Invited Talk

The Greenland Telescope

R. Blundell

***Abstract* — The Greenland Telescope will consist of the ALMA North America prototype antenna, repurposed and modified to operate in the Arctic environment, with the principal scientific goal of imaging the Super Massive Black Hole at the heart of the M87 Galaxy. Many of the major antenna components and subsystems are currently undergoing modification or redesign at numerous facilities, worldwide. We expect to collect and reassemble these into a working telescope in the northeastern US during 2014 and 2015, and conduct science verification and commissioning during the winter 2015 – 2016. These tests will include Very Long Baseline Interferometry.**

***Index Terms* —mm and sub mm wavelength instrumentation, radio telescope facilities, Very Long Baseline Interferometry.**

I. INTRODUCTION

The potential use of mIllimeter wavelength Very Long Baseline Interferometry for the highest angular resolution observations of astronomical objects is well documented [1]. Several pioneering observations have been made, both on quasars used for calibration, and on astronomical objects of particular interest. Indeed, a number of radio observatories are working towards the development of the Event Horizon Telescope with the express purpose of studying in great detail SgrA*, the Super Massive Black Hole (SMBH) at the center of the Milky Way – one of only a few candidate objects large enough to enable detailed observations from the ground. Another such object is the SMBH at the center of M87, where greater mass relative to SgrA* results in a longer dynamical timescale accessible to observations constructed by Earth rotation. The Greenland Telescope will be located at 72 degrees north, close to the peak of the Greenland ice sheet, in order to provide the longest north-south baselines toward M87 when coupled to the Atacama Large Millimeter Array in northern Chile. It will also provide a key link between telescope facilities in Europe and the US; and will thus enable the longest baselines in the east-west direction, and hence the highest angular resolution. Furthermore, since the number of telescope facilities that can operate at millimeter and submillimeter wavelengths is limited, it will provide significantly improved imaging capability over the current array, which includes a maximum of 9 locations: The Plateau de Bure Interferometer (France); The IRAM 30 metre (Spain); The Submillimeter Telescope (Arizona); The Large Millimeter Telescope (Mexico); The Combined Array for Research in Millimeter-wave Astronomy (California); The Submillimeter Array (Hawaii); ALMA and/or the Atacama Pathfinder EXperiment (northern Chile); the South Pole Telescope for southern sources (Antarctica); and the MIT Haystack observatory at the longest wavelengths.

Besides enabling the highest angular resolution astronomical observations, the chosen location, at 72.5 degrees north, is also at high altitude with sufficiently transparent skies to offer the potential of sumbmillimeter single-dish astronomy observations – which may even extend into the Terahertz regime.

II. THE ANTENNA

The antenna, the ALMA North American prototype, was awarded via an open call for proposals, to the Smithsonian Astrophysical Observatory in 2011 by the National Science Foundation Division for Astronomical Sciences, for the express purpose of studying the Super Massive Black Hole at the center of the M87 Galaxy. Being an ALMA prototype, it was originally designed to operate from the high altitude site at Chajnantor in the Atacama Desert of northern Chile. In this environment it was specified to an exacting set of requirements to operate efficiently from centimeter wavelengths to about 0.3 mm. However, it was never

Fig. 1. The ALMA North American prototype antenna before disassembly at the Very Large Array Site, New Mexico, August, 2011.

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intended to operate under the extreme weather conditions that exist in the Arctic. As a result, numerous modifications and design changes are required in order to transform it for Arctic operation. Many of these modifications have been completed with guidance provided largely by our partner institute, the Academia Sinica Institute for Astronomy and Astrophysics of Taiwan. These include reworking the elevation bearings, the replacement of the azimuth bearing, the design and fabrication of a 6-point antenna base support to better enable an even distribution of the antenna load to a wooden raft and snow foundation, which is currently under design in consultation with the Cold Regions Research and Engineering Laboratory (CRREL) – the site recently selected for initial assembly and testing of the refurbished antenna. Other elements that have required significant redesign, or substantial rework include the electronics enclosures to house power systems, cryogenic compressors, and HVAC equipment; and the carbon fiber back up structure, which was repaired and modified to accept electrical wiring required to power a new reflector panel de-ice system that was never envisioned in the original design. The antenna drive motors / gearboxes, and the hexapod drive system that is used to position the secondary mirror, were redesigned for the Arctic environment. The quadrupod was replaced as it had been damaged during the ALMA acceptance testing of the prototype antenna. Insulating panels will be added to the main mechanical structure of the antenna. Additional insulation will be added to the receiver cabin, along with an improved thermal control system, and access to the cabin will be modified to better enable operations in the extreme Arctic environment.

III. THE SITE

The site, Summit Station, Greenland is a dry arctic environment ideally suited to millimeter, and submillimeter astronomical observations. It is potentially feasible to conduct observations in the supra-terahertz windows during the winter months, when the precipitable water vapor drops to about 0.25 mm for 10% of the time. Furthermore, at 72.5 degrees north and 38.5 degrees west, Summit Station is the ideal location to enable the longest baseline interferometry to ALMA in northern Chile, and provide the required additional, essential, link in the coupling of telescopes in northern Europe to those in the western US to better enable quality imaging. With reference to Fig. 3, even though M87 only reaches a maximum elevation angle of about 30 degrees, corresponding to two air masses, the quality of the atmosphere above the site makes Summit Station a viable proposition for VLBI observations at 345 GHz during the winter months.

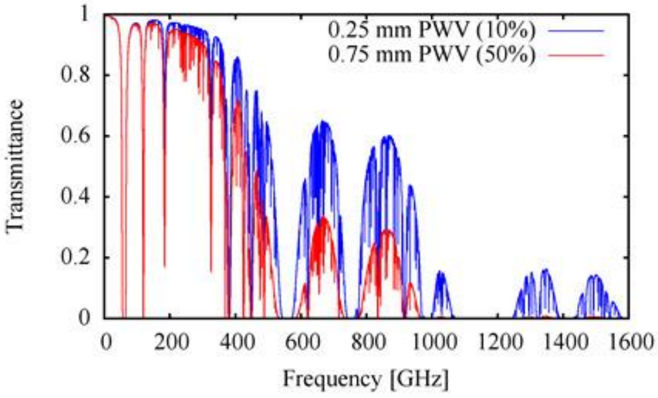

Fig. 2. Expected median and best decile atmospheric transmission versus observing frequency during the October – May observing season at Summit Station.

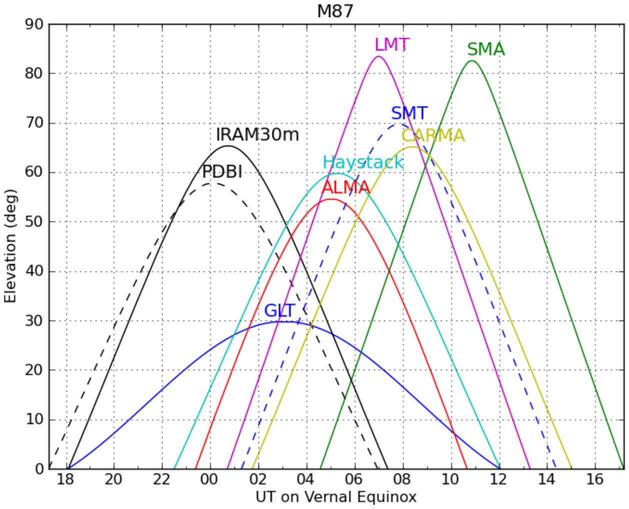

Fig. 3. Common visibility of M87 from millimeter and potential sub-millimeter VLBI stations.

The Summit Station facility was established by the US National Science Foundation (NSF) in 1989, and has been in year-round use since 2003. The scientific activity of the station includes the European Greenland Ice Core Project (GRIP), and the US Greenland Ice Sheet Project 2 (GISP2), which combined form the longest paleo-environmental record in the northern hemisphere, and atmospheric studies which rely on clean air and clean snow. The siting of a large telescope facility at Summit Station is viewed as an opportunity for the clean air, clean snow science to move away from the Station, which has been in active use for more than 20 years; and plans are being developed to enable such a move. Ideally, these activities would continue a few km to the south of the current Summit Station, close enough to the GRIP and GISP2 records, but sufficiently distant from the telescope, power generation equipment, ski-way used for aircraft access, and other scientific activities of which there are many during the summer months.

Access to the site is generally via LC-130, either from Thule Air Base or Kangerluussuaq, and fuel and cargo are hauled to the site once a year via the Greenland Inland Traverse (GrIT), operated by CH2M HILL Polar Services and CRREL in collaboration with the NSF. The GrIT, made up of a series of purpose-built sleds pulled by tractors equipped for Arctic operation, typically leaves Thule in early April and covers the 1,100 km distance to Summit Station in about 3 weeks. Each tractor can pull up to 80 tons, and they are used in parallel when climbing steep inclines, or in tandem on the descent. In order to reduce antenna assembly effort at the site, we are planning to ship in the largest possible subassemblies consistent with safe passage and capacity of the traverse.

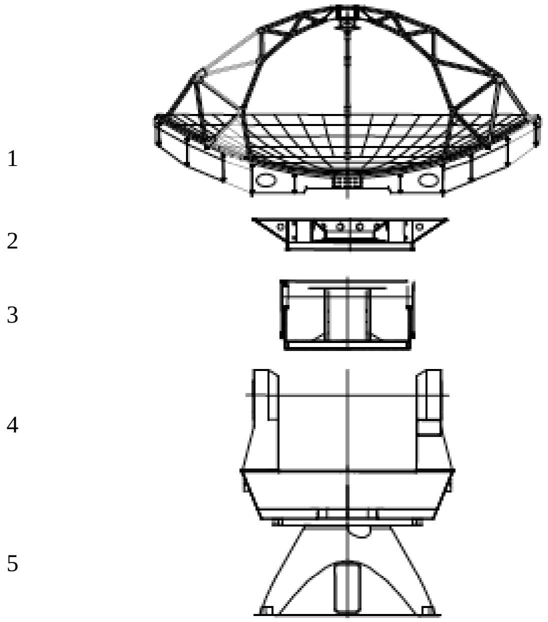

Fig. 4. The antenna may be broken down into large subassemblies to reduce assembly at the top of the Greenland Ice Sheet: 1) Reflector, 2) Reflector support cone, 3) Receiver cabin, 4) Yoke support, 5) Base.

IV. INSTRUMENTATION

The antenna will be equipped with single pixel receivers for the standard millimeter/submillimeter VLBI: 86 GHz, 230 GHz, and 345 GHz. In addition, and depending on the evolution of the science requirements, the antenna will be equipped with a variety of other heterodyne receivers, either single pixel or multi pixel, operating throughout the traditional submillimeter atmospheric windows from 230 GHz, potentially up to 1.5 THz. Bolometric array receivers have proven to be very successful in star formation studies and the search for high red shift galaxies at the APEX telescope and Herschel Space Observatory, and we anticipate similar instrumentation to be developed for the Greenland Telescope.

Several groups, worldwide, are currently focusing on a new class of receiver technology, which will enable arrays of detectors to be fabricated with reasonable spectral resolution (R~3,000). We recently began a collaboration with colleagues at the University of Cambridge to develop the CAMbridge Emission Line Surveyor (CAMELS) [2] that will demonstrate on-chip spectrometer technology for mm-wave astronomical observations. ‘On-chip’ spectrometers use a bank of narrow-band electrical filters, integrated onto the detector chip, which perform spectral channelization at signal frequency. This technology has a number of attractive features, including compactness and ruggedness compared with grating and FTS spectrometers, and the ability to realize systems with wide instantaneous bandwidths. On-chip spectrometers fabricated using Kinetic Inductance Detectors (KIDs) are expected to enable the construction of large format imaging arrays in which each pixel is also capable of wide-band, medium resolution, spectroscopy. This is a potentially revolutionary technology for galactic surveys, Cosmic Microwave Background (CMB) studies, for the detection and identification of high red shift objects, and for Earth observation and atmospheric science.

CAMELS will cover the frequency range 103-114.7 GHz at a resolution of R~3000, and will be tested first during the commissioning phase of the Greenland Telescope. It will target ^{12}CO(1-0) and ^{13}CO(1-0) line-emission from galaxies at redshifts z < 1 and will map emission at kPc scales in the nearest galaxies. A key aim of the project is to explore the operational issues associated with making science-grade observations using on-chip spectrometers, including flux- and frequency- calibration, and coping with different sky backgrounds and observing strategies. The full bandwidth will be divided between two pairs of detectors, each with 256 channels. One pair will cover the 103-109.8 GHz frequency range, the other will cover 109.8-114.7 GHz. Observing conditions in the two sub-bands are very different, and will allow us to investigate the detection of bright objects against a high background at the edge of the atmospheric window, and faint sources against a low background in the window centre. A pair of pixels will be provided at each frequency to allow for sky chopping.

The key technologies being developed in support of this project are:

A. *Optical Coupling Schemes for W-Band:*

Aluminium (Al) is commonly used for the sensing regions of KIDs where the optical photons break Cooper pairs. Simulation work performed at Cambridge has shown that the frequency of the optical signal must be well in excess of the pair-breaking frequency of the superconductor for pair-breaking to occur. In the case of Al, the pair-breaking frequency is 90GHz at 100 mK, making it a borderline absorber at the frequencies we are interested in. The group is therefore investigating β-phase Ta as a sensing material, which has a lower pair-breaking frequency (<70GHz) and a resistivity more compatible with that of the NbN used for the resonators. The coupler geometries currently under investigation are discussed in [1].

B. *Filter-Bank Technology:*

Key to the operation of an on-chip spectrometer is the design of the filter-bank at both the system and element level. At the element level bandpass filters, based on half-wavelength loop-resonators, have been developed which have demonstrated the required R-values in simulation. At the system-level, a statistical framework for analysing the astronomical performance of a filter-bank, given the system level design, (filter shape, overlap, number etc.) has been developed based on maximizing the Fisher criteria.

C. *Multichannel Readout:*

Readout of a KID requires generating a comb of probe tones, then monitoring the change in amplitude and phase after transmission through the resonator arrays. We are currently planning a solution based on the combination of fast ADC/DAC cards and GPU cards as processors.

V. SCHEDULE

Many of the major antenna components are currently being refurbished to enable reliable under in the harsh Arctic climate, a number of other components are being replaced, and several antenna subsystems are still in the design phase. As noted above, we recently selected the Cold Regions Research and Engineering Laboratory at Hanover (New Hampshire) as the site for antenna reassembly and test, and anticipate the arrival of significant sections of the antenna: base support, azimuth bearing, yoke, receiver cabin, back up structure support cone, back up structure support, and quadrupod during the summer. In a parallel effort, we are working with staff at CRREL to prepare a site plan consistent with the requirement that the antenna be fully assembled, debugged, and tested before shipping to Greenland.

Tests to be performed at CRREL include photogrammetry and holography to set and verify the reflector surface, and optical pointing and tracking. We will also test the de-ice system and a new hexapod system to support and position the secondary mirror assembly. Following assembly and verification of performance, the antenna will be equipped with single pixel heterodyne receivers, working at 86 and 230 GHz, in order to perform on sky tests, including first light single dish science verification observations, which will be followed by a series of VLBI test observations.

We have also begun to work with the NSF and subcontractors to define the infrastructure required to support the telescope and telescope operations at Summit Station, close to the peak of the ice sheet. While it seems entirely possible that, with little new infrastructure, the current station could support the additional staff required to assemble, test, and operate the telescope. A telescope control area, increased laboratory facilities, and additional power generation will be required, as well as a well-engineered snow foundation capable of providing a stable platform to enable astronomical observations with the telescope.

According to the current schedule, we anticipate that the infrastructure required to support and operate the telescope will be in place to enable telescope construction to begin during summer of 2018, which should make first light science observations possible from Summit during winter 2018 – 2019.

VI. ACKNOWLEDGEMENT

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