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# The Moon as a diagnostic tool for microwave sensors

*By Martin Burgdorf, T. Lang, S. Michel, S. A. Buehler and I. Hans (Universität Hamburg)*

The upper tropospheric humidity (UTH) is an essential climate variable that is required to monitor the global water vapor climate feedback and hence to understand changes in atmospheric dynamics associated with global warming. It is best measured at mm wavelengths from space, where the presence of clouds is less of a problem than in the infrared. Such observations with microwave humidity sounders began in the early 1990s with instruments that were optimized for the 183-GHz line in combination with two window channels at lower frequencies.

The UTH can vary considerably within a few hours, but the trends caused by climate change manifest themselves as small changes over decades. Detecting them with microwave sensors in space makes high demands on the long-term stability of their flux calibration, which are difficult to meet with their on-board calibration targets, whose own temperature calibrations might slightly drift over the duration of the mission. It is therefore desirable to employ a second invariable reference in order to check the stability of the flux calibration: the Moon.

Weather satellites in polar orbits observe the Moon automatically from time to time, because every scan of a sounding instrument does not only sweep over the Earth but also over reference sources with high and low flux. The latter is usually provided by cold space, i.e., the cosmic microwave background.

Its flux is always measured far from Earth and Sun, but this means that occasionally the Moon moves through the field of view (see Fig. 1). A model of its disk-integrated brightness temperature has been developed by Mo and Kagawa (2007) in order to subtract its contribution to the overall flux received so that the standard calibration routine remained valid. This is particularly important for AMSU-A, where up to a third of the scans in one orbit can be contaminated by the Moon. With MHS (Microwave Humidity Sounder, Goodrum et al., 2014), however, because of the smaller beam width and the deep space view (DSV) being closer to nadir, the intrusions of the Moon last only of the order three minutes (see Fig. 2).

The model for the Moon's brightness temperature is based on the data from the microwave sounders themselves; therefore this natural satellite cannot serve as an absolute reference for these instruments. As the properties of its surface do not change with time, however, it can be used for inter-calibration and checks of the photometric stability. By considering only intrusion events where the Moon moves through the center of the deep space view, and by correcting for changes in its phase angle and distance from the Earth, it becomes possible to reduce the errors in its calculated flux due to periodic variations to about 2%. Dedicated maneuvers enabling observations far apart in time but at the same phase and ideally similar libration of the Moon can be expected to improve this value considerably. The maximum signal of the Moon is best determined by fitting a Gaussian to its light curve. This fit does not only provide information about the gain and the beam pattern, but its exact position in time gives also some idea of the pointing accuracy. It follows from the time difference Δ between the maximum of the light curve and the minimum of the angular distance between the DSV and the Moon, as calculated with the ATOVS and AVHRR Pre-processing Package, by simple multiplication with $\omega$, the angular velocity of the deep space view in the sky:

$$\omega = 360^\circ \cdot sin(90^\circ - \alpha)/P$$

where $\alpha$ is the distance of the DSV direction from nadir, and $P$ is the orbital period. The following table gives an example some missing value for MetOp-A MHS:

| Year | $\bar{\Delta}$ | $\sigma(\Delta)$ | $\sigma m(\Delta)$ | Intrusions considered |
|---|---|---|---|---|
| Jan/Feb | 0.11 | 0.14 | 0.023° | 36 |
| Jan/Feb | 0.00 | 0.12 | 0.018° | 43 |

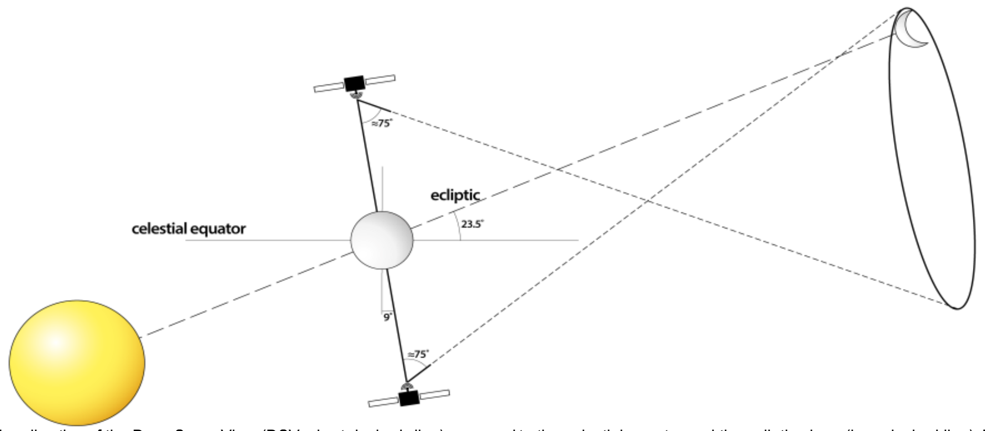


Figure 1: Viewing direction of the Deep Space View (DSV, short dashed line) compared to the celestial equator and the ecliptic plane (long dashed line). For simplicity, the slight tilt of the Moon's orbit against the ecliptic is not displayed. The DSV direction has a typical angle α ≈ 75° against nadir and describes a circle in the sky during one orbit.

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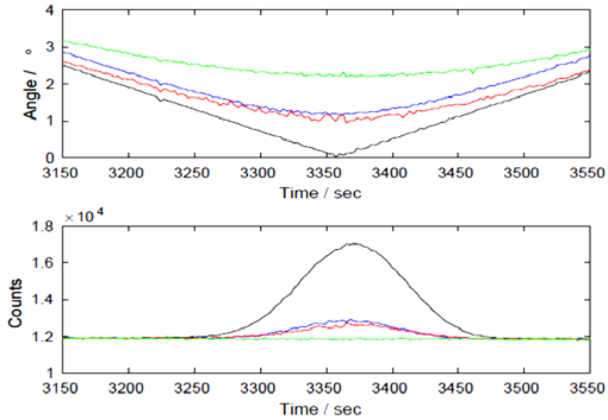


Figure 2: Moon intrusion event with MHS on MetOp-A on Sep 19, 2008 around 22:32 (UT); blue: DSV 1, black: DSV 2, red: DSV 3, green: DSV 4. Top: angle between Moon and space view. Bottom: space view count. In this example, the calculated minimum angle and the measured maximum signal in DSV 2 occur five scans apart, and DSV 1 gives more signal than DSV 3, although its approach to the Moon was calculated to be less close.

Both the mean and the scatter of the differences between the calculated DSV position and the actual pointing along the scan direction are smaller than the uncertainty of **0.3**° claimed in the MHS Level 1 Product Generation Specification. The stronger the signal of the Moon is compared to the one from the internal black body, the tighter are the constraints it can put on the stability of flux calibration and pointing accuracy.

This makes it particularly interesting for the Ice Cloud Imager and the Microwave Imager (Alberti et al., 2012) on MetOp-SG, where it will almost fill the FWHM of the beam.

More details on the appearances of the Moon in the deep space views and the limiting factors of the measurement accuracy can be found in Burgdorf et al. (2016).

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Discuss the article

# GRUAN in the service of GSICS: Using reference ground-based profile measurements to provide traceable radiance calibration for space-based radiometers

*By Jordis Tradowsky (Bodeker Scientific), Greg Bodeker (Bodeker Scientific), Peter Thorne (Maynooth University), Fabien Carminati (UK Met Office), William Bell (UK Met Office)*

The Global Climate Observing System (GCOS) Reference Upper-Air Network (GRUAN) comprises 24 sites that measure vertical profiles of essential climate variables (ECVs) such as temperature, pressure, and water vapour. These measurements are reference quality measurements in that all systematic biases having been accounted for and measurement uncertainties are traceable to internationally recognized measurement standards (Immler et al., 2010). The resultant long-term homogeneity of the measurement series, as well as their network-wide uniformity and coherence, makes them ideally suited for providing a reference standard for space-based radiometric measurements. Reference measurements of the atmospheric state variables influencing radiative transfer through the column, together with, for example, surface emissivity and surface temperature, can be used as input to a state-of-the-art radiative transfer model to simulate top-of-the-atmosphere (TOA) radiances. Propagating the SI traceable uncertainties in the measured vertical profiles of the state variables through to uncertainties in the TOA radiances provides a degree of SI traceability for the simulated radiances. Bootstrapping methods, that also account for vertical autocorrelation in the profiles, can be used to propagate uncertainties from measured variables to the modelled radiances. The modelled radiances, with their robustly determined uncertainty estimates, are also suitable for comparison with space-based radiometric measurements. If satellite

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