Facilities, Equipment, Other

The work described in this proposal will take place at eight locations, as discussed below.

Arizona State University

Several ASU low-frequency developmental efforts will contribute directly to the HERA effort. ASU will support the deployment of an antenna beam mapping octocopter system which is currently undergoing testing for MWA, PAPER and other low frequency experiments. This system will enable the precise mapping of the antenna response as a function of frequency. Several developments from the ongoing Experiment to Detect the Global EoR Step (EDGES, supported by NSF grant #1207761) will also be directly applicable. Most notable is an ongoing effort to improve the precision of low-frequency antenna response calibration by two orders of magnitude. The resources at the disposal of the ASU low-frequency laboratory include a 5000 square foot dedicated electronics lab complete with vector network analyzers, FPGA development stations, high-accuracy noise sources, outdoor antenna test facility, 6-axis micromill and several highly qualified technicians.

Adjacent to the Low-Frequency laboratory is the Laboratory for Astronomical and Space Instrumentation (LASI) which assembles and tests space instrumentation. Proximity to the ASU Machine Shop (which has produced space-qualified hardware for Mars missions) offers quick custom machining and integration of pieces in instrument assembly.

The ASU High Performance Computing Initiative maintains a 5000-node cluster (Saguaro) with 11 TB of aggregate RAM and 215 TB of high-speed disk space that is available to all students and researchers through an internal time allocation process. A cluster dedicated to low-frequency astronomy, consisting of three high-power (16 core, 128G of RAM, 75TB of storage) nodes suitable for algorithm development and data exchange, is maintained by the co-I and available to all collaborators.

Massachusetts Institute of Technology

As part of the MIT's group participation in the MWA and with support from an MRI grant, a dedicated cluster of PC-Linux computers and storage are being purchased and installed in a phased manner as they are needed to accommodate MWA data. The final configuration will consist of $\sim$15 computers and >1.0 Pbytes of storage space. The computers will typically have 12 cores and 100 GB of RAM, providing enough compute power to produce the data cubes required for EoR science as the data arrive at MIT. The MWA data-taking will be complete by May 2015, and the cluster processing capacity will be made available to HERA in September 2015, when it is anticipated that the standard pipeline processing of MWA data will be complete.

At MIT, we have developed a 21 cm power spectrum estimation pipeline using quadratic estimator and Fisher matrix formalism to optimally measure power spectra and rigorously keep track of estimator errors and correlations. The technique was adapted (Liu & Tegmark 2011) from earlier work on the CMB and galaxy surveys, accelerated to run in $\mathcal{O}(N \log N)$ by exploiting various symmetries (Dillon et al. 2013a), and applied successfully to MWA prototype data (Dillon et al. 2013b). The statistical technology and code is straightforwardly adaptable to analyzing HERA data, and is furnished to the project.

The hexagonal layout of the HERA array core allows unprecedented opportunities for automated precision calibration and quality control using massive baseline redundancy (Liu et al 2010). This approach was successfully prototyped in the MITEoR experiment, and the resulting hardware and software is now available for HERA use. This includes the MITEoR 64 dual-polarization correlator, including 4 ADCx64 boards, 4 ROACH-II processing boards, 8 ROACH-I processing boards and two data acquisition servers, as well as 64 dual-polarization MITEoR elements with analog signal chains, including nodes, Walsh modulation boards, and receivers. The use of this system, as well as the underlying technology and software libraries, are being furnished to the HERA project.

The massive baseline redundancy of HERA also provides a potential for significant efficiency improvements to the correlator though 2D FFT's on the hexagonal antenna lattice, cutting the numerical load scaling of the X-engine from $\mathcal{O}(N^2)$ to $\mathcal{O}(N \log N)$. This would free up a significant fraction of the GPU resources, which could instead be used for automated real-time calibration and quality control.

NRAO

NRAO contributes support for Bradley's and Carilli's involvement in the project, and provides access to the NRAO site near Green Bank, WV, including the infrastructure and systems associated with the PAPER-32 array deployed there, for the purpose of development and field studies of the HERA system. NRAO also contributes support for adding low-frequency functionality to the CASA software package. This software is publicly available, and will directly benefit HERA's foreground imaging initiatives.

NRAO provides access to the PAPER field station located on the NRAO Green Bank, WV observatory site. This field station houses a work area and plenty of space to deploy additional instrumentation. Positioned within the National Radio Quiet Zone, this site is an ideal venue for sensitive radio-frequency measurements due to its remoteness from large urban areas and its exceptional laboratory infrastructure. A relatively large amount of outdoor space is available adjacent to the station for the deployment of antennas under test. A satellite downlink measurement system is here, and the PAPER array is located nearby. Electromagnetic enclosures are used to house all instrumentation to prevent self-interference as well as interference with Observatory telescopes, in strict adherence to the radio emissions control policy of the Observatorys Interference Protection Group (IPG).

PAPER equipment deployed at Green Bank will be used for antenna testing, absolute-calibration balun development, feed development, and other preliminary on-antenna testing activities. The deployed system in Green Bank consists of 32 dual-polarization PAPER antennas, with associated analog electronics, cables, and power, and a 32-antenna correlator. This correlator consists of 16 quad-ADC boards, 8 IBOB processing boards, 4 ROACH processing boards, and a data-acquisition server. Network infrastructure on site permits the direct transfer of data products to the computing server at UPenn.

A 800 sq. ft. research laboratory is located at the NRAOs Technology Center. It is equipped with two complete micro-assembly workstations for component fabrication and rework as well as a suite of basic instruments necessary for evaluation and repair. In addition, the laboratory contains several signal generators, power meters, spectrum analyzers, an impedance bridge, network analyzers, and noise figure meters for radio-frequency applications. A small anechoic chamber is available for antenna impedance measurements, and an computer-controlled environmental chamber is ready for studies of thermal- and humidity-induced effects on component and subsystem designs. Feed and balun development will routinely make use of the NRAO machine shop facilities.

For feed development, NRAO provides access to the latest computer-aided design software.

Autocad Inventor is used for three-dimensional mechanical drawings. Agilents Advanced Design System (ADS) is available for circuit and subsystem modeling while CST Microwave Studio is used for electromagnetic simulations of antenna and other RF structures. In addition, CF Design is available for modeling thermal conduction and radiation pathways.

South Africa

The recent and manifold infrastructure developments in South Africa are of direct benefit to the project. These relate to the radio-quiet observatory in the Karoo area of Northern Cape, South Africa, where PAPER has been observing over the last several years, as well as the PAPER electronics and support infrastructure directly.

The PAPER equipment will be used directly in this project up through the 127-element design. This allows use of a thoroughly commissioned system for science observations until there is the need for the larger correlator. The PAPER 128 dual-polarization correlator includes 16 ADCx16 boards, 8 ROACH-II processing boards, 8 servers each hosting 2 GTX690 dual-GPU cards, and two data acquisition servers. The data compression and storage system includes 5 computing servers and a 220 TB raid storage system. In addition, the 128 PAPER elements, with analog signal chains, nodes, and receivers will be used as part of the first observations in an imaging configuration. The 12-meter container, 120 dB shielded EMC enclosure housing the correlator and electronics along with the power infrastructure (transformers, reticulation, and UPS) and HVAC system will also all be used.

South Africa will relocate the PAPER equipment to a new nearby site that had previously been set aside for SKA-Low. This will include site clearing, road access, power and internet infrastructure and service. As part of the observatory development a new shielded building (the Karoo Array Processing Building) is currently well under construction, and HERA will have use of this facility, which will be connected to the HERA site by a dedicated fiber cable. This facility has a fast internet connection back to the Cape Town headquarters.

The South African group consists of a growing pool of experienced scientists in this field. Key among them is Bernardi, who will participate extensively in this project. South Africa also provides strong liaison support between the groups, building on the excellent experience PAPER has enjoyed. South African researchers will also provide mirror support for the student exchanges described in the Broader Impacts section of the Project Description.

In addition, SKA-SA assists with the unloading, assembly, and storage of shipping crates. Two on-site mobile truck cranes are available, along with use of a 30m x 18m dish construction shed that is shared with the KAT-7 construction. Accommodation is provided for on-site PAPER visitors. Off-road pickup trucks are available for use driving to and from site, as well as while on site. Site staff are available for occasional operations maintenance support.

A digital electronic laboratory is available in the Cape Town SKA-SA offices, complete with hot-air rework stations and test equipment (bench power supplies, signal generators, network analyzers, spectrum analyzers, oscilloscopes up to 100GHz etc). There is an off-site RFI measurement facility near Cape Town (Houwteq) replete with an anechoic chamber, a large hangar shed, an open-area test site, and a vibration room for testing transmitters and receivers.

Cavendish Observatory, Cambridge

Cavendish Observatory will provide scientific and technical staff to assist the project. This will consist of support for a PhD student to explore imaging/calibration using standard software, support for a postdoctoral student to explore novel power spectral approaches, partial support for an engineer for field work and systems testing, and partial support for a senior scientist (Carilli, who has a joint appointment with NRAO).

University of California, Berkeley

The UC Berkeley Radio Astronomy Laboratory (RAL) is located adjacent to the UC Berkeley Astronomy Department. It provides laboratory space and access to digital and radio-frequency test equipment necessary for the detailed characterization and performance testing of components of the proposed correlator development work. Such items include power supplies, signal generators, network analyzers, oscilloscopes, noise generators, filters, attenuators, amplifiers, and other miscellaneous electronic equipment and well as machine tools. RAL also hosts the programming environment targeting the Field-Programmable Gate Array processors on which the proposed correlator work is based. This facility is available to members of the UC Berkeley Astronomy Department.

The Berkeley Wireless Research Center is located adjacent to the UC Berkeley campus. It provides access to additional high-end digital test equipment and software for digital signal processing. It is available to members of the Collaboration for Astronomy Signal Processing and Electronics Research (CASPER).

For the duration of this grant, Berkeley will provide partial support for engineering and management (DeBoer), partial support for engineering (both MacMahon and Dexter), as well as partial summary salary support for (Parsons).

Berkeley will provide a laboratory correlator system for development and testing of correlators; delay spectrum power spectrum pipeline software; the 94-node Henyey compute cluster for local data processing; Matlab; video conferencing software to further the collaboration; and a full-size HERA test antenna.

University of Pennsylvania

The central computing cluster and data archive for PAPER is maintained at UPenn. This currently consists of 22 nodes connected by Gb ethernet. These nodes consist of 16 Dell PowerEdge 1950s (dual 4-core Intel Xeon L5420 2.50GHz) and 6 Dell PowerEdge R410 (32 GB RAM; dual 6-core Intel Xeon E5649 2.53GHz), for a total of 200 cores and 448 GB RAM. Fast working data storage is provided by a network storage system (NSS) based around two Dell MD1200s, with a total RAID storage capacity of 140 TB. The storage has a dedicated head node and internal 10Gbe, with 1 Gbe connections to each compute node. Backup of the NSS is done on to several Silicon Mechanics Storform D59J.v2 machines, each of which is about 55 TB effective in RAID6. We currently have three backing up the 140 TB above. The system was purchased through a combination of the PI's startup funds, internal funding from UPenn's University Research Foundation, a major contribution from the Mt. Cuba Astronomical Foundation, and contributions from Professors M. Sako and G. Bernstein, who share the cluster for processing of DES and SDSS data. Extra space is available to house the additional data analysis and storage hardware described in this proposal to support the HERA array.

University of Washington

The University of Washington is providing software developed as a part of the MWA, including Monitor & Control software, Fast Holographic Deconvolution software, and direct power spectrum analysis software, in addition to a RF testing laboratory (vector network analyzers, spectrum analyzers, mixed mode oscilloscopes, precision system temperature measurements, etc.) and access to an excellent machine shop.

Morales has led the development of the MWA Monitor & Control software, and this will provide a strong code base for developing the associated system for HERA. Morales' group has also been at the forefront of wide-field imaging and foreground subtraction, and has developed the Fast Holographic Deconvolution software that is being used to reduce PAPER imaging data and all MWA Epoch of Reionization data. This code is crucial to reaching the scientific goals of HERA, including the survey and instrumental commissioning with HERA 37, and obtaining the foreground isolation necessary for the ultimate power-spectrum analysis and imaging of the EoR with the full HERA instrument.