A Search for Advanced Extraterrestrial Life with *MeerKAT*

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with

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Abstract

Over the last several decades, observational astronomy has produced a flood of discoveries that suggest that the building blocks and circumstances that gave rise to life on Earth may be the rule rather than the exception. Further, terrestrial biology has shown that life on our own planet can thrive in extraordinarily extreme environments, dramatically extending our notion of what constitutes habitability. In just the last decade, the ubiquity of planets around other stars has become an indisputable fact. The deeper question, yet unanswered, is whether or not life in any form has ever existed in an environment outside of the Earth. As humans, we are drawn to an even more profound question, of whether or not extraterrestrial life may have evolved a curiosity about the Universe similar to our own and the technology with which to explore it.

We know of no way to directly detect intelligent life, but we do know that electromagnetic emission from technologies like our own are readily detectable at interstellar distances if transmitted with sufficient power and observed with sufficient sensitivity. The detection of electromagnetic emission from extraterrestrial technologies can thus be used as a proxy for the detection of extraterrestrial intelligence.

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[1]These collaborators have expressed an interest in engaging with the proposed project but have not directly participated in writing the text of this proposal. We intend the bulk of this proposal to be published in the *MeerKAT Science: On the Pathway to the SKA* conference proceedings, prior to which the collaborators below will be invited to participate as authors.

Here we present the scientific potential for using *MeerKAT* to conduct a search for advanced extraterrestrial life (SETI), the technical requirements necessary to make these observations possible, and formally propose a campaign to conduct them.

Background

Breakthrough Listen: In July 2015, The Breakthrough Prize Foundation announced the *Breakthrough Initiatives* − a series of programs that will investigate the possibility of life beyond Earth and the relationship between humanity and life in the universe. Among the initiatives announced is *Breakthrough Listen*, a US$100M 10−year effort to conduct the most sensitive, comprehensive, and intensive search for advanced intelligent life on other worlds ever performed. The *Breakthrough Listen Initiative* is currently employing three telescopes, the *Green Bank Telescope* and the *Parkes Observatory* operating at radio wavelengths and the optical *Automated Planet Finder*.

Radio emission from advanced technology is well established to be an effective tracer of intelligent life. These signals transit interstellar space easily and are readily detectable with our own current technology if sufficiently luminous. *MeerKAT* presents opportunities for novel and sensitive searches for radio emissions produced by extraterrestrial technology, notably, targeted searches of millions of nearby stars, exploration of regions of the sky that have never before been observed at high sensitivity, and laying the groundwork for future searches with the *Square Kilometre Array*.

A SETI program on *MeerKAT* would be very complementary to other components of the *Breakthrough Listen Initiative*. *MeerKAT* would provide parity in instrumental sensitivity with the GBT and could conduct southern hemisphere targeted observations in parallel with the galactic plane survey conducted with the Parkes Telescope. Array telescopes are the *only way to achieve the BL goal of conducting sensitive cm-wave observations of 1 million nearby stars* and *MeerKAT* is well-positioned to play a key role.

Array telescopes, like *MeerKAT*, naturally allow multiple observations to take place simultaneously. Using digital beamforming with an independent backend, we can can independently steer beams on the sky at targets of interest, toggle between targets, and look at multiple targets at once (Figure 1). This allows a very powerful targeted search for extraterrestrial intelligence to be conducted commensally, without exclusively allocated telescope time.

Here we propose to operate a commensal SETI program on *MeerKAT* in support of the *Breakthrough Listen Initiative* via installation of a custom commensal digital backend colocated in the Karoo Array Processor Building. This system will be capable of phasing all 64 *MeerKAT* antennas to 64 independent sky positions over 856 MHz of dual-polarization bandwidth and conducting a variety of searches for emission indicative of technology on the resultant data streams.[2]

For additional discussion of radio searches for extraterrestrial intelligence in the context of SKA, we refer the reader to (Siemion et al. 2015) and references therein.

[2]We note that as a component of *MeerKAT* technical development, a seven element engineering test array called KAT7 was constructed on the same Northern Cape site that will host *MeerKAT*. KAT7 is currently operating with five of the seven original elements. Although its future is uncertain, KAT7 could be used as an interim step toward *MeerKAT*, and if it continues to function could act as a follow-up facility for a commensal *MeerKAT* campaign.

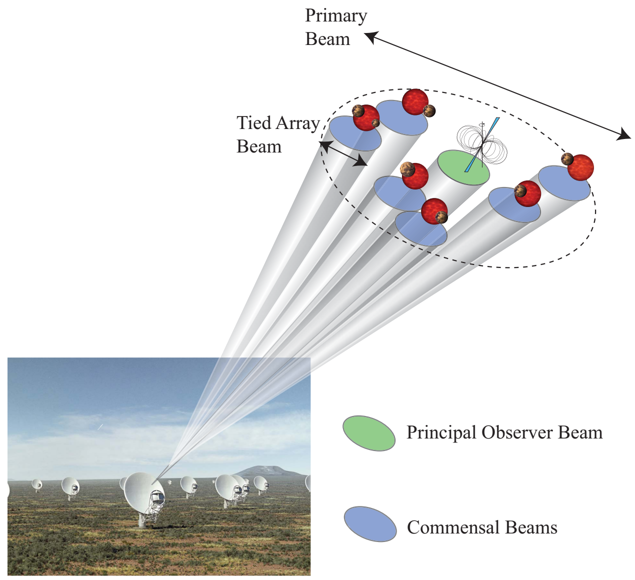

Fig. 1.— An illustration of multibeam SETI searches conducted commensally. As depicted, while a principal observer is conducting a tied-array observation of a pulsar, multiple independent beams can be formed by the proposed independent digital backend and pointed at nearby stars searching for signs of technology

The remainder of this proposal is structured as follows: Section 1 provides a technical description of the instrumentation required to conduct the proposed program and a proposed installation timeline. Section 2 describes a demonstrative commensal observation campaign considering use of MeerKAT by diverse principal observers and Large Survey Projects. Section 3 describes the proposed program in relation to other SETI programs internationally. Section 4 describes the organizational structure of the proposed program. Section 5 provides an overview of Project Management for the proposed program. Section 6 details our public engagement and outreach strategy. Section 7 briefly describes our plans and intentions for participating in developing the scientific and engineering capacity in South Africa. Finally, Section 8 notes opportunities for the proposed project to participate in radio frequency interference (RFI) mitigation efforts at the *MeerKAT* site.

1. Technical Project Description

Here we provide a description of the proposed instrumentation and a tentative deployment timeline. Although in the description below we describe discrete beamformer and SETI signal detection components, a second option is to receive digitized signals from each dish or array element directly into a monolithic computational system (e.g. a GPU cluster), and perform both the beamforming and signal detection operations in succession on the same hardware platform. This has the advantage of minimizing data transport, and is likely preferable for large numbers of beams. This approach also allows virtually unlimited flexibility in how signals are processed. However, it is technically more complex, and in order to get calibration information requires either tight integration with the existing digital infrastructure, or replication of that functionality at increased cost.

1.1. Required Resources

The critical physical resources for enabling the proposed program are space, power and cooling in the Karoo Array Processor Building (KAPB) for digital beamforming and signal processing hardware and full 40 GbE multicast access to digitized voltage data from all 64 individual antenna stations. In brief, and per discussions with SKA-SA personnel, this consists of an Emerson air handling unit (AHU) – 115kW model, 16 APC netshelter racks, 900 mm deep, one or two APC remote controlled zero-U PDUs, a pair of power busbars and associated outlets with circuit breakers (per rack), and switches and cables to extend management network to the PDUs and diagnostic ports of equipment in the racks. We anticipate that digitized voltage data will be provided over 64 40-GbE optical links, and that providing this capacity will require augmentation to the existing *MeerKAT* network infrastructure.

1.2. Project Timeline

October 2016 – PHASE 1
Construct simulation environment at Allen Telescope Array (ATA, 16 antenna) that mimics *MeerKAT*. Deploy single node systems to both *MeerKAT* and the KAT-7 test array.

January 2017 – PHASE 2
Deploy a digital equipment shell in the Karoo Array Processor Building, South Africa, supporting sixteen 42U racks operating within a power envelope of 115kW. Prototype beamformer and signal detection hardware in ATA or simulation environment.

July 2017 – PHASE 3a
Deploy 40 GbE network infrastructure to connect the BL digital equipment shell to the *MeerKAT* telescope.

July 2017 – PHASE 3b
Initial deployment to digital equipment shell: Installation of beamformer hardware, first 25%. Installation of digital recorder hardware, first rack. Demonstration of real-time source tracking and recording to disk.

October 2017 – PHASE 3c
Installation of beamformer hardware, 100% Installation of digital recorder hardware, rack 2. Demonstration of real-time candidate selection. Commence science observations.

July 2018 – PHASE 4
Installation of digital recorder hardware, racks 3-8. Commence the BL Million Star Survey.

2019 - 2020 – PHASE 5
Science observations - Archive and maintenance

January 2021 – PHASE 6
Upgrade GPU and DRAM - full diskless realtime operation. Upgrade storage nodes.

2021 - onward – PHASE 7

Transition to SKA1-Mid.

1.2.1. Design Overview

MeerKAT will provide digitized Ethernet timestreams from all 64 telescopes. From these timestreams, 64 tied-array beams will be formed, upon which the SETI search will be conducted. There will therefore be two main subsystems:

Beamformer subsystem. This subsystem will be FPGA-based, and will likely use the SKARAB platform developed for *MeerKAT*. We will investigate alternative architectures in which FPGAs perform some pre-processing functions, and later stages of beamforming are performed on the SETI Search Subsystem (see below). The beamformer will provide up to 64 tied-array beams at full bandwidth (856 MHz @ 10 bits), channelized into coarse channels.

SETI Search Subsystem. This subsystem will use commodity GPU-based servers to search the tied-array beams for candidate signals in real time, writing signals of interest to disk. When fully installed, 5 PB of local storage will be available.

1.3. Project Phases

This program initially will leverage a development platform at the ATA concurrently with infrastructure implementation on site. We will start with a single beam on *MeerKAT* and upgrade as resources become available. This allows for science as soon as possible, leading into the full science program and future upgrades.

Phase 1 – Development Have an end-to-end demonstration system running at the Allen Telescope Array or a simulation environment at UC Berkeley. Demonstrate signal flow from prototype beamformer through Ethernet, GPU and to disk.

Phase 2 – Shell Construction In cooperation with SKA South Africa, build out necessary equipment shell in the Karoo Array Processor Building at the *MeerKAT* site, provision network capacity, test links.

Phase 3a - Wiring the Shell Install first rack of digital recorder hardware and all Ethernet switches.

Phase 3b - Single Beam Development System Install a system capable of ingesting 16 antenna inputs and forming 1-4 beams at *MeerKAT* site. Demonstrate real-time source tracking and recording to disk

Phase 3c - Eight Beam Recording System Complete installation of beamforming hardware for 64 inputs, capable of 64 beamformed output. Install of digital recorder hardware, racks 2, 3 and 4. Demonstrate 8-beam recording capability and real-time data analysis.

Phase 4 - Full System Deployment Complete installation of digital recorder subsystem. Demonstrate all 64-beams with real-time candidate detection. Initiate science operations.

Phase 5 - Full Scale Science Observations

Phase 6 System Upgrade and Maintenance Upgrade GPUs from Pascal to Volta (performance per watt and peak performance both increase by a factor of 2). This decreases operational costs while at the same time improving performance. Upgrade system DRAM to support full diskless real-time observations. Upgrade fixed disks in storage nodes to improve performance, reliability and capacity.

Phase 7 - Transition to SKA1-Mid Facilitate transition of our observing system from *MeerKAT* to SKA1-Mid. This transition will increase sensitivity by a factor of 4 and, potentially, provide additional bandwidth.

2. Observational Program

The proposed observational program will performed alongside other (principal) users of the telescope, matching observing cadence with that of the principal observer. Most objects that would be included in a targeted SETI catalog, including nearby stars, nearby galaxies, and known transiting exoplanet systems are roughly isotropic on the sky, and thus with a sufficiently large catalog of objects we can be certain that a handful are present within the primary beam of the telescope regardless of where it is pointed. A small amount of observing time for follow up observations, $5-10$ hours per month, would significantly improve the speed and productivity of the commensal program.

The MK telescope time allocation committee has shortlisted ten Large Survey Projects (LSPs) which have been awarded a total of 43,000 hours of telescope time over 5 years (Jonas 2009). Out of these 10 LSPs, 8 of them intend to use the UHF/L/S-band[3] receivers.

MeerGAL (a detailed study of the Galactic plane[4]) and MESMER (a search for CO molecules at high redshift by Heywood et al. (2011)) are surveys proposed to be conducted at X-band, a feed which is not yet confirmed for installation on *MeerKAT*. Thus, here we only consider UHF/L/S programs.

In order to construct a rough description of a commensal SETI survey on MK, we studied the observing program descriptions of the shortlisted LSPs (as available in the literature) and assessed how they could be used for the proposed SETI survey. The list of these 8 LSPs and their respective awarded time along with the sky coordinates targeted of each of them are listed in the Table 1.

Stellar population synthesis

In order to estimate a rough number of known stars towards different lines-of-sight where a given *MeerKAT* LSP would be observing, we generated synthetic stellar catalogs using a population synthesis model. The Gaia mission aims to catalog close to a billion objects in the Milky Way(Perryman et al. 2001; Lindegren et al. 2008). We used the publicly available *Galaxia* (Sharma et al. 2011) sim-

[3] `http://public.ska.ac.za/meerkat/meerkat-large-survey-projects`

[4] `http://slideplayer.com/slide/7688482/`

ulation code to simulate the number and properties of stars to be cataloged by the *Gaia* telescope. *Galaxia* is specially designed to simulate the *Gaia* catalog with $V < 20$ as a likely limit(Lindegren et al. 2008). We simulated the distribution of stars up to a distance of 50 kpc. It should be noted that *Galaxia* generates stars with only absolute magnitude and thus we calculated its apparent magnitude from the distance and corrected them for the dust extinction. *Galaxia* uses the Schlegel et al. (1998) 3-D map of dust in the Milky Way to calculate extinction toward different lines-of-sight. We used these extinctions to measure apparent B and V magnitudes to calculate color index (B-V) for the simulated stars.

Pulsar timing with MK

Pulsar timing in pursuit of gravitational wave detection (Bailes PI) has been granted around 8000 hours of telescope time. One of the goals of this project is to monitor two dozen isotropically distributed millisecond pulsars to investigate any timing irregularities they exhibit due to passing gravity waves(Manchester et al. 2013). We presume these observations will be conducted at L/S band. As these targets are distributed isotropically, this survey is ideal for us to conduct SETI observations of nearby stars in the solar neighborhood. Moreover, the survey will target more than 1000 pulsars (Bailes M. *private communication*) for short observations ($\sim$10 to 15 minutes) on each of them, covering many more fields. This will provide roughly 1000 square degrees of sky coverage for a commensal program. For just the small fraction of pulsars that are likely to be targeted for the timing experiment, we found that *Gaia* will likely discover around 500 thousand stars within their primary-beam fields. Figure 2 shows an HR-diagram for all the simulated stars towards these pulsars. For this LSP, our aim is to use around 20 beams for a targeted observation of a unique catalog star at each epoch of the pulsar observations. Other beams could be used to conduct a survey of the entire primary beam.

LADUMA

The LADUMA (Looking At the Distance Universe with the MK Array) project is a targeted survey of the Extended Chandra Deep Field-South (ECDFS) proposed by Holwerda et al. (2012). This field, which will be observed for 5000 hours in two phases, was selected due to the wealth of multi-wavelength data available. The goal of the project is the detection of neutral hydrogen, HI, near the redshift of unity by line stacking. Using *Galaxia*, we found around 1500 stars in the field which can be targeted for deep observations. For this field, we aim to point 3 beams for deep targeted observations with 4 hours per pointing. The remaining beams will be operated in a step and stare mode which will cover the rest of the primary beam for a deep sky survey.

MIGHTEE

The *MeerKAT* International GigaHertz Tiered Exploration (MIGHTEE) survey aims to study the evolution of star-forming galaxies from Z$\sim$6 to local Universe and quiescent star-forming systems between Z $= 1-4$(Jarvis 2015). The project is divided into 3 major tiers in addition to 2 undefined

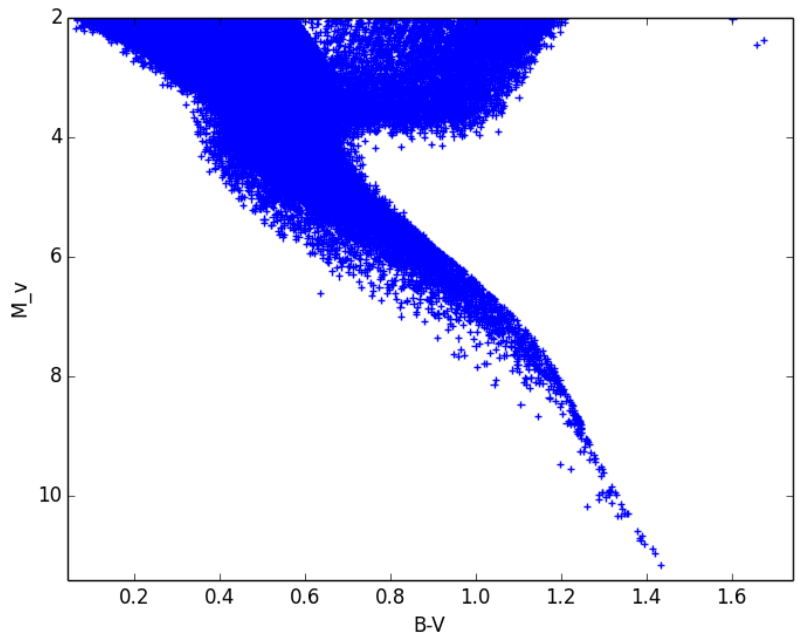

Fig. 2.— The HR-diagram of 500,000 stars in the field of putative *MeerKAT* pulsar timing LSP targets. It should be noted that the stars plotted in this diagram are only limited to visual magnitude V<20, incorporating dust extinctions.

tiers[5]. Tier-1 will be a 1000 square degree survey of the VISTA-VIKING and KIDS fields which will aim to achieve a sensitivity of 5 μJy. This tier would require roughly around 2450 hours of telescope time but it is not yet approved. Tier-2 will focus on smaller fields, 35 square degrees in total, and aim to achieve a sensitivity of 1 μJy. The possible fields for this tier are Elais-S1 (0037-43), XMMLSS (0218-05), ECDFS (0332-27) and COSMOS (1000+02). The third tier will be even more focused, with a single pointing of 1 square degree on Chandra-Deep-Field South, which will push the telescope to its limit of 0.1 μJy. The prospective tiers 4 and 5 would be conducted at a higher frequency of 12 GHz, however the details are yet to be finalized. The sky coverage of the MIGHTEE Tier-2 is sufficiently large to cover a good fraction of Galactic stars for deep targeted observations. Our *Galaxia* population synthesis analysis generated around 7000 target stars in the XMMLSS field, which will be observed for 1950 hours. We aim to conduct deep observations of around 30 min towards each of these stars. Considering calibration overhead, one can expect to get $\sim$1500 hours of total targeted observations. Thus, we should observe roughly 5 stars per hour. We aim to conduct targeted observations using 5 beams, while the remaining beams will be used for raster-scan surveys.

[5]`http://www.ast.uct.ac.za/arniston2011/vdheyden.pdf`

MeerKAT Absorption Line Survey

Gupta (2015) has proposed to conduct a blind survey to detect OH absorbers at z<1.8 using the *MeerKAT* array. The survey has been awarded 4000 hours of observing time. The goal of the *MeerKAT* Absorption Line Survey (MALS) is to study the evolution of atomic and molecular gas, which is largely unexplored due to very few known sources. MALS aims to detect more than 600 21-cm absorbers in the *MeerKAT* sky with Dec<20. MALS observations will be conducted in two tiers with 2000 hours at L-band in the first tier. Since the size of the *MeerKAT* primary beam is $\sim$ one square degree at L-band, we can assume that MALS will probably cover 1000 square degrees of the sky. This assumption is based on the fact that the targets of interest for MALS are also rare and one is likely to find only one per square degree. Thus, this project will provide enormous sky coverage for the proposed program. The second tier of MALS would be conducted at UHF frequencies (0.6 to 1 GHz) on the same targets, thus allowing us to enhance our frequency coverage on the selected targets in the MALS sky.

MHONGOOSE

MeerKAT HI Observations of Nearby Galactic Objects: Observing Southern Emitters (MHONGOOSE) is a survey to conduct deep observations of 30 nearby Galactic objects with 200 hours per source(de Blok 2016). The list of the targets selected[6] for the observations are in the southern sky, overlapping with the Parkes HIPASS, SINGG and SUNGG surveys. One of the key goals of the *Breakthrough Listen Initiative* is to observe 100 nearby Galaxies for rare but very luminous artificial transmitters. MHONGOOSE is thus a natural choice for commensal SETI on these targeted galaxies.

TRAPUM

The *Transient and Pulsars with MeerKAT* (TRAPUM) is a survey to search for new pulsars and transient events such as RRATs, FRBs and Intermittent pulsars (Stappers & Kramer 2016). The survey has been allocated 3080 hours of targeted observations at L-band. Around 40% of the awarded time will be used for a deep Galactic plane survey in search for pulsars and transients. This survey is also ideal for conducting commensal SETI observations of a few hundred thousand stars in the Galactic plane. For TRAPUM, we plan to use all commensal beams for targeted observations of nearby stars in the Galactic plane

A *MeerKAT* HI Survey of the Fornax Cluster

The Fornax cluster is the second closest large cluster after the considerably large Virgo cluster. The aim of this survey is to study galaxy formation and evolution in the cluster environment. The Fornax survey has been awarded 2450 hours of observing time at L-band (Serra 2011). The

[6] `http://mhongoose.astron.nl/sample-selection/sample-table.html`

observing strategy consists of 49 pointings on hexagonal grid with 50 hours per pointing[7]. The survey will aim to cover 11 square degrees. As with LADUMA, here we would employ a hybrid strategy, conducting both targeted observations of nearby stars as well as a raster-scan survey.

ThunderKAT

The Hunt for Dynamic and Explosive Radio Transients with *MeerKAT* (ThunderKAT) is another transient search project with extensive sky coverage at L band[8]. ThunderKAT has been awarded around 3000 hours of targeted observation time to conduct follow-up of explosive events at other wavebands (GRBs, Supernovae, X-ray binary outbursts etc.). The observations will be conducted at 100 min/day for 5 years towards these targets, thus, providing enormous sky coverage. Since the targets for the ThunderKAT survey are not predetermined, it is not possible to provide a comprehensive account of the number of stars in the field. However, we expect ThunderKAT fields to offer an excellent opportunity to extend our targeted survey of nearby stars.

2.1. Sensitivity

Although it is difficult to constrain the luminosity function of engineered emitters, we nevertheless can calculate our sensitivity and estimate the intrinsic equivalent isotropic radiated power (EIRP) that we could detect.

2.1.1. Sensitivity to Narrow Band Emission

Although we intend to employ a variety of signal detection methodologies, including autocorrelation, machine-learning-based signal detection approaches, principal component analysis, etc., (Siemion et al. 2015), it is illustrative to consider detection sensitivity for the simple case of a sinusoid.

The minimum detectable flux, F_i, of a narrow band signal in one polarization is roughly given by[9]:

$$F_i = \sigma_{\mathrm{thresh}} S_{\mathrm{sys}} \sqrt{\frac{\Delta b}{t}}$$

Where σ_{thresh} is the signal/noise threshold, S_{sys} is the system equivalent flux density (SEFD) of the receiving telescope, Δb is the spectral channel bandwidth and t the integration time.

Using 250pc as a characteristic distance to a nearby star, a tied-array SEFD of 10 Jy and a 10 sigma detection threshold, the minimum detectable equivalent isotropically radiated power (EIRP)

[7] www.ast.uct.ac.za/arniston/Downloads_files/4.1%20Serra%20-%20Fornax%20Survey.pdf

[8] http://www.hartrao.ac.za/e-vlbi2011/e-vlbi2011_files/presentations/ThunderKAT_eVLBI2011.pdf

[9] Assuming the intrinsic received signal width is $< \Delta b$, the spectral channel bandwidth

ranges from 1 x 10^{20} ergs/sec (5 minutes − pulsar timing quick observation) to 2 x 10^{19} ergs/sec (4 hours − deep fields). For reference, terrestrial planetary radars have maximum EIRP of $\sim 10^{20}$ ergs/sec and aircraft radar $\sim$ 1 x 10^{17} ergs/sec.

3. Connection to other International SETI Projects

Breakthrough Listen draws upon decades of work by SETI practitioners from around the world, many of whom serve on its scientific advisory board, including Frank Drake, Jill Tarter, Paul Horowitz and Dan Werthimer. The impetus provided by the announcement of this 10-year, US$100-million project is driving a resurgence of interest and enthusiasm for the field. The 10-year timescale for the project provides an excellent opportunity to engage and train the next generation of SETI researchers. Broadly speaking, all the research projects at BSRC build on the recent successes of exoplanet science, which itself evolved from a niche field to one that involves a growing national and worldwide research effort. Our hope is to grow the next generation of researchers who will develop the techniques and instrumentation necessary to expand the power of our search for signatures of technology other than our own, and to determine whether intelligent life is a one-off fluke, or whether there exist other inhabited worlds in our Galaxy.

Breakthrough Listen as a project has an open and collaborative outlook to science. In the first year of the program, the *Breakthrough Listen* lab at UC Berkeley has hosted approximately two dozen US and international visitors, collaborating on a wide variety of topics. We meet frequently with our collaborators at the SETI Institute, an hour's drive from Berkeley, and correspond and collaborate often with groups further afield. Prof. Jason Wright from Penn State University is visiting the Berkeley team for one week per month as part of his sabbatical, and is collaborating on observations, data analysis, development of undergraduate curriculum, and a range of other topics. Additionally, the open -source ethos in our group, as well as encouragement from our sponsor, means that we strive to make the software, data, documentation, and analysis as public as possible. We store *Breakthrough Listen* data in open archives, and our code and documentation in github, for the world (including others in the SETI and broader astronomical communities) to see, and to use as they wish.

In the longer term, the SKA may eventually provide orders of magnitude increases in radio SETI capabilities (Siemion et al. 2015). SKA could be the first telescope capable of detecting truly Earth-like leakage radiation from nearby stars. Scientific engagement in precursor and pathfinder facilities accomplishes both technical development towards a SETI program on actual SKA components, Developing a SETI observing capability with SKA precursor facilities like *MeerKAT* is a critical stepping-stone to SETI programs on SKA1, and eventually the full SKA.

4. Project Organization

Initially we anticipate that the proposed project will consist largely of a collaboration between SKA-SA, UC Berkeley and the University of Manchester / Jodrell Bank, while fitting into the broader *Breakthrough Listen Initiative* program. We are striving to develop an international Science Working Group into which this collaboration would contribute.

5. Management Plan and Data Products

The overall program will be led by *Breakthrough Listen* Project Director Andrew Siemion and additional Co-Principal-Investigators, with input from a Scientific Advisory Board. The project management will strive for broad international representation in both science and engineering teams, with special attention paid to the involvement of groups traditionally underrepresented in STEM (science, technology, engineering and mathematics) disciplines. Graduate students and early-career researchers will be involved at all levels.

Data products will consist of event records and snapshot voltage domain data. All data products will be made publicly available as quickly as possible, using standard (e.g. VOnet) protocols and procedures where appropriate.

A publication policy will be determined at a future date.

6. Public outreach and Popularization Plans

Berkeley SETI Research Center (BSRC), where the science program for the *Breakthrough Listen Initiative* is based, has a long history of engaging the public in the excitement of the search for intelligent civilizations beyond Earth. From the development of SETI@home, a network of citizen scientists volunteering their home computers to aid in the processing of telescope data, to our popular social media platforms (around 10,000 followers on both Facebook[10] and Twitter[11], and 90,000 views of our instructional, researcher profile, and topical videos on YouTube[12]), BSRC has had great success in engaging and inspiring the public.

The BSRC outreach team has produced a broad range of videos and other media highlighting the scientists and the digital hardware involved in *Breakthrough Listen*, and several videos are already in the pipeline featuring the BL deployment at GBT. We anticipate working closely with *MeerKAT* and SKA-SA staff to produce similar pieces showcasing the technology and the people that are driving this project forward.

BSRC researchers are also working with UC Berkeley undergraduates to produce engaging visualizations for public audiences, including interactive webpages where the public can see the BL target list and obtain live information about BL observations at our telescopes. We are also developing a "SETI curriculum" focused on undergraduate education, including walk-throughs of BL analysis using real data from our telescopes[13]. We anticipate expanding these tutorials to include extensive information and data from *MeerKAT*. The *Breakthrough Listen Initiative* is also committed to making as much data as possible publicly available, and we plan to add data from *MeerKAT* to our public archive, where it will be available to scientists worldwide, as well as

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[10] `http://facebook.com/BerkeleySETI`

[11] `http://twitter.com/setiathome`

[12] `http://youtube.com/berkeleyseti`

[13] e.g. `http://bit.do/BL_voyager`

technically proficient members of the public, and students wishing to learn how to analyze radio telescope data.

We are also developing outreach materials for broader audiences, including high school students. This includes efforts to popularize software defined radio (SDR), inexpensive (US$20) equipment that replicates (albeit on a much smaller scale) the equipment that powers our observations. We hope to work with the *MeerKAT* team to explore ways in which inexpensive SDR setups could be used in SA schools and universities.

7. South African Capacity Development

Scientists and engineers at BSRC have been pioneers in many of the efforts to drive forward the technology and related infrastructure that powers the search for other civilizations. Much of this work has involved, and indeed often been driven by, the involvement of students and young researchers.

There has also been extensive student involvement in the Collaboration for Astronomy Signal Processing and Engineering Research (CASPER), developing open-source hardware and tools to enable rapid development of new instruments for radio telescopes. CASPER already has an international dimension, including very significant cooperation with SKA-SA. SKA-SA has hosted two CASPER workshops, which attracted hundreds of participants, including scientists and engineers from around the world, and representatives from industry.

The involvement of *Breakthrough Listen* provides an additional exciting impetus to strengthen these collaborations, including the sharing of knowledge and expertise between the Berkeley group, international collaborators, and the South African research community. The deployment of *Breakthrough Listen* equipment to the *MeerKAT* site will expand the capabilities of the telescope, and help accelerate the path of development of the technologies needed for SKA1-MID. *MeerKAT* is already having great success in engaging the next generation of home-grown scientists and engineers in South Africa, and the involvement of the world's largest search for intelligent civilizations beyond Earth will increase the excitement surrounding this project even more.

8. RFI Environment and the SKA-SA Karoo site

Detecting, identifying and categorizing electromagnetic emission from human technology is a singular challenge in searches for extraterrestrial intelligence. SETI specifically targets emissions known to arise from technology, so it is fundamentally impossible to apply basic flagging as is usually done in conventional radio astronomy. Satellite and aircraft based interference are particular challenges for SETI due to their acceleration relative to stationary ground stations.

Next-generation RFI mitigation is thus a key focus area for the *Breakthrough Listen Initiative* and we look forward to working with SKA-SA and other *MeerKAT* users on this topic.

Additionally, all databases developed (for example satellite RFI characteristics etc) will be made available to SKA-SA, and joint development of future derived databases will be encouraged.

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This preprint was prepared with the AAS LaTeX macros v5.2.

Project	RA(hms)		DEC(dms)		SKY (deg^2)	Frequency (GHz)	Time (hours)	Comments	N Stars
PULSAR TIMING	00:00:00	24:00:00	+00:00:00	-60:00:00	100^x	1.4	8000	PPTA Sources	$\sim 5\times10^5$
LADUMA	03:31:00	03:33:30	-27:36:00	-28:00:00	1$^+$	0.900 - 1.670	5000*	ECDFS Phase 1	$\sim$1500
	03:31:00	03:33:30	-27:36:00	-28:00:00	1$^+$	0.580 - 1.015		ECDFS Phase 2	
MIGHTEE	00:30:30	00:46:00	-42:00:00	-46:00:00	16	1.4	1950*	ELAIS-S1	
	02:12:00	02:30:00	-02:30:00	-06:30:00	35	1.4		XMM-LSS	$\sim$7000
	10:00:18	10:00:38	+02:54:21	+01:30:00	2	1.4		COSMOS	
Fornax	03:10:00	03:54:30	-29:54:00	-38:35:00	11	1.4	2450	Fornax cluster	$\sim$2500
MALS	00:00:00	24:00:00	+20:00:00	-50:00:00	1000	$0.6-1.75$	4000	Quasars	$>1\times10^6$
MHONGOOSE	00:00:00	24:00:00	-10:00:00	-53:00:00	30^3	1.4	6000	Nearby Galaxies	
TRAPUM	00:00:00	24:00:00	+20:00:00	-50:00:00	400^4	1.4	1232	Galactic plane	$>1\times10^6$
THUNDERKAT	00:00:00	24:00:00	+20:00:00	-50:00:00	12	1.4	3000*	Galactic bulge	$>1\times10^6$

^{x} Assuming 100 pointings with multiple epoch with each epoch 30 minute long.

*Time will be divided between different fields for a given survey

$^+$The primary beam size is roughly 1 sq. degrees at L band

$^{++}$The primary beam size is roughly 28 sq. arcmins at 14 GHz. This tier will observe 340 pointing with 4.7 hours each.

^{2}Possible field but not yet defined

^{3}30 pointings with 200 hours per pointing

^{4}A rough estimate of the narrow Galactic plane targeted for the survey

Table 1: A summary of *MeerKAT* LSPs. The number of stars in the last column were calculated using a publicly available population synthesis code called *Galaxia* for each field.