Greenland Telescope:
Single-dish science, instrumentation requirements
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23 May 2019, EAO Futures meeting, Nanjing

October 2018, Thule AFB
Outline:

• Current status
• Single dish science goals
• Summit Station
• Future receivers development
Completion of mechanical assembly of the Greenland Telescope
10 August 2017
Thule Phase 1 Activities 2017-2019

- Antenna assembly (mechanical + electrical) completed at Thule Air Base, Greenland - September 2017
- Hydrogen maser installed in September 2017
- Servo tuning and tests in progress - October 2017
- Fringes demonstrated at Maunakea, with SMA + JCMT, using 230 GHz receivers and VLBI backend
- 86 & 230 GHz receivers installed in late November 2017
- Pointing calibration in November 2017
- Joined the EHT run in April 2018
First fringes on ALMA-Thule baseline, 28 January 2018
EHT observing run April 2018

Keiichi Asada (ASIAA)
Hiroaki Nishioka (ASIAA)
ChenYu Yu (ASIAA)
Nimesh Patel (CfA)
31 March - 9 April 2019, Global Millimeter-wave VLBI Array observations at 86 GHz
Hydrogen maser house

Control room, weather station
Current Instrumentation
### A. Key Characters

<table>
<thead>
<tr>
<th>Receiver ID</th>
<th>VLBI-86 (holography) (TBD)</th>
<th>VLBI-230</th>
<th>VLBI-345</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cartridge diameter (mm)</td>
<td>140</td>
<td>170</td>
<td>170</td>
</tr>
<tr>
<td>Origin</td>
<td>IAA-W-band</td>
<td>OPU-230-ALMA#</td>
<td>IRAM-ALMA-Band 7</td>
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<tr>
<td>Frequency Range (GHz)</td>
<td>84 ~ 96</td>
<td>213.4 ~ 250</td>
<td>275 ~ 373</td>
</tr>
<tr>
<td>IF Range (GHz)</td>
<td>4 - 8</td>
<td>4 - 8</td>
<td>4 - 8</td>
</tr>
<tr>
<td>Output channel</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Polarization</td>
<td>Two circular polarization (Waveguide phase shifter + OMT)</td>
<td>Two circular polarization at 221.1 GHz [To be Verified]</td>
<td>Two linear output with quarter-wave plate</td>
</tr>
<tr>
<td>Sideband</td>
<td>Upper sideband only</td>
<td>To be confirmed</td>
<td>2SB</td>
</tr>
<tr>
<td>Trx (SSB)</td>
<td>50 - 90</td>
<td>70 - 110</td>
<td>70 - 110</td>
</tr>
<tr>
<td>LO Range</td>
<td>80 - 88 GHZ (ALMA Band 6 WCA design)</td>
<td>ALMA Band 6 WCA</td>
<td>ALMA Band 7 WCA</td>
</tr>
<tr>
<td>Target LO Frequency (GHz)</td>
<td>86.6* [To be confirmed]</td>
<td>221.1**</td>
<td>342.6**</td>
</tr>
<tr>
<td>Detector</td>
<td>MMIC HEMT LNA</td>
<td>SIS mixer with permanent magnetic</td>
<td>SIS mixer</td>
</tr>
</tbody>
</table>
Two ROACH2 spectrometers, each with two IF inputs of 2.048 GHz b/w, 32768 channels
Summit Station
Thule Air Base
Position: 76.5° North, 68.7° West
Altitude: 77 m
Temperature: 5°C to -25°C (average)

Summit Station
Position: 72.5° North, 38.5° West
Altitude: 3,200 m
Temperature: -10°C to -50°C (average)
View from level-2 platform

Beginning of Ice sheet (traverse)
3.5 Year Monitoring of 225 GHz Opacity at the Summit of Greenland

Satoki Matsushita, Keichi Asada, Pierre L. Martin-Cocher, Ming-Tang Chen, Paul T. P. Ho, Makoto Inoue, Patrick M. Koch, Scott N. Paine, and David D. Turner

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Received 2016 September 19, accepted 2016 October 28, published 2016 December 21

Abstract

We present the 3.5 years monitoring results of 225 GHz opacity at the summit of the Greenland ice sheet (Greenland Summit Camp) at an altitude of 3200 m using a tipping radiometer. We chose this site as our submillimeter telescope (Greenland Telescope) site, because conditions are expected to have low submillimeter opacity and because its location offers favorable baselines to existing submillimeter telescopes for global-scale Very Long Baseline Interferometry. The site shows a clear seasonal variation with the average opacity lower by a factor of two during winter. The 25%, 50%, and 75% quartiles of the 225 GHz opacity during the winter months of November through April are 0.046, 0.060, and 0.080, respectively. For the winter quartiles of 25% and 50%, the Greenland site is about 10%–30% worse than the Atacama Large Millimeter/submillimeter Array (ALMA) or the South Pole sites. Estimated atmospheric transmission spectra in winter season are similar to the ALMA site at lower frequencies (<450 GHz), which are transparent enough to perform astronomical observations almost all of the winter time with opacities <0.5, but 10%–25% higher opacities at higher frequencies (>450 GHz) than those at the ALMA site. This is due to the lower altitude of the Greenland site and the resulting higher line wing opacity from pressure-broadened saturated water lines in addition to higher dry air continuum absorption at higher frequencies. Nevertheless, half of the winter time at the Greenland Summit Camp can be used for astronomical observations at frequencies between 450 GHz and 1000 GHz with opacities <1.2, and 10% of the time show >10% transmittance in the THz (1035 GHz, 1350 GHz, and 1500 GHz) windows. Summer season is good for observations at frequencies lower than 380 GHz. One major advantage of the Greenland Summit Camp site in winter is that there is no diurnal variation due to the polar night condition, and therefore the durations of low-opacity conditions are significantly longer than at the ALMA site. Opacities lower than 0.05 or 0.04 can continue for more than 100 hr. Such long stable opacity conditions do not occur as often even at the South Pole; it happens only for the opacity lower than 0.05. Since the opacity variation is directly related to the sky temperature (background) variation, the Greenland Summit Camp is suitable for astronomical observations that need unusually stable sky background.

Key words: atmospheric effects – site testing

Online material: color figure

Figure 1. 225 GHz tipping radiometer located on the roof of the Mobile Science Facility (MSF) at the Greenland Summit Camp. (A color version of this figure is available in the online journal.)

Figure 4. Cumulative distribution plots and histograms of 225 GHz opacity in winter (solid lines) and summer (dashed lines). The vertical axis on the left-hand side is for the cumulative distribution plots, and that on the right-hand side is for the histograms. Crosses on the cumulative distribution plots are the opacity quartiles of each season. The quartile for winter and summer are also listed in the figure.
Figure 5: Model of the GLT on the space frame partially embedded in the snow foundation (design of space frame and snow pad in progress). Isometric view showing all 4 side containers and receiver transfer container on the back (Left); sectional side view (Right)

Raffin P, 2014 SPIE paper
Single dish science
Science goals:
1) M87 VLBI
2) Single-dish Submm and THz projects

Review

First-generation science cases for ground-based terahertz telescopes

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Satoko Takahashi,3,4 Ya-Wen Tang,1 Hsian-Hong Chang,1 Kuiyun Huang,5
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Yen-Ting Lin,1 Sundar Srinivasan,1 Pierre Martin-Cocher,1 Hung-Yi Pu,1
Francisca Kemper,1 Nimesh Patel,6 Paul Grimes,6 Yau-De Huang,1
Chih-Chiang Han,1 Yen-Ru Huang,1 Hiroaki Nishioka,1
Lupin Chun-Che Lin,1 Qizhou Zhang,6 Eric Keto,6 Roberto Burgos,6
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Received 2015 August 3; Accepted 2015 October 28
Abstract

Ground-based observations at terahertz (THz) frequencies are a newly explorable area of astronomy in the coming decades. We discuss science cases for a first-generation 10-m class THz telescope, focusing on the Greenland Telescope as an example of such a facility. We propose science cases and provide quantitative estimates for each case. The largest advantage of ground-based THz telescopes is their higher angular resolution (∼4″ for a 10-m dish), as compared to space or airborne THz telescopes. Thus, high-resolution mapping is an important scientific argument. In particular, we can isolate zones of interest for Galactic and extragalactic star-forming regions. The THz windows are suitable for observations of high-excitation CO lines and [N II] 205-μm lines, which are scientifically relevant tracers of star formation and stellar feedback. Those lines are the brightest lines in the THz windows, so they are suitable for the initiation of ground-based THz observations. THz polarization of star-forming regions can also be explored since it traces the dust population contributing to the THz spectral peak. For survey-type observations, we focus on “sub-THz” extragalactic surveys, the uniqueness of which is detecting galaxies at redshifts z ∼ 1–2, where the dust emission per comoving volume is the largest in the history of the Universe. Finally we explore possibilities of flexible time scheduling, which enables us to monitor active galactic nuclei, and to target gamma-ray burst afterglows. For these objects, THz and submillimeter wavelength ranges have not yet been explored.

Key words: dust, extinction — galaxies: ISM — ISM: lines and bands — submillimeter: general — telescopes
• Diffuse ISM
  • Molecules
    • NII line at 205 µm
• Dust continuum: star-forming regions
  • Polarization at THz frequencies
• Bolometer surveys of high redshift galaxies
• Flux monitoring of AGN sources
• Gamma ray bursts
• Spectral-line surveys
• Water maser surveys
• (A) Chemistry and evolution in the diffuse and dense ISM
  
  CO 13-12 line, NII line
  1.5 THz heterodyne (multipixel) receiver

• (B) Collective effects of star-formation in extragalactic sources
  
  650, 850 GHz ; Improve on Herschel resolution
  Bolometer arrays

• (C) Time variable submillimeter Universe
  
  VLBI receivers
Table 2. Representative terahertz lines.

<table>
<thead>
<tr>
<th>Species</th>
<th>Frequency (THz)</th>
<th>Transition</th>
<th>Excitation energy (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>1.037–1.497</td>
<td>(9–8)–(13–12)</td>
<td>248.87486–503.134028</td>
</tr>
<tr>
<td>HCO⁺</td>
<td>1.070–1.337</td>
<td>(12–11)–(15–14)</td>
<td>333.77154–513.41458</td>
</tr>
<tr>
<td>HCN</td>
<td>1.0630–1.593</td>
<td>(12–11)–(18–17)</td>
<td>331.68253–726.88341</td>
</tr>
<tr>
<td>H₂D⁺</td>
<td>1.370</td>
<td>1₀,₁–0₀,₀</td>
<td>65.75626</td>
</tr>
<tr>
<td>N II</td>
<td>1.461</td>
<td>3P₁–3P₀</td>
<td>–</td>
</tr>
<tr>
<td>CH</td>
<td>1.471</td>
<td>N = 2, J = 3/2–3/2, F = 2⁺–2⁻</td>
<td>96.31131</td>
</tr>
<tr>
<td>HD₂⁺</td>
<td>1.477</td>
<td>1₁,₁–0₀,₀</td>
<td>70.86548</td>
</tr>
</tbody>
</table>

Table 3. Luminous protostellar sources for the THz line experiment.

<table>
<thead>
<tr>
<th>Name</th>
<th>L_{bol} (L_{⊙})</th>
<th>D (pc)</th>
<th>α(J2000.0) (h m s)</th>
<th>δ(J2000.0) (° ′ ″)</th>
<th>References*</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1448-mm</td>
<td>4.4</td>
<td>250</td>
<td>03 25 38 87</td>
<td>30 44 05.4</td>
<td>1,2</td>
</tr>
<tr>
<td>NGC1333 IRAS 2A</td>
<td>19.0</td>
<td>250</td>
<td>03 28 55.58</td>
<td>31 14 37.1</td>
<td>1,2</td>
</tr>
<tr>
<td>SVS 13</td>
<td>32.5</td>
<td>250</td>
<td>03 29 03.73</td>
<td>31 16 03.80</td>
<td>2,3</td>
</tr>
<tr>
<td>NGC1333 IRAS 4A</td>
<td>4.2</td>
<td>250</td>
<td>03 29 10.50</td>
<td>31 13 31.0</td>
<td>1,2</td>
</tr>
<tr>
<td>L1551 IRS 5</td>
<td>22</td>
<td>140</td>
<td>04 31 34.14</td>
<td>18 08 05.1</td>
<td>4,5</td>
</tr>
<tr>
<td>L1551 NE</td>
<td>4.2</td>
<td>140</td>
<td>04 31 44.47</td>
<td>18 08 32.2</td>
<td>5,6</td>
</tr>
<tr>
<td>L1157</td>
<td>5.8</td>
<td>325</td>
<td>20 39 06.28</td>
<td>68 02 15.8</td>
<td>1,7</td>
</tr>
</tbody>
</table>

*References: (1) Jørgensen et al. (2007); (2) Enoch et al. (2009); (3) Chen, Launhardt, and Henning (2009); (4) Takakuwa et al. (2004); (5) Froeblich (2005); (6) Takakuwa et al. (2012); (7) Shirley et al. (2000).
Figure 1: Observed and modelled $\text{H}_2\text{D}^+$ spectra.

**a.** The histograms show the ortho-$\text{H}_2\text{D}^+$ (top) and para-$\text{H}_2\text{D}^+$ (bottom) rotational ground-state lines as observed with A SOFIA/GREAT, respectively; the orange lines show the modelled line profiles. Intensities are given as antenna temperature with respect to the local standard of rest. **b.** Energy level diagram (in units of temperature, $E/k$, with constant) of the lowest rotational states of ortho- and para-$\text{H}_2\text{D}^+$.

$\text{H}_2\text{D}^+$ observations give an age of at least one million years for a cloud core forming Sun-like stars

Sandra Brünken, Olli Sipilä, Edward T. Chambers, Jorma Harju, Paola Caselli, Oskar Asvany, Cornelia E. Honingh, Tomasz Kamiński, Karl M. Menten, Jürgen Stutzki & Stephan Schlemmer


At kinetic temperatures $T$ above $\sim$12 K, the ortho/para $\text{H}_2\text{D}^+$ ratio is completely determined in reactions with ortho- and para-H$_2$, and it is closely tied to the evolution of the ortho/para H$_2$ ratio. The shaded vertical region indicates the temperature range applicable to the dense core surrounding IRAS 16293-2422 AB (at radial distances from the core centre of 3,000–6,000 AU), while the horizontal shade indicates the observed ortho/para $\text{H}_2\text{D}^+$ ratio. Together, these limits suggest a dense core age of at least one million years. The gas density, $n(\text{H}_2) = 10^5$ cm$^{-3}$, and the visual extinction, $A_V = 10$ mag, are kept constant in this model.
Time variable AGN sources

Table 7. Candidate AGNs for monitoring observations with the GLT.

<table>
<thead>
<tr>
<th>Name</th>
<th>Alias</th>
<th>$z$</th>
<th>Optical ID</th>
<th>Flux at 15 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0112+2244</td>
<td>S2 0109+22</td>
<td>0.265</td>
<td>BL Lac</td>
<td>0.48</td>
</tr>
<tr>
<td>J0319+4130</td>
<td>3C 84</td>
<td>0.0176</td>
<td>Galaxy</td>
<td>19.4</td>
</tr>
<tr>
<td>J0721+7120</td>
<td>S5 0716+71</td>
<td>0.31</td>
<td>BL Lac</td>
<td>1.2</td>
</tr>
<tr>
<td>J0748+2400</td>
<td>PKS 0745+241</td>
<td>0.4092</td>
<td>QSO</td>
<td>1.15</td>
</tr>
<tr>
<td>J0854+2006</td>
<td>OJ 287</td>
<td>0.306</td>
<td>BL Lac</td>
<td>4.67</td>
</tr>
<tr>
<td>J0958+6533</td>
<td>S4 0954+65</td>
<td>0.367</td>
<td>BL Lac</td>
<td>1.34</td>
</tr>
<tr>
<td>J1104+3812</td>
<td>Mrk 421</td>
<td>0.0308</td>
<td>BL Lac</td>
<td>0.33</td>
</tr>
<tr>
<td>J1217+3007</td>
<td>ON 325</td>
<td>0.13</td>
<td>BL Lac</td>
<td>0.36</td>
</tr>
<tr>
<td>J1230+1223</td>
<td>M 87</td>
<td>0.0044</td>
<td>Galaxy</td>
<td>2.51</td>
</tr>
<tr>
<td>J1653+3945</td>
<td>Mrk 501</td>
<td>0.0337</td>
<td>BL Lac</td>
<td>0.87</td>
</tr>
<tr>
<td>J1719+1745</td>
<td>OT 129</td>
<td>0.137</td>
<td>BL Lac</td>
<td>0.58</td>
</tr>
<tr>
<td>J1806+6949</td>
<td>3C 371</td>
<td>0.051</td>
<td>BL Lac</td>
<td>1.37</td>
</tr>
<tr>
<td>J1927+7358</td>
<td>4C +73.18</td>
<td>0.302</td>
<td>QSO</td>
<td>3.71</td>
</tr>
<tr>
<td>J2022+6136</td>
<td>OW 637</td>
<td>0.227</td>
<td>Galaxy</td>
<td>2.26</td>
</tr>
<tr>
<td>J2143+1743</td>
<td>OX 169</td>
<td>0.2107</td>
<td>QSO</td>
<td>1.09</td>
</tr>
<tr>
<td>J2202+4216</td>
<td>BL Lac</td>
<td>0.0686</td>
<td>BL Lac</td>
<td>4.52</td>
</tr>
<tr>
<td>J2203+3145</td>
<td>4C +31.63</td>
<td>0.2947</td>
<td>QSO</td>
<td>2.6</td>
</tr>
</tbody>
</table>
B1228+126  J1230+123  3c274  △ 1.4–1.1 mm SMA  ⊕ 870 μm SMA

NOTE: Use for planning purposes ONLY! See SMA policy for details.
NOTE: Use for planning purposes ONLY! See SMA policy for details.
Future instruments
Development of 1.5 THz Cartridge-type Multi-pixel Receiver Based on HEB Mixers

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Abstract— A design of 2 × 2 NbN-based hot-electron-bolometer (HEB) mixer array receiver cartridge has been demonstrated here by using multiple local oscillator (LO) beams. In our design, the 1.5 THz LO beam is split into four uniform sub-beams with a spacing of 18 mm by using a power distributor, then arrives at a four-pixel silicon lens with twin slot antenna (TSA) through a large-area beam splitter. An additional four-pixel HDPE lens is located at 120 mm in front of the silicon lens to increase the size of beam waist for fitting to the aperture parameter of sub-reflector of GLT. Some cryogenic tests of cartridge have been carried out. In this article, we report the design, assembly, thermal analysis, and some testing results of cartridge.

Fig. 1 The schematic diagram of the single-pixel and four-pixel cartridge design.

Fig. 2 (a) The four-pixel power distributor module. (b) The calculated transmittance and reflectance of polarizing beam splitters versus thickness.
Progress on the CAmbridge Emission Line Surveyor (CAMELS)

Christopher N. Thomas\textsuperscript{1,*}, Ray Blundell\textsuperscript{2}, D. Glowacka\textsuperscript{1}, David J. Goldie\textsuperscript{1}, Paul Grimes\textsuperscript{2}, Eloy de Lera Acedo\textsuperscript{1}, Scott Paine\textsuperscript{2}, Stafford Withington\textsuperscript{1} and Lingzhen Zeng\textsuperscript{2}

\textsuperscript{1}Cavendish Laboratory, JJ Thomson Avenue, Cambridge, CB3 0HE, UK
\textsuperscript{2}Smithsonian Astrophysical Observatory, 60 Garden Street, Cambridge, MA 02138, USA

Abstract—The aim of CAmbridge Emission Line Surveyor (CAMELS) is to provide an operational demonstration of an Integrated Filter Bank Spectrometer (IFBS) for mm-wave astronomy. The prototype will observe from 103-114.7 GHz, providing of order 500 channels with a spectral resolution of 3000. In this paper we discuss the design of the instrument and ongoing work towards its realisation. Fabrication of a first set of devices to verify the key technologies has recently been completed. We will present results from a measurement campaign to characterise resonator performance and describe our planned optical tests.

The system block diagram of the CAMELS instrument is shown in Fig. 1. The design, which is illuminated from the underside on a membrane, uses horn antennas to detect changes in the sky. The design, which is illuminated from the underside on a membrane, uses horn antennas to detect changes in the sky. The design, which is illuminated from the underside on a membrane, uses horn antennas to detect changes in the sky. The design, which is illuminated from the underside on a membrane, uses horn antennas to detect changes in the sky. The design, which is illuminated from the underside on a membrane, uses horn antennas to detect changes in the sky.

III. Optical Design

Fig. 2 Details of antennas for CAMELS chips. a) Proposed 4-probe horn coupling. b) Concept for test devices. c) Photo of realised antenna on test device.
Qanaaq high school students visit, 5 May 2019