NOAA/MetOp-A/B/TIROS-N-HIRS & TPM comparison

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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 4-15 µm 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 8% (3.7 - 5 µm), and well below 5% (7 - 15 µm) in the -85° to +85° phase angle range.

The Moon at thermal infrared wavelengths: a benchmark for asteroid thermal models

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Overview of HIRS-Moon data set:

- C. Seibert. “HIRS moon intrusions and model calculations”, DOI: 10.5281/-zenodo.6865664 and “A collection of instrument characteristics for all satellites with HIRS/2, HIRS/3 and HIRS/4”, DOI: 10.5281/zenodo.6822188; both July 2022
- Data taken between Jan-1979 and Feb-2021 (123 epochs), from TIROS-N-HIRS2; NOAA6/7/8/9/10/11/12/14-HIRS2; NOAA15/16/17-HIRS3; NOAA18/19-HIRS4; MetOpA-HIRS4, MetOpB-HIRS4 (=16 different satellites, 3 different instruments)
- 19 infrared channels from 3.7 µm (ch19) to 15.0 µm (ch01)
- Measured radiances [Mjy/sr] and brightness temperatures [K], including errors, for all 19 channels (see Seibert 2022, master thesis, Uni Hamburg)
- Based on the satellite longitude/latitude/altitude and the epoch of the observation, the following numbers have been calculated (via JPL/Horizons):
    - Helio-centric distance of the Moon (r_au)
    - Observer-centric distance of the Moon (d_au)
    - Phase angle (Sun-Target-Observer angle; waxing: negative, waning: positive)
    - Angular diameter (equatorial angular width of the target body full disk)

- Heliocentric Moon distances: 0.9841 au … 1.0178 au
- Satellite-centric Moon distances: 359075 km to 408270 km
- Phase angles $\boldsymbol{\alpha}$ (signed S-T-O): -85.4 ° … +82.6 °
- Apparent angular diameters: 1755.6" to 1996.0 "
- Satellite geometries: (Lon/Lat/Alt) = (-168.9 ° …+178.8 °/ -80.7 °…+80.9 °/ 789 km … 891 km above Earth)

Moon Thermophysical Model (TPM) of the Moon (Müller et al. 2021, A&A650, A38):

- Based on work by Lagerros (1996, 1997, 1998), Müller and Lagerros (1998, 2002), Müller (2002), considering 1-d heat conduction, roughness, thermal properties of the surface, shadowing and self-heating into account, it also uses the true illumination and observing geometry (as seen from the satellite)
- 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_{sid} = 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)
- No phase correction was applied (this was suggested as correction of a small phase curve asymmetry seen in the limited HIRS dataset presented in Müller et al. 2021)
- Including different implementations of surface roughness (hemispherical segment craters, gaussian random surfaces)

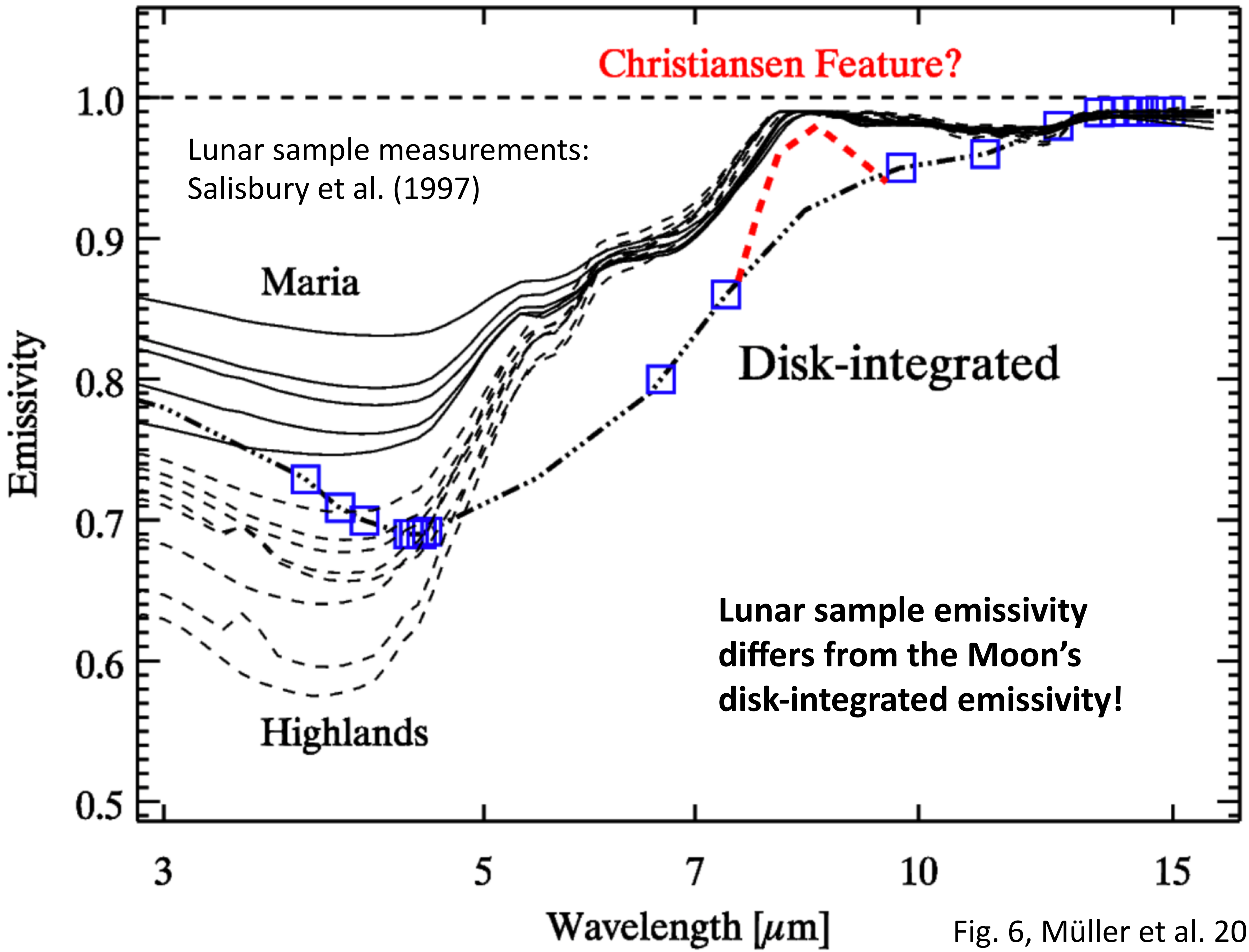
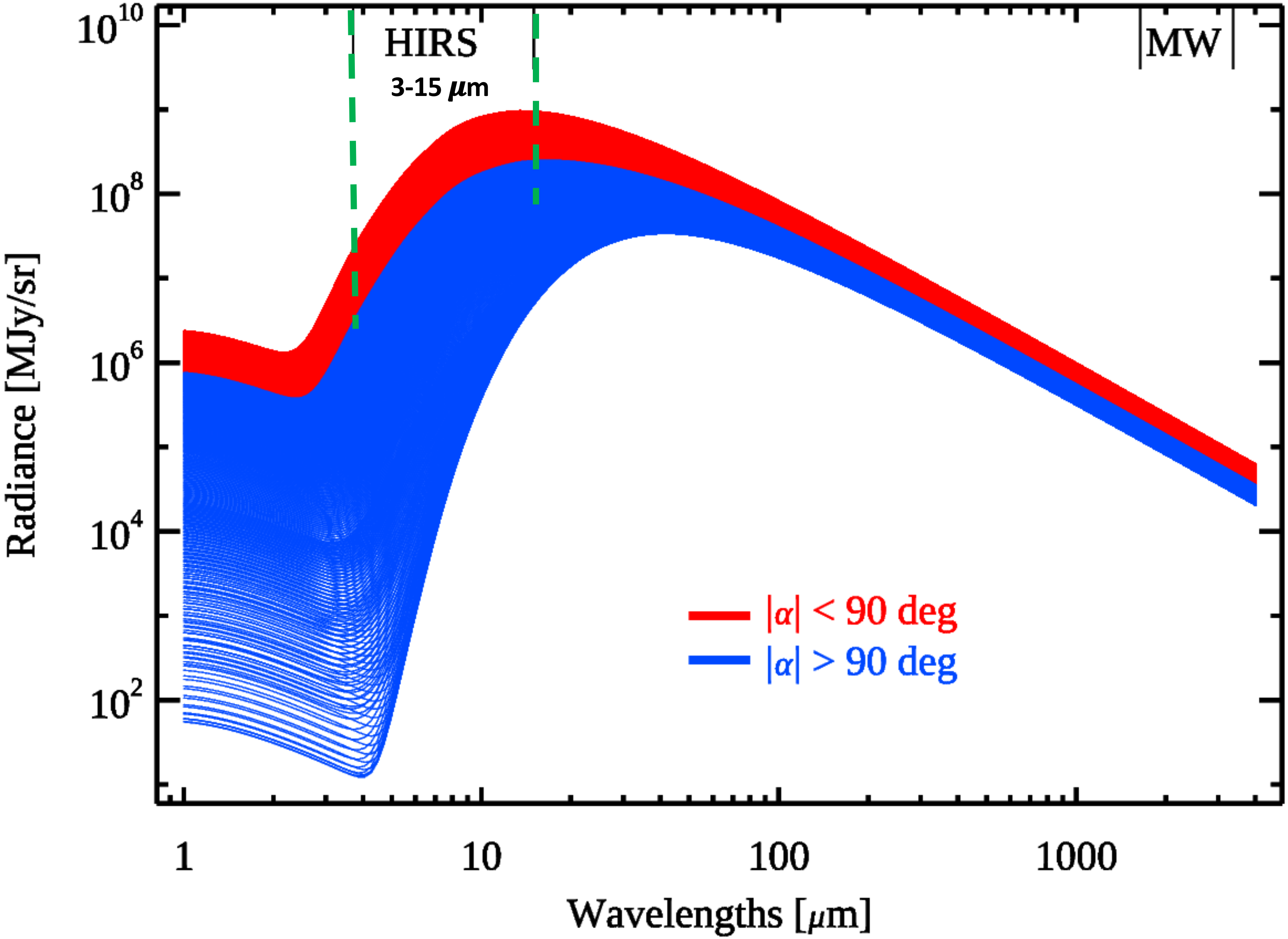
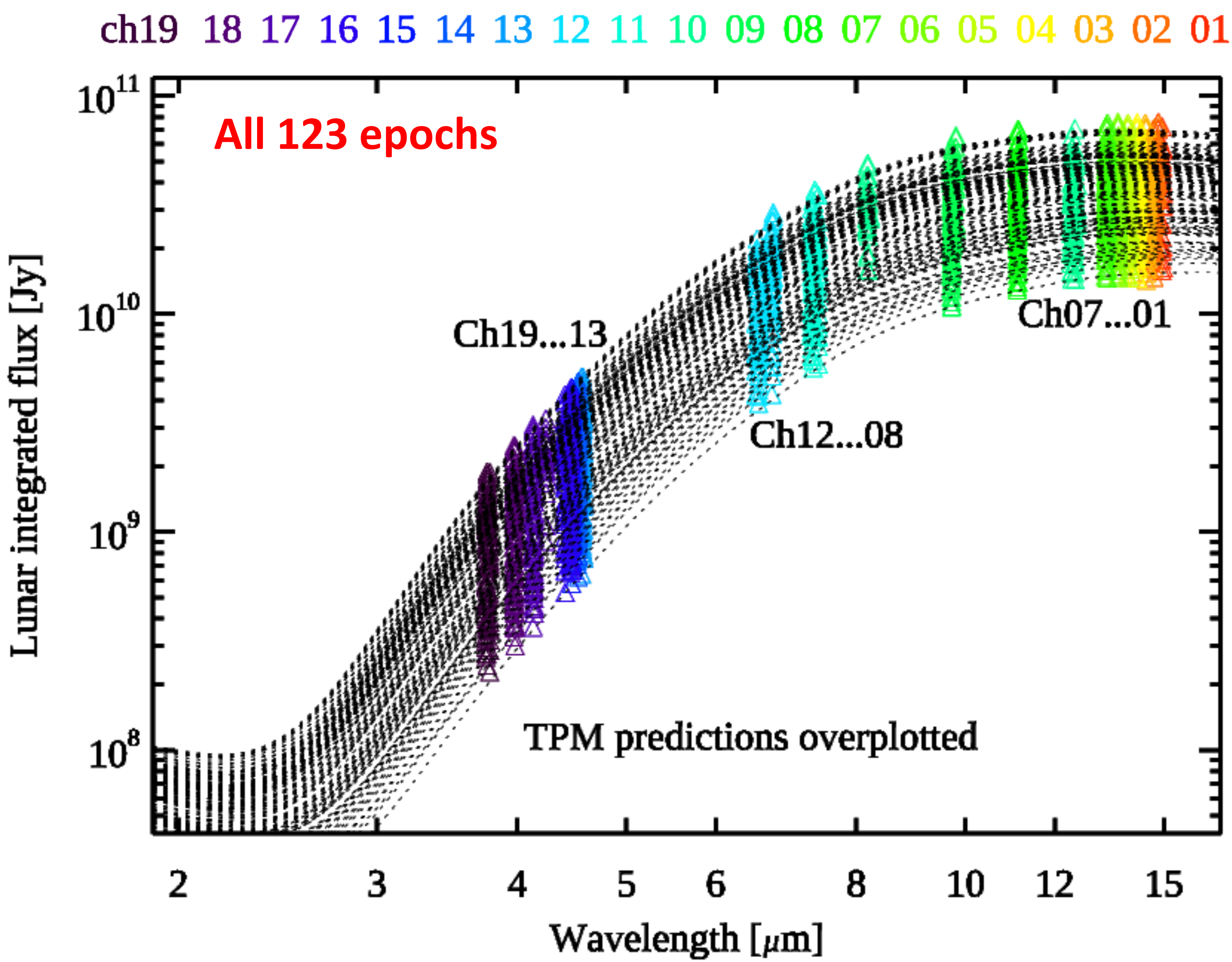


Fig. 6, Müller et al. 2021

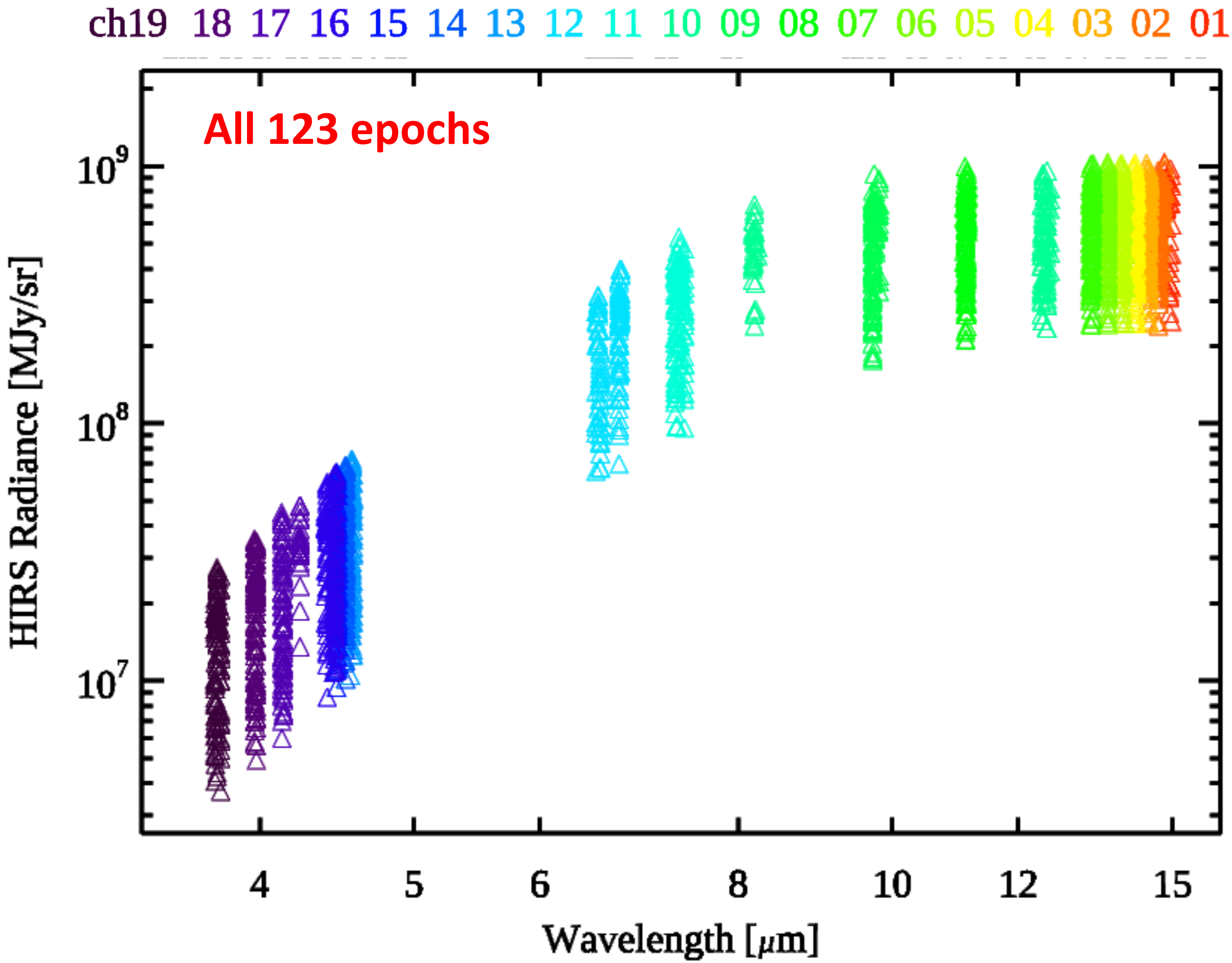


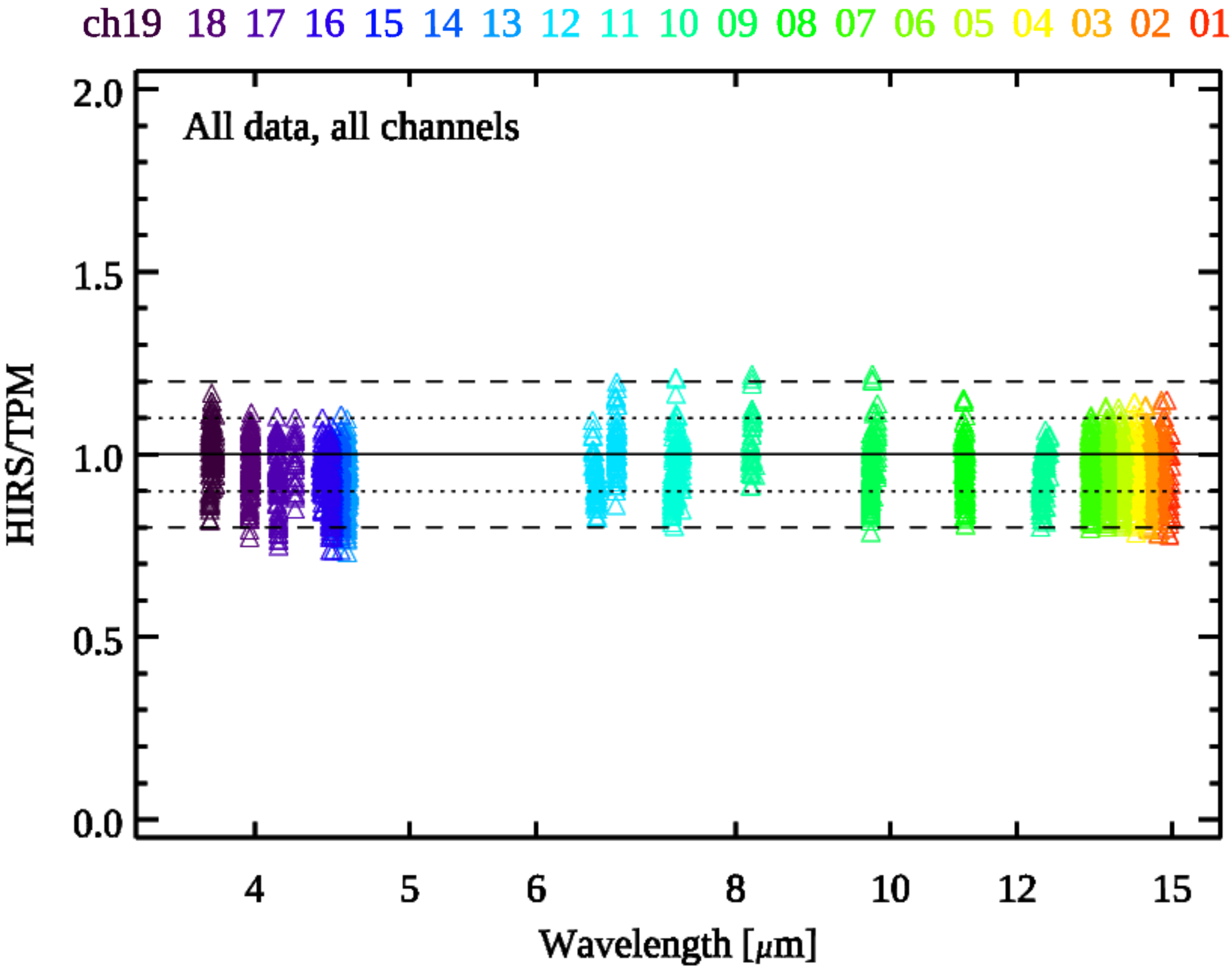
HIRS
3-15 μm
MW
Radiance [MJy/sr]
Wavelengths [μm]
$|\alpha| < 90$ deg
$|\alpha| > 90$ deg
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
1
10
100
1000

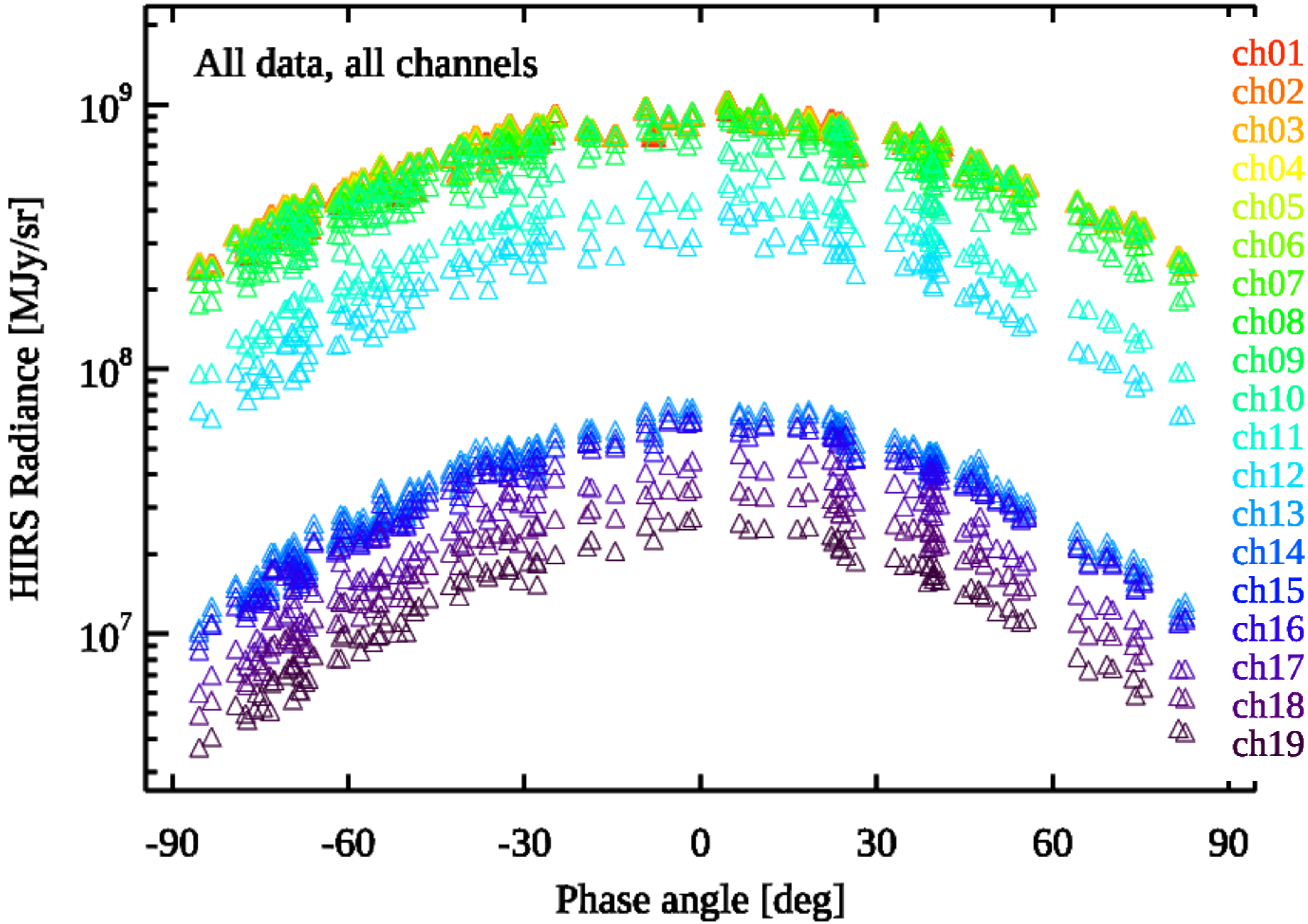
Comparison between HIRS data and TPM predictions



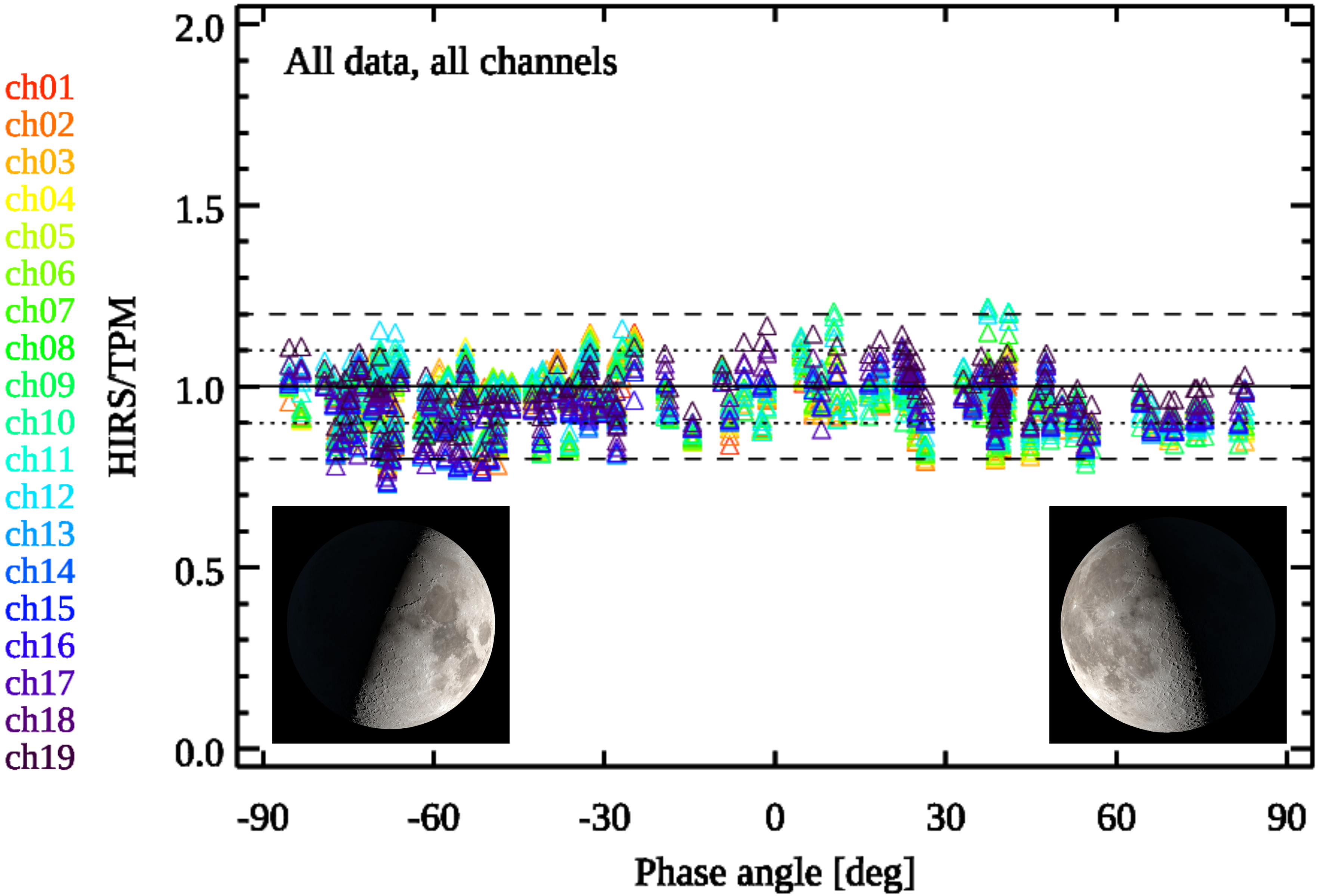
ch19 18 17 16 15 14 13 12 11 10 09 08 07 06 05 04 03 02 01
All 123 epochs
Ch19...13
Ch12...08
Ch07...01
TPM predictions overplotted
Lunar integrated flux [Jy]
Wavelength [μm]

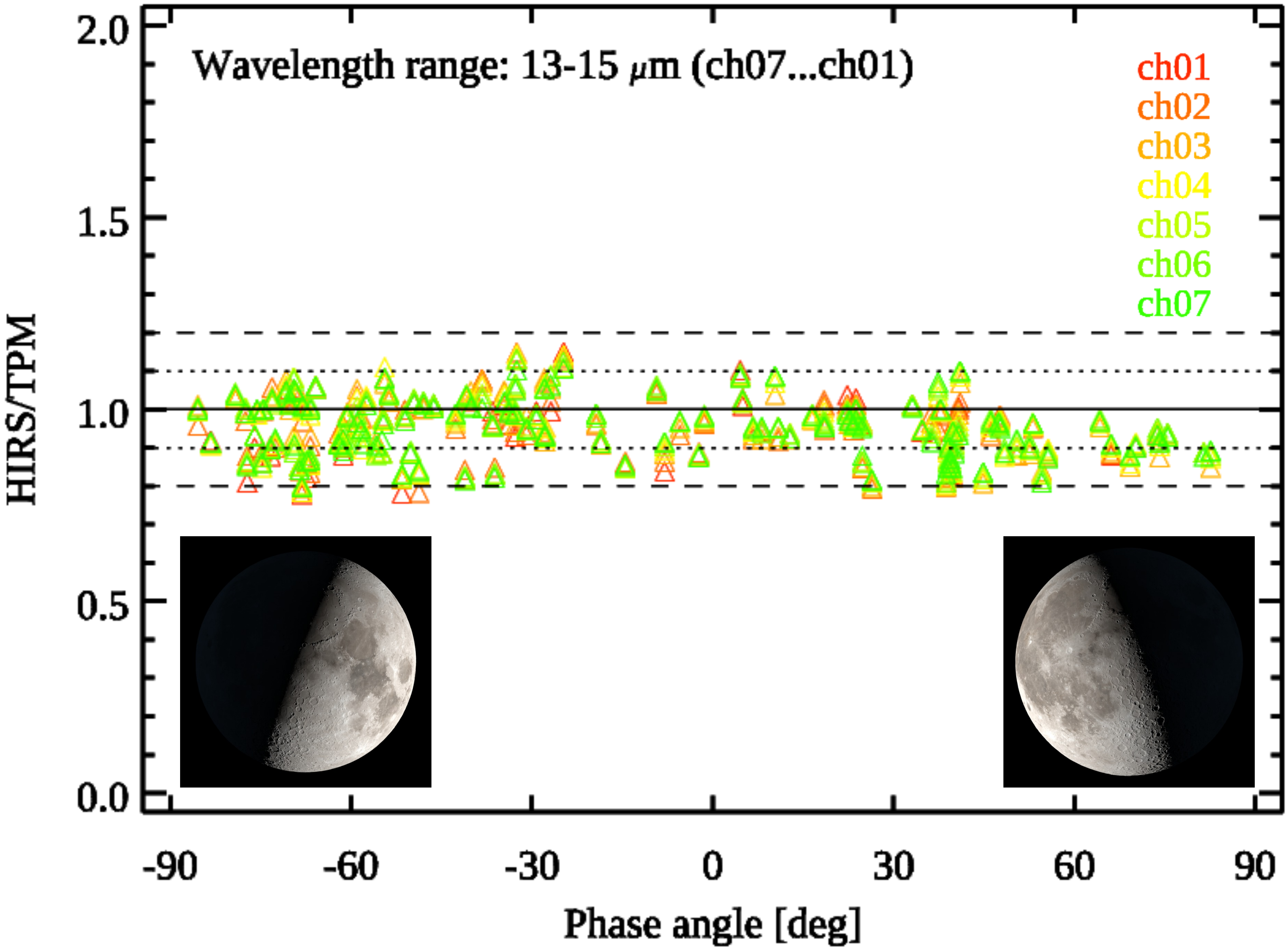

ch19 18 17 16 15 14 13 12 11 10 09 08 07 06 05 04 03 02 01
All 123 epochs
HIRS Radiance [MJy/sr]
10^9
10^8
10^7
4
5
6
8
10
12
15
Wavelength [μm]


ch19 18 17 16 15 14 13 12 11 10 09 08 07 06 05 04 03 02 01
All data, all channels
HIRS/TPM
2.0
1.5
1.0
0.5
0.0
4
5
6
8
10
12
15
Wavelength [μm]

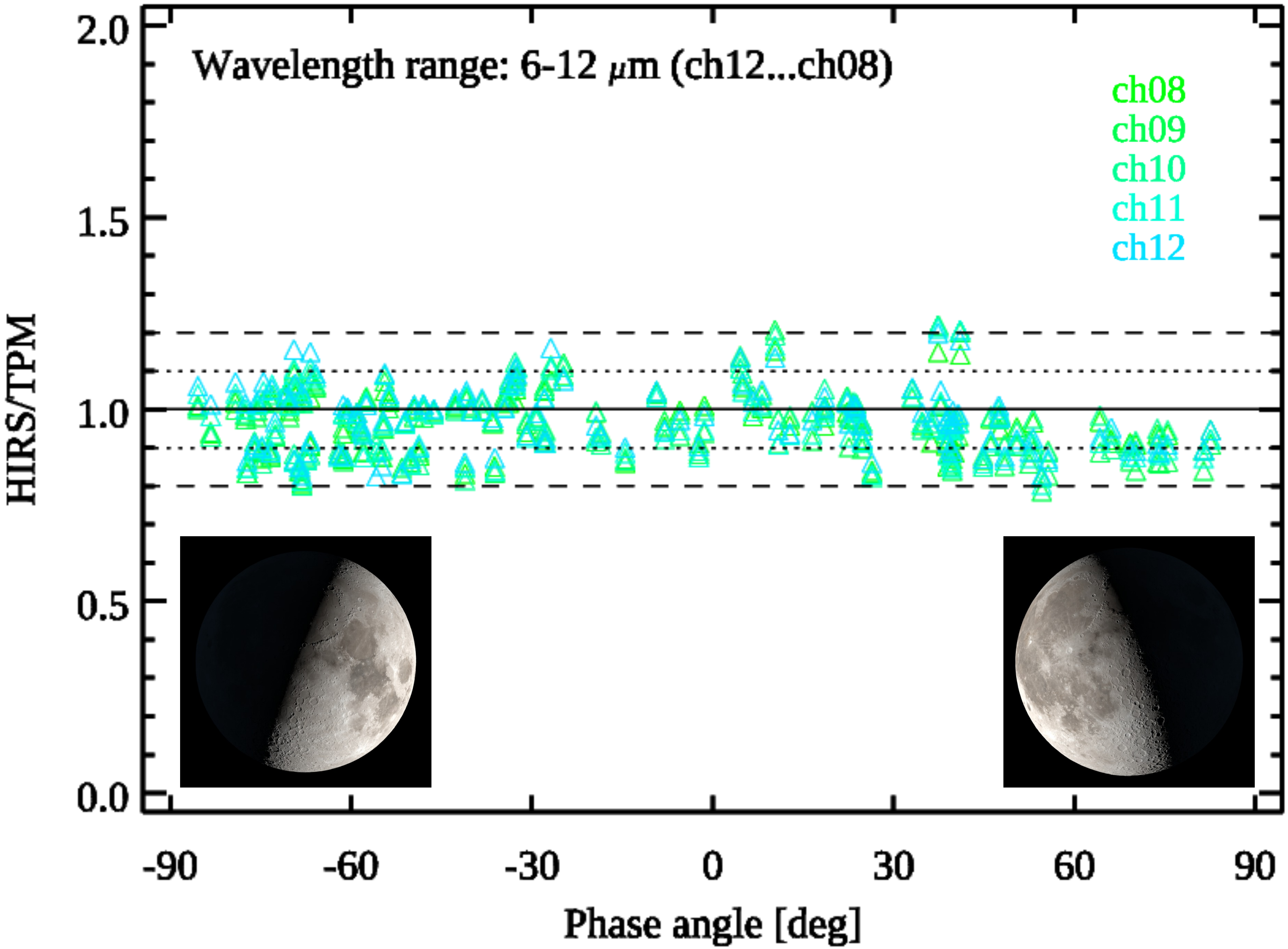


All data, all channels
HIRS Radiance [MJy/sr]
10^9
10^8
10^7
-90
-60
-30
0
30
60
90
Phase angle [deg]
ch01
ch02
ch03
ch04
ch05
ch06
ch07
ch08
ch09
ch10
ch11
ch12
ch13
ch14
ch15
ch16
ch17
ch18
ch19

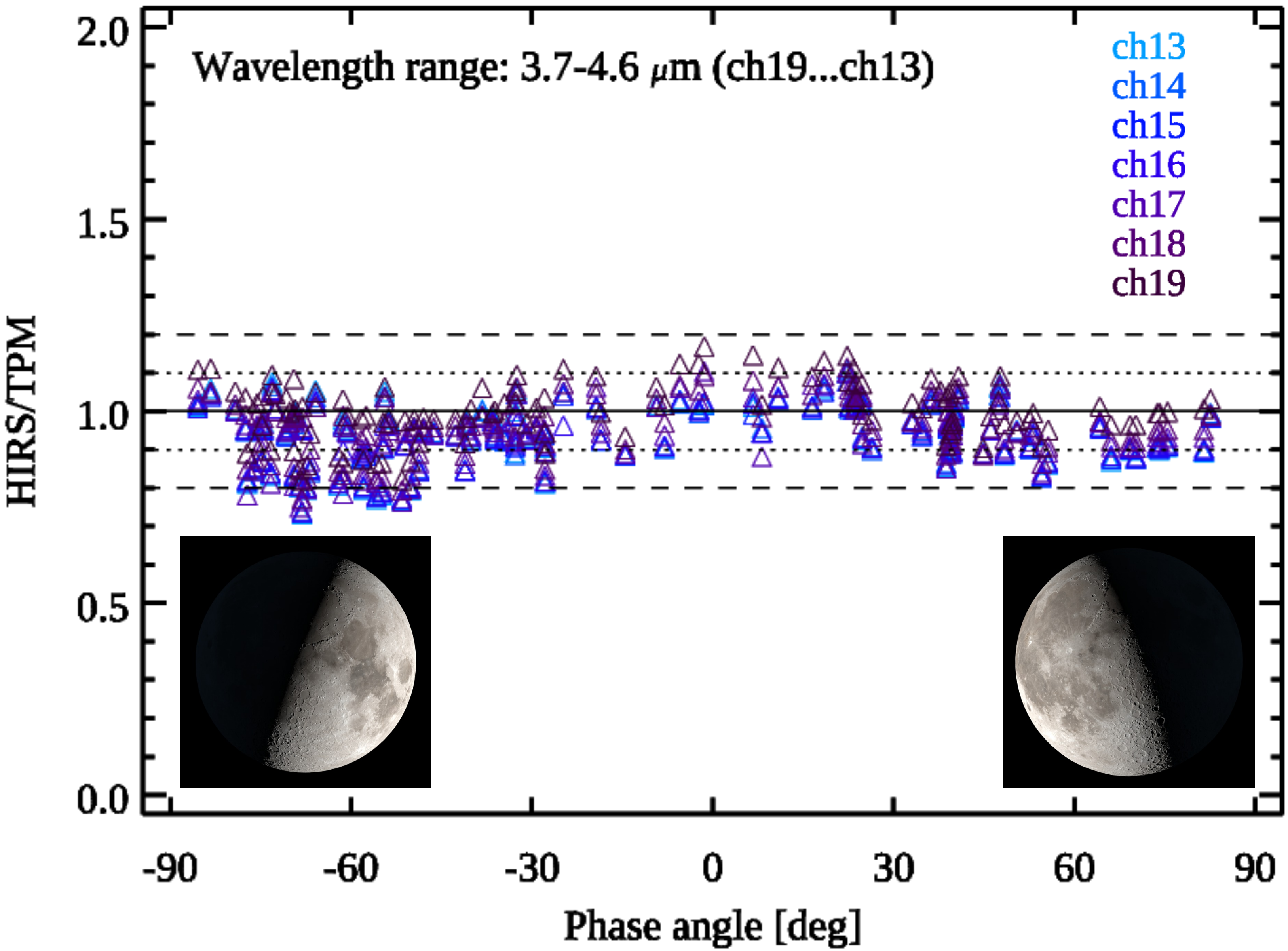

ch01
ch02
ch03
ch04
ch05
ch06
ch07
ch08
ch09
ch10
ch11
ch12
ch13
ch14
ch15
ch16
ch17
ch18
ch19
All data, all channels
HIRS/TPM
2.0
1.5
1.0
0.5
0.0
-90
-60
-30
0
30
60
90
Phase angle [deg]

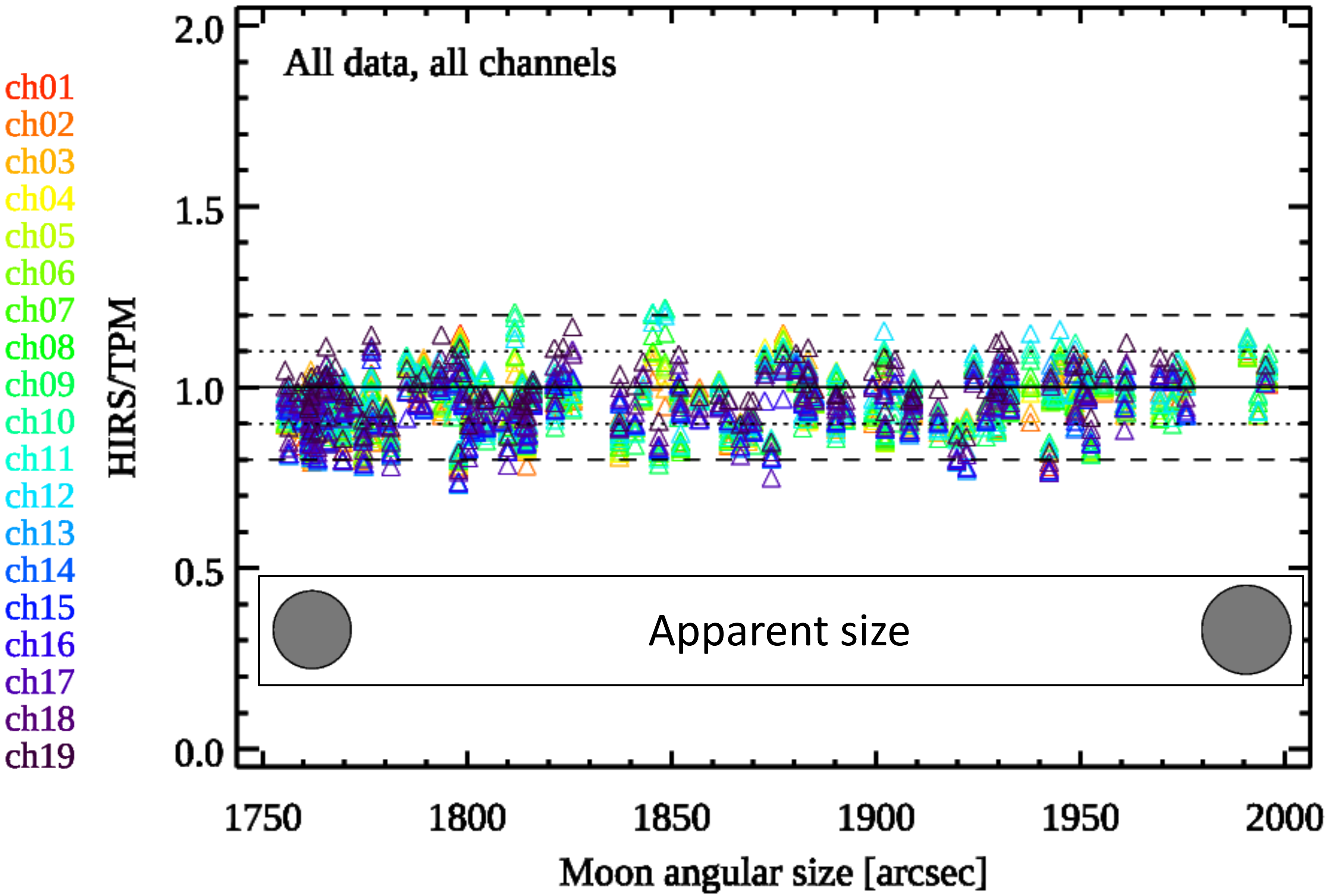


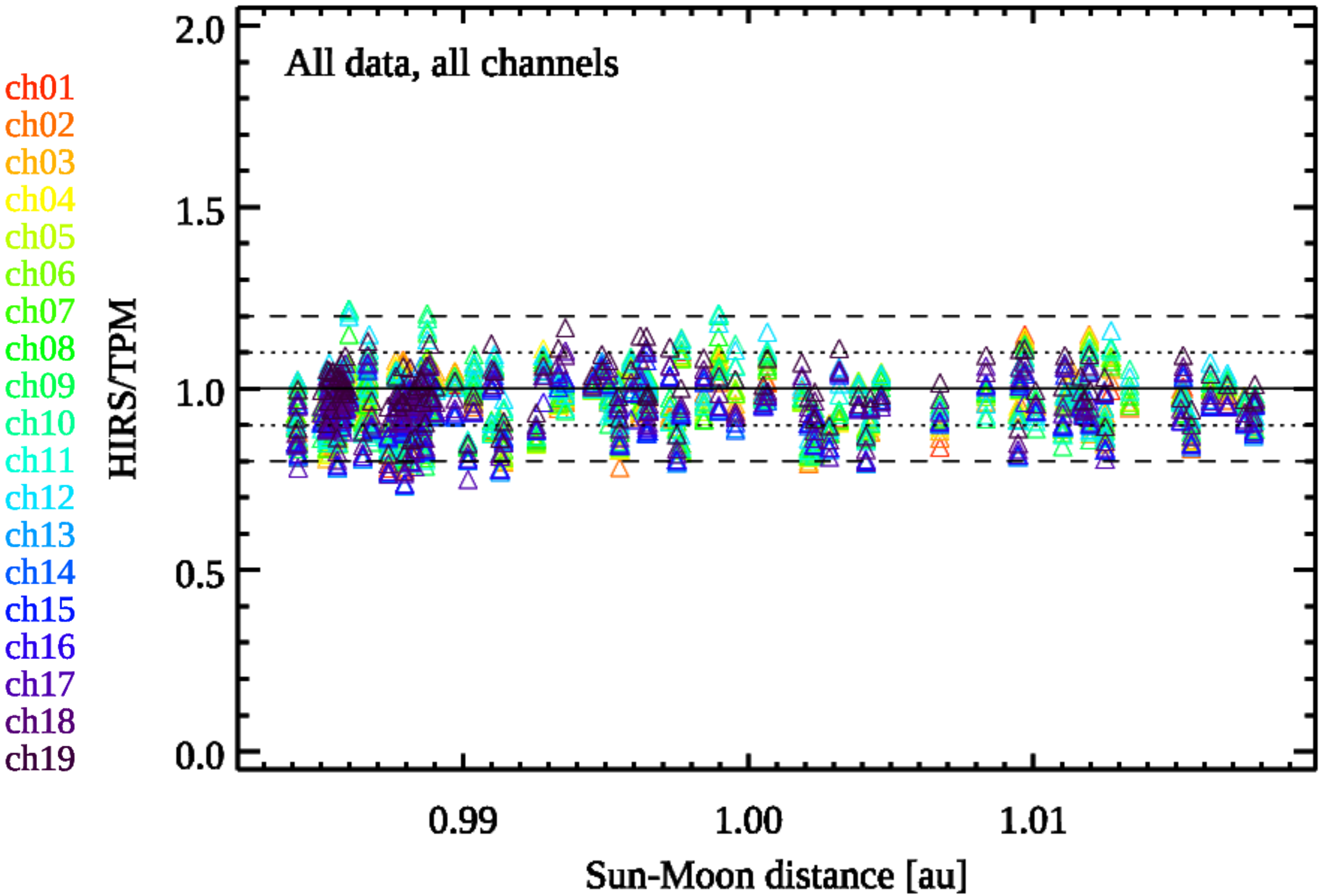
Wavelength range: 13-15 μm (ch07...ch01)
ch01
ch02
ch03
ch04
ch05
ch06
ch07
HIRS/TPM
2.0
1.5
1.0
0.5
0.0
-90
-60
-30
0
30
60
90
Phase angle [deg]



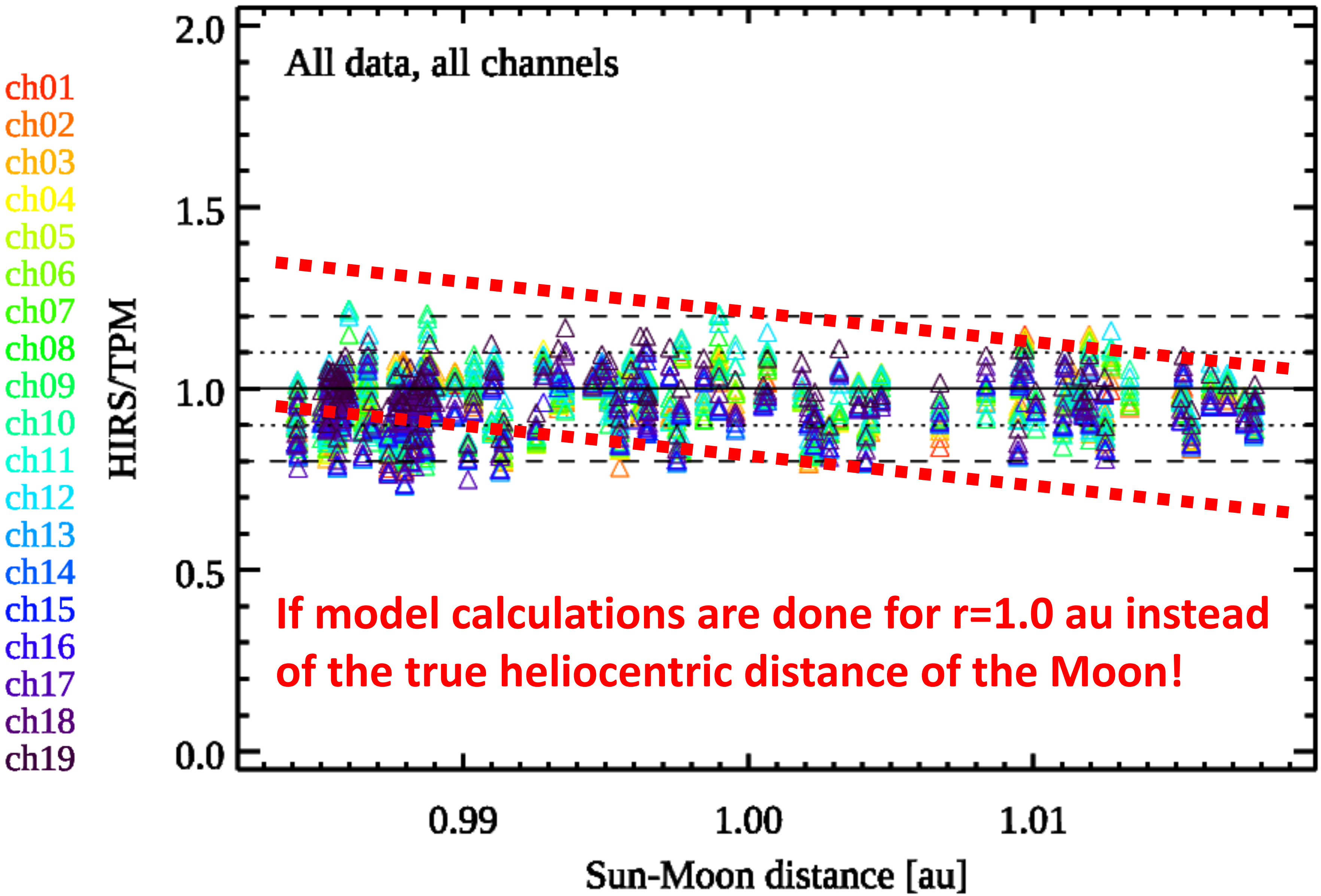
Wavelength range: 6-12 μm (ch12...ch08)
ch08
ch09
ch10
ch11
ch12
HIRS/TPM
2.0
1.5
1.0
0.5
0.0
-90
-60
-30
0
30
60
90
Phase angle [deg]

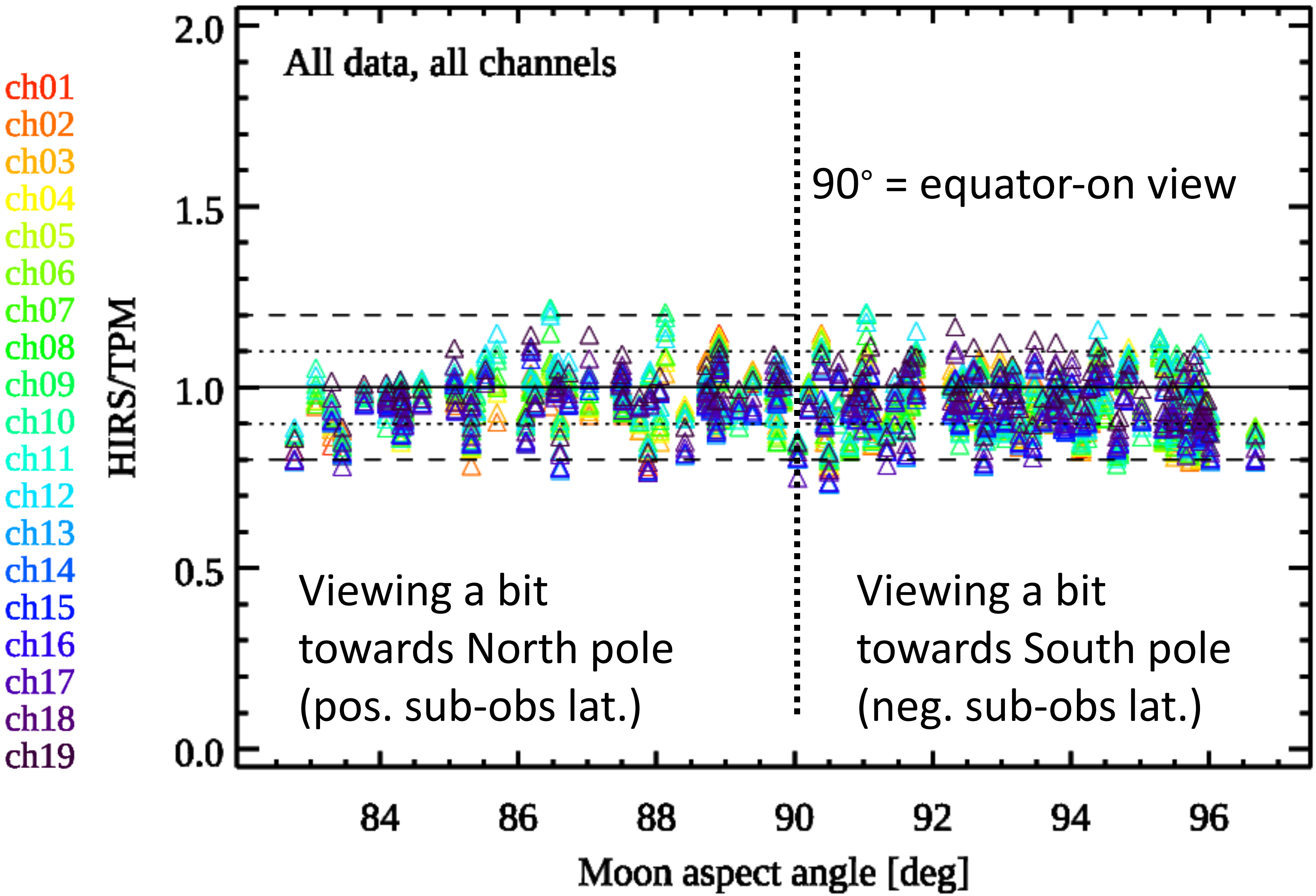

Wavelength range: 3.7-4.6 μm (ch19...ch13)
ch13
ch14
ch15
ch16
ch17
ch18
ch19
HIRS/TPM
2.0
1.5
1.0
0.5
0.0
-90
-60
-30
0
30
60
90
Phase angle [deg]


ch01
ch02
ch03
ch04
ch05
ch06
ch07
ch08
ch09
ch10
ch11
ch12
ch13
ch14
ch15
ch16
ch17
ch18
ch19
All data, all channels
HIRS/TPM
2.0
1.5
1.0
0.5
0.0
Apparent size
1750
1800
1850
1900
1950
2000
Moon angular size [arcsec]



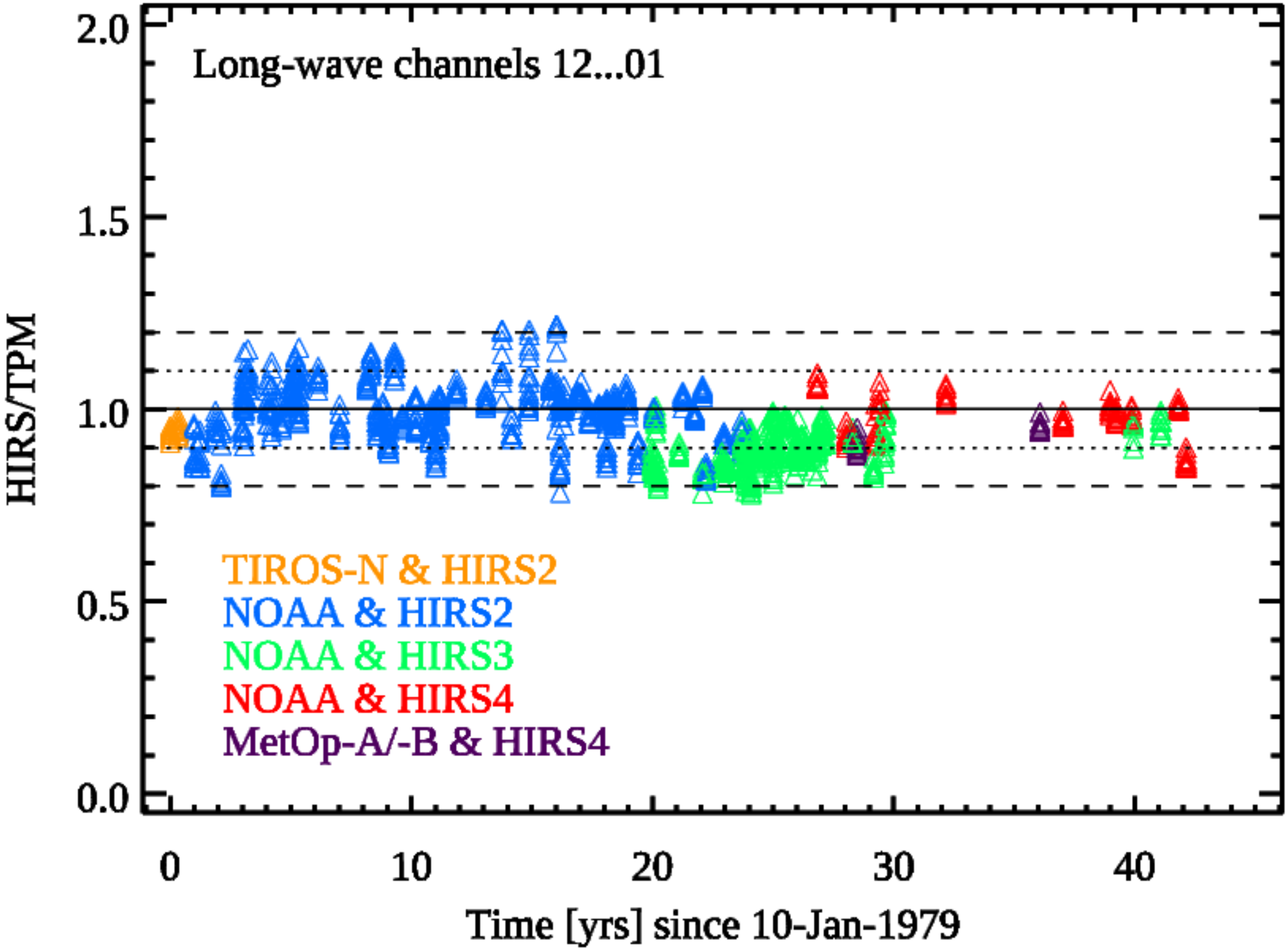
All data, all channels
ch01
ch02
ch03
ch04
ch05
ch06
ch07
ch08
ch09
ch10
ch11
ch12
ch13
ch14
ch15
ch16
ch17
ch18
ch19
HIRS/TPM
2.0
1.5
1.0
0.5
0.0
0.99
1.00
1.01
Sun-Moon distance [au]


ch01
ch02
ch03
ch04
ch05
ch06
ch07
ch08
ch09
ch10
ch11
ch12
ch13
ch14
ch15
ch16
ch17
ch18
ch19
HIRS/TPM
2.0
1.5
1.0
0.5
0.0
All data, all channels
0.99
1.00
1.01
Sun-Moon distance [au]
If model calculations are done for r=1.0 au instead
of the true heliocentric distance of the Moon!

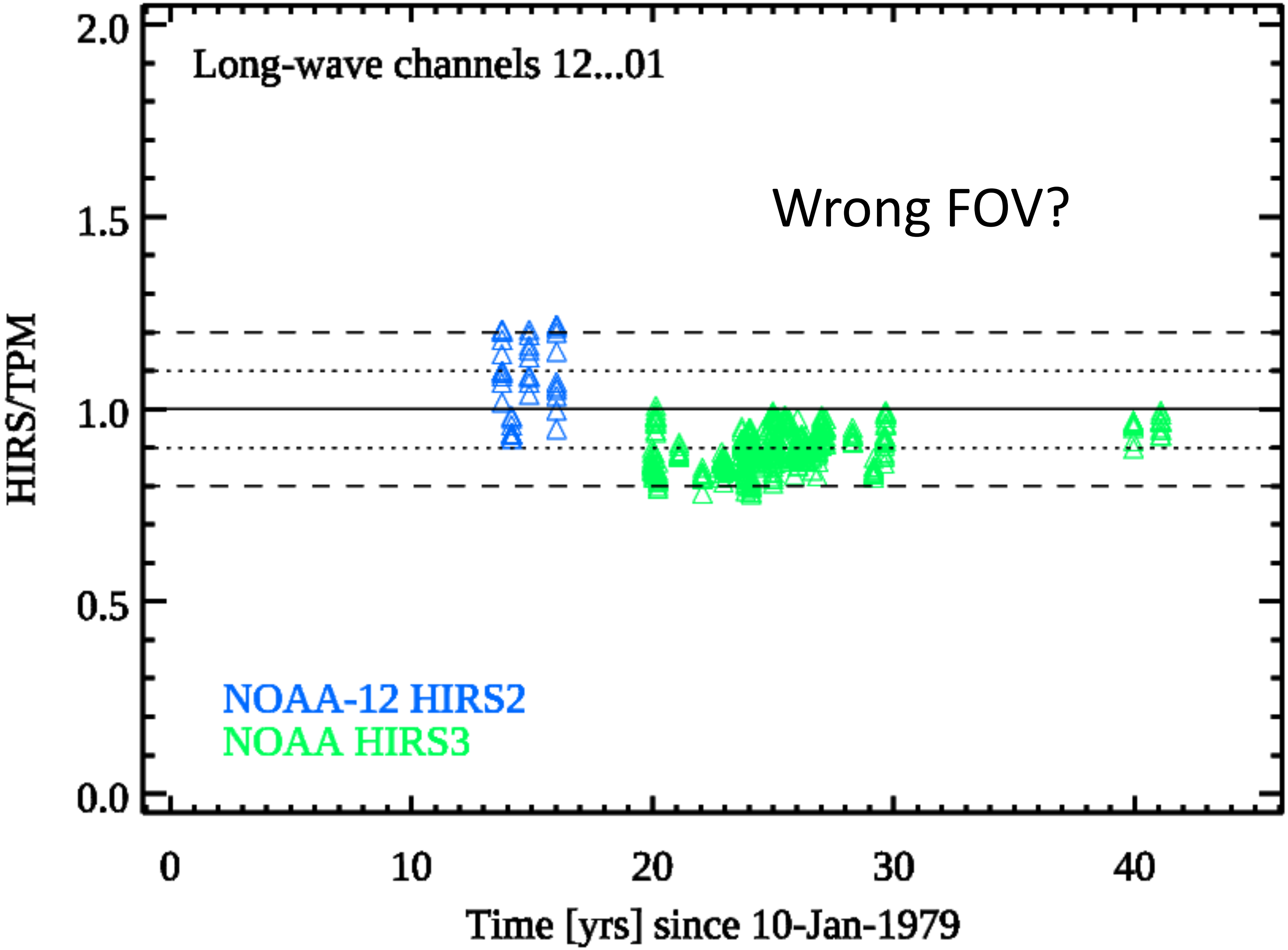


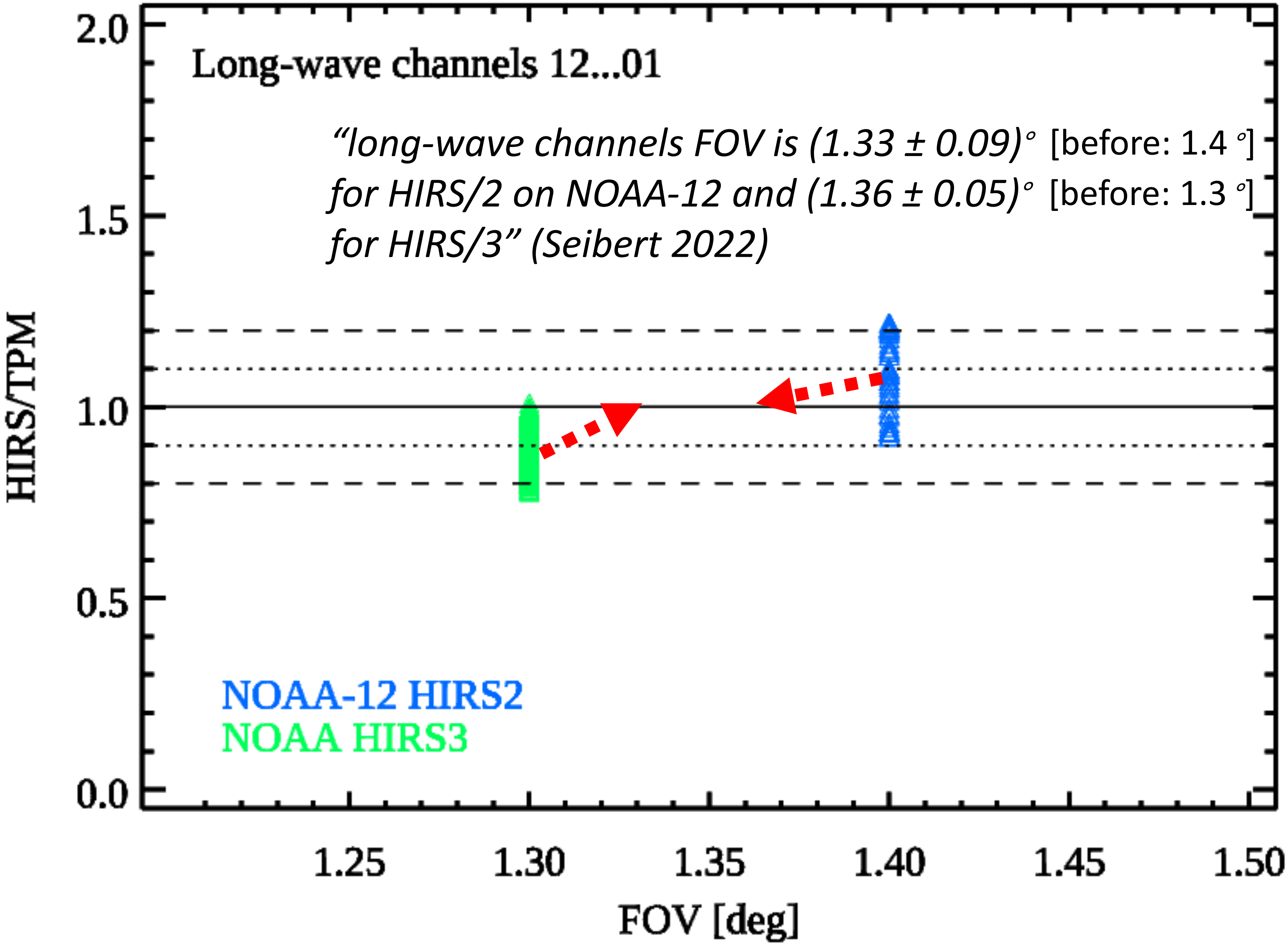
ch01
ch02
ch03
ch04
ch05
ch06
ch07
ch08
ch09
ch10
ch11
ch12
ch13
ch14
ch15
ch16
ch17
ch18
ch19
HIRS/TPM
2.0
1.5
1.0
0.5
0.0
All data, all channels
90° = equator-on view
Viewing a bit towards North pole (pos. sub-obs lat.)
Viewing a bit towards South pole (neg. sub-obs lat.)
84
86
88
90
92
94
96
Moon aspect angle [deg]

Investigating individual HIRS calibration

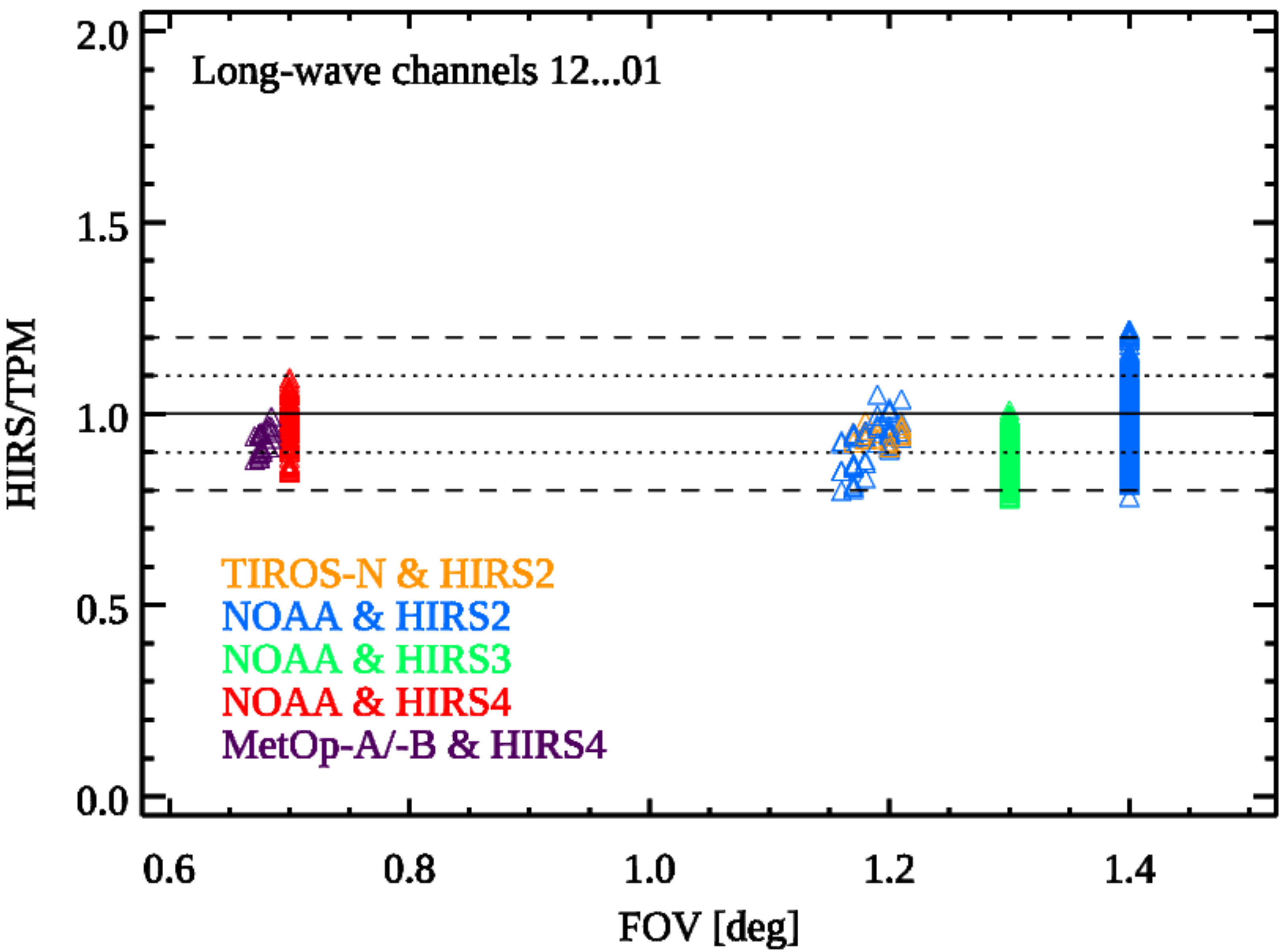


Long-wave channels 12...01
HIRS/TPM
2.0
1.5
1.0
0.5
0.0
0
10
20
30
40
Time [yrs] since 10-Jan-1979
TIROS-N & HIRS2
NOAA & HIRS2
NOAA & HIRS3
NOAA & HIRS4
MetOp-A/-B & HIRS4

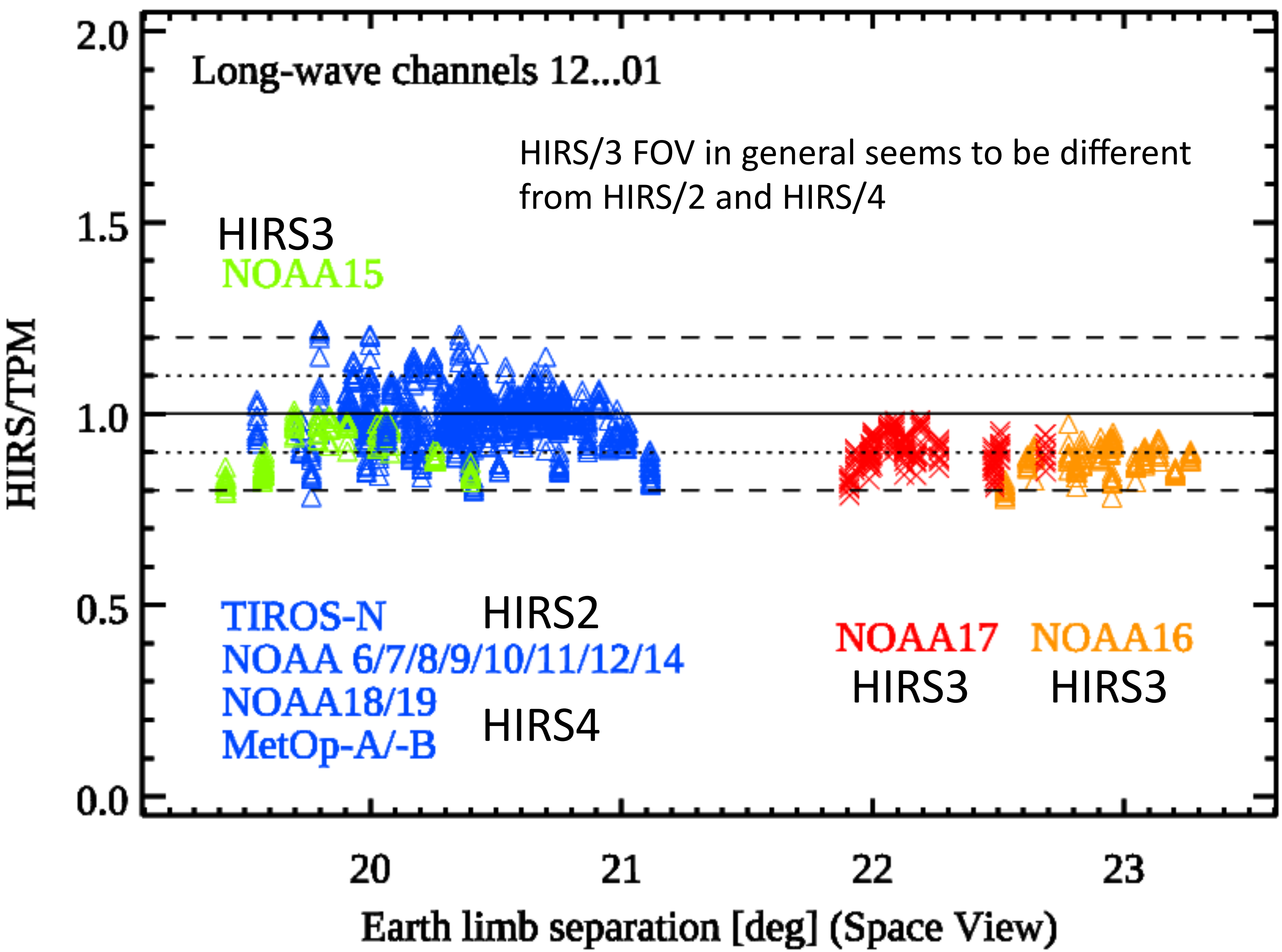

Long-wave channels 12...01
Wrong FOV?
HIRS/TPM
2.0
1.5
1.0
0.5
0.0
0
10
20
30
40
Time [yrs] since 10-Jan-1979
NOAA-12 HIRS2
NOAA HIRS3

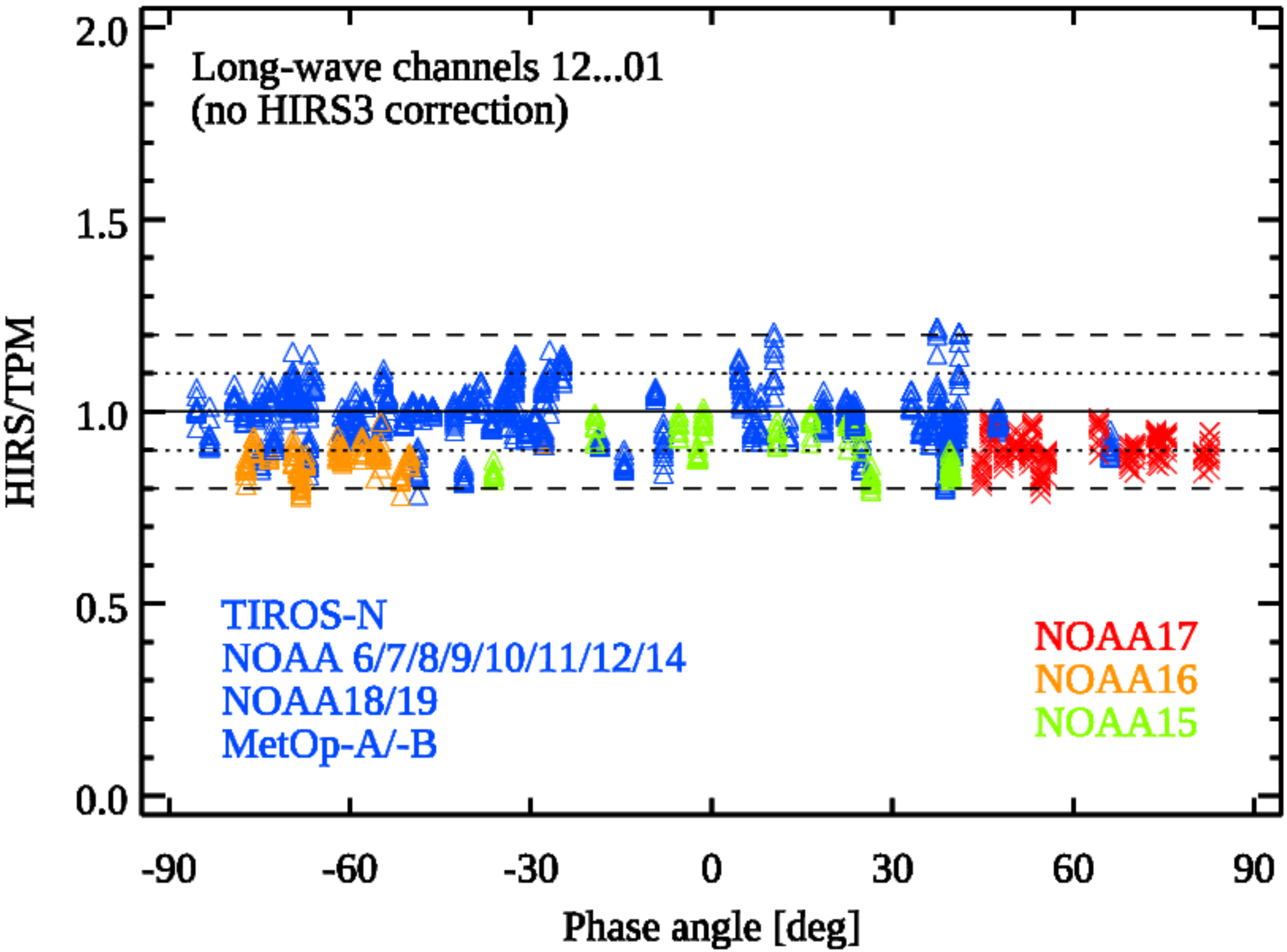


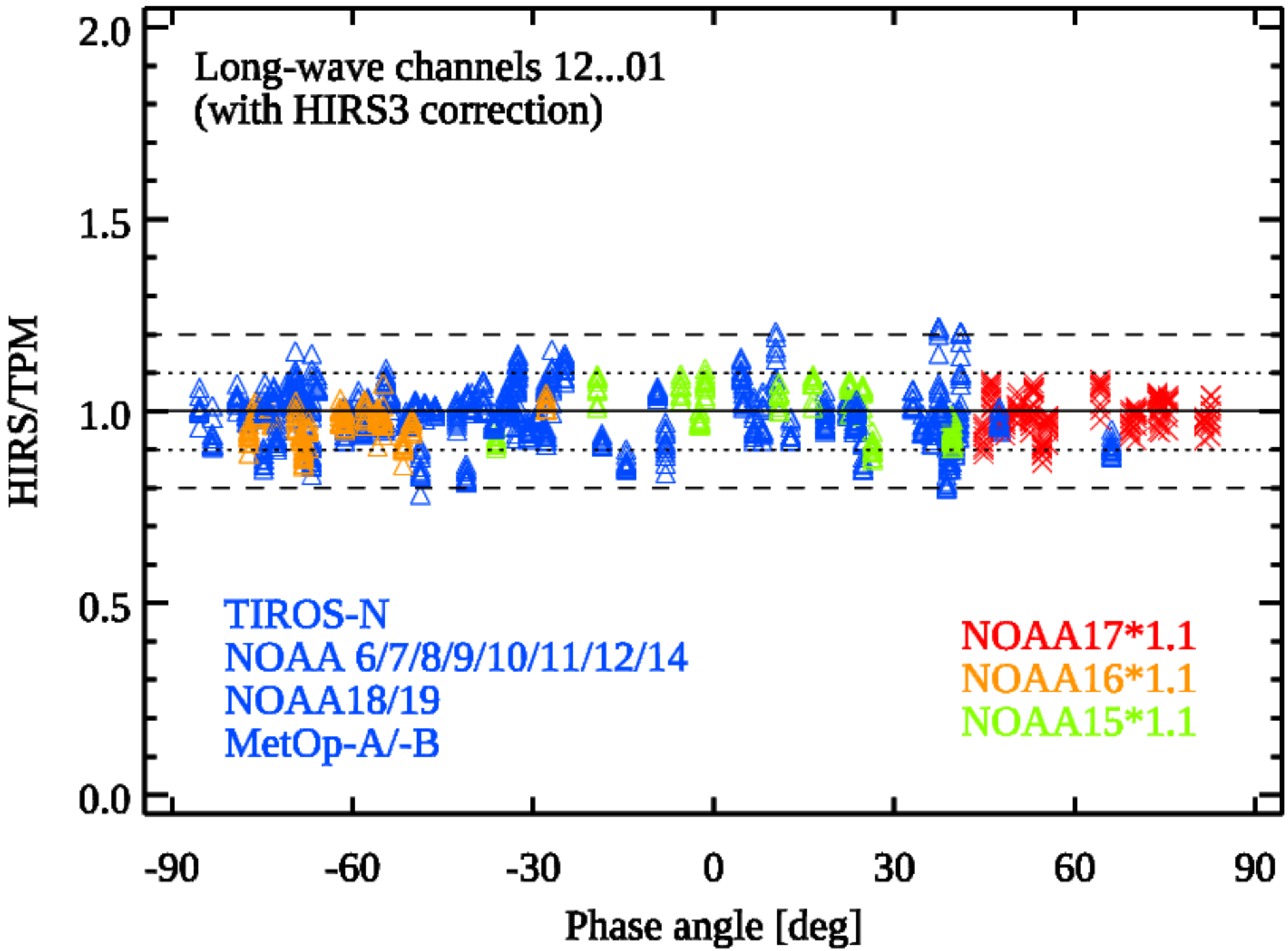
Long-wave channels 12...01
"long-wave channels FOV is (1.33 ± 0.09)° [before: 1.4 °]
for HIRS/2 on NOAA-12 and (1.36 ± 0.05)° [before: 1.3 °]
for HIRS/3" (Seibert 2022)
NOAA-12 HIRS2
NOAA HIRS3
HIRS/TPM
2.0
1.5
1.0
0.5
0.0
1.25
1.30
1.35
1.40
1.45
1.50
FOV [deg]



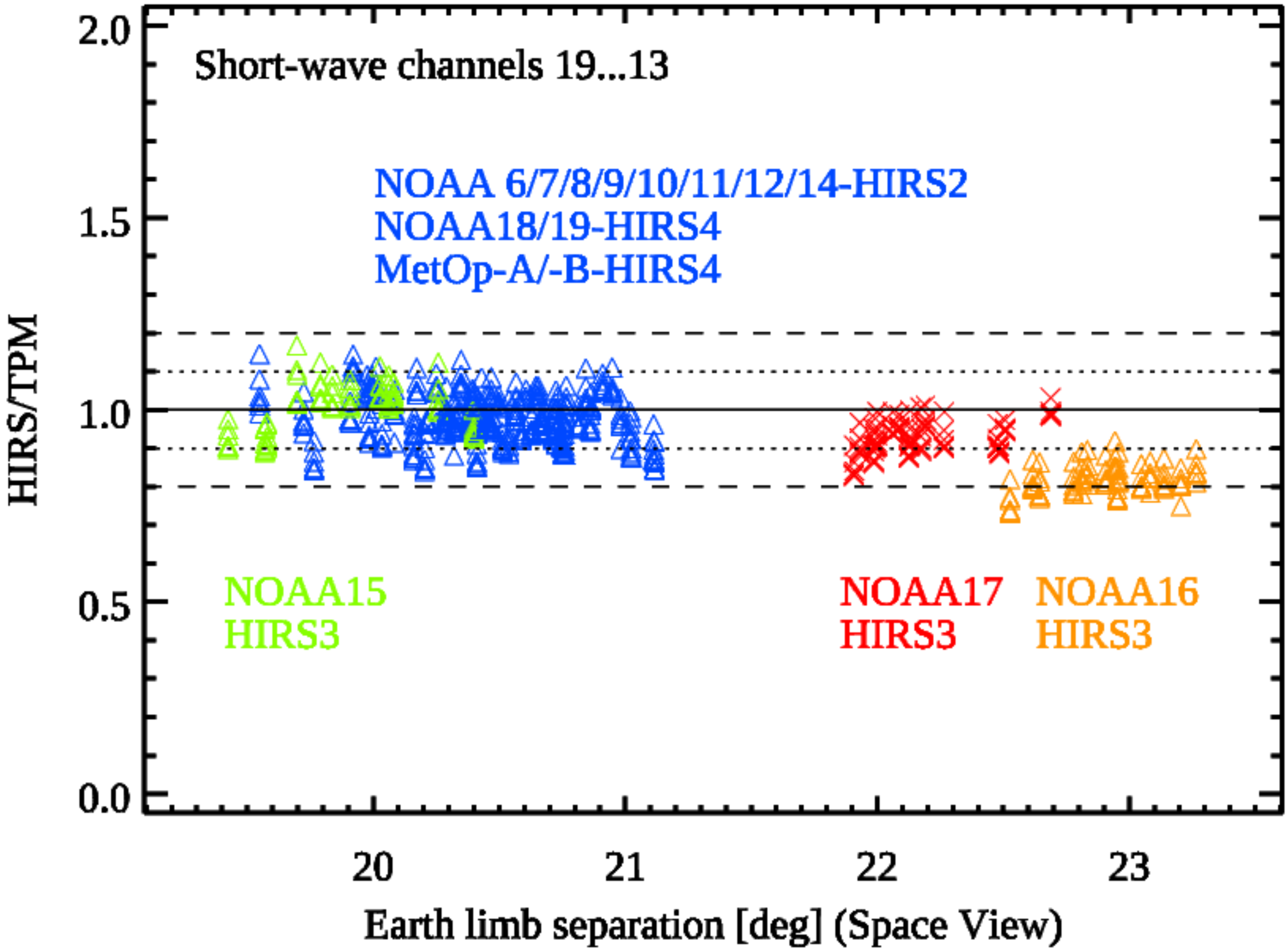
Long-wave channels 12...01
HIRS/TPM
FOV [deg]
2.0
1.5
1.0
0.5
0.0
0.6
0.8
1.0
1.2
1.4
TIROS-N & HIRS2
NOAA & HIRS2
NOAA & HIRS3
NOAA & HIRS4
MetOp-A/-B & HIRS4


Long-wave channels 12...01
HIRS/3 FOV in general seems to be different from HIRS/2 and HIRS/4
HIRS3
NOAA15
TIROS-N
NOAA 6/7/8/9/10/11/12/14
NOAA18/19
MetOp-A/-B
HIRS2
HIRS4
NOAA17
HIRS3
NOAA16
HIRS3
HIRS/TPM
2.0
1.5
1.0
0.5
0.0
20
21
22
23
Earth limb separation [deg] (Space View)

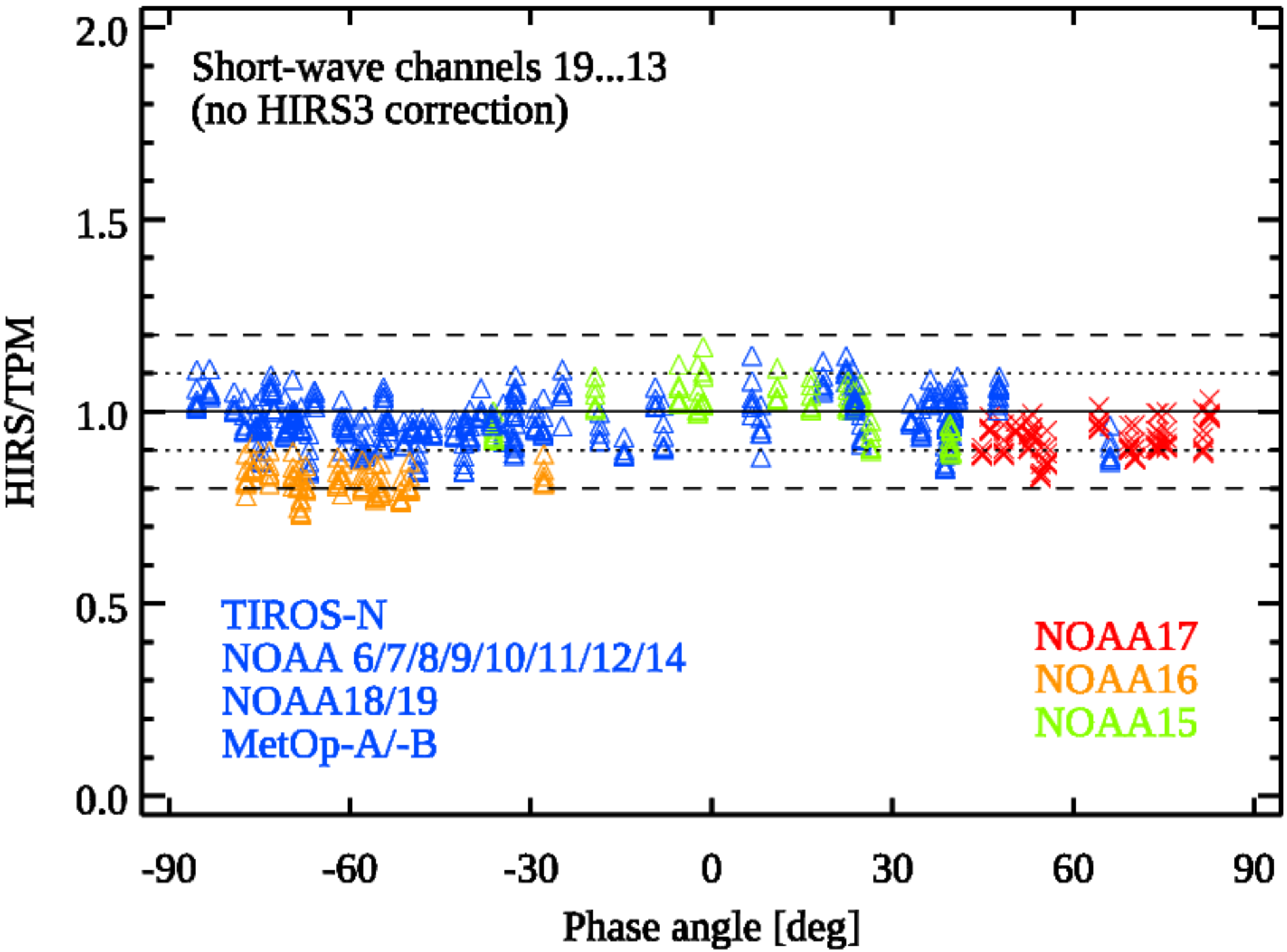

Long-wave channels 12...01
(no HIRS3 correction)
HIRS/TPM
2.0
1.5
1.0
0.5
0.0
-90
-60
-30
0
30
60
90
Phase angle [deg]
TIROS-N
NOAA 6/7/8/9/10/11/12/14
NOAA18/19
MetOp-A/-B
NOAA17
NOAA16
NOAA15



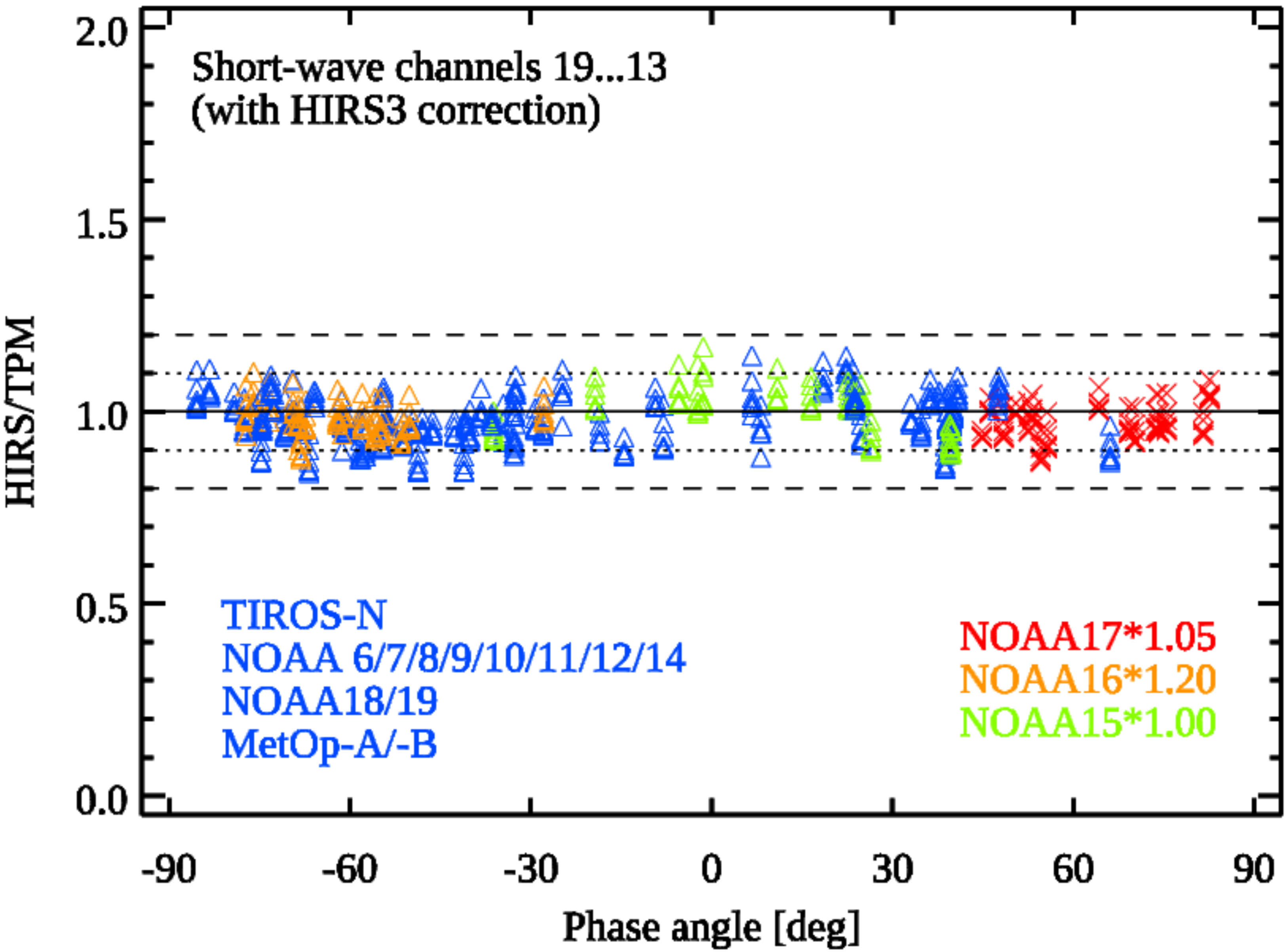
Long-wave channels 12...01
(with HIRS3 correction)
TIROS-N
NOAA 6/7/8/9/10/11/12/14
NOAA18/19
MetOp-A/-B
NOAA17*1.1
NOAA16*1.1
NOAA15*1.1
HIRS/TPM
Phase angle [deg]
2.0
1.5
1.0
0.5
0.0
-90
-60
-30
0
30
60
90

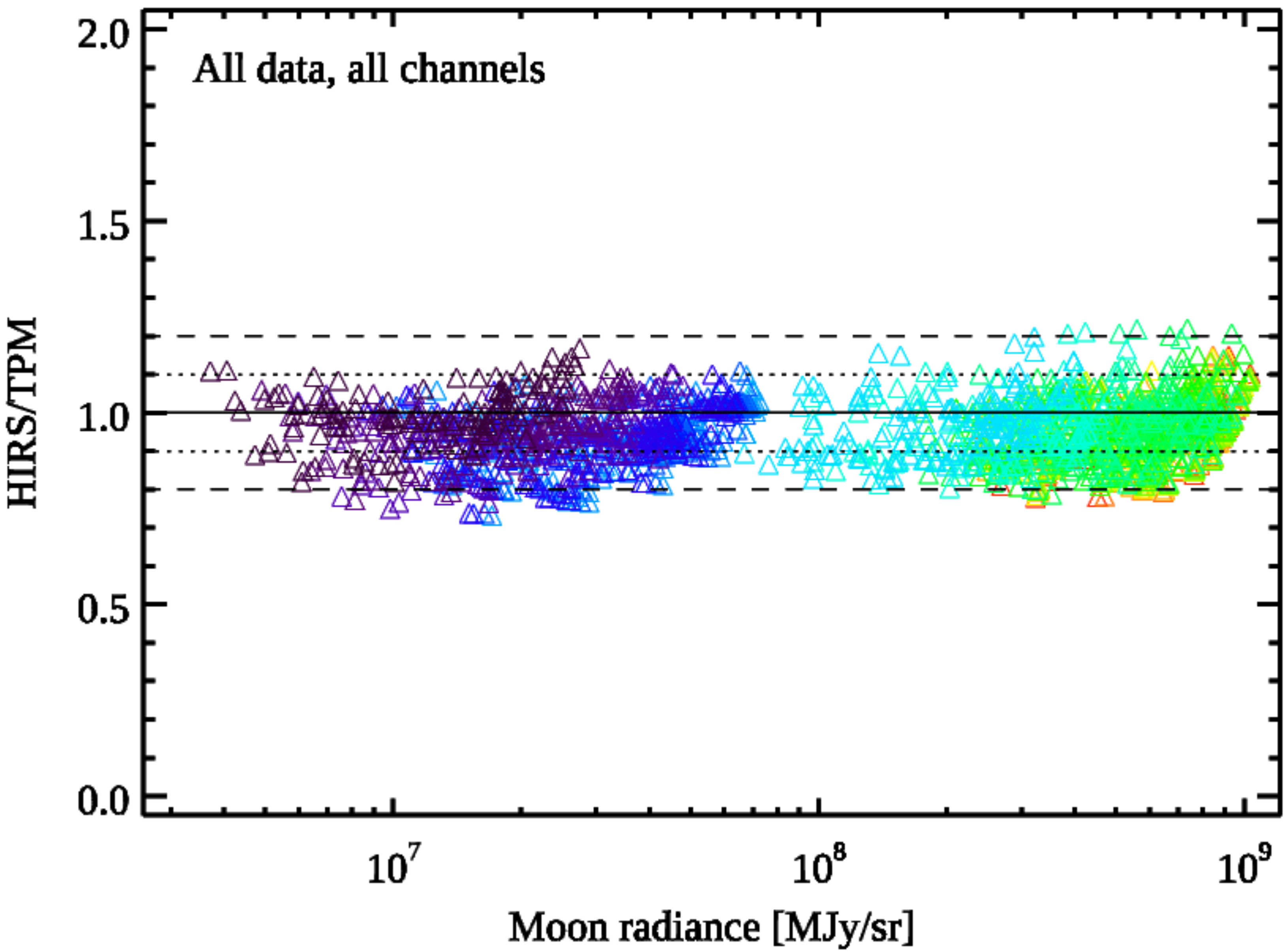


Short-wave channels 19...13
NOAA 6/7/8/9/10/11/12/14-HIRS2
NOAA18/19-HIRS4
MetOp-A/-B-HIRS4
NOAA15
HIRS3
NOAA17
HIRS3
NOAA16
HIRS3
HIRS/TPM
Earth limb separation [deg] (Space View)
2.0
1.5
1.0
0.5
0.0
20
21
22
23

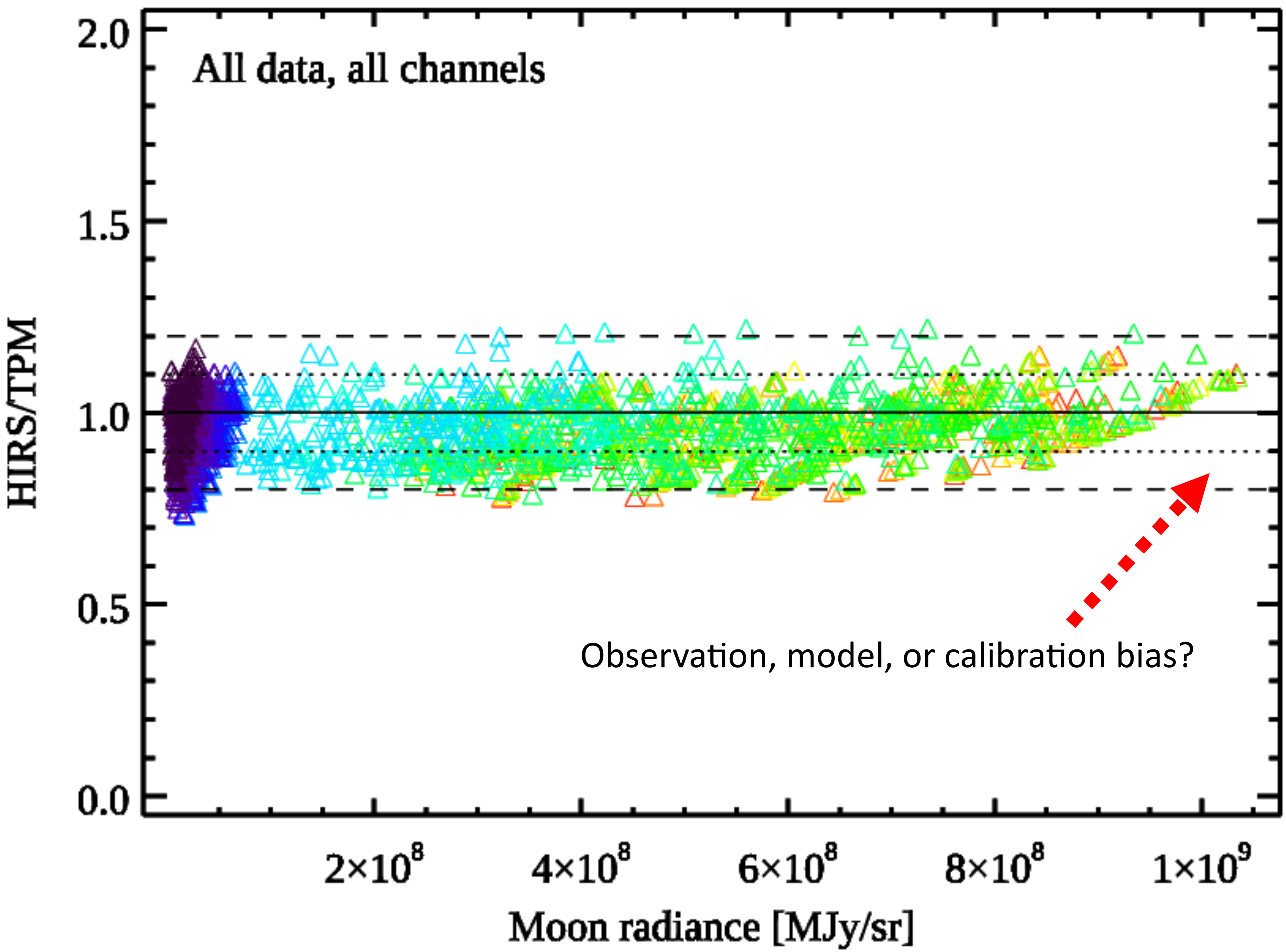


Short-wave channels 19...13
(no HIRS3 correction)
TIROS-N
NOAA 6/7/8/9/10/11/12/14
NOAA18/19
MetOp-A/-B
NOAA17
NOAA16
NOAA15
HIRS/TPM
Phase angle [deg]
2.0
1.5
1.0
0.5
0.0
-90
-60
-30
0
30
60
90


Short-wave channels 19...13
(with HIRS3 correction)
HIRS/TPM
2.0
1.5
1.0
0.5
0.0
-90
-60
-30
0
30
60
90
Phase angle [deg]
TIROS-N
NOAA 6/7/8/9/10/11/12/14
NOAA18/19
MetOp-A/-B
NOAA17*1.05
NOAA16*1.20
NOAA15*1.00



All data, all channels
HIRS/TPM
Moon radiance [MJy/sr]
2.0
1.5
1.0
0.5
0.0
10^7
10^8
10^9


All data, all channels
HIRS/TPM
2.0
1.5
1.0
0.5
0.0
2×10^8
4×10^8
6×10^8
8×10^8
1×10^9
Moon radiance [MJy/sr]
Observation, model, or calibration bias?

TPM Results

- Overall, the HIRS radiances are matched very well, for all 19 IR channels and over the wide phase angle range from -85.4 ° to +82.6°, including opposition (full Moon)
- We tested the HIRS/TPM ratios against wavelength, phase angle, time, Sun-Moon and Satellite-Moon distance, Moon rotational phase, aspect angle, and apparent angular size of the Moon (note that the TPM predictions are used on absolute scale, no shifting or scaling has been done): There are no obvious trends or correlations in the HIRS/TPM ratios with any of these parameters
- Overall the TPM predictions agree with the calibrated HIRS radiances within 5-20%, however, the larger offset could be due to specific instrument offsets

Minor points:

- The disk-integrated hemispherical emissivity model (Müller et al. 2021) works reasonably well, however in the range of the Christiansen feature between 7.5 and 9.0 µm, there might be a need to re-adjust the emissivity model (currently, lack of data)
- At short wavelengths between 3.7 µm and 4.6 µm (ch19…ch13), there seems to be a small "opposition effect" (in the HIRS/TPM ratios as a function of phase angle) and the measured radiances are a few percent higher than TPM predictions; this could be caused by a surface inhomogeneity (surface albedo variations)
- The very minor asymmetry in phase curve, discussed in Müller et al. (2021), is not obvious anymore when looking at the full data set (the Müller et al. 2021 results were based on 22 epochs, in comparison to the 123 epochs here)
- TPM solution is very sensitive to exact setting (and implementation) of surface roughness and hemispherical spectral emissivity model

HIRS Results

- Excellent data set to validate any thermal model for the interpretation of disk-integrated lunar IR data!
- Inter-comparison between satellites and instruments is easily possible via Moon measurements in comparison with our thermophysical model predictions
- HIRS data cover a time period of more than 40 years! Analysis of long-term trends are possible (but possibly affected by instrument calibration issues)
- Verification of instrument/channel FOV possible, however, there is no “ground-truth” instrument/channel as FOV benchmark

- At very high moon radiances there seems to be a radiance calibration bias
- Seibert (2022) found “that the long-wave channels FOV is $(1.33 \pm 0.09)^\circ$ for HIRS/2 on NOAA-12 and $(1.36 \pm 0.05)^\circ$ for HIRS/3, respectively.”
- Here, we find that the NOAA16 and NOAA17 (both have HIRS3 instruments onboard) perform the deep space view at a larger Earth’s limb separation, and at the same time, the calibrated radiances are systematically lower (HIRS/TPM < 1.0): HIRS/3 radiances are about 10% too low in the long-wavelength channels (ch12-01); at HIRS/3 short-wavelength channels (ch19-13): NOAA-15: ok, NOAA-16 radiances are about 20% too low, NOAA-17 radiances are ~5% too low.
- These radiance offsets can easily be translated into new effective FOV values (radiance $\sim FOV^2$), but a more detailed study for individual channels might be needed