Astro2020 APC White Paper

Argus+: Wide-Field, High Resolution 3mm Molecular Imaging

Type of Activity:
■ Ground Based Project ☐Space Based Project ☐Infrastructure Activity
☐Technological Development Activity ☐State of the Profession Consideration ☐Other

Panel: Radio, Millimeter, and Submillimeter Observations from the Ground.

Principal Author:
Name: David T. Frayer
Institution: Green Bank Observatory (GBO)
Email: dfrayer@nrao.edu
Phone: 304-456-2223

Co-authors:
Felix J. Lockman (GBO), Paul Goldsmith (JPL), Andrew I. Harris (Univ. of Maryland), Kieran A. Cleary (Caltech), Joshua O. Gundersen (Univ. of Miami), Laura Jensen (GBO), Alvaro Hacar (Leiden University), Che-Yu Chen (Univ. of Virginia), Will Armentrout (GBO), Natalie Butterfield (GBO), Larry Morgan (GBO), Amanda Kepley (NRAO), Jialu Li (Univ. of Maryland), Ian Stephens (CfA/SAO), Sarah Sadavoy (CfA/SAO), Kevin Harrington (Univ. of Bonn, AIfA), Jaime Pineda (Max-Planck), Zhi-Yun Li (Univ. of Virginia), Anthony Readhead (Caltech), Sarah Church (Stanford), Steven White (GBO), Randy McCullough (GBO), Galen Watts (GBO), Dennis Egan (GBO), Martin Bloss (GBO)

Project Endorsers:
Loren Anderson (West Virginia Univ.), Héctor G. Arce (Yale Univ.), Tracy Becker (Southwest Research Institute), Robert Benjamin (U. Wisconsin-Whitewater), Alberto Bolatto (Univ. of Maryland), Amber Bonsall (GBO), Sara Cazzoli (Instituto de Astrofisica de Andalucia), Suchetana Chatterjee (Presidency University), Chian-Chou Chen (T.C.) (ESO), Claudia Cicone (INAF, University of Oslo), Martin Cordiner (NASA GSFC), Simon Dicker (U. Penn), James Di Francesco (NRC of Canada), Chuanfei Dong (Princeton), Rachel Friesen (NRAO), Tapasi Ghosh (GBO), J. Christopher Howk (Notre Dame), Alvaro Labiano (CSIC-INTA), Adam Leroy (Ohio State Univ.), Natalia Lewandowska (West Virginia Univ.), Amy Lovell (Agnes Scott), Ryan Lynch (GBO), Ron Maddalena (GBO), Brett McGuire (NRAO), Maura McLaughlin (West Virginia Univ.), Anthony Minter (GBO), Tony Mroczkowski (ESO), Hooshang Nayyeri (UC Ivine), Karen O'Neil (GBO), Dominic Pesce (CfA/Harvard & Smithsonian), Francesco Piacentini (Sapienza University of Rome), D.J. Pisano (West Virginia Univ.), Bindu Rani (NASA GSFC), Anthony Remijan (NRAO), Graca Rocha (JPL/Caltech), Erik Rosolowsky (U. Alberta), Chis Salter (GBO), Andrew Seymour (GBO), Yancy Shirley (University of Arizona), David Thilker (Johns Hopkins University), John Tobin (NRAO), Tony Wong (University of Illinois), Francisco Villaescusa-Navarro (Flatiron Institute), Al Wootten (NRAO)

Executive Summary:

The Green Bank Observatory[1] plans to construct a 144-element radio camera for spectroscopic studies in the 3mm band (74 –116 GHz) to operate as an open skies instrument on the Green Bank Telescope (GBT). The new camera, called Argus+, will provide a ten-fold increase in mapping speed compared to the current 16-element Argus pilot version of the instrument. Combining the $6' \times 6'$ field of view of Argus+ with the $6.5'' - 10''$ beam of the 100m GBT will provide high spatial dynamic range maps of interstellar molecules that are critical in understanding the physical processes and astrochemistry associated with star formation, from the scale of entire galactic disks to the sub-parsec scale of interstellar filaments and dense molecular cores. The GBT with Argus+ will be unequaled worldwide for wide-area 3mm spectroscopic mapping, and will be a critical complement to ALMA, which has high angular resolution but a small field of view. The full cost of the construction and deployment of the instrument is $12.8M, including institutional overheads.

1 Key Science Goals and Objectives

1.1 Background and Motivation

"The story of how successive generations of stars form from the gas and dust in the interstellar medium in both benign and exotic environments is fundamental to our understanding of, on the larger scale, the galaxies in which stars reside and, on the smaller scale, the planetary systems they might host" [1, DS2010 p 53]. This statement is just as relevant today as it was during the last decadal survey.

The question of how stars form out of interstellar gas is one of the outstanding problems of modern astrophysics, and the power of wide-area images of the radio sky to advance our understanding of star formation is profound. This is particularly true for molecular emission in the 3mm atmospheric window (74 –116 GHz) which hosts a treasure trove of fundamental transitions of important molecules, especially the low-J energy transitions that best trace the youngest star-forming clouds. Lines of ^{12}CO, ^{13}CO and C^{18}O trace the general molecular medium. Species like HCN, HNC, HCO$^+$, N$_2$H$^+$, and N$_2$D$^+$ trace the dense cloud cores from which stars form, while other species, such as SiO, trace shocks from protostellar outflows [32,39,44]. Mapping of molecular lines over wide areas has already made important contributions to solving some of the fundamental issues in star formation [6,9,20,22,23,38], particularly when these wide-field maps are combined with other tracers of the cool interstellar medium such as dust and HI [30,45,46].

As highlighted by many of the Astro2020 Science White Papers, wide-field mapping of molecular lines is key to furthering our understanding of the processes associated with star formation. **At least seven Astro2020 Science White Papers specifically called out the need for a large-format 3mm camera (e.g., N>100 elements) on a large single-dish telescope, such as the GBT, to study important science questions related to the formation of stellar systems and the associated physical processes and astrochemistry over wide spatial scales [10,18,31,35,36,40,47].**[2] In

[1] The Green Bank Observatory is a facility of the National Science Foundation and is operated by Associated Universities, Inc.

[2] The Astro2020 Science White Paper citations are marked in bold text throughout.

this Astro2020 APC White Paper, we propose to construct a 144-element heterodyne radio camera for the GBT that would operate in the 3mm band, called Argus+. This instrument would provide the scientific community with wide-field, high resolution 3mm molecular imaging capabilities unequaled worldwide.

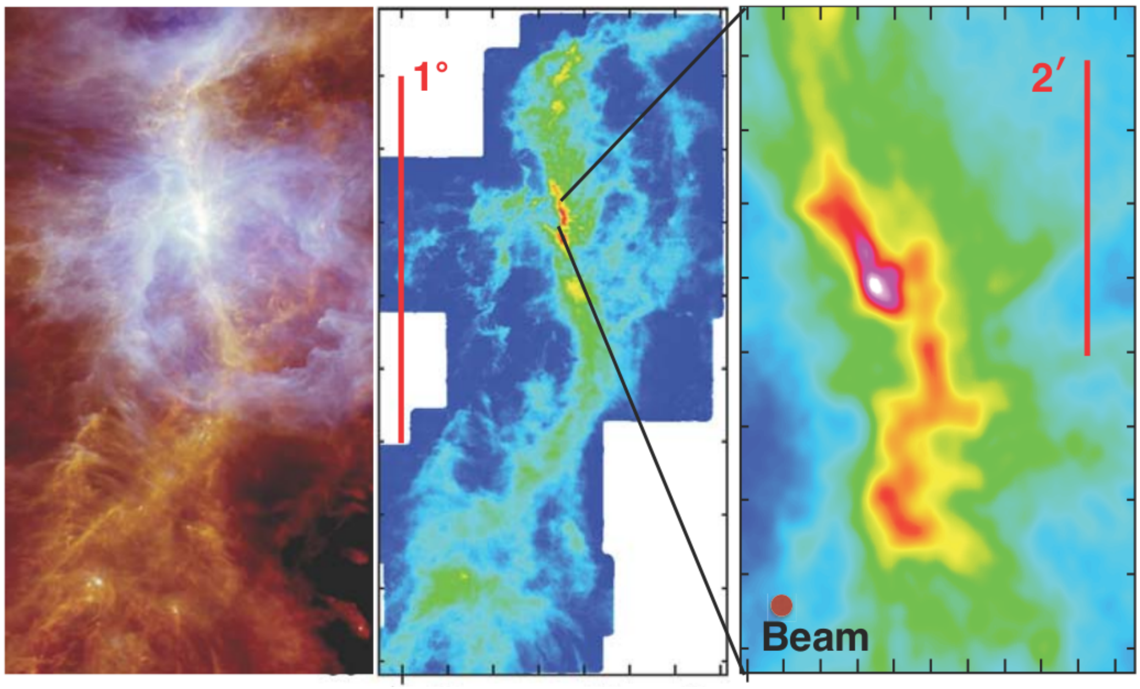


Figure 1: The power of high spatial dynamic range spectral line maps. On the left is a three-color (70μm+160μm+250μm) infrared continuum image of the Orion region from the *Herschel Space Observatory*. The center panel shows the integrated ^{13}CO emission map from the CARMA/Nobeyama survey on the same scale [26]. There is a ^{13}CO velocity-spectrum at every colored pixel. The right panel shows an enlarged portion of that survey with the beam size in the lower corner. The central map required 650 hours with the CARMA interferometer plus dozens of hours on the Nobeyama telescope to obtain the short spacings. The proposed Argus+ instrument will be able to make maps of this size and sensitivity at an identical angular resolution in only $\sim$40 hours of mapping time, opening up large areas of the sky for high spatial dynamic range imaging in molecular lines. (*Herschel* image credits: ESA/*Herschel*/André, Ph., Polychroni, D., Roy, A., Könyves, V., Schneider, N. for the Gould Belt Survey Key Program).

1.2 Scientific Justification

There are many gaps in our understanding of how nature assembles stars and solar systems from what is initially diffuse interstellar gas. The *Herschel Space Observatory* made groundbreaking wide-area measurements of molecular clouds and filaments through their infrared dust emission at an angular resolution of $20'' - 40''$ [Fig. 1; 3,5,25,27]. These data, along with *Spitzer* infrared dust surveys [14], have shown that filamentary structures, ~ 0.1 pc in thickness, are common in the interstellar medium, and it is possible that most stars form there [4,8,37]. But dust emission traces just a fraction of the gas [39] and, in any case, to fully understand the physical properties of these clouds and their evolution requires information on their kinematics, temperature, and density, that can only be supplied by spectral lines. Some of the key questions for star formation that Argus+ will address include:

- How do filaments form and evolve [3,4,**18**,43]?
- What are the mass accretion rates and formation time scales of dense cores within filaments **[18]**?
- And on the larger scale: what determines the distribution of dense gas across entire galaxies and how does this relate to star formation [19,24,28,29,**31**,48]?

In addition to understanding the physical processes associated with star formation, wide-area spectral-line surveys are key for disentangling the complex astrochemistry throughout the ISM and star-forming cores **[36,40]**.

However, the processes that influence star formation operate over an enormous range of linear scales, from galactic encounters on scales of $\sim$10 kpc that can set the overall star formation rate, to the sub-parsec scale of a cluster or a single star. Other important scales include the $\sim$1 kpc thickness of spiral arms, the 10–100 pc size of molecular clouds, the 1–10 pc length of molecular filaments, and the 0.1–1 pc size of dense cores out of which protostellar systems ($\lesssim 0.01$ pc) form. Large-area maps of nearby star-forming molecular clouds with $\sim$ 0.01–0.1 pc resolution are key to understanding the kinematics of gas within dense cores and filaments, their connection to the local environment within the molecular cloud complexes, and ultimately, the factors that regulate star formation. In addition to Galactic astronomy, Argus+ can map the entirety of nearby galaxies at the resolution needed to resolve individual cloud complexes to study star-formation and chemistry within different galactic environments, enabling direct comparisons with the nearby Galactic regions.

Acquiring and assembling consistent information spanning 6 orders of magnitude in spatial scale is a daunting task, but one that must be accomplished to make progress in understanding star formation [2,4,12]. A solution lies in the deployment of heterodyne mm-wave cameras on large single-dish telescopes such as the Robert C. Byrd Green Bank Telescope (GBT) which can deliver high spatial dynamic range maps of key molecules, with high angular resolution, high mapping speed, high sensitivity, and excellent velocity resolution. For example, at the frequency of 93 GHz for N_2H^+ (which is used to study dense molecular cores [11]), the GBT resolution is $8''$ which corresponds to 0.005 pc (1000 AU) at the distance of 140 pc for the nearby star-forming Taurus Molecular Cloud. Hence, the spatial resolution, as well as the spectral resolution, of the GBT/Argus+ is sufficient to measure the kinematics of the envelopes of young protostellar systems and constrain the initial conditions of protostellar disk formation within nearby star-forming regions [11].

Both the GBT and ALMA have similar collecting area and sensitivity within the 3mm band and are very complementary in terms of the spatial scales probed for the studies of nearby star-forming regions (at distances of 130–450 pc [e.g., 13]); ALMA is well suited to observe spatial scales from $\sim 10^{-4}$ pc to $\sim 10^{-2}$ pc, while the GBT can can observe spatial scales from $\sim 10^{-2}$ pc to $\gtrsim 10^{2}$ pc. Although the ALMA interferometer has amazing capabilities for molecular spectroscopy on the smallest angular scales, it suffers from spatial filtering of larger scale emission and a small field of view. This is where the GBT comes into play [7]. The GBT/Argus+ can provide the basic molecular data that link the large-scale properties of molecular cloud complexes on scales $\sim 100\,\mathrm{pc}$, down to the sub-parsec scale of filaments and compact star-forming cores. By mapping large areas, the GBT/Argus+ could also discover interesting new regions within molecular complexes that would enable follow-up higher spatial resolution imaging with ALMA.

Table 1: **Large Area Mapping Time**

Map Size, Frequency, and Sensitivity	ALMA	ACA	TP	Argus	Argus+
(1) 1 sq-deg, 110 GHz, $\sigma = 1\,\mathrm{K}$, $1\,\mathrm{km\,s^{-1}}$	35hr	310hr	660hr	10hr	1hr
(2) 1 sq-deg, 110 GHz, $\sigma = 0.2\,\mathrm{K}$, $1\,\mathrm{km\,s^{-1}}$	190hr	1760hr	2940hr	170hr	17hr
(3) 1 sq-deg, 93 GHz, $\sigma = 0.1\,\mathrm{K}$, $0.1\,\mathrm{km\,s^{-1}}$	3.9khr	32khr	55khr	2khr	0.2khr
(1) 1000 sq-deg, 110 GHz, $\sigma = 1\,\mathrm{K}$, $1\,\mathrm{km\,s^{-1}}$	35khr	310khr	660khr	10khr	1khr
(2) 100 sq-deg, 110 GHz, $\sigma = 0.2\,\mathrm{K}$, $1\,\mathrm{km\,s^{-1}}$	19khr	176khr	294khr	17khr	1.7khr
(3) 10 sq-deg, 93 GHz, $\sigma = 0.1\,\mathrm{K}$, $0.1\,\mathrm{km\,s^{-1}}$	39khr	320khr	550khr	20khr	2khr

The above mapping times (in hr and khr [10^3hr]) to reach the listed sensitivity levels in Kelvin [Tmb] at 110 GHz and 93 GHz (the frequency of ^{13}CO and the dense core tracer N_2H^+, respectively). The ALMA (12m Array), ACA (7m Array), and TP (ALMA Total Power Array) values were derived using the Cycle-7 ALMA Observing Tool based on the most compact ALMA configuration (C43-1), while the values for Argus and Argus+ include all the extra overheads required for accurate calibration and telescope corrections for high-frequency GBT observations. Large area mapping projects that take ~1–2 khr with the GBT/Argus+ would be possible if carried out over multiple years, while the corresponding time needed to reach similar sensitivities and mapped areas for ALMA+ACA/TP would be impossible.

Table 1 shows the relative mapping time between Argus+ and ALMA for three potential use cases: (1) Shallow mapping of ^{13}CO at 110 GHz with $1\,\mathrm{km\,s^{-1}}$ spectral resolution; (2) deeper mapping of ^{13}CO at 110 GHz with $1\,\mathrm{km\,s^{-1}}$ spectral resolution; (3) and mapping of N_2H^+ with $0.1\,\mathrm{km\,s^{-1}}$ spectral resolution, corresponding to the data required to study cold dense cores in detail. Even with shallow mapping, the CO lines (case 1) would be well detected over large regions of the Galaxy. The ALMA observations require many independent pointings to cover a wide area (e.g., 21,456 pointings per sq-degree at 110 GHz for the ALMA 12-m interferometer), and very long observations with the ACA(7m) array and the total power (TP) array to provide short-spacing information. The ALMA time estimates in Table 1 are computed for the most compact ALMA configuration, including the associated recommended observing times with the ACA and TP array to provide matching short-spacing data. The mapping times are listed separately for the 12m array (ALMA), the 7m array (ACA), and the ALMA TP Array (TP). The TP data are needed for spatial scales larger than $\gtrsim 60''$, while the ACA provides useful information over spatial scales of ~ 10–$60''$. The integration times required for the GBT/Argus+ are based the standard On-The-Fly (OTF) observing techniques that allow for efficient wide-area mapping, and include all the additional overheads (vanecal/point/focus/OOF) currently needed for accurate calibration and high-frequency observing on the GBT. **Argus+ would enable high-resolution molecular line studies over 10's of sq-degrees which are currently not possible.**

In summary, Argus+ will supply kinematic information on the complex dust structures in star forming regions mapped over wide fields by *Herschel* [3,5], with similar to better spatial resolution, and will thus be the spectroscopic successor to the *Herschel* satellite. With the factor of 10 increase in mapping speed, the entirety of several star-forming molecular clouds and nearby galaxies could be mapped within a reasonable amount of time. The Gould Belt survey of molecular clouds, and perhaps even a Galactic plane survey, could be observed in molecular lines with unprecedented resolution using Argus+. As an open-skies facility instrument of the GBO, it will be available for use by the U.S. scientific community and scientists worldwide.

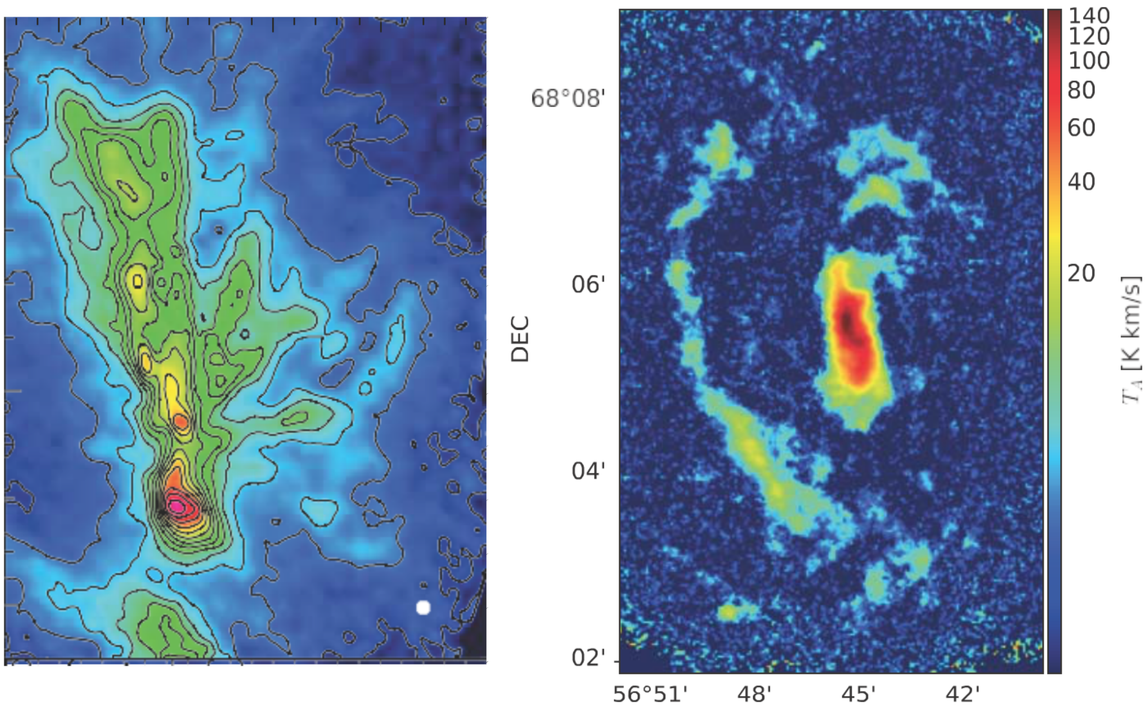


Figure 2: Left: A $6' \times 10'$ region of OMC-1 mapped by Argus in HNC(1-0), with the beam shown in white in the lower right (figure courtesy of Alvaro Hacar (Leiden University)). This 60 square arc-min map that took 4.5 hours with Argus would take about 30 minutes with Argus+. Right: Inner region of the galaxy IC342 mapped in ^{12}CO by Argus, courtesy of Jialu Li (University of Maryland), highlighting the ability of the GBT/Argus to work at 115 GHz.

2 Technical Overview

In recognition of the important science outlined in the previous section and the unique capabilities of the GBT, the NSF funded the development of a 16-pixel heterodyne camera — Argus — through ATI grant 1207825 (P.I. S. Church, Stanford University). Argus was commissioned on the GBT in late 2016 and achieved its expected on-sky performance. Argus is now in routine use on the GBT and is providing an important new capability to the scientific community (e.g., Fig. 2), but a major goal of the Argus project has always been to demonstrate radio camera technologies that could be scaled to larger format cameras in a straightforward way.

With this project the Argus team and the GBO staff will partner to fulfill the promise of Argus. We propose to construct and operate Argus+, a receiver-spectrometer combination that, compared to Argus, will provide a ten-fold increase in mapping speed. Argus+ will have 144 pixels arranged in a 12×12 element camera with a $6' \times 6'$ footprint on the sky. While most of the emission in Figures 1 & 2 would be filtered out by ALMA (without including very long integrations with the ACA and the ALMA Total Power Array), the GBT data will contain information on all scales from the basic angular resolution of the GBT ($6.5''$ – $10''$ for frequencies of 115 GHz to 75 GHz, respectively) to the full map size. Argus+ will provide the U.S. community with new capabilities that it does not otherwise have.

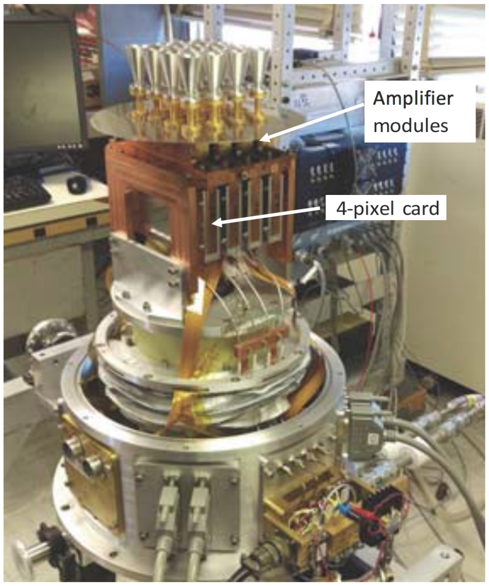
2.1 The Green Bank Telescope: A Unique Asset for 3mm Spectroscopy

The solid-panel, actively controlled surface of the GBT makes it the only 100-meter class telescope with a good main-beam efficiency at 3mm (44% at 86 GHz [16]). Its offset optics allow easy access to a focal plane that can readily accommodate the proposed large-format Argus+ radio camera [33, and references therein]. The GBT has an exceptionally clean main beam over its entire operating range [15]. With its angular resolution of $10''$ – $6.5''$ at 74 – 116 GHz, and open access, the capabilities of the GBT are a unique asset for the U.S. scientific community [7].

The statistical mode of the precipitable water vapor distribution in Green Bank for the high-frequency observing season (October – April) is between 5 and 6 mm [34], which is remarkably dry for the 820m elevation and Eastern United States location of the site. In comparison, this is similar to the Owens Valley site in the high desert of California, albeit there are many more rainy days in Green Bank than in Owens Valley per year. Factoring in winds and requiring the current nighttime limitations for maintaining a quality surface, approximately 900 hrs of excellent high-frequency time is available per year on the GBT (low winds, nighttime, and low opacity). Short-term thermal surface distortions, that are difficult to measure in real time, currently limit the usable 3mm time at the GBT to nighttime hours, but the GBO has been funded through the NSF's MSIP program to develop a laser scanning system that will measure the surface quickly and would allow 3mm operations during daylight hours. The GBT is a facility of the NSF and is currently funded for 60% competitively scheduled peer-reviewed use. This "open-skies" community time is available to anyone worldwide based solely on scientific merit. A large format camera like Argus+ is critical for making the most efficient use of the available community GBT 3mm time.

2.2 The Proposed Argus+ Instrument

The Argus+ project builds on the previously NSF-funded instrument research project Argus, which successfully demonstrated new scalable 3mm-band camera technologies. Argus began as a technology research project, and then became a general user instrument for the GBT without all the resources desired to transform it into a facility instrument. In contrast, the Argus+ instrument will be designed from the start as a facility user instrument, which will be easier to use by the general scientific community with improvements in observatory software.



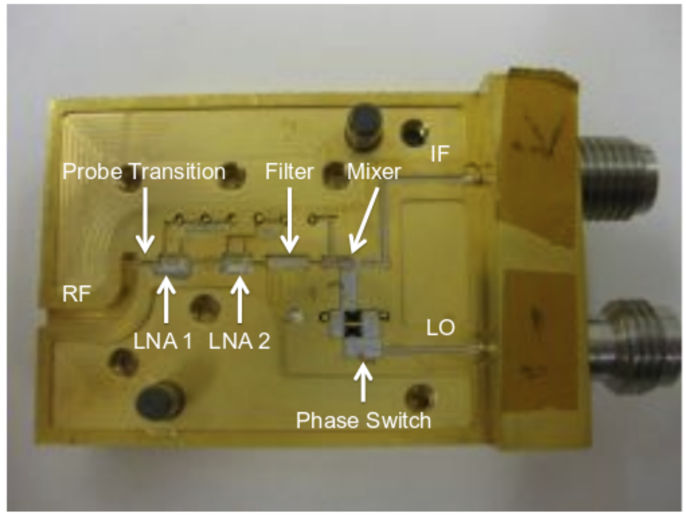


Figure 3: Left: Photograph of Argus during assembly within the GBO lab. Right: Photograph of one of the Argus integrated LNA modules [42].

2.2.1 Argus+ Camera

Argus uses a scalable architecture based on 4-pixel "cards" (Fig. 3). Each pixel comprises a single-polarization MMIC (Monolithic Microwave Integrated Circuit) low noise amplifier (LNA) module, based on indium phosphide high electron mobility (HEMT) amplifiers, designed at the Jet Propulsion Laboratory and manufactured by Northrop Grumman. The modules plug into high frequency cards that route both local oscillator and intermediate frequency signals (cold mixers are included in each module). The Argus+ camera will use 36 4-pixel cards (9 copies of Argus) in a single dewar, with a footprint of $6' \times 6'$ on the sky. Since the changes to the basic Argus modular design are minimal, the technical risk of Argus+ is very low. With 144 pixels and slightly improved noise amplifiers, Argus+ will have 10 times the mapping speed of Argus.

2.2.2 Spectrometer

A new digital spectrometer is required for the 144 pixels of Argus+. This will be located near the existing spectrometer, VEGAS, in the GBT control building and will be built by the team that built VEGAS. Analog intermediate frequency signals (IF) will be sent from the telescope to the spectrometer over fibers, as is currently done with Argus. The Argus+ spectrometer will have a single 600 MHz spectral window for each pixel that can be located anywhere in the Argus+ operational frequency range (74 – 116 GHz). The window will have 131k channels separated by 4.6 kHz for a total velocity coverage of 2,000 $\mathrm{km\,s^{-1}}$ with a channel separation of 0.015 $\mathrm{km\,s^{-1}}$ at 90 GHz. Single mode operation of the spectrometer greatly reduces its complexity and thus development costs, while the 600 MHz bandwidth retains the ability for simultaneous measurements of the HCN and HCO^{+} lines, or the ^{13}CO and $C^{18}O$ lines, with a single LO tuning, as is currently the case for Argus. The Argus+ IF system could be increased from 1.5 GHz to 7.5 GHz at negligible cost, allowing future spectrometer upgrades to increase the instantaneous frequency coverage, as advances in digital technologies become more affordable. These upgrades would greatly benefit spectral-line survey programs. There will be occasions where Argus+ will be used to observe relatively small angular-sized objects with very broad lines (e.g. galactic nuclei), so we will retain the ability to connect a block of 16 pixels of Argus+ to the VEGAS spectrometer for spectroscopy at 1250 MHz instantaneous bandwidth. Thus, there will be no loss of any of the current scientific capabilities when Argus is replaced by Argus+.

2.2.3 LO Upgrade

To fully enable the increased mapping speeds provided by the Argus+ instrument, the local oscillator (LO) synthesizer will be updated on the GBT. Currently, the GBT LO limits frequency switching observations to a 0.4 second switching period. Frequency switching observations are required to map extended regions where nearby line-free "OFF" positions are not available (as is the case for CO and many other species). Given the need to sample data on the sky at $\lesssim 2''$ in the scanning direction to avoid source smearing, the scanning speed of the GBT is effectively limited to only about $5''/\mathrm{s}$ for frequency-switched observations. The current LO would be a limiting factor in the time it takes to map large areas with Argus+ for the bright CO lines [e.g., Table 1, shallow case (1)]. For example, Galactic ^{13}CO with the GBT can be detected in less than 1 second of integration time per beam area on the sky (for $1\,\mathrm{km\ s^{-1}}$ spectral resolution). Dividing this by a reasonable number of data samples (~ 100) that would result from a well sampled OTF map with the 12×12 Argus+ feedhorns results in a required sample time of 10ms. Based on this sample time for frequency switching data, a LO switching period of 10ms would be needed for fast Argus+ scanning. With this faster LO switching, the mapping rate of Argus+ could be increased by a factor 40 over what is currently possible, which is still well below the maximum slew rates of the GBT.

The implementation of a new LO system on the GBT would be straight-forward. The GBO would replace the primary LO synthesizer (LO1a) with two new LO synthesizers and a fast electronic switch. We would adopt the same LO's that are currently being used to upgrade the GBT LO2 synthesizers, so no additional software development or hardware component testing would be required. For redundancy, the secondary LO synthesizer (LO1b) would also be replaced in the same way, so 4 new LO synthesizers would be purchased. The total cost, including labor, amounts to adding only about $50k to the total budget.

2.2.4 Software

The proposed budget includes the software resources required to integrate the instrument into the GBT monitor and control systems to allow for easy use of the instrument by observers. In addition, upgrades to the current GBT pipeline software and computing resources will be made to enable realtime data quality assessments and quick-look image products. These capabilities are currently lacking with the GBT/Argus system and will require significant improvements for the larger data volumes that Argus+ will provide.

The Argus+ pipeline will build upon the current GBT pipeline infrastructure developed by NRAO and modified by E. Rosolowsky for the GBT KFPA and Argus survey teams. These pipeline tools will enable non-GBT experts to process the raw archived Argus+ data effectively. The staff at the Green Bank Observatory will also work with the Argus+ science teams in order to disseminate science quality data products for use by the broader astronomy community.

3 Organization, Partnerships, and Current Status

The Argus+ project will be managed by the Green Bank Observatory in adherence with the NSF's requirements as per its Large Facilities Manual (NSF 17-066). The Green Bank Observatory will oversee the overall engineering design, be responsible for all aspects of the spectrometer, and will integrate the Caltech/JPL modules into the Argus+ instrument. The Green Bank Observatory will also be responsible for the lab testing of the instrument and its and commissioning on the GBT.

Caltech/JPL will oversee the amplifier design, fabrication, and screening, as well as the receiver module assembly, testing, and integration. The receiver modules are the most crucial and technically challenging aspects of the instrument. However, this group has already successfully completed these functions for Argus, and there are no new technology drivers for Argus+. Hence, the project is low risk.

The University of Maryland will provide advice and expertise related to the Argus design expansion. In particular, they will assist with the design of the Argus+ warm electronics and the monitoring and control firmware of the instrument.

The University of Miami designed and oversaw fabrication of the Argus cryostat and is responsible for the design of the cryostat for the Argus+ camera. The cryostat will house the feedhorns, the heterodyne camera modules, and associated power and signal cabling.

4 Schedule

We estimate a total of 4 years to bring Argus+ to completion. Systems engineering and design will occur during years 1 & 2 as personnel are also recruited for the fabrication and testing phase. Construction will occur in year 3, and lab testing and commissioning on the GBT will occur in year 4. Argus+ is expected to be available for the general user community via the NSF's funded open-skies time via the standard GBT proposal call starting in the second semester of year 4 or the first semester of year 5. The instrument has an expected useful science lifetime of at least 10 years.

5 Cost Estimate

The budget presented here covers the full cost of the construction, testing, and commissioning of the Argus+ instrument on the GBT (based on fiscal year 2020 starting values). The cost analysis was done previously for the NSF Mid-Scale Research Infrastructure-1 (Mid-scale RI-1, NSF 19-537) 2019 proposal which was not funded. The budget listed here is similar as previously proposed to the NSF, except for removing the EPO funding and Science Surveys portion of the budget, which is outside of the scope budgeted here for the building and deployment of the instrument. The budget for the NSF proposal has been previously reviewed and approved by AUI/NRAO/GBO, Caltech/JPL, University of Maryland, and the University of Miami for their respective roles in the project.

Table 2: **Budget Summary**

Work Package	**Labor**	**Equipment**	**Travel**	**Subawards**	**Subtotal**	**% of Budget**
Spectrometer	$1,341,620	$274,379	....	....	$1,615,999	13%
Receiver	$1,208,971	$1,325,491	$36,024	$1,557,015	$4,127,501	32%
LO Upgrade	$5,000	$45,000	....	....	$50,000	0.4%
Science & Management	$611,825	....	$86,904	....	$698,729	5%
Software	$1,520,608	$23,000	....	....	$1,543,608	12%
Computing	$70,491	$675,576	....	$20,000	$766,067	6%
Commissioning	$335,258	....	....	....	$335,258	3%
Subtotals	$5,093,773	$2,343,446	$122,928	$1,577,015	$9,137,162	71%
				Overheads:	$3,654,865	29%
				Total:	$12,792,027	100%

6 Broader Impact

Argus+ will be a general purpose wide-area mapping instrument for the research community, ideal for the study of everything from the evolution of comets **[35]** to the study of astrochemistry **[40]** and molecular clouds in the Galaxy **[18]**, nearby galaxies **[31]**, and even high-redshift galaxies and proto-clusters **[21]**. It will provide capabilities not available elsewhere, with open access for U.S. scientists and scientists worldwide [7].

Additionally, Argus+ will have an extraordinary range of educational impacts. The project will involve several undergraduate and graduate students during its construction, commissioning, and early science operations. This impact cannot be overstated, as the coalescing of the U.S. community around larger facilities such as ALMA and the closing of university radio observatories has severely curtailed the opportunities for training the next generation of radio instrumentation specialists. In addition, to the Argus+ partner institutions (Caltech/JPL, the University of Maryland, and the University of Miami), the GBO has close collaborative connections with West Virginia University, the University of Virginia, and the National Radio Astronomy Observatory, which provides the opportunity for project involvement for a significantly larger pool of nearby students and young researchers. A significant amount of construction and testing will occur at the Green Bank site, enabling students from all these institutions to collaborate face-to-face with GBO staff.

The GBO has been on the forefront of STEM education for several decades, integrating scientific discovery into high school and undergraduate curricula [41,49,50]. The GBO is leading an NSF INCLUDES alliance funded for FY2018-FY2023 that aims to improve the persistence of first generation STEM majors. From an educational standpoint, because Argus+ is essentially a scaled-up version of a proven instrument, it is well suited for student involvement at all levels.

7 References

- **[1]** DS2010 — Committee for a Decadal Survey of Astronomy and Astrophysics, New Worlds, New Horizons in Astronomy and Astrophysics, 2010, National Academies Press, Washington, D.C.
- **[2]** Report of the Panel on Planetary Systems and Star Formation. National Research Council. 2011. Panel Reports —New Worlds, New Horizons in Astronomy and Astrophysics. Washington, DC: The National Academies Press. doi: 10.17226/12982.
- **[3]** André et al. 2010, From filamentary clouds to prestellar cores to the stellar IMF: Initial highlights from the Herschel Gould Belt Survey, A&A, 518, L102
- **[4]** André et al. 2014, From Filamentary Networks to Dense Cores in Molecular Clouds: Toward a New Paradigm for Star Formation, Protostars and Planets VI, Henrik Beuther, Ralf S. Klessen, Cornelis P. Dullemond, & Thomas Henning (eds.), University of Arizona Press, Tucson, 914 pp., p.27-51
- **[5]** Arzoumanian et al. 2011, Characterizing interstellar filaments with Herschel in IC 5146, A&A, 529, L6
- **[6]** Bally 2016, Protostellar Outflows, ARAA, 54, 491
- **[7]** Bally et al. 2018, The Case for a Publicly Available, Well-Instrumented GBT Operating at 20-115 GHz, GBT Memo #299
- **[8]** Bergin & Tafalla 2007, Cold Dark Clouds: The Initial Conditions for Star Formation, ARAA, 45, 339
- **[9]** Buckle et al. 2012, The JCMT Legacy Survey of the Gould Belt: mapping 13CO and C18O in Orion A, MNRAS, 422, 521
- **[10]** Butterfied et al. 2019, Investigating the gas in the Galactic Bar: the missing link between the Galactic Disc and the Central Molecular Zone, **Astro2020 Science White Paper**
- **[11]** Chen et al. 2019, Investigating the Complex Velocity Structures within Dense Molecular Cloud Cores with GBT-Argus, MNRAS, submitted
- **[12]** Dobbs et al. 2014, Formation of Molecular Clouds and Global Conditions for Star Formation, Protostars and Planets VI, Henrik Beuther, Ralf S. Klessen, Cornelis P. Dullemond, and Thomas Henning (eds.), University of Arizona Press, Tucson, 914 pp., p.3-26
- **[13]** Evans et al. 2014, Star Formation Relations in Nearby Molecular Clouds, ApJ, 782, 114
- **[14]** Evans et al. 2003, From Molecular Cores to Planet-forming Disks: An SIRTF Legacy Program, PASP, 115, 965
- **[15]** Frayer 2017, The GBT Beam Shape at 109 GHz, GBT Memo #296

- **[16]** Frayer et al. 2019, Calibration of Argus and the 4mm Receiver on the GBT, GBT Memo #302

- **[17]** Friesen et al. 2017, The Green Bank Ammonia Survey: First Results of NH3 Mapping of the Gould Belt, ApJS, 843, 63.

- **[18]** Friesen et al. 2019, Star-Forming Filaments and Cores in Molecular Clouds, **Astro2020 Science White Paper**

- **[19]** Gao & Solomon 2014, The Star Formation Rate and Dense Molecular Gas in Galaxies, ApJ, 606, 271

- **[20]** Goldsmith et al. 2008, Large–Scale Structure of the Molecular Gas in Taurus Revealed by High Linear Dynamic Range Spectral Line Mapping, ApJ, 690, 428

- **[21]** Harrington, Frayer, & Dannerbauer 2019, The Extended Cool Gas Reservoirs within $z > 1$ (Proto-)Cluster Environments, **Astro2020 Science White Paper**

- **[22]** Heyer et al. 1998 The Five College Radio Astronomy Observatory CO Survey of the Outer Galaxy, ApJS, 115, 241

- **[23]** Jackson et al. 2006, The Boston University-Five College Radio Astronomy Observatory Galactic Ring Survey, ApJS, 163, 145.

- **[24]** Kepley et al. 2014, The Green Bank Telescope Maps the Dense, Star-forming Gas in the Nearby Starburst Galaxy M82, ApJ, 780, L13

- **[25]** Kirk et al. 2013, First results from the Herschel Gould Belt Survey in Taurus, MNRAS, 432, 1424

- **[26]** Kong et al. 2018, The CARMA-NRO Orion Survey , ApJS, 236, 25

- **[27]** Könyves et al. 2015, A census of dense cores in the Aquilla cloud complex: SPIRE/PACS observations from the Herschel Gould Belt Survey, A&A, 584, A9

- **[28]** Krumholz & Thompson 2007, The Relationship between Molecular Gas Tracers and Kennicutt-Schmidt Laws, ApJ, 669, 28

- **[29]** Lada et al. 2012, Star Formation Rates in Molecular Clouds and the Nature of the Extragalactic Scaling Relations, ApJ, 745, 190

- **[30]** Lee et al. 2015, Cold and warm atomic gas around the Perseus molecular cloud. II. The impact of high optical depth on the HI column density distribution and its implication for the HI-to-H2 transition, ApJ, 809, 56

- **[31]** Leroy et al. 2019, Physical Conditions in the Cold Gas of Local Galaxies, **Astro2020 Science White Paper**

- **[32]** Leroy et al. 2017, Millimeter-wave Line Ratios and Sub-beam Volume Density Distributions, ApJ, 835, 217

- **[33]** Lockman et al. 2018, The National Science Foundation's AST Portfolio Review of 2012 is Not Relevant to the Green Bank Telescope of 2017, GBT Memo #298
- **[34]** Lockman & Maddalena 2010, Weather Conditions at Green Bank Relevant to Observing at mm-Wavelengths, GBT Memo #267
- **[35]** Lovell et al. 2019, Ground-based Observations of Small Solar System Bodies: Probing Our Local Debris Disk, **Astro2020 Science White Paper**
- **[36]** McGuire et al. 2019, Closing Gaps in Our Astrochemical Heritage: From Molecular Clouds to Planets, **Astro2020 Science White Paper**
- **[37]** McKee & Ostriker 2007 Theory of Star Formation, ARAA, 45, 565
- **[38]** Narayanan et al. 2008, The Five College Radio Astronomy Observatory CO Mapping Survey of the Taurus Molecular Cloud, 2008, ApJS, 177, 341
- **[39]** Pety et al. 2017, The anatomy of the Orion B giant molecular cloud: A local template for studies of nearby galaxies, A&A, 599, A98
- **[40]** Remijan et al. 2019, Observational Astrochemistry in the Next Decade, **Astro2020 Science White Paper**
- **[41]** Rosen et al. 2010, Pulsar Search Collaboratory, Astronomy Education Review, 9, 1
- **[42]** Sieth 2016, Argus: A 16-pixel Millimeter-wave Spectrometer, Ph.D. Thesis, Stanford
- **[43]** Seo et al. 2015, An Ammonia Spectral Map of the L1495-B218 Filaments in the Taurus Molecular Cloud. I. Physical Properties of Filaments and Dense Cores, ApJ, 805, 185
- **[44]** Shirley 2015, The Critical Density and the Effective Excitation Density of Commonly Observed Molecular Dense Gas Tracers, PASP, 127, 299
- **[45]** Stanimirovic et al. 2014, Cold and warm atomic gas around the Perseus molecular cloud. I. Basic Properties, ApJ, 793, 132.
- **[46]** Storm et al. 2016, CARMA large area star formation survey: Dense gas in the young L1451 region of Perseus, ApJ, 830, 127
- **[47]** Thilker et al. 2019, The Nature of Low-Density Star Formation, **Astro2020 Science White Paper**
- **[48]** Usero 2015, Variations in the Star Formation Efficiency of the Dense Molecular Gas across the Disks of Star-forming Galaxies, AJ, 150, 115
- **[49]** Williamson et al. 2014, The Space Public Outreach Team (SPOT): Adapting a successful outreach program to a new region, CAPjournal, No. 16, p. 8
- **[50]** Williamson et al. 2016, D. Skynet Junior Scholars Professional Development to Support STEM Exploration in a Variety of Settings, Connected Science Learning Vol.1 p 2.