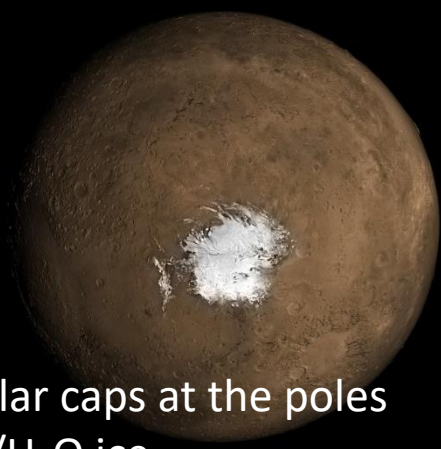


Water ice clouds detection with NOMAD LNO nadir channel on board ExoMars TGO

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Mars quick facts

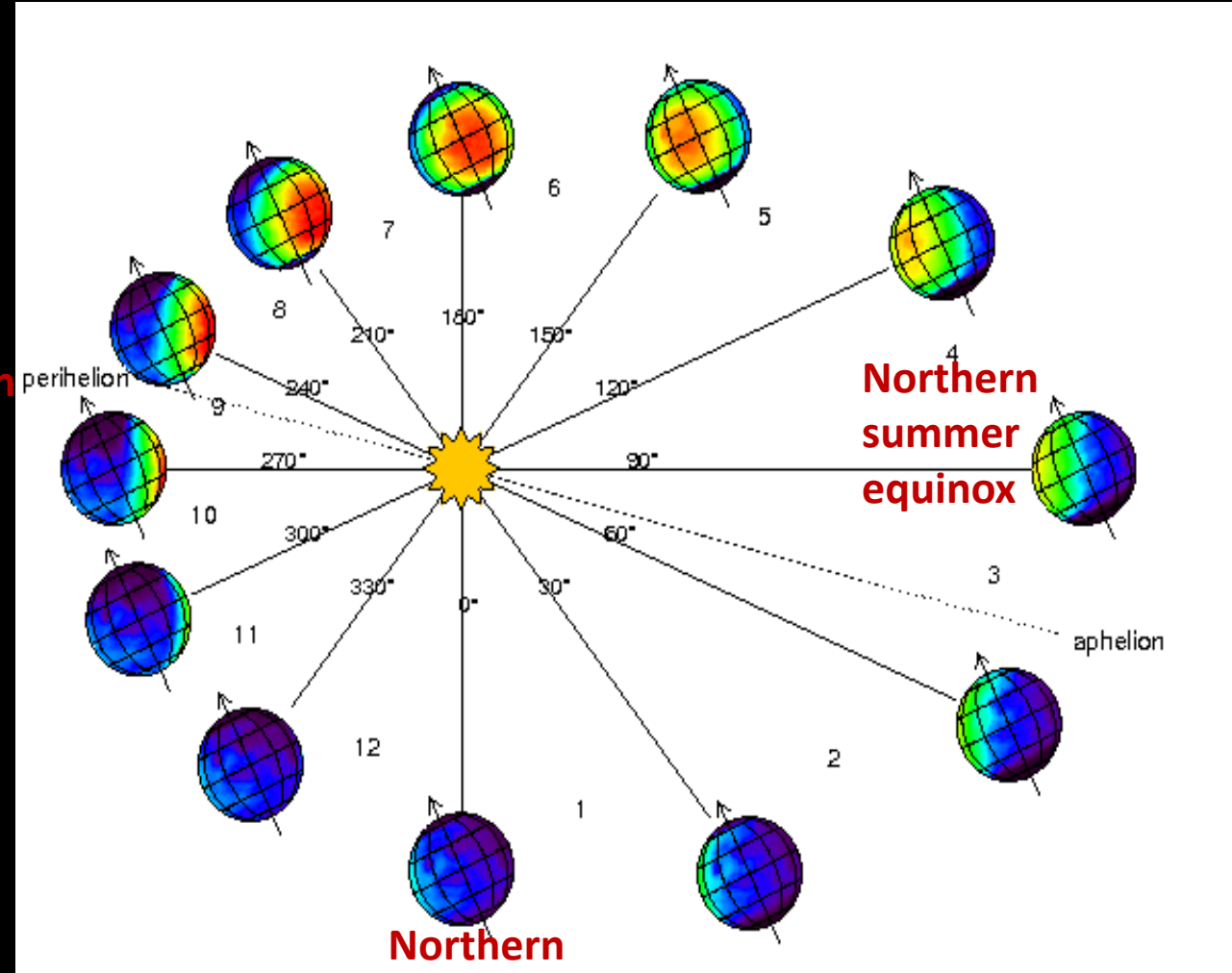
1. Mars has two polar caps at the poles
 - Surface CO₂/H₂O ice
2. Seasons on Mars
 - Use of Solar Longitude (L_S): Mars-Sun angle

As a result:

- Variation in the extent of the polar ice caps
- Process of sublimation and condensation in the polar regions
- Important gas exchanges between surface and atmosphere
- Global climate circulation

Northern winter equinox

Northern autumn equinox



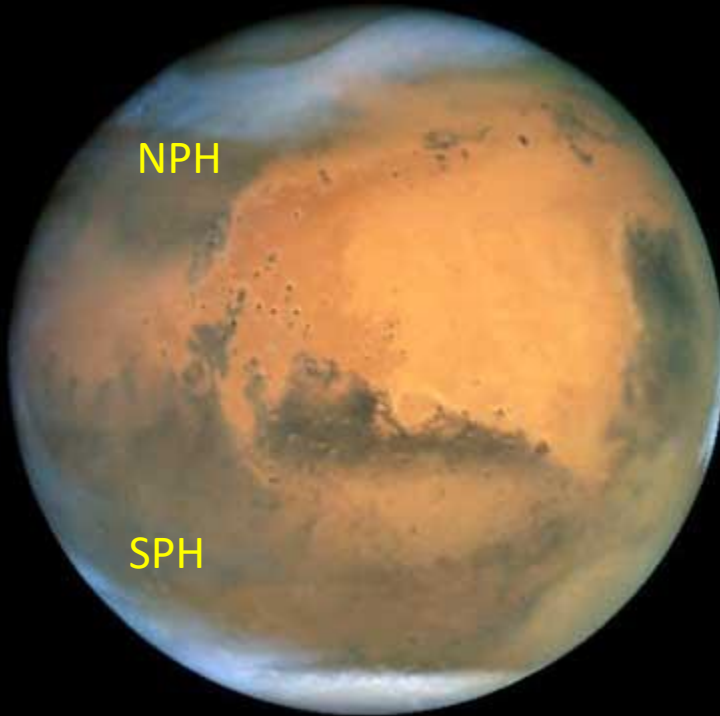
Northern spring equinox

Northern summer equinox

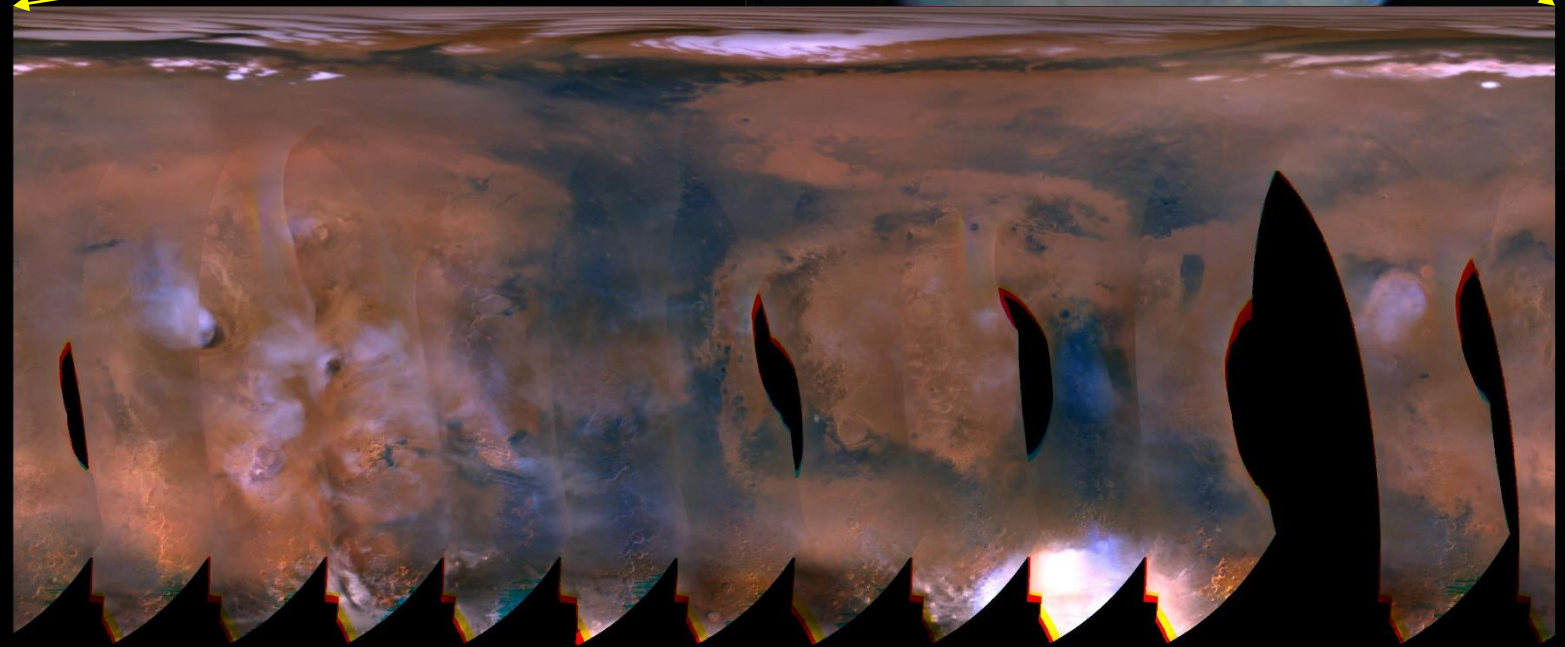
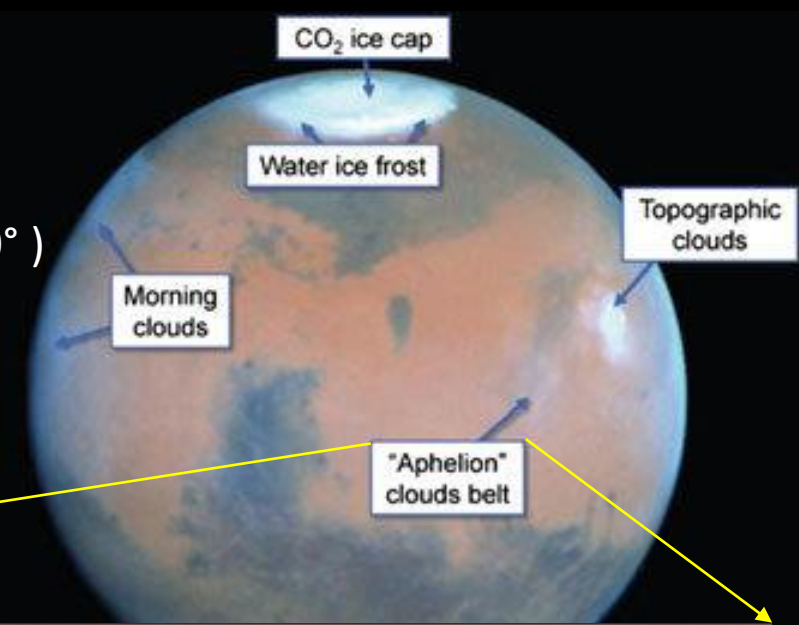


Mars quick facts

- Two main cloud structures
 - Polar Hood (PH) at high latitudes ($L_S = 10^\circ - 70^\circ$ and $L_S = 100^\circ - 200^\circ$)
 - Aphelion Cloud Belt (ACB) at mid-latitudes ($L_S = 60^\circ - 160^\circ$)



Observation of the Polar Hood – NASA Hubble Telescope (June 2001)

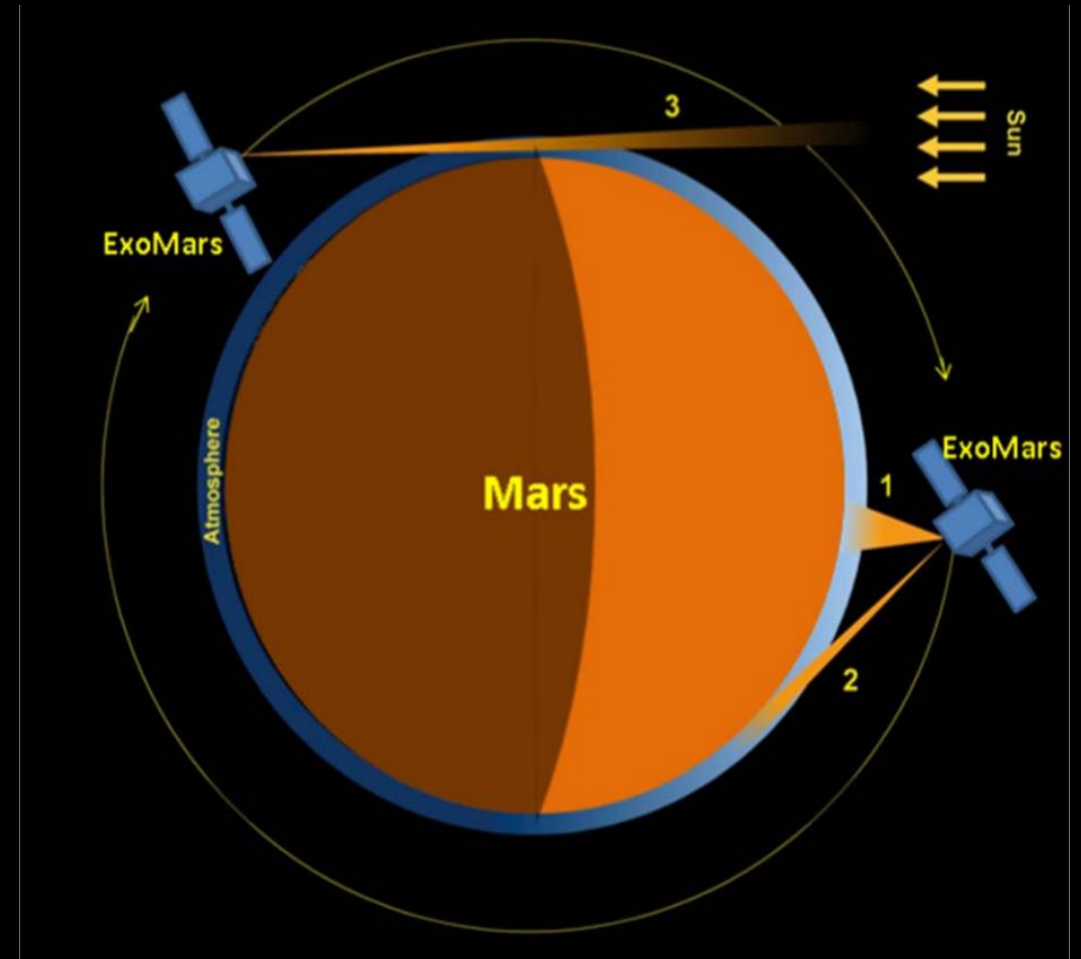


Observation from MRO-MARCI during the aphelion season



The Nadir and Occultation for MArs Discovery (NOMAD) instrument

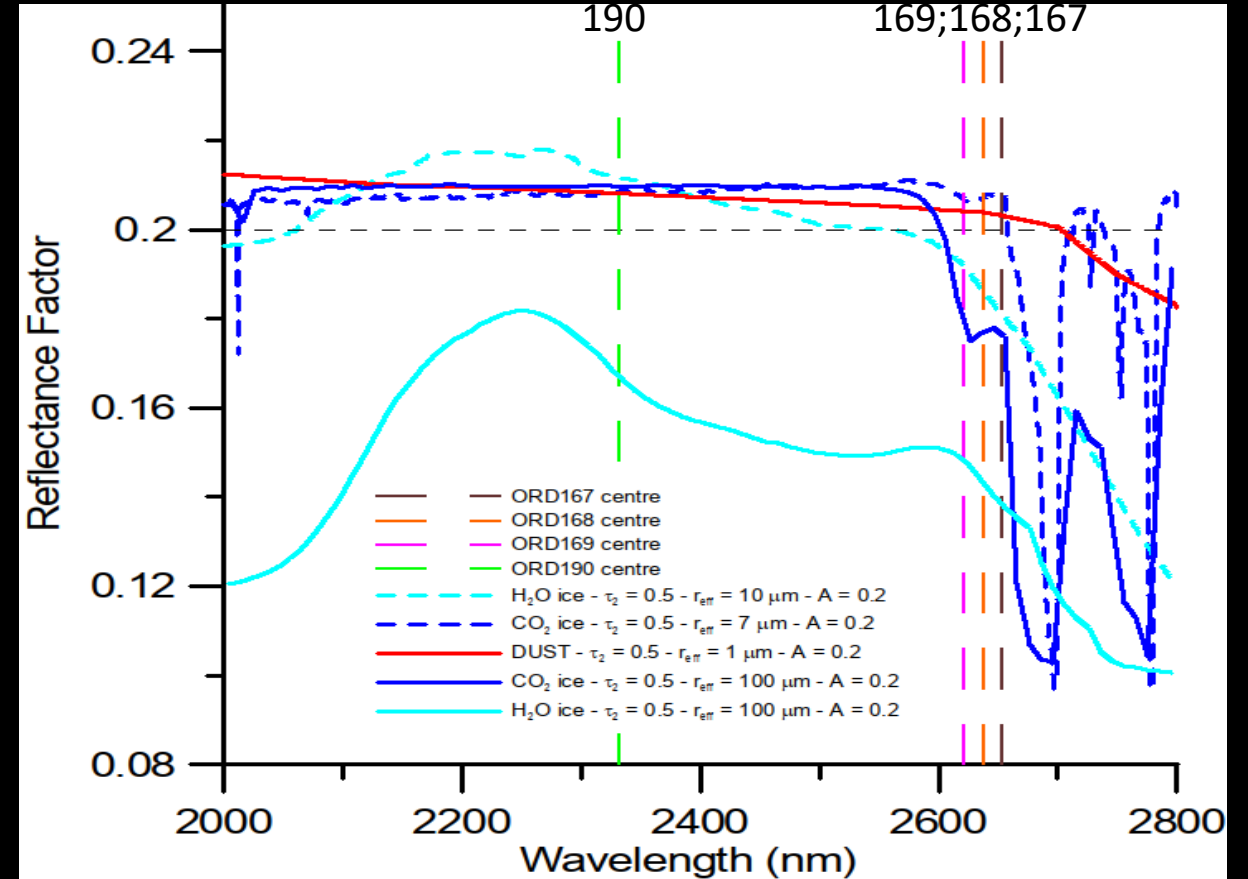
- 2016 ExoMars Trace Gas Orbiter (TGO) mission
- Scientific phase: since March 2018 -> ongoing
- **NOMAD:** suite of 3 high resolution spectrometers
 - SO channel in the IR
 - UVIS channel in the UV-visible range
 - **LNO channel** in the IR
 - ✓ Use of LNO nadir observations
 - ✓ Spectral range: 2,3 – 3,8 μm
- Observations using diffraction orders
- In nadir mode: difficulty to discern dust from frost and cloud
- **Objective:** Method allowing to identify **water ice clouds**





1. Ice signatures in LNO data

- Based on Oliva et al. (2022): Use of the strong ice absorption band at 2,7 μm
 - Surface ice detection
 - Ice Index (spectral ratio)
 - Order 190 [2,32 – 2,34 μm] and order 169 [2,61 – 2,63 μm]
- For this work: use of 3 diffraction orders
 - Order 169: 2,61 – 2,63 μm
 - Order 168: 2,63 – 2,65 μm
 - Order 167: 2,64 – 2,66 μm
- Order 190 not appropriate for water ice clouds (next slide)



Simulated ice and dust spectra in the 2 - 2.8 μm range obtained by the MITRA tool (Adriani et al., 2015; Sindoni et al., 2017; Oliva et al., 2017, 2018)

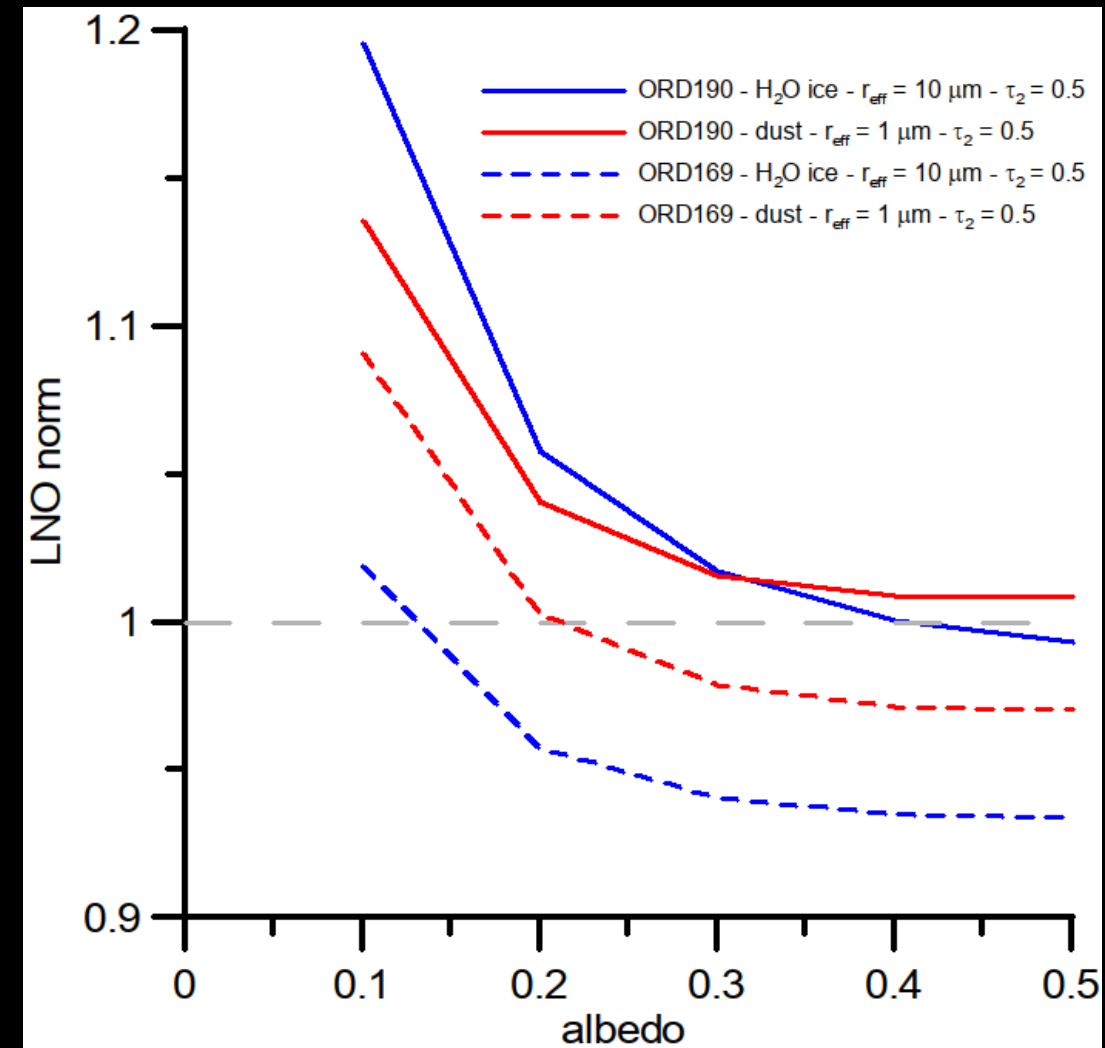


2. LNO data normalisation

- Main source of signal: surface reflectance
- Important to take into account albedo spatial variations over the whole Martian surface
- Derive the **LNO_{Norm} ratio**

$$\text{LNO}_{\text{Norm}} = \text{Reflectance factor} / \text{Martian albedo}$$

- Reflectance factor = LNO measured radiance divided by the Solar flux at Mars and by the cosine of solar zenith angle
- Martian albedo = referent TES bolometric albedo (0.3 to 2.9 μm) (Christensen et al., 2001)
- Degeneracy problem with order 190
 - Dust appears brighter at high albedo
 - Ice Index (Oliva et al., 2022) not appropriate for water ice cloud



Simulations obtained by the MITRA tool (Adriani et al., 2015; Sindoni et al., 2017; Oliva et al., 2017, 2018)

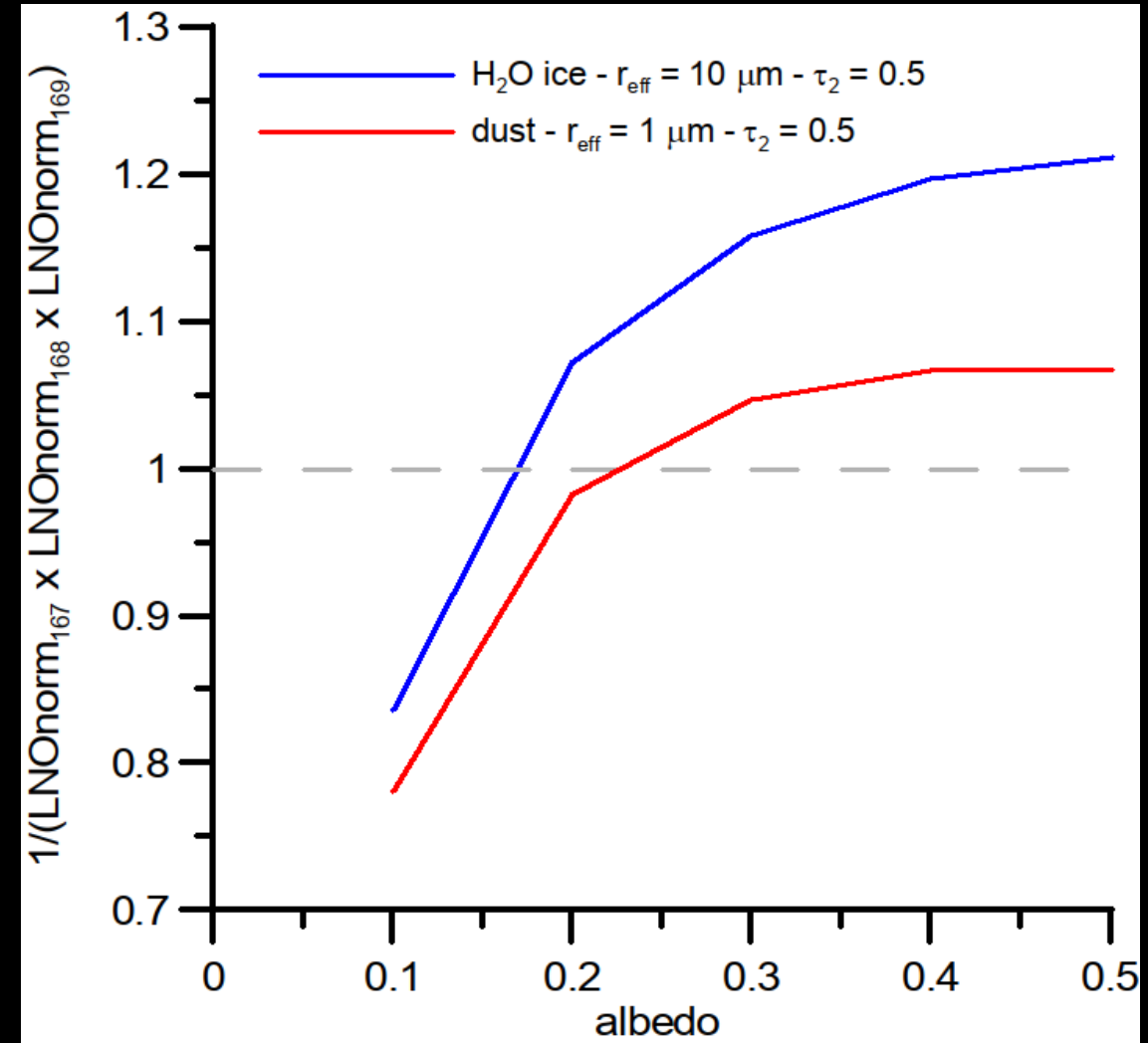


3. The Frost and Cloud Index (FCI) at 2,7 μm

1. Use of 3 orders close to 2,7 μm : 167; 168; 169
2. Use of LNO_{Norm} ratio
3. Derive a dedicated index for this work

$$FCI = \frac{1}{LNO_{\text{Norm } 167} * LNO_{\text{Norm } 168} * LNO_{\text{Norm } 169}}$$

- ✓ Amplify ice signatures
- ✓ Large values for ice



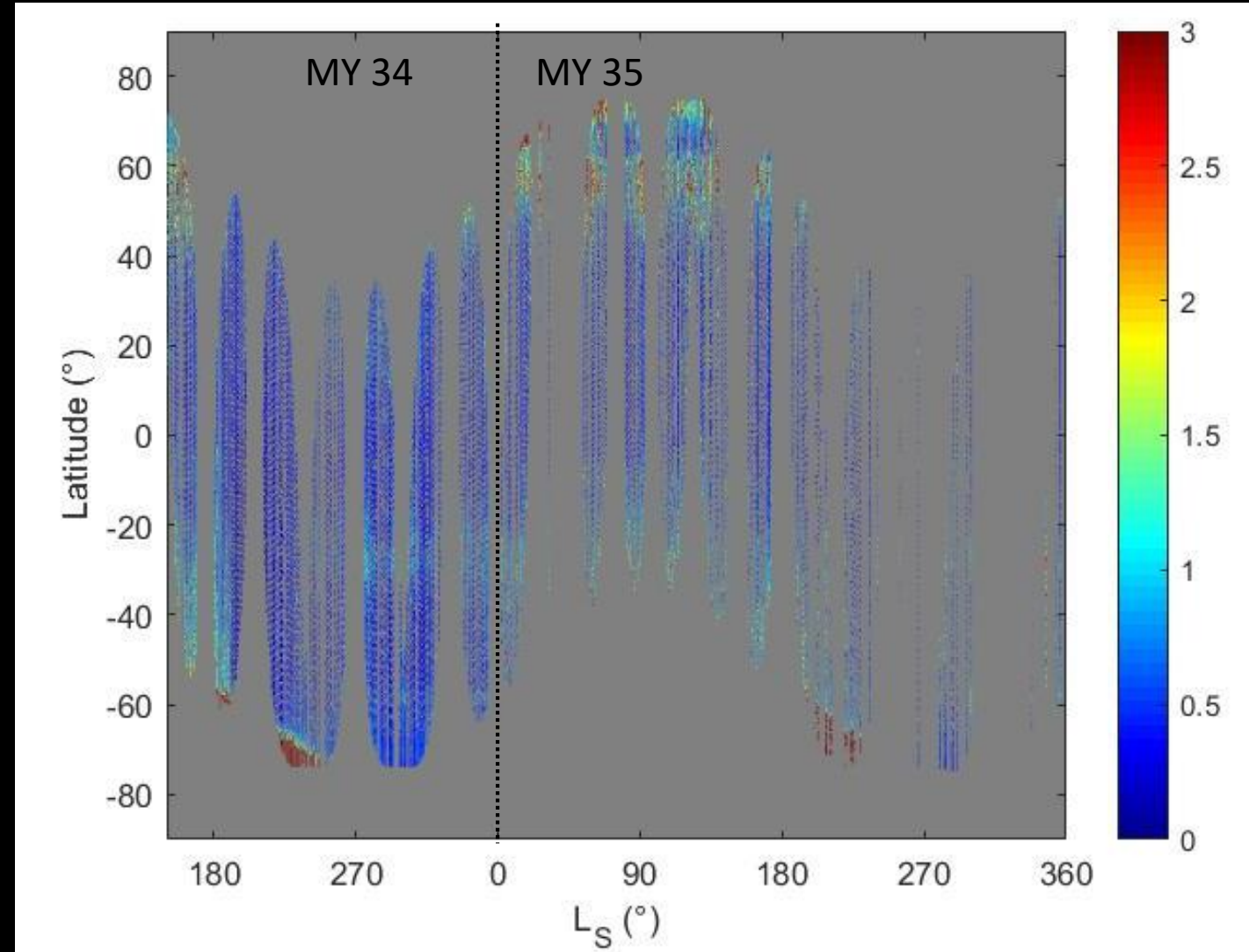
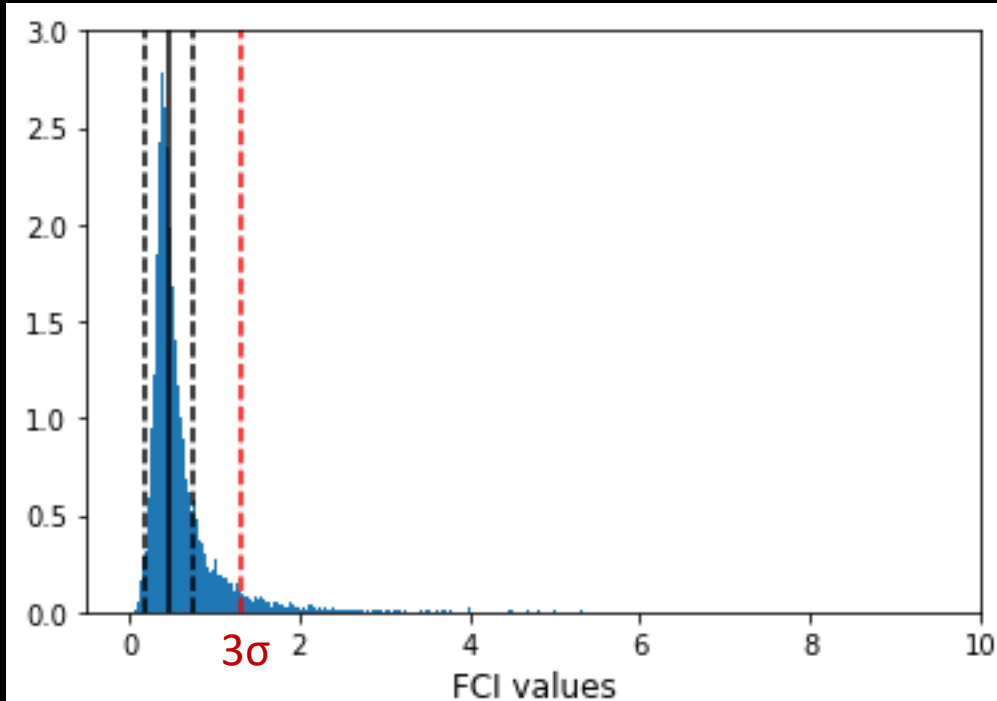
Simulations obtained by the MITRA tool (Adriani et al., 2015; Sindoni et al., 2017; Oliva et al., 2017, 2018)



4. The Frost and Cloud Index (FCI) at 2,7 μm

$$\text{FCI} = \frac{1}{\text{LNONorm } 167 * \text{LNONorm } 168 * \text{LNONorm } 169}$$

- Observations from March 2018 to February 2021 (~ 1,5 Martian Years)
- Remove the worst-case scenarios with large illumination angles ($\text{SZA} < 60^\circ$)
- Latitudinal-seasonal map
- FCI values distribution strongly peaked ($\mu = 0,48 \pm 0,28$)
- Polar caps correlation with $\text{FCI} > 3\sigma$

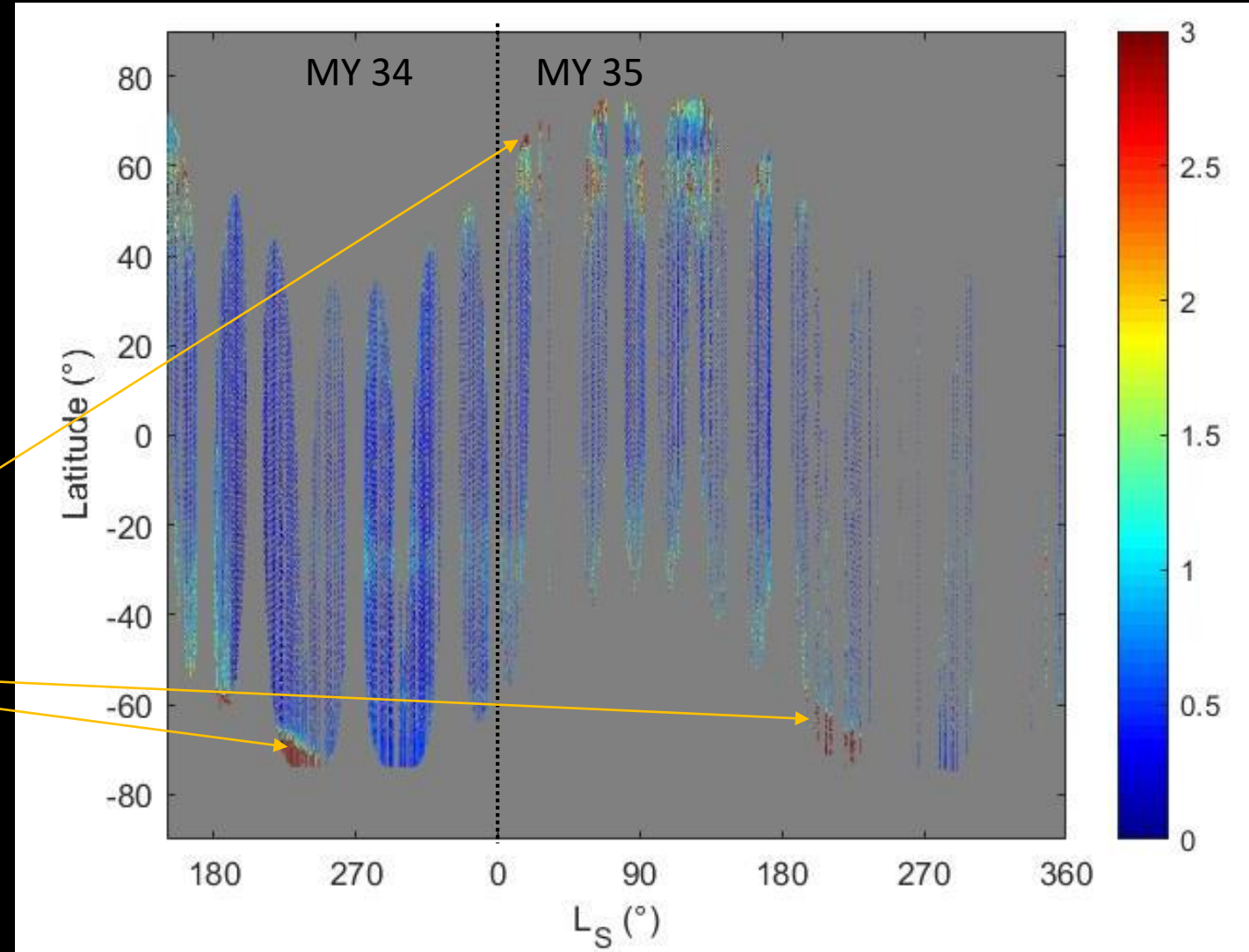
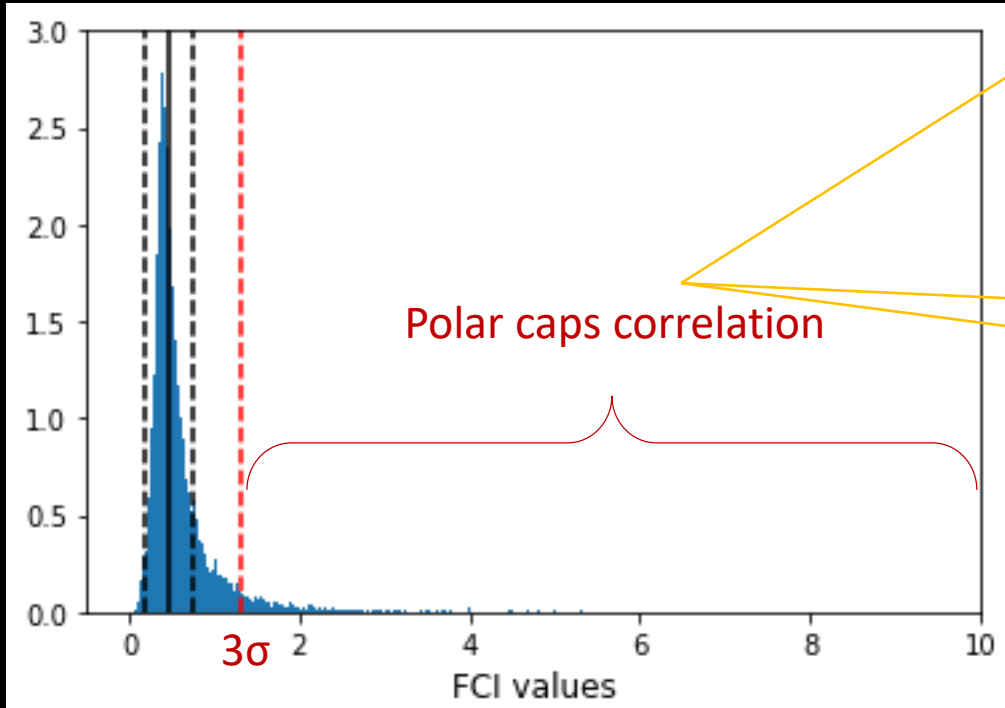




4. The Frost and Cloud Index (FCI) at 2,7 μm

$$\text{FCI} = \frac{1}{\text{LNONorm}_{167} * \text{LNONorm}_{168} * \text{LNONorm}_{169}}$$

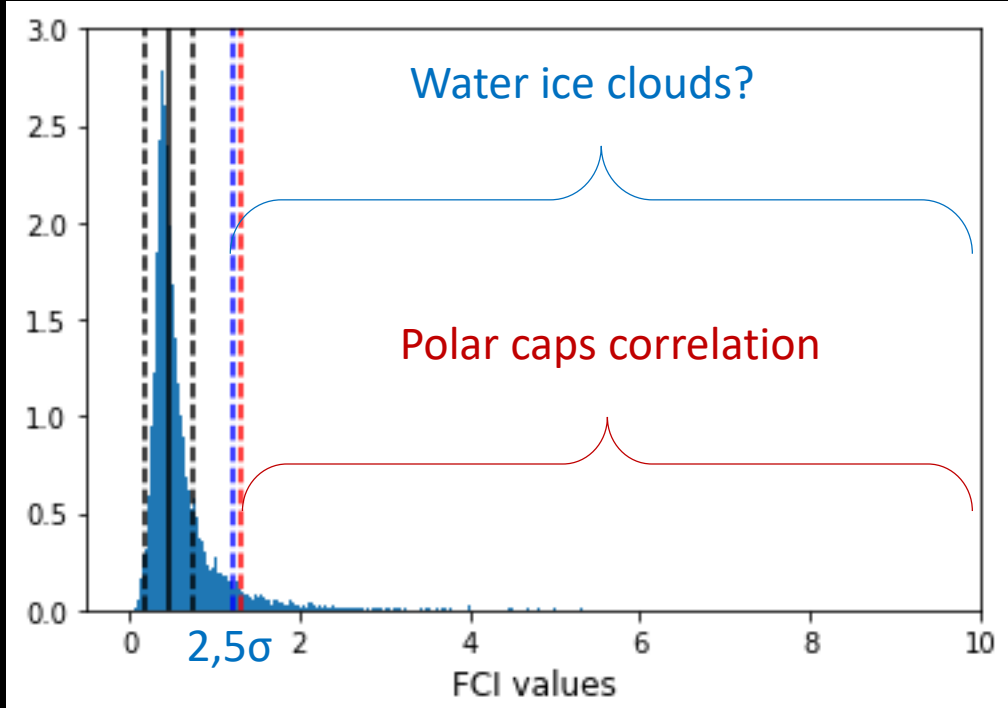
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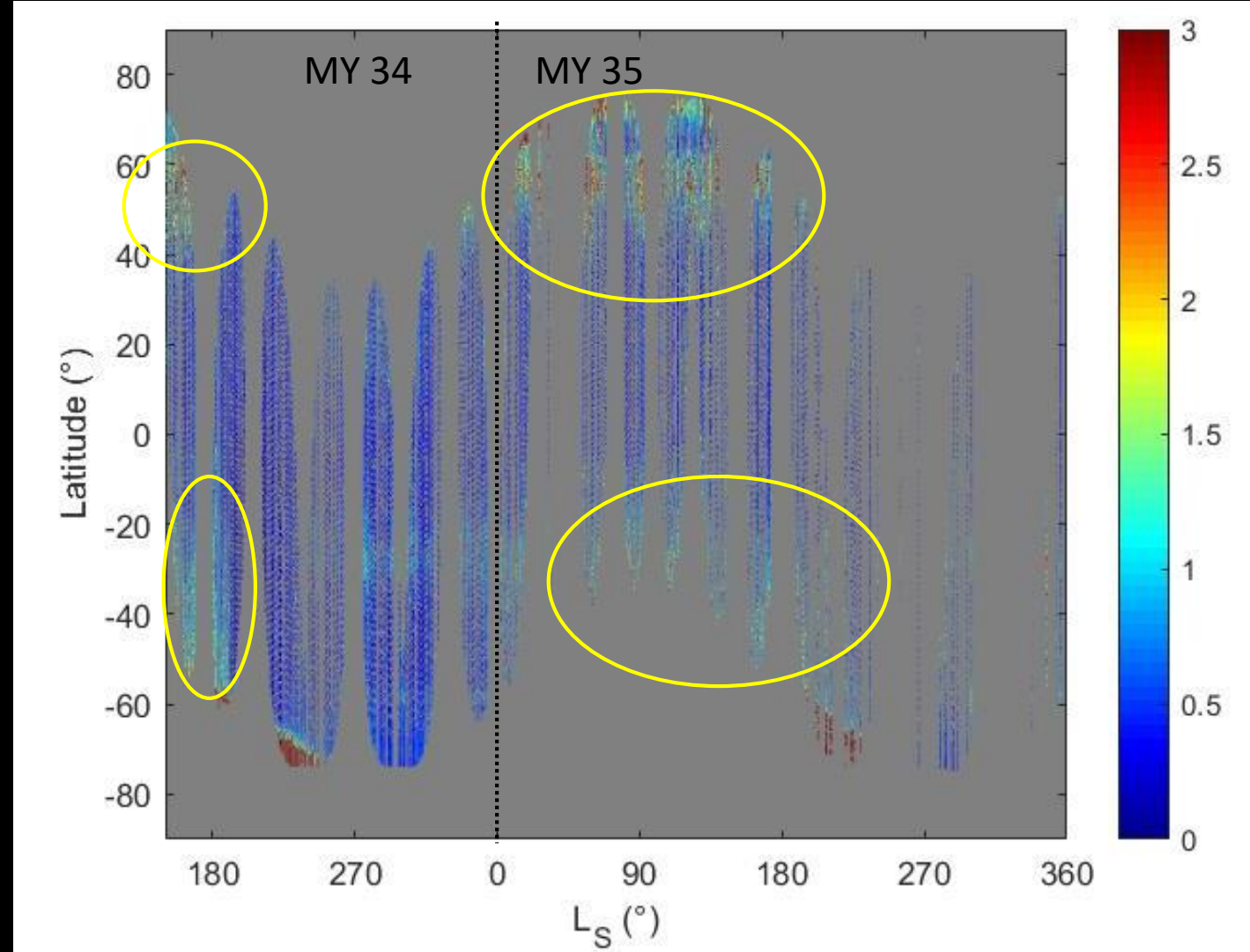


5. Outside the polar regions

- High FCI values outside the polar regions
- Estimation of an average value $\sim 2,5\sigma$
- Correlation with water ice clouds?



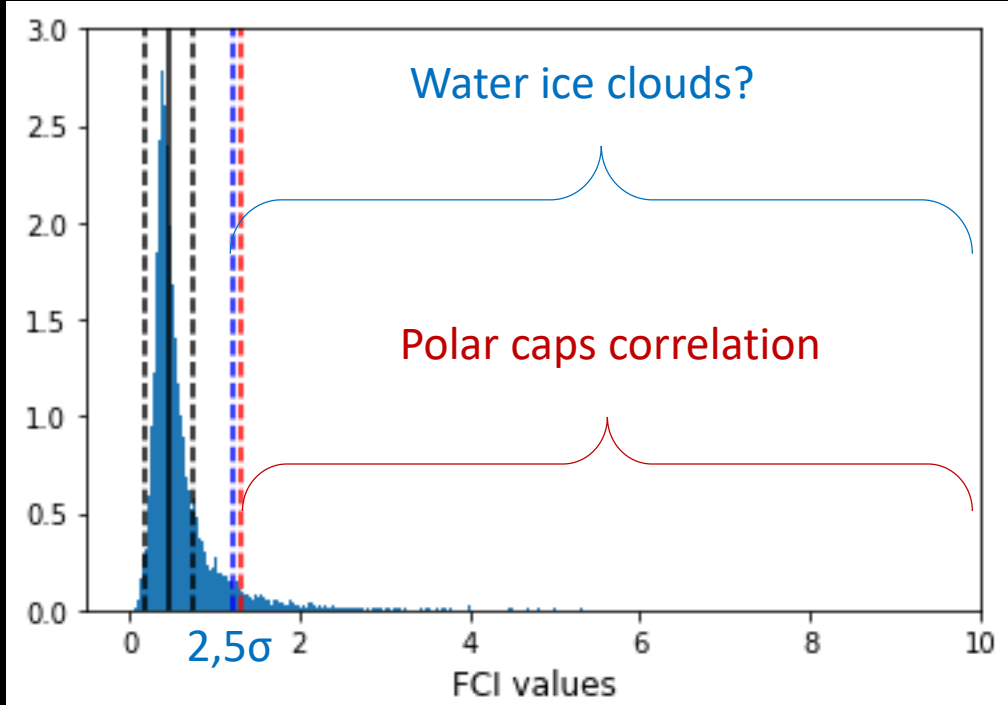
$$FCI = \frac{1}{LNONorm\ 167 * LNONorm\ 168 * LNONorm\ 169}$$



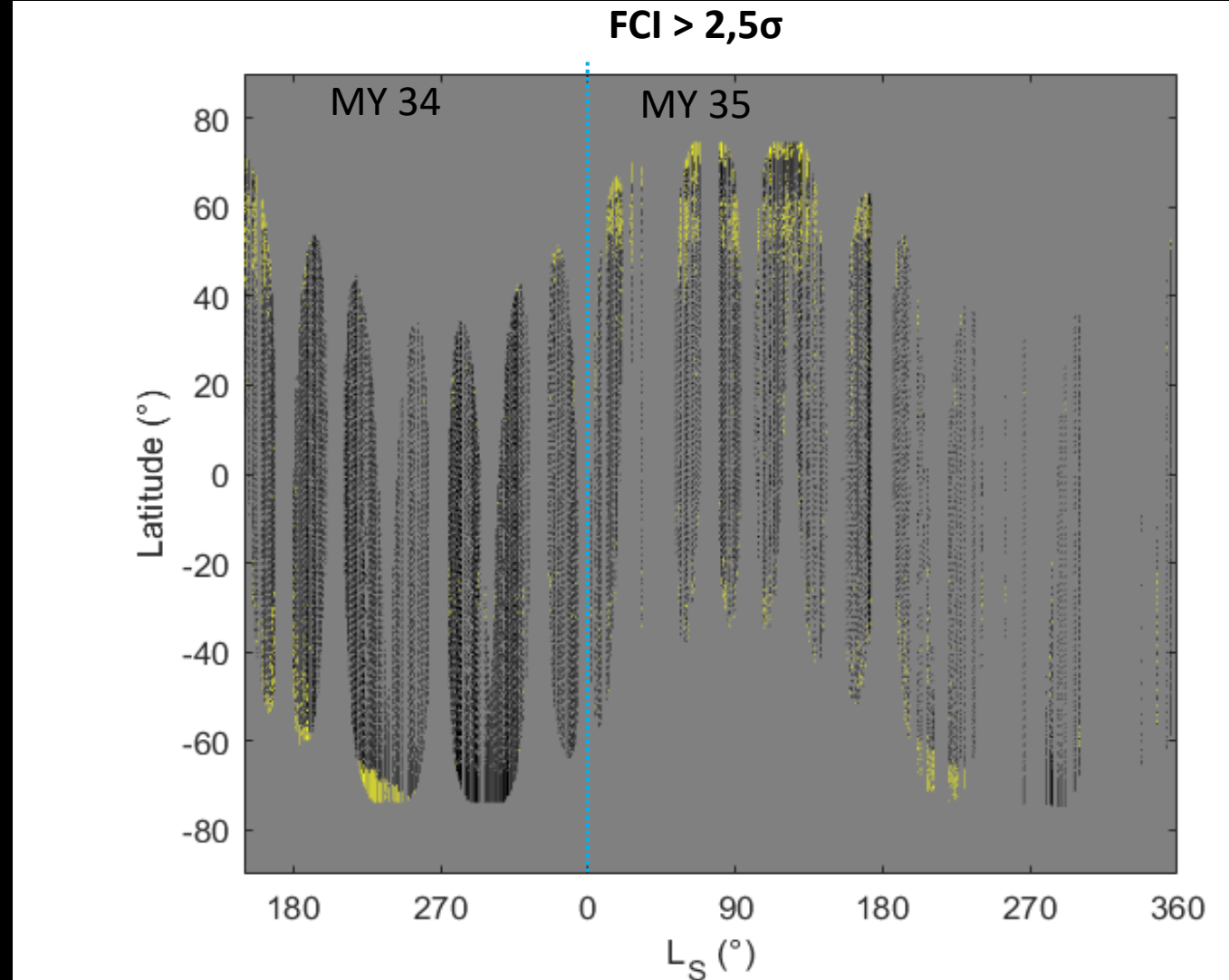


6. Water ice clouds?

- Use of $2,5\sigma$ as « threshold »
- Take into account the local time and the surface temperature (Mars Climate Database – MCD)
- Compare with global climate model and other datasets
- Compatible with the **Polar Hood**



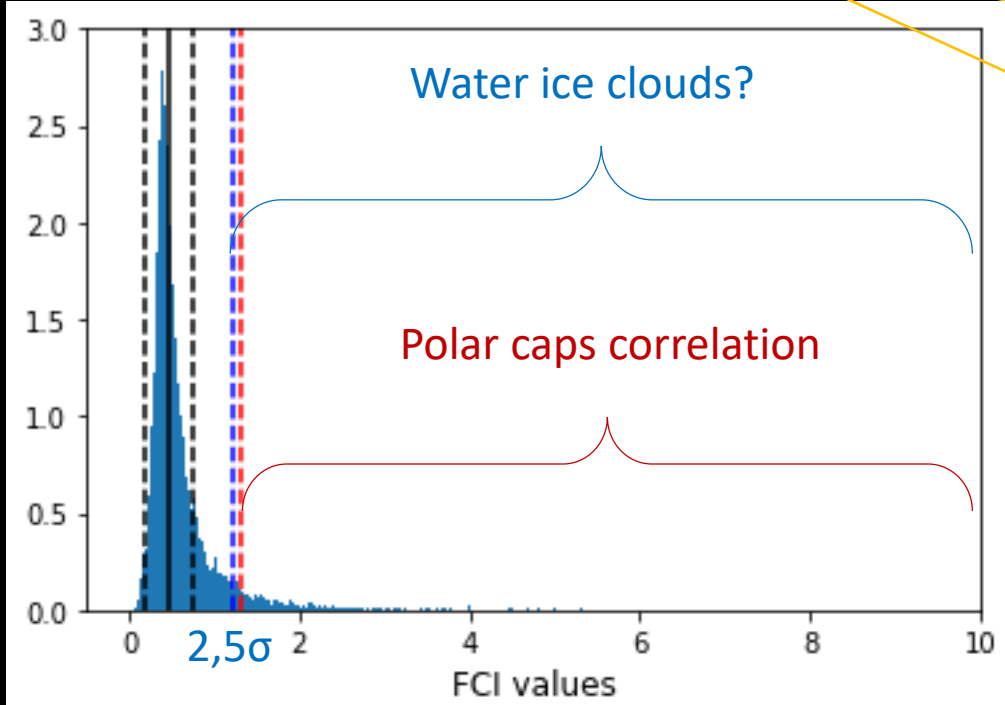
$$FCI = \frac{1}{LNONorm\ 167 * LNONorm\ 168 * LNONorm\ 169}$$



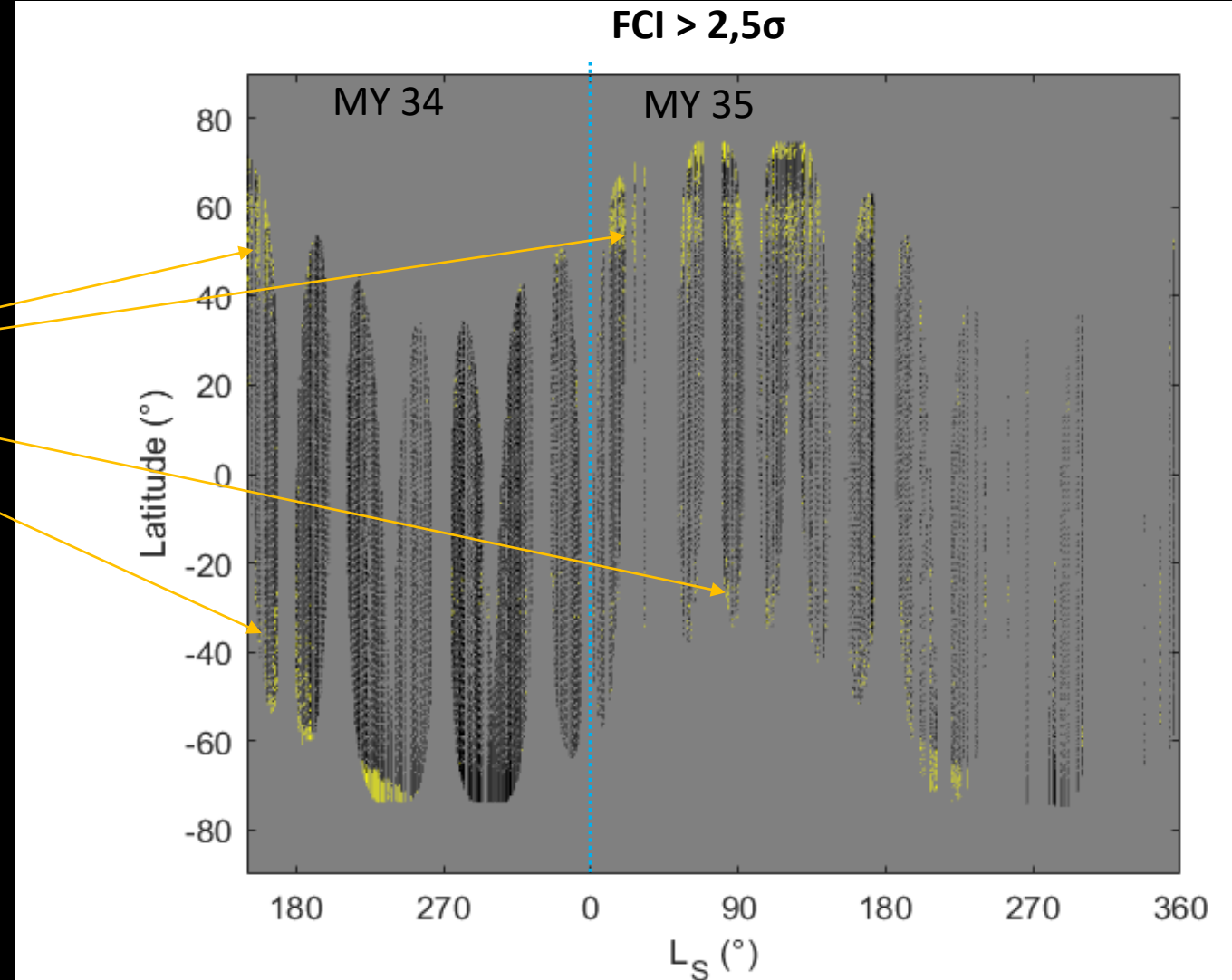


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- Compatible with the **Polar Hood**



$$FCI = \frac{1}{LNONorm\ 167 * LNONorm\ 168 * LNONorm\ 169}$$





7. Polar Hood

$$FCI = \frac{1}{LNONorm\ 167 * LNONorm\ 168 * LNONorm\ 169}$$

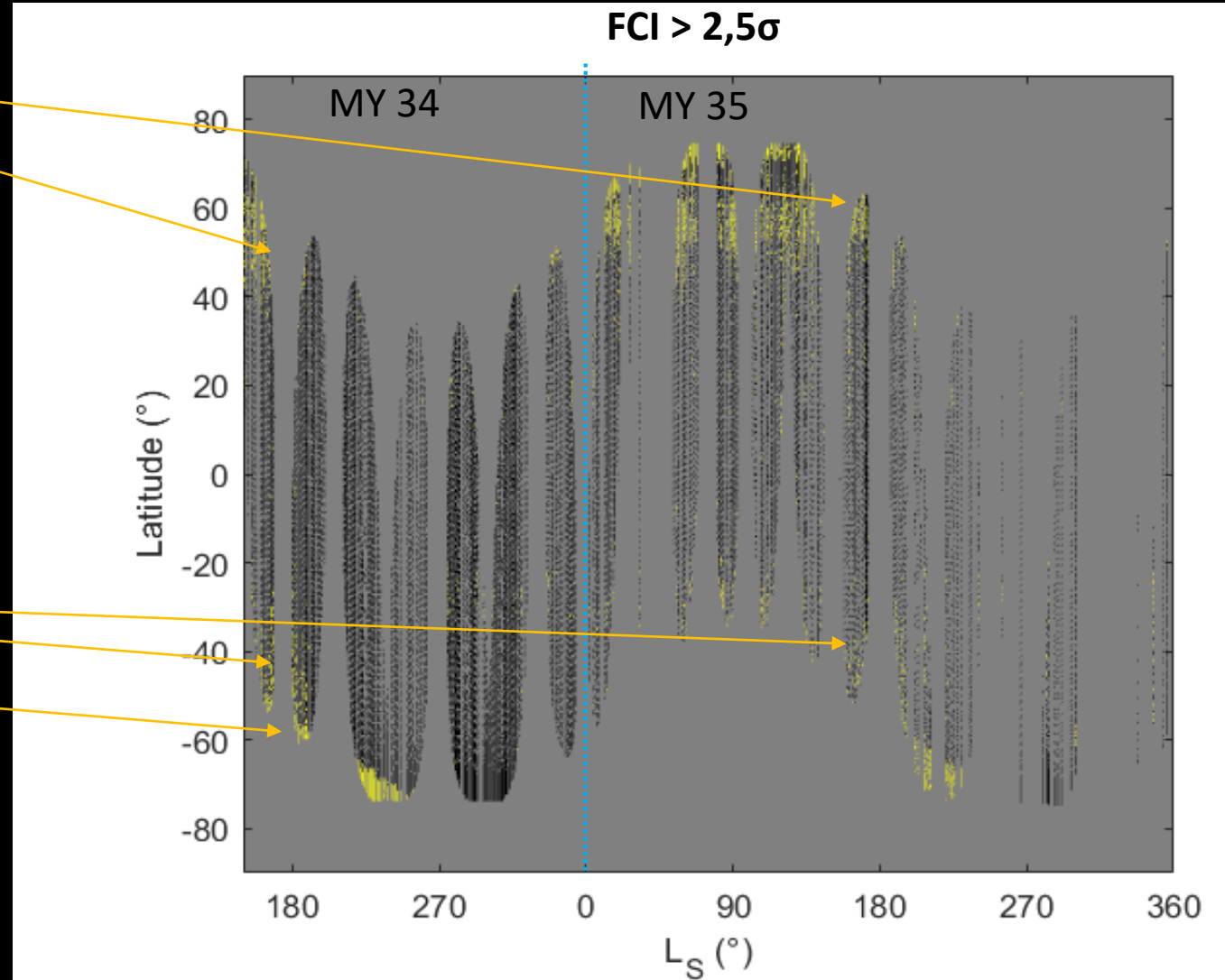
FCI > 2,5σ

NPH

SPH

Polar cap

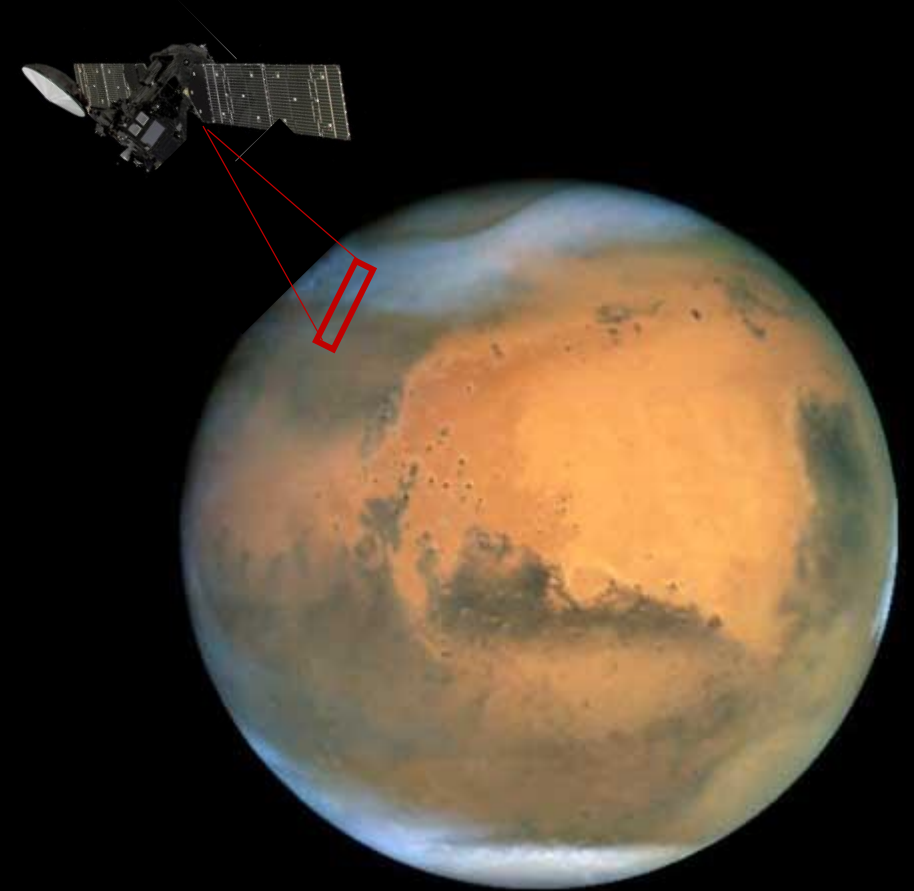
Observation of the Polar Hood – NASA Hubble Telescope (June 2001)





Conclusion

1. We have investigated the possibility to detect water ice clouds with the NOMAD nadir channel.
2. NOMAD is a high resolution spectrometer working with selected diffraction orders.
3. In nadir mode, discerning suspended dust from cloud can be problematic.
4. We presented a method taking advantage of the ice absorption band at $2,7 \mu\text{m}$.
5. We derived the Frost and Cloud Index (FCI).
6. Results are compatible with the polar caps and the Polar Hood.





References

- [1] Karatekin et al., 2005, *Adv. Space Res.*, 38(4),739-744.
- [2] Vandaele, A.C., et al., 2018. NOMAD, an Integrated Suite of Three Spectrometers for the ExoMars Trace Gas Mission: Technical Description, Science Objectives and Expected Performance. *Space Sci Rev* 214(80). <https://doi.org/10.1007/s11214-018-0517-2>
- [3] Langevin et al., 2007. Observations of the south seasonal cap of Mars during recession in 2004–2006 by the OMEGA visible/near-infrared imaging spectrometer on board Mars Express. *Journal of Geophysical Research: Planets*, 112(E8), DOI: 10.1029/2006JE002816.
- [4] Mars Global Data Sets, http://mars.asu.edu/data/tes_albedo/
- [5] Forget, F., Hourdin, F., Fournier, R., Hourdin, C., Talagrand, O., Collins, M. (1999). Improved general circulation models of the Martian atmosphere from the surface to above 80 km. *Journal of Geophysical Research*. 24155. doi:10.1029/1999JE001025.

$$\text{LNO}_{\text{Norm}} = \text{Reflectance factor} / \text{Martian albedo}$$

- Order 169
- High values for dust
- Low values for ice
- Very noisy

