Potential of the Moon as a calibration target for IASI instruments

Bojan SIC, Emmanuel DUFOUR, Jérôme DONNADILLE, Tristan LALANNE – NOVELTIS

Elsa JACQUETTE, Laura LE BARBIER, Sébastien MARCQ, Olivier VANDERMARCQ, François BERMUDO – CNES

Jean-Christophe CALVEL – AKKA

NOVELTIS cnes CENTRE NATIONAL D'ÉTUDES SPATIALES

4th Lunar Calibration Workshop

Presentation outline

- Motivation
- Lunar infrared radiance model
- Simulations of IASI observations
- Model-observations comparison
- Conclusions

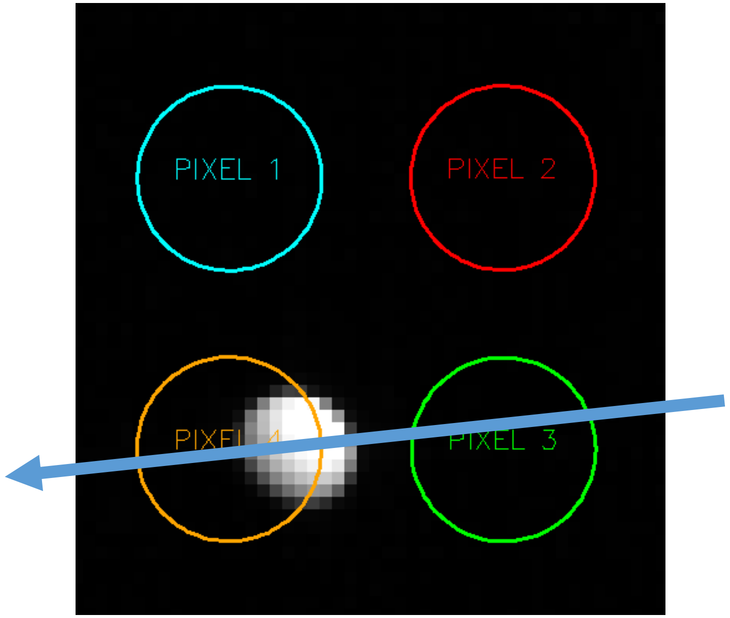
Motivation

- IASI is an infrared sounder on MetOp (EPS) satellites
- Calibration of IASI observations
  - Absolute radiometric calibration < 0,5 K @280K
  - Inter-comparisons between sounders < 0,2 K @280K, but nevertheless inter-comparisons between IASI instruments using Earth View acquisitions are not perfect.
- Why consider the Moon as a calibration source?
  - No atmosphere on the Moon
    - Spectra are nearly flat → easier to calibrate the whole spectrum
    - Radiometric time variability can be "perfectly" determined/calculated
  - Already used as a calibration source in VIS and NIR, but not in TIR
- How might lunar observations be used and can the current IASI performances be reached?
  - Absolute calibration
  - Inter-calibration (relative) between the instruments
  - Analyses of radiometric calibration stability over time

→ CNES study conducted by NOVELTIS to explore these questions

How does IASI see the Moon?

- The Moon passes regularly, twice a month, through a calibration view @zenith - Cold Space View 2 (CS2)
- The Moon phase (illuminated surface %) during the transits is ~10% (6-17%) and ~90% (83-94% = 33-48° phase angle)
- CNES adapted the on-board coding tables for cold space (used to encode the on-board spectra) to the lunar dynamics
- Moon observations were planned (CNES/EUMETSAT) and the Moon was successfully observed during 5 months in 2019 and from January 2021 to January 2022
  - Only ~90% phase transits observed



How can lunar observations be used for calibration?

- Necessity to develop a lunar infrared radiance model
- Simulation of IASI lunar observations
  - position and size determination in the IASI FOV, IPSF convolution
- Model-observations comparison
- Estimation of the performance

Lunar infrared radiometric model

➢ A lunar infrared radiance model has been developed

- Calculation of thermal emissive (dominant) and solar reflective component (contribution up to 30% in SWIR)

$$L_{eMoon}(\lambda) = \epsilon(\lambda)\, B(\lambda, T_{Moon})$$

$$L_{rSun}(\lambda) = \sum_{lon,lat} (\pi \cdot F_{SunIN}(\lambda) \cdot \cos(\theta) \cdot r_{Moon}(lon, lat, \lambda)) \quad \theta < 90°$$

in a high spatial resolution of 0.5°

- Terrestrial reflective component is negligible (maximal contribution of 0.00104%)
- Coverage of the whole IASI spectral domain 645-2760 cm^{-1} (3.6-15 µm)

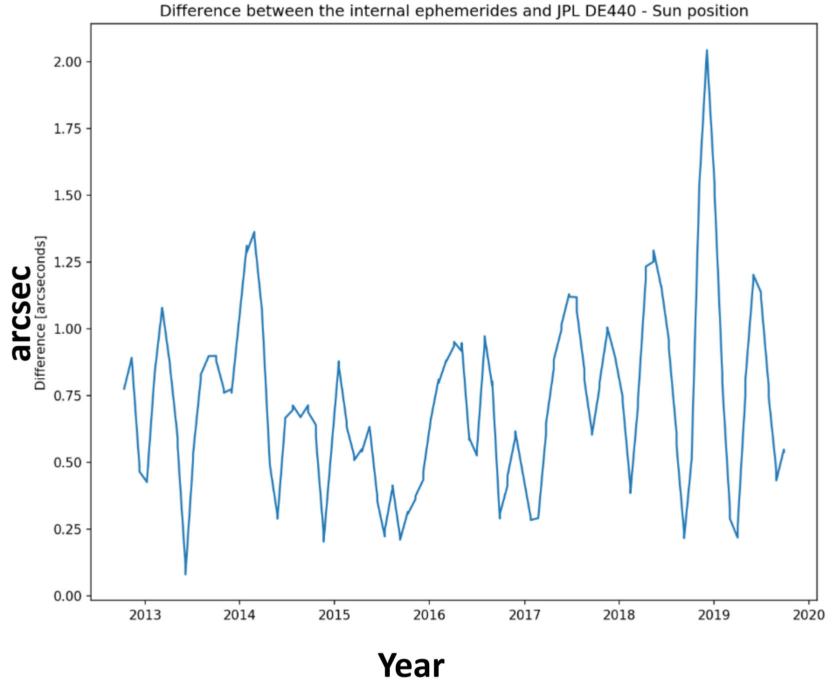
➢ Key quantities/parameters to determine for the calculation of infrared Moon radiances

- Sun-Moon-satellite geometry (positions, distances, lunar phase and orientation)
- Surface temperature of the Moon surface
- Emissivity/reflectivity of the Moon surface
- Soil type distribution for the emissivity/reflectivity application

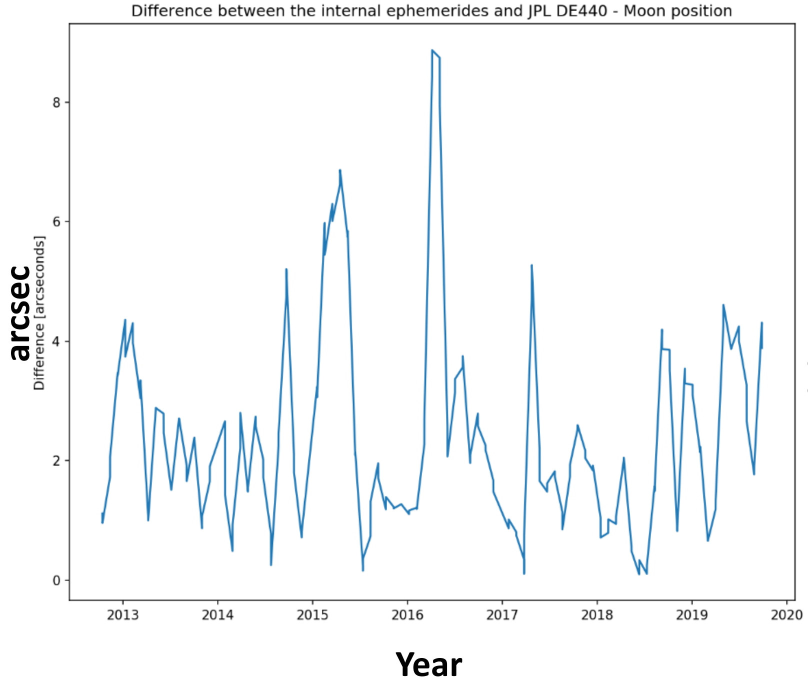
Lunar infrared radiometric model

- Sun-Moon-satellite geometry (positions, distances, lunar phase and orientation)
  - Calculated with the semi-analytic models VSOP87 (Sun) & ELP2000-82B (Moon) developed by Paris Observatory
  - Good agreement with JPL ephemeris (DE440) – verified for 780 dates of IASI Moon transits

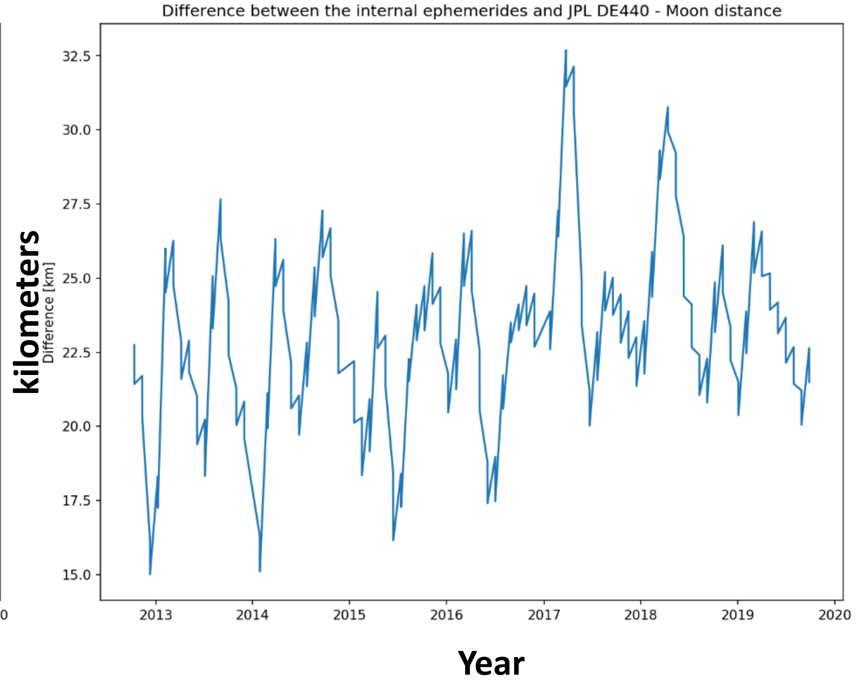
Sun positions <2''



Moon positions <9''

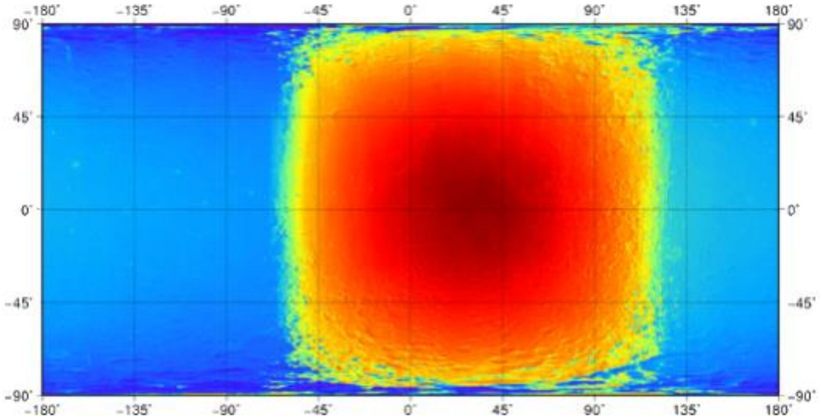


Moon – satellite distance <35km



Lunar infrared radiometric model

➢ Surface temperature derived from LRO/Diviner bolometric temperature L4 product

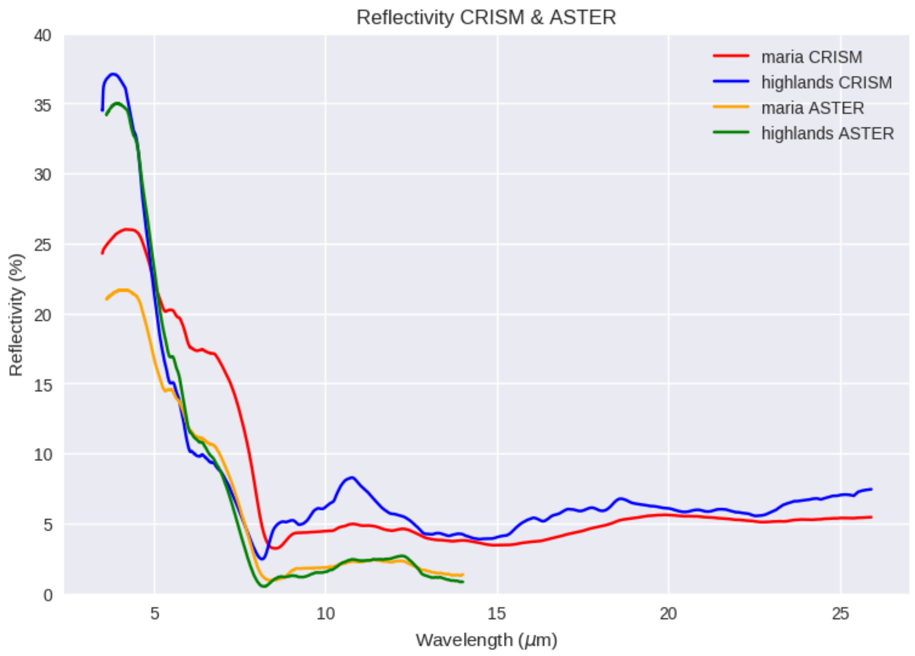


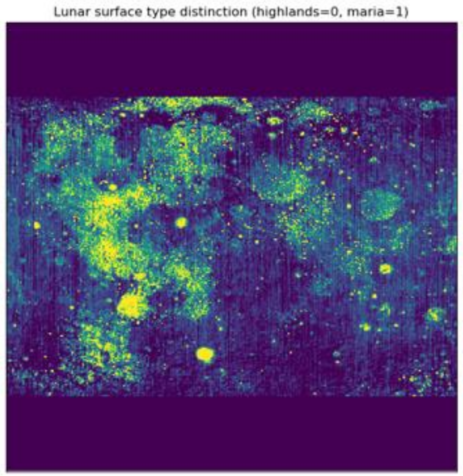
- Cumulative product (2009-2015) with a temporal resolution of 1h (15°) and a high spatial resolution (0.5°)
- Contains the relief effects, but it is an averaged dataset
  - No libration
  - No changes in solar irradiance (implemented in the model)
- It is a bolometric temperature dataset, necessary conversion to surface temperature
- Determination of the coordinate system and calculation of the subsolar point to apply a T_{surf} map correctly
  - Modified selenographic coordinated system with (0,0) always in the sub-observer point (satellite / Earth's center)
- We implemented also T_{surf} models (influenced by LRO/Diviner data):
  - Semi-analytical from Vasavada et al. (2012)
  - Empirical from Hurley et al. (2015)

Lunar infrared radiometric model

➢ Emissivity of the Moon surface

- Data from Apollo samples
  - JHU data (Salisbury et al. (1997)) in ASTER/ECOSTRESS spectral library
  - RELAB/BU data in CRISM spectral library (compiled for MRO/CRISM)
  - Quite significant differences
  - Studies suggest that samples should be measured in Moon-like conditions
- Lambertian approximation
- Distinction between typical highlands and maria (+impact craters)
  - Apollo 11 & 12 – maria
  - Apollo 15, 16 & 17 – highlands
- To distinct soil types, different datasets were considered :
  - Albedo (LRO/LOLA)
  - Chemical composition (Clementina)
  - Surface rugosity (LRO/LOLA)
  - Slope (LRO/LOLA)
  - **Rock abundance (LRO/Diviner)**
    - **Empirical thresholds implemented with a gradual transition**

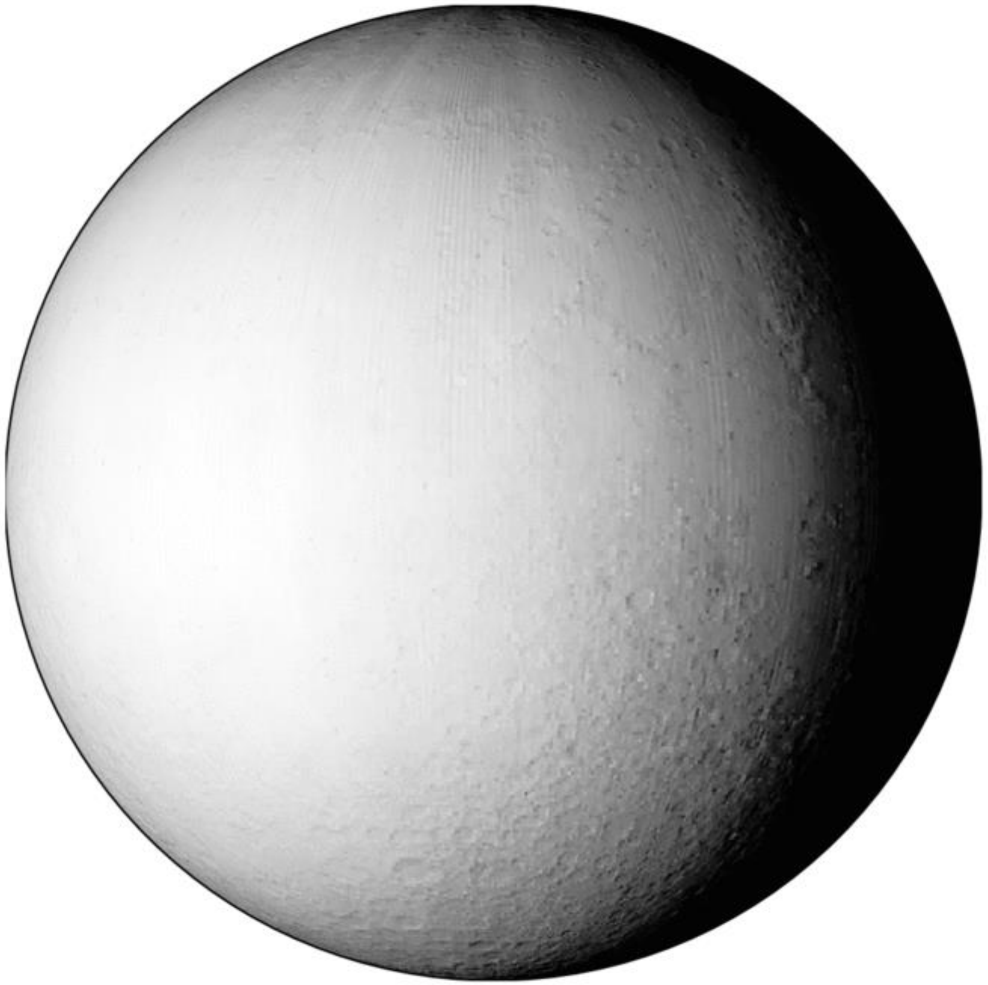




Lunar infrared radiometric model

- Radiance

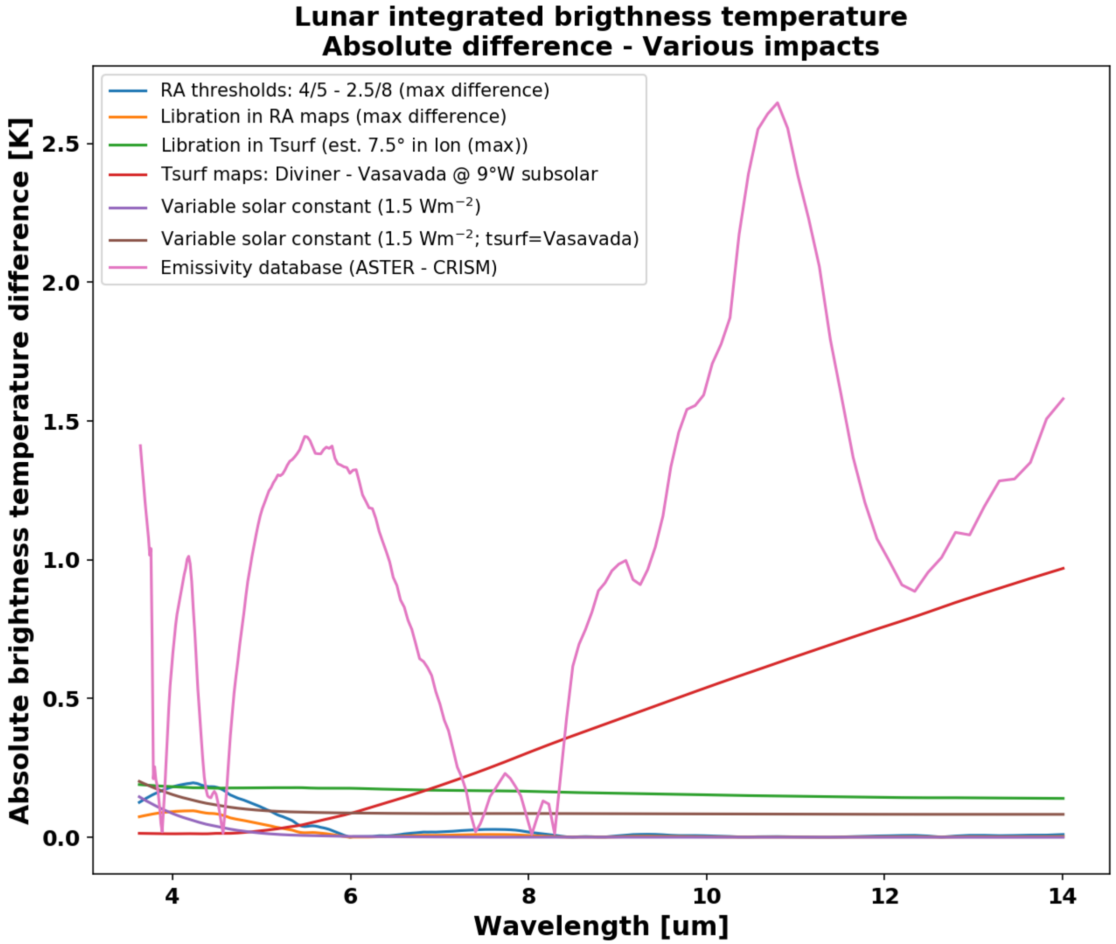
$$\left[\frac{W}{m^2\ sr\ m^{-1}}\right]$$



Lunar infrared radiometric model

- First performance estimation of the model was done with various sensitivity tests
  - Impact of various approximations and parameters on the calculated brightness temperature

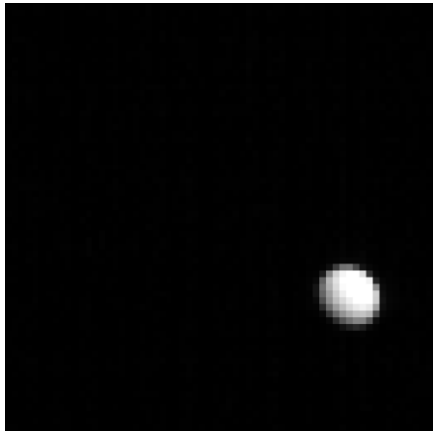
Surface temperature maps • Observations vs. models/parametrisations • Impact of terrain • Impact of libration • Impact of variability of solar constant on surface temperature (parametrization)
Soil type maps • Impact of threshold rock abundance values • Impact of libration
Solar component • Impact of variability of solar constant on radiance
Emissivity • Difference between spectral bases



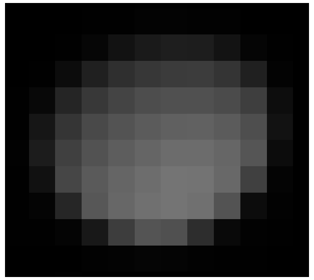
- Important differences in emissivity
- Observations are more performant than parametrizations.
- Neither of other impacts exceeds 0.2K.

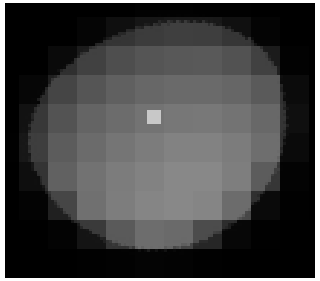
Simulation of IASI observations

- Simulation of IASI observations
  - Determine the position of the Moon in the field of view of IASI's imager (IIS)
  - Colocate the position in IIS with IASI's FOV
  - Convolve the modelled radiance with the IASI IPSF (4 pixels, 3 bands)



- Position in IIS (imager) FOV in one image
  - Calculate (theoretically) the Moon phase, size and orientation in the IIS FOV
  - The best results are obtained when the barycenter-center vector is calculated (simulation) and then applied on the observed barycenter.
  - Precision of ~0.25 pixel IIS

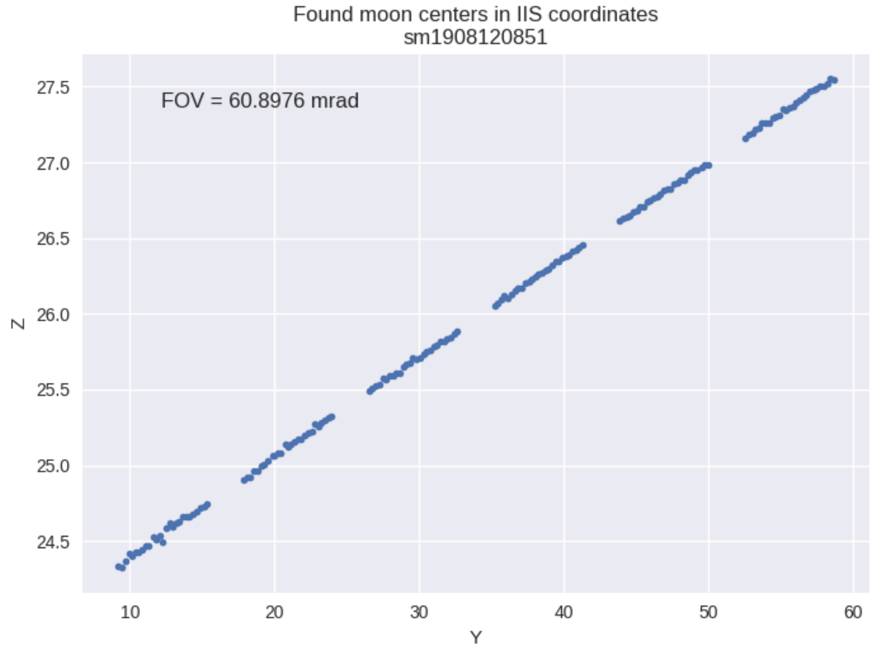




- Position can be improved by considering a series of images.

Simulation of IASI observations

- Improvement of the position by considering a series of images
  - The trajectory of the satellite and movement of the instrument (yaw steering) are known → we can calculate the angle and the angular velocity of the Moon transit in IIS FOV.
  - The minimization of the distances permitted us to improve the precision of the Moon in IIS to ~0.1 IIS pixel.
  - Also permitted a better in-flight estimation of :
    - FOV IIS
      - IASI-B: 60.71 ± 0.12 mrad
      - IASI-C: 61.22 ± 0.11 mrad
      - This adds some uncertainties in the quality of IASI/imager coregistration
    - Orientation of the IIS image
      Yaw steering angle has a systematic bias of 0.1° ± 0.02°.



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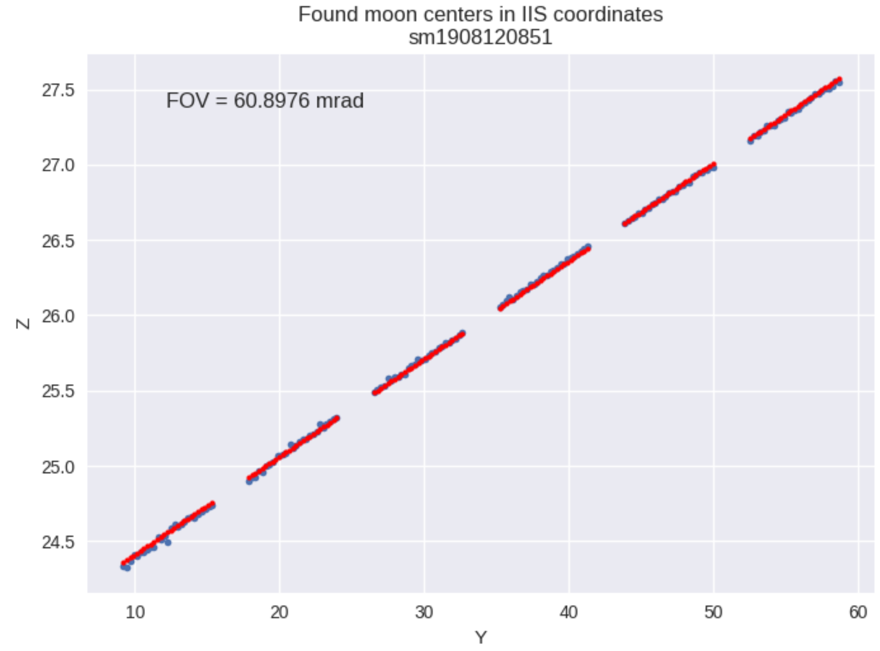
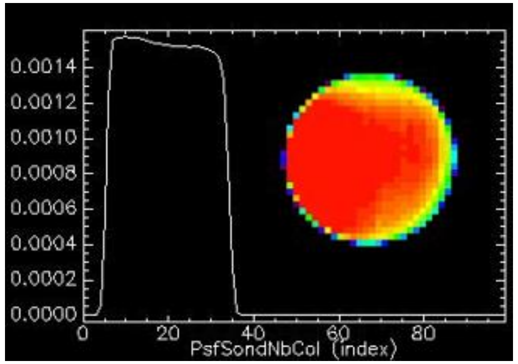


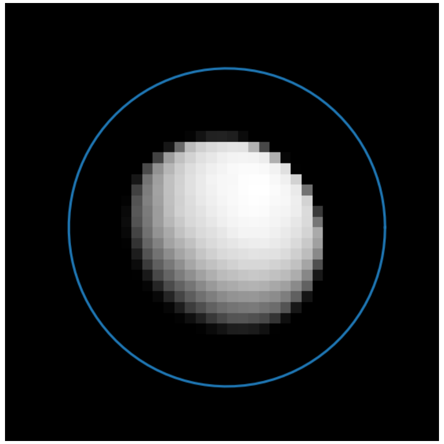
Simulations and Observations

- After the colocation applied, the modelled radiances are convolved with the IASI IPSF of the concerned pixel to obtain a simulated IASI lunar observation.
  - Operational IPSFs are normalized (OK for IASI observations but not for lunar simulations) → had to be denormalized to take into account physical differences between pixels (inter-band differences are emissivity spectral base dependent)
    - Some uncertainties exist with IPSFs (exact size, quality of measurements)

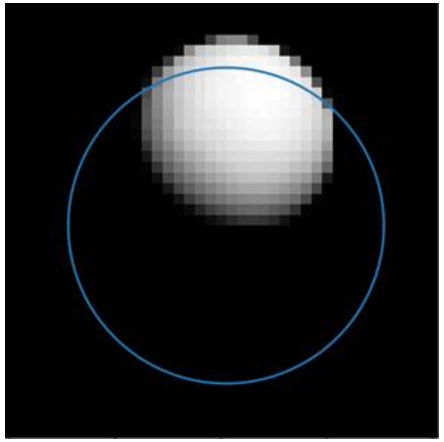


- Three possible types of Moon transits

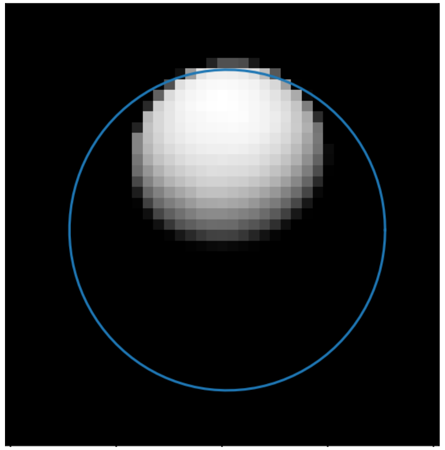
Central



Partial



Bordering



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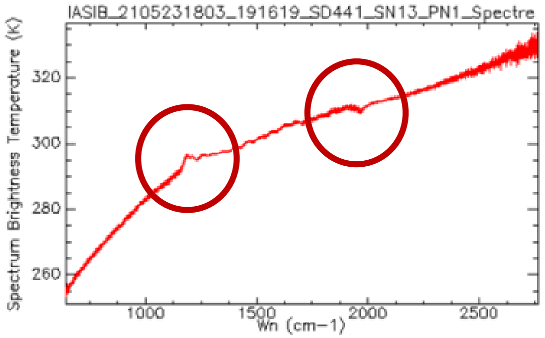
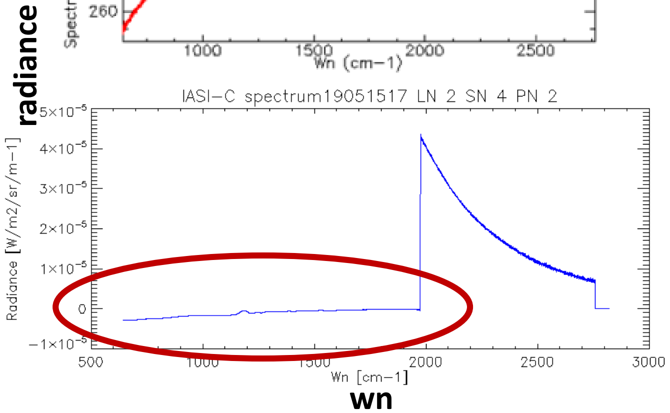
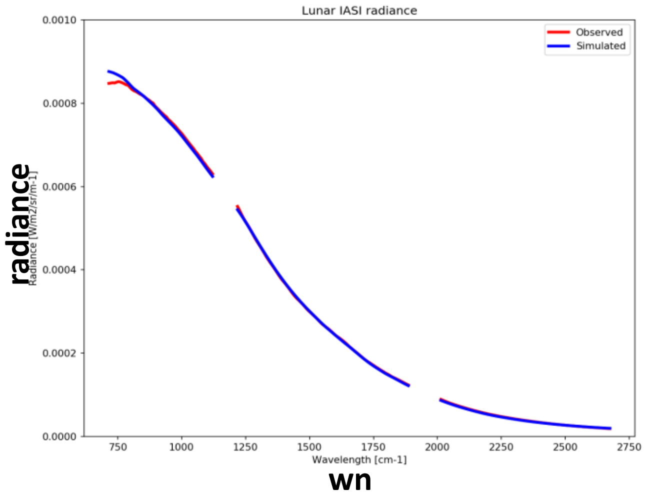
IASI lunar observations

- The Moon covers 35%-43% of the IASI FOV
- Smooth inter-bands are present only during central transits
- For the partial transits there is a systematic complete loss of some bands (coding table underflow)
- All this makes partial transits unusable, and bordering transits should be used with caution.
- There were detector (and coding table) saturations May-August 2021
  - Period when the moon irradiance was at maximum for the IASI transits
- Noise reduction is performed with a reduction of spectral resolution (0.25 cm^{-1} -> 7.5cm^{-1}).
- Simulations and observations can finally be compared.

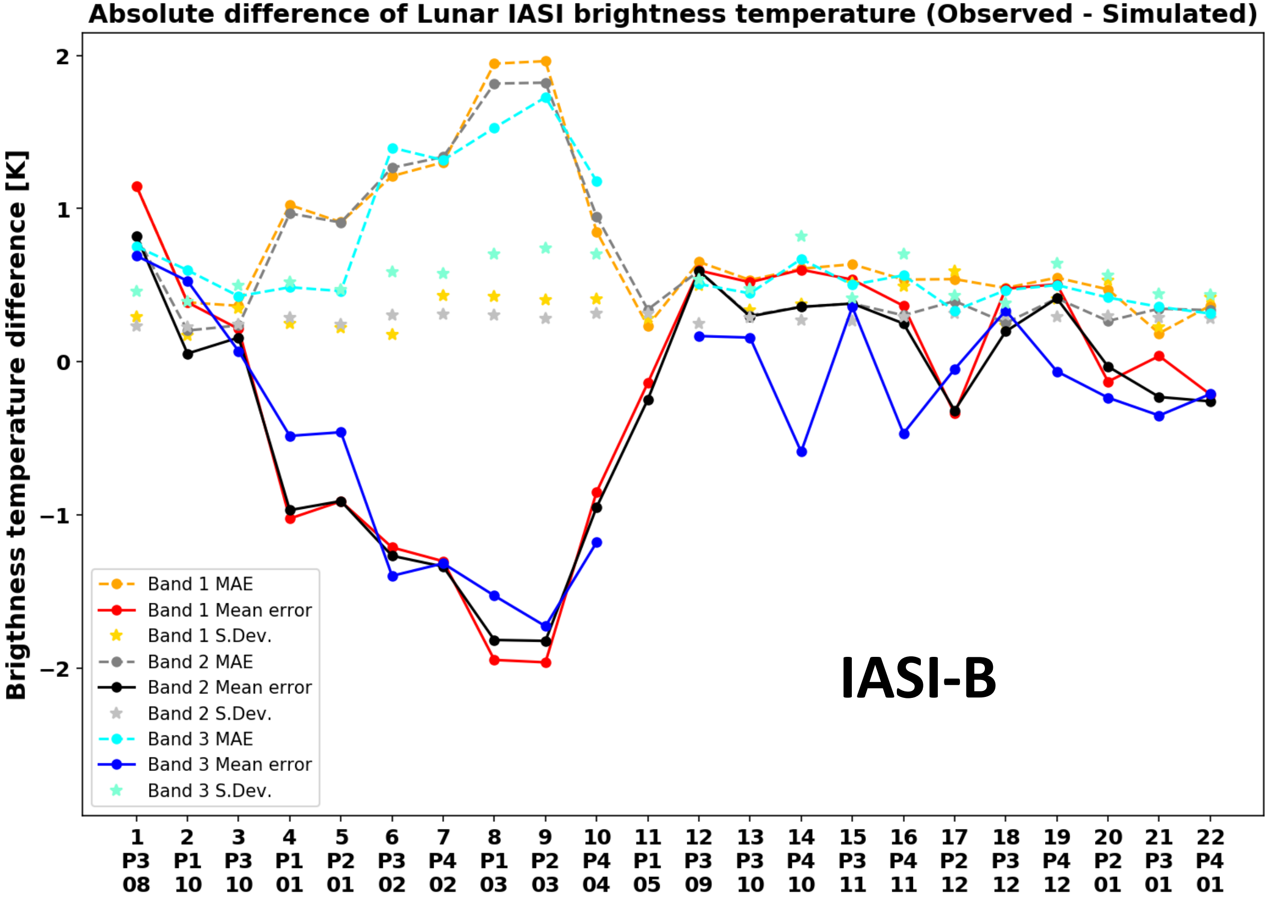


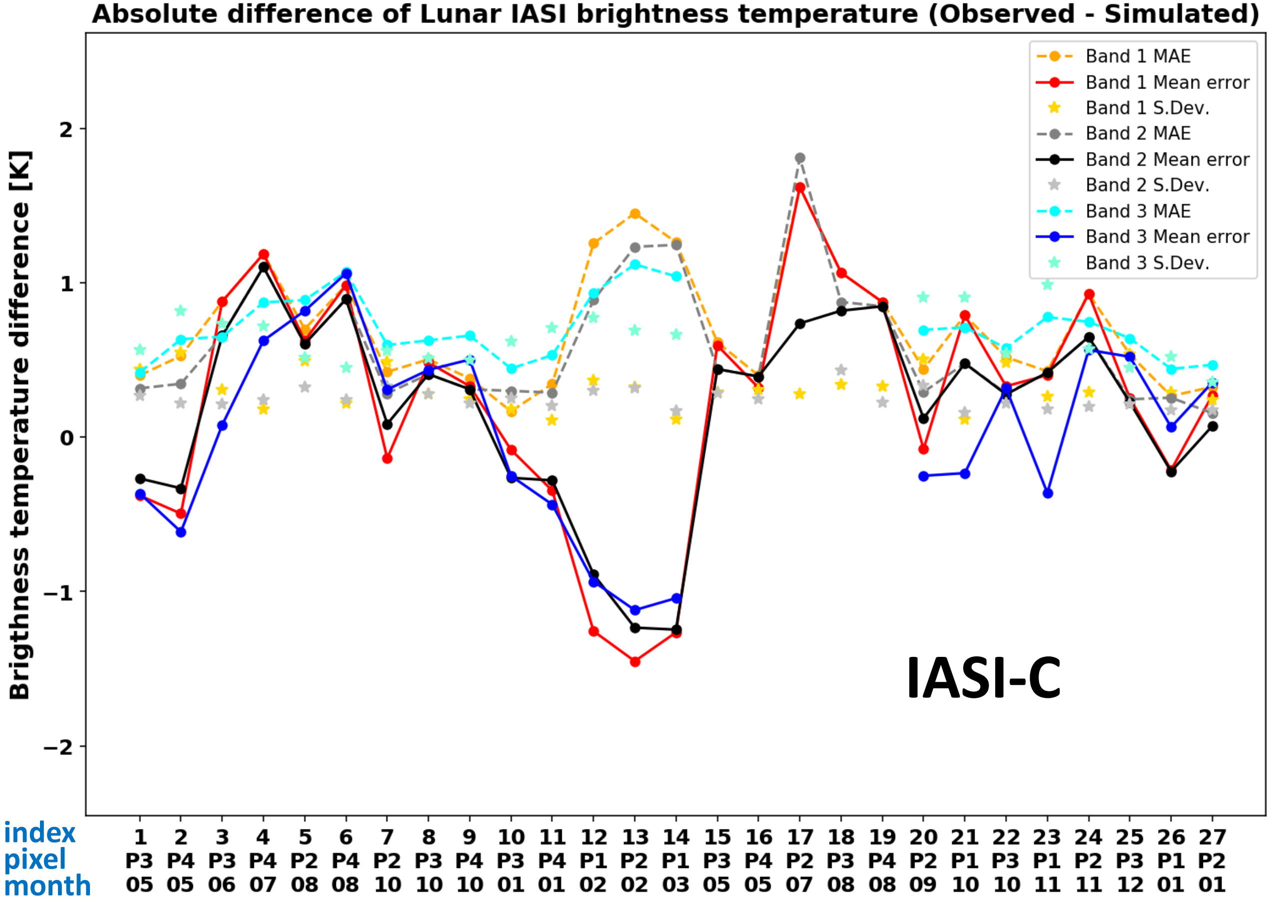




Results

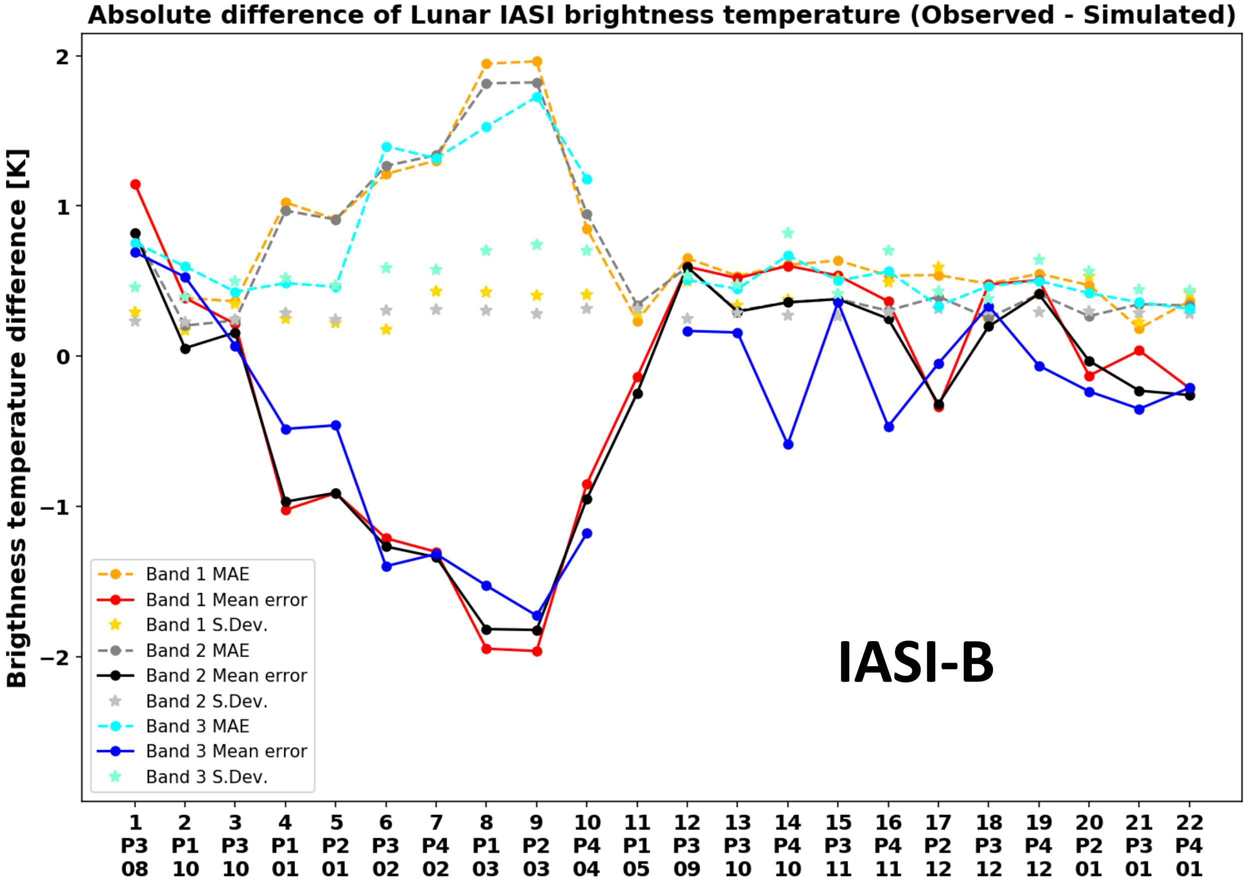
- In absolute values, the comparison shows a ~2.5K accuracy between the simulations and observations.
- Results between the bands are quite consistent, but there is a strong temporal variation

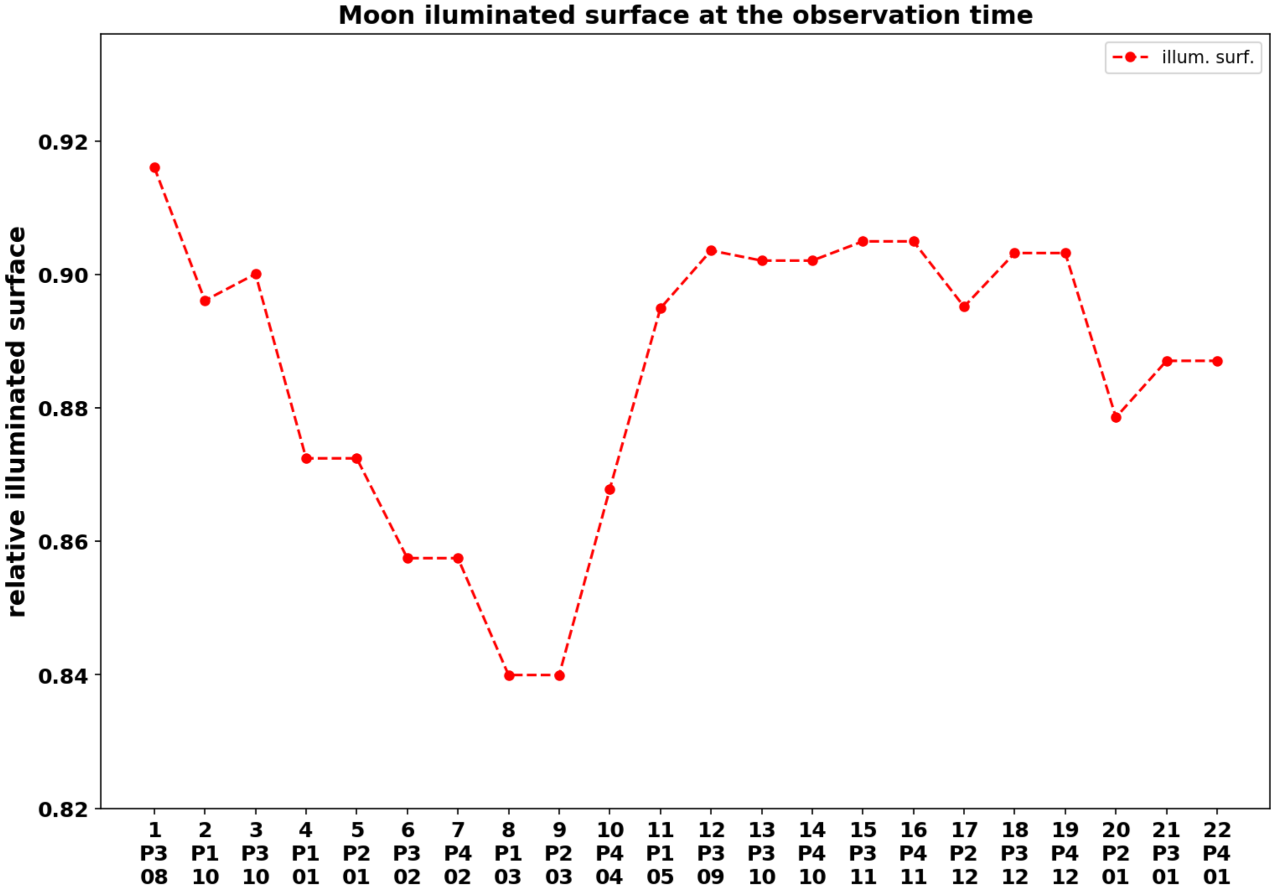




Results

➢ The observed bias shows a strong dependency of lunar phase and is clearly model-related





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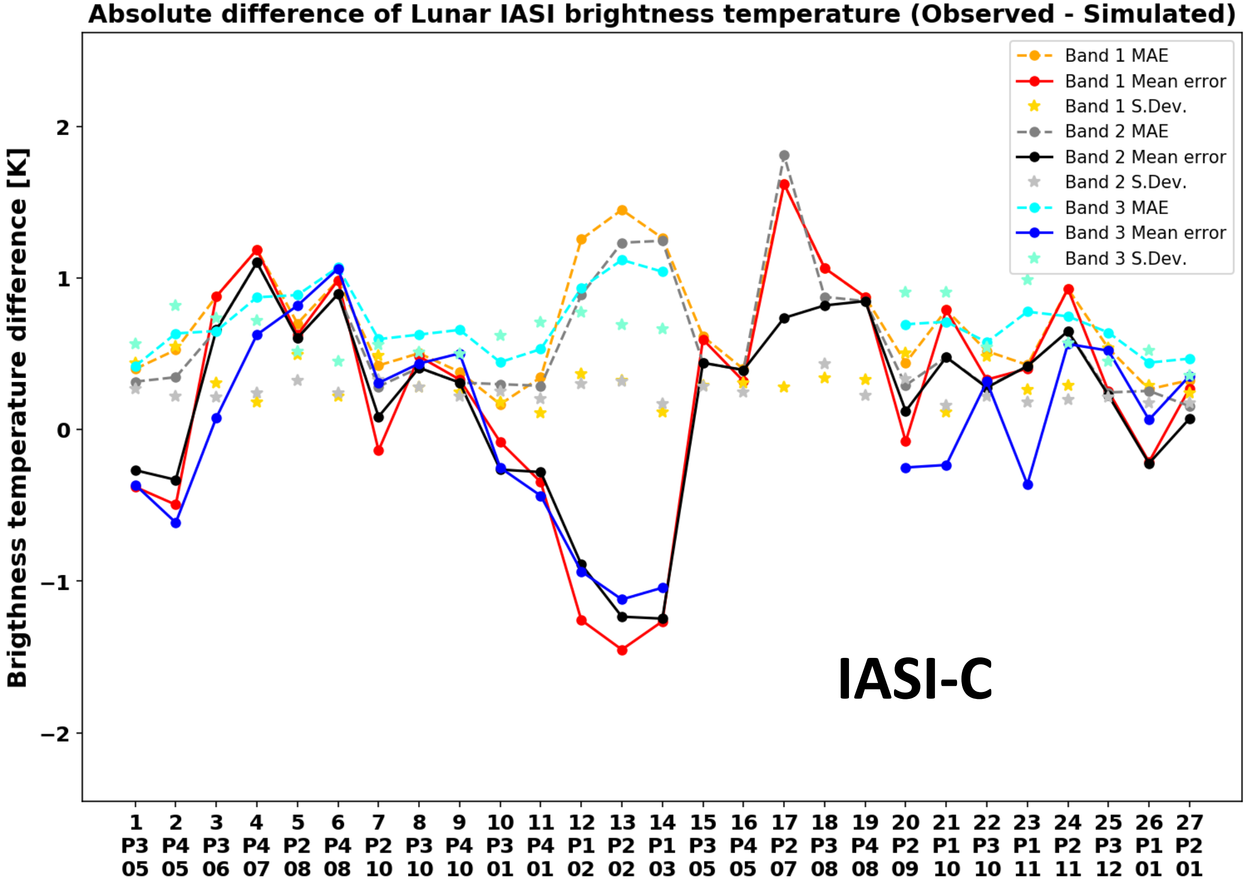
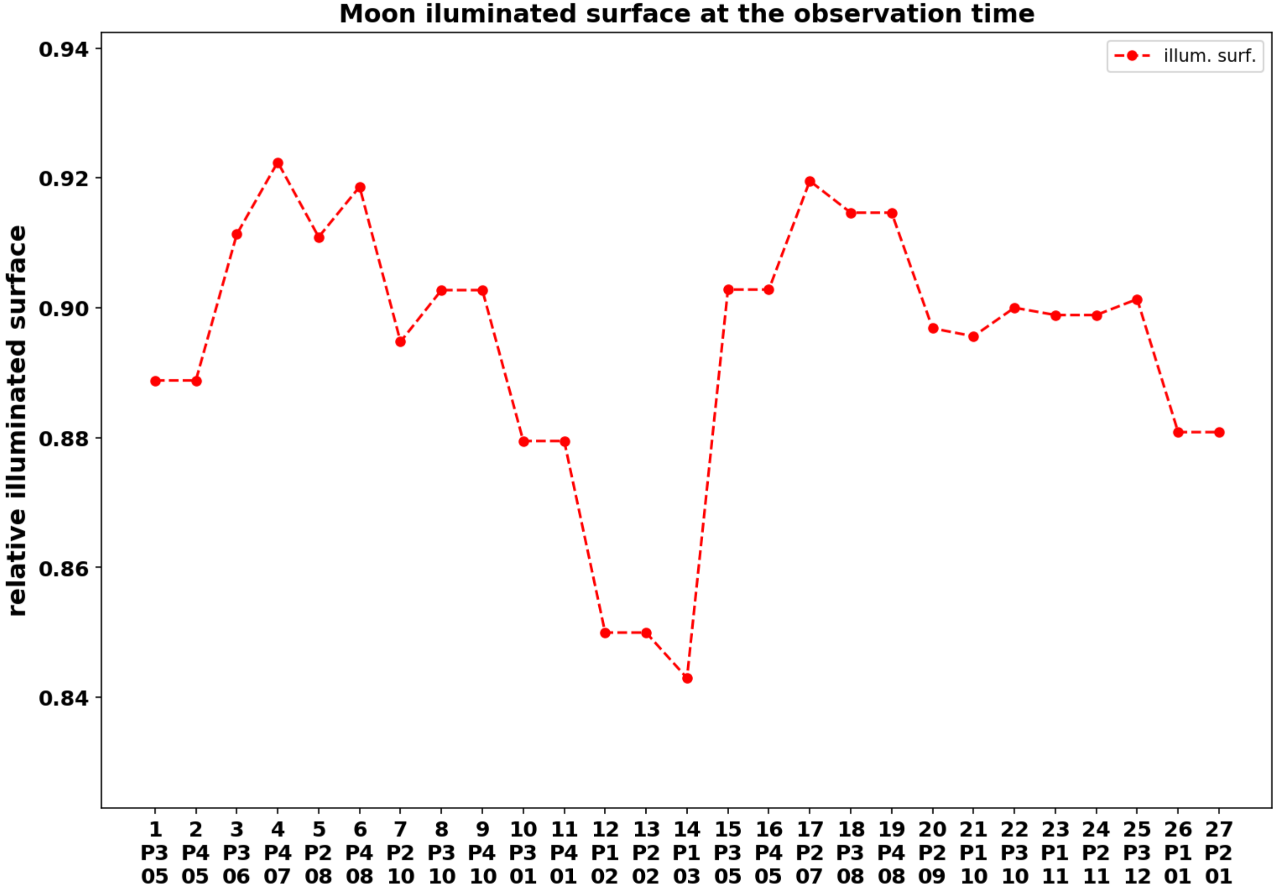




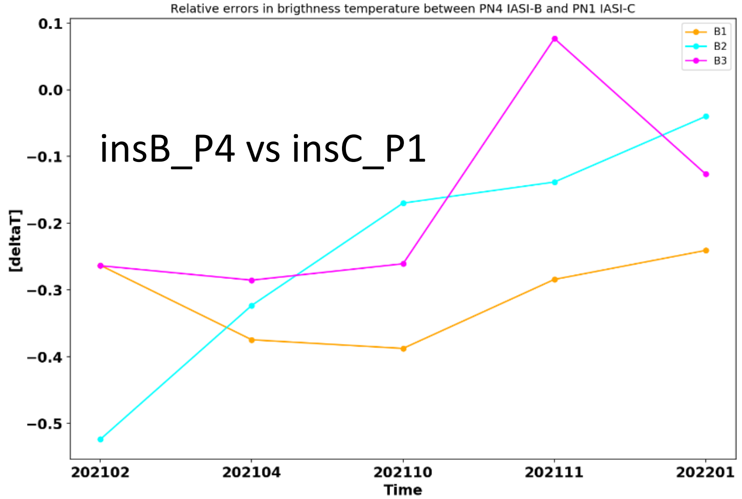
Results

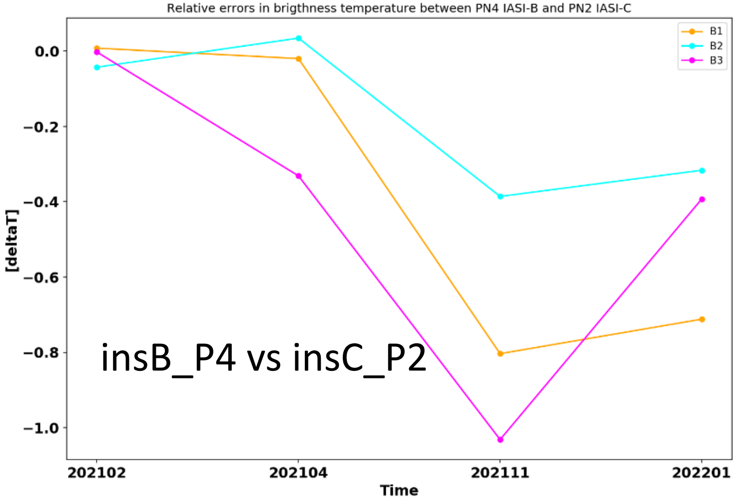
- The observed bias shows a strong dependency of lunar phase and is clearly model-related
  - Although the moon phase range is the IASI data is quite small (84-92%)
- After extensive tests, it seems that the cause of the bias is the Lambertian approximation
- It appears that the Moon infrared emissivity is strongly directional
  - LRO/Diviner data suggests the same
  - We currently explore this question further
  - This effect impacts both the emissive and the reflective components
- Given the very high correlation of the bias to lunar phase, the hope is that a correction of this effect will improve an absolute accuracy of the simulation to ≤ 0.5 K
- Standard deviations of the differences between the bands suggest this
  - Band B3 behavior is more different probably because of the solar reflective contribution (more uncertainties)

std [K]	B1-B2	B1-B3	B2-B3
IASI-B	0.14 K	0.42 K	0.36 K
IASI-C	0.23 K	0.39 K	0.32 K

Results

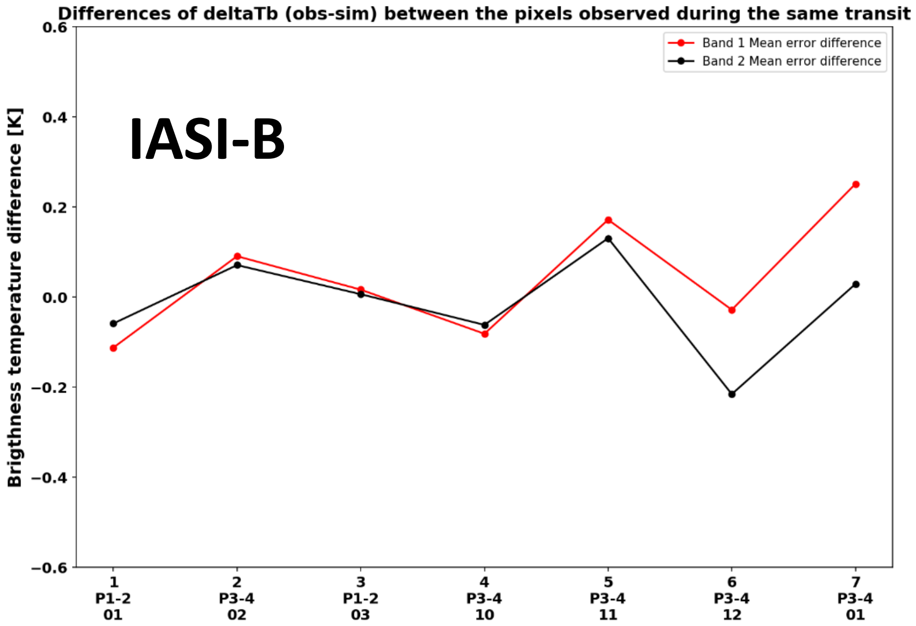
- In relative values, we performed inter-instrument comparisons between various pixel pairs (where we obtained enough data points).
  - The results give an accuracy of 0.5 – 1 K.
  - This is worse than what the 2019 data suggested (only 2 data points available gave an estimated accuracy of 0.2K)
  - And less good than Earth-view based massive relative comparisons (<0.2K)
  - It is presumed that colocation uncertainties are a strong contributor to these uncertainties (?)
  - Relative comparison of pixel pairs observed during a same transit to estimate this contribution (time difference of ~15 sec between observations)
    - In that timescale the impact of the physical model is negligeable

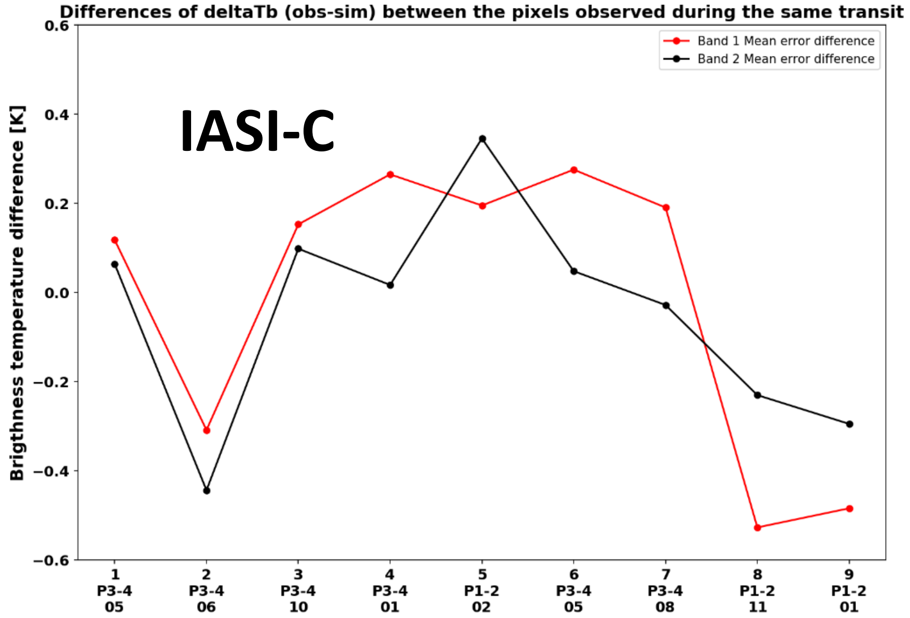




Results

- Relative comparison of pixel pairs observed during a same transit (time difference of 15 sec)





- Colocation is more precise with IASI-B than (±0.2K impact) with IASI-C (±0.5K impact)
  - Results confirmed with other imager-sounder co-registration tests that we performed
- Colocation uncertainties is the most important contributor to relative inter-instrument results (~0.5 K), but not the only one

Conclusion and further plans

- We are investigating a potential to use the Moon as calibration source for IASI observations in thermal infrared.

- The lunar observations are obtained in 2019 & 2021 and an infrared radiance model is developed.
  - Related uncertainties are identified and analyzed (simulations and observations).

- Results give an accuracy of ~2.5K in absolute and 0.5–1K in relative values.
  - Absolute results are dominated by the model (directional emissivity), and relative results by the imager-sounder colocation uncertainties
  - Solving these two identified sources would approach the results to the Earth-view based performance
  - Different approaches could be employed to address the directionality of lunar soil emissivity:
    - LRO/DIVINER data from its off-nadir campaign (performed in the phase 3 since 2016 and mid to high latitudes might be already decently covered)
    - Inversion approach using IASI data (high spectral resolution, spatially integrated, moon phase dependent)
    - Modelling or parametrisation approach (mature enough? various results suggest that the multiple scattering is important)

- We can conclude that the modeling is (also) hard in the infrared domain!

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Distribution of the IASI observations

- CNES and EUMETSAT recognize that IASI lunar data is quite unique and that it might be very interesting to the scientific community
- The wish to start distribute it in the coming weeks and the preparations are on-going
- If you are interested in exploring the IASI lunar dataset, you can approach me in order to make sure that the distributed data will correspond to your needs/ideas

Thank you for your attention