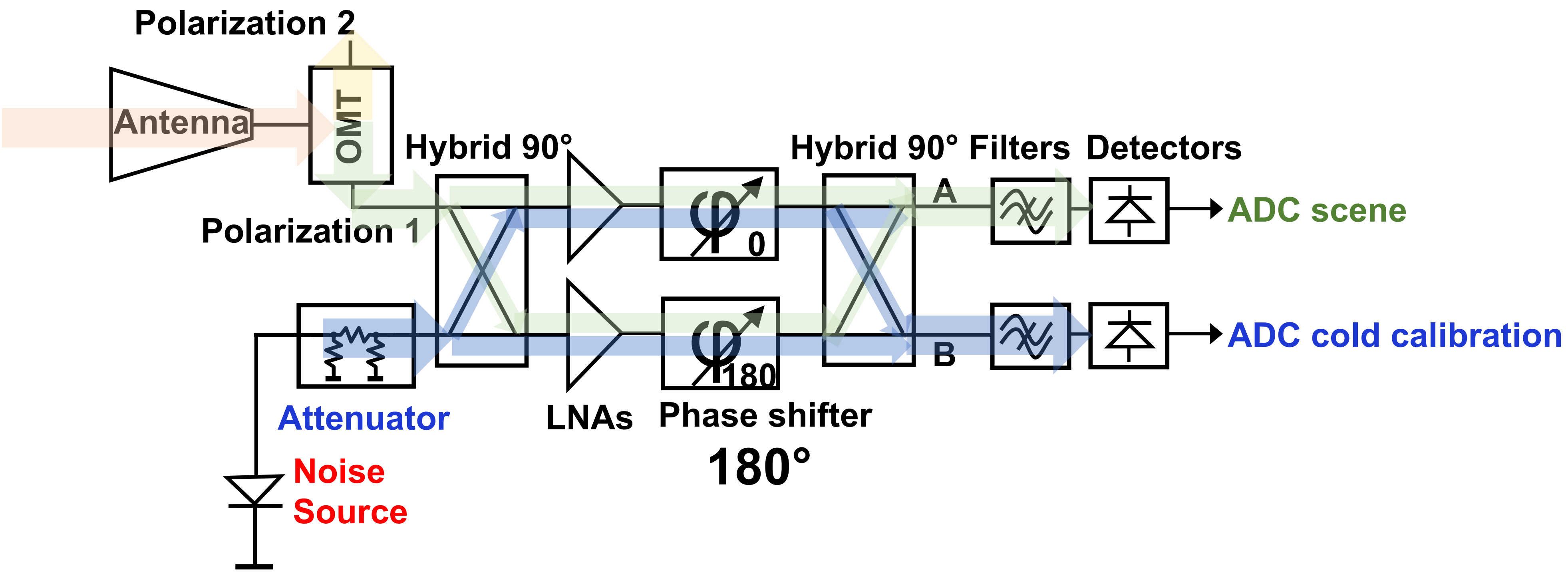
Direct Detection Pseudo Correlation Radiometer



Direct Detection Pseudo Correlation Radiometer

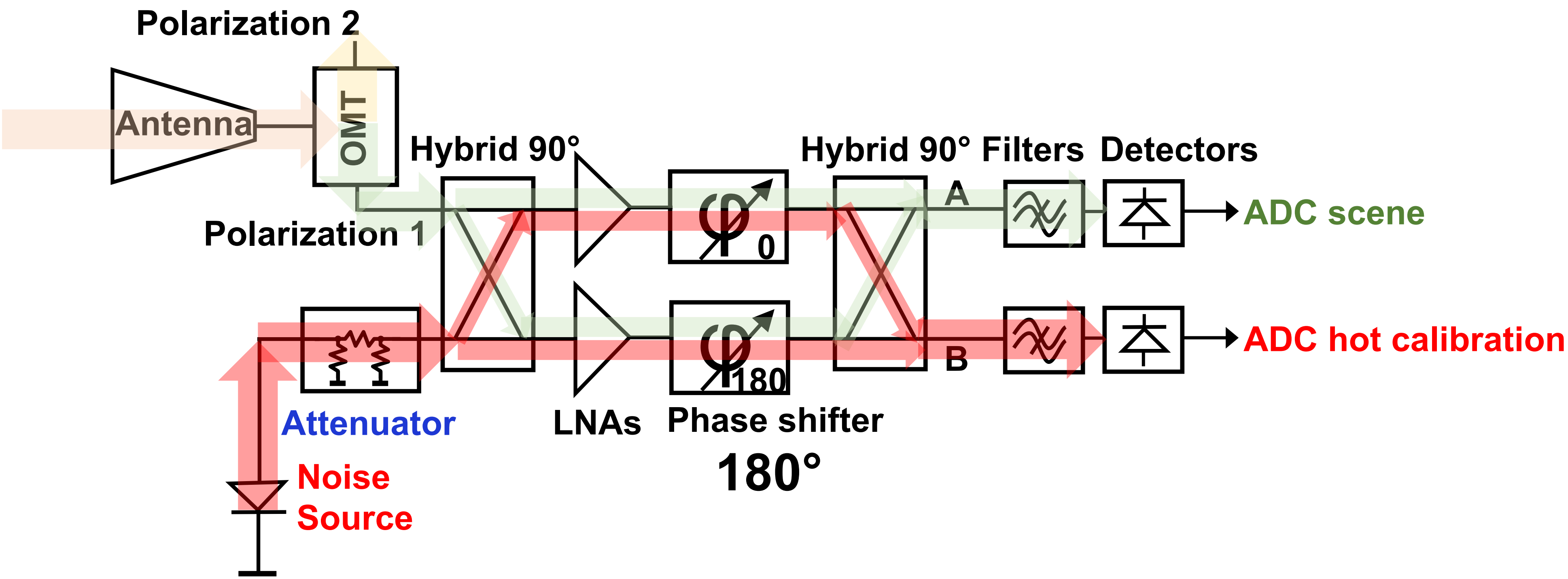


Direct Detection Pseudo Correlation Radiometer

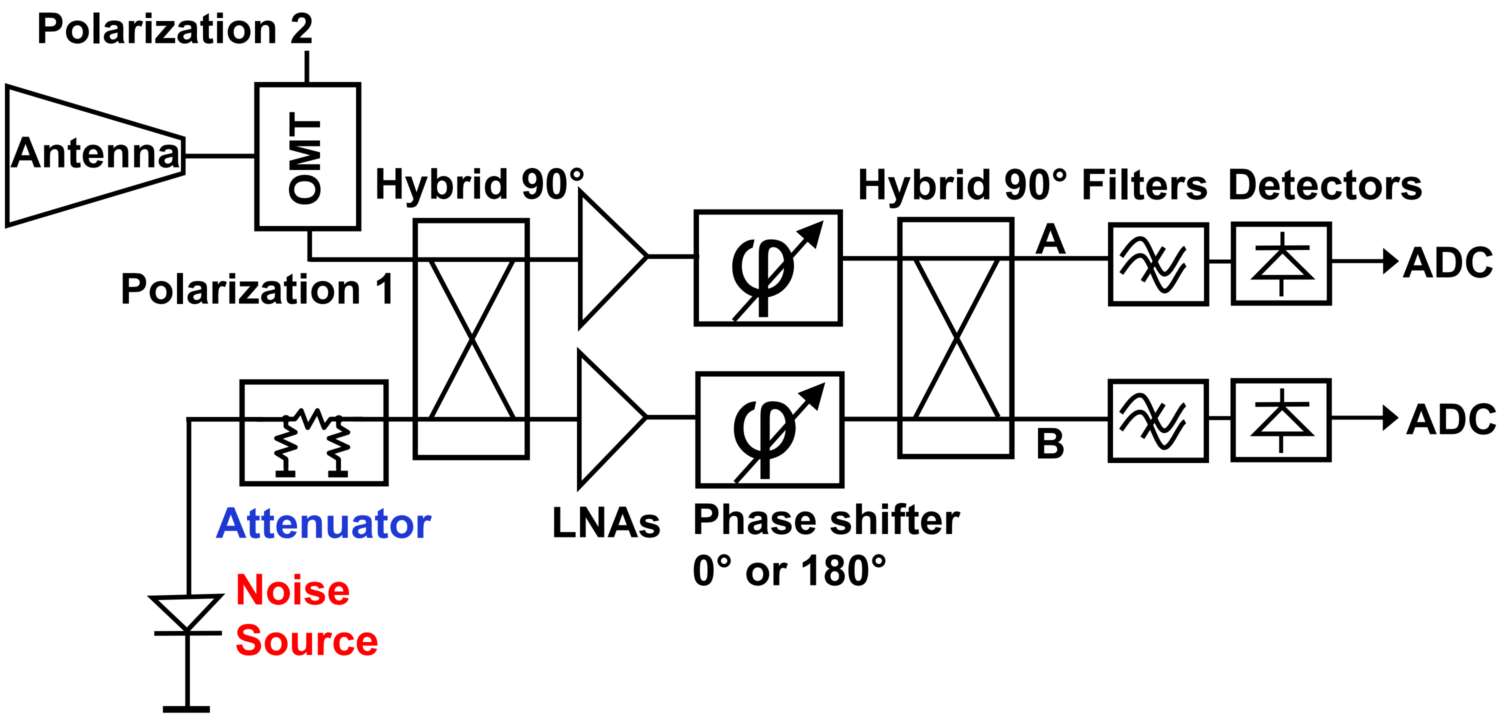


180°

Direct Detection Pseudo Correlation Radiometer



Direct Detection Pseudo Correlation Radiometer



Simultaneous calibration and observation

Sensitivity improvement by $\sqrt{2}$

Same signal paths for calibration and observation

Fast phase switching (~100 Hz) eliminates 1/f noise

Switching element doesn’t need to be in front of the receiver – improved sensitivity

Calibration Concept

Receivers are constantly monitored by their internal calibration references

Temperature of internal calibration references is carefully monitored

Temperature of radiometer receiver components is carefully monitored

Calibration correlates the internal calibration references to scene T_B

Calibration will compensate:

- The dirt or other impurities on antenna lenses
- Internal references drifts
- Radiometer receiver drifts

Receivers gain and offset are monitored => no need for thermal stabilization

Autonomous Calibration

No artificial calibration targets need to be built or maintained.

Vicarious calibration:

Tipping calibration, window channels (e.g., Han and Westwater, 2000)

Surface below radiometer (of a known temperature and emission coefficient)

Ambient atmosphere temperature (opaque, absorptive channels)

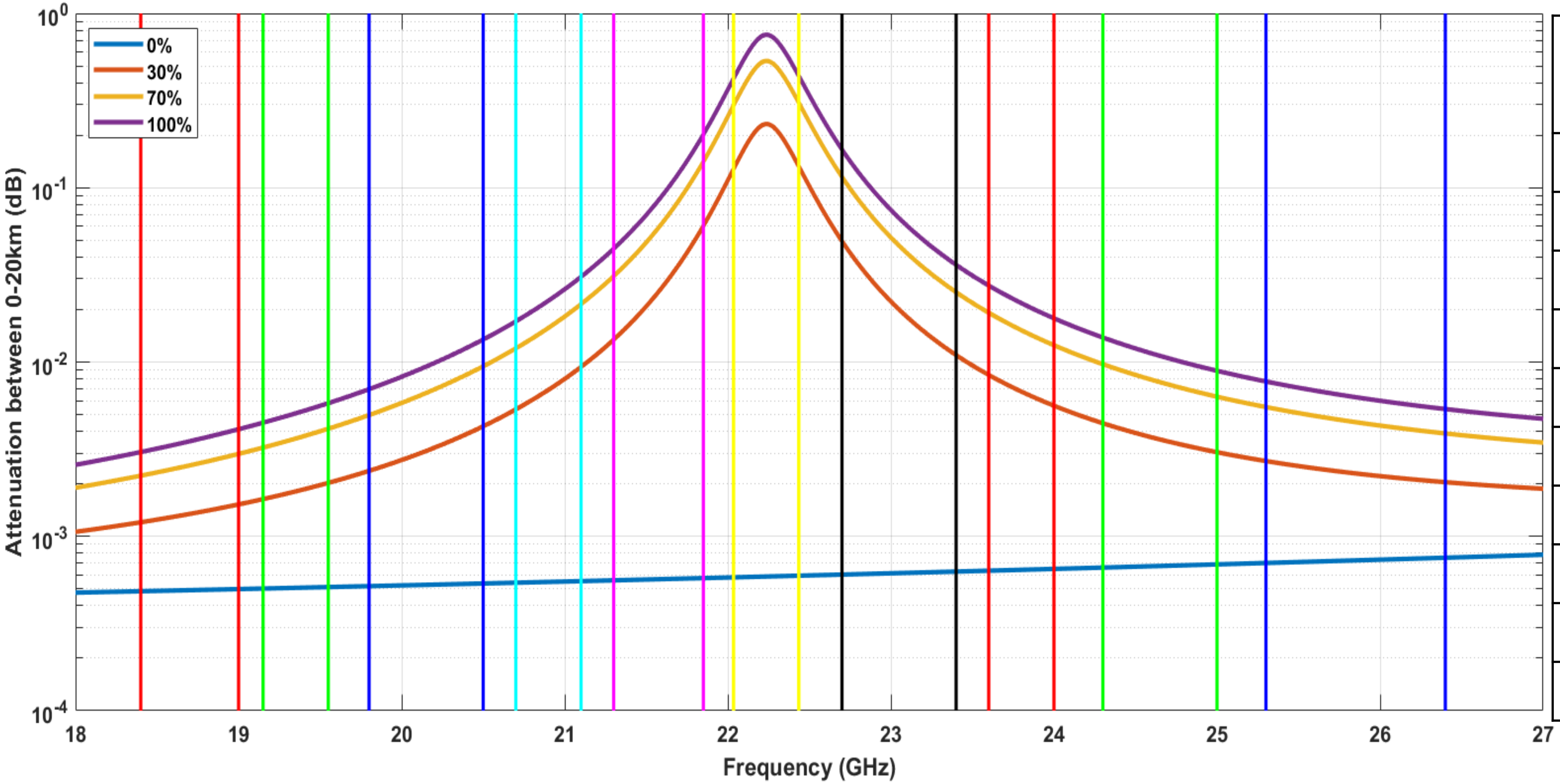
Diurnal temperature variation (surface & atmosphere)

Sun transition though the aperture (e.g., 6°beamwidth, ΔT_B ~83 K, Moon ~4.5 K)

Zenith view – correlating calibration of two polarizations receivers

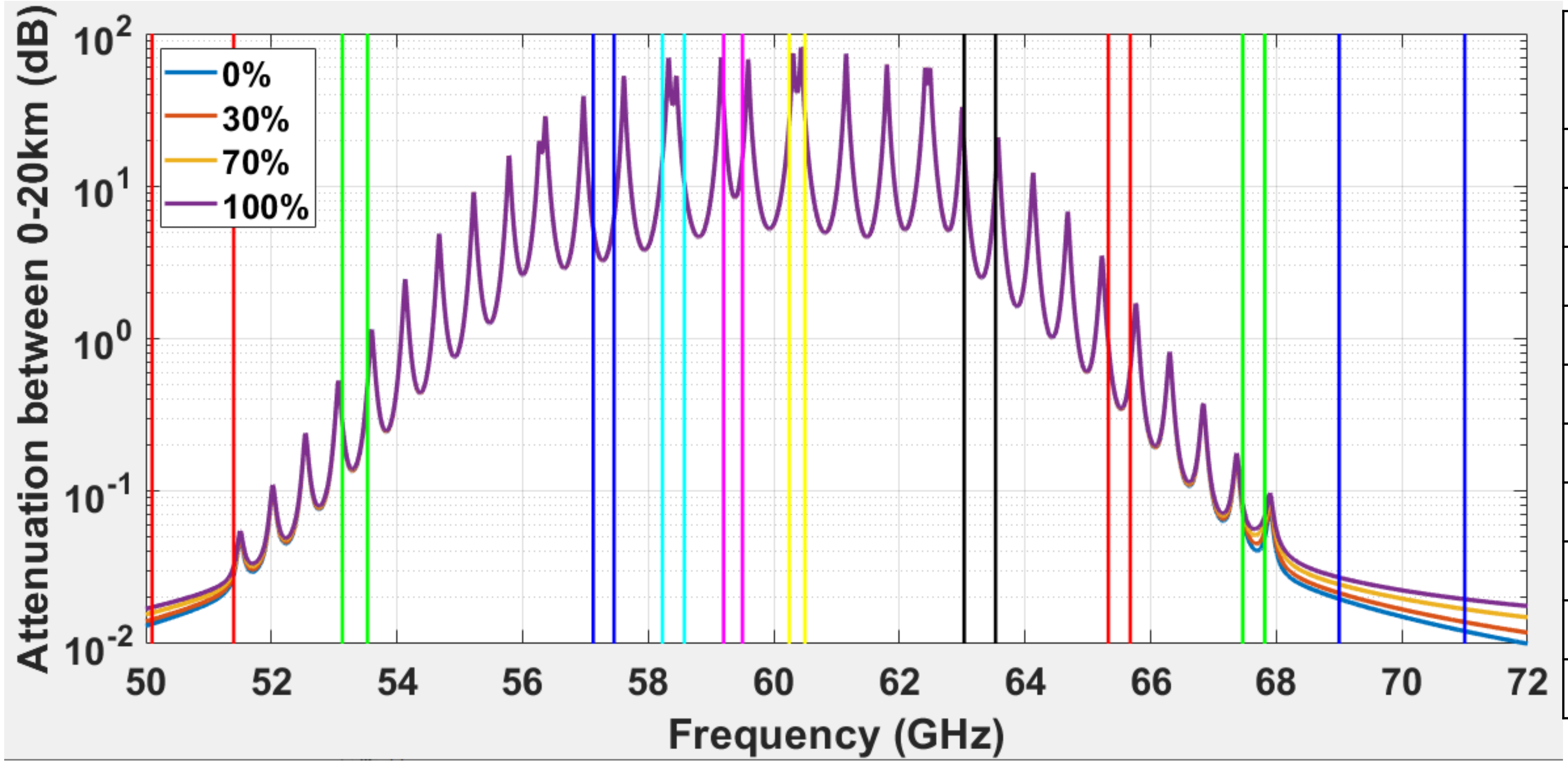
A weekly, or bi-weekly or a monthly vicarious calibration occurrence is possible

APR 18-27 GHz, 10 Channel Radiometer



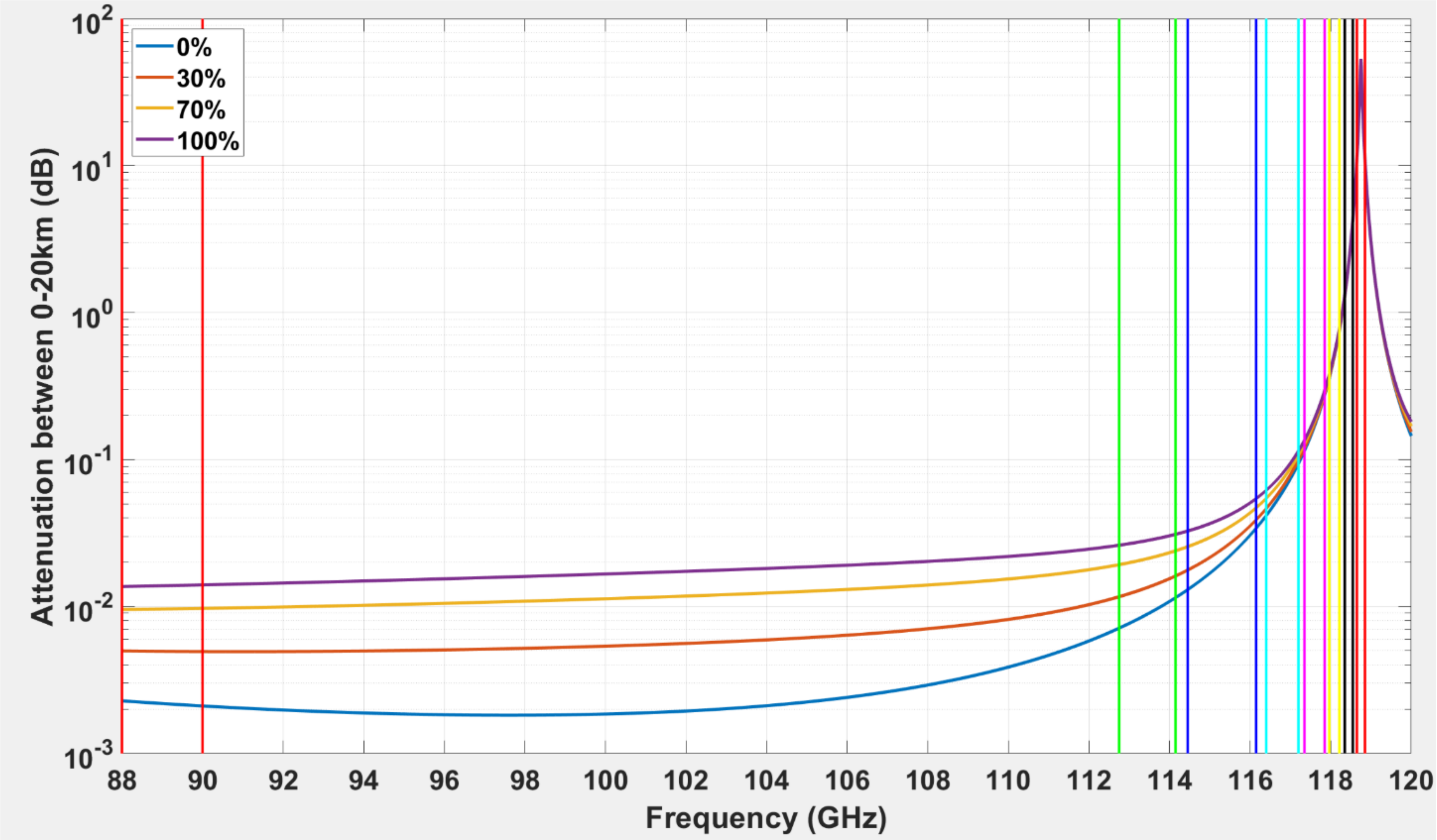
#	Cf (GHz)	Bandwidth (MHz)
1	18.7	600
2	19.35	400
3	20.15	700
4	20.9	400
5	21.575	550
6	22.235	400
7	23.05	700
8	23.8	400
9	24.65	700
10	25.85	1,100

APR 50-72 GHz, 10 Channel Radiometer



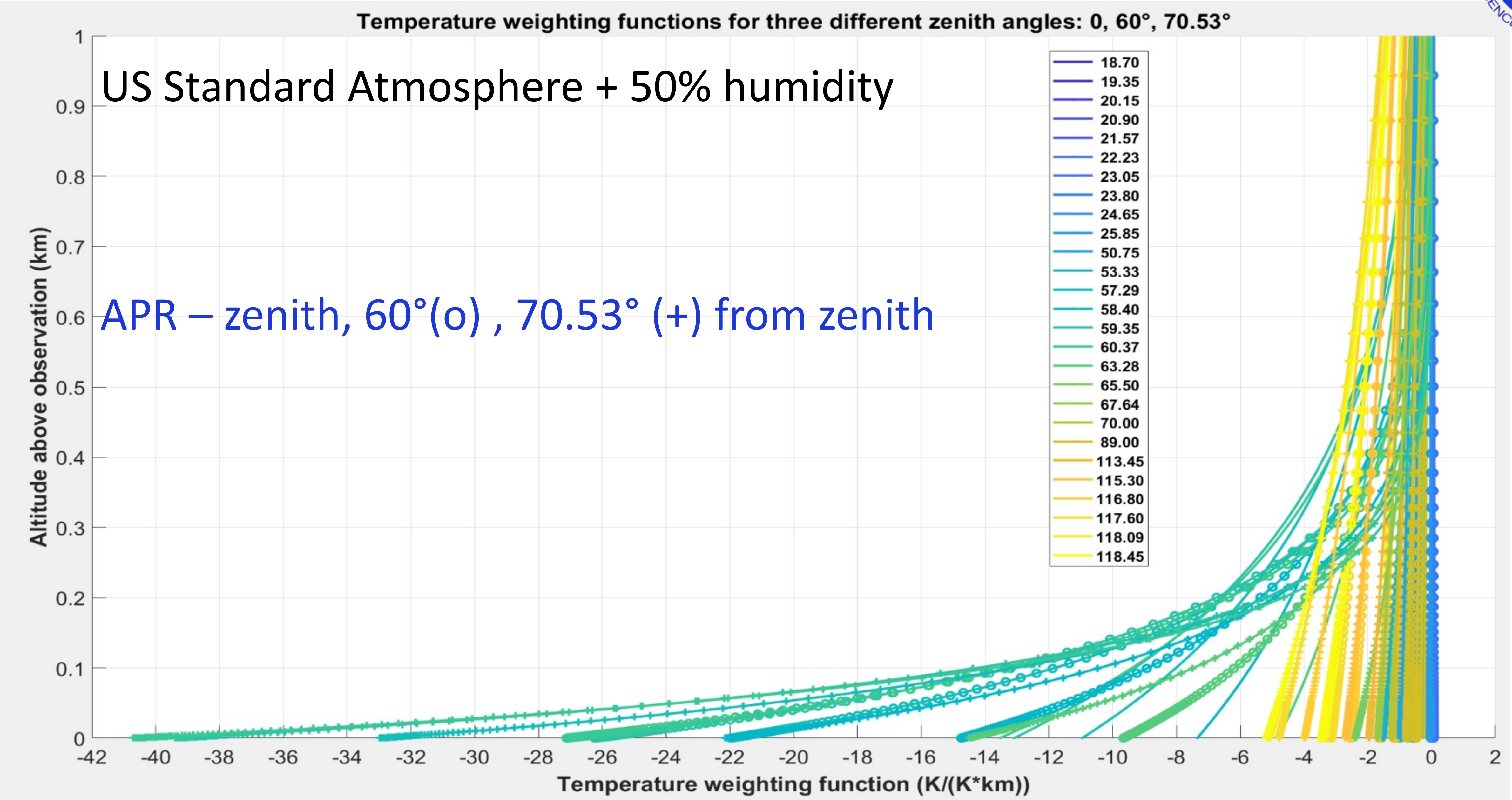
#	Cf (GHz)	Bandwidth (MHz)
1	50.75	1,300
2	53.33	400
3	57.29	330
4	58.4	350
5	59.35	300
6	60.37	250
7	63.28	500
8	65.5	350
9	67.64	350
10	70	2,000

APR 90-120 GHz Radiometer, 8 Channels



#	Cf (GHz)	Bandwidth (MHz)
1	89	2,000
2	113.45	1,400
3	115.3	1,700
4	116.8	800
5	117.6	500
6	118.09	250
7	118.45	200
8	118.75	200

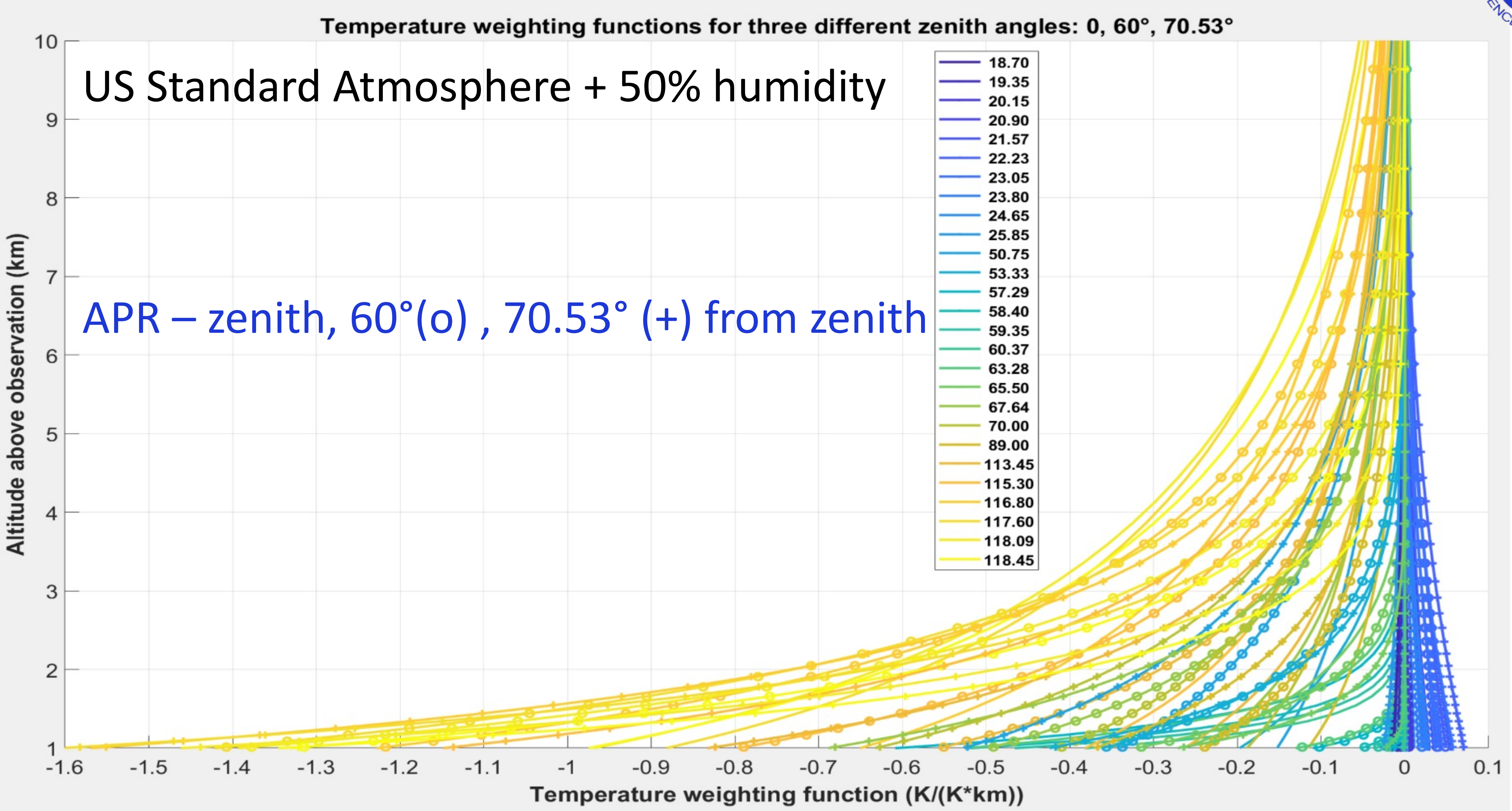
APR temperature profiling, 0 to 1 km



US Standard Atmosphere + 50% humidity

APR – zenith, 60°(o) , 70.53° (+) from zenith

APR temperature profiling, 1 to 10 km

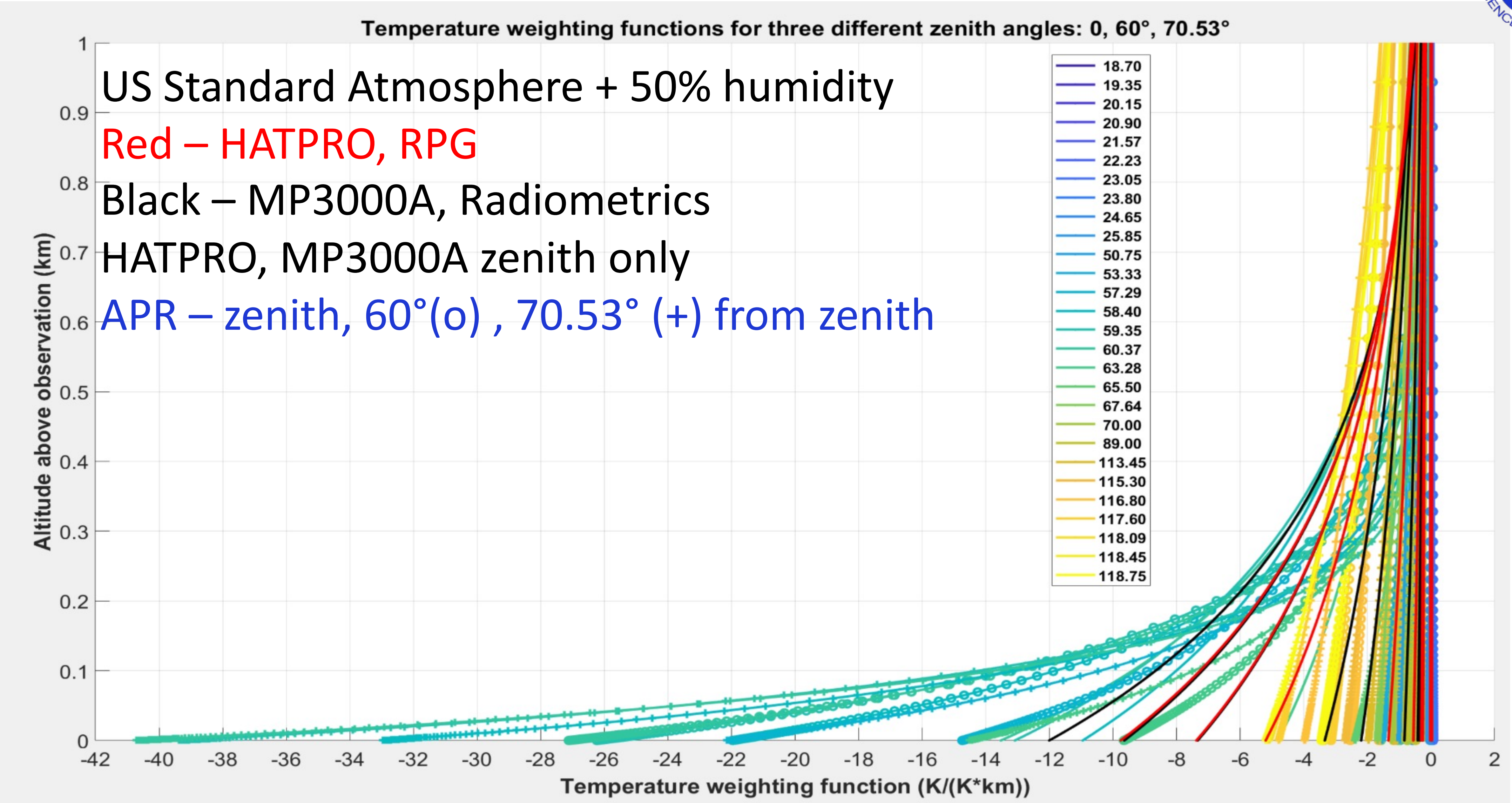


Temperature weighting functions for three different zenith angles: 0, 60°, 70.53°

US Standard Atmosphere + 50% humidity

APR – zenith, 60°(o) , 70.53° (+) from zenith

Temperature PBL profiling, APR, HATPRO, MP3000A



US Standard Atmosphere + 50% humidity

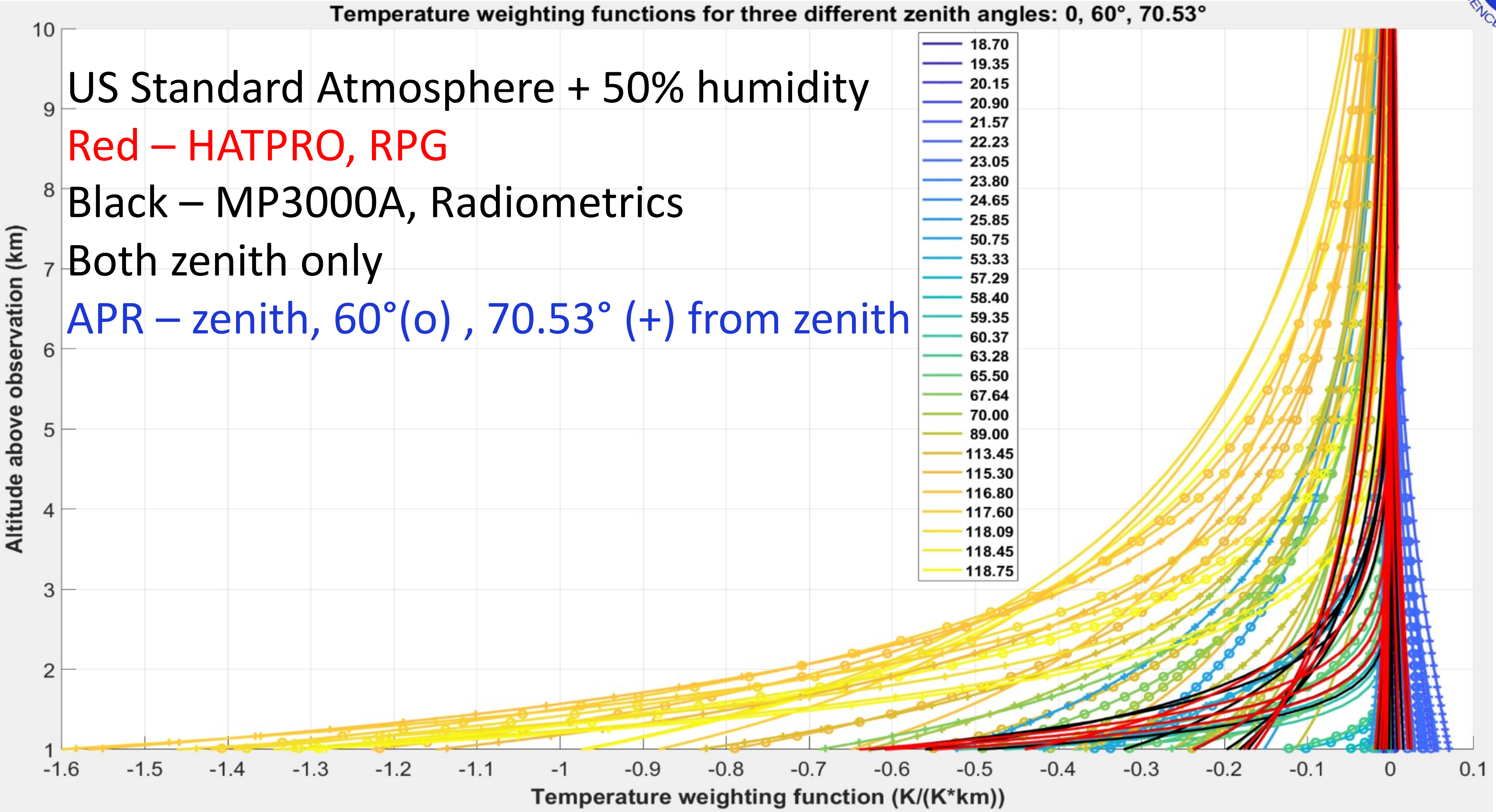
Red – HATPRO, RPG

Black – MP3000A, Radiometrics

HATPRO, MP3000A zenith only

APR – zenith, 60°(o) , 70.53° (+) from zenith

Temperature PBL profiling, APR, HATPRO, MP3000A



Temperature weighting functions for three different zenith angles: 0, 60°, 70.53°

US Standard Atmosphere + 50% humidity

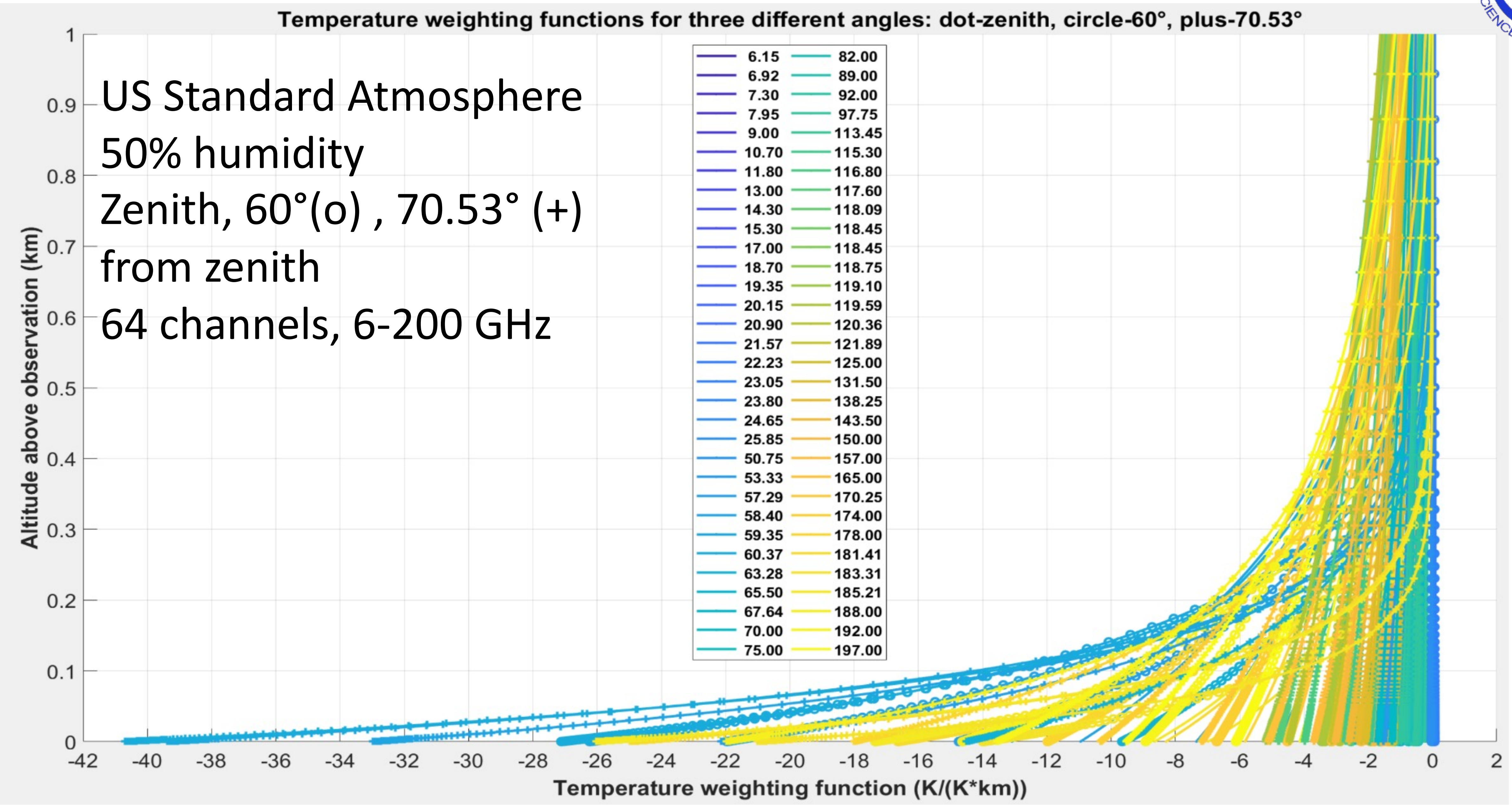
Red – HATPRO, RPG

Black – MP3000A, Radiometrics

Both zenith only

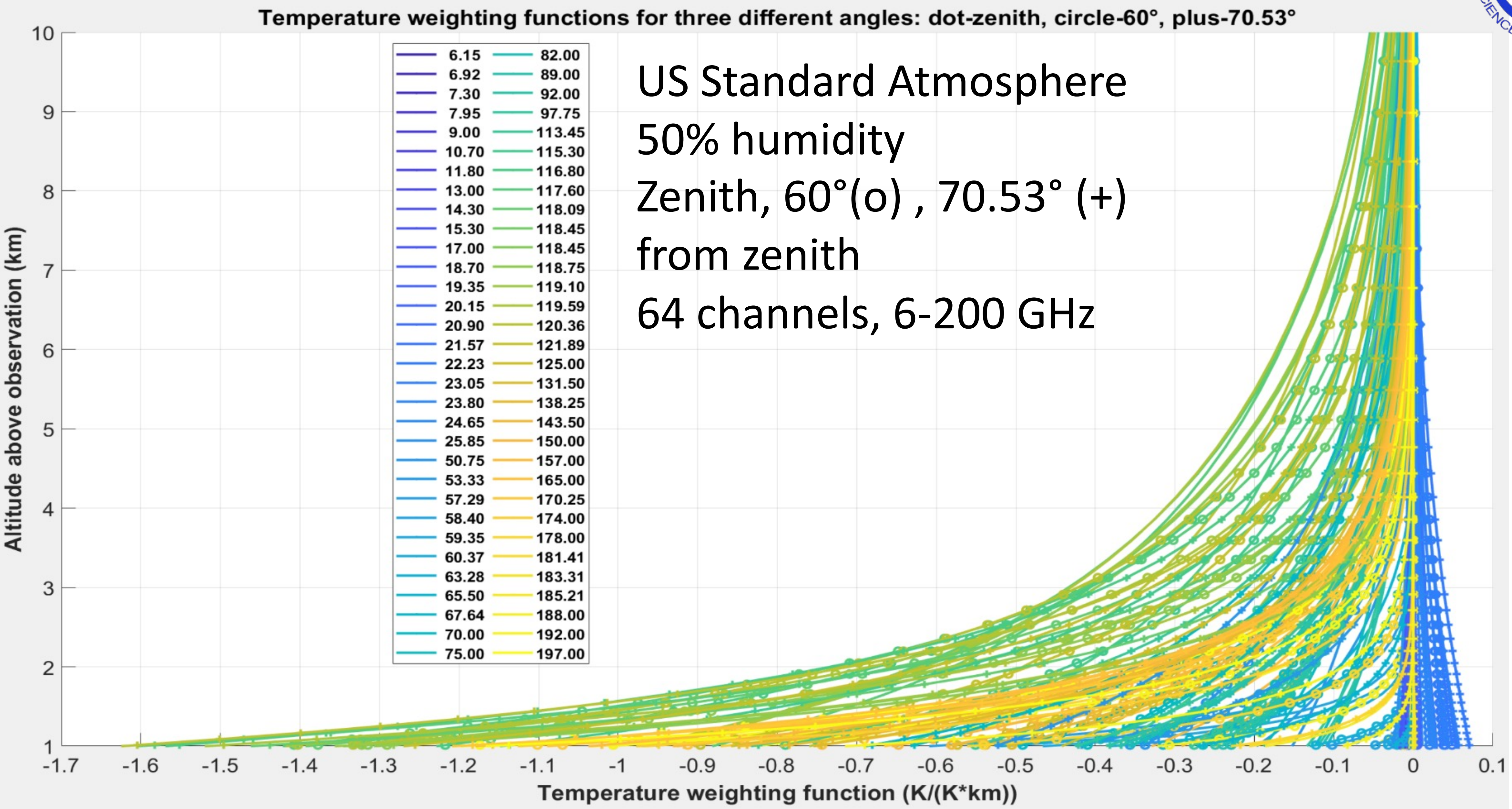
APR – zenith, 60°(o) , 70.53° (+) from zenith

Temperature PBL – Hyperspectral <200 GHz



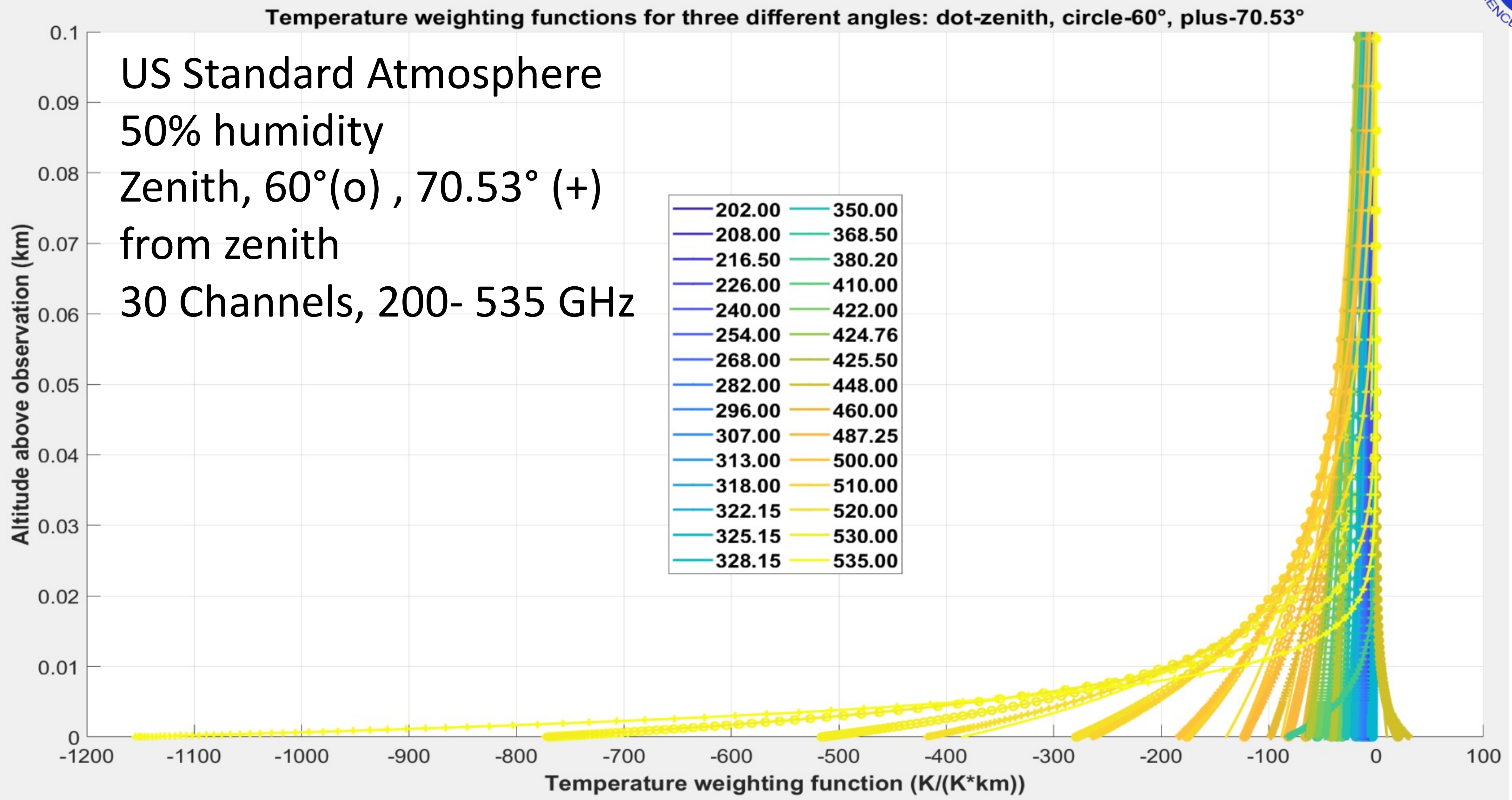
US Standard Atmosphere
50% humidity
Zenith, 60°(o) , 70.53° (+)
from zenith
64 channels, 6-200 GHz

Temperature PBL – Hyperspectral <200 GHz



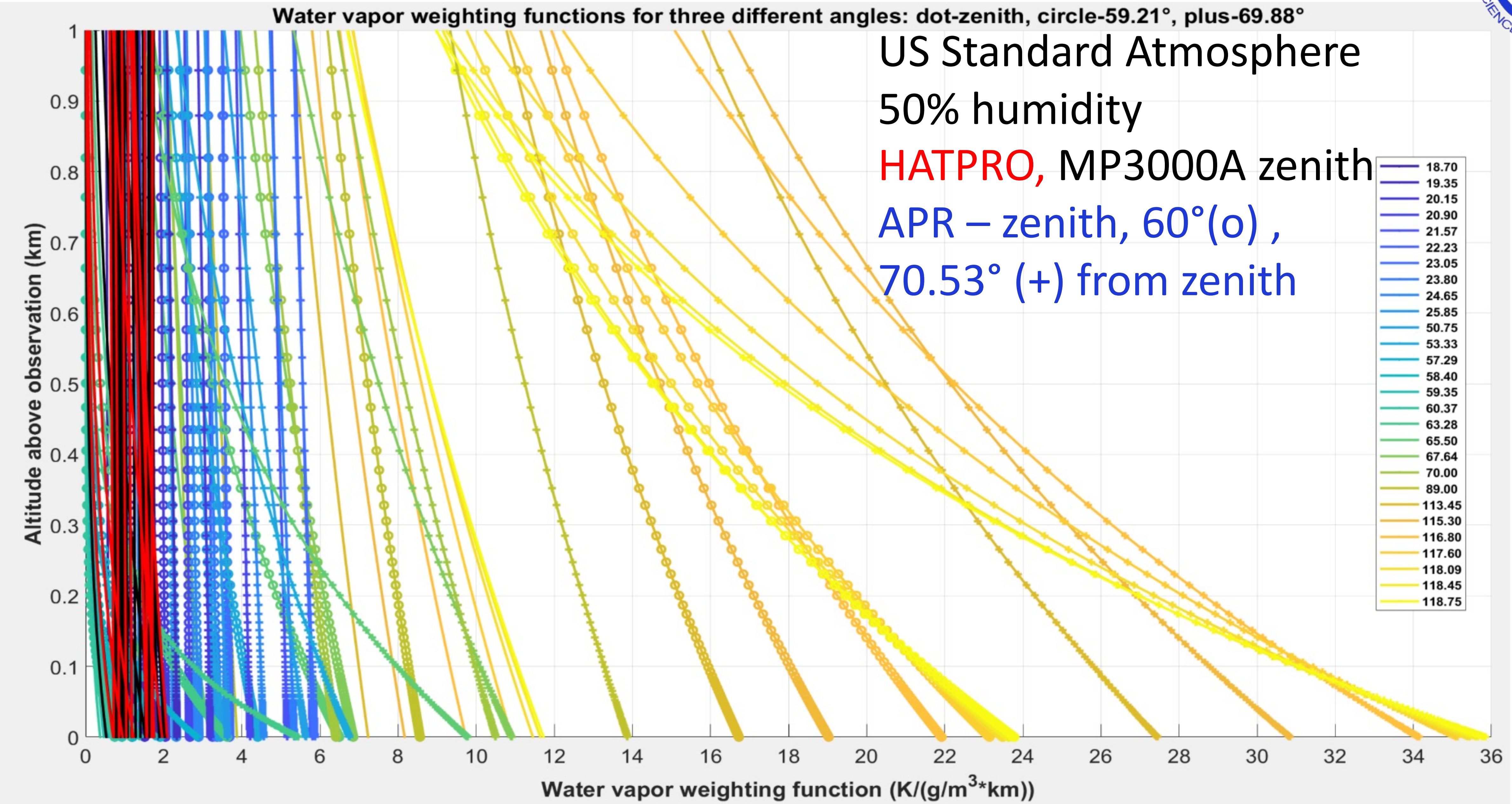
US Standard Atmosphere
50% humidity
Zenith, 60°(o) , 70.53° (+)
from zenith
64 channels, 6-200 GHz

Temperature PBL – Hyperspectral >200 GHz



US Standard Atmosphere
50% humidity
Zenith, 60°(o) , 70.53° (+)
from zenith
30 Channels, 200- 535 GHz

APR water vapor profiling, up to 1 km



Water vapor weighting functions for three different angles: dot-zenith, circle-59.21°, plus-69.88°

US Standard Atmosphere

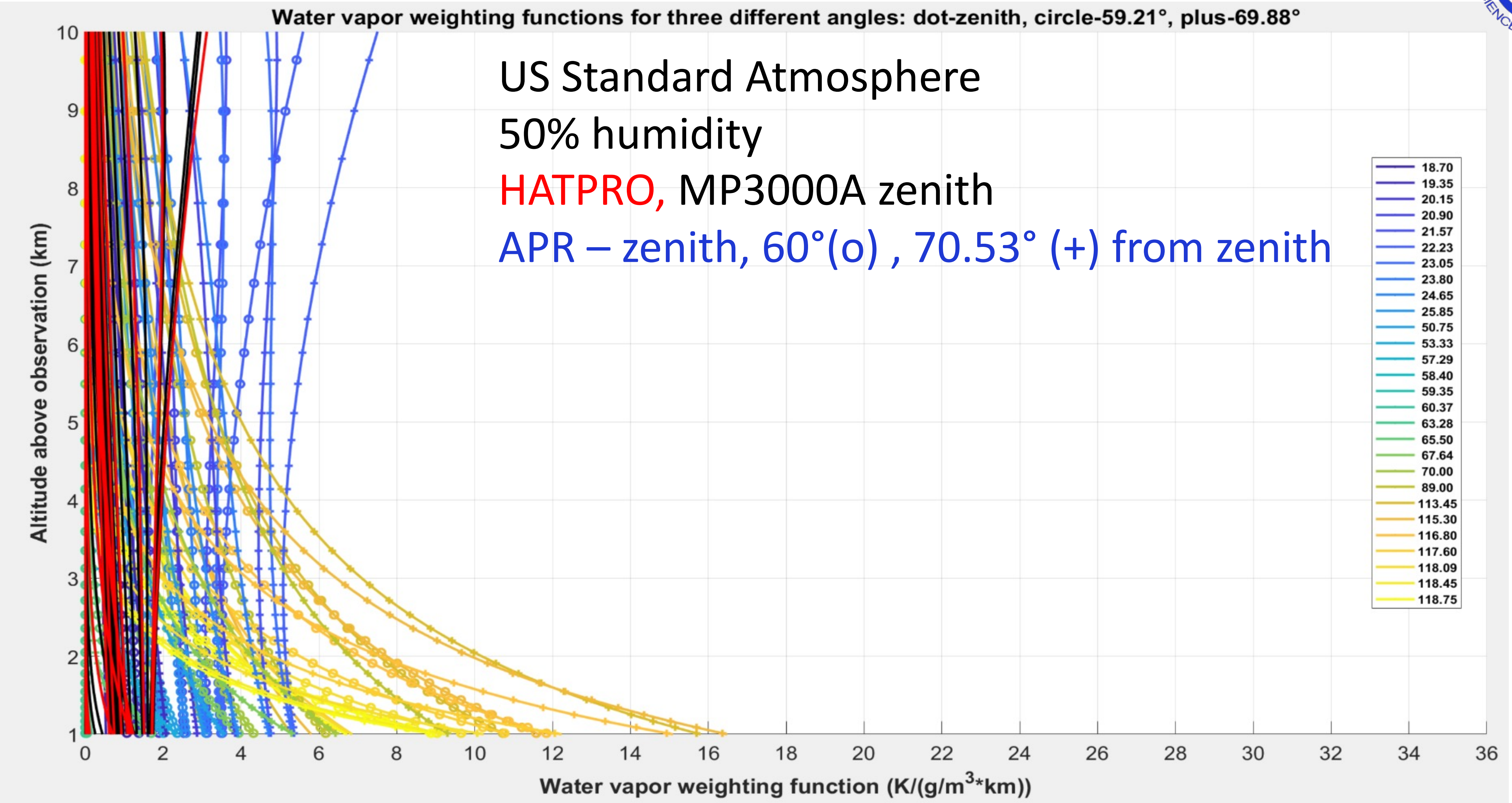
50% humidity

HATPRO, MP3000A zenith

APR – zenith, 60°(o) ,

70.53° (+) from zenith

APR temperature profiling, 1 to 10 km



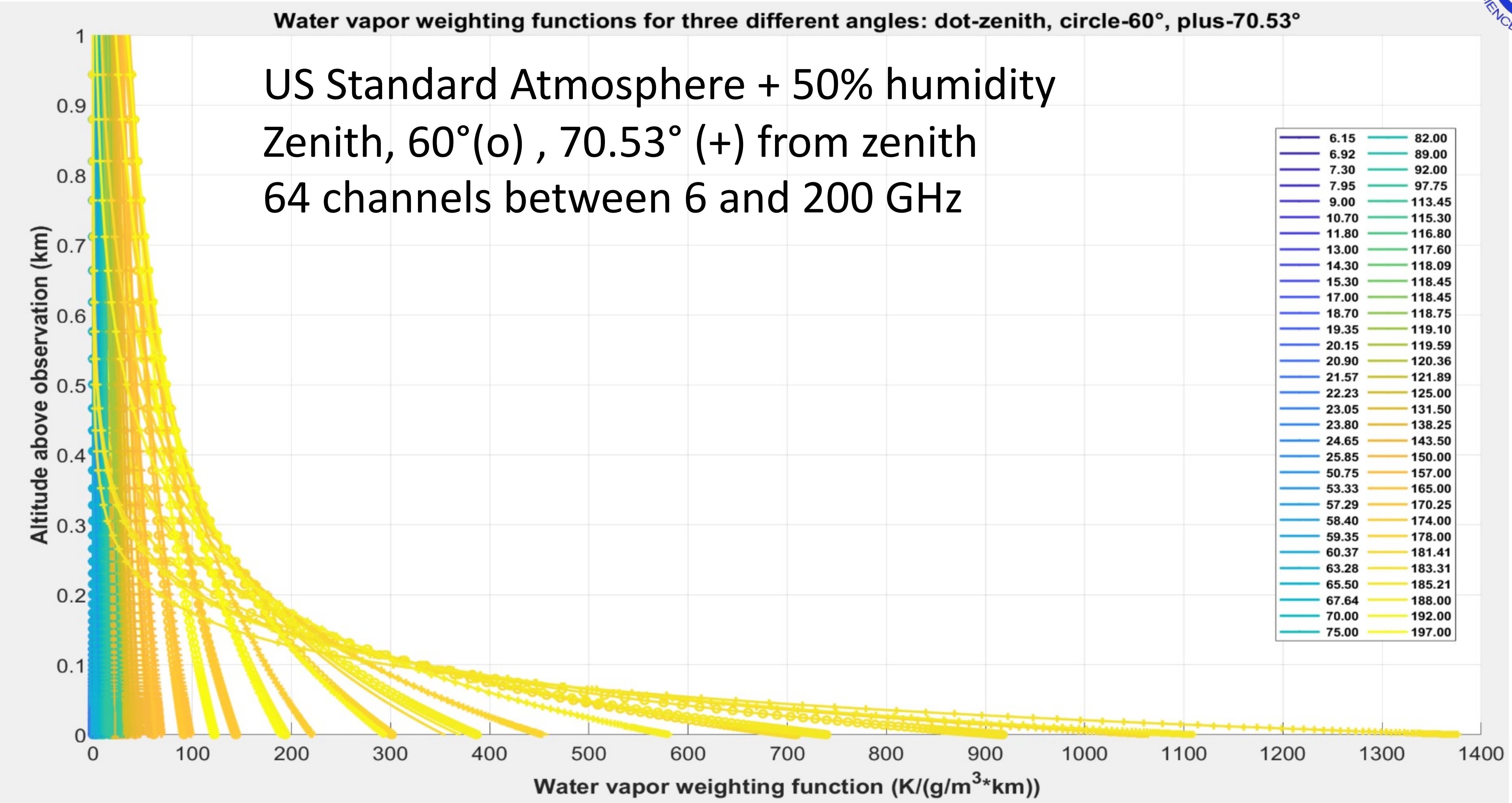
US Standard Atmosphere

50% humidity

HATPRO, MP3000A zenith

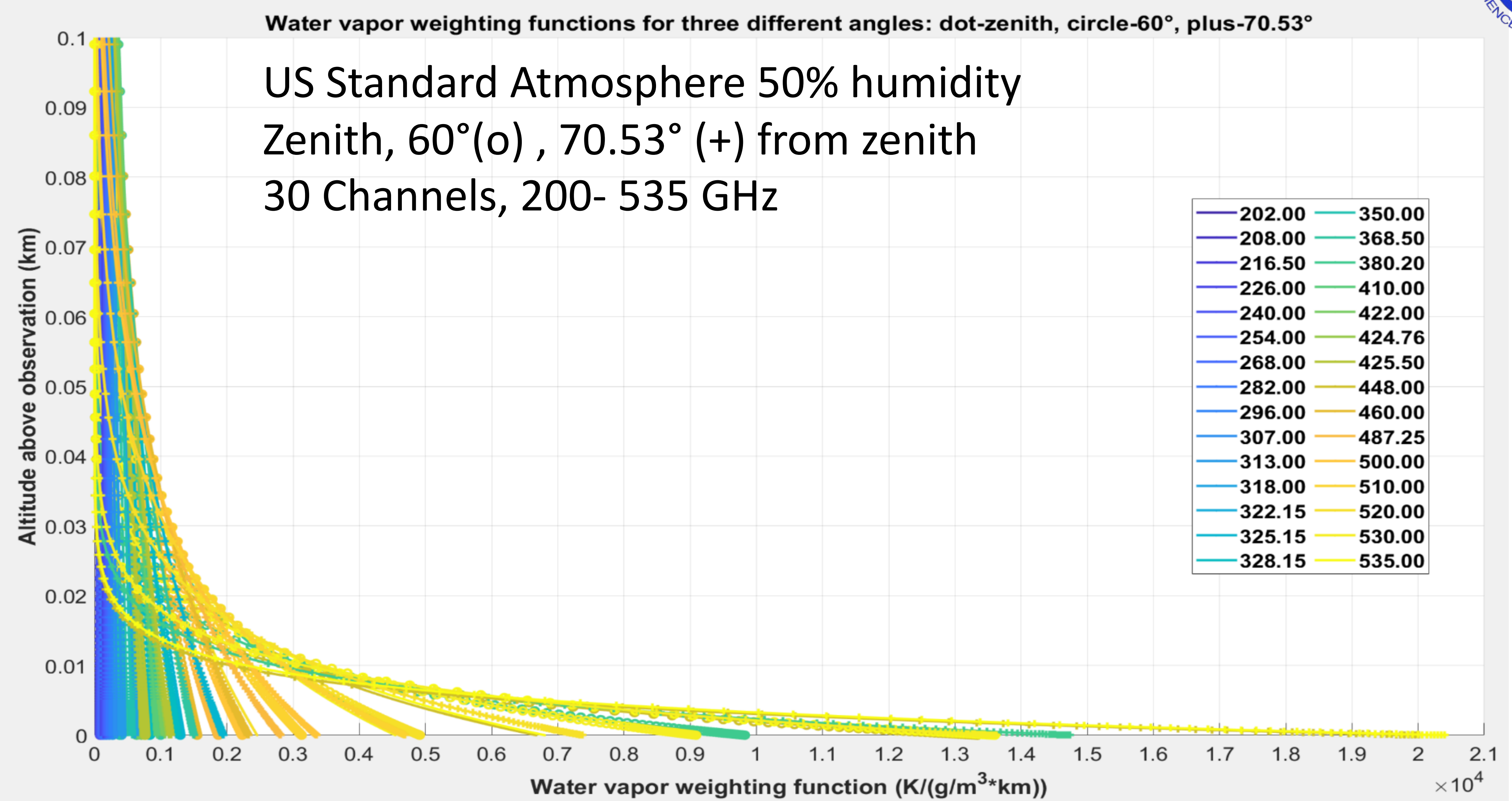
APR – zenith, 60°(o) , 70.53° (+) from zenith

Water vapor PBL – Hyperspectral <200 GHz



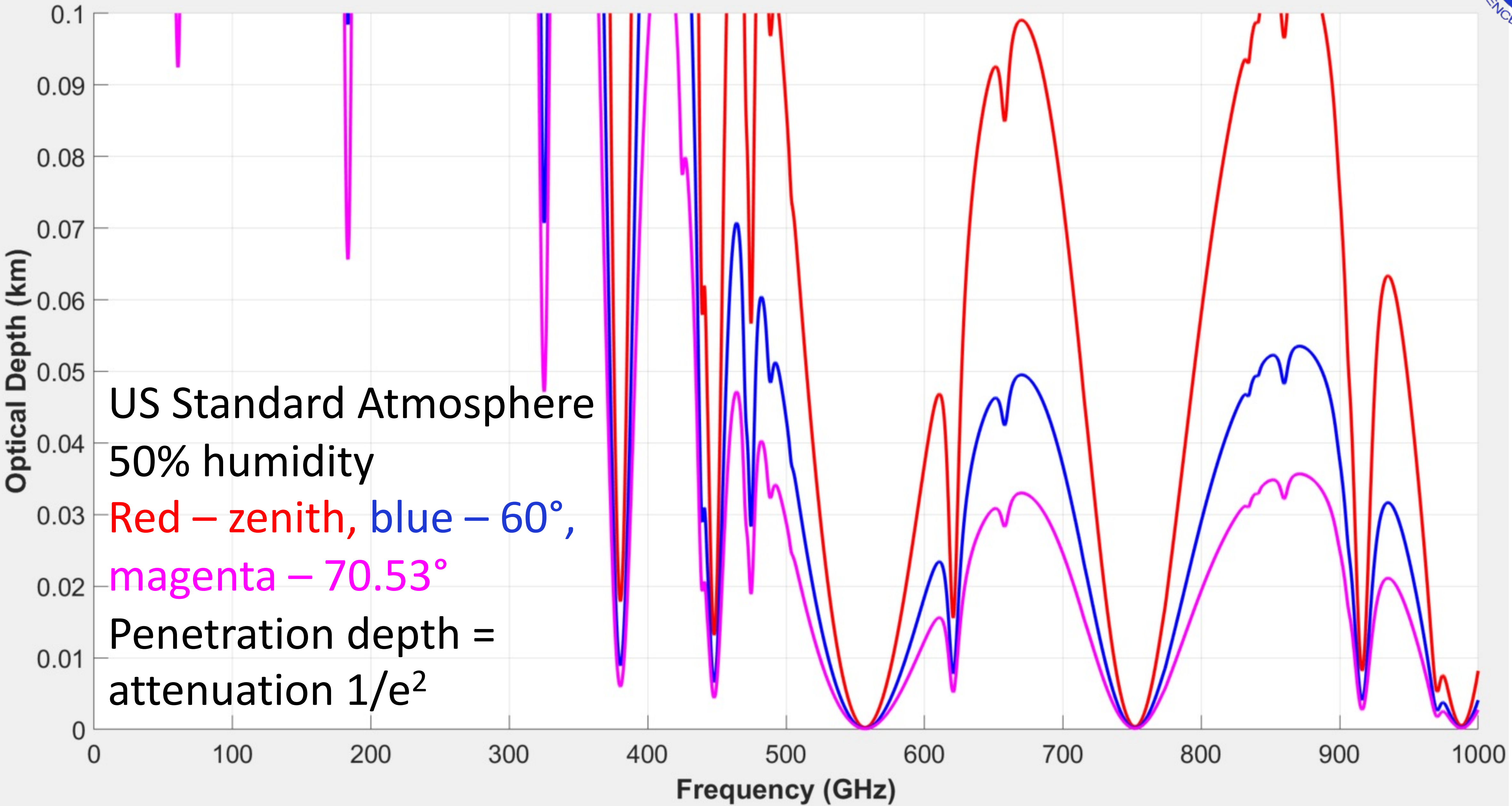
US Standard Atmosphere + 50% humidity
Zenith, 60°(o) , 70.53° (+) from zenith
64 channels between 6 and 200 GHz

Water vapor PBL – Hyperspectral >200 GHz



US Standard Atmosphere 50% humidity
Zenith, 60°(o) , 70.53° (+) from zenith
30 Channels, 200- 535 GHz

Penetration depth up to 1,000 GHz up to 100 m



US Standard Atmosphere

50% humidity

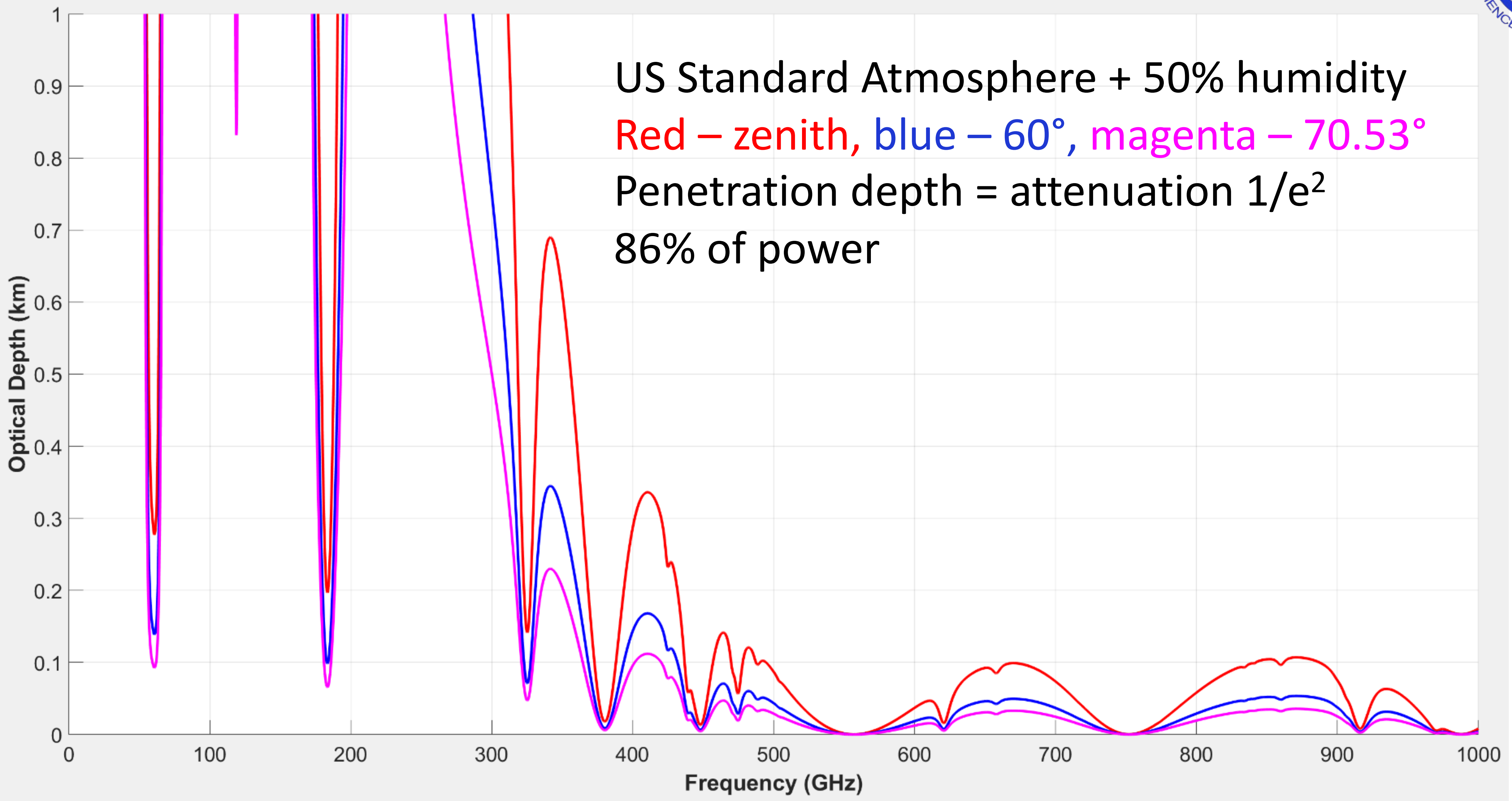
Red – zenith, blue – 60°,

magenta – 70.53°

Penetration depth =

attenuation $1/e^2$

Penetration depth up to 1,000 GHz up to 1 km



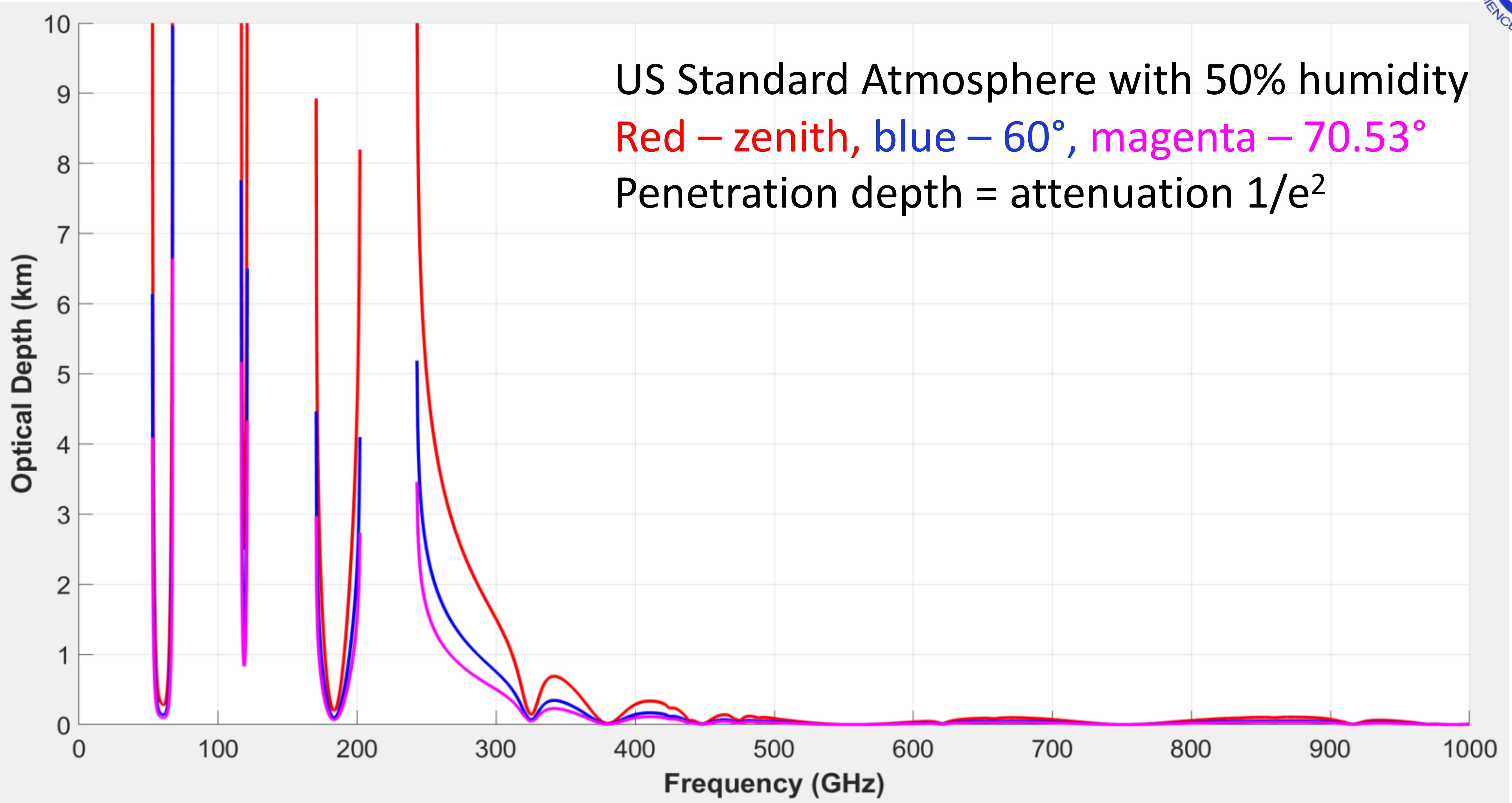
US Standard Atmosphere + 50% humidity

Red – zenith, blue – 60°, magenta – 70.53°

Penetration depth = attenuation 1/e^2

86% of power

Penetration depth up to 1,000 GHz up to 10 km



US Standard Atmosphere with 50% humidity

Red – zenith, blue – 60°, magenta – 70.53°

Penetration depth = attenuation 1/e^2

Observed variables

Temperature profiles with high vertical and temporal resolution
Humidity profiles with high vertical and temporal resolution
Cloud liquid water
Precipitable water
Rain rate & precipitation rate retrieval
Supercool liquid detection & retrieval
Planetary boundary layer height
Diurnal variation
Local water and energy cycle observations

Sampling of the atmosphere without interruptions – noise reduction
Full 360° sample in 0.5 seconds
Diurnal variations - 24 hours a day profiles
Dual polarization observations – noise reduction
Multiple channels observed at the same time – noise reduction

Conclusion

A microwave radiometer is the BEST tool for PBL observations

A robust and autonomous sensor is technologically possible

No artificial or cryogenic targets are needed

Under all atmospheric conditions

TRL 5-6

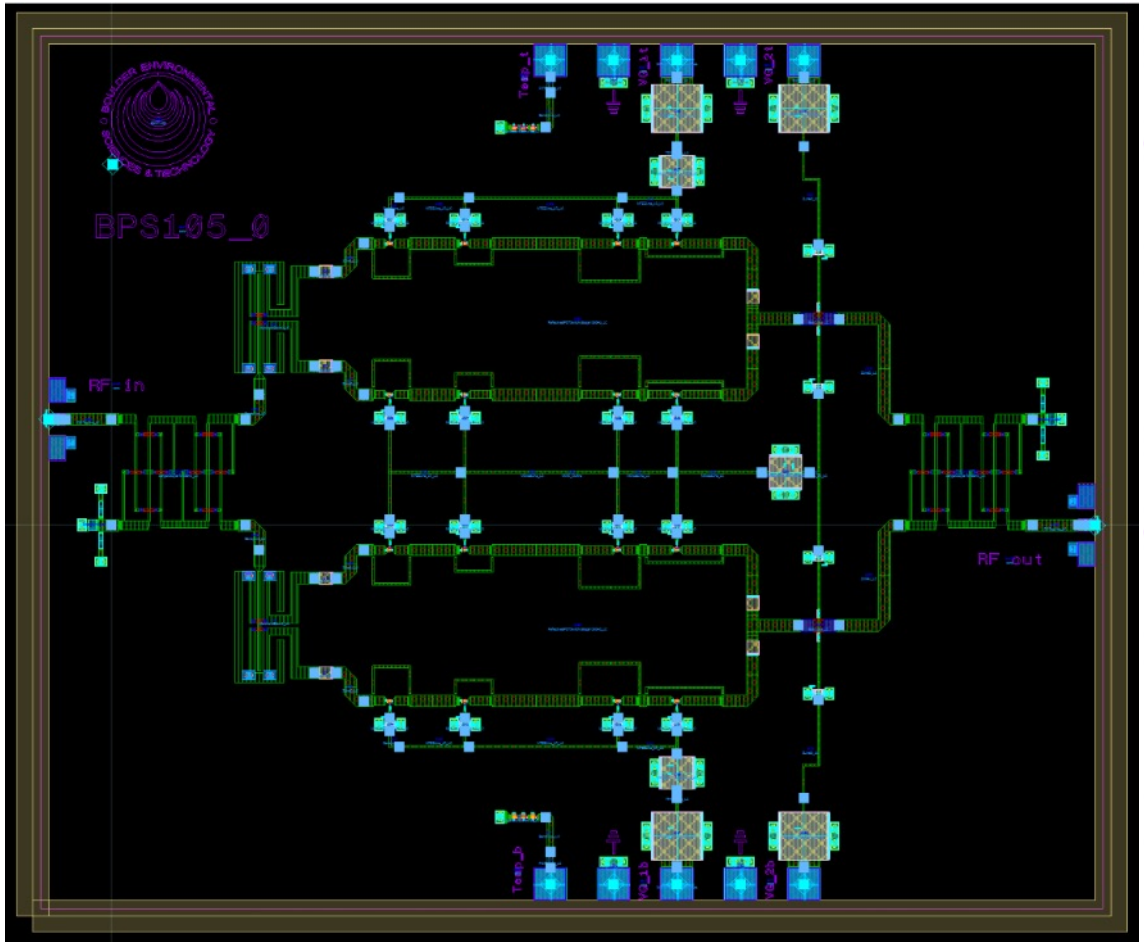
Extra Slides

A NASA proposal reviewer:

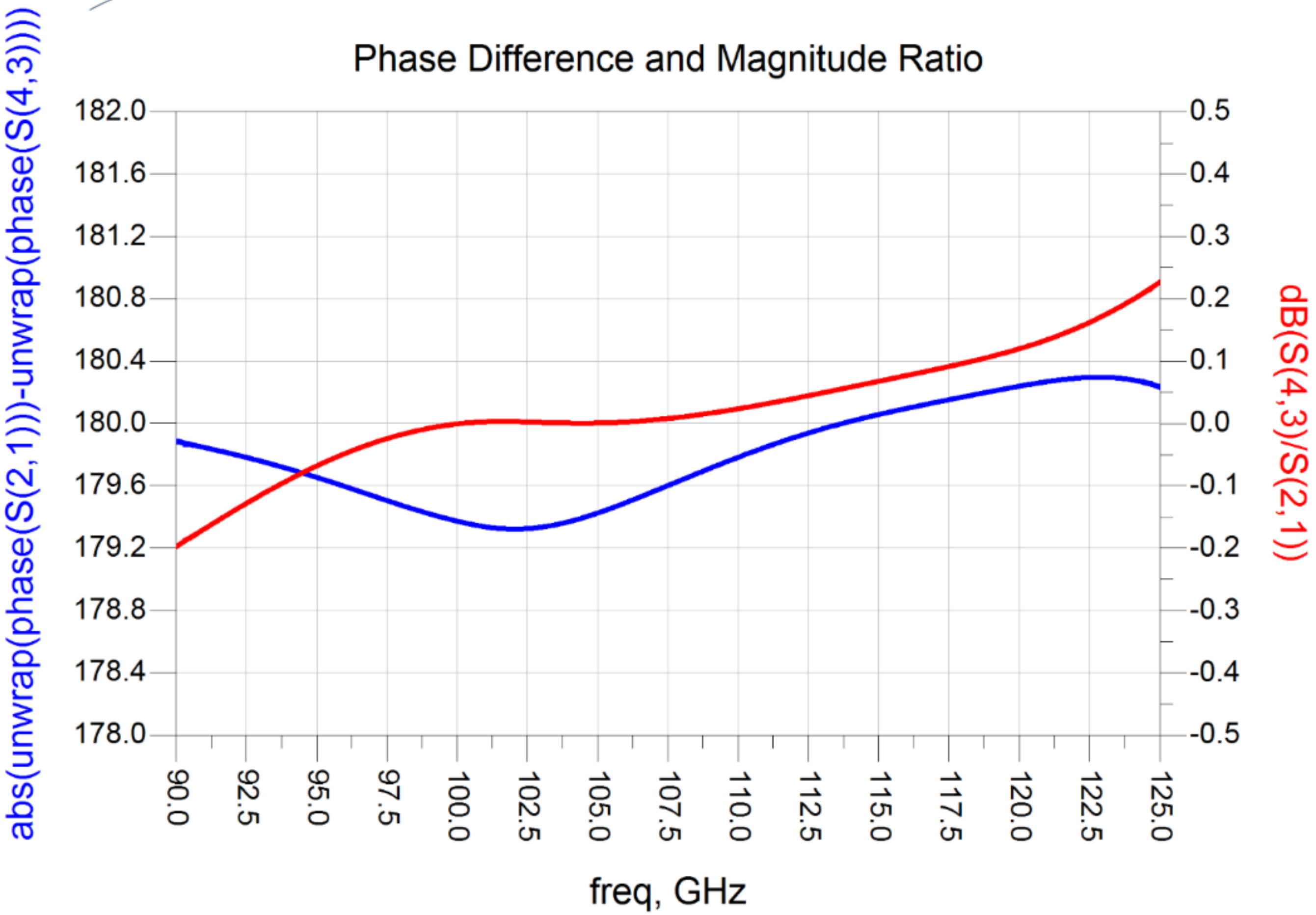
There is a commercialization challenge because the market is niche, and the technology is difficult.

TRL 5-6

180° Phase Shifter, 90-125 GHz



2.7 x 3.3 mm



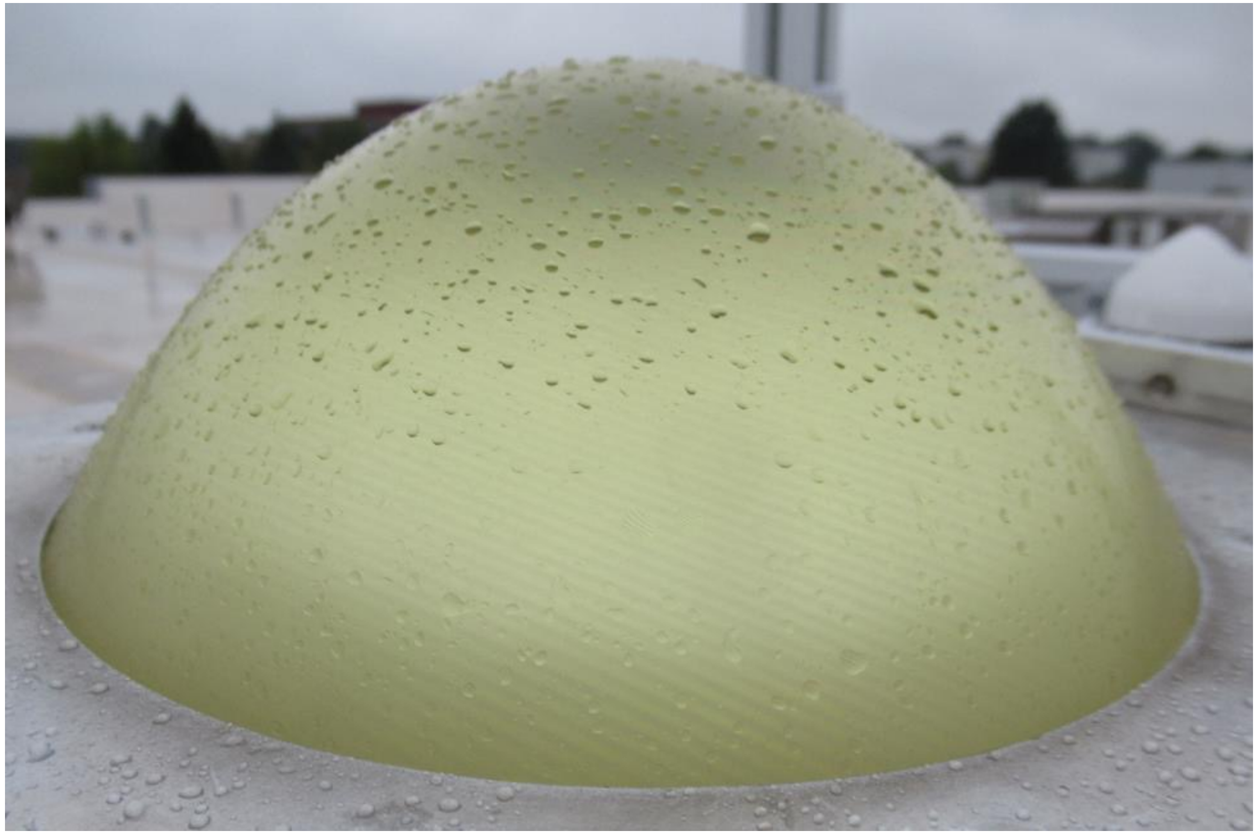
Rainy day, September 21, 2022 – 20 GHz lens

BOULDER ENVIRONMENTAL SCIENCES & TECHNOLOGY

Static, no scanning (15 minutes)

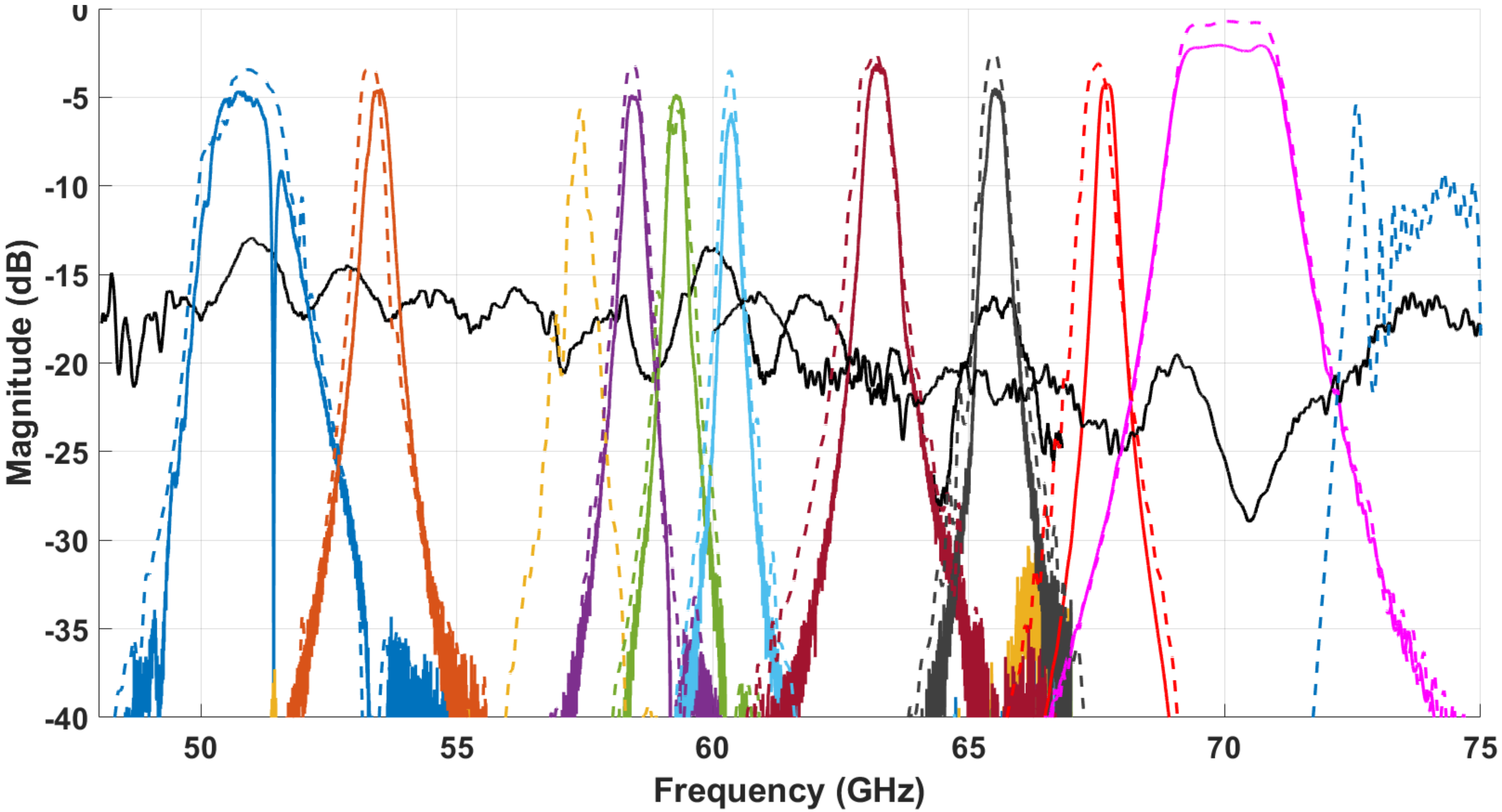
5:47 pm

Normal operation cycle



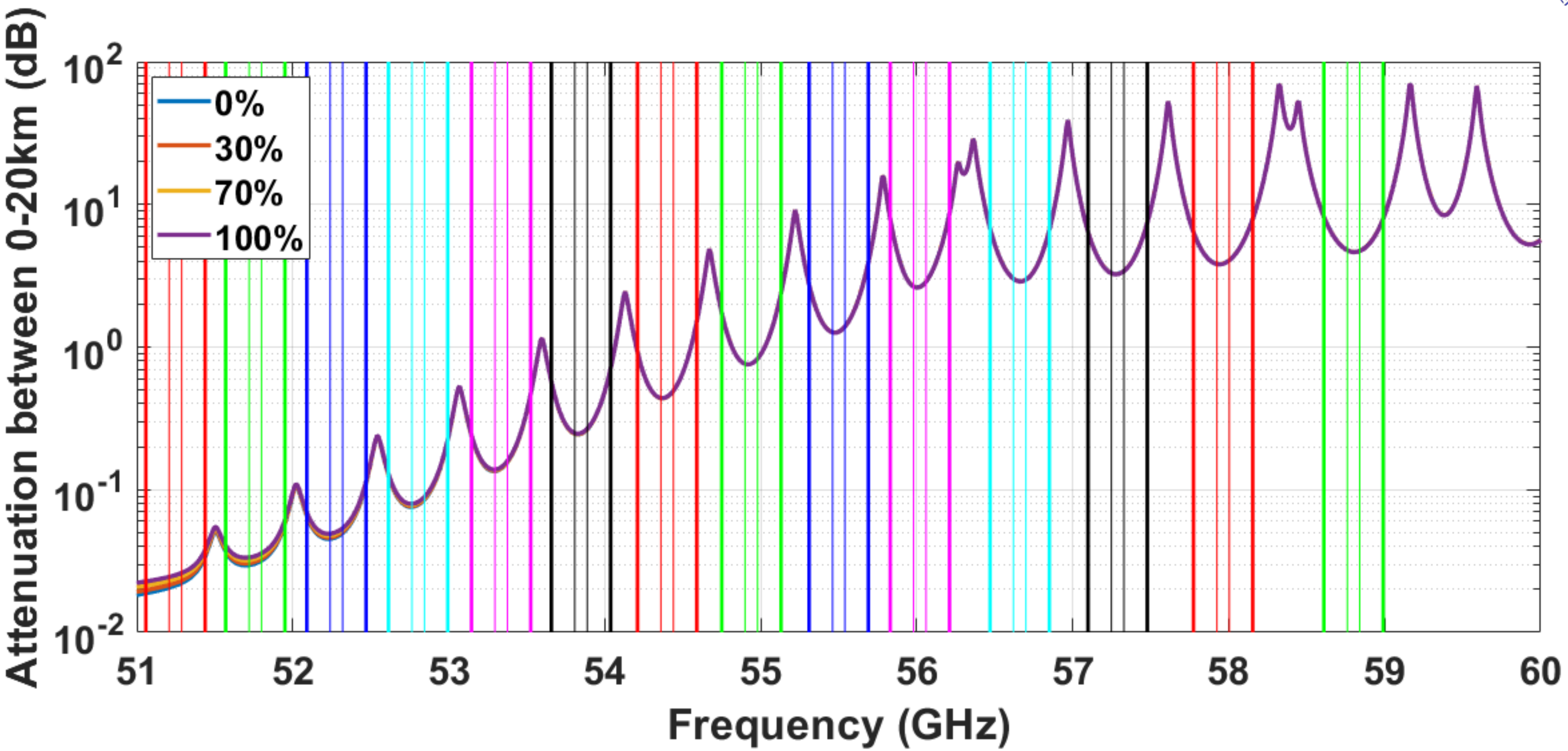
5:49 pm

50-72 GHz Multiplexer, 10 Channels

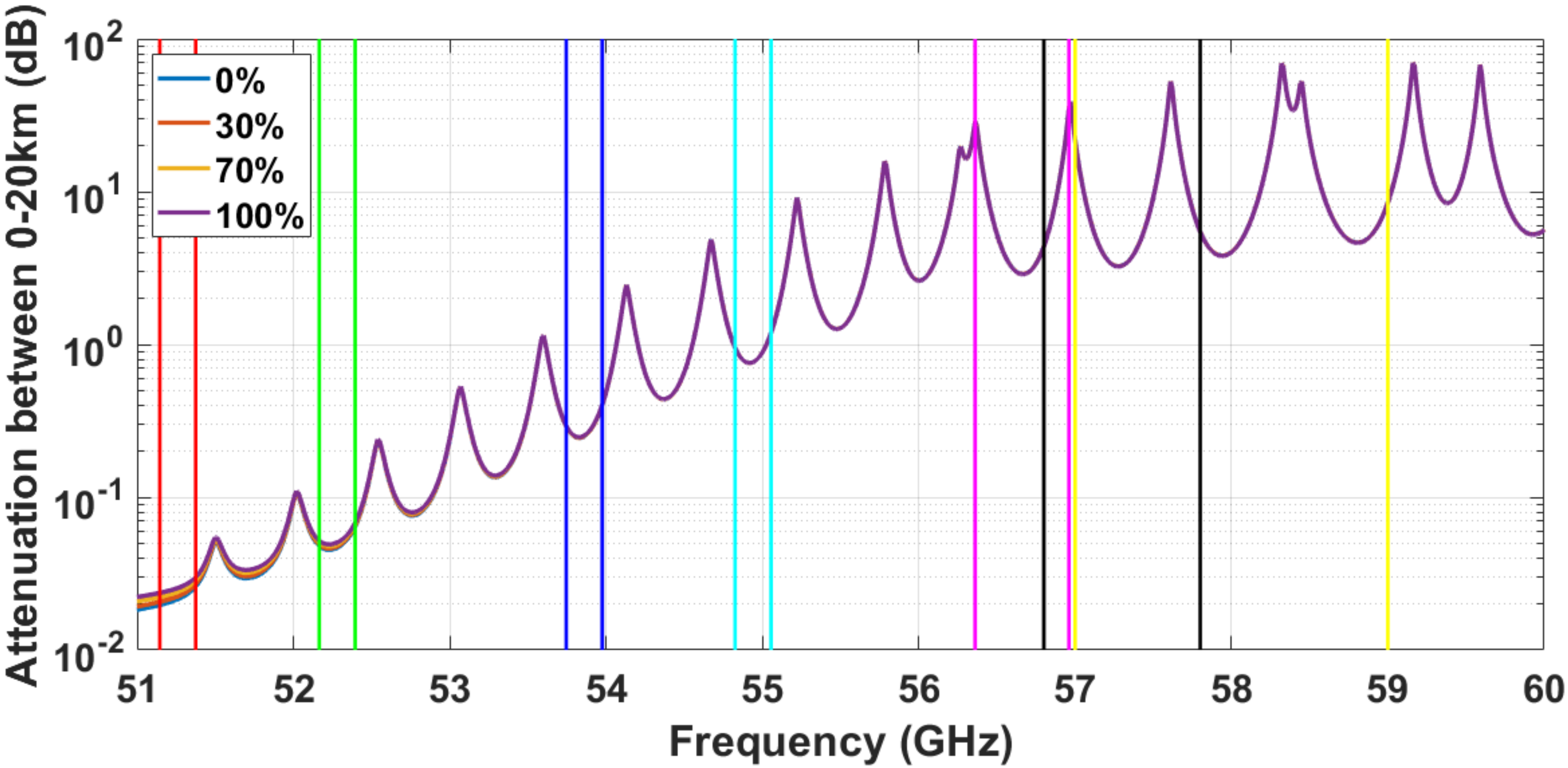


Simulations – dashed, measurements – full lines

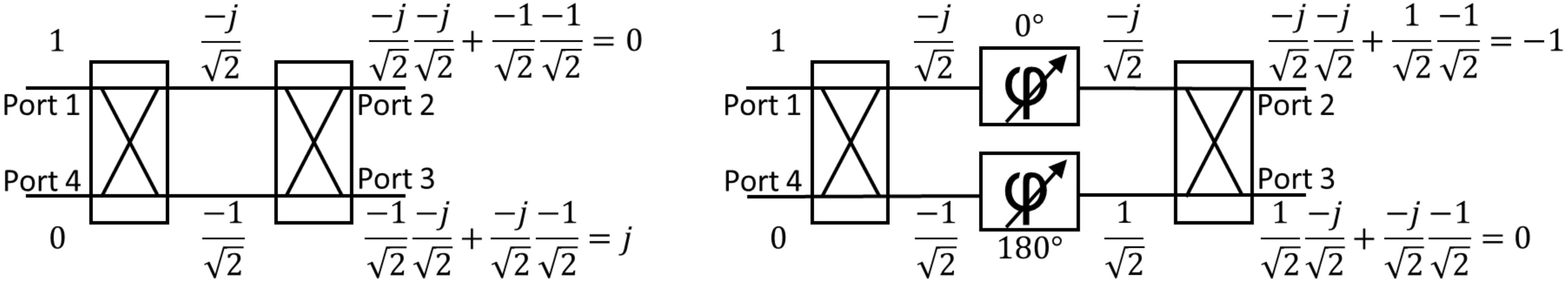
Radiometrics, MP3000A, 14 Channels



Radiometer Physics, GmbH, HATPRO, 7 Channels

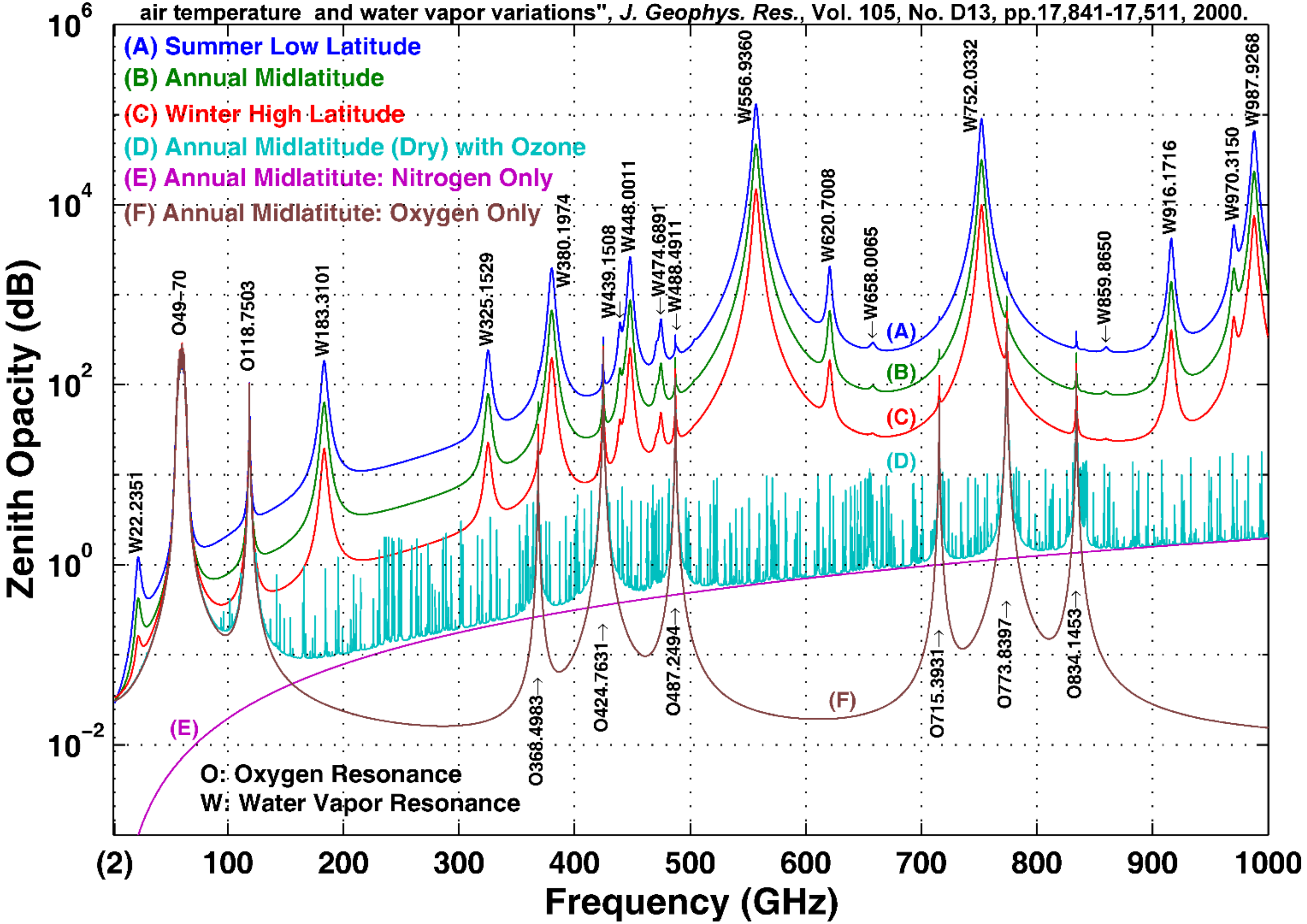


Pseudo Correlation Radiometer - Math



Adding a 180° phase shift into the circuit changes output from port 3 to port 2

Klein, M., A.J. Gasiewski: "Nadir sensitivity of passive millimeter and submillimeter wave channels to clear air temperature and water vapor variations", *J. Geophys. Res.*, Vol. 105, No. D13, pp.17,841-17,511, 2000.

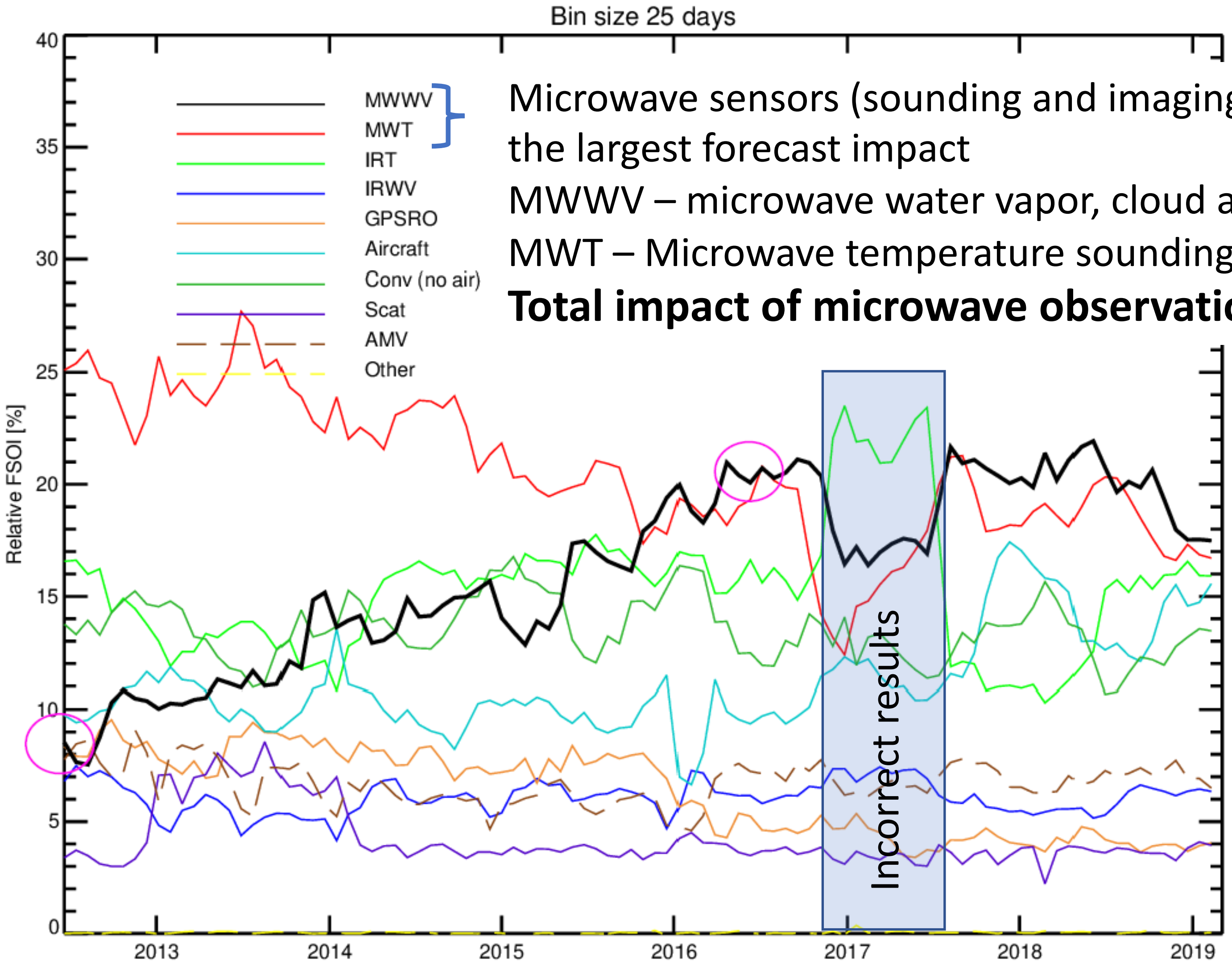


Forecast Sensitivity Observation Impact - ECMWF

Forecast Sensitivity Observation Impact of major observing systems in ECMWF operation

Summer 2006
(from Cardinali, 2009)

Microwave WV	6.2 %
Microwave T	35.5 %
Infrared	28.0 %



Microwave sensors (sounding and imaging, or their combination) have the largest forecast impact

MWWV – microwave water vapor, cloud and precipitation

MWT – Microwave temperature sounding

Total impact of microwave observation – 40.5% (out of 100%)

August 2016

Microwave WV	20.4%
Microwave T	20.1 %
Infrared	21.9 %

Lupu, C. (2019). Data assimilation diagnostics: Assessing the observations impact in the forecast. ECMWF Data assimilation training course.

Beer-Lambert law

Beer-Lambert law

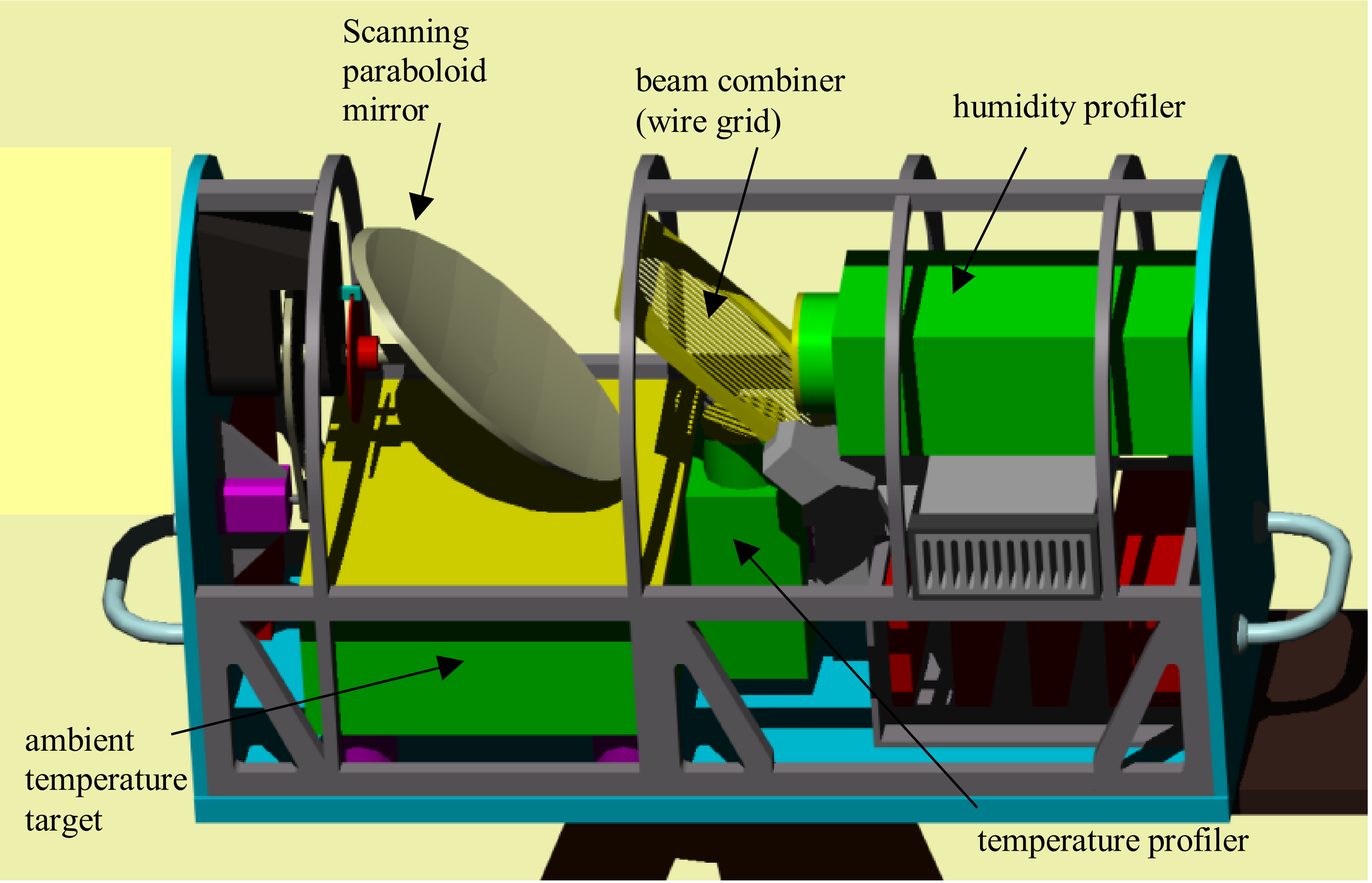
As per Beer-Lambert law, the electromagnetic wave intensity inside a material drops down exponentially from the surface as $I(Z) = I_0\ e\text{-}^{\alpha z}\delta_p = 1/\alpha$ Where δ_p: the penetration depth which describes electromagnetic waves decay inside of a material. The above equation defines the depth at which the power or intensity of the field falls down to 1/e of the surface value. The power of the wave in a certain medium is directly proportional to the square of the field quantity. One may describe the penetration depth at which the amount of the electric field has dropped down to 1/e of the surface value. Also, at which point the wave power has consequently dropped down to $1/e^2$ or nearly 13% of the surface value.

JPL MARS van ~ 1970

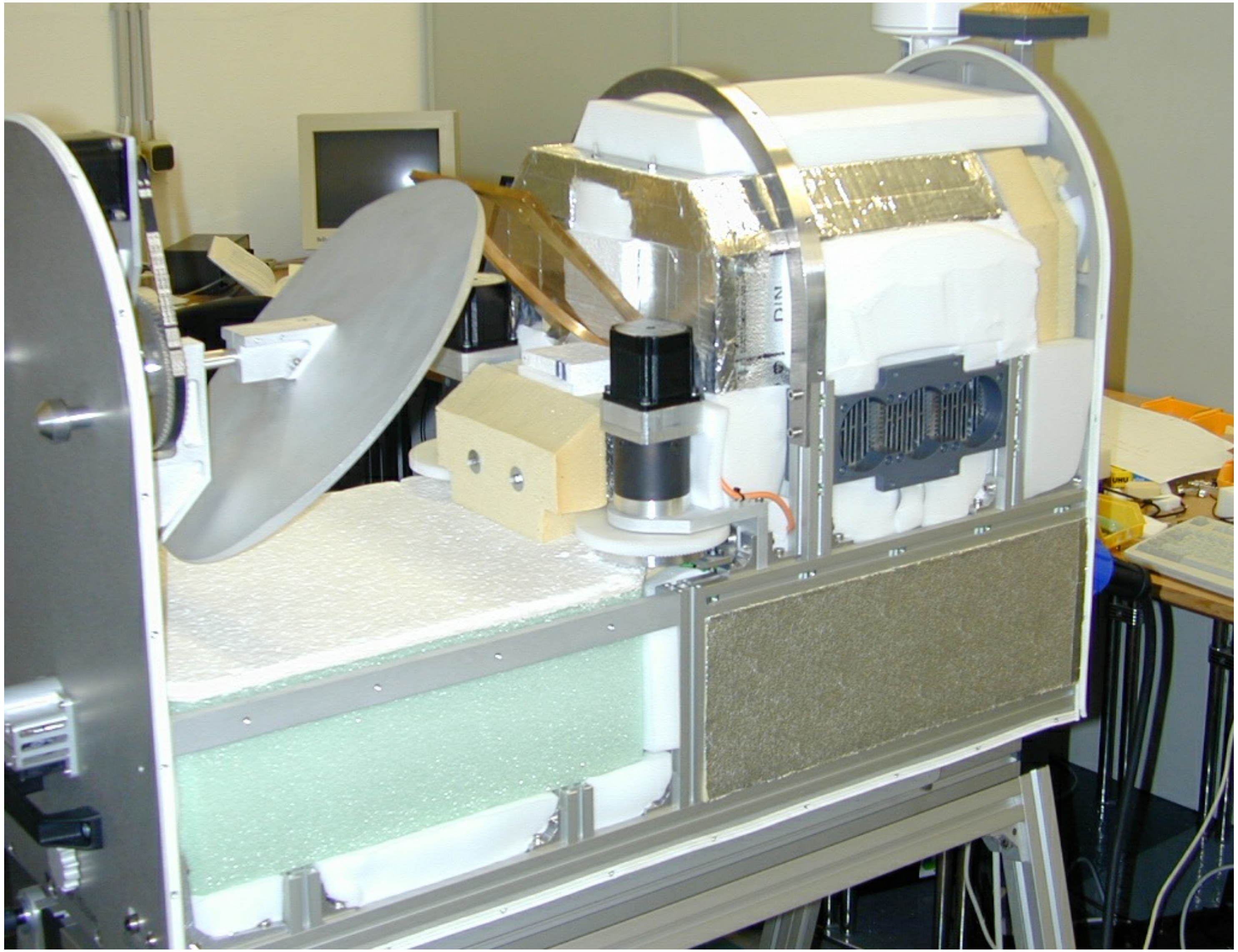
JPL-MARS Van

D-Unit Radiometer

Principle System Layout



Receiver Thermal Stabilization



Team - an engineering company

Jacob Moynihan
Microwave

Angel Madrid
Physicist

Colton Dunlap
Microwave

Wesley Middleton
Microwave

Kurt Ramsdale
Electronics

Marian Klein
CEO

George O’Connor
CNC

Michael Krause
Mechanical

Noah
Security

Madison Eble
Aerospace

Jennifer LaBrecque
Bookkeeping