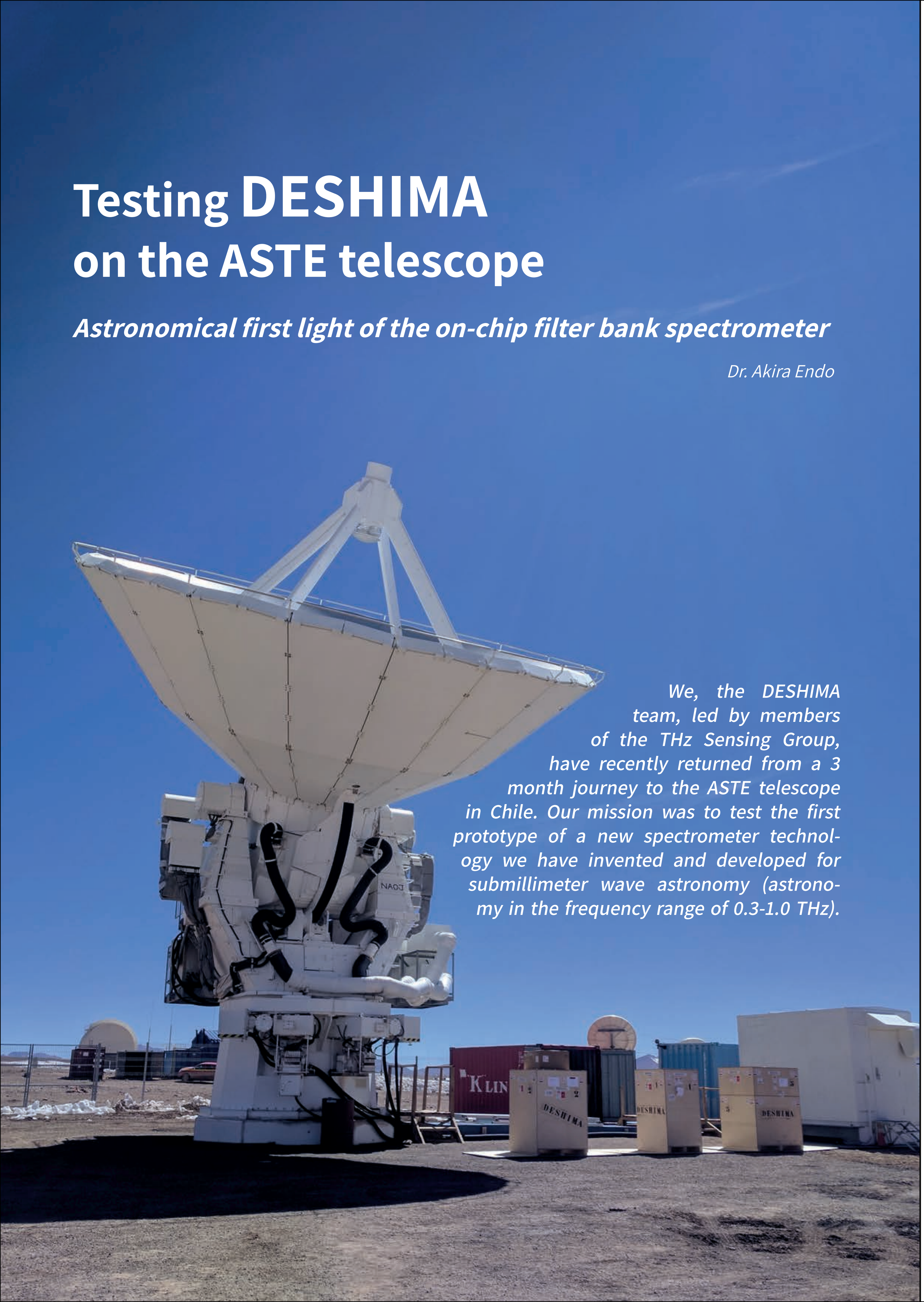
# Testing DESHIMA on the ASTE telescope

## *Astronomical first light of the on-chip filter bank spectrometer*

*Dr. Akira Endo*



*We, the DESHIMA team, led by members of the THz Sensing Group, have recently returned from a 3 month journey to the ASTE telescope in Chile. Our mission was to test the first prototype of a new spectrometer technology we have invented and developed for submillimeter wave astronomy (astronomy in the frequency range of 0.3-1.0 THz).*

Because it was the first time that the *on-chip filter bank spectrometer* (or any instrument based on kinetic inductance detectors) was installed on the ASTE telescope, the goal we had set prior to the campaign was to test whether various system components behave the same or differently compared to tests in the Cryolab of the Else Kooi Laboratory. Indeed, preparing and conducting cryogenic experiments at 4800 m altitude under low oxygen level, in a tiny telescope cabin that tilts and rotates, was a very interesting challenge, requiring also automation for remote control. Ultimately DESHIMA was able to make its astronomical 'first light', detecting a handful of astronomical objects, ranging from near-by to distant. Throughout the campaign, we enjoyed the fantastic collaboration with astronomers from Japan. While our results should soon appear in peer-reviewed scientific journals, in this article, we would like to introduce some of our live experience in conducting exact sciences outdoors, that you will not find in typical scientific literature.

### DESHIMA: cosmology with nano-technology

DESHIMA, the **De**ep **S**pectroscopic **Hi**gh-redshift **Ma**pper, is an instrument and experiment that aims to measure the cosmological redshift of dusty, massive starburst galaxies (also known as 'sub-millimeter galaxies' for their brightness in the submillimeter part of the electromagnetic spectrum) in the early Universe, by mapping redshift to spectroscopic channels of a superconducting filter bank on a chip, in a 1:1 manner (Figure 1). By constructing a filter bank using superconducting microelectronics, DESHIMA aims to ultimately cover a frequency range of 240-720 GHz, which translates to a cosmological redshift of $z$ = *1.6-6.9* (from 0.8 till 4 billion years after the Big Bang), if we use an emission line from C+ (1.9 THz at rest frame) as a tracer. This is a much wider instantaneous bandwidth, and hence a much broader redshift coverage, compared to heterodyne receivers or optical spectrometers that are currently being used in the field of submillimeter wave astronomy. The realisation of such an on-chip spectrometer has become possible with the world-leading technology at SRON (the group of Jochem Baselmans) and TU Delft (THz Sensing Group) of *kinetic inductance detectors*, which enable the integration of thousands of extremely sensitive submillimeter wave detectors in a scalable fashion. The ultimate goal of the DESHIMA project is to construct a 3D map of the dusty Universe, to unveil the dust-enshrouded part of the cosmic history of star- and galaxy-formation.

In figure 1, one can see that the signal from the telescope is focused onto an antenna, from which a superconducting transmission line extends. The signal is separated into individual frequency channels by means of superconducting NbTiN microresonators that act as narrow band-pass filters. At the end of each filter is a Microwave Kinetic Inductance Detector (MKID, or KID). The signal is absorbed in the Al section of the KID. The cone depicted above the chip (adopted and modified from the original article [1]) illustrates the redshift range that DESHIMA maps to the filterbank, when using the C+ line as a tracer.

The origin of the DESHIMA project dates back to around 2009, in a series of discussions among Akira Endo, Jochem Baselmans and Teun Klapwijk: this could be seen as a tripoint of astronomy, instrument science and solid state physics. The research and development of hardware for DESHIMA is currently ongoing in a collaboration between TU Delft (THz Sensing Group) and SRON, with strong involvement of students from TU Delft. The electromagnetic design of the filter bank chips and the optics are mainly done in the THz Sensing Group. The fabrication of the superconducting spectrometer chip is currently done in the clean rooms of TU Delft (Kavli Institute of Nanoscience) and SRON. The performance of these

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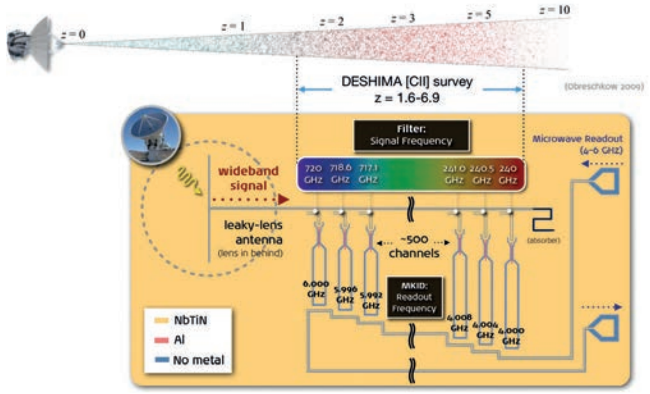

*Figure 1.* Conceptual drawing of the on-chip filter bank being developed for DESHIMA.

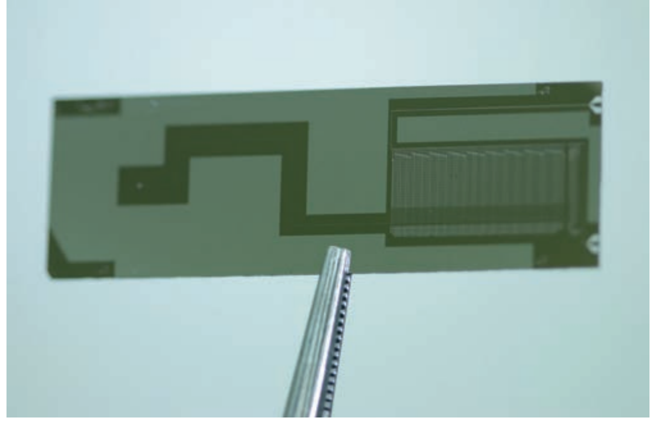

*Figure 2.* A DESHIMA filter bank chip, held by a pair of tweezers. The chip is 42 mm x 14 mm in size.

*Figure 3.* Transportation of the DESHIMA cryostat for installation requires a lot of care to avoid mechanical shocks.

chips are tested in the Cryolab located in the Else Kooi Lab of TU Delft, and in the laboratory at SRON. Advanced hardware for the cryogenic optomechanical setup and readout electronics was developed at SRON.

In the beginning of 2017, the entire system of DESHIMA, including the chip, optics, cryogenics and electronics became one in the Cryolab, and we could measure spectra of gas in the laboratory. The moment had come to take the instument out of the lab and point it at the sky.

*Figure 4.* Installation of the DESHIMA cryostat (protected in a plastic bag) to the ASTE cabin.

## Preparing and running a cryogenic experiment in the desert of the Andean Mountains

An astronomical experiment like DESHIMA has many similarities to typical experiments in low temperature physics and circuit quantum electrodynamics (such as those being performed at QuTech of TU Delft), in the sense that they can use similar microwave circuit architectures, use similar cryogenics to cool the chip down, and use similar isolation techniques to reduce noise from the environment. Yet the most distinct difference that characterise astronomical experiments is that you always have a window from the chip to the external world, to allow your device to respond to the light from the sky: light that has travelled for many (sometimes even billions of) years since it was emitted. In addition, the experiment has to be taken out of the laboratory, and has to be performed at the focus of a telescope, which is typically a much harsher environment compared to a laboratory in a University building.

> *“Despite many critical moments in which one failure could terminate the entire mission, we were able to successfully install the DESHIMA system in the cabin”*

On October 6, we installed DESHIMA in the cabin of the ASTE telescope, a high-precision 10 m parabolic antenna operated by the National Astronomical Observatory of Japan (NAOJ). This involved many challenges that we experienced for the first time:

- Transporting massive, fragile equipment from the Netherlands to the Atacama Desert of Chile;
- Integration of the cryogenic optical structure in the basecamp located in the village of San Pedro de Atacama, and subsequently carrying it up the rough road on a 4WD truck;
- Lifting the cryostat to the cabin of the telescope using a forklift and scissor lift;
- Final assembly of components while adjusting our bodies to the low oxygen level; etc.

Despite the many critical moments in which one failure could terminate the entire mission, we were able to successfully install the DESHIMA system in the cabin, which was certainly nothing else than the result of good preparation and tremendous support from the staff of NAOJ.

On October 19, we made a scan over Saturn and saw the spectrometer responding strongly. This was the first astronomical signal captured by the new technology of on-chip filter bank spectrometer. Things had gone so unexpectedly smoothly, that we needed to ask one of the astronomers from Japan to come 1 week earlier than the original planning to start developing software pipelines for astronomical data reduction. After 34 days and nights of observation from then, DESHIMA has seen the Moon, planets, carbon star, red hypergiant star, star forming region , spiral galaxy, Ultra-Luminous Infrared Galaxy, and also performed 3-4 nights of ambitious long integration high redshift galaxies in very good weather. We are currently very busy analysing all the data that has been collected, which contain invaluable information for the next upgrade [2].

*Figure 5.* After a successful installation of the DESHIMA cryostat in the Cassegrain cabin of the ASTE telescope.

## Team Spirit

Finally, I would like to express that it was an extreme pleasure to lead this team of extremely enthusiastic people with a diverse background, in terms of both profession and culture. Everybody was there with his own motivation, and multiple members convinced their host institutes to support their participation in this campaign, from around the world. Many people who I regard as friends, from different times of my carrier, came to do exciting science together. If you are a University student reading this article, one thing you should do during your studies is make many good friends who are different from yourself: those relations will become the treasure of your life. And last but not least, I would like to thank the family members of all participants, for their generous support at home that enabled this mission.

## Further readings

### Student projects

If you are interested doing a MSc. project in DESHIMA or another astronomical instrumentation mission, send an email to me (a.endo@tudelft.nl) or contact researchers in the THz Sensing Group.
*http://terahertz.tudelft.nl/*

### Kinetic inductance detectors (KIDs)

New 1000-pixel space camera system now mature enough.
*http://bit.ly/2mGhqmw*

***Watch the video about the DESHIMA/ ASTE mission by TU Delft TV:***

*Figure 6.* The DESHIMA team extremely excited to detect the first astronomical signal with an on-chip filterbank spectrometer.

[1] *Obreschkow et al., Astrophys Journal, vol. 698, p. 1467, 2009.*
[2] *A. Endo, C. Sfiligoj, S. J. C. Yates, J. J. A. Baselmans, D. J. Thoen, S. M. H. Javadzadeh, P. P. van der Werf, A. M. Baryshev, T. M. Klapwijk, “On-chip filter bank spectroscopy at 600-700 GHz using NbTiN superconducting resonators,” Appl. Phys. Lett. 103, 032601 (2013). See: http://bit.ly/2FNAk3C*