FINAL REPORT

1 General Information

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Project title: Establishing the Moon as Reference for Climate Data Records from Microwave Sounders (MW-Luna and MW-Luna 2)

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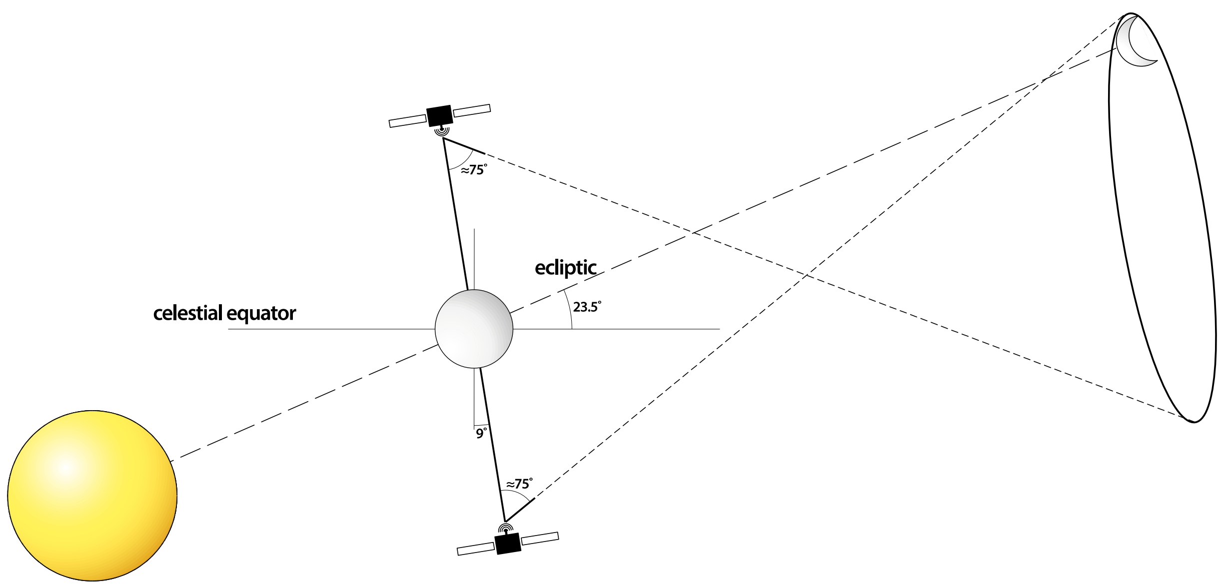

2 Summary

Satellite microwave sounders provide measurements of certain essential climate variables. For characterizing changes over time of these variables, it is important to detect and remove any calibration drifts present in these instruments. Their photometric stability is usually checked with inter-sensor comparisons (Zou et al., 2006, 2018), assuming that all calibration drifts are uncorrelated – a sort of a priori justification. A truly convincing assessment, however, can only be obtained by means of an absolute, stand-alone flux reference like the Moon (Kieffer et al., 1999).

We identified 9000 instances of the Moon appearing in the deep space view of the Microwave Humidity Sounder (MHS) on different satellites during routine operations. Its disk-integrated brightness temperatures were calculated and then used to validate a new model (Liu & Jin, 2021). Its predictions were found to agree with the measured values within 3 K or less, i. e. they are more accurate than previously available models by at least a factor of three. From these observations we derive an upper limit of 1 K / decade for the calibration drifts with MHS. This is still more than a factor ten larger than what is required for climate variables, but the new model establishes the Moon as flux reference between 89 and 190 GHz, rendering on-board calibration targets superfluous.

In addition to the observations with microwave sounders we also considered spectra obtained with the Cross-track Infrared Sounder (CrIS, Chen et al., 2022). NOAA identified 667 orbits of the Suomi National Polar-orbiting Partnership (SNPP), where the waxing Moon appeared in the field of view, and 326 such orbits of NOAA-20. We developed software that uses this data set to calculate the disk-integrated lunar radiance for almost any wavelength band in the range 3.9 - 15.4 μm and phase angles between +45° and +95°, again with the intention to simplify calibration. As the observations from SNPP are spread over more than ten years, and CrIS has hundreds of channels in each band, it was possible to check here the photometric stability with unprecedented precision. It turned out that at least one channel has a calibration trend on the order of +100 mK / decade. Given the fact that the required stability of an infrared radiometer for measuring atmospheric and surface climate variables is 80 mK / decade or better (Ohring et al., 2005), this finding might give a hint of what caused the considerable discrepancies among climate variable datasets from different instruments (Lang et al., 2020).

We also found that Venus can be used as reference for cross-calibration of infrared imagers in *geostationary* orbit, because the night side of this planet is a large, uniform area, whose radiance stays constant within 2% on a timescale of twelve hours. This is

three times more precise than vicarious calibration methods at visible wavelengths, e. g. RadCalNet (Choi et al., 2025).

Bestimmte Klimavariablen lassen sich am besten mit satellitengestützten Mikrowelleninstrumenten messen. Um ihre langfristigen Veränderungen zu charakterisieren, ist es wichtig, etwaige Schwankungen in der Kalibrierung von diesen Instrumenten zu erkennen und zu korrigieren. Ihre photometrische Stabilität wird hierzu üblicherweise dadurch überprüft, dass man die Messwerte verschiedener Satelliten miteinander vergleicht (Zou et al., 2006, 2018), wobei angenommen wird, dass ihre Kalibrierungsfehler nicht korreliert sind – dies wäre aber erst noch zu beweisen. Eine unanfechtbare Fehlerabschätzung kann darum nur durch eine zusätzliche, ganz eigenständige Flussreferenz wie den Mond erzielt werden (Kieffer et al., 1999).

Wir identifizierten 9000 Beobachtungen des Mondes mit dem Microwave Humidity Sounder (MHS) auf verschiedenen Satelliten, die während des normalen Betriebs, das heißt ohne besondere Manöver, anfielen. Die „Strahlungstemperatur" der Mondscheibe wurde bestimmt und anschließend mit den Voraussagen eines neuen Modells (Liu & Jin, 2021) verglichen. Die berechneten und gemessenen Werte lagen dabei höchstens 3 K auseinander, d. h. sie sind mindestens um einen Faktor drei genauer als zuvor verfügbare Modelle. Aus diesen Beobachtungen leiteten wir eine obere Grenze von 1 K pro Jahrzehnt für die Kalibrierungsänderungen bei MHS ab. Dies ist zwar zehnmal schlechter als die Genauigkeit, die für die betrachteten Klimavariablen erforderlich ist, aber das neue Modell ermöglicht es dennoch, den Mond als Flussreferenz zwischen 89 und 190 GHz einzusetzen, wodurch Gerätschaften zur Kalibrierung an Bord überflüssig werden.

Zusätzlich zu den Beobachtungen mit Mikrowelleninstrumenten betrachteten wir auch Spektren des Mondes, die mit dem Cross-track Infrared Sounder (CrIS, Chen et al., 2022) gewonnen wurden. NOAA identifizierte hier 667 Umlaufbahnen des SNPP-Satelliten (Suomi National Polar-orbiting Partnership), bei denen der zunehmende Mond in das Blickfeld geriet, sowie 326 solcher Umlaufbahnen von NOAA-20. Wir entwickelten Software, die diesen Datensatz nutzt, um die Mondstrahlung für nahezu jedes Wellenlängenintervall im Bereich von 3,9 bis 15,4 µm und Phasenwinkel zwischen +45° und +95° zu berechnen, wiederum mit dem Ziel, die Flusskalibrierung auf eine solidere Grundlage zu stellen. Da sich die Beobachtungen von SNPP über mehr als zehn Jahre erstrecken, und CrIS bei Hunderten von verschiedenen Wellenlängen misst, war es möglich, hier die photometrische Stabilität mit beispielloser Präzision zu überprüfen. Es stellte sich heraus, dass zumindest bei den kürzesten Wellenlängen ein Kalibrierungstrend von etwa +100 mK pro Jahrzehnt auftritt. Aufgrund der Tatsache, dass die erforderliche Stabilität eines Infrarotradiometers zur Messung von Klimavariablen 80 mK pro Jahrzehnt beträgt (Ohring et al., 2005), könnte dieses Ergebnis einen Hinweis auf die Ursache der erheblichen Unterschiede zwischen den Klimadatensätzen verschiedener Instrumente geben (Lang et al., 2020).

Wir fanden außerdem heraus, dass Venus als Referenz für die Kalibrierung von Infrarotsatelliten in *geostationärer* Umlaufbahn dienen kann, denn die Nachtseite dieses Planeten ist ein ausgedehntes, gleichmäßig helles (im Infraroten) Areal, dessen Strahlung innerhalb von 2 % auf einer Zeitskala von zwölf Stunden konstant bleibt. Dies ist dreimal präziser als Kalibrierungsmethoden bei sichtbaren Wellenlängen, die auf der Beobachtung bestimmter Referenzorte auf der Erde beruhen, z. B. RadCalNet (Choi et al., 2025).

3 Progress Report

3.1 Background and Objectives of the project

Observations from satellite microwave sounders play an important role in measuring the long-term trends for climate change monitoring. Calibration drift has been one of the main sources of uncertainties in the satellite-measured temperature trends and characterization of the temporal variability of upper tropospheric humidity (Zou et al., 2018). Normally a calibration drift is considered absent, when two instruments have no relative drifting error between them. This reasoning, however, is fallacious, because they could both have the same calibration drift, especially when they use the same method of calibration. Hence a very stable reference is needed: the Moon.

The Moon is used since many years for sensor response temporal trending in the reflected solar wavelength range (Kieffer & Wildey, 1996). While the absolute accuracy of the corresponding lunar models cannot be verified with better than 5% uncertainty, drifts can be characterized with sub-percent precision given a sufficiently long time series of Moon observations (Kieffer, 2022). The main objective of MW-Luna was to achieve a similar performance at longer wavelengths, with the ultimate goal to establish the Moon as a climate-quality radiometric calibration reference.

Models of the microwave brightness temperature existed already before MW-Luna started (Linsky, 1973, Keihm & Langseth, 1975, Krotikov & Pelyushenko, 1987), but they did not agree well with observations (Bennett et al., 1992, Pardo et al., 2005, Appel et al., 2019). Reference observations obtained over a large range of phase angles were clearly needed. As lunar radiation intrudes the deep space view of microwave sounders occasionally during routine operations, i. e. without special spacecraft pitch-maneuvers, a constantly increasing number of observations of the Moon was accumulated by different weather satellites, which could be used to constrain models. These observations turned out to be useful as well for characterizing various properties of the beams of the microwave sounders in flight.

The more observational data become available, the higher is the precision of the measured radiance of the Moon. The data rate generated by microwave sounders is low, however, because these instruments are limited to a few tens of spectral channels only, so we decided to extend the scope of the project to hyperspectral sounders. Such instruments do not exist for millimeter-waves, but they are available for the thermal infrared. The Moon appears also here from time to time in the deep space view, and by binning the data from hundreds of channels, even small effects influencing the sensor response can become statistically significant. An empirical model based on such observations is best suited as calibration reference in the mid-infrared, because the uncertainty of the measurements is much smaller than the uncertainty of the thermophysical properties of the Moon assumed by models.

3.2 Results and Findings

3.2.1 Characterization of Satellite-Borne Microwave Sounders in Flight

The Moon can be used to characterize the properties of microwave sounders in flight (Burgdorf et al., 2021), and this was demonstrated with AMSU-B (Advanced Microwave Sounding Unit) and MHS (Microwave Humidity Sounder).

- Pointing Accuracy and Co-Alignment: We checked the properties given by EUMETSAT for the deep space view on MHS (https://user.eumetsat.int/s3/eup-strapi-media/pdf_mhs_char_data_des_255730e8d4.pdf) with observations of the Moon in different channels. There are considerable discrepancies between our results and the plots published by EUMETSAT; we found for example a misalignment that is twice as large as allowed by the requirements.
- Antenna patterns: We could demonstrate that the beam pattern of MHS on Metop is neither axisymmetric nor Gaussian, contrary to what is suggested in some documents. In several cases the beam widths claimed by MATRA MARCONI SPACE (results from ground tests in document 3175-JA291-DPQ MHS-DP-JA291-MMP) were significantly smaller than the values obtained with our measurements. Using the Moon as absolute flux reference, however, requires knowledge of the exact beam width, because it fills only part of the field of view (FOV). The beam can be characterized very precisely with a technique developed by Zhou & Yang (2019), using dedicated spacecraft maneuvers.
- Conclusion: The results from tests with the Moon in flight seem to be less compliant with the requirements than the ground tests by the manufacturer.

3.2.2 The Moon as a Tool for the Calibration of HIRS

Constanze Seibert identified 123 intrusions of the Moon in the deep space view of HIRS (High-resolution Infrared Radiation Sounder) on 16 different satellites. In addition to validating a thermo-physical model of the Moon (Müller et al, 2021), she could identify and correct systematic errors in the size of the FOV of several satellites as published on web pages and in various documents (Seibert et al., 2022). Again, the characterization of instrumental properties did not include special maneuvers of the weather satellites, and they could be carried out many years after the end of the operational phase.

3.2.3 The Moon as a Microwave Calibration Reference

An on-board blackbody causes additional costs simply by its weight and space requirements, and its use introduces several sources of common effects that cause uncertainties (Hans et al., 2019). As vicarious calibration has been recognized as an effective method for calibrating satellite optical sensors, we suggest the Moon as a calibration reference for microwave sounders that is equivalent to vicarious calibration sites on Earth. This concept requires an accurate model of the lunar brightness temperature.

Previously published models of the disk-averaged brightness temperature of the Moon have uncertainties of more than 6 K at wavelengths between 1.5 and 3.5 mm (Keihm et al., 2025). Typical inter-satellite biases of microwave sounders, however, are smaller than 4 K (Hans et al., 2019), so the brightness temperature of the Moon should be known with that accuracy at least. A new model (Liu & Jin, 2021) was validated with several thousand observations of the Moon with MHS on different satellites. This way it was proven to be a sufficiently accurate, absolute calibration reference for space-borne instrumentation. This model could even reproduce the microwave light curves of a total eclipse of the Moon, a task that caused considerable problems for other models (e. g. Pardo et al., 2005). Hence the disk-integrated microwave radiation of the Moon can now be provided with confidence for all phase angles closer than 90° to full Moon and all possible distances from the Sun at 89, 157, 183, and 190 GHz (see Figure 1).

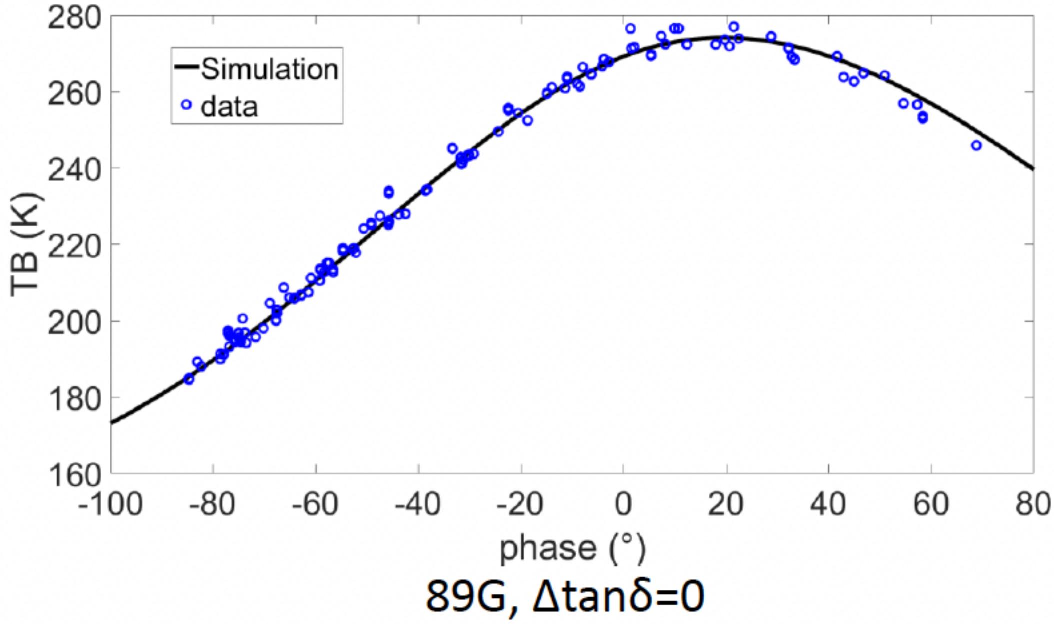

Figure 1. Comparison of the disk-integrated brightness temperature of the Moon as measured with MHS on NOAA-19 at 89 GHz and a model simulation for different phase angles. The agreement is similar at other frequencies.

3.2.4 The Moon as an Infrared Calibration Reference

With 993 observations of the Moon with CrIS on SNPP and NOAA-20, it has become possible to derive the lunar brightness temperature in the wavelength ranges 3.9 - 4.6μm, 5.7 – 8.3μm, and 9.1 – 15.4μm as a function of the phase angle of the Moon and its distance from the Sun with high precision. The brightness temperature measured with NOAA-20 at the shortest wavelengths is 0.4 K higher than with SNPP. This must be caused by a difference of 0.06% in the diameter of the FOVs, because the absolute accuracy is on the order of 0.2 K for the measured brightness temperature of the Moon. Observations of the Moon with CrIS are available for phase angles between 45° and 95°, i. e. between waning gibbous and last quarter. We took advantage of this extremely accurate data set with a program that calculates the lunar radiance for any relative spectral response function within the wavelength channels of CrIS (see Figure 2). Hence, we provide the means to use the Moon as photometric reference for most infrared sounders in sun-synchronous orbits. At the longest wavelengths, however, lunar spectra of CrIS can be affected by spectral ringing, so an inspection of the results for anomalies is advised.

The case of CrIS demonstrates, how the Moon can be a common reference site for satellites in the same sun-synchronous orbit, but on opposite sides of the Earth at any given moment, i. e. without any simultaneous nadir overpasses.

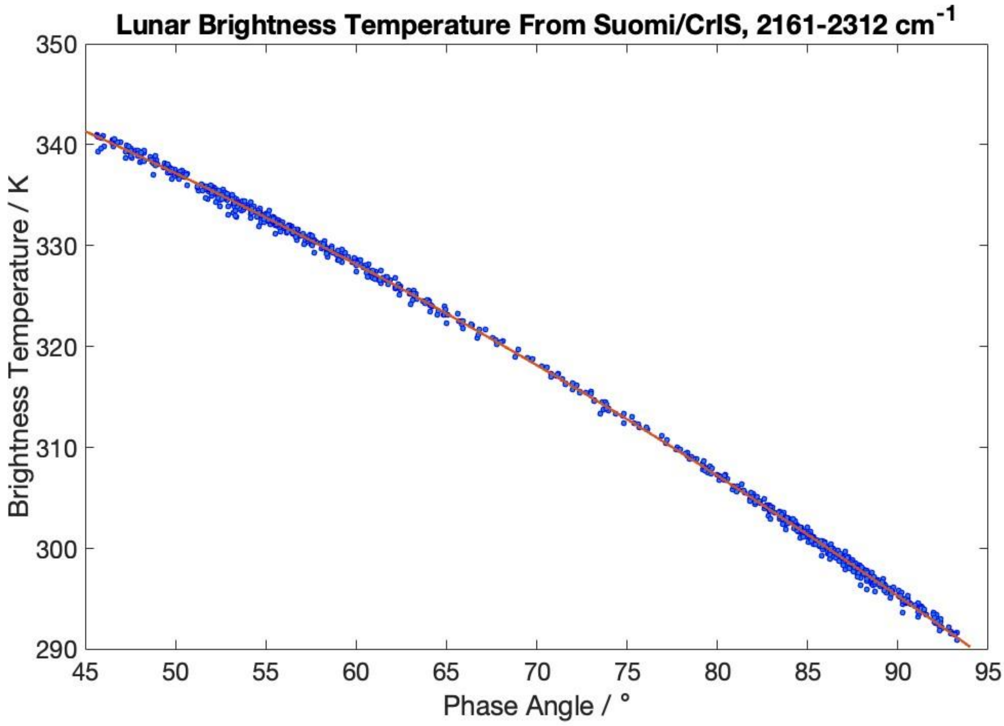

Figure 2. Comparison of the disk-integrated brightness temperature of the Moon as measured with CrIS on SNPP in the short-wave channel and a polynomial using phase angle and distance between the Sun and the Moon as input parameters (red line).

It is interesting to note that the shortwave channel on SNPP has a significant calibration drift: The measured brightness temperature of the Moon changes by 50 – 100 mK / decade. This is in qualitative agreement with an earlier finding reported at the twenty-fifth international TOVS study conference: The strongest bias trend between CrIS and VIIRS on SNPP was found at 4.05 μm (https://itwg.ssec.wisc.edu/wordpress/wp-content/uploads/2025/10/itsc25_wg_report.pdf).

3.2.5 Mercury and Venus as Tools for Inter-Calibration of Infrared Imagers

At an IEEE International Geoscience and Remote Sensing Symposium it was suggested to use Mercury as calibration target at infrared wavelengths for the Advanced Baseline Imagers on the Geostationary Operational Environmental Satellites (Fulbright et al., 2023). The large scatter of its radiance in the measurements made its use as radiometric calibrator unfortunately quite questionable. Work within MW-Luna, however, demonstrated that inferior conjunctions of the planet Venus offered great opportunities for inter-calibration of imagers in geostationary orbits with channels operating in the thermal infrared. This is, because Venus is big enough to cover several pixels completely, and its brightness temperature does not change significantly within twelve hours, the maximum time difference between observations with different satellites. Venus can appear close to the Earth’s limb when seen from the vantage point of a geostationary satellite, and this alignment can repeat after 24 hours. This means that Venus is well suited as common reference site for geostationary satellites on opposite sides of the Earth, i. e. satellites without matchups (Burgdorf et al., 2024).

3.3 Deviations from the Original Concept

The main deviation from the original concept was to search for calibration drifts in the lunar observations with CrIS and not with AMSU-A (Advanced Microwave Sounding Unit-A). Special focus had originally been directed on AMSU-A, because its calibration drift is one of the main sources of uncertainty in the satellite-measured temperature trends in the troposphere and lower stratosphere (Zou et al., 2018). The trends in question, however, amount typically to only 0.04 K per decade, and there are simply not enough observations of the Moon with the required precision for a meaningful check. CrIS, on the other hand, achieves a very high signal-to-noise ratio, when the average from many channels is calculated. This instrument can measure the upper tropospheric humidity (UTH), and it provides therefore complementary information to AMSU-B and MHS. Given the fact that the HIRS trends in brightness temperature are noticeably weaker than those obtained from AMSU-B/MHS (Chung et al., 2016), it is worthwhile to investigate the possibility of systematic errors in the datasets from infrared radiometers and spectrometers.

An aim from the original concept that was not achieved was the calibration of astronomical observations. CLASS (Cosmology Large Angular Scale Surveyor), for example, used the disk-integrated Moon for calibration of its Q-band array with an ad hoc model based on measurements made by the Chang’E satellite mission (Xu et al., 2020). It should be noted that Chang’E-1 and -2 had significant absolute calibration issues (Keihm et al., 2022).

3.4 Quality-Enhancing Measures

The largest contribution to the uncertainty in the measurement of the absolute radiance of the Moon at microwave frequencies with weather satellites is the uncertainty of the beam size. Ground tests have produced values that are in most cases too small, i. e. they led users to believe that the instruments were compliant with requirements, when this was not the case. An additional complication is that the beams are neither Gaussian nor circular symmetric, as is falsely stated in numerous documents and is wrongly suggested by characterizing them with a single number, the “half-width”. To correct these misleading test results, we calculated the beam half-width in the cross-scan direction from the duration of the intrusions of the Moon in the deep space view. The more consistent the measurements from different orbits are, the more justified is the assumption of a circular-symmetric, Gaussian beam. With MHS, we used our newly calculated “half-width” instead of the values given in official documents, except for Metop-C, where the uncertainty of our measurement was too large. An error of the beam size affects inter-calibration, but it is not relevant for checks of radiometric stability or the dependence of the measured brightness temperature on phase angle or distance from the Sun.

When comparing our findings with results obtained independently with other methods there are some pitfalls one wants to avoid. Here are a few examples of deceptive contradictions that upon close inspection rather prove the validity of our approach.

1. SEVIRI produced very consistent values for the radiance of Venus, although the 13.4 μm channel was known to show temporarily a cold bias, caused by ice contamination. These anomalies, however, never happened during the observations of Venus considered by us, because this planet was only used as reference when in inferior conjunction.
2. The good agreement between CrIS and HIRS/4 did not contradict the bias identified in the HIRS/IASI comparison with MetOp. This is, because all suitable observations of the Moon with HIRS/4 provided by C. Seibert were made with NOAA satellites, except for one.
3. The calibration drift of the SW channel of CrIS on SNPP is at least in qualitative agreement with inter-sensor comparisons suggesting that this channel/satellite combination has by far the highest trend when compared to VIIRS.
4. By analyzing thousands of observations of the Moon, we have gathered a colorful mix of paths through the deep space view, phase angles, and apparent lunar diameters. This means that our findings concerning photometric drift or stability

are largely independent from possible response variations within infrared pixels, asymmetries of microwave beam shapes or the maximum temperature on the lunar disk being off-center, because whatever effects are caused by such anomalies, they will basically just increase the scattering of the measurements.

5. The difference in radiance between HIRS/4 and our empirical model based on lunar observations with CrIS is about 3%. For comparison: At visible wavelengths the difference between model and observation amounts up to 22% (Kieffer, 2022).

3.5 Research Data and Methods

The brightness temperatures of the Moon measured with microwave sounders are available on Zenodo (DOI 10.5281/zenodo.17733213). They include data from MHS on NOAA-18 and NOAA-19 that are covering phase angles between -85° (waxing Moon) and 69° (waning Moon) for the frequencies 89, 157, 183, and 190 GHz. This range of phase angles corresponds to the fact that the deep space view of a satellite in sun-synchronous orbit points away from the Sun. The brightness temperatures were calculated with a program that is available on Zenodo as well, it uses level 1b data from MHS and AMSU-B that are available from the Comprehensive Large Array-data Stewardship System (CLASS).

The measurements were used to validate a model (Liu & Jin, 2021) for calculating the lunar brightness temperature as a function of phase angle and distance from the Sun. Here we paid particular attention to the beams of MHS on NOAA-18 and NOAA-19 and confirmed that they were in good approximation Gaussian-shaped with the correct half-width. Taking advantage of the results from this investigation, the Moon can now be used as flux reference with an absolute accuracy of about 2 K. For characterizing the beam of instruments, the method by Zhou & Yang (2019) is recommended, if a pitch-over maneuver is possible.

The radiance of the Moon was measured in the three channels of CrIS (650 – 1095 cm^{-1}, 1210 – 1750 cm^{-1}, 2155 – 2550 cm^{-1}) for phase angles between 45° and 95° (waxing Moon). There are 2211 spectral elements in total, and a program in Python is available to calculate the disk-integrated radiance of the Moon as a function of its phase angle and distance from the Sun for any relative spectral response function within the available wavenumber ranges, i. e. most channels of infrared sounders. The software to achieve this is one of the project-specific results, and it makes quick inter-calibration possible. The spectra of the Moon with CrIS were provided by courtesy of Yong Chen from NOAA.

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4 Published Project Results

4.1 Category A

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