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# TiEMPO: open-source time-dependent end-to-end model for simulating ground-based submillimeter astronomical observations

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**Abstract** The next technological breakthrough in millimeter–submillimeter astronomy is three-dimensional imaging spectrometry with wide instantaneous spectral bandwidths and wide fields of view. The total optimization of the focal-plane instrument, the telescope, the observing strategy, and the signal-processing software must enable efficient removal of foreground emission from the Earth’s atmosphere, which is time-dependent and highly nonlinear in frequency. Here, we present Time-dependent End-to-end Model for Post-process Optimization (TiEMPO) of the DEep Spectroscopic HIgh-redshift MAppler (DESHIMA) spectrometer. TiEMPO utilizes a dynamical model of the atmosphere and parameterized models of the astronomical source, the telescope, the instrument, and the detector. The output of TiEMPO is a time stream of sky brightness temperature and detected power, which can be analyzed by standard signal-processing software. We first compare TiEMPO simulations with an on-sky measurement by the wideband DESHIMA spectrometer, and find good agreement in the noise and sensitivity. We then use TiEMPO to simulate the detection of the line emission spectrum of a high-redshift galaxy using the DESHIMA 2.0 spectrometer in development. The TiEMPO model is open source. Its modular and parametrized design enables users to adapt it to optimize the end-to-end performance of spectroscopic and photometric instruments on existing and future telescopes. © *The Authors*. Published by SPIE under a Creative Commons Attribution 4.0 International License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.JATIS.8.2.028005](https://doi.org/10.1117/1.JATIS.8.2.028005)]

**Keywords:** millimeter-wave; astronomy; simulations; submillimeter-wave; kinetic inductance detectors; on-chip spectrometers; atmosphere.

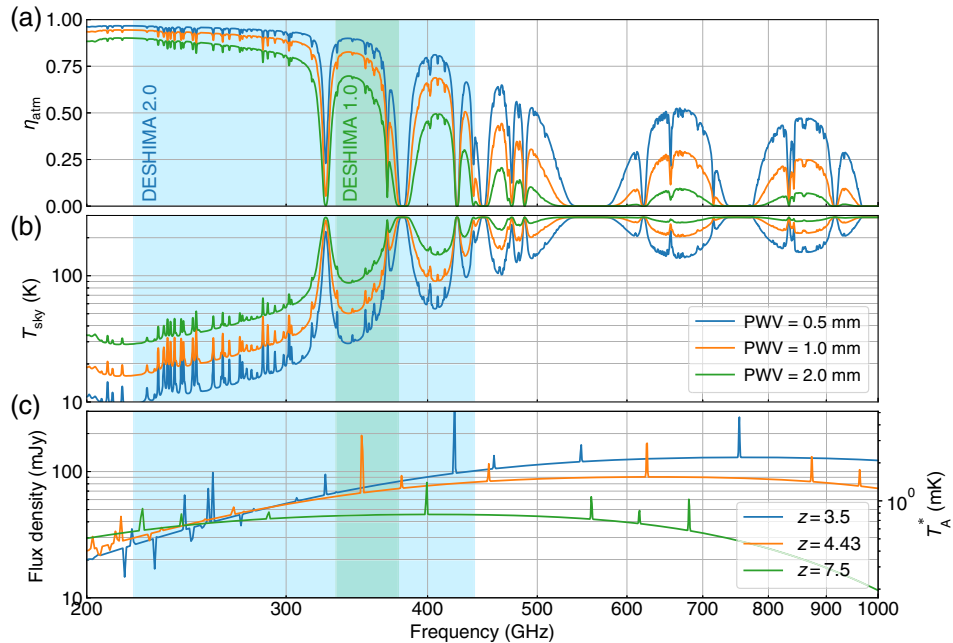
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## 1 Introduction

The rapidly growing instantaneous bandwidth<sup>1–5</sup> and field-of-view<sup>6–8</sup> of millimeter–submillimeter (mm–submm) astronomical instruments and telescopes are advantageous not only for collecting more astronomical signal but also for characterizing and removing the foreground emission of the Earth’s atmosphere.<sup>9</sup> Even at the best sites for submm astronomy on the ground, the brightness temperature of the Earth’s atmosphere in the submm range is  $\geq 20$  K, which can be  $\sim 10^3$  to  $10^5$  times stronger than the astronomical signal (see Fig. 1). Conventional heterodyne instruments on single-dish telescopes have a typical instantaneous bandwidth of several GHz, which is small compared with the atmospheric “windows” (the frequency bands over which the atmosphere is relatively transparent). In this narrow-band case, the effect of the atmosphere can often be approximated with a baseline that is linear in frequency. However, the (ultra-)wideband spectrometers in development, such as the DEep Spectroscopic HIGH-redshift MAPper (DESHIMA),<sup>1,2,10</sup> are influenced by the nonlinear frequency dependence of the atmosphere because they measure across one or even multiple atmospheric windows with strong absorption bands in between. On the one hand, this poses new challenges on the observation and signal-processing techniques to remove the nonlinear atmospheric emission.<sup>9</sup> On the other hand, the wideband spectral information of the atmosphere could enable the development and use of advanced signal processing methods for characterizing and ultimately removing the atmospheric component to extract the astronomical signal in a better way.<sup>11,12</sup> The requirements for applying such techniques are expected to drive the design of future telescopes and focal-plane instrument systems.<sup>6–8</sup>

Here, we present the Time-dependent End-to-end Model for Post-process Optimization (TiEMPO) of the DESHIMA spectrometer. TiEMPO is a numerical model for simulating



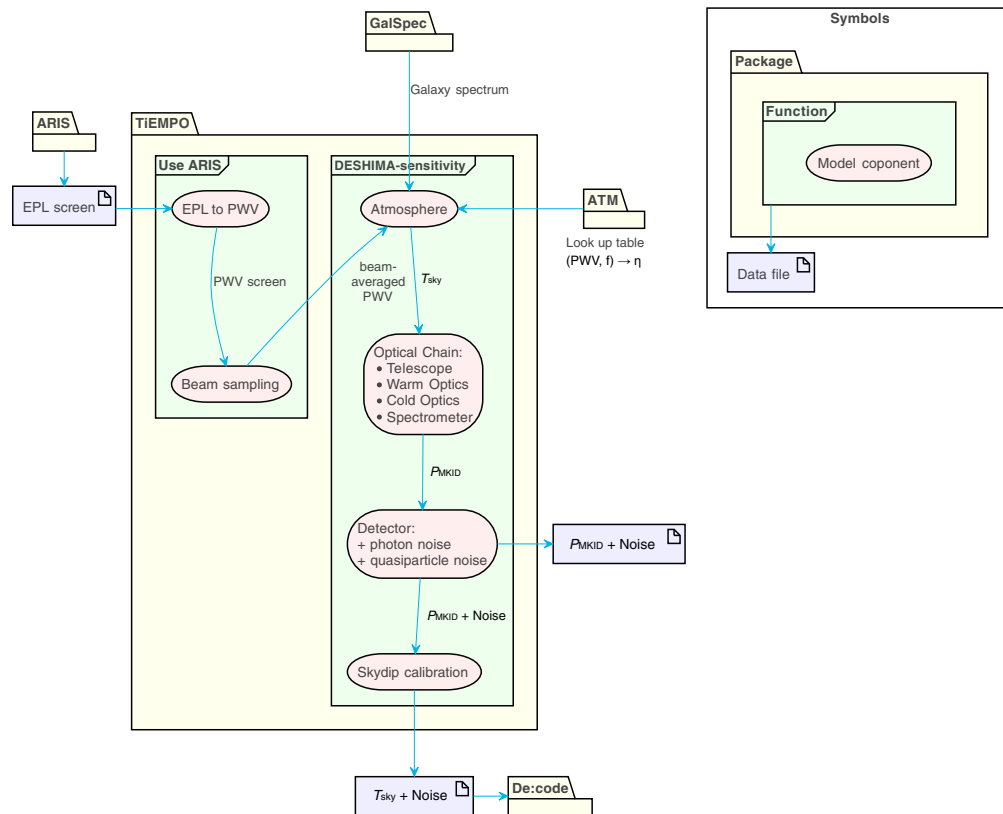
**Fig. 1** Atmospheric transmittance  $\eta_{\text{atm}}$  (a) and sky brightness temperature  $T_{\text{sky}}$  (b) at zenith ( $\theta = 90$  deg) as functions of frequency, for three values of precipitable water vapor (PWV). The instantaneous frequency coverage of DESHIMA 1.0<sup>1</sup> and the future DESHIMA 2.0 (see Sec. 4) are indicated by the green and blue shades, respectively. The range of DESHIMA 1.0 is an example of one atmospheric “window.” DESHIMA 2.0 spans multiple atmospheric windows with absorption-bands in between. (c) GalSpec-simulated spectrum of a galaxy with a far-infrared luminosity of  $L_{\text{FIR}} = 10^{13.7} L_{\odot}$ , placed at three different redshifts. The spectrum for  $z = 4.43$  is given as input to TiEMPO in Sec. 4. The right vertical axis is a rough indication of the corresponding atmosphere-corrected antenna temperature  $T_A^*$ , assuming a  $\varnothing 10$  m telescope with an aperture efficiency of 0.6.

wideband submm astronomical observations through the Earth’s atmosphere; it produces time-stream data that can be fed to data-analysis software<sup>11–13</sup> as if they were taken with a real instrument operated on a telescope. To account for the nonlinear, dynamic, and inhomogeneous transmittance of the atmosphere, TiEMPO utilizes the Atmospheric Transmission at Microwave (ATM) model<sup>14</sup> to simulate the spectral dependence and the Astronomical Radio Interferometer Simulator (ARIS) model<sup>15–17</sup> to simulate the spatial/temporal variations. Compared with the Time Ordered Astrophysics Scalable Tools (TOAST)<sup>18</sup> package developed independently by the cosmic microwave background community, TiEMPO is primarily motivated by ultra-wideband spectroscopy of astronomical objects and includes a physical noise model of microwave kinetic inductance detectors (MKIDs). TiEMPO is distributed as an open-source Python package, and the scripts are available on a public repository<sup>19</sup> to encourage further use and development by the astronomical community to study cases for different telescope/instrument systems.

## 2 TiEMPO Model

### 2.1 Overview

TiEMPO is an end-to-end model, containing models of the astronomical source, the atmosphere, the telescope, the cryogenic instrument optics, and an integrated superconducting spectrometer with MKIDs (see Fig. 2). The details of the TiEMPO model can be found in Refs. 21 and 22, and the source code is publicly available.<sup>19</sup> In the following we provide an overview of the modules, in the order of signal propagation from the astronomical source to the detector.



**Fig. 2** System diagram of TiEMPO, showing each component with its input and output. TiEMPO depends on external packages ARIS,<sup>15,16</sup> ATM,<sup>14</sup> and GalSpec.<sup>20</sup> TiEMPO outputs calibrated sky brightness temperature  $T_{sky}$  and detector output  $P_{MKID}$ , which contains photon noise, quasiparticle recombination noise, and atmospheric noise. The output timestream data can be analyzed by post-processing software such as De:code.<sup>13</sup>

## 2.2 Spectrum of a Dusty High-Redshift Galaxy

The galaxy spectrum was created using the GalSpec package,<sup>20</sup> which we distribute as an open-source Python package that can be used outside of TiEMPO. Our goal is to create a galaxy template that is similar to the types of galaxies that we will be trying to detect with DESHIMA and with which we are able to model the potential future science cases. As such, we use an empirical approach to the creation of a galaxy spectrum, combining the continuum shape and spectral line luminosities from recent studies of observed local and high-redshift galaxies. The continuum is based on the two-component modified-black body fit to 24 galaxies at  $z > 2$  with Herschel (250, 350, and 500  $\mu\text{m}$ ) and SCUBA-2 (850  $\mu\text{m}$ ) fluxes.<sup>23,24</sup> Here, we normalize the spectrum to the total far-infrared luminosity by integrating the spectrum from 8 to 1000  $\mu\text{m}$ . The spectral lines are simulated with a more creative approach that can be tailored to specific science goals. Relatively shallow observations, aimed at detecting atomic lines and CO, are simulated using spectral line luminosity scaling relations. Here we use the scaling relations from Ref. 25 for atomic lines and Ref. 26 for both CO and [CI] lines. The scaling relations of Ref. 25 are based on local star-forming and ultra-luminous infrared galaxies and high-redshift submm galaxies, whereas the scaling relations of Ref. 26 are based mostly on local galaxies. Deeper observations might resolve more complex molecular lines in both emission and absorption, such as H<sub>2</sub>O, HCN, HCO<sup>+</sup>, CH<sup>+</sup>, NH, NH<sub>2</sub>, OH<sup>+</sup>, and HF. These species are only incidentally seen at high redshift (e.g., Refs. 27 and 28), and thus we rely on the line detections in the nearby ULIRG Arp 220 to supplement our spectrum for these molecular species.<sup>29</sup> Here, instead of scaling to the far-infrared luminosity, we scale the line brightness to the observed continuum at the line's frequency. For this complete galaxy spectrum, we note that the brightness of these spectral lines is a probe of the conditions of the interstellar medium. As such, the line brightnesses (and even the continuum) are known to vary by up to 1 dex from source to source, which must be taken into account when applying for the necessary observation time or detection limits. Throughout this study, we assume a uniform line velocity width of 600 km s<sup>-1</sup> (full width half maximum), which is found to be the mean for typical submillimeter galaxy<sup>30</sup> and in line with recent observations of South Pole Telescope and bright Herschel sources.<sup>31–33</sup>

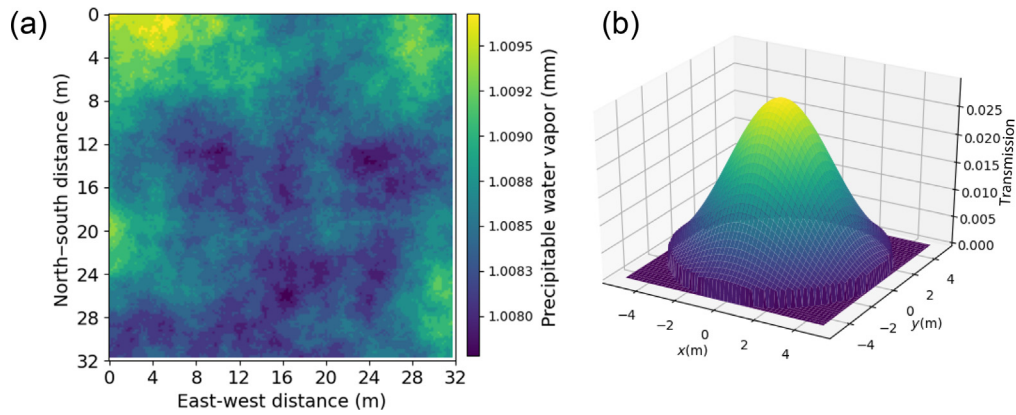
## 2.3 Creation of the Atmosphere Screen

Our goal here is to obtain the line-of-sight transmittance of the atmosphere  $\eta_{\text{atm}}$ , which depends on the time  $t$  and telescope pointing angle  $(\theta, \phi)$ . Here,  $\theta$  and  $\phi$  are the elevation and azimuth angles of the telescope pointing, respectively. We start from the observation that the mm–submm  $\eta_{\text{atm}}$  at zenith ( $\theta = 90^\circ$ ) is correlated with chiefly one variable, the precipitable water vapor (PWV).<sup>34</sup> Water vapor not only absorbs the submm waves but also introduces an extra path length (EPL) that is dependent on the line-of-sight PWV.<sup>35</sup> ARIS<sup>15,16</sup> uses a set of spatial structure functions<sup>36</sup> to produce a phase screen, i.e., a two-dimensional map of EPL as shown in the left panel of Fig. 3. Input parameters of ARIS include the inner and outer scales and exponents, the spatial size and resolution of the screen, and the root-mean-square (RMS) fluctuation of EPL in combination with a distance. Further details about the parameters can be found in Ref. 16, and typical values for the Atacama Large Millimeter–Submillimeter Array (ALMA) site are reported in Ref. 17.

TiEMPO converts an EPL screen to a PWV screen, using the following relation derived from the Smith–Weintraub constants<sup>37</sup> of EPL and the ideal gas law (see Ref. 21 for details), which is given as

$$d\text{EPL} = 10^{-6} \rho R \left( k_2 + \frac{k_3}{T} \right) d\text{PWV} \sim 6.587 \cdot d\text{PWV}. \quad (1)$$

Here,  $k_2 = 70.4 \pm 2.2 \text{ K mbar}^{-1}$  and  $k_3 = (3.739 \pm 0.012) \cdot 10^5 \text{ K}^2 \text{ mbar}^{-1}$  are the Smith–Weintraub constants,<sup>37</sup>  $\rho = 55.4 \cdot 10^3 \text{ mol m}^{-3}$  is the number density of molecules in liquid water,  $R = 8.314 \cdot 10^{-2} \text{ mbar m}^3 \text{ K}^{-1} \text{ mol}^{-1}$  is the gas constant, and approximately  $T = 275 \text{ K}$  is the physical temperature of the atmosphere. Note that  $d\text{EPL}$  and  $d\text{PWV}$  are differences from arbitrary mean values of the optical path length and PWV, respectively. In TiEMPO the user can



**Fig. 3** (a) Colormap of the output of ARIS for a  $32\text{ m} \times 32\text{ m}$  sky window converted to PWV with Eq. (1). (b) The truncated Gaussian that is used as the telescope beam shape in the model. The volume of the Gaussian is normalized to unity, and it is truncated at a radius of 5 m, where its height is 10% of its peak height (Video 1, Mp4, 1070 KB [URL: <https://doi.org/10.1117/1.JATIS.8.2.028005.1>]).

specify a mean PWV, around which the PWV fluctuates according to the ARIS-modeled EPL and Eq. (1). The mean PWV can be set to a constant or a vector that represents a slowly changing weather condition. The created PWV screen moves spatially in one direction, at the user-specified wind velocity, assuming that the structure of phase fluctuations is invariant when the atmosphere moves with the wind.<sup>38</sup> See Fig. 3(a) and Video 1 for an example of the moving atmosphere created in TIEMPO.

#### 2.4 Sampling of the Atmosphere by the Telescope Near-Field Beam

The water vapor in the atmosphere above the Atacama Desert is contained mostly in the layer up to  $\sim 1$  km from ground,<sup>39</sup> which is well within the near field of the telescope. Therefore, the beam pattern at this height has a similar pattern to the power distribution over the primary mirror of the telescope. In this study, we assumed that the PWV screen is 1 km above the telescope. For simulating DESHIMA on Atacama Submillimeter Telescope Experiment (ASTE) using TIEMPO, we assumed a Gaussian power pattern as shown in Fig. 3(b), which drops to  $-10$  dB at the telescope radius of 5 m. The PWV map created in Sec. 2.3 is filtered with this beam pattern, so the received power from the atmosphere is a weighted average within the beam. The user may include an arbitrary beam pattern in TIEMPO when detailed information is available from the design or measurement.

#### 2.5 Far-Field Beam of the Telescope

The far-field telescope beam is modeled by two properties: the main beam solid angle  $\Omega_{\text{MB}}$  and the main beam efficiency  $\eta_{\text{MB}}$ .<sup>1,40</sup>  $\Omega_{\text{MB}}$  represents the solid angle of the beam excluding the side lobes.  $\eta_{\text{MB}}$  is the fraction of the beam contained in the main beam, out of the total reception pattern. The (total) beam solid angle, with the side lobes included, is then given by

$$\Omega_{\text{A}} = \frac{\Omega_{\text{MB}}}{\eta_{\text{MB}}}. \quad (2)$$

We use the beam solid angle to define the effective aperture area as

$$A_{\text{c}} = \frac{\lambda^2}{\Omega_{\text{A}}}, \quad (3)$$

where  $\lambda$  is the wavelength. Now, we express the aperture efficiency  $\eta_{\text{A}}$  as

$$\eta_A = \frac{A_e}{A_p} = \frac{\eta_{MB}}{\Omega_{MB}} \frac{\lambda^2}{A_p}, \quad (4)$$

where  $A_p$  is the physical area of the telescope primary mirror. From these quantities, the single-mode power density (in  $\text{W Hz}^{-1}$ ) of the astronomical source is calculated as

$$P_f = \frac{1}{2} F_f A_e, \quad (5)$$

where  $F_f$  denotes the flux density in  $\text{W m}^{-2} \text{Hz}^{-1}$  ( $= 10^{26}$  Jy) and the factor  $1/2$  compensates for the fact that the flux density is calculated using two polarizations, but the power density that TiEMPO calculates is for single-polarization assuming the coupling of the signal to a single-mode (on-chip) antenna and transmission line.<sup>2</sup>

## 2.6 Radiative Transfer

For calculating the single-mode radiation transfer from the astronomical source to the detector, a subset of the DESHIMA-sensitivity software<sup>41</sup> was used. Each component in the optical chain is modeled with a black body power density and a transmission factor  $\eta_i$ . The single-mode power density of a black body is equivalent to the Johnson–Nyquist noise and is given by

$$P_f = \frac{hf}{e^{k_B T} - 1}. \quad (6)$$

Here,  $h$  is the Planck constant,  $f$  is the frequency,  $k_B$  is the Boltzmann constant, and  $T$  is the physical temperature of the emitter.<sup>42</sup> The spectral power before the detector is computed by cascading the radiation transfer of each component as

$$P_{f,\text{out}} = \eta_i P_{f,\text{in}} + (1 - \eta_i) P_{f,i}, \quad (7)$$

where  $P_{f,\text{out}}$  is the power density of the radiation that comes out of the component,  $P_{f,\text{in}}$  is the power density of the radiation going in,  $\eta_i$  is the transmittance of the component, and  $P_{f,i}$  is the power density of the component.

## 2.7 Spectrometer

TiEMPO is able to model any direct-detection (imaging-)spectrometer that couples the wideband input power into one or more spectral channels. Examples include integrated filterbank spectrometers that use a filterbank<sup>1-3</sup> or an integrated grating<sup>4,5</sup> and optical grating spectrometers. Currently, TiEMPO takes five spatial pixels (a center pixel pointed toward the astronomical source, and top, bottom, right, and left pixels viewing only the atmosphere) to simulate position-switching observations, but the pixel count can be increased to model multi-pixel imaging arrays. If the number of spectral channels per pixel is set to unity, then the model can represent a monochromatic imaging camera.

TiEMPO can import the spectral response of each detector, obtained from the design<sup>43</sup> or a measurement.<sup>44</sup> Here, we assumed a simple Lorentzian-shaped spectral transmission, which is a good approximation for a filterbank channel,<sup>2</sup> or a detector behind an optical (or substrate-integrated) grating.<sup>5</sup> The frequency dependence was implemented by dividing the frequency range of 210 to 450 GHz (10 GHz wider on each side than the nominal DESHIMA 2.0 band, to take into account power coupling from outside of the band) into 1500 bins. The resulting efficiency is used to compute the power density with the radiation transfer equation, Eq. (7). Finally, the power in each bin is calculated as

$$P_{\text{bin } i} = \Delta f P_{f,\text{bin } i}. \quad (8)$$

Note that the  $P_{\text{bin } i}$  in Eq. (8) is the expected (i.e., noiseless) value of the power. To calculate the frequency-integrated power detected by each detector at each moment  $t$ ,  $P_{\text{MKID}}(t)$ , we must consider noise (see Sec. 2.8).

## 2.8 Detected Power and Noise

The best possible sensitivity of a pair-breaking detector like an MKID is set by the photon noise and quasiparticle recombination noise. The commonly-used narrow-band approximation for the noise equivalent power (NEP) limited by photon- and recombination-noise is given by<sup>1</sup>

$$\text{NEP}_{\text{MKID}} = \sqrt{2\overline{P}_{\text{MKID}}(hf + \overline{P}_{\text{MKID}}/\Delta f) + 4\Delta_{\text{Al}}\overline{P}_{\text{MKID}}/\eta_{\text{pb}}}. \quad (9)$$

Here,  $\overline{P}_{\text{MKID}}$  is the expected value of the power absorbed by the MKID,  $\Delta_{\text{Al}} = 188 \mu\text{eV}$  ( $\sim 91 \text{ GHz} \cdot h/2$ ) is the superconducting gap energy of aluminum, and approximately  $\eta_{\text{pb}} = 0.4$  is the pair-breaking efficiency.<sup>45</sup> In TiEMPO we use the more general, integral form of the NEP<sup>46</sup> to take into account a frequency-dependent optical efficiency over a wide bandwidth, for each detector of the spectrometer. This method also accounts for photon-bunching of the wideband signal. Because the fluctuations in energy in different spectral bins are uncorrelated,<sup>47</sup> we can calculate the standard deviation in power for each spectral bin per sampling rate ( $1/f_{\text{sampling}}$ ) from

$$\sigma = \text{NEP}_{\text{MKID}} \sqrt{\frac{1}{2} f_{\text{sampling}}}, \quad (10)$$

and add those together to obtain the combined detector output, as given by

$$P_{\text{MKID}} = \sum_{i=1}^{\#\text{bins}} P_{\text{bin } i, \text{ with noise}}. \quad (11)$$

Note that this is equivalent to calculating the detector NEP directly from the integral, which is expressed as

$$\text{NEP}_{\text{MKID}}^2 = \int 2P_f(hf + P_f) + 4\Delta_{\text{Al}}P_f/\eta_{\text{pb}} df. \quad (12)$$

The integration over a wide bandwidth taking the filter spectral transmission into account is especially relevant for spectral channels that are near strong emission lines and absorption bands of the atmosphere.<sup>10</sup>

## 2.9 Sky Temperature Calibration

After computing the noise-added power that is measured by the MKIDs, we want to relate this back to the original signal from the sky. We do this by expressing the received power in sky brightness temperature  $T_{\text{sky}}$ : the physical temperature of a black body that would have the same intensity as the semitransparent sky.<sup>1</sup> To this end we take the Johnson–Nyquist equation, which is given by

$$T_{\text{sky}} = \frac{hf}{k_{\text{B}} \ln\left(\frac{hf}{P_f} + 1\right)}. \quad (13)$$

To relate the MKID power  $P_{\text{MKID}}$  to  $T_{\text{sky}}$ , TiEMPO internally performs a skydip simulation<sup>10</sup> using the DESHIMA-sensitivity<sup>41</sup> script. A skydip is a series of measurements in which the telescope “dips” from a high elevation (pointing at zenith) to a low elevation (pointing almost horizontally). When the elevation is lower, the telescope looks through a thicker layer of atmosphere, increasing the opacity and hence the power and the sky temperature, allowing us to



construct a relationship between the two. In our simulations, we use elevation values in the range of  $\theta = 20$  deg to 90 deg. The power and sky temperature data are interpolated for each channel and saved in the model. TiEMPO reuses these interpolation curves, so they only need to be created once. For further details on the numerical skydip calibration, see Ref. 21.

### 3 Comparing a TiEMPO Simulation with On-Sky DESHIMA 1.0 Measurements

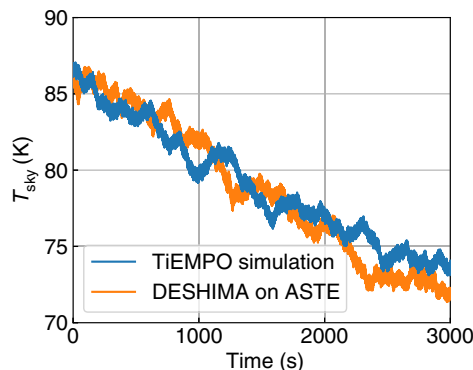
To verify the TiEMPO model, we made a simulation of an atmosphere observation using input parameters that resemble a real measurement done with the DESHIMA spectrometer on the ASTE telescope.<sup>48</sup> DESHIMA is an integrated superconducting spectrometer with MKID detectors. The first generation of DESHIMA, which we will hereafter call DESHIMA 1.0,<sup>1</sup> has an instantaneous band of 332 to 377 GHz, with a frequency spacing of  $f/\Delta f = 380$  approximately. (The half-power bandwidth of each filter is  $f/\Delta f = 300$  on average.<sup>2</sup>) ASTE is a 10-m Cassegrain reflector located on the Pampa la Bola plateau of the Atacama Desert in northern Chile, at an altitude of 4860 m. DESHIMA 1.0 was operated on ASTE during October to November 2017.<sup>1</sup> The measured response of the MKIDs was converted to sky brightness temperature  $T_{\text{sky}}$  using the skydip calibration method explained in detail in Ref. 10.

We use the data taken from a measurement on November 17, 2017, in which the telescope was pointed close to zenith ( $\theta = 88$  deg) for 3000 s. The PWV measured with the radiometer of the ALMA was 1.7 mm at the beginning of the measurement, corresponding to a  $\sim 350$  GHz sky brightness temperature of  $\sim 80$  K. In Fig. 4, we show the time-evolution of the measured  $T_{\text{sky}}$  taken with the 355 GHz channel of DESHIMA 1.0 (blue curve). The DESHIMA measurement indicates that the PWV dropped continuously over the course of the measurement, from  $\sim 1.7$  to  $\sim 1.3$  mm.

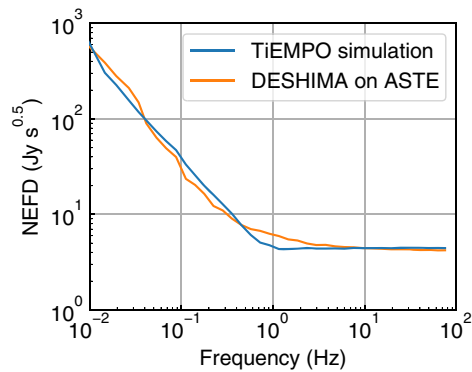
We ran a few simulations in TiEMPO to fine-tune the input parameters to achieve good agreement between simulation and measurement in the noise-equivalent-flux-density (NEFD) spectrum, which we present in Fig. 5. The resulting TiEMPO-simulated time trace of measured  $T_{\text{sky}}$  for the 355 GHz channel is compared with that of the DESHIMA 1.0 measurement in Fig. 4. Qualitatively, both curves show two types of fluctuations that are behaving similarly: the low-frequency and large-amplitude fluctuations are due to atmospheric noise, whereas the high-frequency and small-amplitude fluctuations are due to photon noise and quasiparticle recombination noise.

To compare the noise in the simulation and measurement more quantitatively, we take the noise spectrum of the time traces. Before taking the spectrum, we convert  $T_{\text{sky}}$  to flux density as

$$F_f(T_{\text{sky}}) = \frac{2\Omega_{\text{MB}}}{\eta_{\text{MB}}\lambda^2\eta_{\text{atm}}} \frac{hf}{e^{hf/kT_{\text{sky}}} - 1}. \quad (14)$$



**Fig. 4** Time stream of the measured  $T_{\text{sky}}$  at 355 GHz, for a TiEMPO simulation (blue) and DESHIMA/ASTE observation on the ASTE telescope (orange).



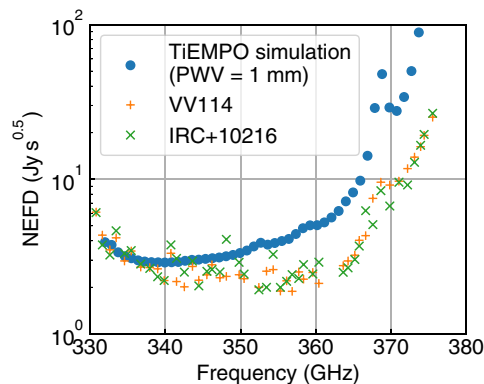
**Fig. 5** NEFD spectra, derived from the power spectral densities of the time-series data presented in Fig. 4, for the TiEMPO simulation (blue) and DESHIMA/ASTE observation (orange).

Subsequently, we calculate the noise equivalent flux density (NEFD) by

$$\text{NEFD} = \sqrt{\frac{\text{PSD}\{F_f(t)\}}{2}}, \quad (15)$$

where  $\text{PSD}\{\}$  denotes the operation of taking the power spectral density. The factor  $\sqrt{2}$  is introduced because we define the NEFD for an integration time of 1 s. In Fig. 5, we show the resulting NEFD spectra for the simulation and measurement. At  $\lesssim 1$  Hz, the NEFD curves exhibit the  $1/f$ -noise generated by the atmospheric fluctuations. At  $\gtrsim 1$  Hz, the spectra flatten out to the white photon (and recombination) noise level. This form of noise spectra is often seen in mm–submm observations.<sup>49</sup> The simulation agrees well with the measurement for both the photon (and recombination) noise level and the atmospheric  $1/f$ -noise. Near the  $1/f$  knee frequency at  $\sim 1$  Hz, the measurement shows a slight excess compared with the TiEMPO simulation. This is most likely the contribution from the dielectric two-level system noise of the MKIDs, which can also be included in TiEMPO in the future. Examples of early implementations can be found in Refs. 12 and 44.

We plot the photon and recombination noise NEFD of all 49 simulated channels in Fig. 6, together with the measured NEFD of DESHIMA 1.0 on ASTE based on actual measurements of astronomical lines.<sup>1</sup> Considering the above-mentioned simplified filter model, as well as the fact that the measurements were taken across nights with different atmospheric conditions,<sup>1</sup> the agreement is good. A more detailed analysis taking into account the measured characteristics of each channel<sup>44</sup> finds an even closer agreement.



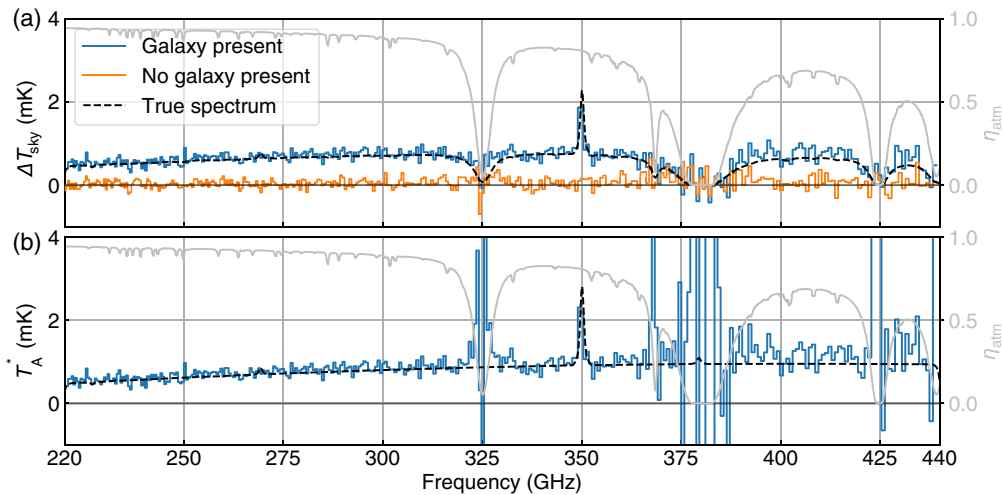
**Fig. 6** NEFD at the flat photon-noise level for a TiEMPO-simulation with the PWV set to 1.0 mm, compared with the NEFD of DESHIMA 1.0 based on actual detection of astronomical emission lines, from the luminous infrared galaxy VV 114 and the post-asymptotic giant branch star IRC+10216.<sup>1</sup> The peaks at around 353 and 368 GHz are lines of  $\text{O}_3$  and  $\text{O}_2$ , respectively.

In summary of this section, the output of TiEMPO resembles the on-sky measurement of DESHIMA 1.0, in both the time domain and the frequency domain. The end-to-end system sensitivity inferred from the simulation is in good agreement with the actual measurement of astronomical sources performed by DESHIMA 1.0 on ASTE.

#### 4 TiEMPO Simulation of Observing a High-Redshift Galaxy with DESHIMA 2.0 on ASTE

As an example application of TiEMPO, we simulate the observation of a virtual luminous dusty galaxy ( $L_{\text{FIR}} = 10^{13.7} L_{\odot}$ ) at redshift  $z = 4.43$  and velocity width  $600 \text{ km s}^{-1}$  using the DESHIMA 2.0 spectrometer on the ASTE telescope. DESHIMA 2.0 is an upgrade of DESHIMA 1.0, which is currently under development.<sup>50</sup> The target instantaneous frequency coverage is 220 to 440 GHz, with a frequency spacing and half-power channel bandwidth of  $f/\Delta f = 500$ . The system will include a rotating mirror in the cabin optics that enables position switching on the sky at a rate of up to 10 Hz. Assuming the use of this beam chopper, we simulated a so-called ABBA chop-nod observing technique<sup>22,51</sup> with a beam-chopping frequency of 10 Hz between on-source and off-source positions and a nodding cycle of 60 s to subtract the atmospheric emission from the spectrum. The total simulated observation time was 1 h. The input spectrum of the galaxy was simulated using GalSpec. The telescope elevation angle was kept constant at 60 deg, and the weather condition was set to mean PWV = 1.0 mm; RMS fluctuation of the EPL for 1 km distance of  $\sigma_{\text{EPL}} = 50 \mu\text{m}$ , which is typical for the ALMA site [see for example Fig. 2(b) in Ref. 17]; and wind velocity =  $9.6 \text{ m s}^{-1}$ .

The resulting spectrum after applying the ABBA atmosphere removal scheme is presented in Fig. 7. The top panel shows the spectrum in  $\Delta T_{\text{sky}}$ , that is, before correcting for atmospheric absorption. The spectrum shows the detection of the redshifted [CII] line at 350 GHz and the dust



**Fig. 7** TiEMPO-simulated detection of a high-redshift dusty galaxy with the upcoming DESHIMA 2.0 instrument on ASTE. The galaxy spectrum was simulated using GalSpec, with input parameters as follows: far-infrared bolometric luminosity  $10^{13.7} L_{\odot}$ ; redshift  $z = 4.43$ ; and velocity width  $600 \text{ km s}^{-1}$ . The total observing time was 60 min, out of which half was pointing on-source. (a)  $\Delta T_{\text{sky}}$ , which is the difference in sky temperature  $T_{\text{sky}}$  between on-source and off-source obtained with the ABBA chop-nod method. The blue spectrum is the result of placing a galaxy at the on-position, and the orange spectrum is the result of no galaxy being present. The dashed curve is the expected spectrum of the galaxy, multiplied by the atmospheric transmittance  $\eta_{\text{atm}}$  (gray) and smoothed with a Lorentzian window of  $f/\Delta f = 500$  to account for the resolving power of the spectrometer. (b) The atmosphere-corrected antenna temperature  $T_{\text{A}}^* = \Delta T_{\text{sky}}/\eta_{\text{atm}}$ . The blue curve shows the simulated spectrum, and the dashed curve is what is expected directly from the input galaxy spectrum.

continuum emission. In the same figure, we show that a reference simulation without a galaxy yields a zero-centered spectrum as expected. Dividing the  $\Delta T_{\text{sky}}$ -spectrum by the frequency-dependent atmospheric transmittance  $\eta_{\text{atm}}$  yields the spectrum presented in the bottom panel, where the scale is now atmosphere-corrected antenna temperature  $T_{\text{A}}^*$ . In this way, TiEMPO is able to simulate end-to-end observations of future instruments and forecast their scientific products. The TiEMPO data can also be used to optimize observing strategies and signal-processing techniques before the instrument is deployed.

## 5 Conclusion and Future Prospects

We have presented the TiEMPO model and verified its applicability by comparing its output with on-sky measured data and simulating the operation of a future instrument. The TiEMPO model is highly parametrized and modular, so it can be adjusted to different observation techniques, telescopes, and instruments. This can be done by either simply adjusting the input parameters or by relatively simple modifications of the Python code. For example, some of the authors have adapted TiEMPO to simulate scan-mapping observations<sup>52</sup> or include excess detector noise.<sup>44</sup> TiEMPO can also import arbitrary frequency-dependent transmission curves from models or measurements to replace the Lorentzian filter transmission used in this article.<sup>44</sup> The time-dependent telescope elevation can be given as a user-specified vector. If the detector is not a pair-breaking type (e.g., superconducting transition-edge sensors), then the recombination noise term can be omitted in Eq. (9).

It would seem especially interesting to use TiEMPO for the design and optimization of large mm–submm telescopes, such as the Large Submillimeter Telescope<sup>7</sup> and Atacama Large Aperture Submillimeter Telescope,<sup>6</sup> as well as for optimizing instruments and observing techniques on existing large telescopes like the Large Millimeter Telescope.<sup>53</sup> These telescopes have diameters in the range of 30 to 50 m, so they sample a larger column of atmosphere that contains a larger number of patches of water vapor that can influence the noise behavior. The combination of TiEMPO and ARIS can already simulate observations with telescopes of these sizes, in combination with the wideband direct detection imaging spectrometers that are considered to be candidates for future instruments. Note that the current TiEMPO models only the transmittance of the atmosphere, and it does not model the wavefront distortion caused by the dynamical and spatially dependent EPL.<sup>54</sup> Because ARIS provides an EPL screen, this would be an interesting direction for future development.

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## Code Availability

TiEMPO,<sup>19</sup> GalSpec,<sup>20</sup> DESHIMA-sensitivity,<sup>41</sup> and De:code<sup>13</sup> are all available as Python packages and distributed on a public repository.

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