On-sky Responsivity Calibration of the Integrated Superconducting Spectrometer

Tatsuya Takekoshi[1,2], Junya Suzuki[3,4], Kenichi Karatsu[5,6], Yoichi Tamura[7], Tai Oshima[8,9], Akio Taniguchi[7], Shin'ichiro Asayama[8], Tom J. L. C. Bakx[7,8,10], Jochem J. A. Baselmans[5,6], Sjoerd Bosma[6], Juan Bueno[5], Kah Wuy Chin[8,11], Yasunori Fujii[8], Kazuyuki Fujita[12], Robert Huiting[5], Soh Ikarashi[6], Tsuyoshi Ishida[1], Shun Ishii[8,13], Ryohei Kawabe[8,9,11], Teun M. Klapwijk[6,14], Kotaro Kohno[1,15], Akira Kouchi[12], Nuria Llombart[6], Jun Maekawa[8], Vignesh Murugesan[5], Shunichi Nakatsubo[16], Masato Naruse[17], Kazushige Ohtawara[8], Alejandro Pascual Laguna[5,6], Koyo Suzuki[7], David J. Thoen[6,18], Takashi Tsukagoshi[8], Tetsutaro Ueda[7], Pieter J. de Visser[5], Paul P. van der Werf[19], Stephen J. C. Yates[5], Yuki Yoshimura[1], Ozan Yurduseven[6], Akira Endo[6,18]

1. IoA/Univ. of Tokyo, 2. UEC Tokyo, 3. Kyoto Univ., 4. KEK, 5. SRON, 6. EEMCM/TU Delft, 7. Nagoya Univ., 8. NAOJ, 9. SOKENDAI, 10. Cardiff Univ., 11. DoA/Unif. of Tokyo, 12. ILTS, Hokkaido Univ., 13. Joint ALMA Observatory, 14. Moscow State Pedagogical Univ., 15. RESCEU, Univ. of Tokyo, 16. ISAS/JAXA, 17. Saitama Univ., 18. Kavli Institute of NanoScience/TU Delft, 19. Leiden Univ.

e-mail: tatsuya.takekoshi@ioa.s.u-tokyo.ac.jp

[Abstract] We are developing an ultra-wideband spectroscopic instrument, DESHIMA (Deep Spectroscopic HIgh-redshift Mapper), based on the technologies of an on-chip filter-bank and Microwave Kinetic Inductance Detector (MKID) to investigate dusty star-burst galaxies in the distant universe at millimeter and submillimeter wavelength. On-site experiment of prototype DESHIMA was performed using the ASTE 10-m telescope. We established a reliable responsivity model that converts frequency responses of the MKIDs to line-of-sight brightness temperature. Using a skydip data set under various precipitable water vapors (PWV, 0.4-3.0 mm), obtained by the ALMA radiometers, we estimated the responsivity model parameters. The line-of-sight brightness temperature of sky is estimated using an atmospheric transmission model and obtained two parameters of the responsivity model for each MKID. As a result, we obtain temperature calibration uncertainty of 1σ=4%, which is enough smaller than other photometric biases. In addition, the mode of forward efficiency of 0.88 in our responsivity model is consistent with an expected value from the geometrical support structure of the telescope. We also estimate line-of-sight PWVs of each skydip observation using frequency response of MKIDs and confirm the consistency with PWVs obtained by ALMA.

Introduction: DESHIMA on ASTE 2017

In Oct.-Nov. 2017 we had a first on-sky demonstration of DESHIMA, a new spectroscopic instrument using MKIDs combined with on-chip superconducting filterbank (Fig 1a) covering 332–377 GHz with 49 spectral channels ($\Delta\nu/\nu \sim 380$) using the ASTE 10-m telescope. In this session, we successfully detected some astronomical targets, for instance, redshifted CO(J=3–2) line of VV114, a luminous infrared galaxy at the redshift of 0.020 (Fig 1b).

We present a reliable calibration technique to established the responsivity model that converts raw readout data to line-of-sight brightness temperature of sky emission.

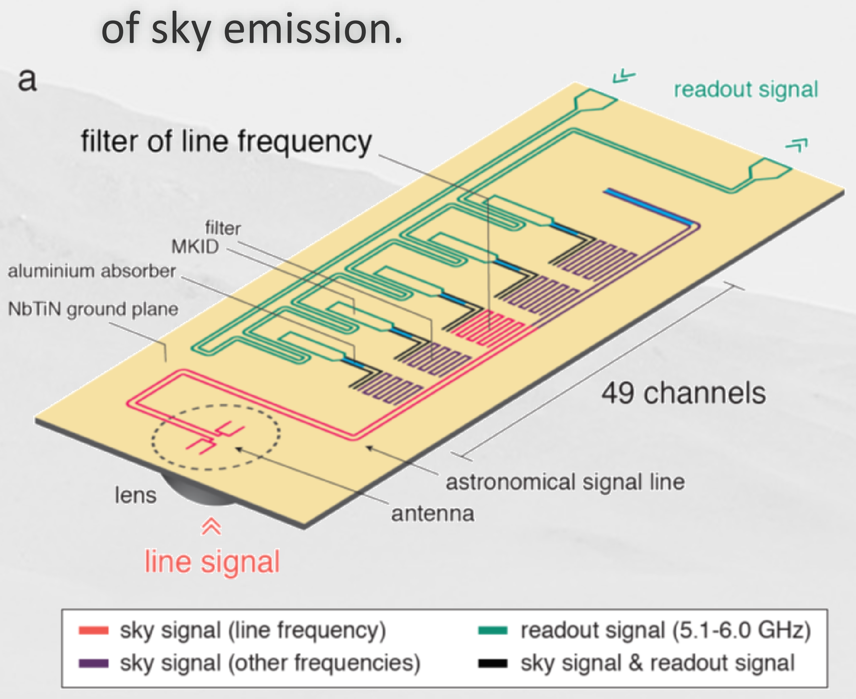

Fig 1a. Schematic of the superconducting filterbank chip used in the DESHIMA 2017 session.

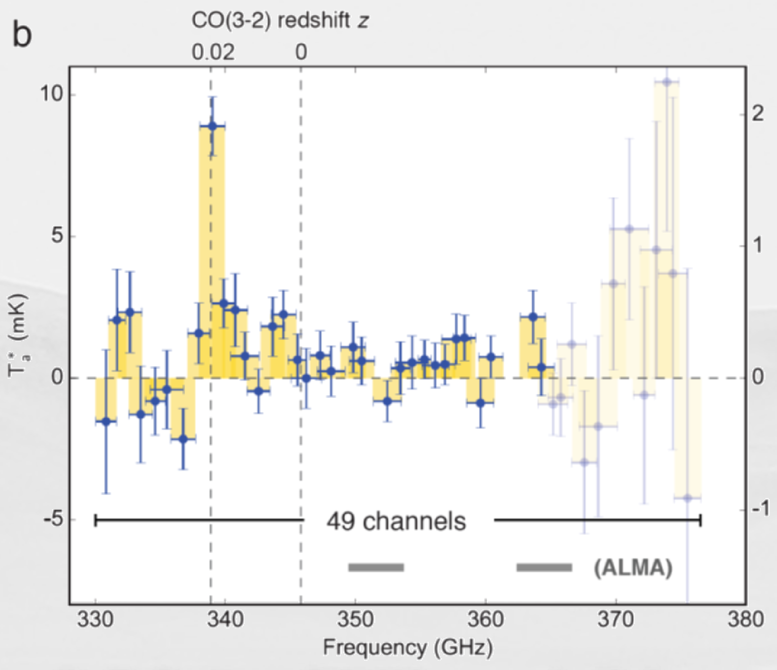

Fig 1b. Spectrum of VV 114 measured with the DESHIMA on ASTE.

Method

We define the relative shift in readout resonance frequency $f(T)$: $\delta x(T) \equiv (f(T) - f(T_{load}))/f(T_{load})$, which is a direct readout value of an MKID. Here T is brightness temperature at the cryostat windows. We use an optical chopper as a standard of the resonance frequency at $T_{load} \simeq 274$ K. The relation between δx and T for NbTiN/Al hybrid MKID is $\delta x(T) = p_0(\sqrt{T + T_{CW}} - \sqrt{T_{load} + T_{CW}})$, where p_0 is a factor of proportionality and T_{CW} is the Callen-Welton correction temperature (-8.4K@350GHz). Considering sky brightness temperature, $T = \eta_{fwd} T_{sky} + (1 - \eta_{fwd}) T_{amb}$, where T_{amb} is ambient temperature and η_{fwd} is forward efficiency. Thus, we can write a responsivity equation:

$$T_{sky}(\delta x) = \frac{1}{p_0{}^2 \eta_{fwd}} \left(\delta x + p_0\sqrt{T_{load} + T_{CW}}\right)^2 - \frac{1}{\eta_{fwd}}(T_{CW} + (1 - \eta_{fwd}) T_{load})$$

We need to estimate T_{sky} by a different method. Skydip observation provides the relation between the telescope elevation (El) and δx (Fig 2). Assuming the relation between optical depth τ and PWV by an atmospheric transmission model (ATM, Pardo et al. 2001), we can estimate T_{sky} using the equations:

$$T_{sky}(\mathrm{El}, \mathrm{PWV}) = (1 - \eta_{atm}) T_{atm} \text{ and}$$

$$\eta_{atm}(\mathrm{El}, \mathrm{PWV}) = \int g(\nu) e^{-\tau(\nu, \mathrm{PWV}) \csc(\mathrm{El})} d\nu,$$

where $g(\nu)$ is normalized frequency response function of each MKID ($\int g(\nu)\, d\nu = 1$).

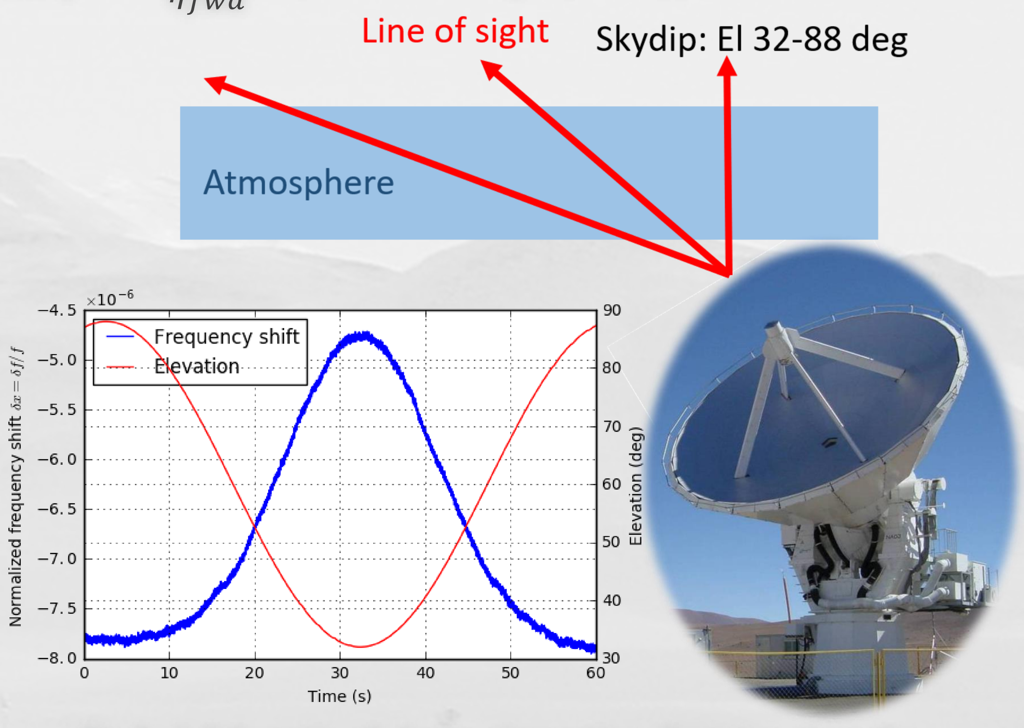

Fig 2. A Schematic of skydip observation. Scanning along the elevation provides different power input of atmospheric emission to the MKIDs.

Result of On-sky Responsivity Model

Fit result with skydip data

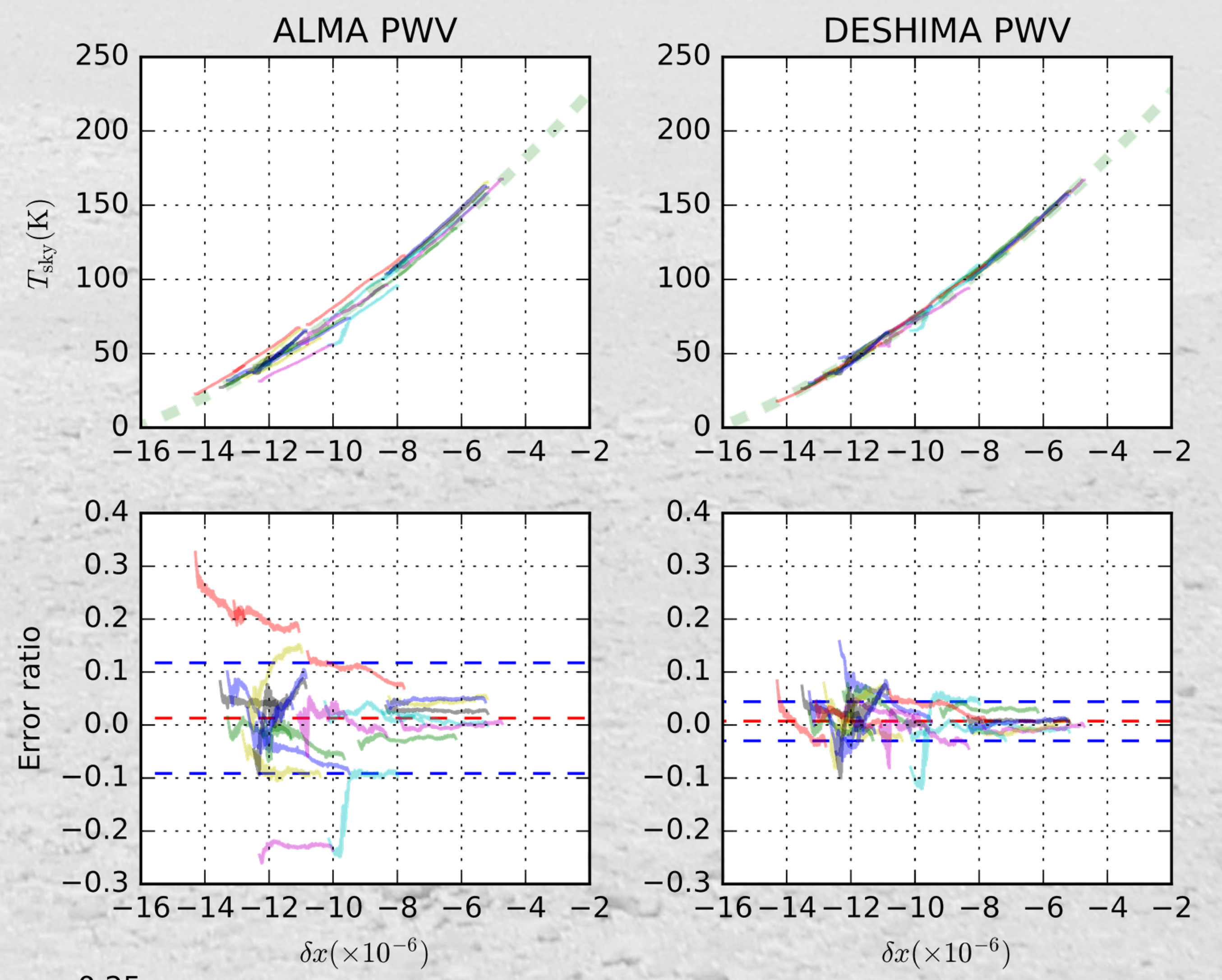

Fig 3. An example of the responsivity model fit (KID #20, 335.5 GHz). Top Left and Right panels show the relation between dx and Tsky calculated using ALMA and DESHIMA PWVs, respectively. Dashed green lines represent the obtained responsively model curve. Solid lines corresponds to each skydip data. Bottom Left and Right panels show the error ratio of responsivity curve. Red and blue dashed lines are the means and standard deviations of the error ratio.

Table 1. Statistics of model parameters for 40 filter pixels.

Model PWV	Mean offset	Mean 1σ error
ALMA	+1.0%	9.9%
DESHIMA	+0.8%	4.0%

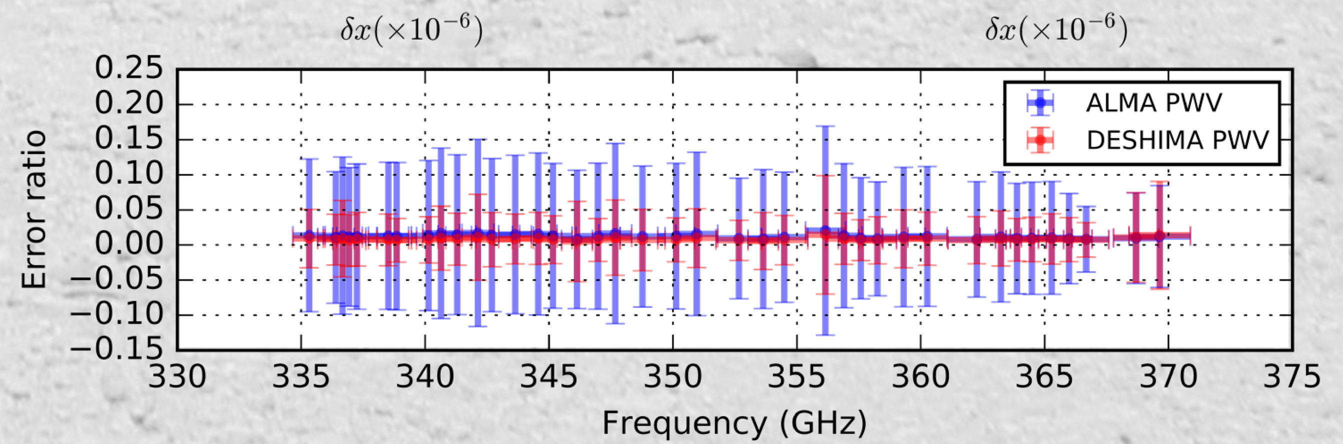

Fig 4. Frequency dependence of error ratio.

In the entire observation period of the DESHIMA 2017 session, we obtained 22 skydip data, which showed the typical range of the PWV of 0.4—3.0 mm, with the median value of 0.9 mm (obtained by the radiometers mounted on each ALMA telescopes as a median value, Nikolic et al. 2013).

An example of the responsivity model fit (ch. 20 at 335.5 GHz) is shown in Fig. 3 (left). Using the obtained parameters, we estimated line-of-sight PWVs (DESHIMA PWV) and re-calculated the error ratio, as shown in Fig 3 (right). The statistics for all filter pixels are shown in Fig 4 and Table 1. The 1σ error of 4% is smaller than other photometric errors by chopper wheel method and planet flux model (typically 5-20%) Thus, **we obtained flux calibration errors of 1σ=4% from the responsivity model curves and estimated PWVs from DESHIMA itself.**

Frequency dependency of the fitting parameters

Fig 5. Frequency dependencies (Right) and KDEs (Left) of the responsivity model parameters, p0 (Top) and ηfwd (Bottom).

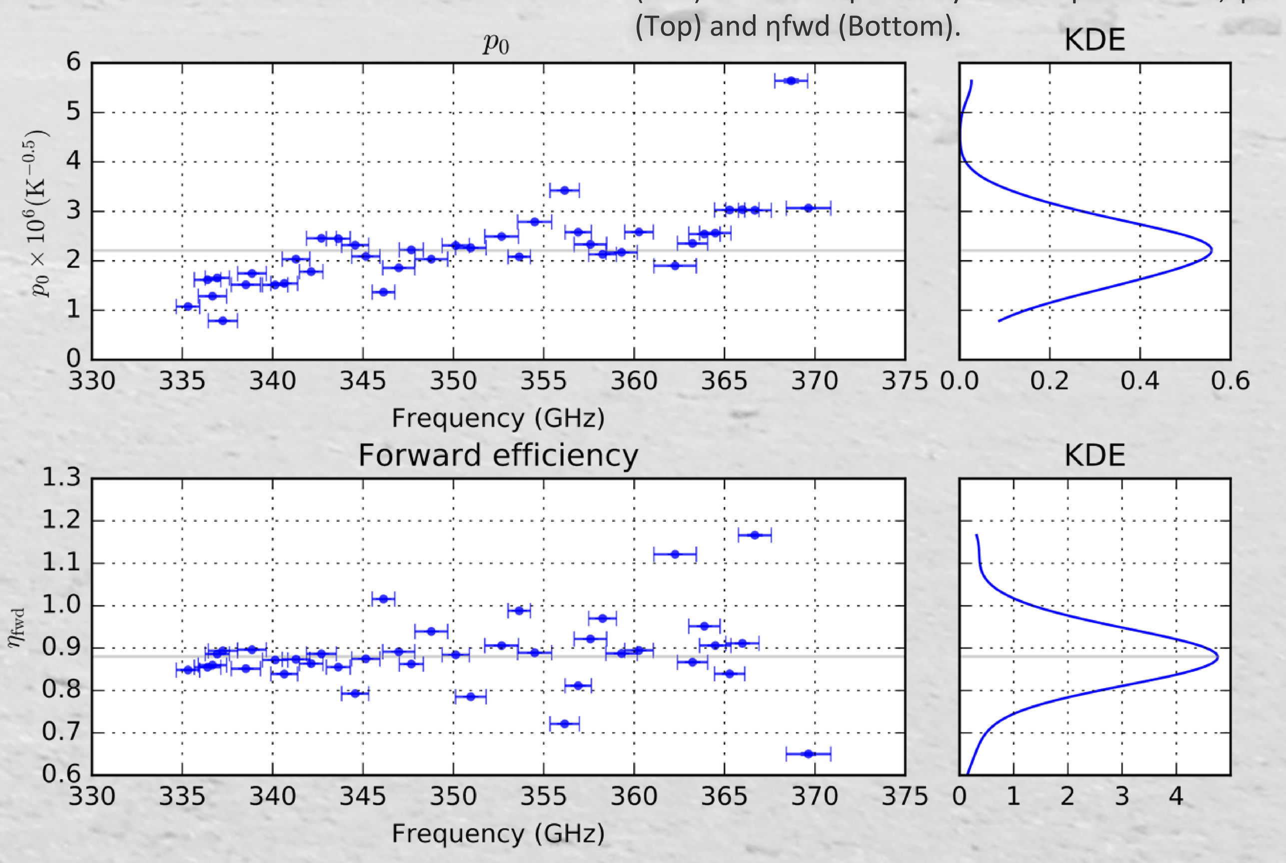

Fig 5 shows the frequency dependencies and kernel density estimates (KDEs) of the responsivity model parameters. The mode of forward efficiency was 0.88, which was consistent with the expected forward efficiency of 0.87 from aperture blockage of the sub-reflector and its support legs of the ASTE telescope.

Consistency of PWV estimate

We also checked the consistency between the ALMA and DESHIMA PWVs as shown in Fig. 6. We confirmed good correspondence between the ALMA and DESHIMA PWVs. This supports that obtained responsivity parameters are reliable and the DESHIMA PWVs is available as a line of-sight radiometer of the ASTE telescope.

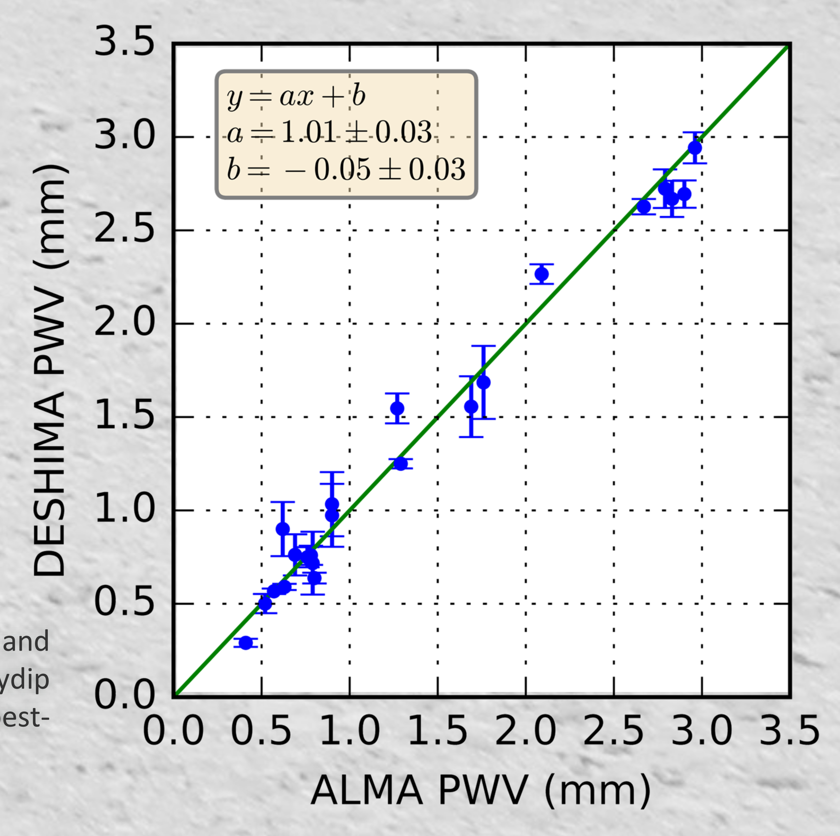

Fig 6. Relation between ALMA and DESHIMA PWVs obtained by each skydip observation. Green line shows the best-fit linear function of the relation.

Summary

As a result of the DESHIMA first light session on the ASTE telescope, we succeeded to establish a reliable responsivity model using the skydip data. Our responsivity model reproduced expected forward efficiency of the ASTE telescope, and archived photometric error of 1σ=4%, which is better than other photometric errors. We are planning next DESHIMA session in 2020 using new filterbank chip operated at 220—440 GHz with $\Delta\nu/\nu \sim 500$. Our responsivity calibration method will be tested for further improvement.