Modelling the Microwave Radiation of the Moon

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Goal: to find a thermophysical model (TPM) solution which can predict the disk-integrated flux (radiance, brightness temperature) of the Moon, in the microwave (MW) regime, and over a phase angle range between -90° (waxing) and +90° (waning Moon) with high accuracy.

Result: our lunar TPM predicts the Moon's disk-integrated thermal emission with an **absolute accuracy** of better than 3% (157, 183, 190 GHz) and better than 2% (89 GHz) in the -84° to +76° phase angle range.

- Building up on work by Yang, Burgdorf, et al. (2018, 2020, 2022) …

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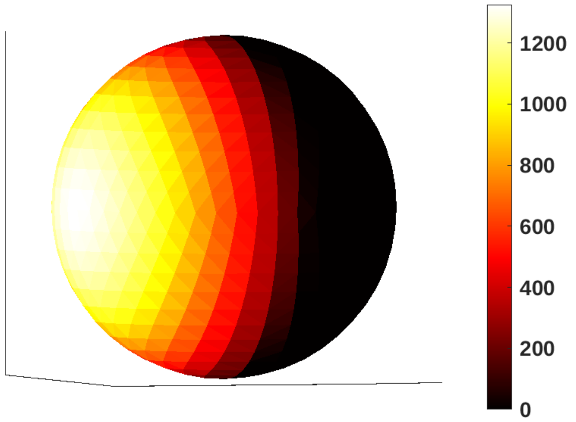
- Based on a well-tested thermophysical model (TPM) adopted for the Moon (Müller et al. 2021)
- About 30 years of experience using TPM predictions of selected well-known asteroids for calibration of IR/submm/mm ground, airborne and space observatories (ISO, Spitzer, Herschel, AKARI, ALMA, SOFIA, partially also JWST)
- The focus is on the interpretation of "disk-integrated" signals (not so much on disk-resolved 2-D maps) in the 89-190 GHz regime
- Tested for a restricted lunar phase angle range from -90° (waxing) $\leqq \alpha \leqq$ +90° (waning), including opposition (α = 0°)

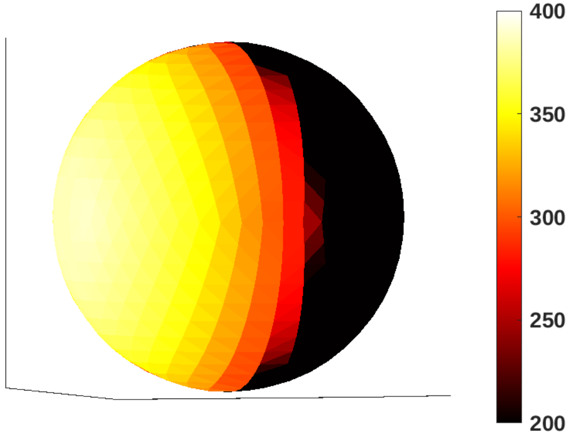
- Building up on work by Yang, Burgdorf, et al. (2018, 2020, 2022) …

Thermophysical Model (TPM)

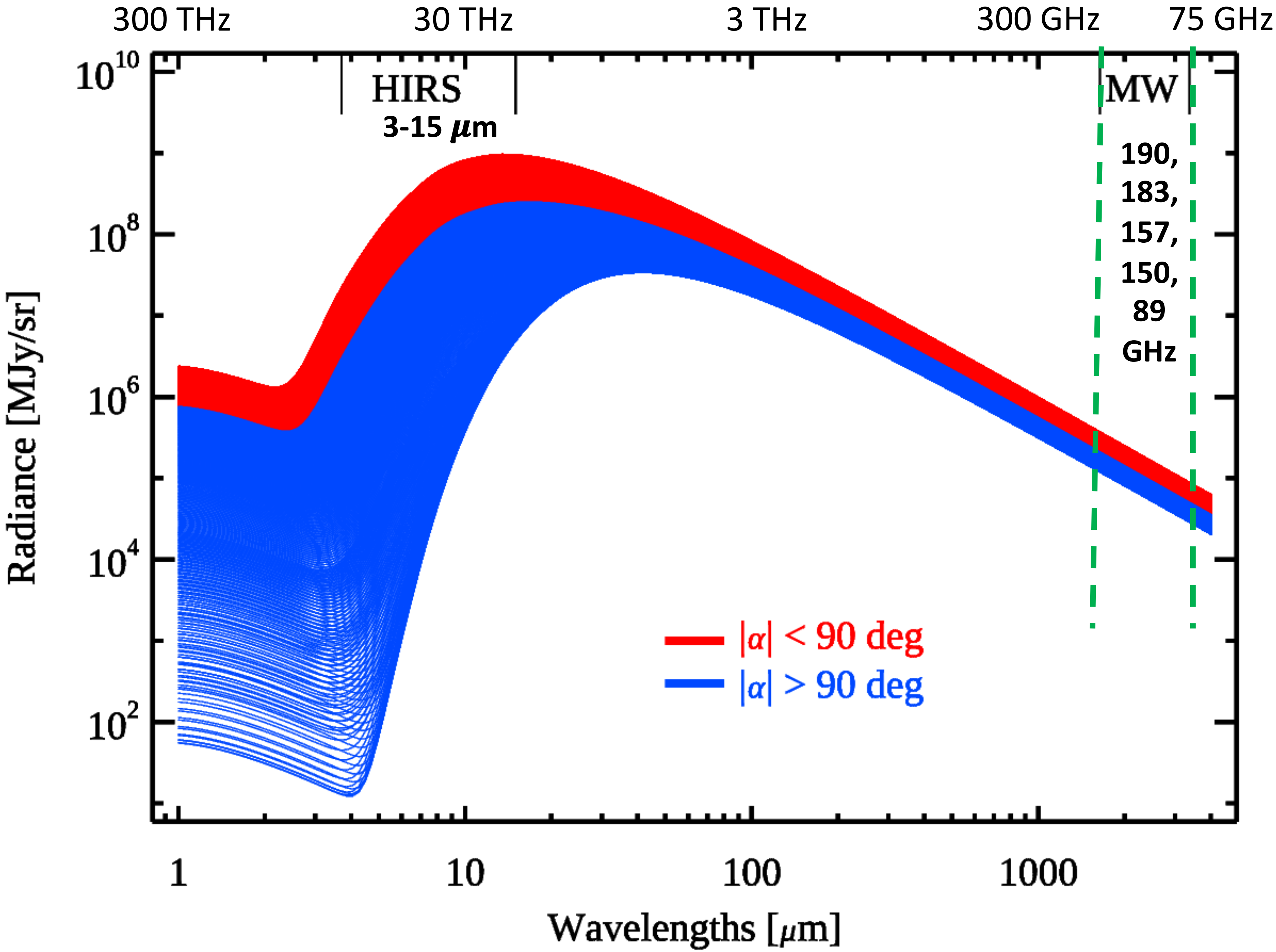
- **Model references:**
  - Lagerros (1996, 1997, 1998); Müller & Lagerros (1998, 2002); Müller (2002)
  - Müller, Burgdorf et al. (2021): "The Moon at thermal infrared wavelengths: a benchmark for asteroid thermal models", A&A 650, A38
- **Model aspects:**
  - uses the true illumination and observing geometry (as seen from satellite)
  - considers 1-d heat conduction, shadowing and self-heating
  - Moon is modelled as an oblate spheroid with r_{equ}=1738.1 km and r_{pol}=1736.0 km (r_{equ}/r_{pol} = 1.0012), spin pole at $(\lambda,\beta)_{ecl}$ = (88.43°, 214.45°), P_{syn} = 29.530589 days, with a thermal inertia of 55 tiu (Hayne et al. 2017), and a surface roughness of 32° (Rozitis & Green 2012; Bandfield et al. 2015), absolute magnitude of -0.089 mag (Bowell et al. 1989), and a phase integral of q=0.43 (Muinonen et al. 2010), visual geometric albedo 0.12 (NASA Moon factsheet)
  - Bolometric and spectroscopic (hemispherical) emissivities
- **What is less important for disk-integrated TPM predictions in the MW regime?**
  - Details of the surface (structural details like craters, maria/highlands, compositional details, albedo variations)
  - Roughness (very low influence in the micro-wavelength regime)

Illumination [Wm^{-2}]





Temperature [K]



300 THz
30 THz
3 THz
300 GHz
75 GHz
HIRS
3-15 μm
MW
190,
183,
157,
150,
89
GHz
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
Radiance [MJy/sr]
$|\alpha| < 90$ deg
$|\alpha| > 90$ deg
1
10
100
1000
Wavelengths [μm]

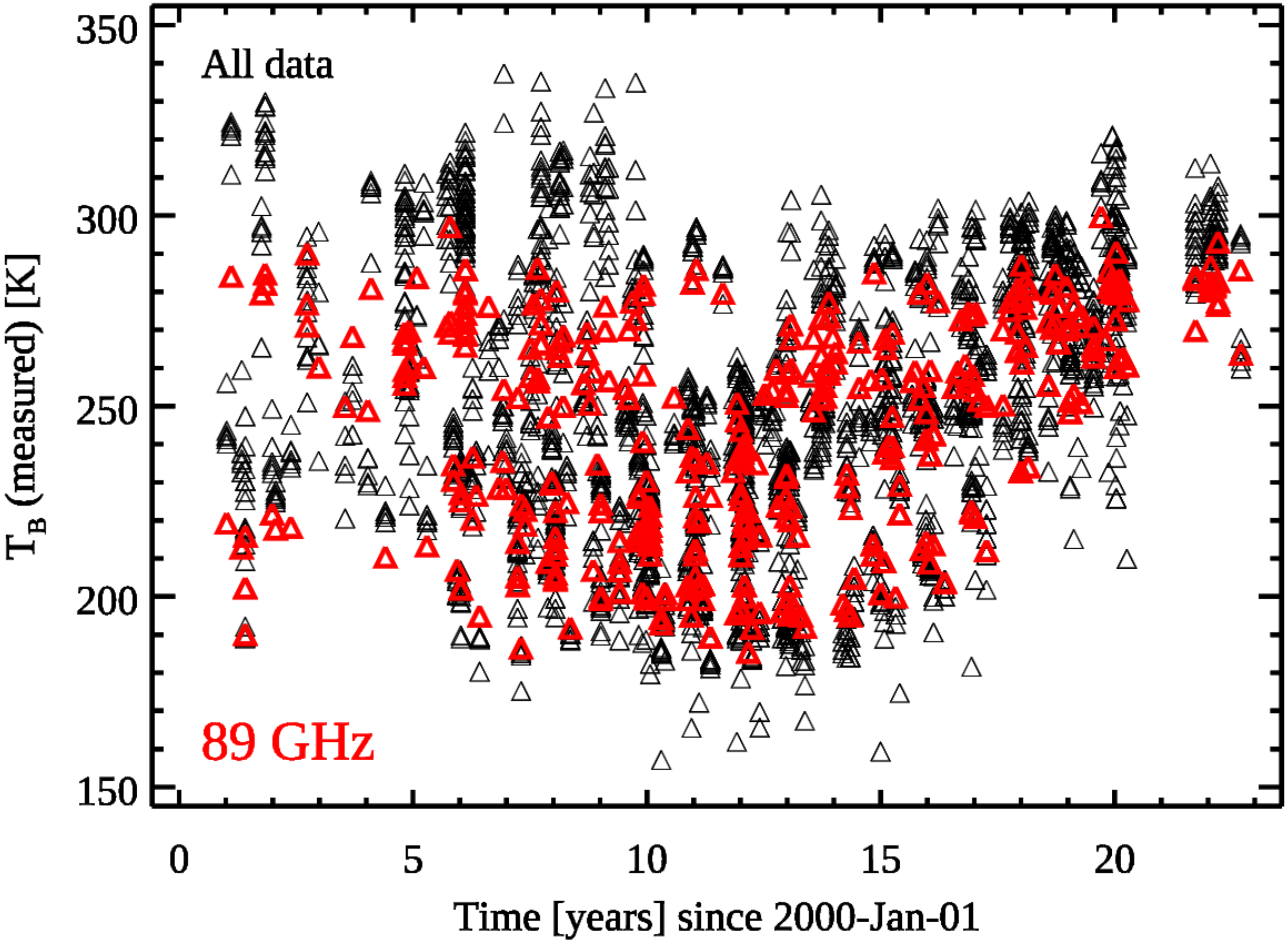
Microwave measurements

- **Which MW data were used?** (provided by Martin Burgdorf)
  - NOAA-15, NOAA-16, NOAA-17: AMSU-B at 89 (ch16), 150 (ch17), 183 GHz (ch18/19/20)
  - NOAA-18, NOAA-19: MHS at 89 (H1), 157 (H2), 183 (H3,H4), 190 GHz (H5)
  - Metop-A, Metop-B, Metop-C: MHS at 89 (H1), 157 (H2), 183 (H3,H4), 190 GHz (H5)
  - 384 data points at 89 GHz, 88 at 150 GHz, 293 at 157 GHz, 691 at 183 GHz, 298 at 190 GHz, **∑ = 1754 individual points**

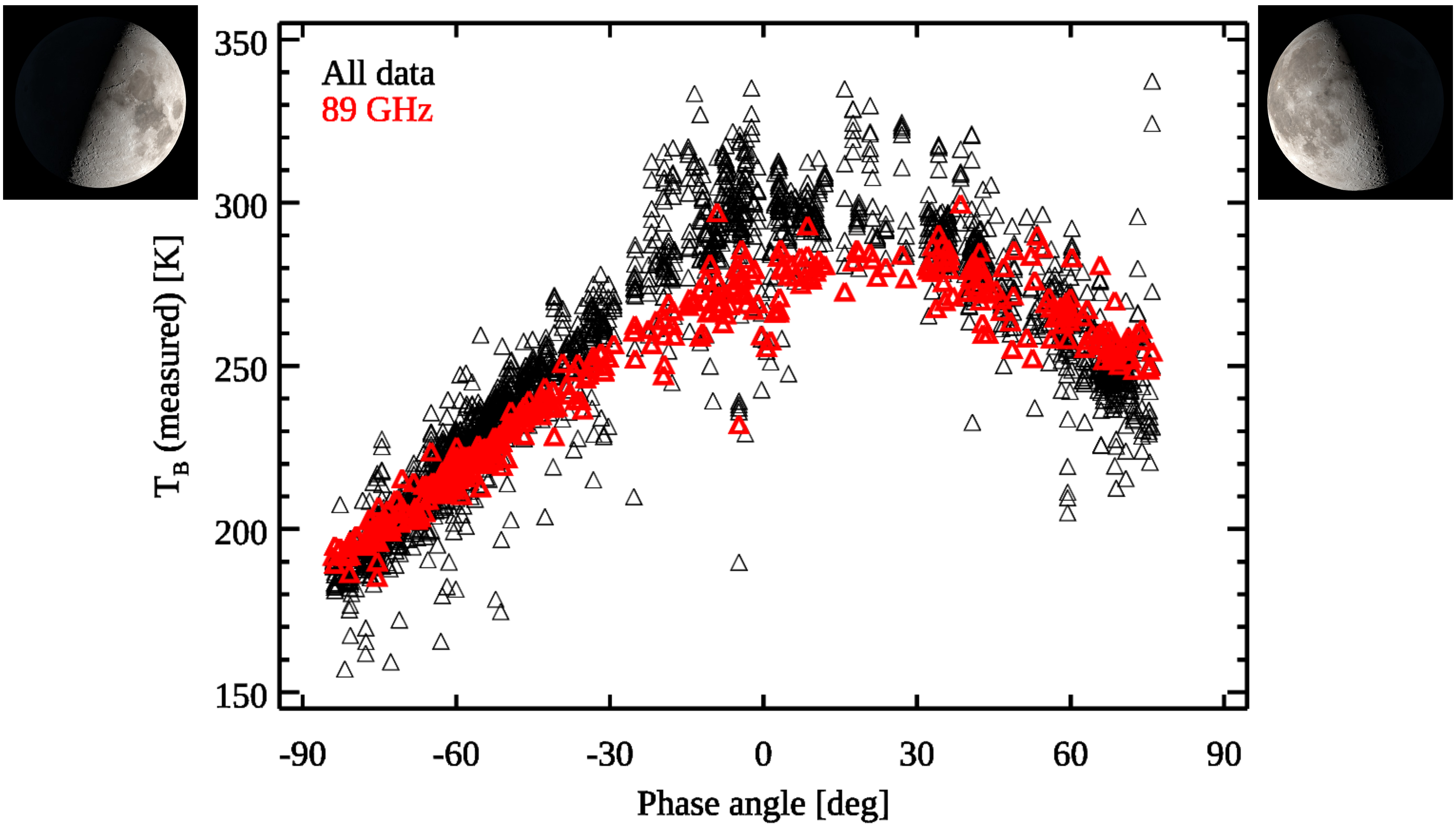
- **Observing geometries:**
  - Covering the time period between Jan 2001 to Sep 2022
  - Phase angle: -84.0° (waxing) $\leqq \boldsymbol{\alpha} \leqq$ +75.9° (waning)
  - Moon's heliocentric distance: 0.9838 au < r_{helio} < 1.0181 au,
  - Moon's geocentric distance (apparent size in arcsec): 356999 km < Δ < 406164 km
  - Apparent size: 1764.6 arcsec < Ø < 2007.7 arcsec
  - Aspect angle: 83.3° (including North pole) < γ < 96.7° (including South pole)

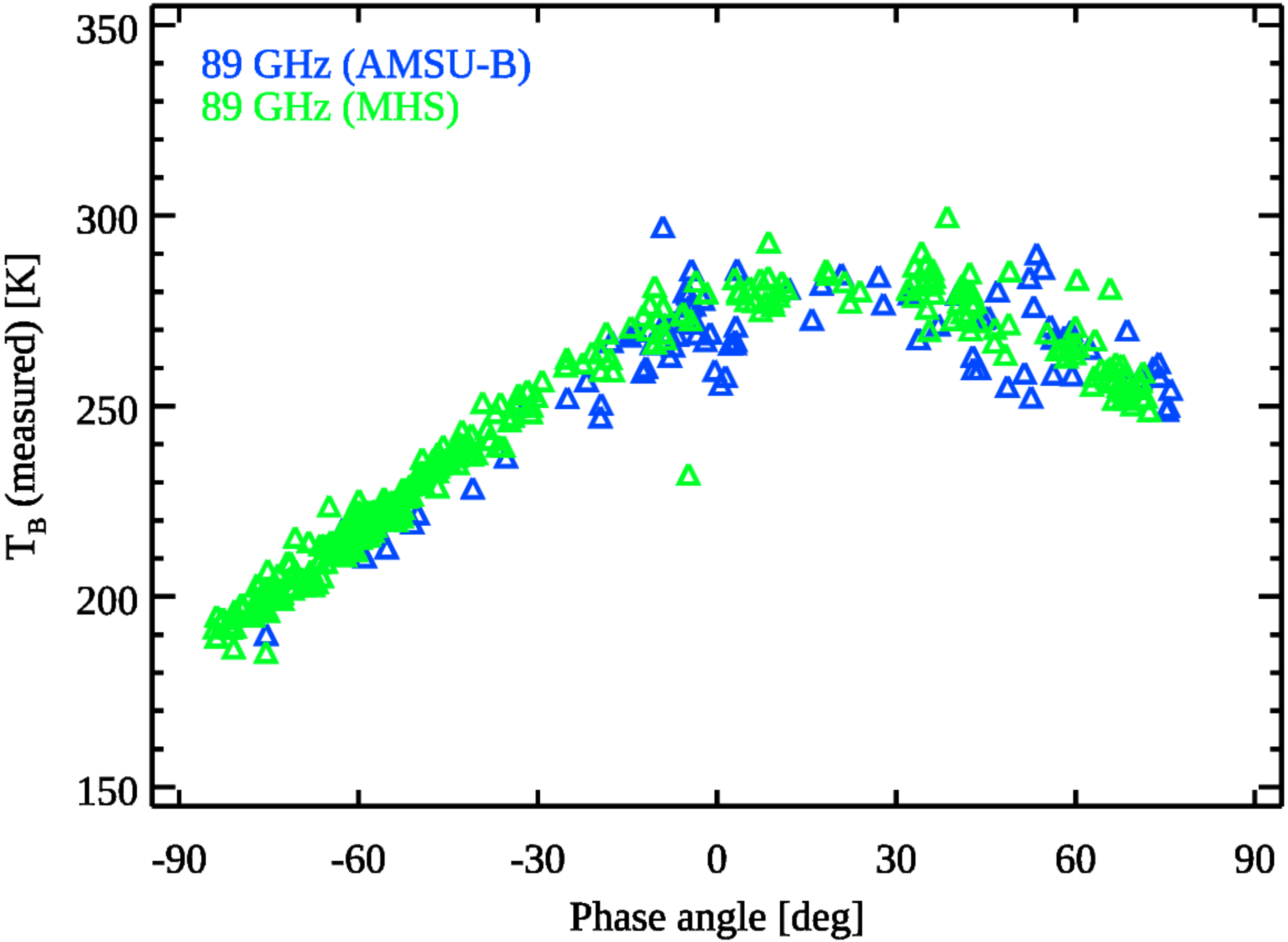
- **Measured quantities:** radiance [MJy/sr] or [$Wm^{-2}Hz^{-1}sr^{-1}$], translated into brightness temperature T_B [K] and in-band flux [$Wm^{-2}\mu m^{-1}$] or monochromatic flux density [Jy]

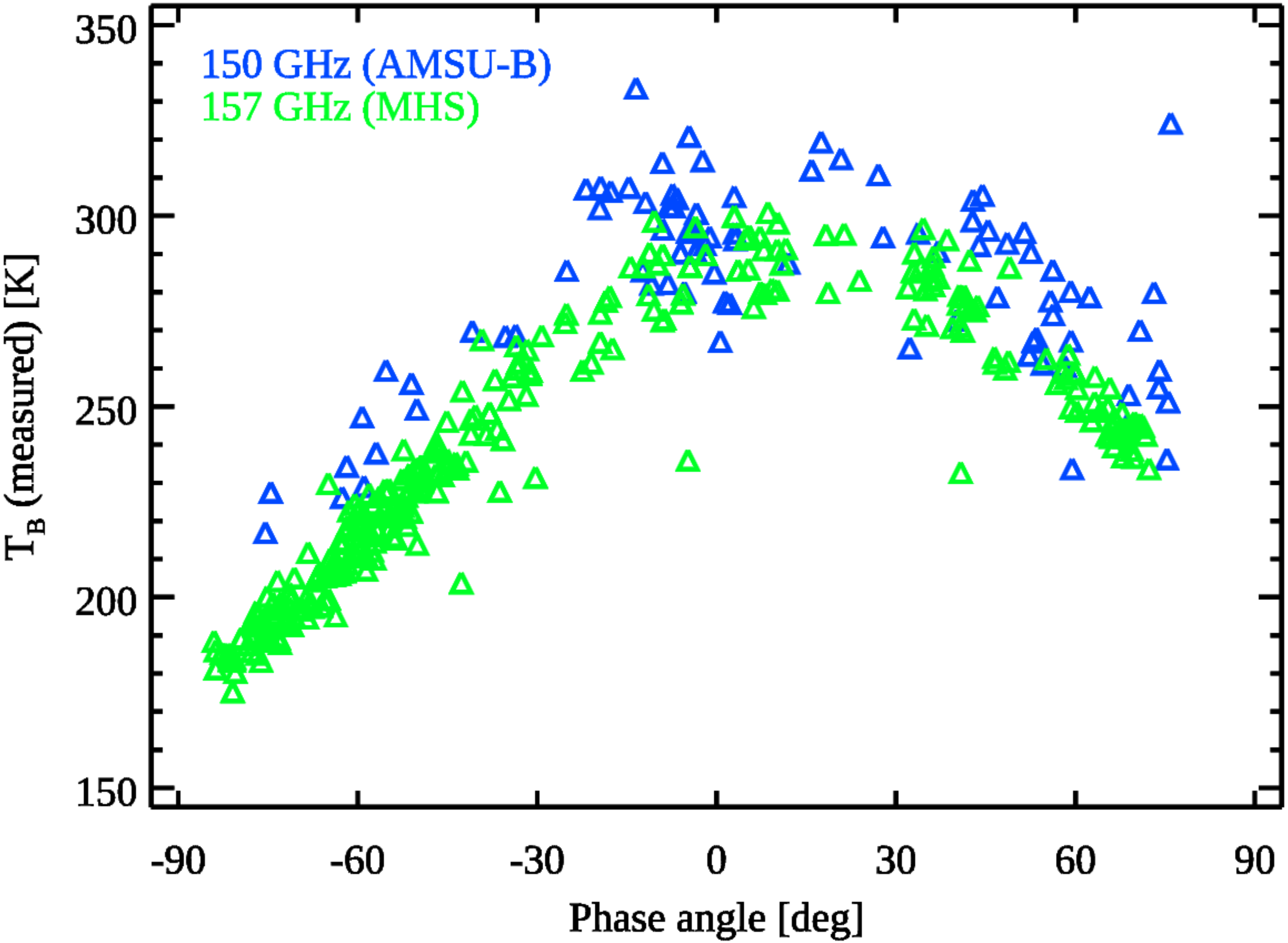
Microwave measurement overview

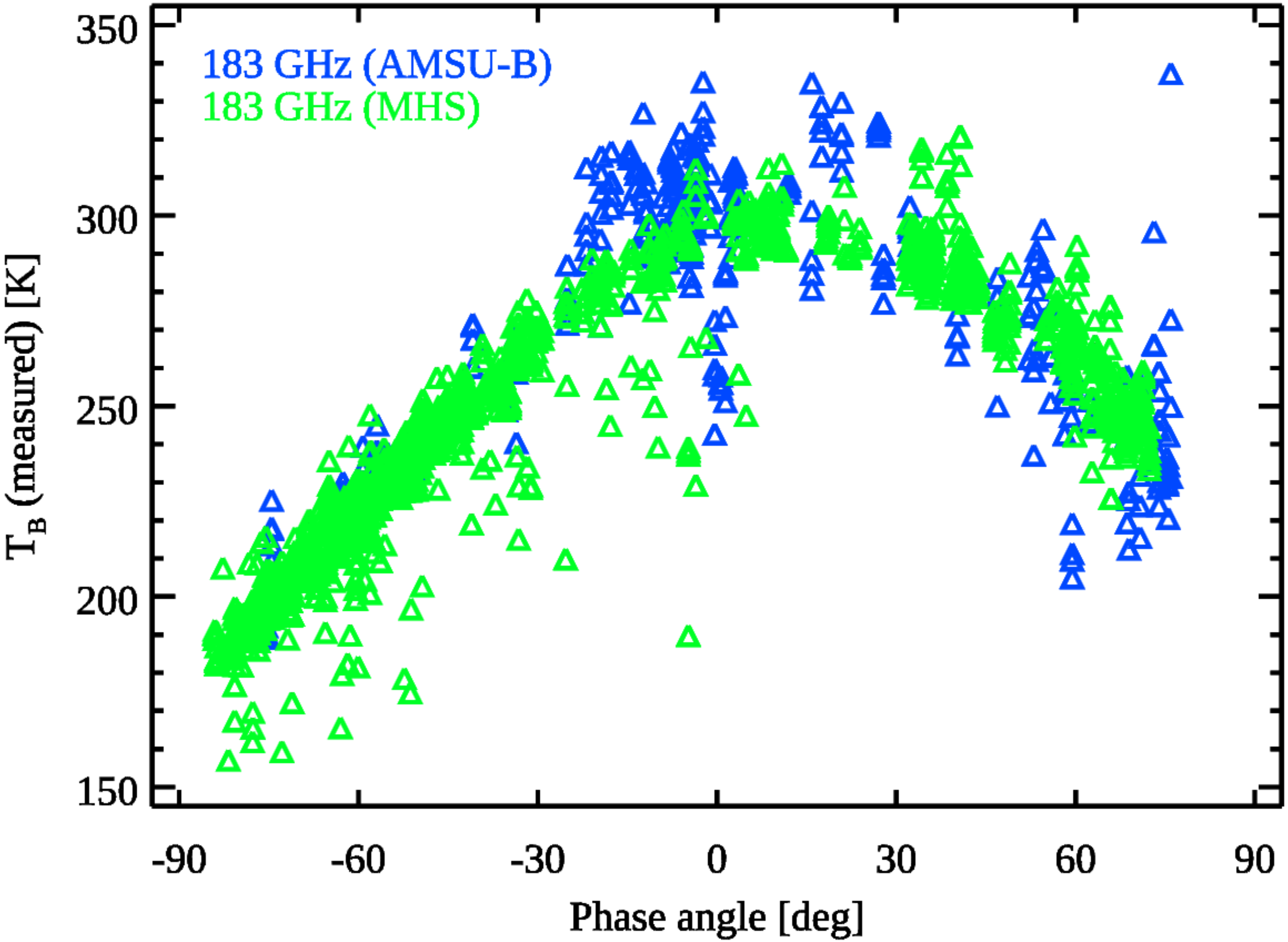


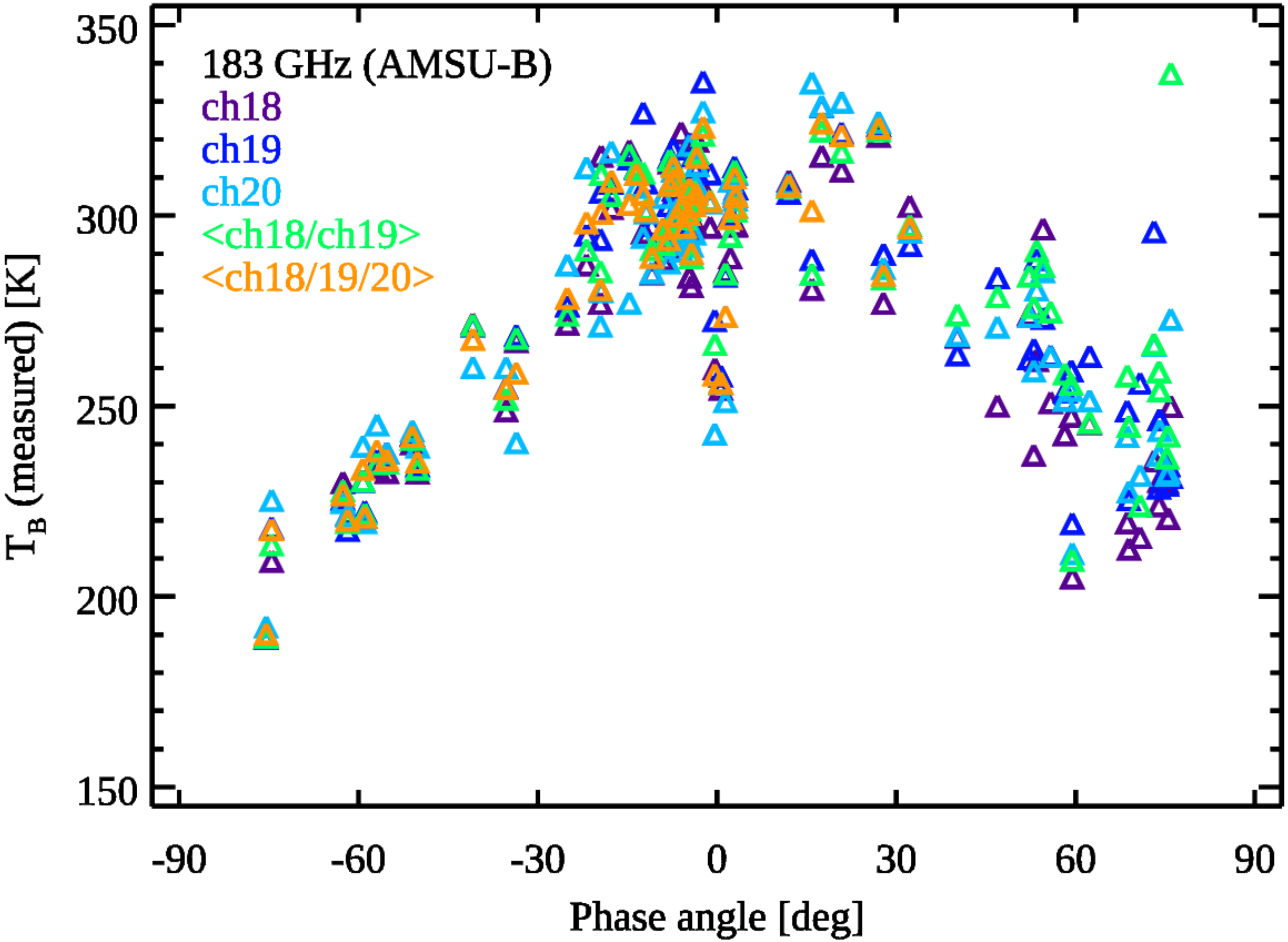
All data
89 GHz
350
300
250
200
150
T_B (measured) [K]
0
5
10
15
20
Time [years] since 2000-Jan-01

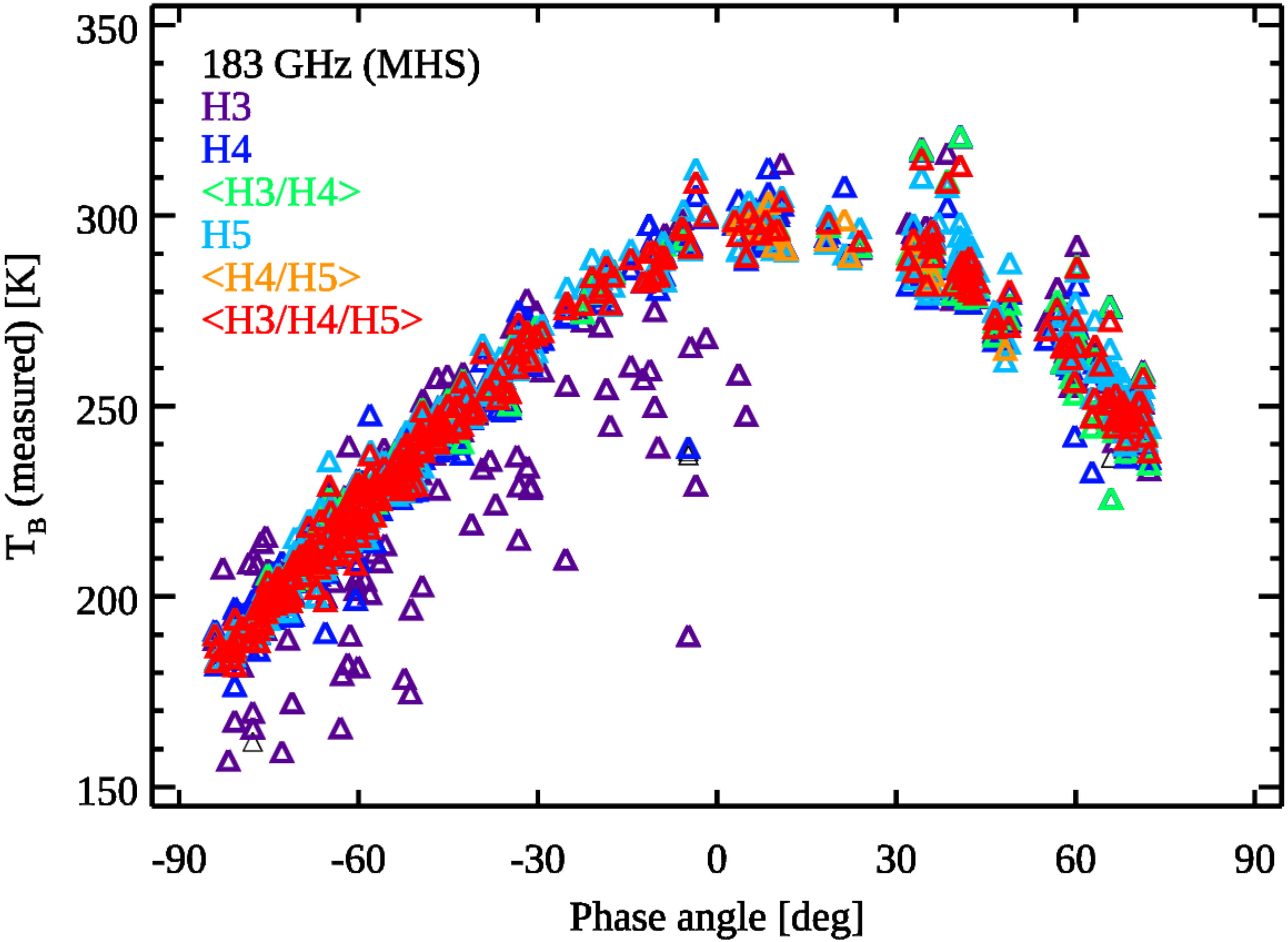

All data
89 GHz
350
300
250
200
150
T_B (measured) [K]
-90
-60
-30
0
30
60
90
Phase angle [deg]


89 GHz (AMSU-B)
89 GHz (MHS)
350
300
250
200
150
-90
-60
-30
0
30
60
90
T_B (measured) [K]
Phase angle [deg]

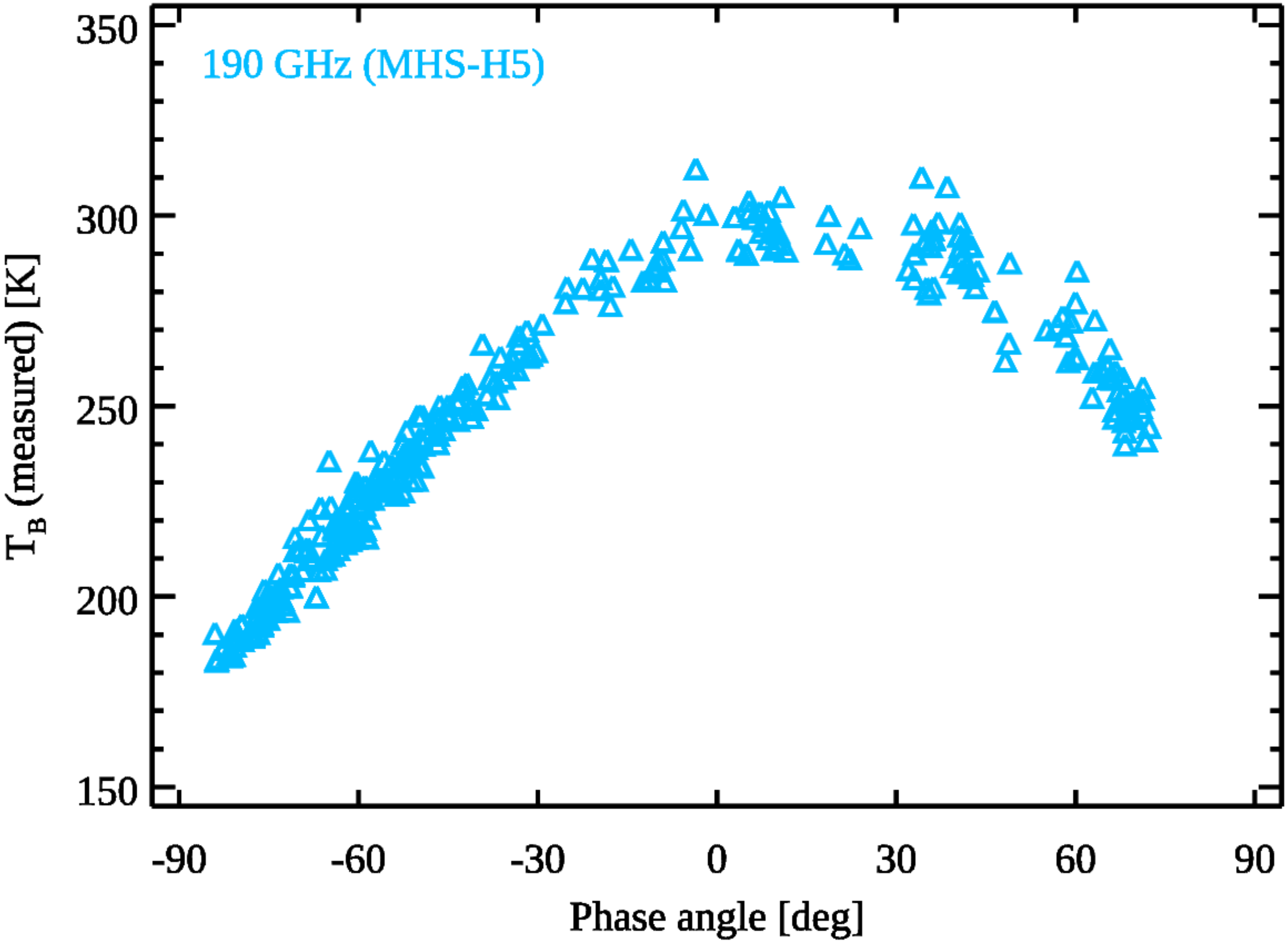

150 GHz (AMSU-B)
157 GHz (MHS)
350
300
250
200
150
T_B (measured) [K]
-90
-60
-30
0
30
60
90
Phase angle [deg]


183 GHz (AMSU-B)
183 GHz (MHS)
350
300
250
200
150
T_B (measured) [K]
-90
-60
-30
0
30
60
90
Phase angle [deg]


183 GHz (AMSU-B)
ch18
ch19
ch20
<ch18/ch19>
<ch18/19/20>
350
300
250
200
150
-90
-60
-30
0
30
60
90
T_B (measured) [K]
Phase angle [deg]



183 GHz (MHS)
H3
H4
<H3/H4>
H5
<H4/H5>
<H3/H4/H5>
T_B (measured) [K]
Phase angle [deg]
350
300
250
200
150
-90
-60
-30
0
30
60
90

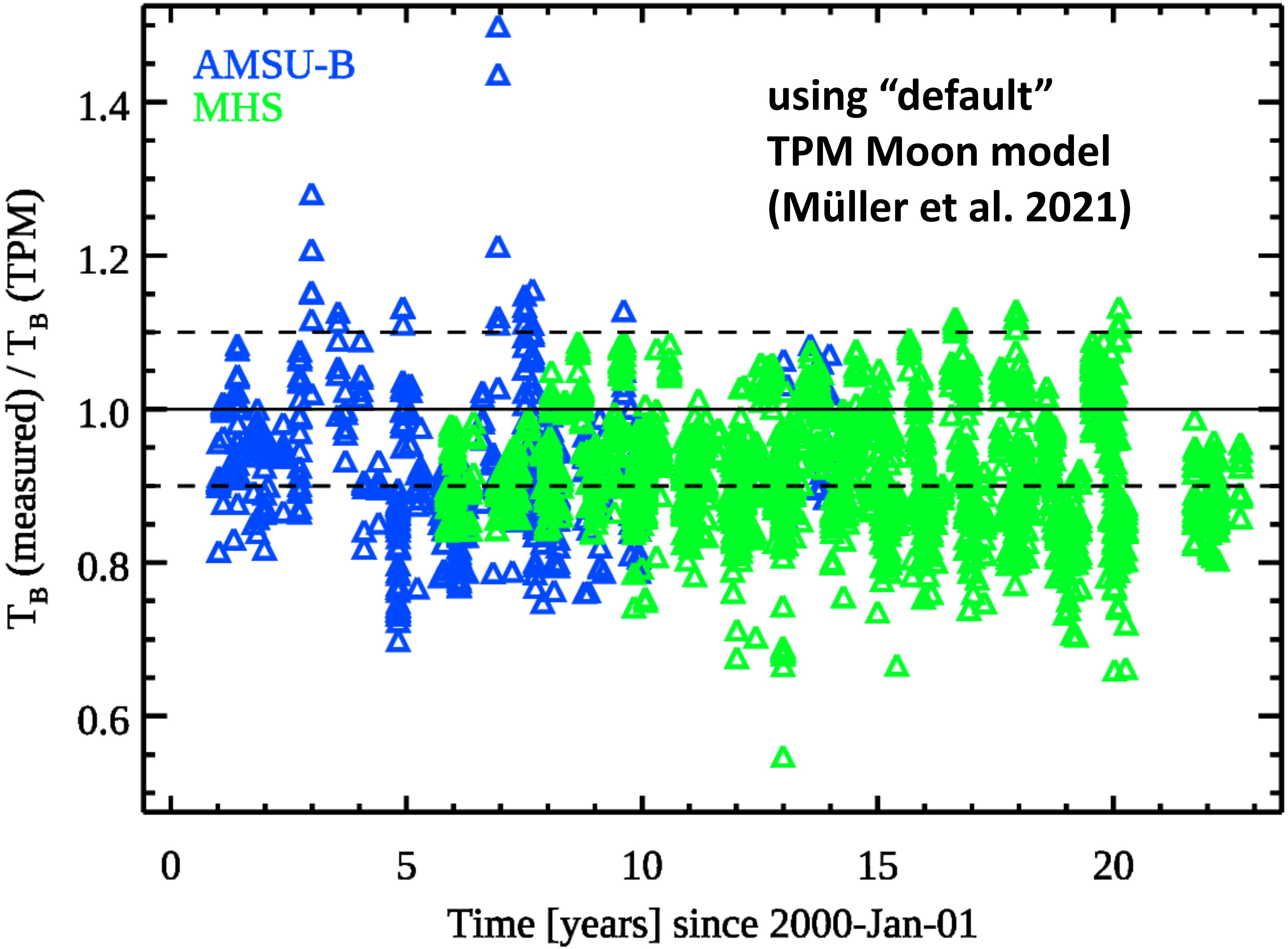


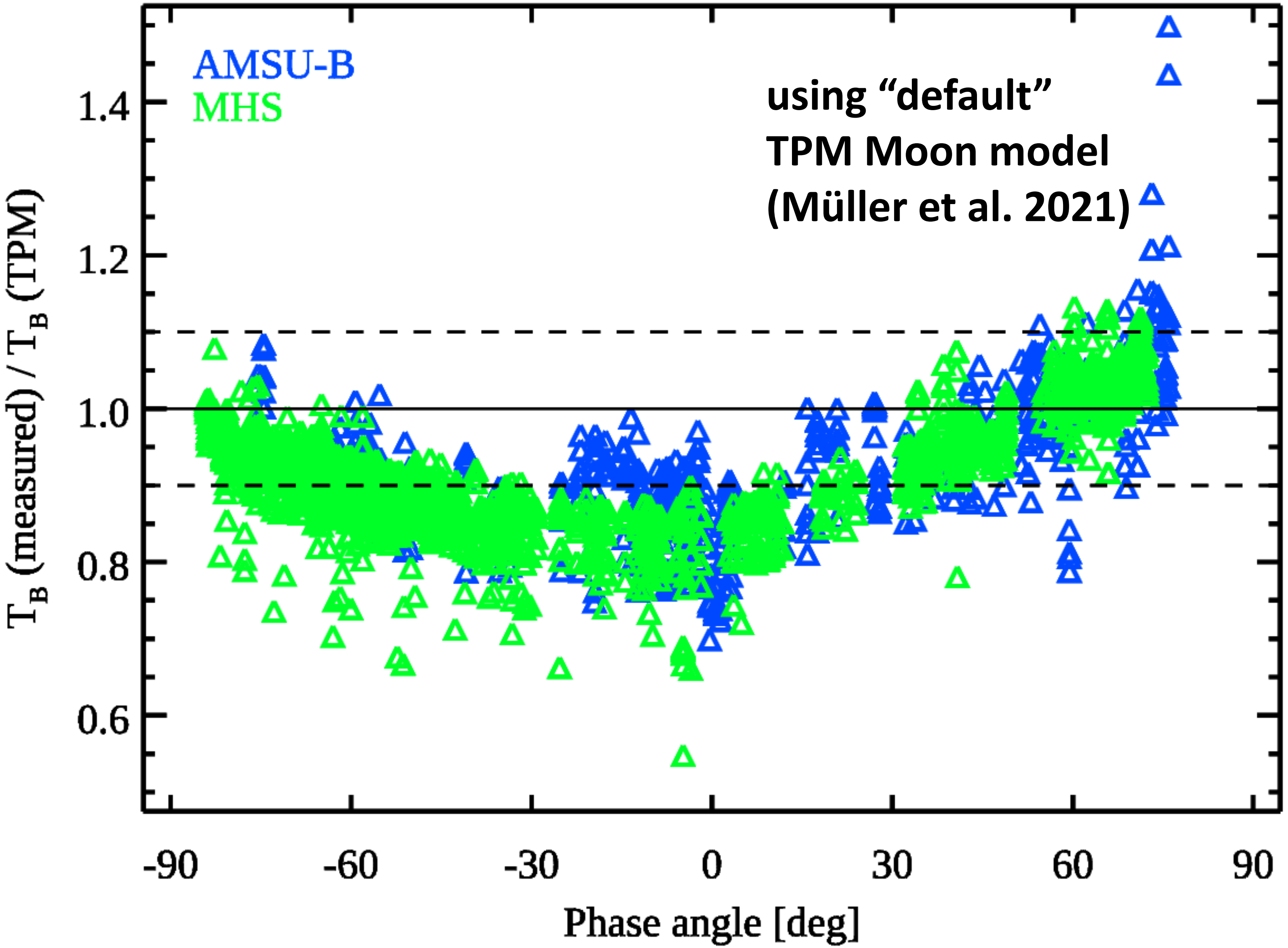
190 GHz (MHS-H5)
350
300
250
200
150
T_B (measured) [K]
-90
-60
-30
0
30
60
90
Phase angle [deg]

Notes on the MW brightness temperatures

- The measured T_B values go up to about 300-325 K, depending on the frequency and ignoring some outliers
- AMSU-B data show in general a lager scatter, indicating lower measurement quality (no explicit errors are given)
- Some data sets have an unequal coverage in phase angle range
- The highest T_B values are reached at lowest heliocentric distance of the Moon (r_{helio}= 0.98 au)
- Fits to the T_B vs phase angle α plots (at 89, 150/157, 183/190 GHz) give T_B(max) phase angles of about 13°…25° deg (30-60 hours after full moon)
- But these fits are not very accurate: the Moon's heliocentric and observer-centric distance can be different, also the aspect angle can vary, leading to different T_B values for the same phase angle!

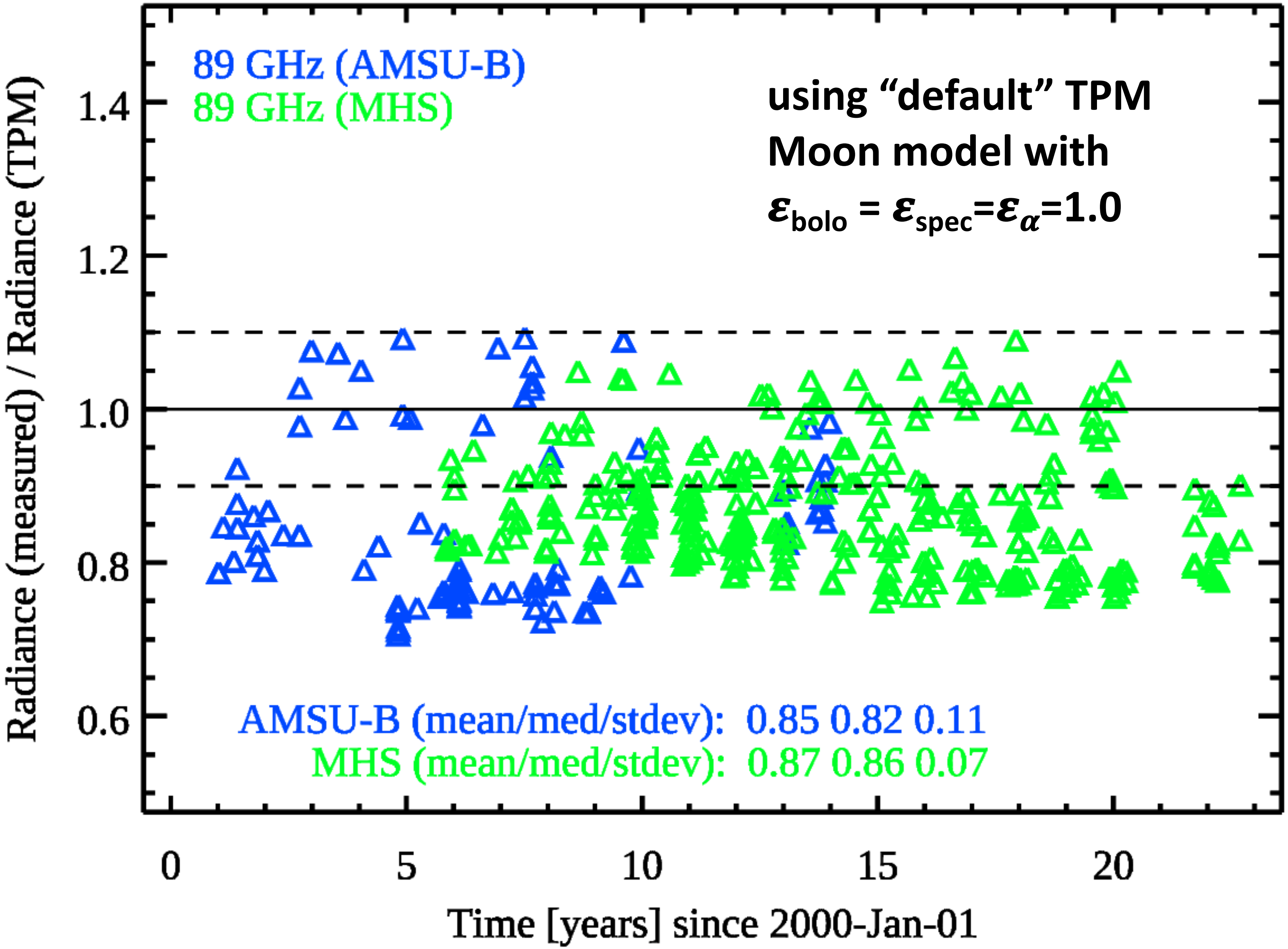
Comparison between MW measurement and TPM predictions


AMSU-B
MHS
using "default"
TPM Moon model
(Müller et al. 2021)
1.4
1.2
1.0
0.8
0.6
T_B (measured) / T_B (TPM)
0
5
10
15
20
Time [years] since 2000-Jan-01

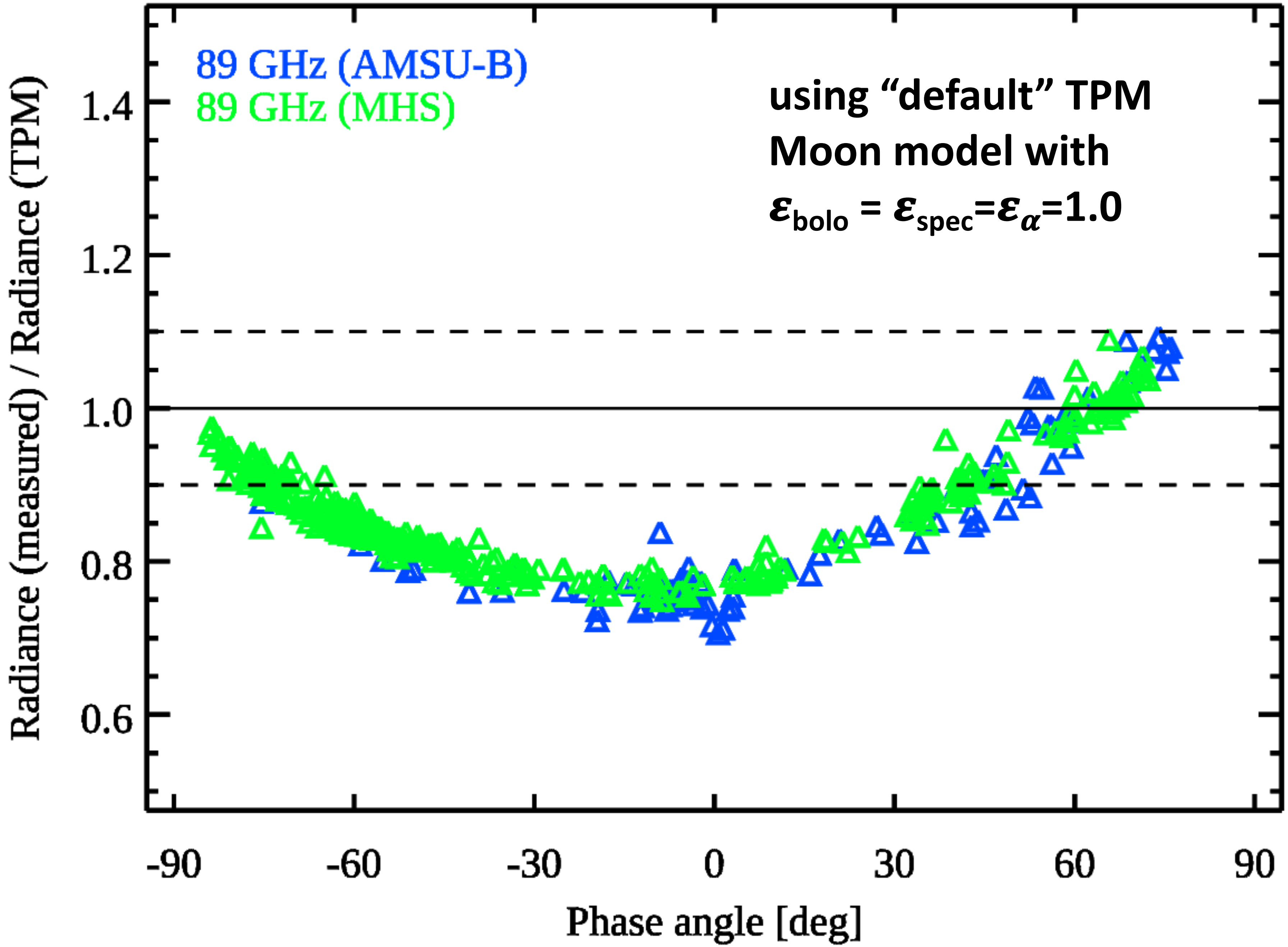

AMSU-B
MHS
using “default”
TPM Moon model
(Müller et al. 2021)
1.4
1.2
1.0
0.8
0.6
T_B (measured) / T_B (TPM)
-90
-60
-30
0
30
60
90
Phase angle [deg]

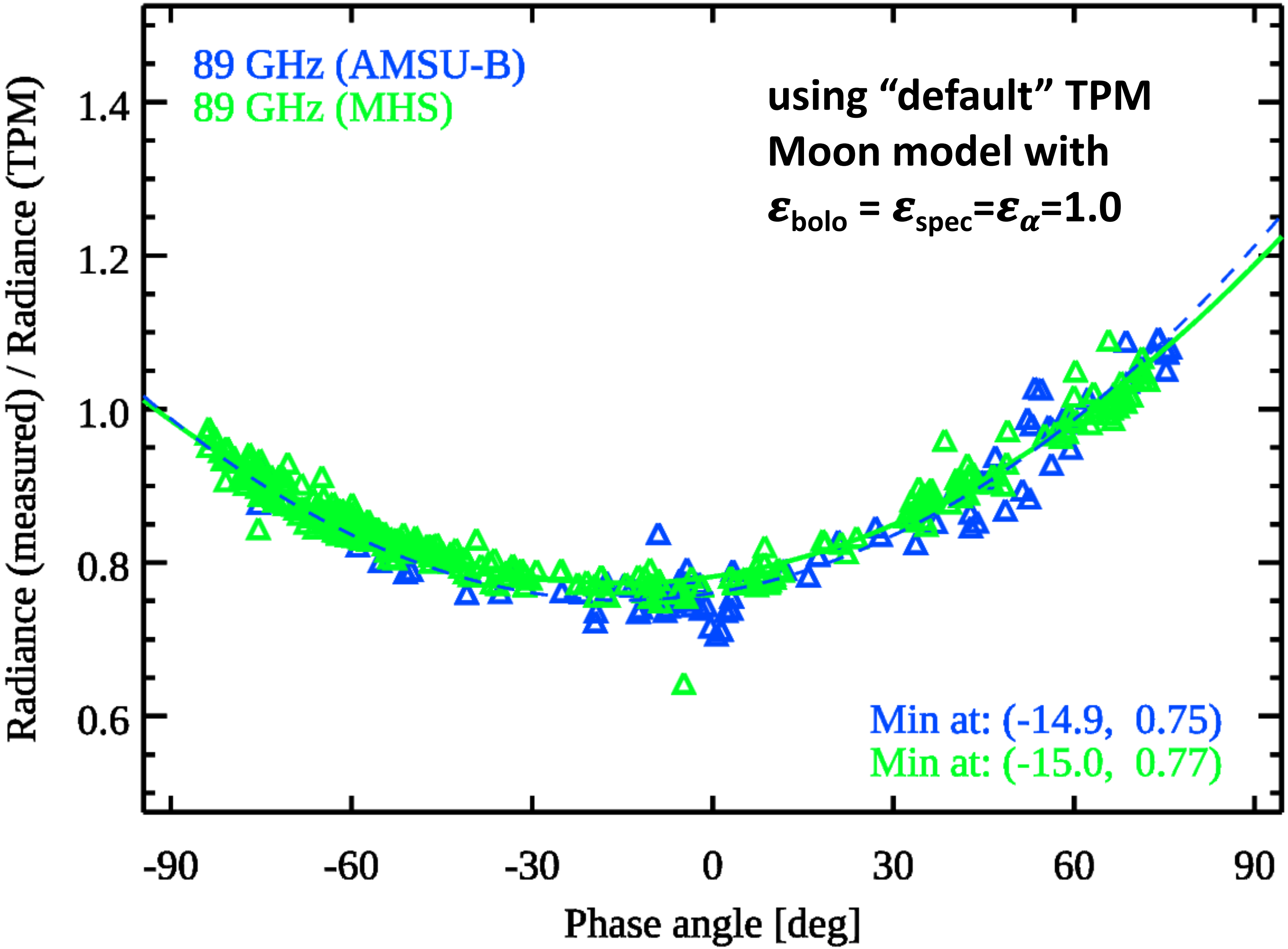
Comparison between MW measurement and TPM predictions

- ”Default” TPM Moon model (validated at IR wavelengths) is not a great solution (mean Obs/TPM ratio is 0.92) and shows a mismatch which has a phase angle dependency
- Handling individual frequencies separately
- Switching from T_B [K] to radiance [MJy/sr] or [$Wm^{-2}Hz^{-1}sr^{-1}$] (closer to measured quantities)
- **Goal:** to determine the MW emissivity phase function (hemispherical effective emissivity in the MW regime)

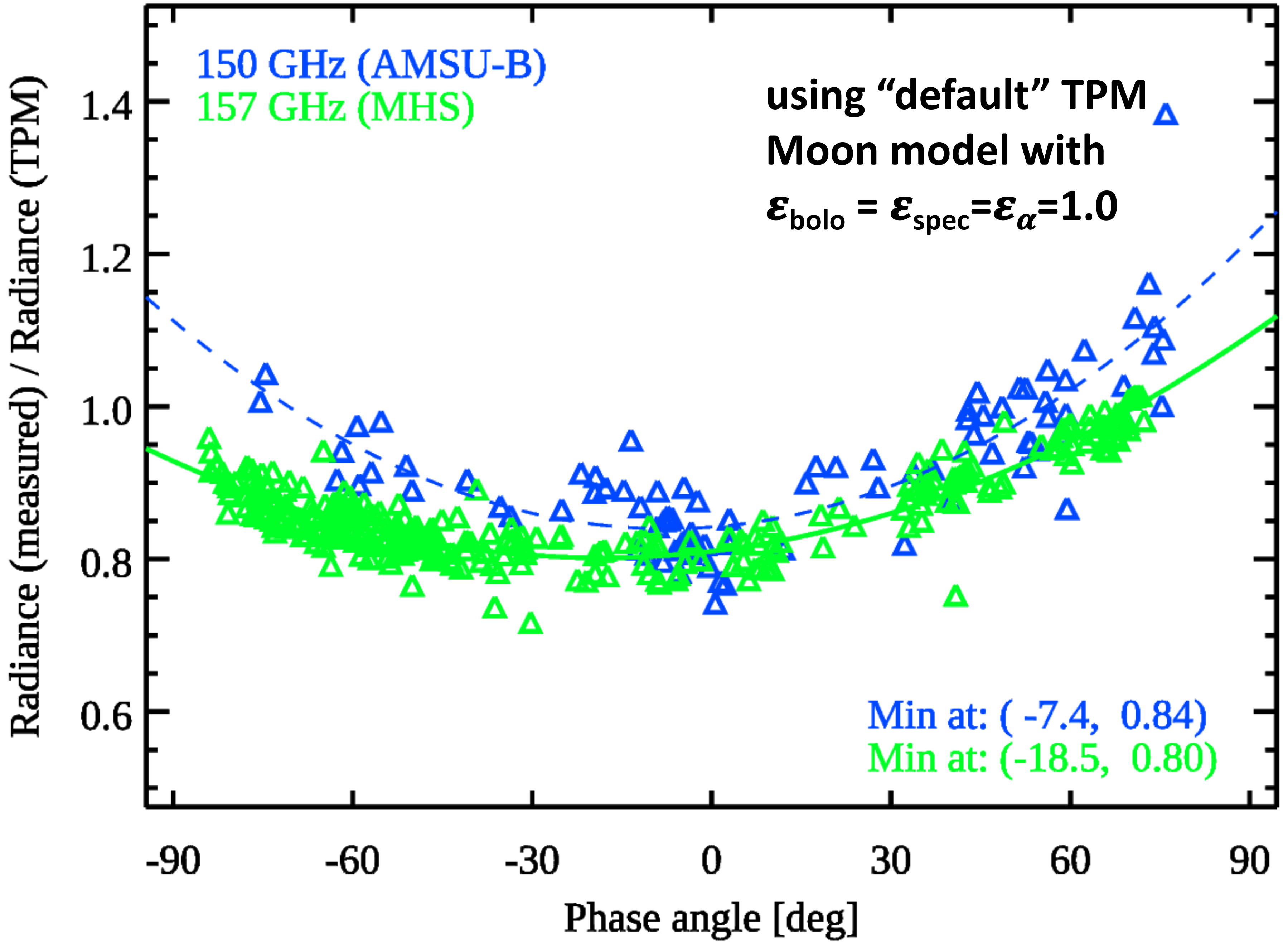


89 GHz (AMSU-B)
89 GHz (MHS)
using "default" TPM
Moon model with
$\varepsilon_{bolo} = \varepsilon_{spec} = \varepsilon_{\alpha} = 1.0$
AMSU-B (mean/med/stdev): 0.85 0.82 0.11
MHS (mean/med/stdev): 0.87 0.86 0.07
Radiance (measured) / Radiance (TPM)
Time [years] since 2000-Jan-01

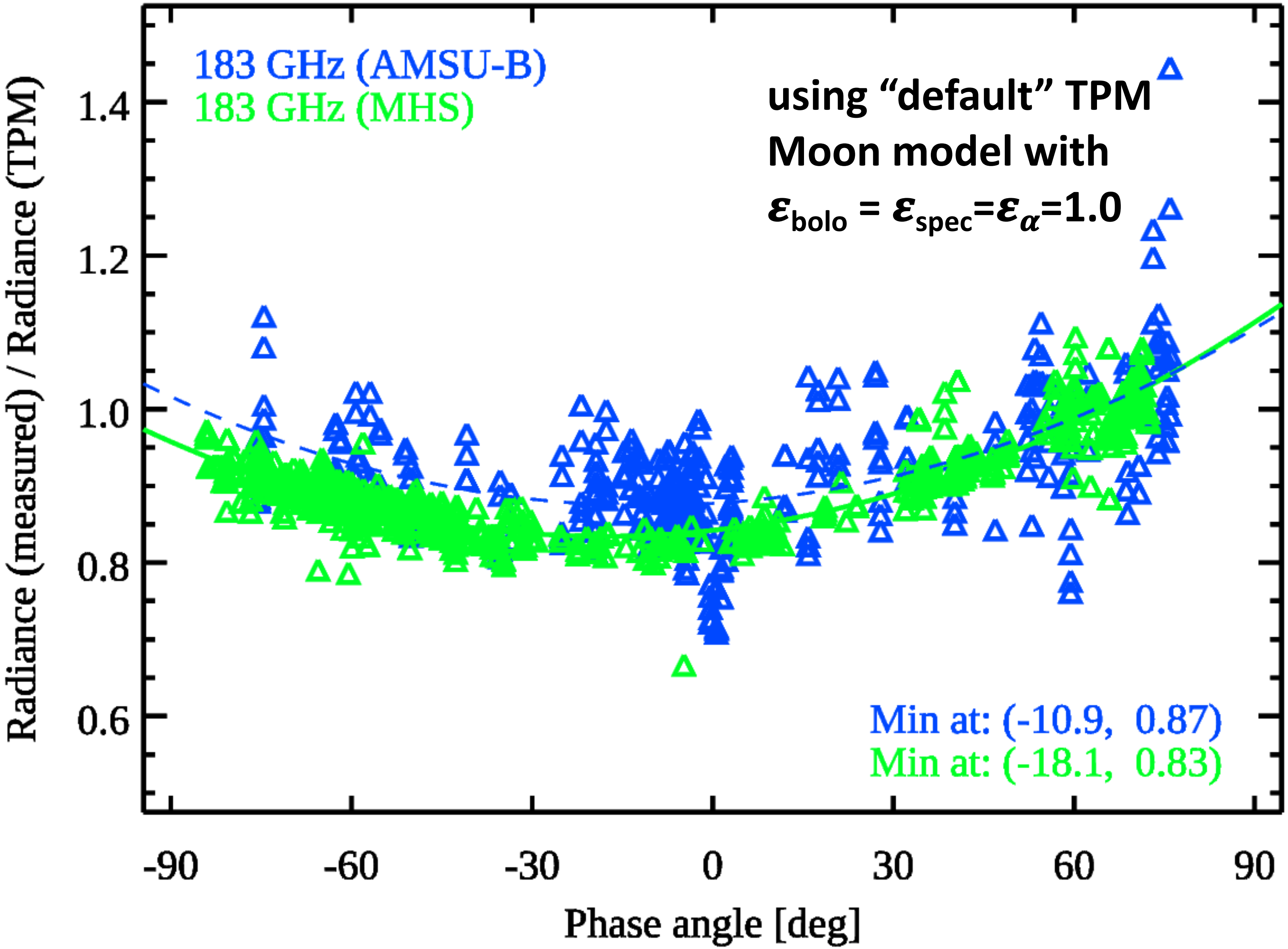

89 GHz (AMSU-B)
89 GHz (MHS)
using “default” TPM
Moon model with
ε_{bolo} = ε_{spec}=ε_{α}=1.0
Radiance (measured) / Radiance (TPM)
1.4
1.2
1.0
0.8
0.6
-90
-60
-30
0
30
60
90
Phase angle [deg]

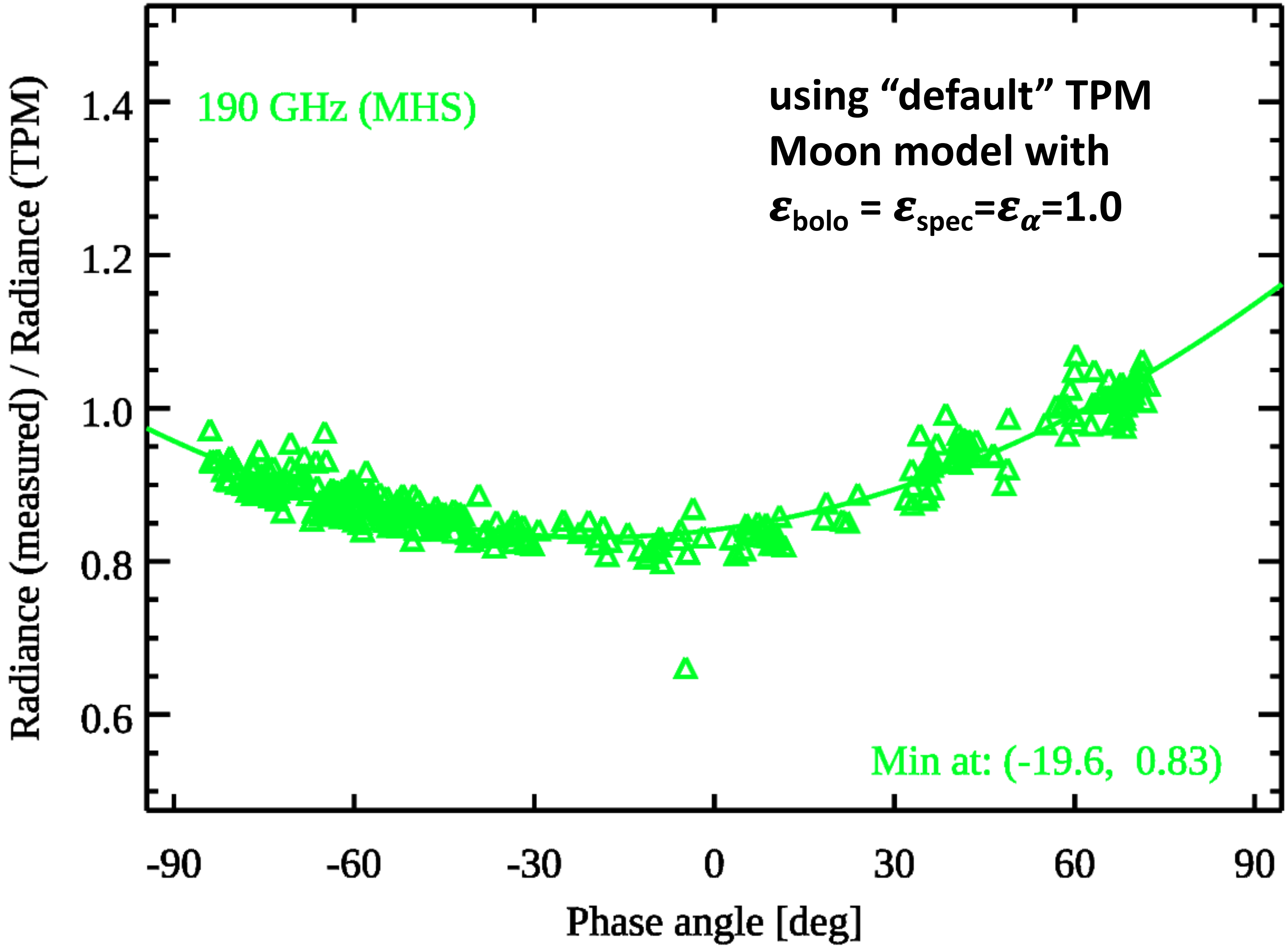


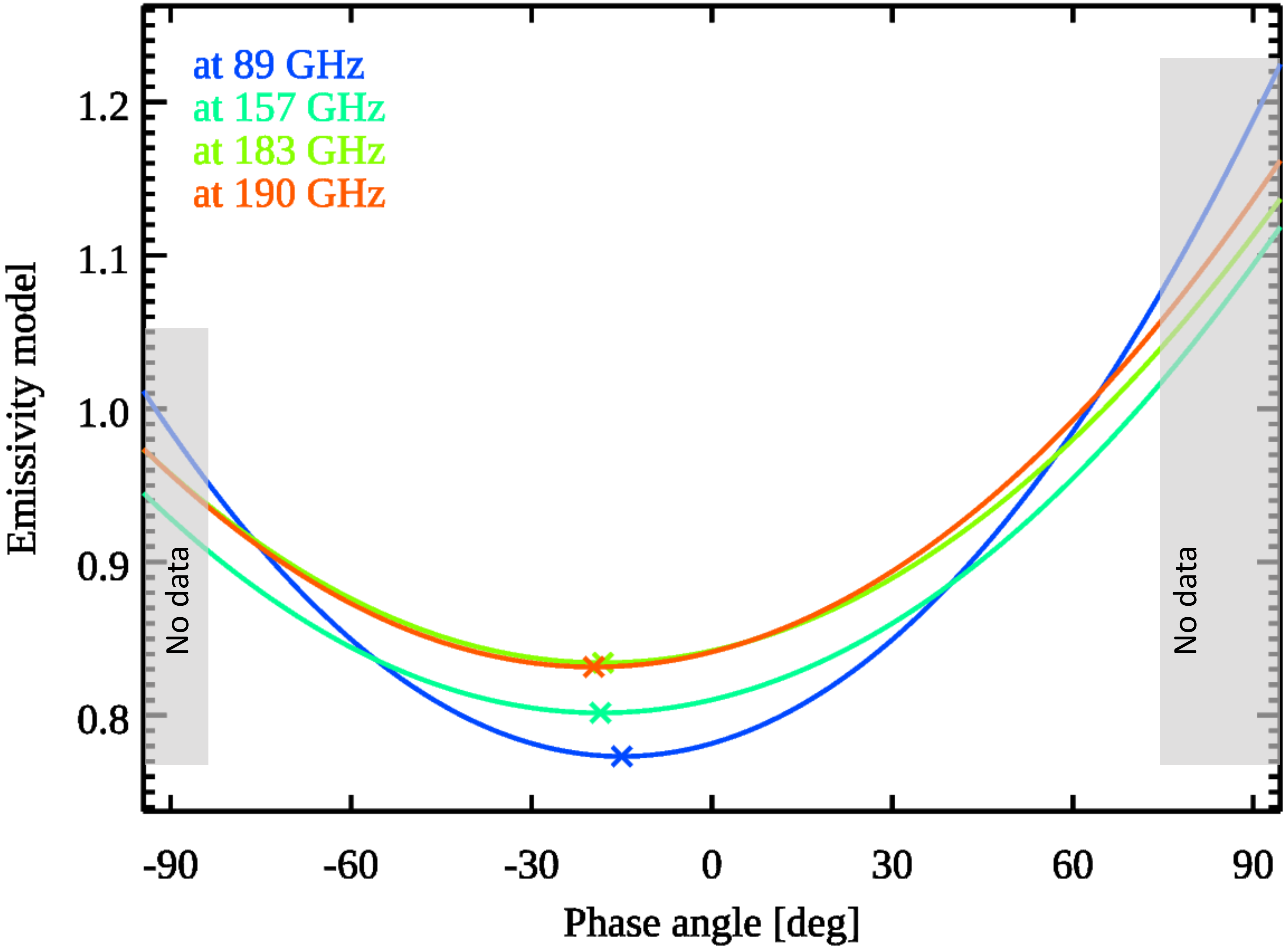
89 GHz (AMSU-B)
89 GHz (MHS)
using “default” TPM
Moon model with
$\varepsilon_{bolo} = \varepsilon_{spec}=\varepsilon_{\alpha}=1.0$
Min at: (-14.9, 0.75)
Min at: (-15.0, 0.77)
Radiance (measured) / Radiance (TPM)
0.6
0.8
1.0
1.2
1.4
-90
-60
-30
0
30
60
90
Phase angle [deg]



150 GHz (AMSU-B)
157 GHz (MHS)
using "default" TPM
Moon model with
$\varepsilon_{bolo} = \varepsilon_{spec} = \varepsilon_{\alpha} = 1.0$
Min at: (-7.4, 0.84)
Min at: (-18.5, 0.80)
Radiance (measured) / Radiance (TPM)
1.4
1.2
1.0
0.8
0.6
-90
-60
-30
0
30
60
90
Phase angle [deg]


183 GHz (AMSU-B)
183 GHz (MHS)
using "default" TPM
Moon model with
$\varepsilon_{bolo} = \varepsilon_{spec} = \varepsilon_{\alpha} = 1.0$
Min at: (-10.9, 0.87)
Min at: (-18.1, 0.83)
Radiance (measured) / Radiance (TPM)
Phase angle [deg]
1.4
1.2
1.0
0.8
0.6
-90
-60
-30
0
30
60
90

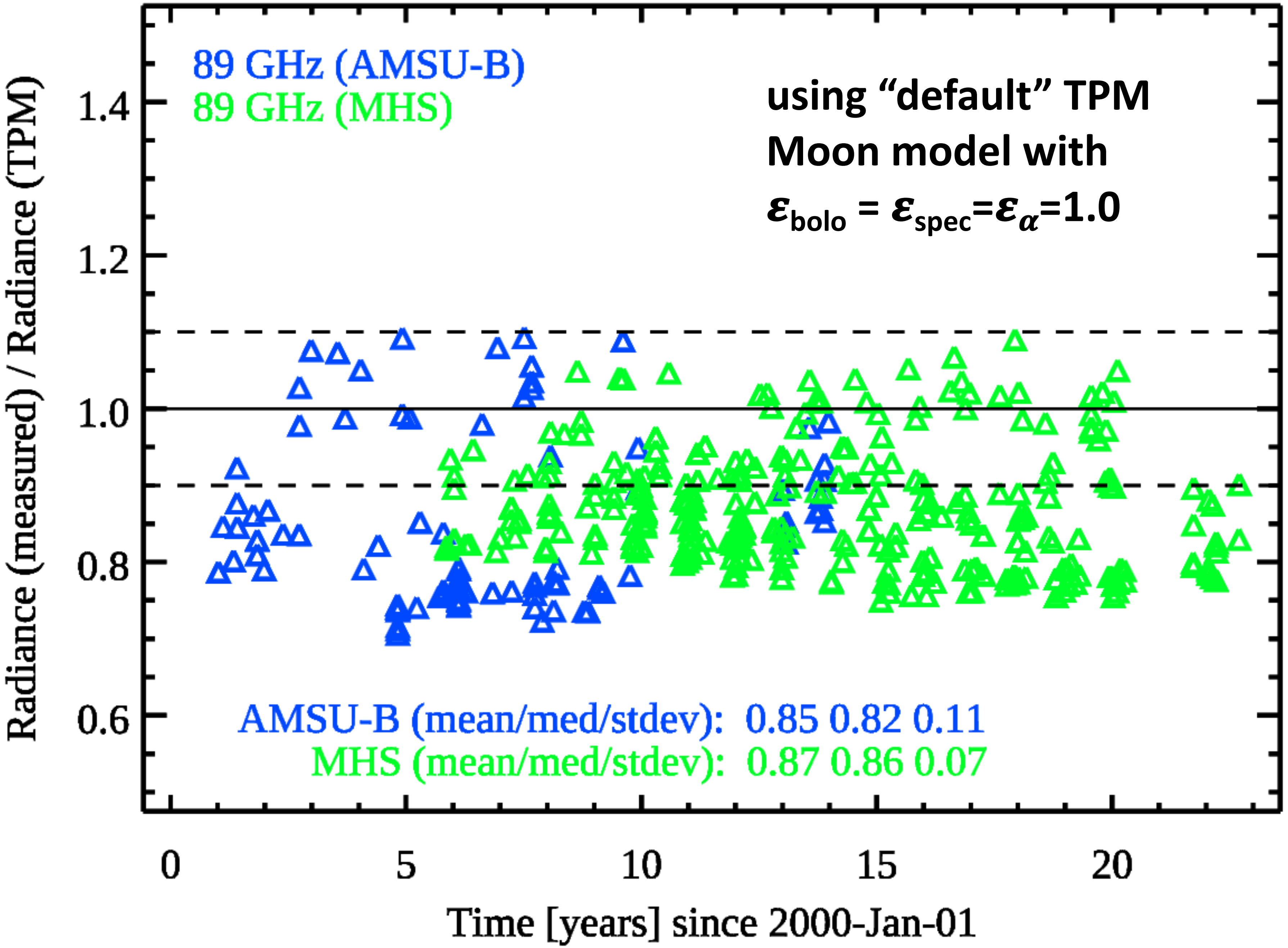

190 GHz (MHS)
using “default” TPM
Moon model with
$\varepsilon_{bolo} = \varepsilon_{spec}=\varepsilon_{\alpha}=1.0$
Min at: (-19.6, 0.83)
Radiance (measured) / Radiance (TPM)
Phase angle [deg]
1.4
1.2
1.0
0.8
0.6
-90
-60
-30
0
30
60
90


at 89 GHz
at 157 GHz
at 183 GHz
at 190 GHz
No data
No data
Emissivity model
1.2
1.1
1.0
0.9
0.8
-90
-60
-30
0
30
60
90
Phase angle [deg]

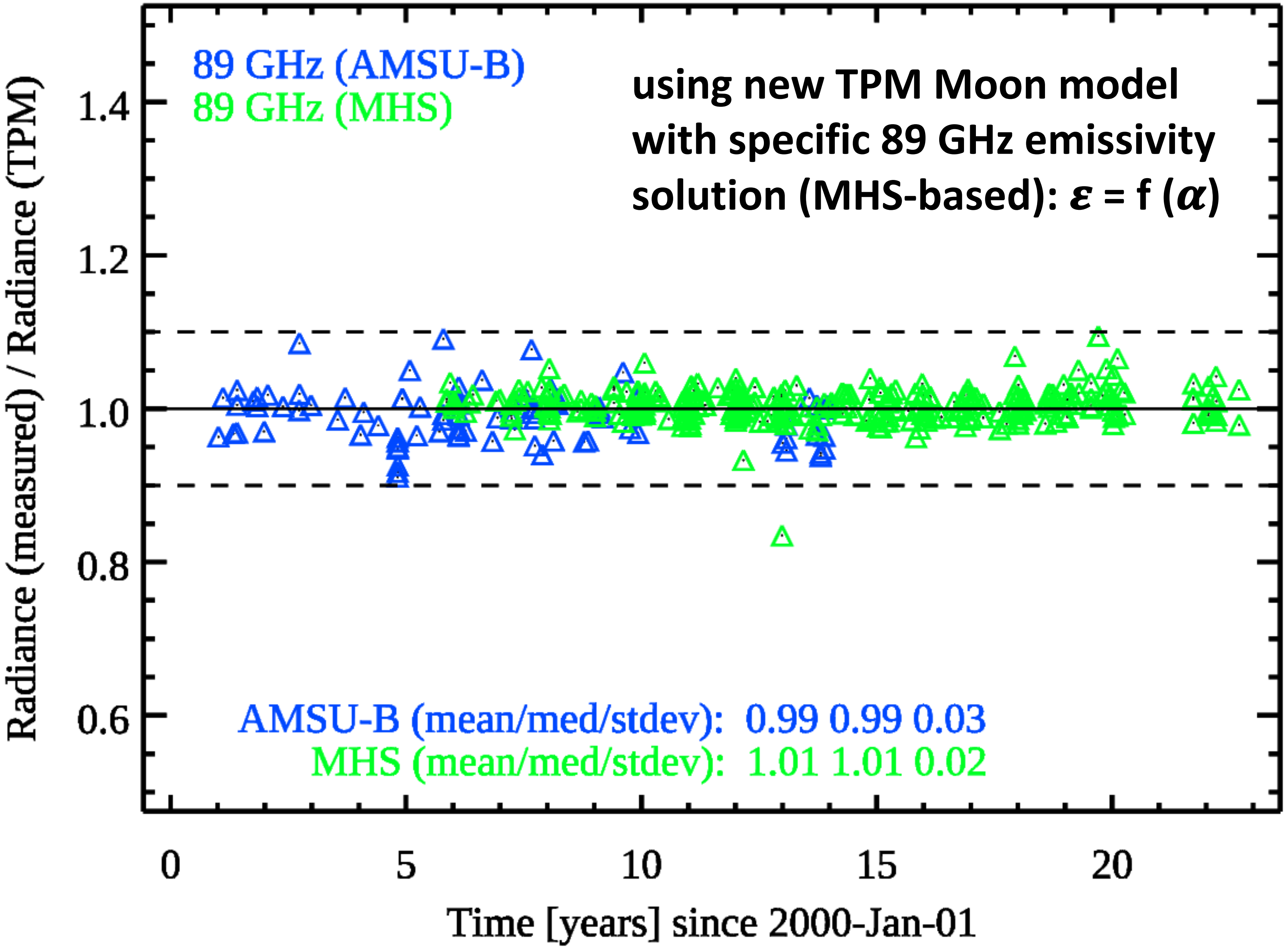
Notes on the MW phase function (effective emissivity)

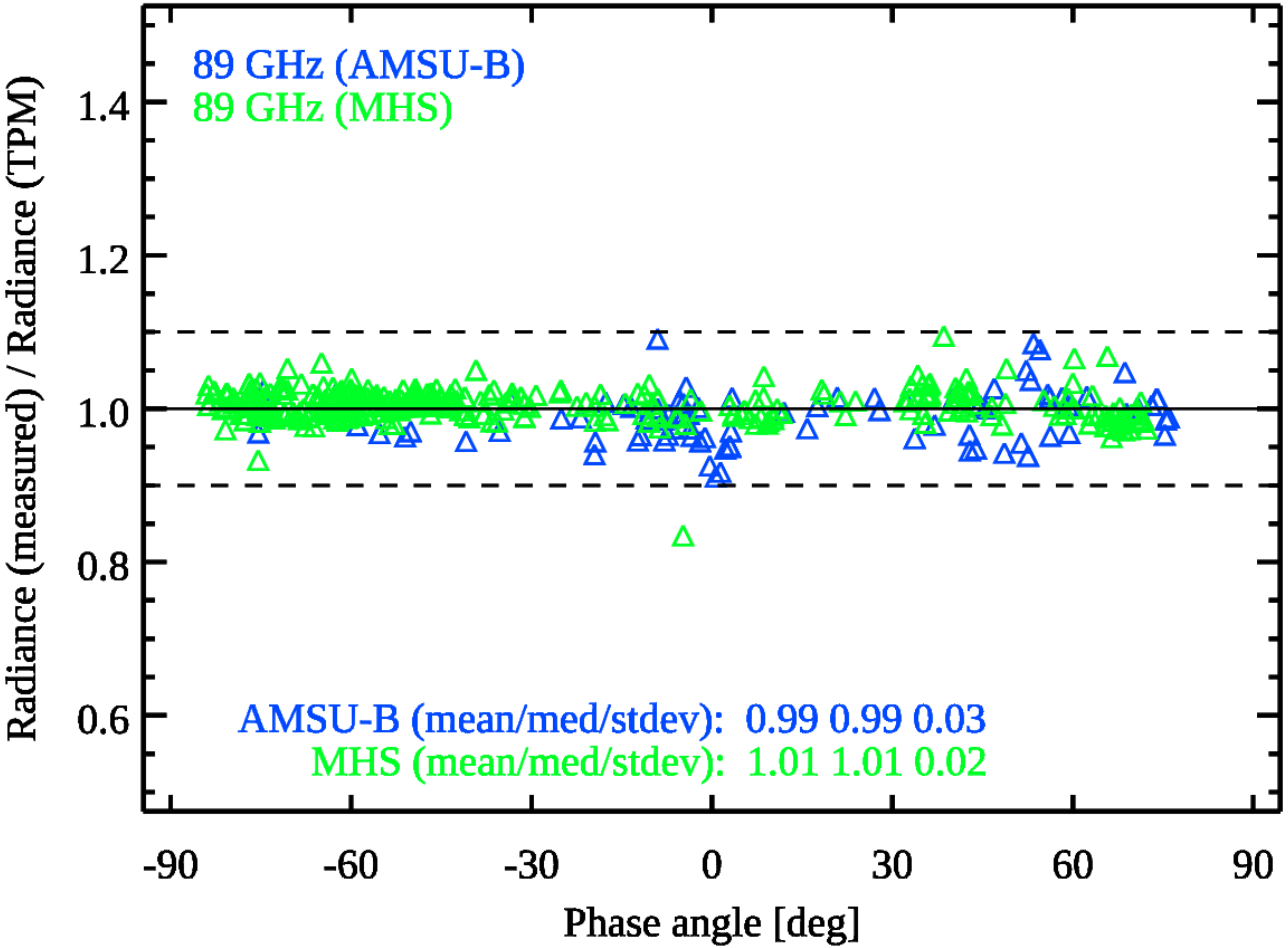
- By comparing the measured MW radiance with “default” TPM predictions (assuming a bolometric emissivity of $\boldsymbol{\varepsilon}_{\text{bolo}}$= 1.0, a spectral emissivity $\boldsymbol{\varepsilon}_{\text{spec}}$=1.0 and a phase-angle independent emissivity $\boldsymbol{\varepsilon_\alpha}$=1.0) it is possible to determine the “phase function” for a given frequency
- Minimal (hemispherical) spectral emissivity values between 0.77 (at 89 GHz) to about 0.83 (at 190 GHz) are found
- The minimal (hemispherical) emissivity values are found at phase angles between -15° (at 89 GHz) and -20° (at 190 GHz), i.e. about 32 h to 43 h **before** full Moon
- At large phase angles (> ~60°, waning Moon), we see a MW hemispherical spectral emissivity close to 1.0 and above. Here, the effective temperature is larger than the brightness temperature (without affecting the known bolometric emissivity). Reason: transparency of the top-layer surface? Anisotropic emission in the MW regime? Others?
- Introduction of a phase-angle dependent emissivity $\boldsymbol{\varepsilon_\alpha}$ to obtain a modified lunar MW TPM
- Instead of a (hemispherical) spectral emissivity model (like in the mid-IR, see Müller et al. 2021), we use now a (hemispherical) phase-angle emissivity model in the MW regime

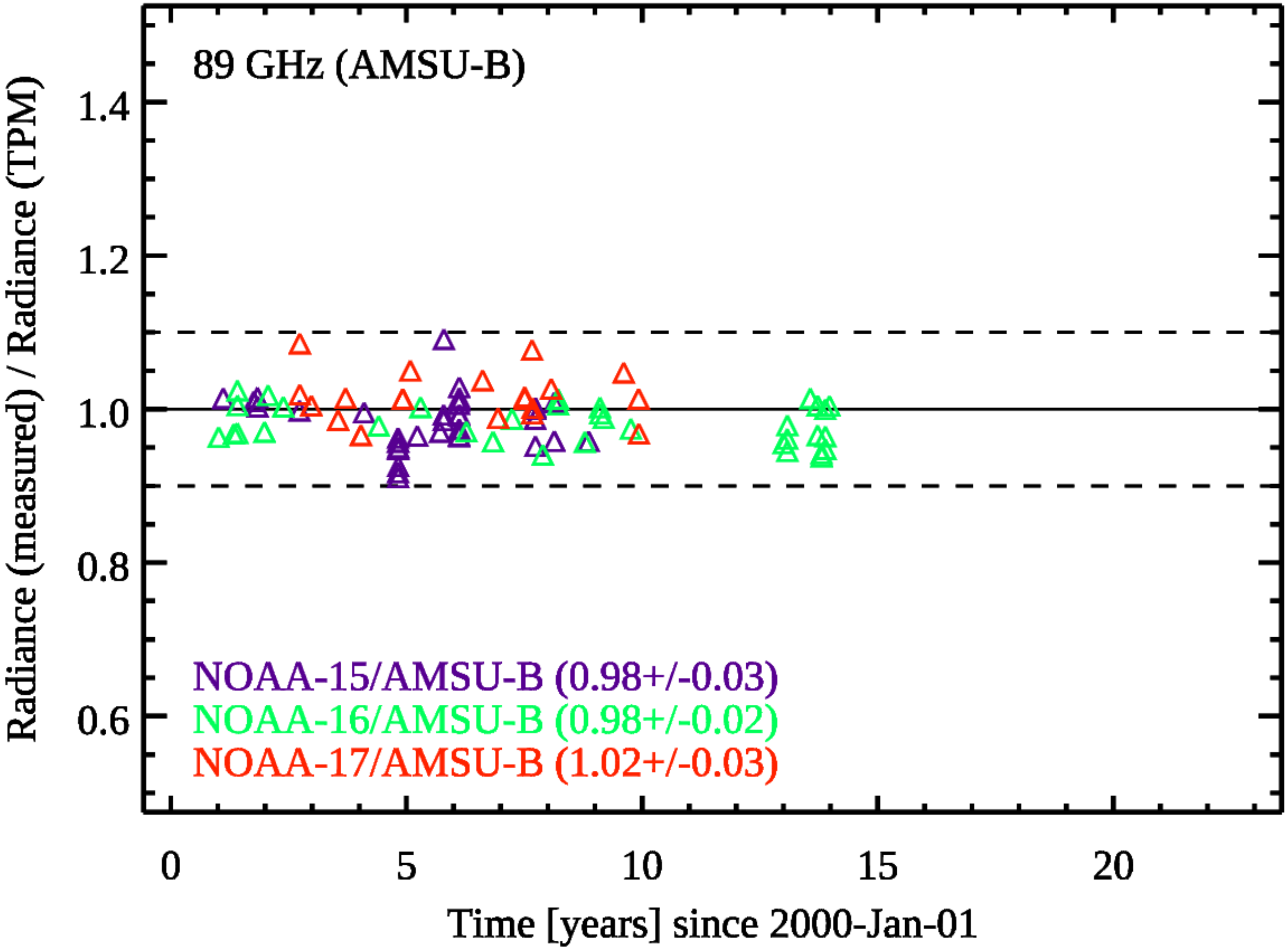
Comparison between MW measurement and the new lunar MW TPM solution



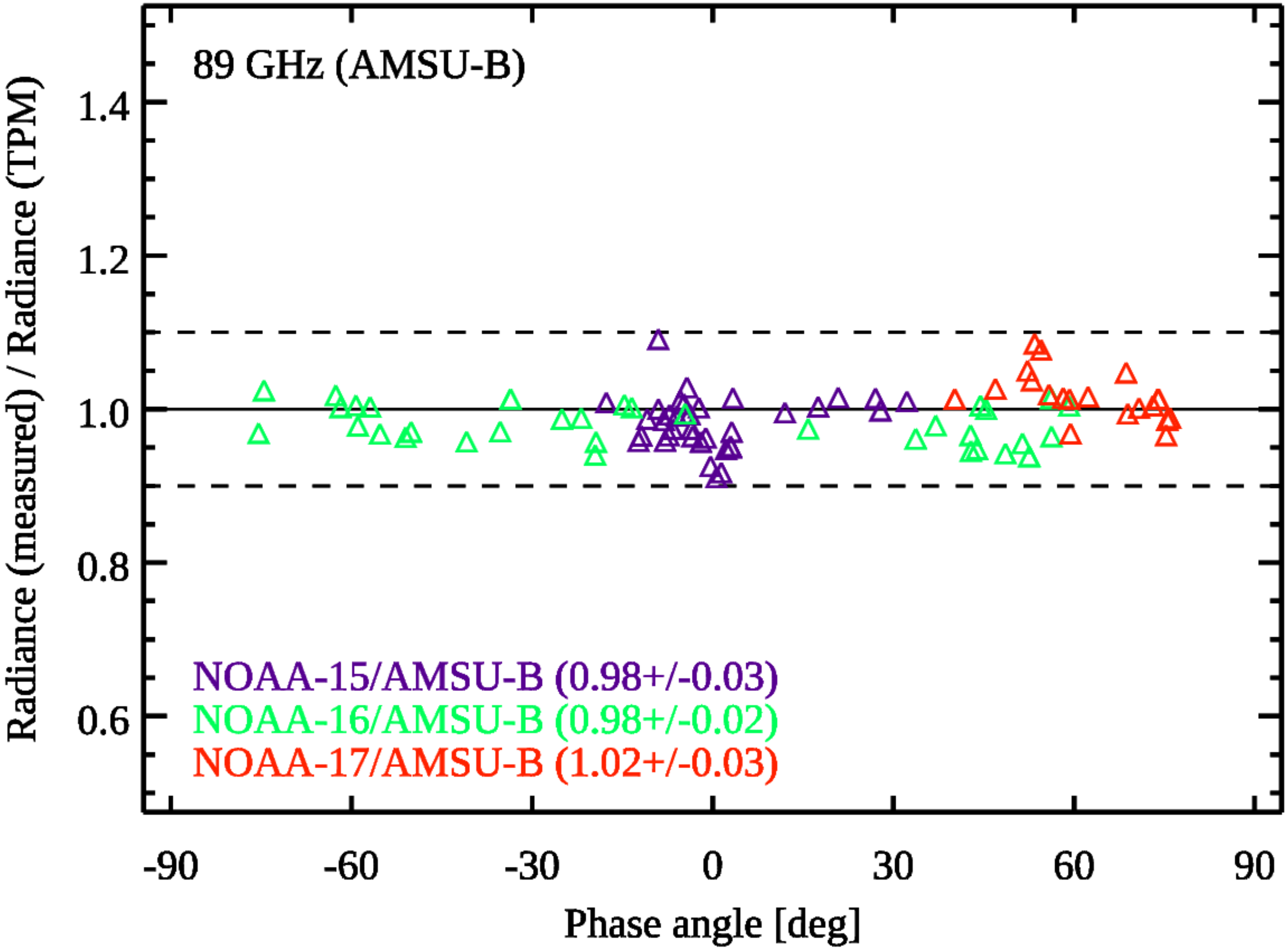
89 GHz (AMSU-B)
89 GHz (MHS)
using "default" TPM
Moon model with
$\varepsilon_{bolo} = \varepsilon_{spec}=\varepsilon_{\alpha}=1.0$
AMSU-B (mean/med/stdev): 0.85 0.82 0.11
MHS (mean/med/stdev): 0.87 0.86 0.07
Radiance (measured) / Radiance (TPM)
1.4
1.2
1.0
0.8
0.6
0
5
10
15
20
Time [years] since 2000-Jan-01


89 GHz (AMSU-B)
89 GHz (MHS)
using new TPM Moon model
with specific 89 GHz emissivity
solution (MHS-based): ε = f (α)
1.4
1.2
1.0
0.8
0.6
Radiance (measured) / Radiance (TPM)
AMSU-B (mean/med/stdev): 0.99 0.99 0.03
MHS (mean/med/stdev): 1.01 1.01 0.02
0
5
10
15
20
Time [years] since 2000-Jan-01

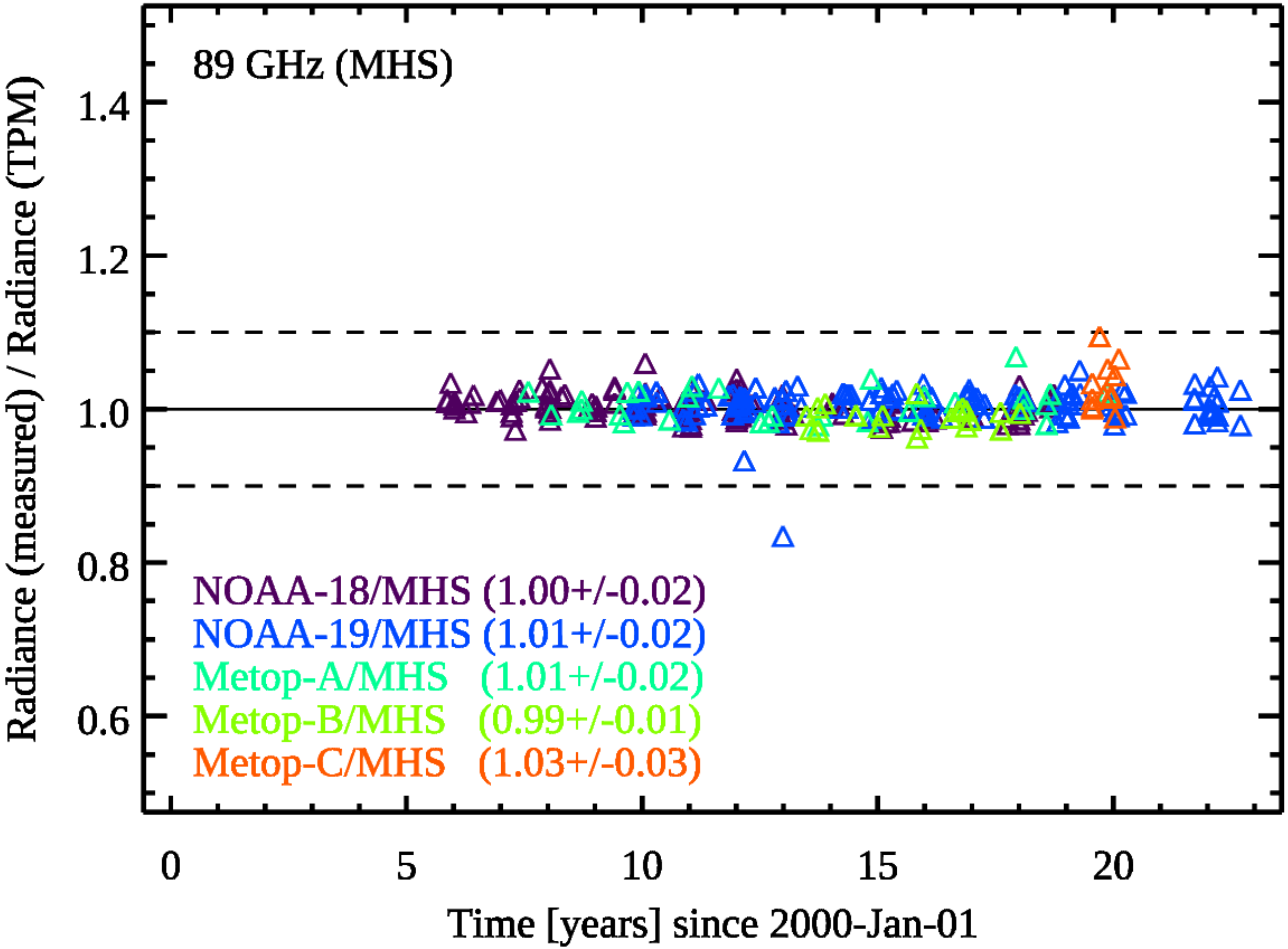

89 GHz (AMSU-B)
89 GHz (MHS)
AMSU-B (mean/med/stdev): 0.99 0.99 0.03
MHS (mean/med/stdev): 1.01 1.01 0.02
Radiance (measured) / Radiance (TPM)
Phase angle [deg]
1.4
1.2
1.0
0.8
0.6
-90
-60
-30
0
30
60
90

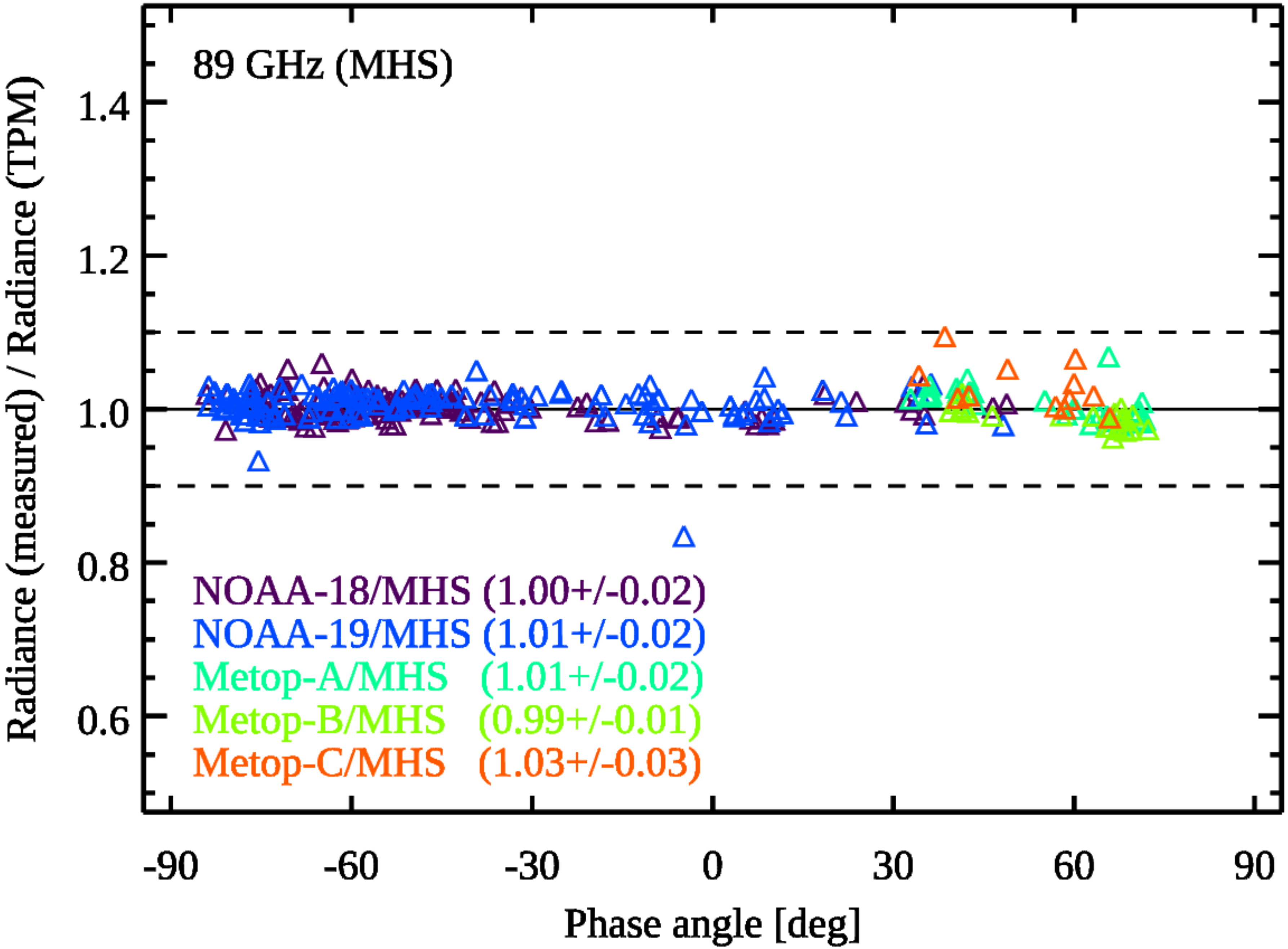


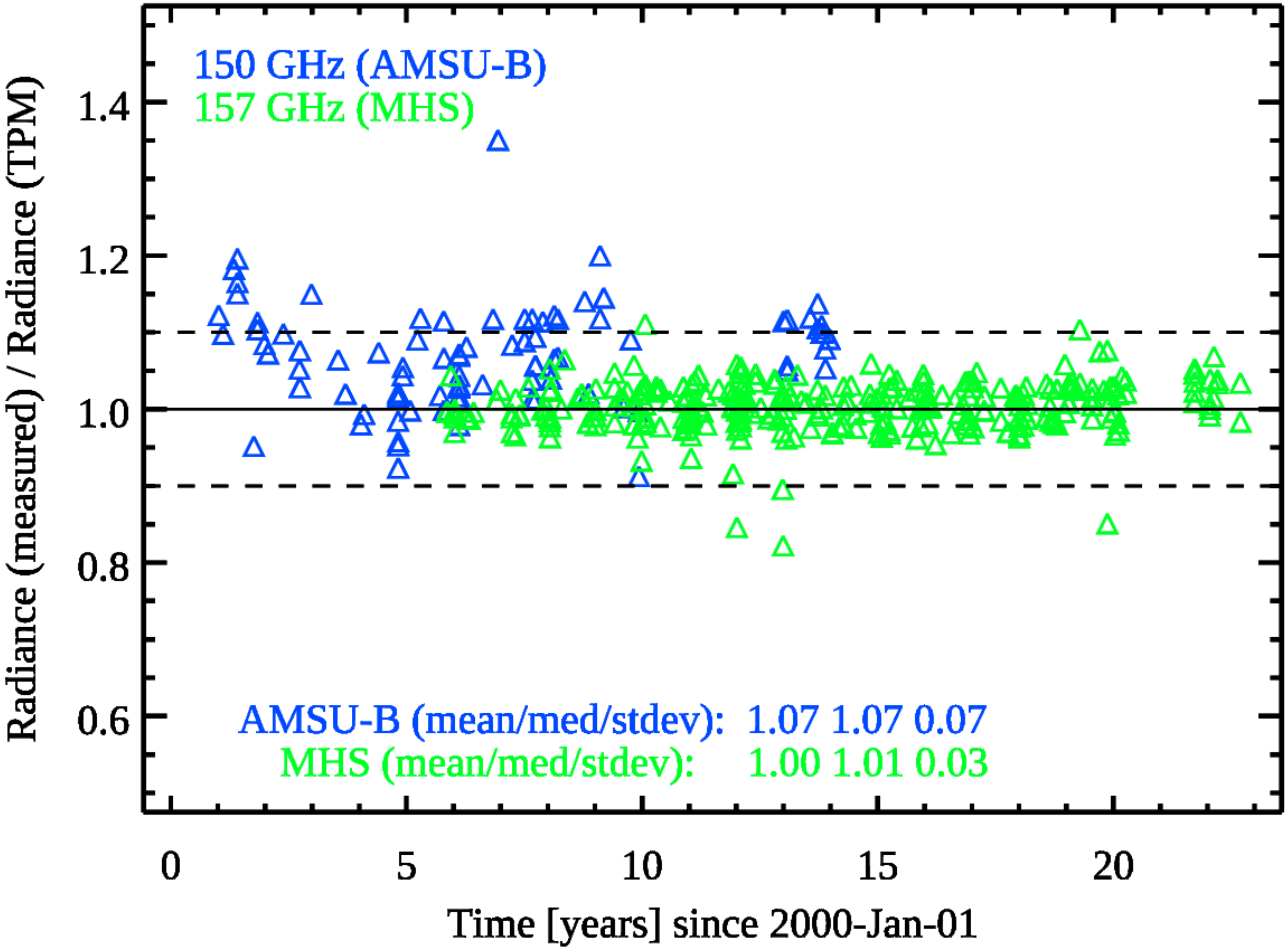
89 GHz (AMSU-B)
Radiance (measured) / Radiance (TPM)
1.4
1.2
1.0
0.8
0.6
0
5
10
15
20
Time [years] since 2000-Jan-01
NOAA-15/AMSU-B (0.98+/-0.03)
NOAA-16/AMSU-B (0.98+/-0.02)
NOAA-17/AMSU-B (1.02+/-0.03)

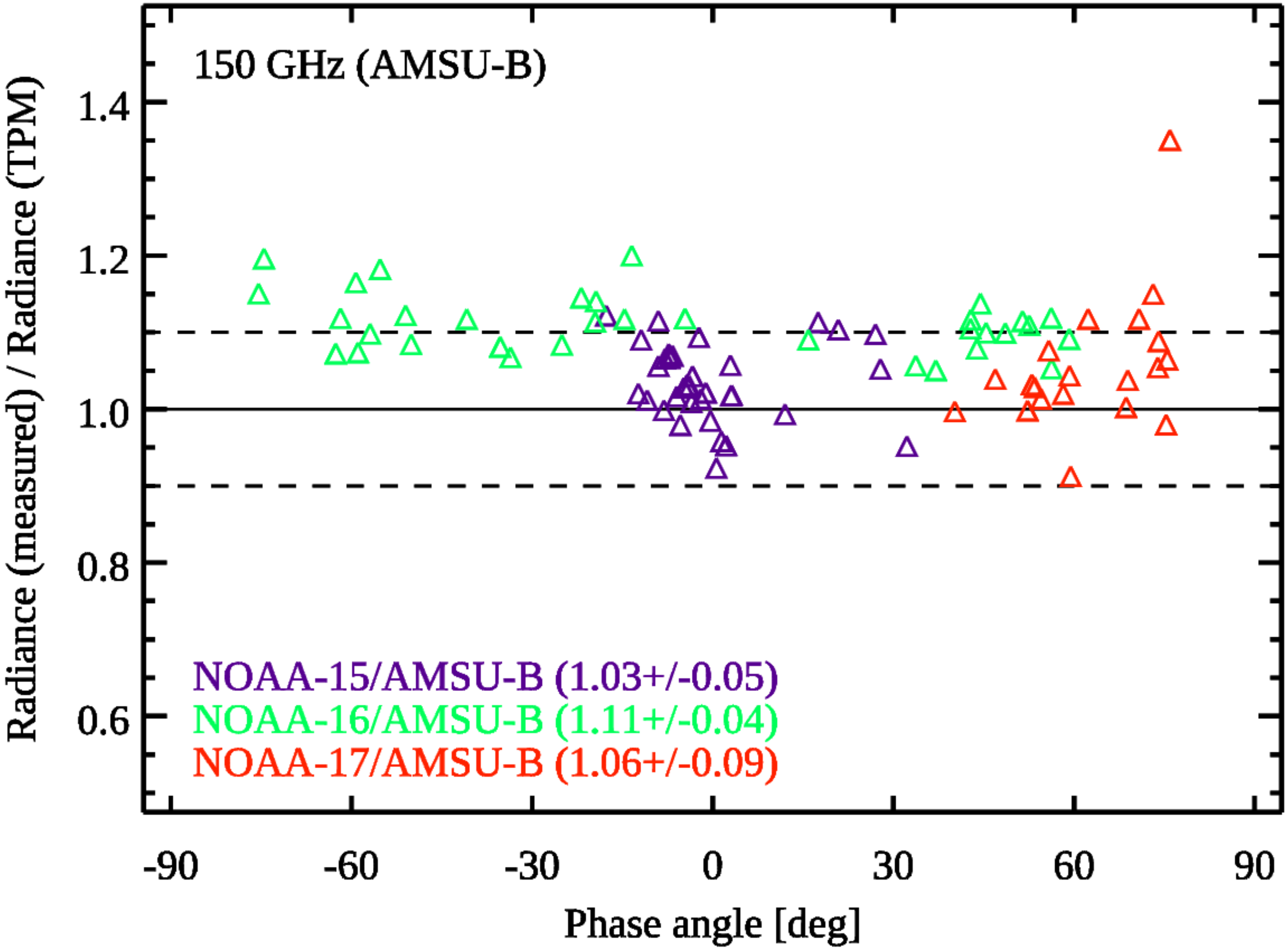


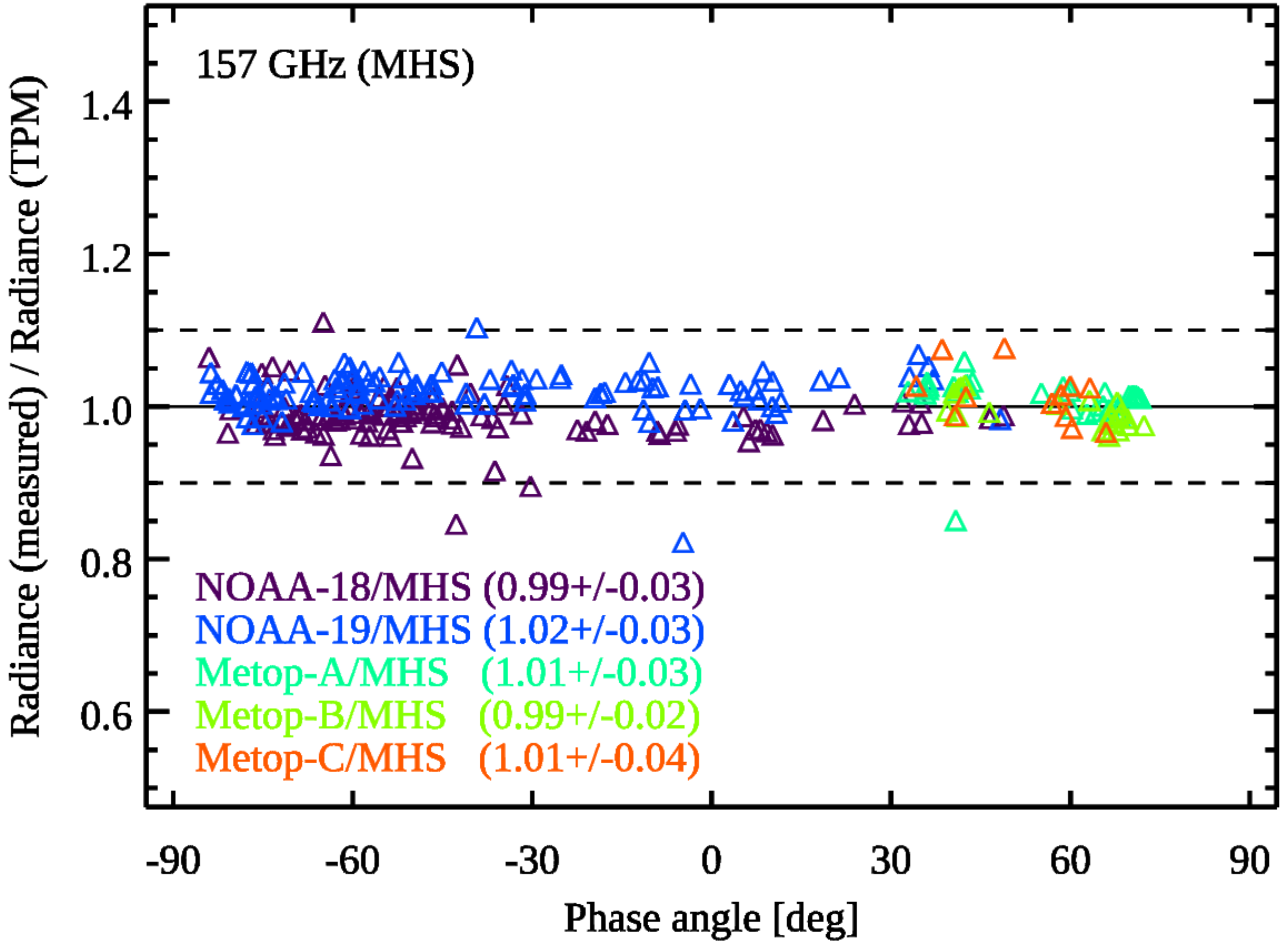
89 GHz (AMSU-B)
Radiance (measured) / Radiance (TPM)
1.4
1.2
1.0
0.8
0.6
-90
-60
-30
0
30
60
90
Phase angle [deg]
NOAA-15/AMSU-B (0.98+/-0.03)
NOAA-16/AMSU-B (0.98+/-0.02)
NOAA-17/AMSU-B (1.02+/-0.03)


89 GHz (MHS)
Radiance (measured) / Radiance (TPM)
1.4
1.2
1.0
0.8
0.6
0
5
10
15
20
Time [years] since 2000-Jan-01
NOAA-18/MHS (1.00+/-0.02)
NOAA-19/MHS (1.01+/-0.02)
Metop-A/MHS (1.01+/-0.02)
Metop-B/MHS (0.99+/-0.01)
Metop-C/MHS (1.03+/-0.03)

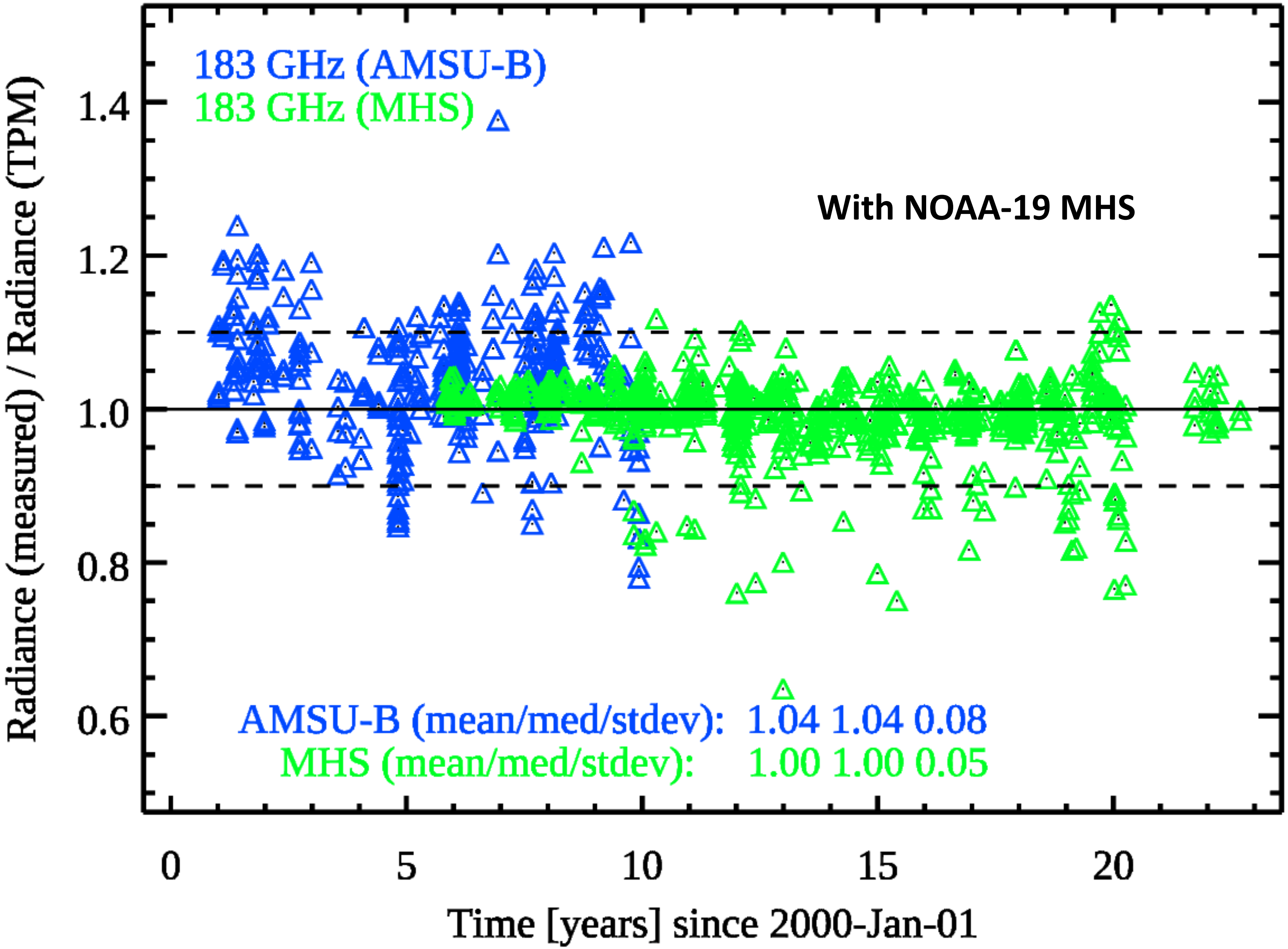

89 GHz (MHS)
Radiance (measured) / Radiance (TPM)
1.4
1.2
1.0
0.8
0.6
NOAA-18/MHS (1.00+/-0.02)
NOAA-19/MHS (1.01+/-0.02)
Metop-A/MHS (1.01+/-0.02)
Metop-B/MHS (0.99+/-0.01)
Metop-C/MHS (1.03+/-0.03)
-90
-60
-30
0
30
60
90
Phase angle [deg]


150 GHz (AMSU-B)
157 GHz (MHS)
AMSU-B (mean/med/stdev): 1.07 1.07 0.07
MHS (mean/med/stdev): 1.00 1.01 0.03
Radiance (measured) / Radiance (TPM)
Time [years] since 2000-Jan-01
1.4
1.2
1.0
0.8
0.6
0
5
10
15
20

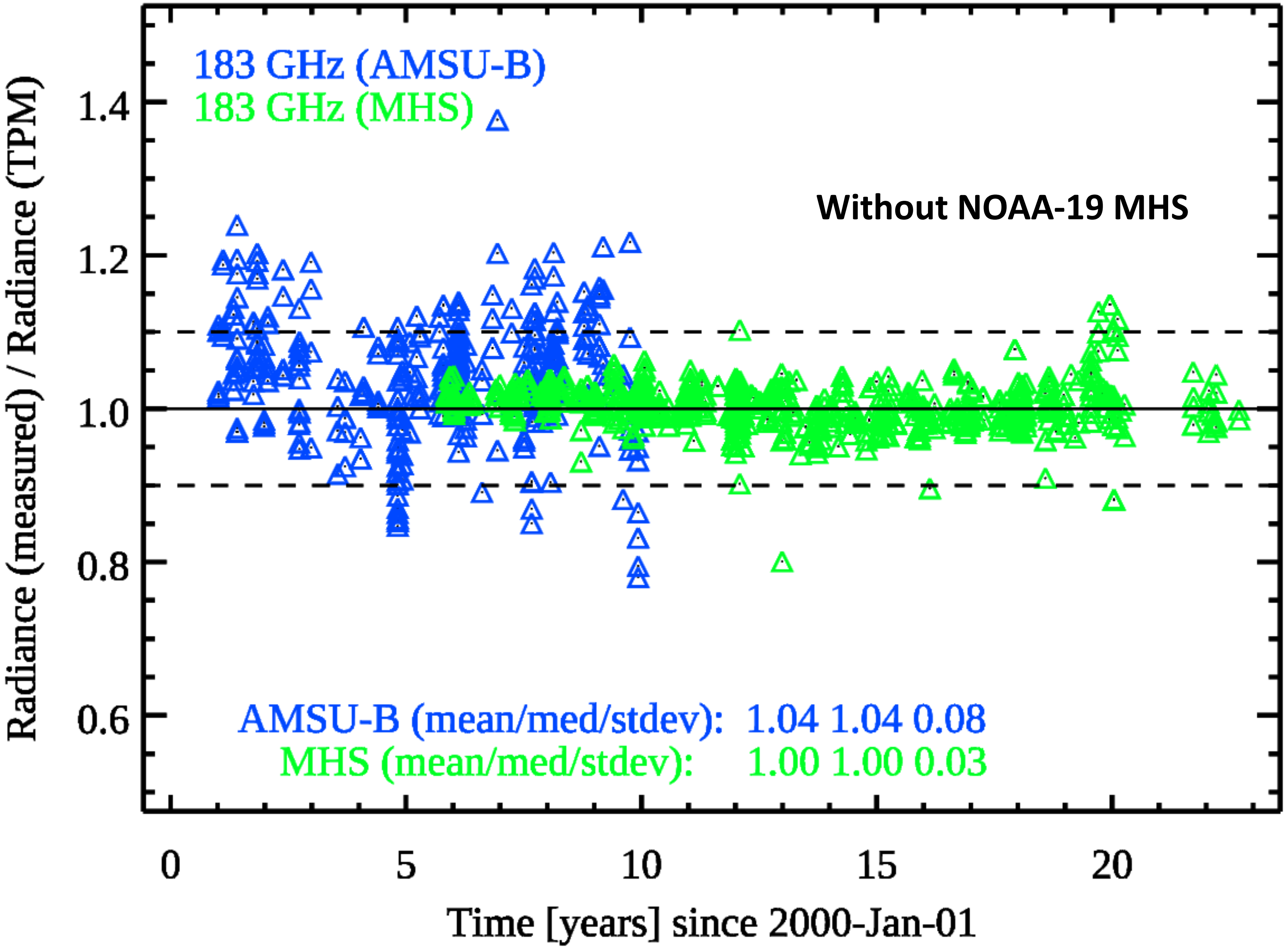

150 GHz (AMSU-B)
Radiance (measured) / Radiance (TPM)
1.4
1.2
1.0
0.8
0.6
-90
-60
-30
0
30
60
90
Phase angle [deg]
NOAA-15/AMSU-B (1.03+/-0.05)
NOAA-16/AMSU-B (1.11+/-0.04)
NOAA-17/AMSU-B (1.06+/-0.09)

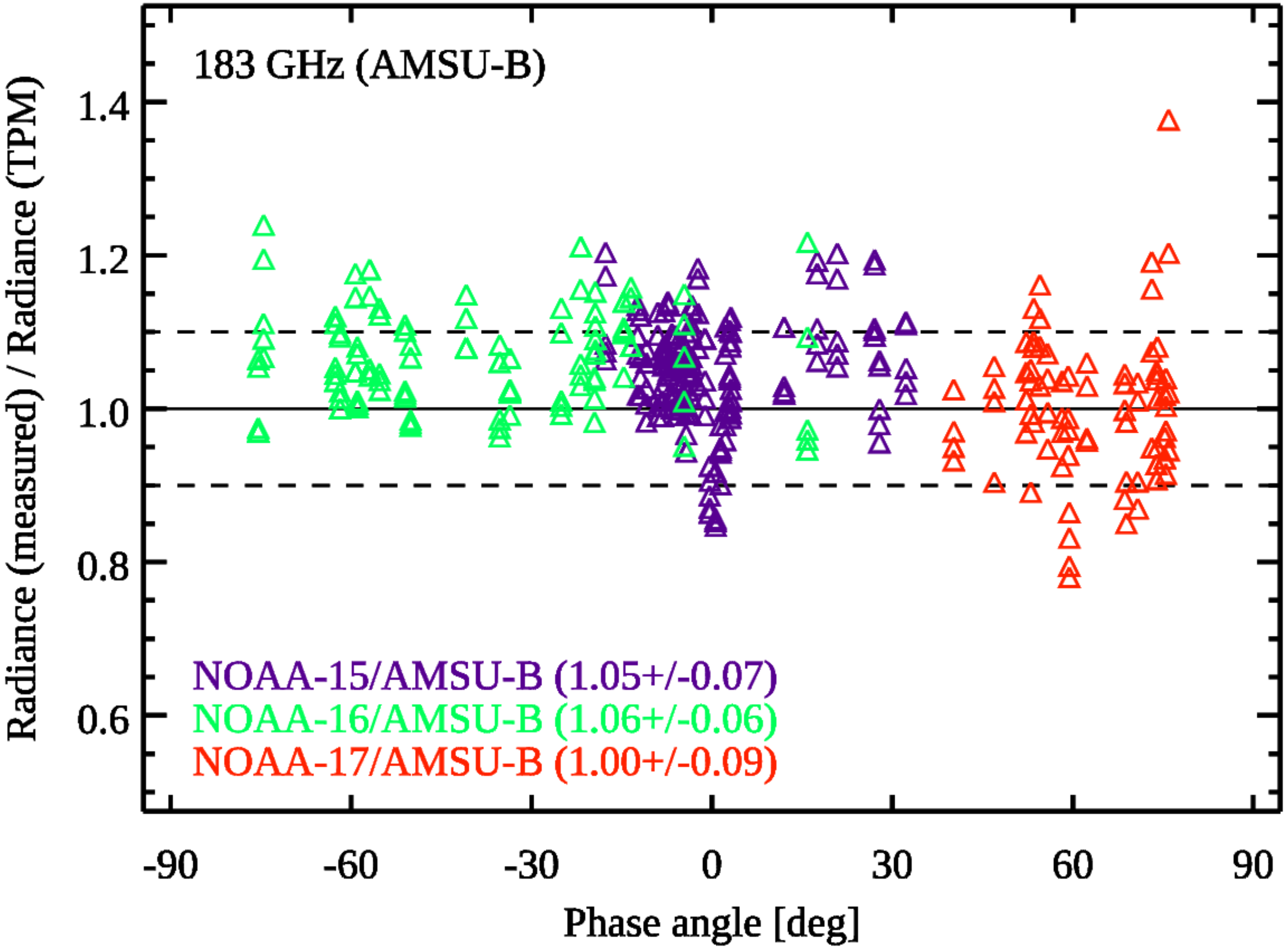


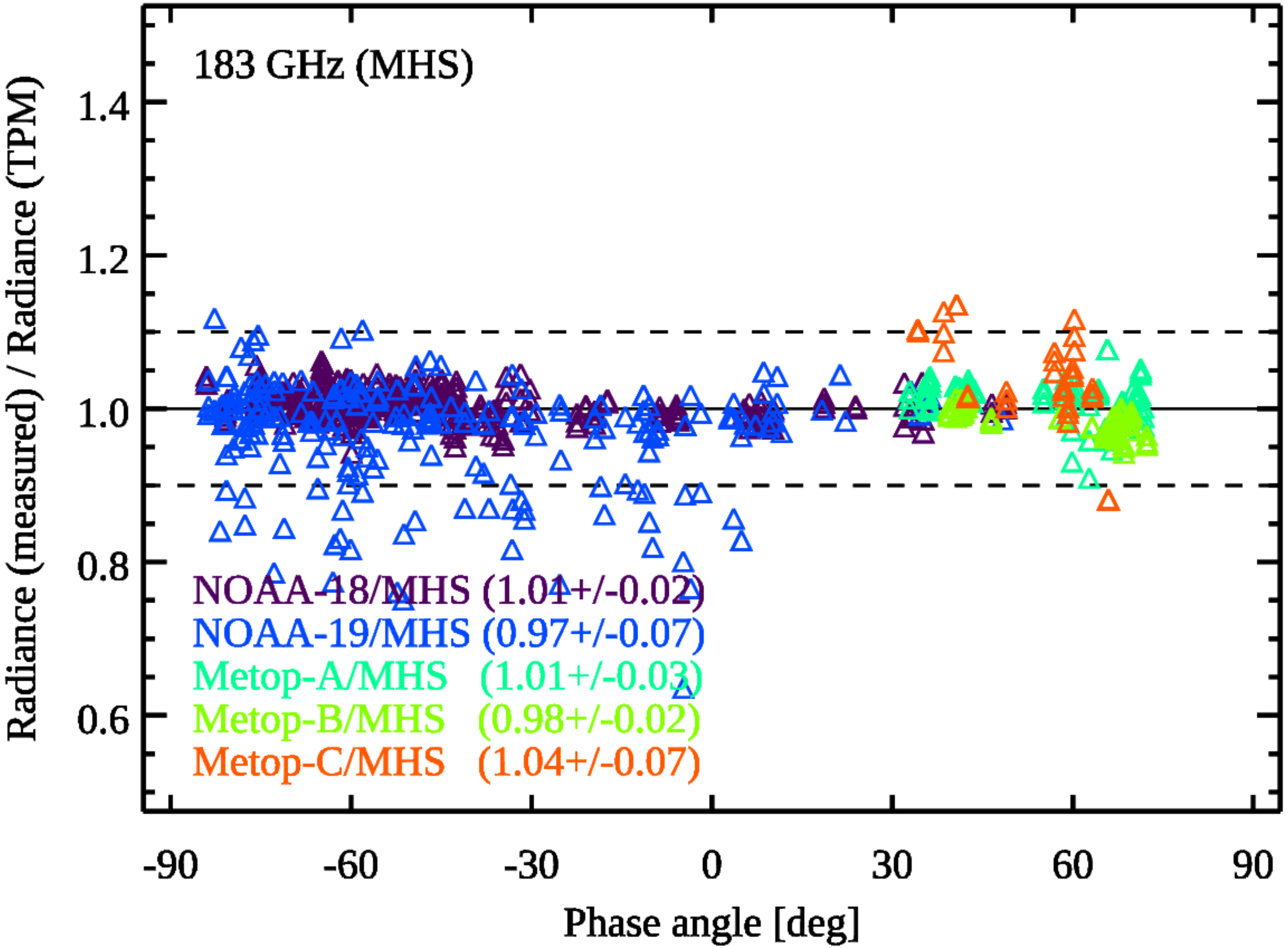
157 GHz (MHS)
Radiance (measured) / Radiance (TPM)
1.4
1.2
1.0
0.8
0.6
NOAA-18/MHS (0.99+/-0.03)
NOAA-19/MHS (1.02+/-0.03)
Metop-A/MHS (1.01+/-0.03)
Metop-B/MHS (0.99+/-0.02)
Metop-C/MHS (1.01+/-0.04)
-90
-60
-30
0
30
60
90
Phase angle [deg]



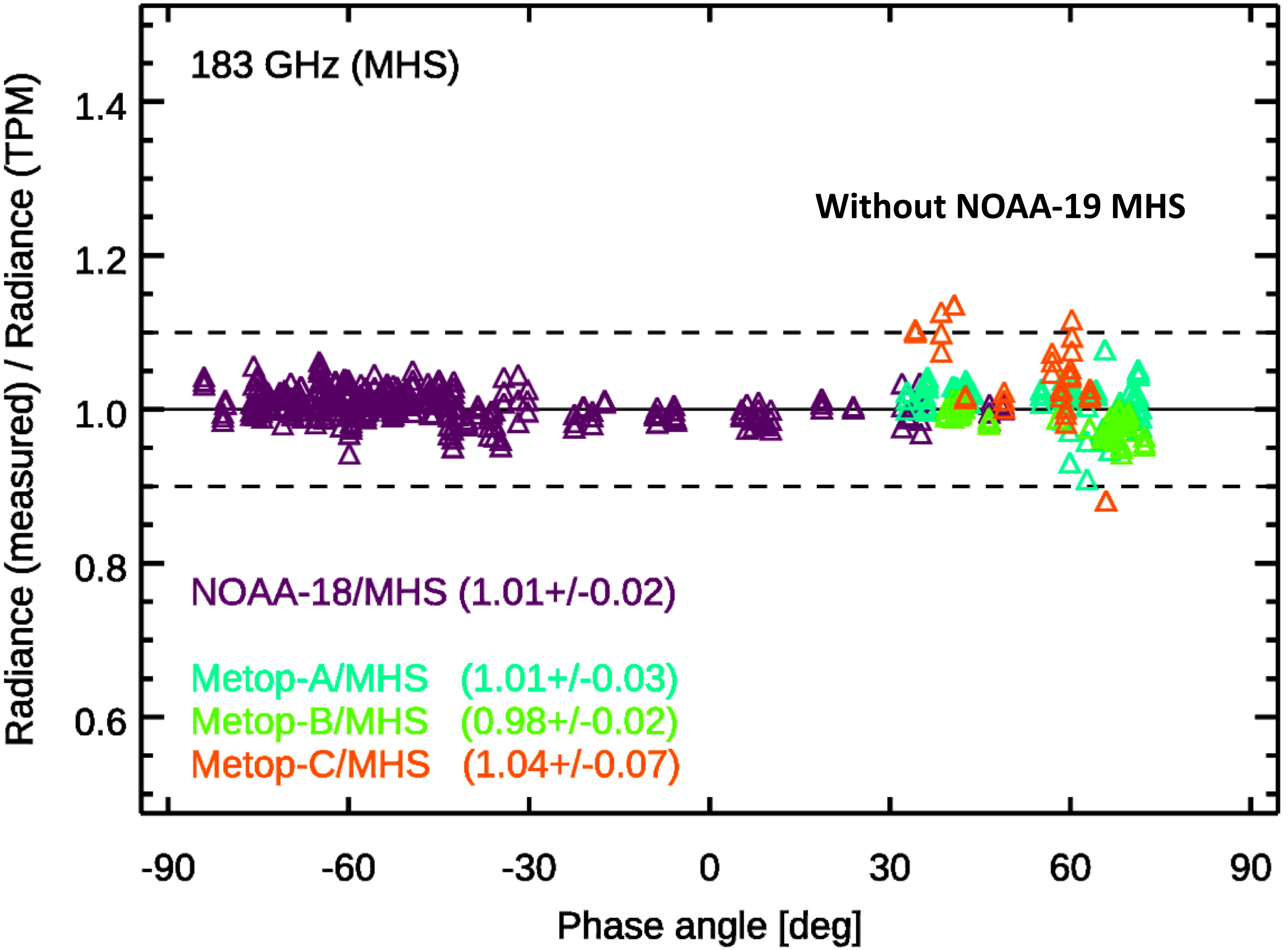
183 GHz (AMSU-B)
183 GHz (MHS)
With NOAA-19 MHS
AMSU-B (mean/med/stdev): 1.04 1.04 0.08
MHS (mean/med/stdev): 1.00 1.00 0.05
Radiance (measured) / Radiance (TPM)
1.4
1.2
1.0
0.8
0.6
0
5
10
15
20
Time [years] since 2000-Jan-01


183 GHz (AMSU-B)
183 GHz (MHS)
Without NOAA-19 MHS
AMSU-B (mean/med/stdev): 1.04 1.04 0.08
MHS (mean/med/stdev): 1.00 1.00 0.03
Radiance (measured) / Radiance (TPM)
1.4
1.2
1.0
0.8
0.6
0
5
10
15
20
Time [years] since 2000-Jan-01

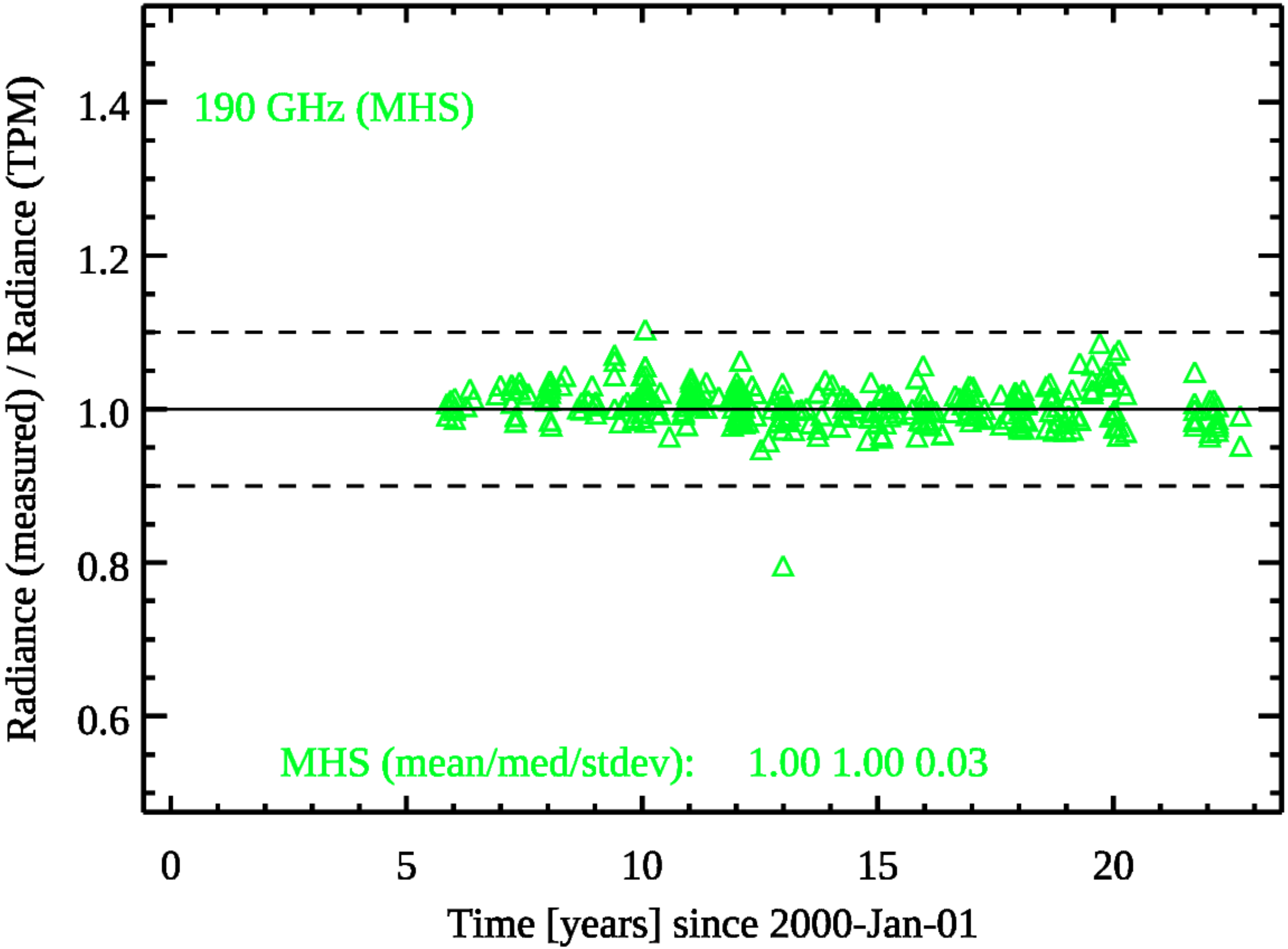

183 GHz (AMSU-B)
Radiance (measured) / Radiance (TPM)
1.4
1.2
1.0
0.8
0.6
-90
-60
-30
0
30
60
90
Phase angle [deg]
NOAA-15/AMSU-B (1.05+/-0.07)
NOAA-16/AMSU-B (1.06+/-0.06)
NOAA-17/AMSU-B (1.00+/-0.09)

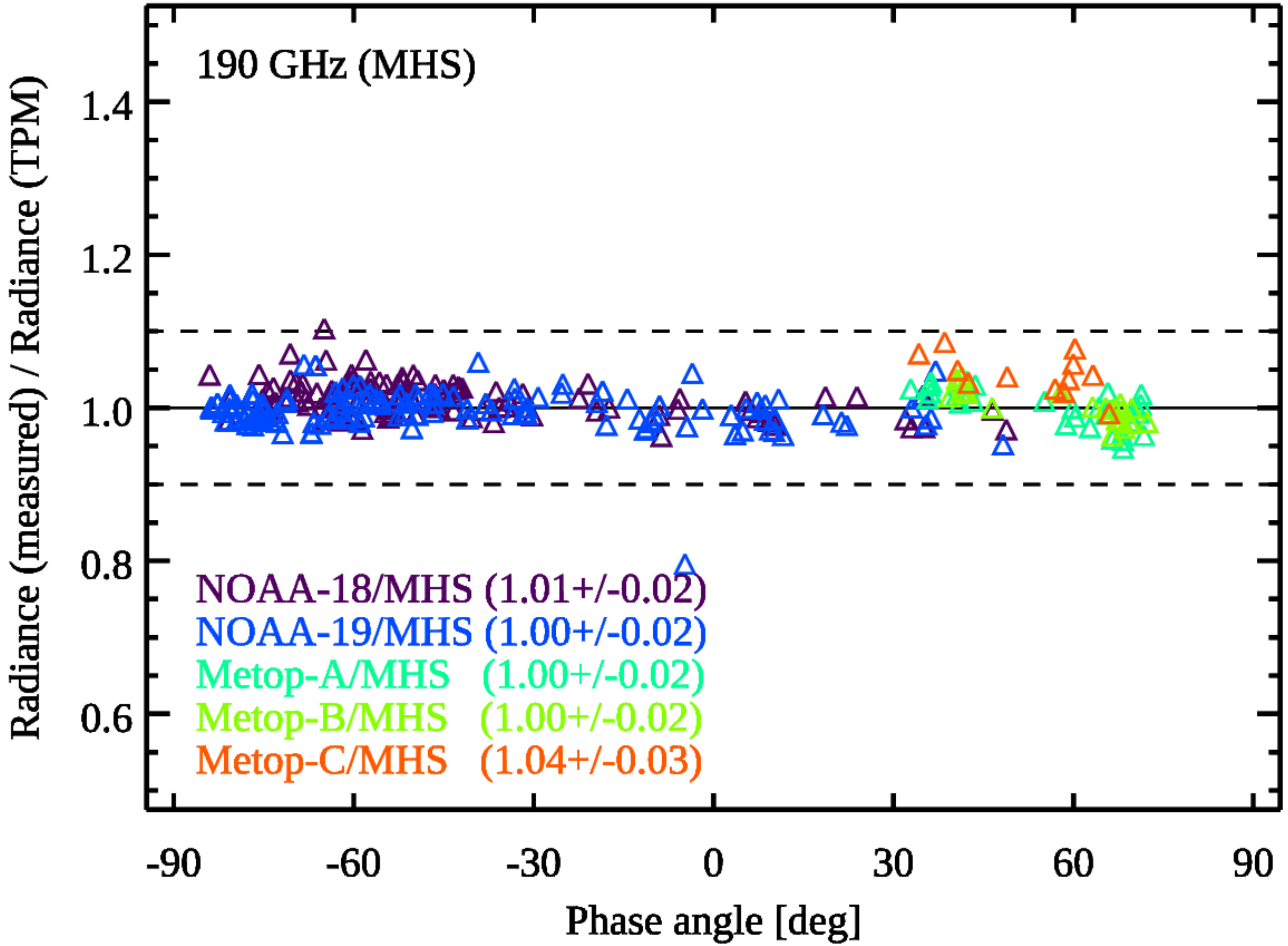


183 GHz (MHS)
Radiance (measured) / Radiance (TPM)
1.4
1.2
1.0
0.8
0.6
-90
-60
-30
0
30
60
90
Phase angle [deg]
NOAA-18/MHS (1.04+/-0.02)
NOAA-19/MHS (0.97+/-0.07)
Metop-A/MHS (1.01+/-0.03)
Metop-B/MHS (0.98+/-0.02)
Metop-C/MHS (1.04+/-0.07)



183 GHz (MHS)
Without NOAA-19 MHS
NOAA-18/MHS (1.01+/-0.02)
Metop-A/MHS (1.01+/-0.03)
Metop-B/MHS (0.98+/-0.02)
Metop-C/MHS (1.04+/-0.07)
Radiance (measured) / Radiance (TPM)
1.4
1.2
1.0
0.8
0.6
-90
-60
-30
0
30
60
90
Phase angle [deg]


190 GHz (MHS)
MHS (mean/med/stdev): 1.00 1.00 0.03
Radiance (measured) / Radiance (TPM)
Time [years] since 2000-Jan-01
1.4
1.2
1.0
0.8
0.6
0
5
10
15
20



190 GHz (MHS)
1.4
1.2
1.0
0.8
0.6
Radiance (measured) / Radiance (TPM)
NOAA-18/MHS (1.01+/-0.02)
NOAA-19/MHS (1.00+/-0.02)
Metop-A/MHS (1.00+/-0.02)
Metop-B/MHS (1.00+/-0.02)
Metop-C/MHS (1.04+/-0.03)
-90
-60
-30
0
30
60
90
Phase angle [deg]

Summary

- **AMSU-B & MHS Moon data at 89, 150, 157, 183 and 190 GHz (from 8 different satellites): 1754 individual measurements in total**
- The AMSU-B data are more noisy in general , individual satellites have only a very restricted coverage in phase angle
- The NOAA-19 MHS H3 data are very noisy (not been used in phase function calculations)
- Also the Metop-C MHS data are difficult: offsets and poor phase angle coverage
- Our lunar TPM (validated in the mid-IR regime) matches the AMSU-B & MHS microwave data very well, but only after introducing a phase-angle dependent (hemispherical) spectral emissivity (the Moon's bolometric emissivity remains untouched)
- The effective emissivity is found to be between 0.77 to 0.83 at phase angles of -20° to -15° (waxing) and rises to values above 1.0 at large positive and very large negative phase angles
- The quality of the emissivity solution is limited by the data quality and phase angle coverage.
- No remaining correlations of the MW/TPM ratios with phase angle, heliocentric distance, apparent Moon size, aspect angle, sub-solar and sub-observer longitudes and latitudes, …
- **The estimated (current) absolute accuracy of the model prediction: 1-3%, depending on the frequency, and over the tested phase angle range: -84.0° (waxing) $\leqq \alpha \leqq$ +75.9° (waning)**
- An absolute model accuracy of +/- 1% in radiance corresponds to +/- 1.5-3.5 K, depending on frequency and lunar phase angle

Next Steps?

- More MW data available? Better coverage in phase angle? Beyond half-moon? Lower or higher frequencies? From other satellites/instruments?
- Measurement errors? Identify outliers?
- Publication with these MW measurements and the specific TPM is planned

Lunar MW model predictions can be requested from tmueller@mpe.mpg.de

- The following information is needed: epoch of measurement, exact measurement frequency, expected model output (radiance, flux, brightness temperature), position of the satellite, [for low-Earth orbit satellites it is currently sufficient to use geocentric position]
- For direct comparison with the model predictions one has to use the measured quantities directly, unscaled for distances or angles!