The TolTEC camera: polarimetric commissioning and performance of the continuously rotating half-wave plate

Dennis Lee, Giles Novak, Marc Berthoud, John Bussan, Robert Golenia, et al.

Dennis Lee, Giles Novak, Marc Berthoud, John Bussan, Robert Golenia, Eric Van Clepper, Grant Wilson, N. S. DeNigris, Zhiyuan Ma, Michael McCrackan, Kamal Souccar, Laura Fissel, Akanksha Bij, Felix Thiel, Itziar Aretxaga, Daniel Ferrusca Sr., Philip Mauskopf, Emily Lunde, Peter Ade, Carole Tucker, Giampaolo Pisano, Erin Guilfoil Cox, Laurence Sabin, Carlos Carrasco-Gonzalez, Alice Pasetto, Arturo Gómez-Ruiz Sr., Chat Hull, Jason Austermann, James Beall, Jiansong Gao, Michael Vissers, "The TolTEC camera: polarimetric commissioning and performance of the continuously rotating half-wave plate," Proc. SPIE 12190, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy XI, 121901O (31 August 2022); doi: 10.1117/12.2627725

Event: SPIE Astronomical Telescopes + Instrumentation, 2022, Montréal, Québec, Canada

The TolTEC Camera: Polarimetric Commissioning and Performance of the Continuously Rotating Half-wave Plate

Dennis Lee[a,b], Giles Novak[a,b], Marc Berthoud[a], John Bussan[c], Robert Golenia[c], Eric Van Clepper[a,b], Grant Wilson[d], N. S. DeNigris[d], Zhiyuan Ma[d], Michael McCrackan[d], Kamal Souccar[d], Laura Fissel[e], Akanksha Bij[e], Felix Thiel[e], Itziar Aretxaga[f], Daniel Ferrusca[f], Philip Mauskopf[g], Emily Lunde[g], Peter Ade[h], Carole Tucker[h], Giampaolo Pisano[i], Erin Guilfoil Cox[a], Laurence Sabin[j], Carlos Carrasco-Gonzalez[j], Alice Pasetto[j], Arturo Gomez-Ruiz[f], Chat Hull[k], Jason Austermann[l], James Beall[l], Jiansong Gao[l], and Michael Vissers[l]

[a]Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA), Northwestern University, Evanston, IL, USA
[b]Department of Physics and Astronomy, Northwestern University, Evanston, IL, USA
[c]Northwestern University Research Shop, Northwestern University, Evanston, IL, USA
[d]Department of Astronomy, University of Massachusetts Amherst, Amherst, MA, USA
[e]Department of Physics, Engineering Physics, & Astronomy, Queen's University, Kingston, ON, Canada
[f]Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), Puebla, Mexico
[g]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA
[h]Cardiff University, Cardiff, Wales
[i]Department of Physics, La Sapienza University of Rome, Italy
[j]Universidad Nacional Autónoma de México, Mexico City, Mexico
[k]National Astronomical Observatory of Japan, Chile
[l]National Institute of Standards and Technology (NIST), Boulder, CO, USA
[m]Universidad Nacional Autónoma de México, Ensenada, Mexico

ABSTRACT

An ambient-temperature continuously rotating half-wave plate (CRHWP) modulates the input polarization signal thereby enabling removal of low-frequency ($1/f$) noise from polarized flux measurements. This $1/f$ noise arises from atmospheric turbulence as well as from effects intrinsic to certain detectors. Here, we describe the design and performance of the half wave plate rotator and achromatic half-wave plate for the the new imaging polarimeter, TolTEC. These components are mounted in front of the cryostat window and operate at ambient temperature. The half-wave plate rotator (HWPR) spins the half-wave plate at 2 revolutions per second. The rotation mechanism consists of nine air bearings to provide low-friction motion and a frameless torque motor to directly drive rotation. The orientation of the rotor and half-wave plate are recorded using a high-precision optical encoder. We review the experimental requirements and technical design of the rotator as well as the associated electronics, pneumatics, and software.

Keywords: polarimetry, mm-wave, toltec

1. INTRODUCTION

TolTEC is a new imaging polarimeter mounted on the 50-meter Large Millimeter Telescope (LMT)[1] in Mexico. It consists of $\sim$ 7000 polarization-sensitive kinetic inductance detectors (KIDs) designed to observe at 1.1, 1.4, and 2.0 mm. Descriptions on the design and status of the instrument can be found detailed in prior publications.[2,3]

Send correspondence to D. Lee (dennislee@u.northwestern.edu)

Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy XI,
edited by Jonas Zmuidzinas, Jian-Rong Gao, Proc. of SPIE Vol. 12190,
121900O · © 2022 SPIE · 0277-786X · doi: 10.1117/12.2627725

More in-depth discussion of specifics systems can also be found for TolTEC's cryogenics,[4] software,[5] and the optics.[6]

In this paper, we focus on the continuously rotating half-wave plate (CRHWP). The purpose of the CRHWP is to mitigate the various sources of $1/f$ noise. This includes both uncorrelated $1/f$ noise from the detectors and correlated $1/f$ noise noise from the atmosphere. The half-wave plate rotator (HWPR) components of the CRHWP were fabricated in Northwestern University in 2018. The half-wave plate itself is being fabricated at Cardiff University. Compatibility testests were completed in the summer of 2019 with the rest of the instrument at the University of Massachusetts at Amherst. Extensive additional testing was performed at Northwestern in the fall of 2020. During the fall of 2021, the TolTEC instrument, along with the HWPR components, were delivered to the LMT to begin assembly and commissioning.

In Section 2, we discuss the design of the CRHWP and review its constituent components. In Section 3, we present the results of in-lab testing. In Section 4 we present our commissioning plans for polarimetric capabilities of TolTEC.

2. DESIGN OF HALF-WAVE PLATE ROTATOR AND ACHROMATIC HALF-WAVE PLATE

The titanium-nitide (TiN) kinetic inductance detectors (KIDs) used by TolTEC are susceptible to uncorrelated low-frequency noise ($1/f$ noise).[7] In addition, correlated $1/f$ noise originating from the atmosphere is expected to be several orders of magnitudes brighter than any desired astronomical signal. These effects can have the potential to severely degrade the observations. Continuous modulation of the signal using a continuously rotating half wave plate (CRWHP) is a common method of mitigating $1/f$ noise[8,9] By spinning the CRHWP at an appropriately high rate, the continuous modulation shifts the input signal to above the $1/f$ noise regime.

Figure 1. *Left:* Exploded view of the half-wave plate rotator (minor components excluded). *Right:* Assembled half-wave plate rotator in the receiver room of the Large Millimeter Telescope in Mexico.

In brief, the half-wave plate rotator mechanism is designed to rotate a half-wave plate at a rate of 2 Hz thus pushing the polarized optical signal to 8 Hz in the detector time-streams. Mounted in front of the window into the cryostat, it modulates the signal prior to it entering the cryostat. The rotation of the half-wave plate is achieved using air bearings and driven by a frameless torque motor. The orientation of the HWP is recorded using an optical encoder. This information is read and processed by a rack mounted computer via an I/O card. In the follow sections, we detail the components of the HWPR and their function. An exploded as well as assembled photograph of the HWPR is shown in Figure 1. An overall schematic design of the HWPR system is shown in Figure 2 and basic specifications are shown in Table 1.

Table 1. Half-Wave Plate Rotator Specifications

Nominal Rotation Rate	2 rotations per second
Total Weight	$\sim$ 72.6 kg (160 lbs)
Weight of Rotating Components	$\sim$ 21.6 kg (47.6 lbs)
HWP Clear Aperture	310 mm

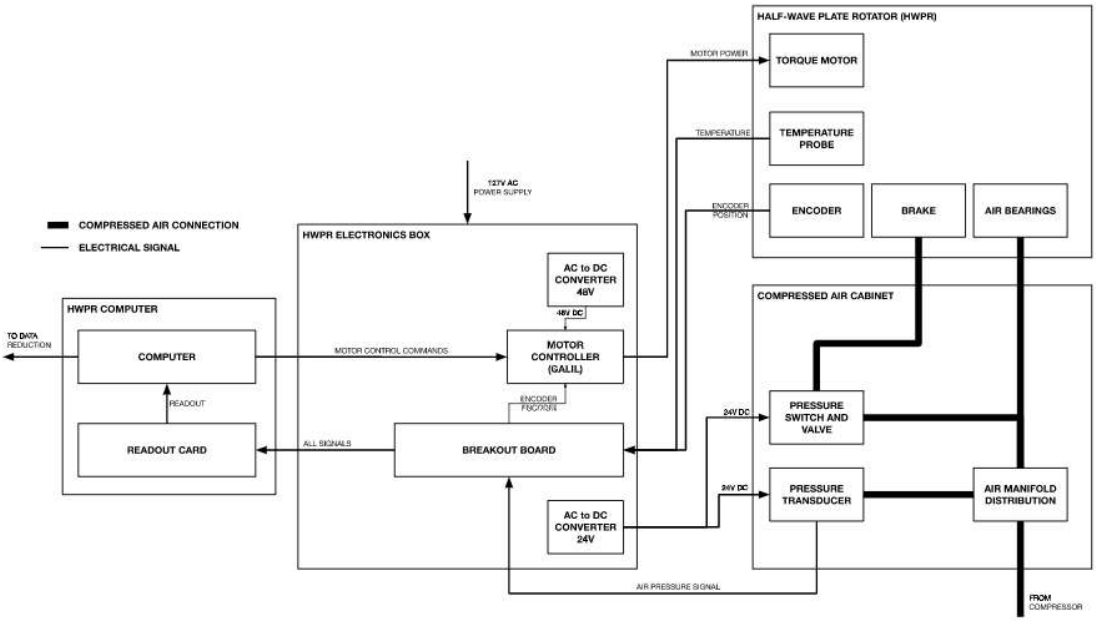

Figure 2. Overall Schematic Diagram of the HWPR System.

2.1 Hardware

2.1.1 Air Bearings

The rotating components of the HWPR are levitated by a total of nine air bearings: three radial air bearings and six axial air bearings from New Way Air Bearings. These operate by forcing air through a porous graphite medium. Operating at 100 psi, these air bearings provide low-friction and contactless rotation. Without any mechanical contact, this minimizes any vibrations between the HWP and the receiver. Furthermore, the lack of contact increases the longevity of the air bearings and reduces any needed maintenance or replacement.

2.1.2 Readout Electronics

A Renishaw high precision encoder ring is mounted on the rotor to measure the orientation of the rotor and HWP. The encoder ring consists of 65,536 lines distributed along the 417 mm diameter. Used in conjunction with a Renishaw VIONiC 4x interpolation optical read head, this system is capable of a resolution of $\approx$ 4.94 arcseconds. A commercial off-the-shelf Sensoray S826 PCI Express I/O card is used to read the encoder signal at a sample rate of 1 kHz. This information is then timestamped with a pulse-per-second signal shared between all TolTEC components before being sent to the data processing computer. The Sensoray S826 was chosen due to its GHz-precision oscillator. This permits a highly precise timestamping and thus orientation tracking of the HWP. This will be crucial in the removal of the spurious polarization signal associated with the half-wave plate synchronous signal (see Section 2.1.5).

2.1.3 Torque Motor and Motor Controller

The rotation of the rotator is powered by a frameless torque motor from Allied Motion (MF0510015-A00). A torque motor was chosen as it does not require timing belts or gears to spin the rotator. By avoiding mechanical contact via components like timing belts and gears, vibrations and other unwanted motions are prevented from being coupled to the system. Power to the rotator is supplied from a dedicated 48VDC power supply via a Galil DMC-30012 motor controller.

2.1.4 Compressed Air Supply

Air is supplied via a two-stage air compressor. In order to achieve the required pressure of 100 psi while at the observatory's elevation of 15,200 ft., the compressor is required to be capable of reaching 200 psi. From the compressor, the air travels through a series of air filters and oil separators in order to minimize moisture and contaminants that may have entered the air supply. In particular, oil originating from the compressor motor may inadvertently enter the supply. This can be particularly detrimental to the air bearings which can be damaged by the presence of oil.

In addition to operating the air bearings, compressed air is also used for the anti-condensation system. In order to prevent dust or other external contaminates from affecting the optical encoding, nozzles are installed along the edge of the optical encoder surface continuously blowing the surface with air. This ensures that any external particulates are quickly dislodged and prevents the condensation of water on the surface of the encoder.

2.1.5 Half-Wave Plates

Two achromatic HWPs will be used as polarizers for TolTEC; one optimized for the bands centered on 1.1 mm and 1.4 mm, and another optimized for the bands centered on 1.4 mm and 2 mm. As opposed to monochromatic wave plates, achromatic HWPs enable operation over a range of wavelengths.[16] While in theory, one HWP can be used to span all three bands, an important consideration is the minimization of an artifact known as the 2Ω half-wave plate synchronous signal (HWPSS).

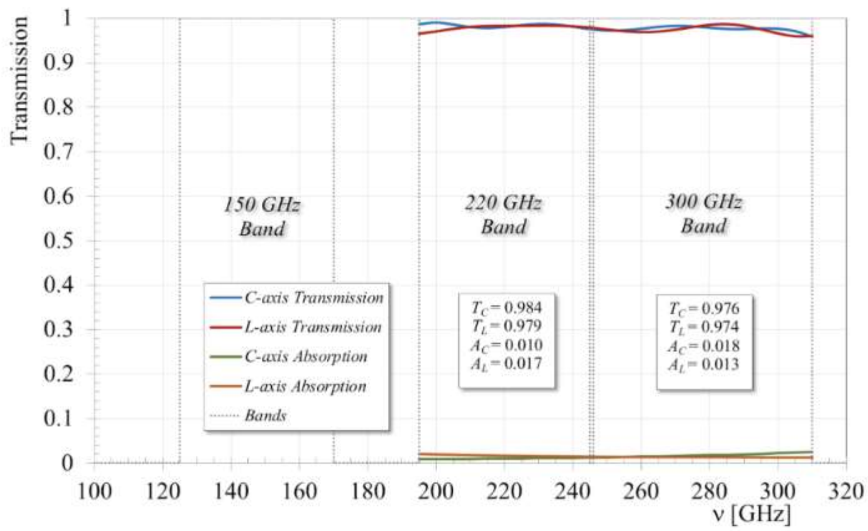

Figure 3. Specifications of the high-frequency half-wave plate being fabricated. Designed for the 1.1 mm and 1.4 mm bands of TolTEC.

The 2Ω HWPSS results from the differing emissivities and reflectivites of the HWP's two orthogonal axes. These properties cause the power incident on the detector to vary at a frequency twice that of the CRHWP's rotation frequency. Should this effect be sufficiently large, it can cause power variations, and therefore KID resonant frequency variations, that are large enough to cause a significant reduction in the signal-to-noise ratio. This is because as the resonant frequency moves away from the probe tone frequency the signal decreases while the noise in the detector readout system does not. To ensure that HWP designs result in minimal power variation, extensive modeling and simulation of potential HWP designs was carried out prior to manufacture. Evaluations of multiple variations for a single three-band HWP result in high performance compromises between the bands (i.e. reducing the HWPSS for one band inevitably increases it for at least one other band). We found two two-band HWPs to be a suitable solution to this problem. Each HWP is designed to minimize impact of the 2Ω HWPSS in both its respective bands, while still preserving the benefit and flexibility of multi-band observations. The specifications for the high-frequency HWP are shown in Figure 3.

2.1.6 Mechanical Safety

Due to the large rotation mass and the exposed rotating components, a series of mechanical safety features are put into place. A mechanical brake is installed with a replaceable brake pad designed to be engaged whenever the rotator is powered off and stowed. The brake also engages if a loss of power and/or a loss of pressure (via a pressure switch) is detected. The pressure switch is set at 75 psi and engages automatically. A loss of power will similarly automatically engage the mechanical brake. In addition, an emergency stop button is located near the rotator itself. Pushing the button cuts power to various components and engages the brake, thereby causing the motion to immediately stop.

2.2 Software

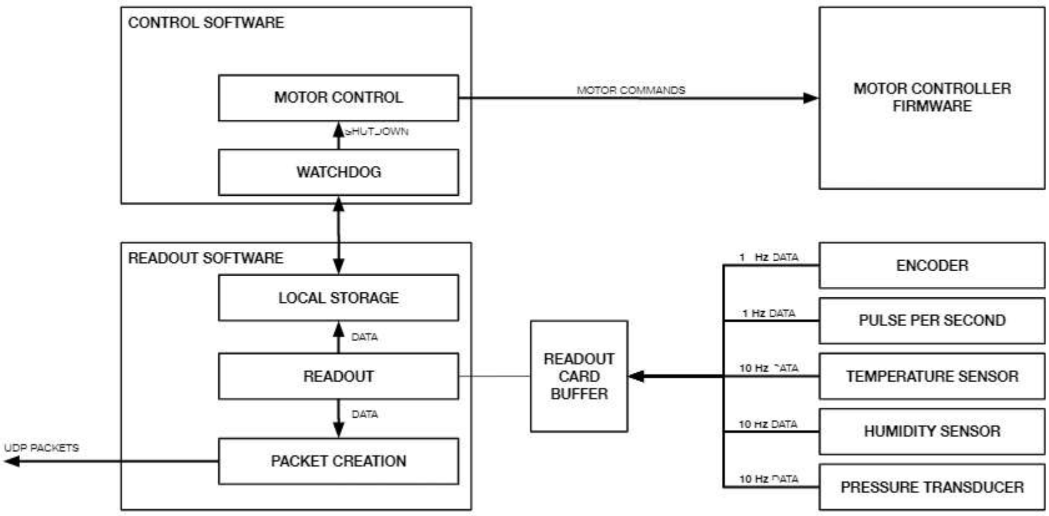

Figure 4. Software diagram

Control and readout of the HWPR is done using software running on a dedicated rack-mount computer. The layout for the software is shown in Figure 4. Rotation of the HWPR is monitored and controlled via a command line interface accessed locally (for maintenance or debugging purposes) or remotely by the main TolTEC computer. The HWP positional data from the optical encoder is separately readout by the S826 I/O card and the Galil motor controller. The positional data sent to the Galil motor controller is used to monitor the rotation and is regularly logged for debugging purposes. Positional data readout by the S826 I/O card is packaged into UDP packets to be sent to the main TolTEC data storage. In addition, a pulse per second (PPS) signal is also readout by the S826 I/O card. This signal is shared by all TolTEC hardware is designed to enable the merging and correlation of all data time streams including the detector signal timestreams. This signal is also packaged into UDP packets and collected.

Housekeeping data related to the operation of the HWPR is also collected here. This includes temperature and humidity data of both the electronics and the HWPR and the pressure of the overall system. In addition to general monitoring, this data is used to operate a software fail-safe. Should the temperature reach a certain threshold or the system experiences a sudden pressure drop, the control software will automatically stop the rotation. This system is in addition to the mechanical fail-safes described in Section 2.1.6.

3. IN-LAB PERFORMANCE

Evaluation of the performance and capabilities of the HWPR proceeded in the laboratory between November 2020 and December 2020. In order to test the reliability, robustness, and the stability of the HWPR, the rotator was rotated at its nominal rotation rate of 2 Hz continuously for a period of three weeks. Figure 5 shows the power spectral density of the HWPR for each day of the three week period (excluding the first and last days). The performance is comparable to what has been achieved by other instruments (e.g, POLARBEAR-2[11]) and is expected to be a stable and effective method of long-term rotation.

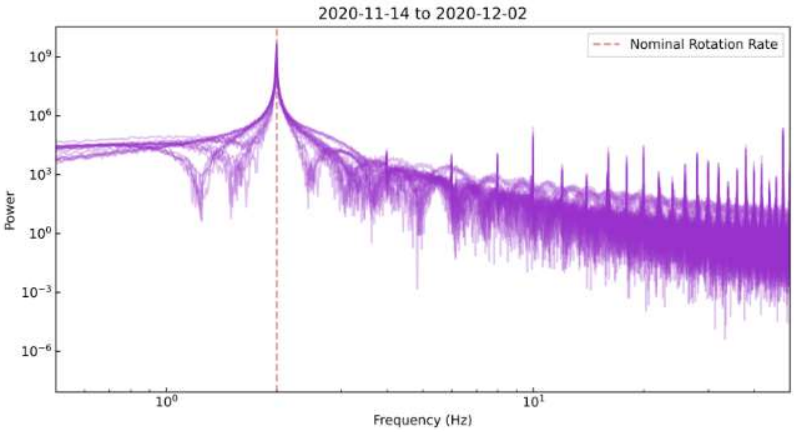

Figure 5. Power Spectral Density of rotation of the HWPR. The dashed vertical line corresponds to the nominal 2 rotations per second rate. Excludes the first and last day due to acceleration and deceleration.

While able to precisely time and read the encoder signal of the rotator, a limitation of the S826 I/O card is the relatively small buffer on the card. It possesses a 16 value buffer. Once exceeded, the buffer is then continuously overwritten in a first-in, first-out manner. At the nominal readout speed of 1 kHz, this buffer will thus need to be readout and saved every 16 milliseconds. Due to the use of a standard Linux distribution (i.e., Ubuntu 20.04.4 LTS) and not a real-time operating system (RTOS), it is possible that the instructions to readout the buffer may not be executed in a timely manner. As a result, data points stored in the buffer of the S826 card may not be saved in time and thus "dropped".

Over the course of the long duration test, we characterized the frequency and length of the gaps that these dropped counts produce. In total, ~ 1.78 billion data points on the rotational position of the rotator were saved. We find that, in that time period, 514 gaps were found. These gaps ranged from 2 ms long, corresponding to skipping one count, to 12 ms long, corresponding to skipping 11 counts. In total, 1611 counts were "dropped" due to not being readout in a timely manner. The distribution of these gaps are shown in Figure 6. While these gaps/"dropped" counts could be potentially mitigated with a RTOS, the versatility and relative simplicity of using a standard Linux distribution provides substantial maintenance benefits.

4. CONCLUSION AND FUTURE WORK

The purpose of the CRHWP for TolTEC is to mitigate the effects of uncorrelated $1/f$ noise from the TiN KIDs and correlated $1/f$ noise from the atmosphere. The HWPR is designed to rotate an achromatic HWP stably and continuously at 2 revolutions per minute. This is done through the use of components such as air bearings and a frameless torque motor that permit smooth rotation while limiting potentially detrimental mechanical contact.

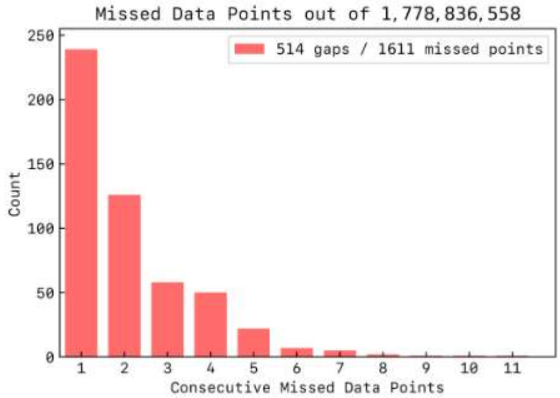

Figure 6. Histogram of gaps in the data collection. Over the course the continuous three week operation of the half wave plate rotator, out of 1.7 billion data points collected, 514 gaps were detected. While these could be potentially mitigated with a real-time operating system, the versatility and relative simplicity of using a standard Linux distribution provide substantial maintenance benefits.

In-lab performance and characterization of the HWPR has shown good stability and reliability. The manufacture of the first of the two required achromatic HWPs is in progress. The high-frequency (1.1 mm and 1.4 mm) HWP is expected to be delivered in late summer 2022. Commissioning of the TolTEC camera at the LMT is currently underway. Polarimetric commissioning is expected to begin in Fall 2022 with the installation of the CRHWP system.

REFERENCES

[1] Hughes, D. H., Jáuregui Correa, J.-C., Schloerb, F. P., Erickson, N., Romero, J. G., Heyer, M., Reynoso, D. H., Narayanan, G., Perez-Grovas, A. S., Souccar, K., Wilson, G., and Yun, M., "The Large Millimeter Telescope," in [*Ground-based and Airborne Telescopes III*], Stepp, L. M., Gilmozzi, R., and Hall, H. J., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7733**, 773312 (July 2010).

[2] Bryan, S., Austermann, J., Ferrusca, D., Mauskopf, P., McMahon, J., Montaña, A., Simon, S., Novak, G., Sánchez-Argüelles, D., and Wilson, G., "Optical design of the TolTEC millimeter-wave camera," in [*Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy IX*], Zmuidzinas, J. and Gao, J.-R., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10708**, 107080J (July 2018).

[3] Wilson, G. W., Abi-Saad, S., Ade, P., Aretxaga, I., Austermann, J., Ban, Y., Bardin, J., Beall, J., Berthoud, M., Bryan, S., Bussan, J., Castillo, E., Chavez, M., Contente, R., DeNigris, N. S., Dober, B., Eiben, M., Ferrusca, D., Fissel, L., Gao, J., Golec, J. E., Golina, R., Gomez, A., Gordon, S., Gutermuth, R., Hilton, G., Hosseini, M., Hubmayr, J., Hughes, D., Kuczarski, S., Lee, D., Lunde, E., Ma, Z., Mani, H., Mauskopf, P., McCrackan, M., McKenney, C., McMahon, J., Novak, G., Pisano, G., Pope, A., Ralston, A., Rodriguez, I., Sánchez-Argüelles, D., Schloerb, F. P., Simon, S., Sinclair, A., Souccar, K., Torres Campos, A., Tucker, C., Ullom, J., Van Camp, E., Van Lanen, J., Velazquez, M., Vissers, M., Weeks, E., and Yun, M. S., "The TolTEC camera: an overview of the instrument and in-lab testing results," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **11453**, 1145302 (Dec. 2020).

[4] DeNigris, N. S., Wilson, G. W., Eiben, M. E., Lunde, E., Mauskopf, P., and Contente, R., "Developing a Large-Scale Cryogenic System for the Simultaneous Operation of Three Detector Focal Planes in TolTEC, A New Multichroic Imaging Polarimeter," *Journal of Low Temperature Physics* **199**, 789–797 (Jan. 2020).

[5] Ma, Z., McCrackan, M., DeNigris, N. S., Souccar, K., Wilson, G. W., Horton, P., Lee, D., Mauskopf, P., Novak, G., Rodríguez-Montoya, I., and Zaragoza-Cardiel, J., "The TolTEC data analysis pipeline and software stack," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **11452**, 114522O (Dec. 2020).

[6] Lunde, E., Ade, P., Berthoud, M., Contente, R., DeNigris, N. S., Doyle, S., Ferrusca, D., Golec, J., Kuczarski, S., Lee, D., Ma, Z., Mauskopf, P., McCrackan, M., McMahon, J., Novak, G., Pisano, G., Simon, S., Souccar, K., Tucker, C., Underhill, M., Van Camp, E., and Wilson, G., "The optical design and performance of TolTEC: a millimeter-wave imaging polarimeter," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **11453**, 114534A (Dec. 2020).

[7] Vissers, M. R., Austermann, J. E., Malnou, M., McKenney, C. M., Dober, B., Hubmayr, J., Hilton, G. C., Ullom, J. N., and Gao, J., "Ultrastable millimeter-wave kinetic inductance detectors," *Applied Physics Letters* **116**, 032601 (Jan. 2020).

[8] Essinger-Hileman, T., Kusaka, A., Appel, J. W., Choi, S. K., Crowley, K., Ho, S. P., Jarosik, N., Page, L. A., Parker, L. P., Raghunathan, S., Simon, S. M., Staggs, S. T., and Visnjic, K., "Systematic effects from an ambient-temperature, continuously rotating half-wave plate," *Review of Scientific Instruments* **87**, 094503 (Sept. 2016).

[9] Takakura, S., Aguilar, M., Akiba, Y., Arnold, K., Baccigalupi, C., Barron, D., Beckman, S., Boettger, D., Borrill, J., Chapman, S., Chinone, Y., Cukierman, A., Ducout, A., Elleflot, T., Errard, J., Fabbian, G., Fujino, T., Galitzki, N., Goeckner-Wald, N., Halverson, N. W., Hasegawa, M., Hattori, K., Hazumi, M., Hill, C., Howe, L., Inoue, Y., Jaffe, A. H., Jeong, O., Kaneko, D., Katayama, N., Keating, B., Keskitalo, R., Kisner, T., Krachmalnicoff, N., Kusaka, A., Lee, A. T., Leon, D., Lowry, L., Matsuda, F., Matsumura, T., Navaroli, M., Nishino, H., Paar, H., Peloton, J., Poletti, D., Puglisi, G., Reichardt, C. L., Ross, C., Siritanasak, P., Suzuki, A., Tajima, O., Takatori, S., and Teply, G., "Performance of a continuously rotating half-wave plate on the POLARBEAR telescope," *Journal of Cosmology and Astroparticle Physics* **2017**, 008 (May 2017).

[10] Pisano, G., Ritacco, A., Monfardini, A., Tucker, C., Ade, P. A. R., Shitvov, A., Benoit, A., Calvo, M., Catalano, A., Goupy, J., Leclercq, S., Macias-Perez, J., Andrianasolo, A., and Ponthieu, N., "Development and application of metamaterial-based half-wave plates for the NIKA and NIKA2 polarimeters," A&A 658, A24 (Feb. 2022).

[11] Hill, C. A., Beckman, S., Chinone, Y., Goeckner-Wald, N., Hazumi, M., Keating, B., Kusaka, A., Lee, A. T., Matsuda, F., Plambeck, R., Suzuki, A., and Takakura, S., "Design and development of an ambient-temperature continuously-rotating achromatic half-wave plate for CMB polarization modulation on the POLARBEAR-2 experiment," in [*Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII*], Holland, W. S. and Zmuidzinas, J., eds., *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **9914**, 99142U (July 2016).