DESHIMA sky removal method for astronomical observations with an ultra-wideband submillimeter spectrometer

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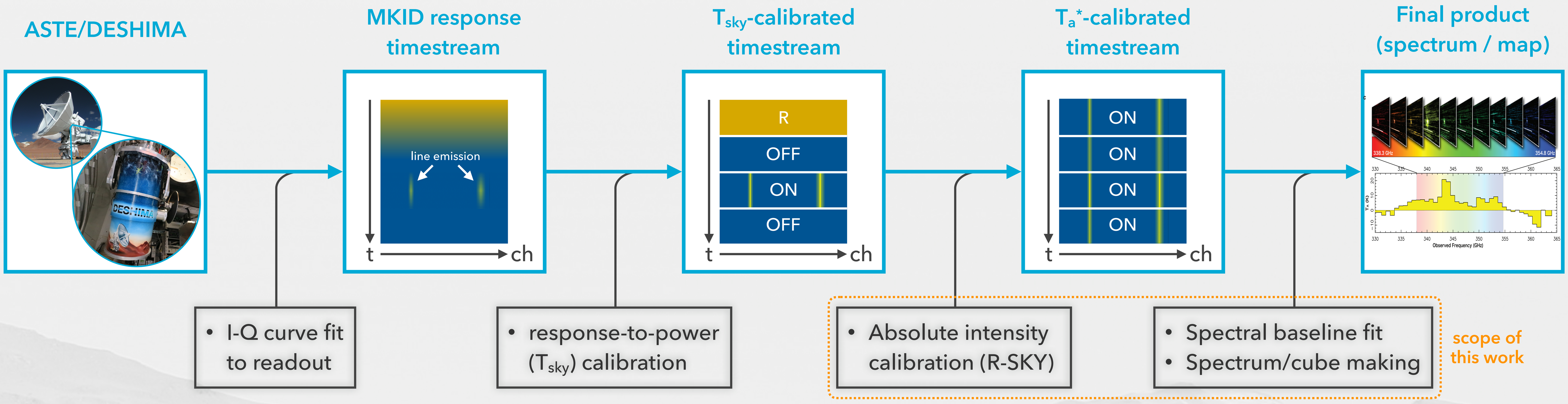
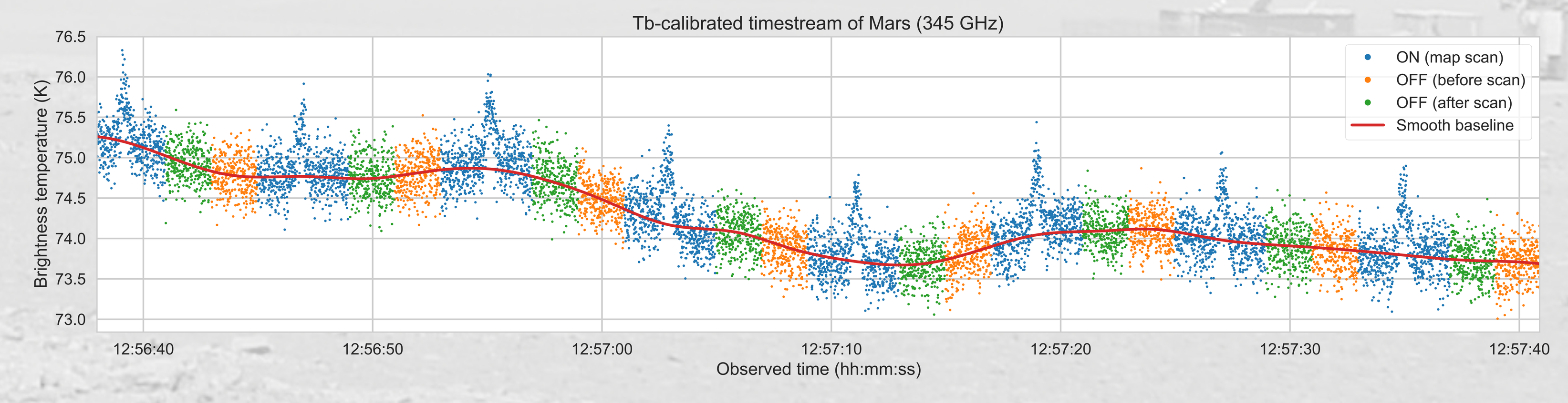
We present a new method to remove sky emission from ultra-wideband submillimeter wave spectra, measured with emerging instruments such as DESHIMA (DEep Spectroscopic HIgh-redshift MApper). DESHIMA has an instantaneous bandwidth of 45 GHz (Endo et al. 2019b), and is being upgraded to 220 GHz (Poster No. 259 by A. Pascual Laguna). When the instantaneous frequency coverage is so wide, the sky baseline becomes a non-linear spectrum and therefore requires an atmospheric model for fitting. We demonstrate that the method reduces the non-flatness of an astronomical spectrum better than the conventional methods. As this method can also estimate a continuum spectrum, it may offer a new way of sky removal for astronomical continuum observations.

1. Introduction: end-to-end data reduction process of DESHIMA



2. Absolute intensity calibration

After response-to-power (T_{sky}) calibration (Poster No. 229 by T. Takekoshi), we conduct a one-load chopper wheel (R-SKY) calibration in the same manner as heterodyne receivers. In the case of on-the-fly (OTF) mapping observations, we further try to estimate and subtract the scanning effect of each scan by a smooth-curve fitting in order to improve the S/N ratio.



Timestream of T_b-calibrated DESHIMA data of a Mars continuum mapping. We estimate and subtract baseline fluctuation by a smooth-curve fitting using off-source measurements before and after each scan of the mapping.

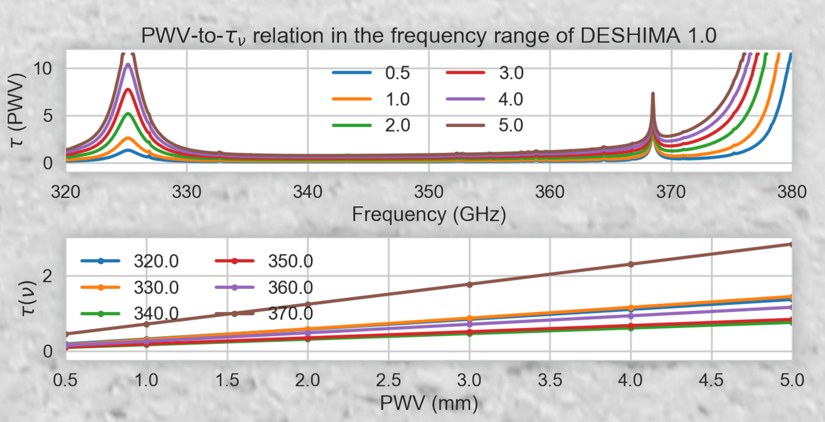
3. Ultra-wideband (UWB) sky removal

In the case of an ultra-wideband (UWB) spectrometer such as DESHIMA, spectral baseline (sky level) of a spectrum is not constant but has a strong frequency dependence, even after the chopper wheel calibration. The calibrated antenna temperature can be expressed in detail as:

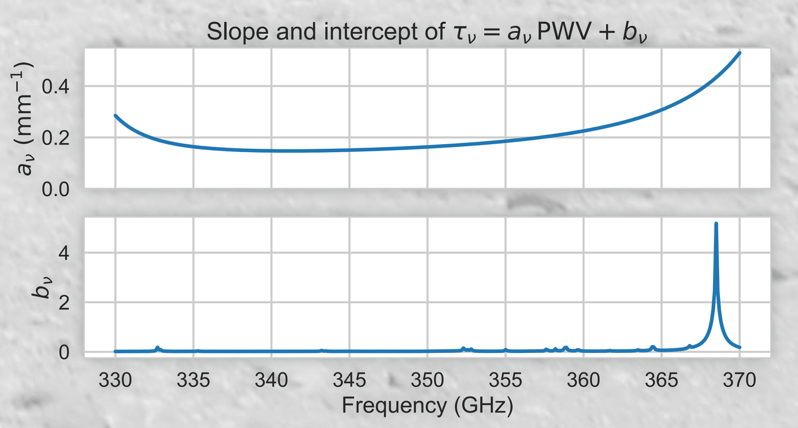
$$T_\nu^{\mathrm{cal}}(t) = \underline{T_\nu^{A*}(t)} + \underline{T^{\mathrm{atm}}\frac{\mathrm{d}\,\tau_\nu}{\mathrm{d}\,\mathrm{PWV}}}\,\delta\,\mathrm{PWV}(t)$$

linear
non-linear

where δPWV(t) is a precipitable water vapor (PWV) change in a scan (on-source) from its off-source. We find that $d\tau_\nu/dPWV$ has a non-linear spectrum which can be calculated by an atmospheric model. Using the non-linearity, we develop a UWB baseline subtraction method which estimates δPWV(t) instead of baseline itself: <u>It can remove only spectral baseline (2nd term) and keep continuum and line emission (1st term).</u>



(Top) atmospheric τ_ν spectra as a function of PWV (0.5-5.0 mm) calculated by the ALMA ATM model. (Bottom) PWV-to-τ_ν relation at several frequencies.

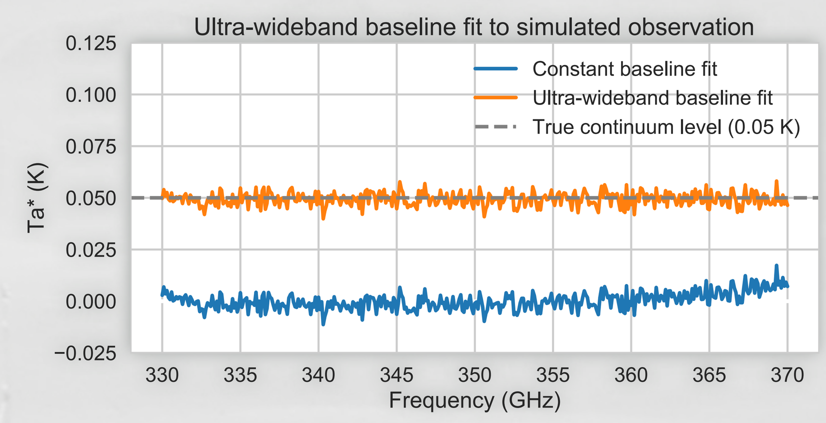


The PWV-to-τ_ν relation can be expressed as a linear function $\tau_\nu = a_\nu$ PWV + b_ν. The top panel shows the non-linearity of a_ν (equivalent to $d\tau_\nu$ / dPWV).

4. Applications of the UWB sky removal

<u>4.1 Simple simulation of a continuum observation</u>

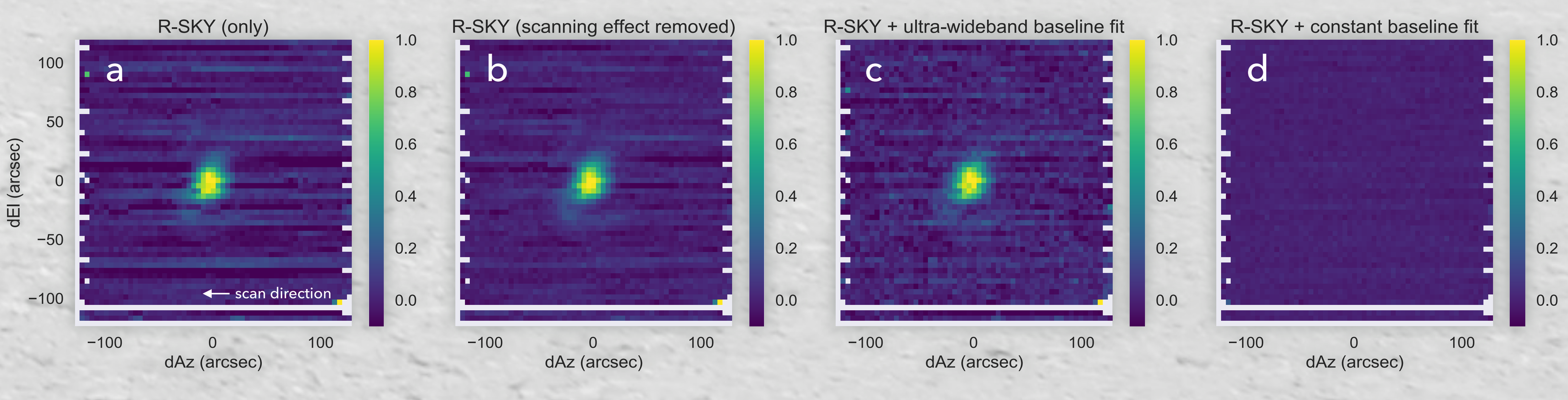
We demonstrate that the new UWB baseline subtraction can estimate a continuum emission at the exact level, while conventional constant baseline subtraction does not.



A simulation of continuum observation in DESHIMA frequency range. The model continuum level is 0.05 K while δPWV changes ± 10^{-3} mm in a scan.

<u>4.2 Mars continuum map observation by DESHIMA</u>

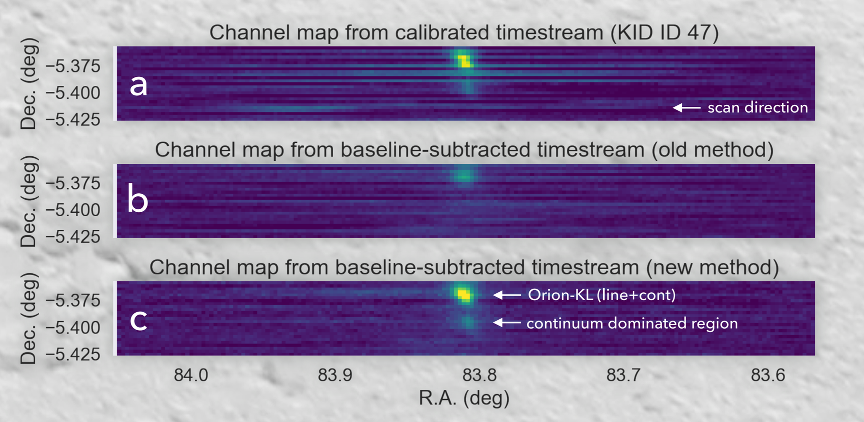
We demonstrate that the new UWB baseline subtraction removes the scanning effect due to PWV change, while it can keep the continuum emission from Mars better than the conventional constant-baseline fit.



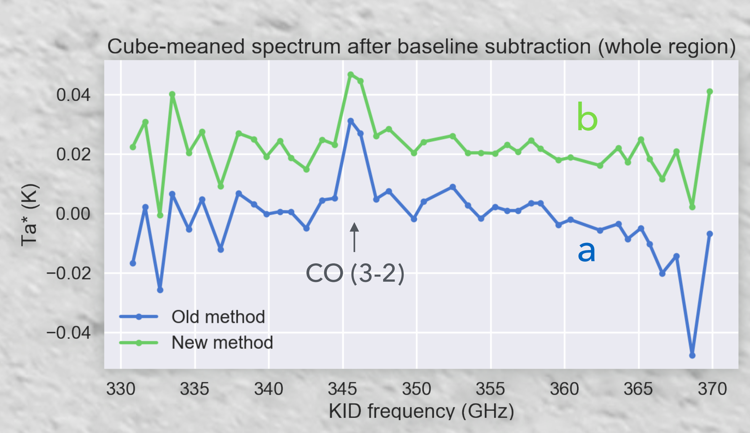
Continuum map of Mars by DESHIMA 1.0 with different data reduction: (a) Reduced with only R-SKY calibration. (b) R-SKY calibration with smooth curve fit. (c) R-SKY and the UWB baseline fit. (d) R-SKY and constant baseline fit.

<u>4.3 Orion-KL cont-line map observation by DESHIMA</u>

We demonstrate that the new UWB baseline subtraction can remove the scanning effect and keep the both continuum and line emission from Orion-KL region better than the conventional constant-baseline fit.



CO (3-2) maps of Orion-KL region by DESHIMA 1.0 with different reduction methods: (a) Reduced with only R-SKY calibration. (b) R-SKY and constant baseline fit. (c) R-SKY and the UWB baseline fit.



Spectra of Orion-KL after baseline subtraction of different methods: (a) constant baseline. (b) the UWB baseline.