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CUAHSI
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FACILITIES FOR TRANSFORMING HYDROLOGICAL SCIENCE

A Technical Report for the Hydrologic Measurement Technology Facility of CUAHSI

Developed by the CUAHSI Hydrologic Measurement Systems Standing Committee

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EXECUTIVE SUMMARY

Major advances in measurement technology, supported by satellite observations and computing power, provide the opportunity to greatly increase our understanding of the world's hydrosphere in the coming decades. To reveal the physical, chemical, and biological systems that interact and participate in the hydrologic cycle, scientists urgently need to break new ground. For these new discoveries to be realized, a national-level investment in measurement infrastructure will be needed, akin to the investments made in oceanography, polar research, and atmospheric sciences at their critical developmental periods over the past four decades. This paper presents the concept of a Hydrologic Measurement Technology Facility (HMTF) that would catalyze hydrologic research by putting key measurement technologies in the hands of researchers.

This HMTF will have measurement technology, mobilized nationwide and to any point in the hydrosphere, at its core. The hydrologic community will gain access to the tools needed to characterize research sites and measure critical fluxes. Many of these tools are expensive, but are often needed only once in the life of a project; thus the use of a centralized facility is practically ideal from the perspective of cost, as well as for maintaining the expertise to operate the tools. In this sense, the most important aspect of the instrumentation support is the center's staff of scientists, engineers, and technicians who will knit together complex packages of novel and cutting edge tools into calibrated solutions to scientific discovery. In addition to supporting field campaigns, the staff will host a continuing program of visiting scientists who will form the human linkage between the world of university research and bring cutting-edge instrumentation ideas to be developed and tested at the HMTF.

The facility will be run entirely following the NSF peer-review process. The projects will be reviewed and selected by a panel in support of a spectrum of services for individuals and teams, as well as the proposed CUAHSI system of long-term hydrologic observatories. In the model developed here, the staffing will include approximately 10 scientists, 20 technical staff supported by administrative assistants, and the involvement of about 10 visiting scientists at any given time. Its initial establishment will require the purchase of approximately $21M in equipment, with an annual recurring budget of approximately $12M.

1. INTRODUCTION

1.1. CONTEXT

Water and its abundance, availability, quality, and predictability are imperative natural resource issues. Population pressures and global changes over the next decades will increase focus and concern over diminishing stocks of usable water and increasingly uncertain water supply, as well as the frequency of extreme hydrologic events (i.e., floods and droughts) and risk of exposure to water-borne contaminants, pollutants, and disease. These trends result from greater human pressures on available water supplies and delivery systems, changing patterns of land use and development, and the prospect of a rapidly changing and increasingly variable climate. In this environment, evaluating tradeoffs between competing uses and claims for water are likely to pose significant challenges for water management and policy, requiring sound scientific information and understanding. The ability to predict the effects of global change on the hydrologic regimes across the Earth is requisite to the orderly development of society.

In spite of the growing societal need for water, the science of water—hydrology and related fields—has lagged behind in its ability to provide critical information and to predict the consequences and impacts of hydrologic events. For example, we cannot predict, with the accuracy necessary for effective countermeasures, the timing of landslides, the heights of floodwaters, the fates of contaminants released into surface or subsurface waters, or the magnitude or duration of regional droughts. These are the aspects that make it to the local newsroom; at scientific meetings across the globe it is further recognized that the needs and opportunities have grown exponentially over the past decades, and the present strategy of response is not adequate to meet this challenge.

Improving our predictive capacity in hydrology will require a fundamental transformation and upgrading of the tools we use to conduct hydrologic science, including facilities, training, observational networks, data and information systems, education, and outreach. This document presents our proposal for transforming the technological infrastructure for hydrologic sciences by establishing a national Hydrologic Measurement Technology Facility (HMTF). Here we consider the scientific justification for new infrastructure, outline the goals and objectives of the facility, envision how such a facility would operate, and consider an implementation and funding strategy.

1.2. SCIENTIFIC JUSTIFICATION

In the last 50 years, hydrology has moved from an **engineering** activity that emphasized application-specific studies, to a well-defined **scientific** discipline in its own right prepared to address the most fundamental aspects of the planetary system. It now encompasses a wide range of sub-disciplines, including surface and subsurface physical hydrology, biogeochemistry, hydrometeorology, geomorphology, and ecohydrology, and includes observations, models, and experiments over scales ranging from dynamics of aerosols and individual raindrops to global water cycles and fluxes. Fundamental scientific problems confronting modern hydrology include

- Developing full accounting of water budgets over continents and oceans;
- Characterizing trends and variability of hydrologic processes under past, present, and potential future climates;
- Predicting regional patterns, causes, and magnitudes of floods, droughts, and other extreme hydrologic phenomena;
- Quantifying rates of movement of water, sediment, solutes, and contaminants in surface and subsurface waters;

- Coupling carbon, nitrogen, and water cycles; and
- Exploring linkages among the hydrosphere, geosphere, and ecosphere over a wide range of spatial and temporal scales.

To make progress towards solving these problems, accurate measurements must be taken at all scales, from soil pores up to watersheds, as part of intensive field campaigns. Fortunately, there has been an explosion of new technology in the last decade, from new satellites for remote sensing of water, snow, and climatic trends to digital ground-penetrating radar for observing movement of water through the soil and geologic mantle.

At present, few hydrologists have access to costly instruments that measure physical, chemical, and biological properties of interest in the field at any scale, or trace movement of water and its dissolved and suspended fellow travelers. Existing equipment is often prohibitively expensive, hugely complex in setup and operation, and requires high levels of expertise to tease out the final values. Although some researchers at national laboratories and faculty at certain universities are able to use limited sets of instruments, it is essentially unheard of to have access to the entire suites of equipment necessary for critical measurements. The time, expertise, and support needed to design new instrumentation is likewise far beyond the scope of the individual hydrologist. Even if researchers were able to access and employ such instruments in the field, there is no standard for data transfer and access by the broad community, with the result that many measurements see limited use.

Because of this, hydrologists have been forced to either rely on a few limited field experimental observations to test and refine concepts, or make use of numerical simulations with questionable parameterizations and without needed field observations. Figure 1 illustrates one level of data limitation hydrologists are generally burdened with: not knowing the land surface topography. Present technology allows for 2-m resolution, as shown in the top image, while USGS data provides no better than 10-m resolution, and the highly anticipated SRTM data set of the U.S. will be at the 30-m pixel size.

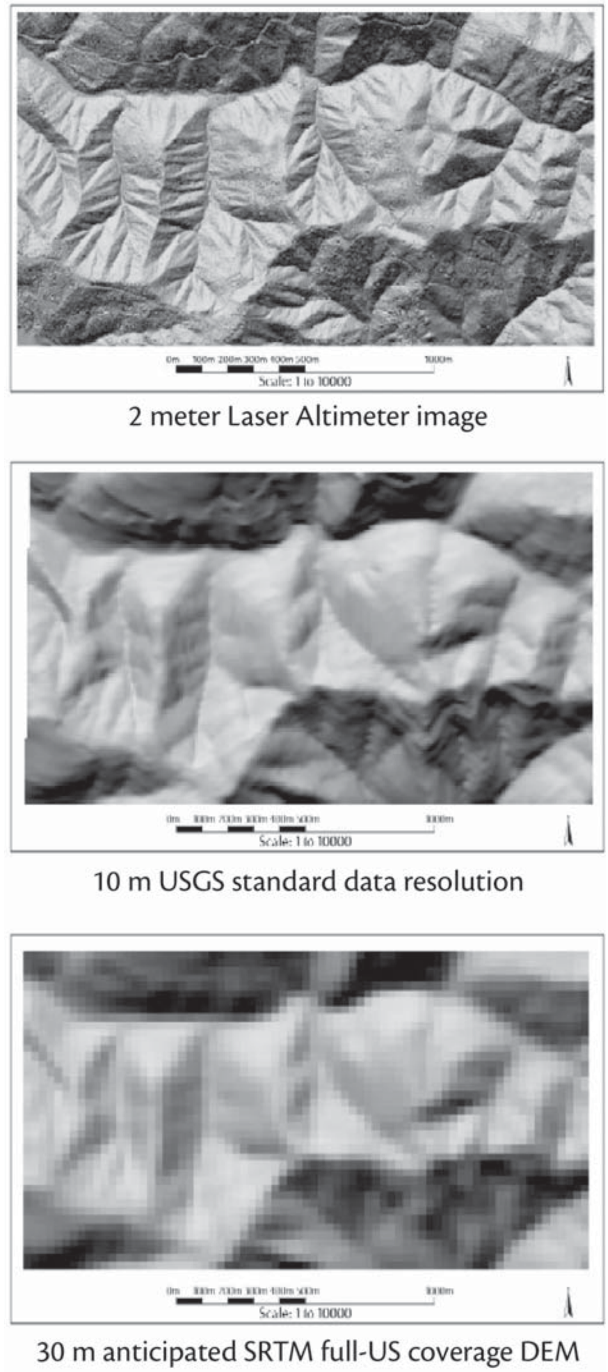


Figure 1: Shaded relief maps, Oregon Coast Range. The center map is derived from a digitized USGS 7.5′ quadrangle map (currently the best available data in the U.S.) that was then gridded to 10 m. The lower map shows the data that will be available from the SRTM mapping mission for the continental United States. The upper map is derived from Airborne Laser Swath Mapping. Predictions based on the lower resolution map cannot capture the hydraulically driven landslides that have been documented for this region. From Dietrich, W.E., et al., Water Science and Application 2, 195-227, 2001.

Prediction of water movement based on the lower blurry images will yield far inferior results, as demonstrated by Dietrich et al. (2001). It is unacceptable to continue working without access to the data sets that will be required to provide crisp understanding of the hydrosphere. Individual scientists and multidisciplinary teams in hydrology have innovative ideas regarding which key aspects of a hydrologic problem must be measured in the field, but are hampered by lack of technical expertise in instrument and support services to undertake field campaigns to measure and test key ideas. As a result, their efforts to make progress in critical areas have essentially stalled—just when the need and potential for new discovery is exploding. Hydrology as a field of scientific inquiry can be categorized as an area rich in ideas, but poor in accessible technology. Making real progress across the broad front of water problems confronting today's hydrologists, and by extension, society, requires a major new investment in hydrologic technology and infrastructure commensurate with the scale, magnitude, and importance of these problems.

2. VISION FOR THE HYDROLOGIC MEASUREMENT TECHNOLOGY FACILITY (HMTF)

If the scientists engaged in deepening our understanding of hydrologic systems are to be widely successful, they need both the infrastructure and technical support to facilitate the integrated field campaigns that will allow them to ask the questions and undertake the measurements necessary to understand processes in the field. This technological support must include training to help scientists select and grasp the capabilities of the currently available tools. Once necessary methods have been identified, researchers must have access to the complex and expensive equipment packages that will best advance hypothesis development and testing. And just as importantly, researchers must be assisted in the proper installation and operation of field instrumentation. High temporal and spatial resolution measurements, as part of an intensive field campaign, require complex networking of sensors, radio-communications, and data acquisition.

To accomplish this, we propose to establish the Hydrologic Measurement Technology Facility (HMTF) under the umbrella of CUAHSI. The HMTF will provide instrumentation and technical support for university investigators to obtain the high-quality data required to test hypotheses of hydrologic processes in the context of field campaigns. This program will assure that adequate instrumentation is purchased, developed, deployed, and maintained to accomplish this goal. The HMTF has three overarching objectives:

1. To serve as a center for the application of state-of-the-art instrument and measurement systems to hydrological problems;
2. To serve as a development laboratory for critically needed new instrumentations required to allow scientific discovery in hydrology; and
3. To support individual investigators, scientific teams, and long-term hydrological observatories in acquiring, designing, deploying, maintaining, and analyzing hydrological information and data.

The HMTF will be dedicated to putting the essential tools in the hands of scientists where critical components of the hydrologic cycle are expressed. This will require taking the HMTF staff and equipment a mile above the land's surface to remotely sense broad-scale processes; to the middle of a lake to understand nutrient cycling; to the heart of surging flood waters; and below the Earth's surface where contaminants are transformed into harmless minerals. The mobilization platforms required to carry out these missions are dictated by the locations under study. For example: to access the subsurface and install specialized down-hole sensors and geophysical equipment will require specialized drill rigs; to make measurements in lakes, karst geology, and rivers will require remotely controlled submersible vehicles; to access flooded lands and remote natural locations will require helicopter transport; to carry out LIDAR elevation studies and capture local-scale, remotely sensed data (e.g., stream temperature) will require airplane mobilization; and taking equipment to even the least remote sites will require trucks. The HMTF is designed to take the best tools to the most interesting locations to make critical measurements of hydrologic processes.

Measurement equipment supported by the HMTF will be selected on the basis of the impact it will have on the advancement of hydrologic science. The mission is to facilitate critical measurements that would not occur due to barriers insurmountable without the HMTF. Broadly these barriers fall into three categories: **financial**, **logistical**, and **technical**.

The most easily understood is the difficulty in making measurements using very-high-cost equipment—**financial** barriers. Experiments that require capital-intensive tools such as geophysical characterization, laser altimetry, or Raman LIDAR frequently fall victim to the financial obstacle. Typically these exotic tools must be tuned to operate for hydrologic investigations and are used once in the life of a field experiment so cannot be justified for purchase by an institution despite their ability to provide a critical set of observations. The provision of these tools, with operators as required to assure the successful deployment and operation, are an obvious and urgently needed role for the HMTF.

The **logistical** barrier is manifest in systems of equipment either high or moderate cost that require highly specialized technical attention to make operational. Examples of pure logistical barriers are networks of low-cost sensors with data collection via telemetry: without specific experience in radio telemetry and sensor technology investigators can neither design nor deploy such essential systems. In our survey of the hydrologic community it was striking that the most sought-after assistance was in establishing distributed stream gauging stations. For anyone who has attempted such an installation, it is clear that the success of such an installation rests largely on the proper choice of site, flume design, and automated stage recording hardware.

By **technical** obstacles we refer to measurement needs where tools do not exist. In cases deemed to be critical to the hydrologic community the HMTF will undertake the development of new measurement tools to fill critical needs. An example of a tool developed under such circumstances for the atmospheric science community is the Dropsonde developed by the NCAR ATD (see Sidebar 1). Because of the small commercial demand of hydrology, many of the tools that could provide critical measurements are simply not available, often due to lack of development funds. The purpose of the technical systems support is to develop, and where possible, spin off new tools and make them available to the entire community through standard commercial channels.

The HMTF support staff must include both hydrologists and computer and electrical engineers to help design, deploy, and maintain field instrumentation as discussed above. HMTF support staff will install and operate the new NSF/HMTF equipment in the field. The staff will provide help with experimental design, sampling and measurement techniques, data processing, field data quality assurance, data analysis, and specialized software, and they will design and fabricate specialized equipment.

This new facility will support scores of single-investigator focused projects each year as well as a select set of longer-term multidisciplinary field campaigns. This mix of small and large projects is vital for ensuring wide participation and access to HMTF resources, thereby enabling the most rapid discoveries possible in hydrologic sciences. The HMTF will support projects from individual investigators approved through peer review, and will devote considerable effort to the development, installation, and operation of the equipment used by the CUAHSI Long-Term Hydrological Observatories (LTHO) to ensure that these facilities are fully configured with appropriate and compatible instruments for making comparative observations of hydrologic processes.

The HMTF, in conjunction with the CUAHSI information technology facility, will maintain an open archive of all data collected via its platforms or data collection systems, and will also provide the software necessary to use the data. This policy will foster scientific research through simple and timely community access to all data collected by the new HMTF equipment facilities.

The HMTF will also offer all qualified scientists competitive access to instrumentation. A joint HMTF, university, and NSF Facilities Advisory Council will hear advice on specific facility use requests twice a year from a Facilities Advisory Panel. HMTF will work closely with the community it serves. Community members (e.g., past, present, and future users) will serve on the advisory and allocation panels. Thus, the user community will guide the direction of the facilities and determine the use of the systems. Community members

SIDEBAR 1. LESSONS FROM NCAR'S ATMOSPHERIC TECHNOLOGY DIVISION (ATD)

The model proposed for a new HMTF draws heavily upon the lessons learned in the development of the highly successful Atmospheric Technology Division (ATD) at the National Center for Atmospheric Research (NCAR), the seismic community (The Incorporated Research Institutions for Seismology [IRIS]), and the U.S. Geological Survey Upper Midwest Environmental Sciences Center (http://www.umesc.usgs.gov/). When the NCAR was proposed by the University Consortium for Atmospheric Research (UCAR) and funded by NSF some 40 years ago, it was based in part on the need for a facility to support instruments and experimentation that would not be possible at universities. Atmospheric science programs at universities cannot maintain equipment such as experimental aircraft, radar, extensive collections of masts and towers, and probes, nor can they maintain expertise in instrument calibration, development, and field implementation. ATD provides these kinds of comprehensive, high-quality, and reliable atmospheric observing systems to the university-based research community for climate and weather research. ATD continuously develops new sensors and instruments to support a variety of scientific disciplines. These sensors are made available on a competitive basis to interested researchers upon request.

A parallel argument is made here for such an instrumentation facility in hydrology, as individual university hydrologists cannot maintain the expensive and exhaustive instruments needed for field research. Such instrumentation includes LIDARs, microwave instrumentation (for soil moisture), soil and water-quality sampling devices, laser imaging devices for sediment and turbulent flow measurement, infiltrometers, seepage meters, extensive collections of rain and stream gauges, suction lysimeters, chemical analysis, and more. The ATD demonstrates how creating a center of technical expertise and support services has transformed atmospheric science, with almost every modern atmospheric science institution around the world making use of the technology developed, and often directly provided, by the ATD.

will also serve on the review panels when (in the long run) NSF makes its periodic reviews.

HMTF will pursue the development of new technologies as new science questions arise and technology evolves. The infusion of new ideas and expertise in research and technology is an important form of communication with the university community that enriches the entire scientific community. For these purposes, HMTF will operate a post-doc and visiting scientist program. These exchanges will help build community ownership of the program.

The infrastructure to be provided by HMTF will include a design, fabrication, and calibration facility—a machine facility supported by state-of-the-art engineering design tools. It will provide solid and planar design tools, a system that allows users at home campuses to interact with the designers through a friendly client-server version of their design software, and computer controlled tools that allow very complex parts to be produced and refined in a dynamic process involving university scientists, HMTF staff, and projects that address the needs of society.

3. THE STRUCTURE OF THE HMTF

In this section we address the physical infrastructure of the HMTF by discussing the role of hardware support, presenting examples of available systems that are likely to be included in the HMTF instrument set, discussing instrument development opportunities, and finally, describing the facilities required to provide these services. At the outset we emphasize that the ultimate makeup of equipment and facilities will be determined by the peer-review oversight and direction process discussed below.

The HMTF will be located at a single site where the staff and HMTF-held instruments are maintained and prepared for use. The single-site model avoids redundancy in tools stored in various smaller facilities, provides a critical mass of expertise and staffing to solve complex measurement problems, and will provide a focus for the hydrologic community for technology and related training. This facility will be under the umbrella of CUAHSI; however, it is likely to exceed the housing capabilities of a single university. For this reason, we expect that the facility will be a community resource without special ties to any single member or state, akin to the ATD model discussed above.

The HMTF will identify two categories of tools: those that are best provided directly by the HMTF, and those that would be best provided to the community though contracted services. At this time, we do not attempt to identify which will fall into each of these categories, since these decisions will be made by the NSF-appointed facility oversight committee. However certain characteristics make some equipment more suitable to be kept by the HMTF; these include complexity, need for field support, at least 4-year life of application, and utility to a broad range of scientists. Examples are boats outfitted with specialized sounding and sampling equipment, and precipitation radars. Contracted facilities are those that already exist at universities around the country, are primarily used in a standardized manner, and those that will be employed by small subset of the community. An example of a service likely to be contracted is the isotopic analysis of water samples on mass spectrometers. This is a service we need to provide, but by making use of existing technicians and machines, the HMTF can avoid large fixed costs and leverage the investments already made by the NSF and other national agencies.

To address the community's needs, the HMTF will engage in a set of activities. Most obvious is the direct provision of hardware solutions. Less widely recognized is the need to develop new tools for hydrologic investigation. As illustrated in the five sidebars, these activities span the refinement of single tools to integration of complex measurement systems.

Although the HMTD and CUAHSI initiative are primarily intended to provide support and service for the university-based hydrologic community, we envision strong partnerships with other federal agencies charged with conducting research on water resources. These agencies include the U.S. Geological Survey, Bureau of Reclamation (BoR), Army Corps of Engineers, USDA Forest Service, USDA Natural Resources Conservation Service, and Environmental Protection Agency, among others. These agencies have at their disposal resources, hardware, facilities, and research talent that can complement and leverage resources available to the HMTD. For example, the USGS stream gauging network is likely to serve as a proving ground for instruments and measurement systems developed at HMTD. Public lands administered by the Forest Service or dams and reservoirs operated by the BoR or Corps are also likely to play a role in testing and deployment of hydrologic observation systems.

We anticipate that while HMTD would not fund or support individual government scientists who receive direct federal dollars through their agencies' allocation and budgeting process, HMTD resources would be available to collaborative

SIDEBAR 2. THE OPPORTUNITY OF INVESTMENT IN GROUND PENETRATING RADAR

Hydrologists depend almost entirely on the fortuitous development of instruments for other commercial applications that can be employed in the pursuit of scientific objectives. Ground Penetrating Radar (GPR) provides an example of this scenario, but also the unrealized opportunities that exist due to the lack of investment in measurement technology development. GPR shines bursts of radar into the subsurface, and illuminates the stratigraphy through the echoes. The time between burst and echo indicates the product of the distance to the layer and the speed of radar signal transit. Unlike in pure water or open atmosphere, the travel velocity in the subsurface is strongly controlled by the water content of the material, since water has a very high dielectric. It has been recently demonstrated that in addition to identifying the geologic setting the GPR signals often contain enough information to determine the entire water profile at a site. As of this time, an efficient inversion algorithm such as that shown for resistivity surveys shown in Figure 2 is not available for dielectric from GPR, from which water content could then be computed. This potential may be unrealized because the commercial producers and users of GPR are not particularly interested in the distribution of water. The HMTF will invest in the development of GPR methods and interpretation of signals from other geophysical equipment to realize this potential. This will provide not only a critically needed tool for subsurface water budgeting, but also a new capability for industrial users that will enhance the value of this technology for all end users.

research teams including both university and government scientists. Specific proposal mechanisms would need to be worked out, but we expect that the process would closely follow current NSF guidelines for outside agency involvement in NSF grants.

3.1. LABORATORY AND TECHNICAL SUPPORT

The key contribution of the HMTF is the provision of working packages of technology with which individuals and teams can take precise and revealing measurements. As described below, this will require instrument system configuration, calibration, development, and assistance in deployment. This dictates a level of staff, mechanical construction capabilities, and test and measurement capacity that will support these efforts.

3.1.1. Staff Support

Each major focus area (e.g., surface, subsurface, and remote sensing) will require a lead scientist to direct instrument development and quality assurance, technical support for both maintenance and development, and a visiting scientist program to assure bi-directional communication with the larger community. These human resources are in fact more fundamental to the success of the HMTF than the equipment itself, in that a key obstacle to advancement at this time is investigators unable to assemble these specialized skills for short-duration campaigns. The specific composition of the staff envisioned is presented in section 3.3.

3.1.2. Distribution of Effort

The main task areas of the HMTF staff will be (1) field deployment of systems and support of the hydrologists conducting field campaigns; (2) technical support of the LTHO

SIDEBAR 3. RAMAN LIDAR AS A HYDROLOGIC TOOL

While a cupped hand can capture rain, accurate and affordable measurement of evaporation over a landscape is an open problem. A Raman backscatter water vapor LIDAR can determine the concentration of water vapor along a line of sight in the atmosphere, from which the rate of evaporative flux can be obtained.

LIDAR may be used as a vertical sounder to determine the vertical profile of water vapor concentration, allowing visualization of large-scale processes. In a horizontal scanning mode the LIDAR can reveal the three-dimensional water vapor concentration over 2 km^2. The figure above compares the LIDAR-measured evaporation rates over salt cedar compared to a thermal image, showing the high-resolution complex patterns revealed. How can this technology be brought from a several million dollar curiosity to an accessible tool for the larger hydrologic community? The HMTF will have the affordable implementation of measurement of evaporation as a primary mission, and LIDAR technology will be central to success.

operation; and (3) development of the new observational technologies. To ensure that the technical staff understands the experimental needs of the hydrologic research community, all members of the staff will be engaged in all task areas. The specific effort distribution will vary greatly among the staff—it may look like 10%-10%-80%, respectively, for some, and 80%-10%-10% for others.

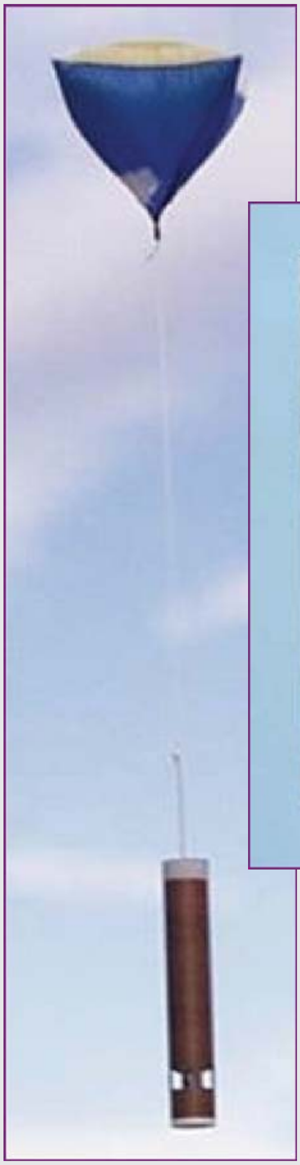
The field deployment and support will consist of preparing fully functional and calibrated instruments before the campaigns, installing and testing them at the experiment location, and training the PI and his or her research group (e.g., graduate students) in their use. This will impose uniform, high standards developed by the HTMF on all PIs using the current and calibrated equipment. This will provide a higher degree of consistency of the experimental results and, consequently, more applicable achievements.

The extent of the technical support for the LTHOs will depend on the specific structure and scope of the observatories, which are being defined in parallel to this proposal. As a minimum, the HMTF staff will be a technical expertise resource to the technical staff of the LTHOs. Support will possibly include tasks such as calibrating and testing the instruments deployed at the LTHOs, technical evaluation and testing of upgrades and new developments, troubleshooting, formulating the technical aspects and requirements of new capabilities, etc.

Development of new instruments will be a critical task of the HTMF. Involvement in this task will ensure that the staff is up to date on new technologies in relevant fields such as communications or power storage and supply, biotechnology, nanotechnology, information technology. HMTF will constantly work toward improving hydrologic measurement instruments whether there is commercial market for such improvements or not. The goals of such developments will

SIDEBAR 4. AN EXAMPLE OF A TRANSFORMATION IN TECHNOLOGY THROUGH NSF FACILITIES: ATD'S DROPSONDE

Research and operational users once had an urgent need for wind and thermodynamic measurements over the oceans. NCAR's Atmospheric Technology Division needed to upgrade its dropsonde technology to keep pace with new global navigation systems. ATD surveyed user needs and assembled multi-agency funding to produce a new sonde greatly exceeding the performance of existing technology.



The ATD dropsonde team merged commercial sensors and GPS technologies with a ATD-designed battery-operated microprocessor-controlled data acquisition and telemetry system in a new structural chassis. Finally, ATD developed a unique square-cone parachute for the new dropsonde that streams behind the sonde immediately on launch, gradually fills to cushion impact on components, and in flight provides a stable descent without pendulum motions or rotation. ATD met cost and schedule goals with a new sonde that for most users exceeded the 95% goals for successful launches and successful data.

After evaluation and quality control, ATD manufactured the first 1300 dropsondes to meet users' immediate research and operational needs. ATD then licensed the sonde to a commercial manufacturer. Nearly all research aircraft now fly the ATD dropsonde systems, with over 5,000 deployed per year worldwide. Operational users include the USAF and NOAA hurricane hunter fleets. The dropsondes represent one of the most important surveillance tools for hurricane track prediction.

The HMTF will take on projects equivalent to the dropsonde, tackling new technologies to make measurements where at present we have no data, putting tools into researchers hands, and handing off the technology to private companies to promote broad support for hydrologic and environmental measurements.

SIDEBAR 5: CHALLENGES AND OPPORTUNITIES OF PRECIPITATION RADAR

Rainfall exhibits extreme variability both in space and time and across scales. This variability affects many hydrologic processes in which the scale of variability is much below that provided by the operational rainfall data. High-resolution rainfall data are required for detailed modeling of mass and energy transport processes at the interface of the land surface, the subsurface, and the atmosphere. They are needed for development of theories on how processes interact across a range of temporal and spatial scales. Such data are also required for uncertainty quantification of the operational rainfall observing system both *in situ* and based on radar and satellite remote sensing.

The hydrologic research community needs inexpensive (X-band and C-band) low-power radars, including mobile, with polarimetric capabilities. Track or trailer based radars can be easily moved from place to place to provide data with resolution as high as 100 m by 100 m for support of field studies. As these radars could easily cover an area with a 50 km radius, they can support studies of small and average size watersheds, providing data adequate for scaling analysis. When configured into a small-area network and complemented with portable rain gauges, disdrometers, rain profilers, in addition to the existing operational radar and rain gauge network, they will supply unprecedented data in terms of resolution, quality, and accuracy.

All LTHOs should be equipped with low-power polarimetric radar networks. Polarimetric capabilities are necessary as they make data quality control much easier. Detection and removal of echo due to permanent and anomalous propagation ground targets, contamination by a layer of melting ice that gives rise to abnormally high radar reflectivity values, and other artifacts can be easily recognized. From this perspective the additional potential of polarimetric measurements for improved radar-rainfall estimation is a bonus. X-band polarimetric radars cost on the order of $0.5M and can be operated by hydrologists and hydrometeorologists with limited training in radar systems.

Similar radars can be installed on moving platforms such as trailers or tracks. They can be moved from place to place and easily deployed in the field. Their high mobility makes feasible the concept of "flood chasing," similar to that of storm or tornado chasing. To provide high-quality quantitative observations of precipitation both the permanent and short-term experimental sites should be equipped with rain gauges and disdrometers readied for quick deployment. Such experiments were successfully conducted in Europe and Japan.

be to make the instruments more reliable, more accurate, less expensive to build and operate. Examples of the immediate needs for such developments include, but are not limited to, the following: high-range scanning LIDAR for water vapor measurements; integrated accurate multisensor systems for geophysical measurements relevant to groundwater movement; portable multisensor systems for remote sensing of discharge; inexpensive low-power disdrometers that could one day replace rain gauges; and a portable network of high-resolution polarimetric radars.

The HMTF will also be involved in training and education. This will be accomplished by providing short courses prior to field experiment deployment, organizing short- and longer-term visits of university graduate students and researchers, and a postdoctoral associate program that will focus on new instrument development.

3.1.3. Laboratory and Development Facilities

The HMTF must have the ability to design, produce, test, and calibrate the complete range of hydrologic tools. Many of these activities will require fabrication of unique and evolving systems. A complete machine tool facility, electrical test and measurement laboratories, and calibration facility will be critical components of the HMTF.

The fabrication facilities will be equipped to facilitate team development of instrumentation systems. This will be based on digital component design and computer controlled production. This mode allows for web-based teams to collaborate on development and rapid refinement of design concepts with intermediate physical model testing.

Laboratory-based test and measurement facilities will be crucial to the development of novel sensors, integration of suites of sensors, and maintenance of all hardware systems. The test and measurement facilities will provide the backbone of the sensor development program, with microwave frequency tools and complete circuit design and prototyping capabilities. The calibration facility is fundamental to providing the end users of HMTF tools with known precision. At present, the lack of community standards for instrument performance relegates much of the data collected to single-use status because there are no quantified confidence bands on measurements. Sensor calibration facilities must service measures of stream flow, aqueous chemistry, soil water, geophysical, subsurface, and micrometeorological components. These facilities will set an international set of standards for these measures, and will provide contract services for external corporations and agencies that seek to maintain HMTF quality control standards.

3.1.4. Hardware Aspects of the HMTF

The missions in providing hardware support are to

1. Provide critical tools that investigators otherwise could not use due to availability, cost, complexity, or lack of awareness.
2. Support the needs of the observatory program (characterization and monitoring).

The community peer-review process will select the technology supported by the HMTF. Criteria for inclusion will require that the methodology under consideration be

1. Reliable
2. Widely useful
3. In an emergent state with practicable opportunity for offering major advancement in scientific hypothesis testing

Tools that will be purchased, developed, and maintained by the HMTF will include both off-the-shelf components and systems of tools that together constitute novel systems. The selection process will follow that outlined above, but it is illuminating to consider the current opportunities. Facilities of off-the-shelf tools that are currently underutilized in hydrologic sciences due to structural impediments (chiefly economic and lack of technical support) include:

- **High-resolution mapping of elevation and canopy cover**: Airborne LIDAR
- **Analysis of isotopic tracers**: Mass Spectrometer (e.g., δO^{18}, Cl^{36}).
- **Geological setting**: Access (drill rig); Geophysical characterization (e.g., GPR, Resistance Tomography, seismic, induced current [EM], Magnetometer).
- **Precipitation fields**: Radar, rain gage networks.
- **Micro-meteorological conditions**: sonics, radiation, humidity sensors

Some of these facilities will be most efficiently provided by contracting from universities (e.g., mass spectrometer). Others, which require extensive consultation with experts for experimental design and interpretation (e.g., geophysical characterization) will demand support staff and instruments to be maintained by the HMTF. As has been found in oceanography and atmospheric sciences, the platforms that mobilize these tools are often more critical than the tools themselves. In the context of hydrology, mobilization will require trucks, boats, submersibles, helicopters, and light aircraft to bring the tools and scientists to the measurement locations (e.g., lakes, flooding rivers, remote mountains).

Perhaps the greatest currently unrealized opportunities are specialized characterization methods specific to the study of hydrologic systems. These include the following:

- Hyporheic characterization: protocol for conducting and analyzing high-dynamic range pulsed tracer studies
- Subsurface biogeochemistry: Push-pull tests, including monitoring of DO, pH, anionic tracers, sorbed tracers, and substrate consumption.
- Stream losses: vertical temperature profiling of stream beds
- High-resolution hydrogeologic conditions: dipole well test
- Unsaturated hydrogeology: cone penetrometers-permeameter systems
- Real time sediment flux: TDR

The HMTF will make accessible a suite of tools to facilitate discovery across processes. Each of these developments includes assembly of systems of instrumentation with an analytical development to provide an interpretation of the data obtained. Here the HMTF will provide complete systems of instrumentation with the technical staff required to properly design field missions, ensure calibration and reliable operation, and even to assist in operating the equipment in the field. This facility will enable university scientists to make the complex suites of measurements required to address the complex biogeohydrologic conundrums that until now have remained beyond the scope of the single-investigator approach supported by the NSF.

3.1.5. Focus on Geophysical Tools: A Facility to Enable Geophysical Characterization of Subsurface Hydrology

The HMTF will have three broad themes: subsurface, surface, and remote sensing. Here we expand on one of these themes, subsurface geophysics, to illustrate the need, character, and opportunity for facilities infrastructure.

Surface geophysics is the tool that allows non-invasive characterization of subsurface conditions. In addition, if boreholes are available, down-hole and hole-to-surface geophysical measurements provide essential insight into specific field situations. An underlying theme of these investigations is that, because even under the best of conditions, geophysical tools "see through a glass darkly," there is substantial synergy in combining two or more complementary methods to study the same area. Over the last several decades, enormous advances have been made in the acquisition, processing, and interpretation of surface and down-hole data, but to quantitatively address the emerging needs of the hydrological community, a quantum increase in the coordination and funding of these efforts is required.

Applications of Geophysics to Groundwater and Hydrogeology. Surface geophysics is used to non-invasively determine the fundamental character of the subsurface. Is a field site underlain directly by bedrock or by unconsolidated sand and gravel? In the latter case, geophysics can characterize the distribution of soil moisture in the unsaturated zone, determine the depth to the water table for unconfined aquifers, and delineate the depth, thickness, and lateral dimensions of groundwater aquifers. An example of the potential of contemporary geophysical tools, in this case a resistivity array coupled with numerical inversion, to delineate hydrogeologic features is presented in Figure 2. Clearly this type of information is critical to the understanding of subsurface hydrologic components of a watershed, but due to high cost and the need for trained operators these tools are currently inaccessible to U.S. university faculty.

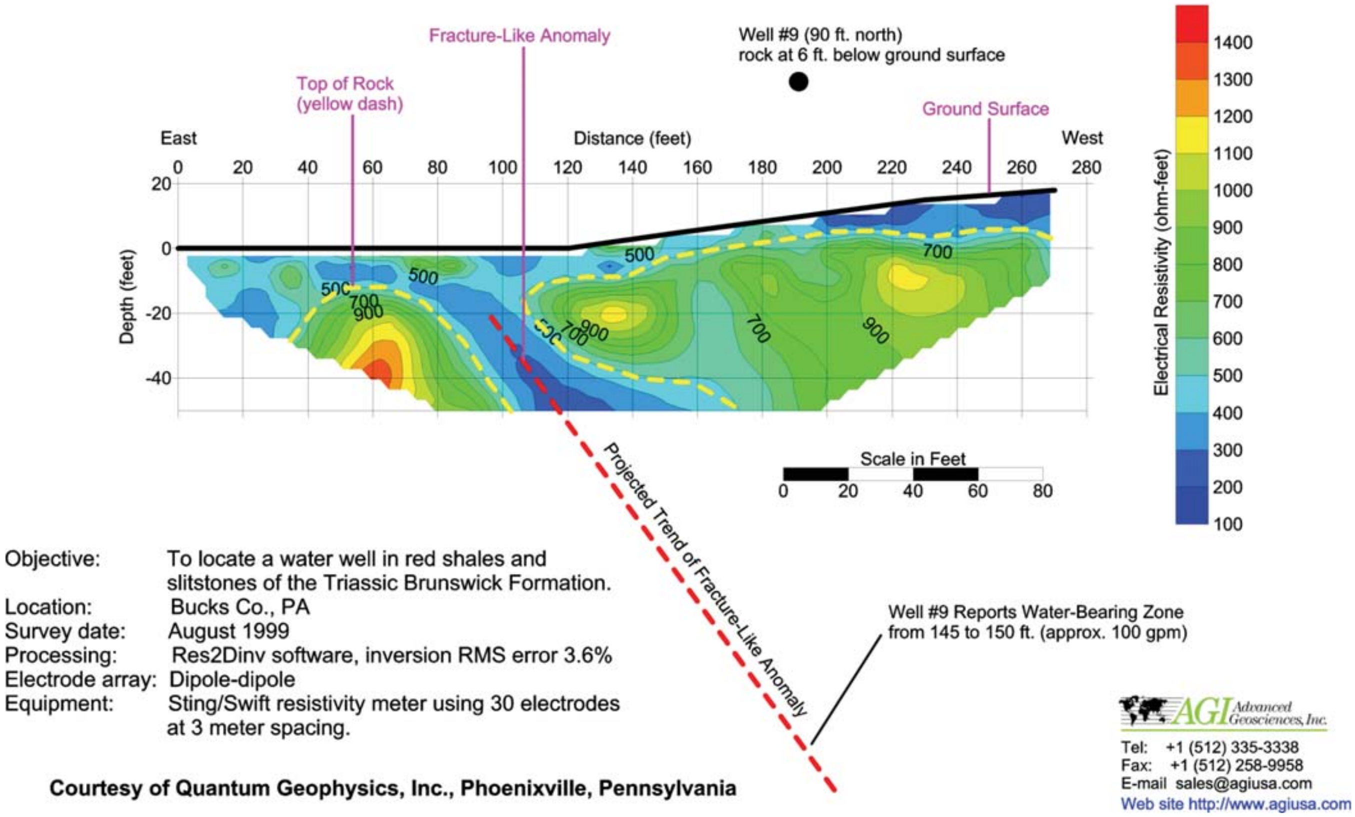


Figure 2. Example of detailed geological data obtained using resistivity tomography based on multi-electrode system coupled with numerical inversion to reconstruct the distribution of a 2-dimensional slice of a complex subsurface hydrologic setting (provided by Advanced Geosciences Incorporated).

Surface geophysics complements available sampling from boreholes or trenching operations because the latter observations are usually limited in coverage—drill hole samples may provide quality data, but only for a limited volume. Geophysical data at the surface can effectively extrapolate information away from the vicinity of a drill hole, and interpolate information between drill holes.

Matching Geophysical Measurements to Geologic Conditions in the Subsurface. Surface geophysical investigations involve applying one or more of the following techniques to characterize the Earth's subsurface: ground-penetrating radar (GPR); seismic refraction and reflection; gravity; DC resistivity in sounding or tomographic modes (e.g., Figure 1); electromagnetic frequency domain and time domain; and magnetics. GPR can be excellent for high-resolution images of low electrical conductivity media, but often benefits from DC resistivity and/or seismic data to identify the physical nature of a particular "reflector" or "refractor" at depth. Seismic refractions could suggest a planar discontinuity in the subsurface, but DC resistivity data might be needed for the interpreter to differentiate between bedrock and the groundwater table.

Borehole Geophysical Investigations employ combinations of video, acoustic, thermal, electrical, electromagnetic, seismic, and/or radioactive monitoring methods, among others. Integrated analyses of such data lead to near field and far field images of, for example, water content, bedrock fractures, and sediment stratigraphy, that provide key insight into hydrogeological processes.

3.2. DATA HANDLING—INFORMATION SYSTEMS

HMTF will develop an archive of all data collected through the use of HMTF platforms or data-collection systems. The policy will be foster scientific research through simple and timely community access to all the data collected during the intensive field campaigns, as well as at long-term field sites. The software necessary to use the data collected in the field will also be provided and continually upgraded. We anticipate that this support will fall under the umbrella of the Hydrologic Information Systems Standing Committee.

3.3. STAFF, POSTDOCTORAL, AND VISITING SCIENTIST STRUCTURE

The staff of the HMTF will be the heart of its success. Three categories of staff are proposed: administrators, measurement specialists, and facilitators.

Administration staff will consist of a single director with assistants for budget, logistics, and outreach, all of whom will be aided by scientist sub-directors of each HMTF section. There will be sections dedicated to the three basic suites of equipment: subsurface, surface, and remote sensing. Subsurface will include three subsection leaders in geophysics, aquifer testing, and subsurface biogeochemistry. Surface water will have four subsection leaders in stream, soil, snow, and micrometeorology. Remote sensing will have three subsections of near surface, airborne, and satellite systems. Each section will have one administrative assistant, two technicians, two engineers and positions for two post-docs and one visiting scientist.

Facilitation includes members of the engineering design team (two staff); calibration facility (two staff); machine facility (two staff); and mobilization (one staff).

In total, this represents a scientific team of 14, 11 specialized technicians, 8 engineers, and 6 administrative assistants. This 39-member team will be complemented by the constantly rejuvenating system of 9 visiting scholars (described below), indicating a fixed cost staff of about 48 people.

Postdoctoral/Visiting Scientists. We will admit three new postdoctoral students each year for a two-year visit, and three visiting scientists each year (brief visit and sabbatical program) to help in the development of specific instrument packages and associated software support (e.g., inverse methods). These visitors fulfill three critical functions. First, they bring current needs to the facility, presenting the staff with cutting edge issues for instrumentation and measurement systems. Second, they bring new ideas and techniques being developed in universities to a fully equipped technical staff prepared to transform these ideas into tools. Finally, these visitors will take home the seeds of new ideas and tools from which the techniques developed at the HMTF will take root in the larger scientific community.

3.4. STRATEGY FOR SUPPORTING HYDROLOGIC OBSERVATORIES: LARGE CAMPAIGN STUDIES

A primary mission of the HMTF is support of community based multi-investigator studies (e.g., the large-scale NASA intensive campaign experiments of the 1980s and 1990s including FIFE, HAPEX, BOREAS), the CUAHSI Hydrologic Observatories, and that which we refer to generically as Large Campaign Support (LCS). LCS projects require that the HMTF maintain the capacity to develop and install extensive standardized instrument packages. The list of typical requirements for supporting LCS activities shown below demonstrates that these efforts will involve extensive use of state-of-the-art tools and analysis techniques that go far beyond simple installation of off-the-shelf parts.

Typical LCS support functions of HMTF:

1. Provide high-resolution DEMs and canopy cover profiles (airborne LIDAR);
2. Install high-resolution precipitation monitoring system (ground-based radar and disdrometer network);
3. Characterize and monitor stream network:
    i. Hyporheic through tracer transport (one-time study)
    ii. Temperature monitoring along reaches (continuous in time)
    iii. Major ion monitoring (continuous in time)
    iv. Stream bed temperature profiles (full year study)
    v. Gauging of flow (permanent installation)
    vi. Sediment monitoring (continuous monitoring)
4. Characterize and monitor aquifers
    i. Depth to water and fluctuation in water level
    ii. Permeability profile
    iii. Major ionic composition
    iv. Biogeochemistry
5. Geological Characterization: geophysics.
6. ET monitoring (e.g., micrometeorological tools, LIDAR, scintilometer)
7. Vadose uptake (infiltration capacity) and fluctuation and spatial distribution of vadose storage (e.g., TDR network, instruments for vadose hydrogeologic characterization).

A summary of the major tools and mobilization platforms that will be required by the HMTF is provided in Section 4.

4. BUDGET

The anticipated budget for the HMTF will include both capital investment and recurring annual costs. The initial investment will cover facility setup and the initial suite of instruments. The annual cost will cover staff salaries, field deployment of the instruments, sensor calibration and maintenance, shop upkeep, new instrument purchases, research and development of new instruments, and the visiting scientist program.

The initial investment funds should be used to procure the following set of observational capabilities:

- Instruments needed for deployment at the LTHO
- Mobile scanning LIDAR for measurements of water vapor
- Mobile remote sensors for measurements of stream discharge
- Mobile high-resolution rainfall measurement network
- Mobile multi-frequency radiometers
- Airborne passive and active radiometers and LIDAR systems
- River surveying boats
- Helicopter-based flood surveying laboratory
- Submersible river/lake/karst surveying laboratory
- Mobile geophysical instruments
- Portable hydromet stations
- Portable borehole construction and down-hole instruments

Some of these are off-the-shelf systems and some would be developed by the HMTF using existing technologies. We estimate that the total cost of the above systems will be about $20M. This does not include the instruments needed for the establishment of LTHOs.

The initial cost of setting up the HMTF will depend on the matching contributions from those who will propose to host it. The initial cost certainly will not include the building infrastructure. For example, if an institution proposing to host the HMTF contributes a state-of-the-art machine shop, this will considerably reduce the required initial investment cost. The initial cost will include setting up a full sensor calibration laboratory, a suite of high-quality electronic measurement instrumentation, a microwave laboratory, an optical bench, etc.

The annual cost will consist of about 55% for staff salary, 20% for field deployment and maintenance, 5% for the visiting scientist program, and 20% for research and development. We expect that there is potential for some of the annual cost to be recovered by federal agencies' use of the facilities, as has occurred with ATD.

The blend of background and skills necessary for effective operation of HMTF includes about 20% engineers, 40% scientists, 30% technicians, and 10% administrators. The initial number of staff personnel will be about 48 (see section 3.3). The director should be a scientist or engineer with strong background in field experimentation. If we assume the fringe benefits to be about 25% of the salary and the overhead rate to be 50% of the direct cost, based on the above distributions of expertise and tasks, we estimate the annual budget to be about $12M with a initiation investment of about $20M in large equipment and system development. These numbers will be refined as the details of the location of the HMTF, the LTHOs, and the initial suite of instruments are established.

5. IMPLEMENTATION PLAN

The HTMF as envisioned here will require a significant investment in buildings, equipment, and support staff, and will require considered and open participation by the community to bring it to full operation. Here we sketch the major steps in establishing the HMTF.

1. A call for proposals will be developed by CUAHSI to be published as soon as possible following NSF commitment of funds to the project. The national call for proposals to nonprofit organizations will highlight the critical aspects discussed in the HMTF planning document. Important to highlight in the call will be the concept that this facility will empower university investigators who have ideas and plans for developing improved understanding of processes in the water cycle through field experimentation (world-wide campaigns and long-term sites), and have so far lacked such a national facility.

2. A four-month period for the community to respond with proposals. The organization(s) that propose to house the centralized HMTF will discuss in detail how their institution (e.g., university) will develop and run the facility. A timeline for implementation along with details on how they will provide the necessary space to house the associated laboratories (e.g., fabrication, machine shop, calibration laboratory, storage space, offices) including cost shares and space leasing costs will be required. They will propose initial major instrumentation and support vehicle purchases (e.g., aircraft, boats, trucks). The size and scope of expertise of the HMTF personal will be given in detail as well (i.e., Ph.D. hydrologists, engineers, computer experts, technicians, secretaries/accounting).

3. The proposals will be reviewed through the regular NSF procedures and the award will be announced in month 8.

4. The successful institution will immediately begin hiring the HMTF leadership team and securing space upon announcement of award. Equipment acquisition will begin in month 12. Technical staff will calibrate and develop use protocols for equipment as it arrives throughout the second year of operation.

5. The initial solicitation for HMTF support on projects will go out in month 12, with announcement of successful applications in month 18 and support activities beginning as specified in the proposals.

6. Support of LTHO equipment selection, acquisition, calibration, and installation will begin in month 14.

The implementation plan must correspond to the range of studies carried forward by the scientific community. The support will be balanced between support of single investigator/small team projects and LSC efforts. Both the approximately 25/yr small projects (under $100,000) and the approximately 5/year large projects (≈$0.5M each) will be selected through a proposal request and allocation process run by an external NSF scientific review panel.

Scientific proposals are generated either by university or HMTF PIs. Proposals are submitted to NSF where they receive the usual external review and are evaluated for scientific and programmatic merit by the panel. At the same time, the proposal is submitted as a facility request to the HMTF, where a feasibility assessment and cost estimate are developed by HMTF staff working together with the submitting PI and university. Proposals slated for funding and completed feasibility/cost assessments are submitted to the Facility Advisory Panel (FAP) for evaluation. The FAP provides advice to the PI as well as to the Facility Advisory Committee, which makes the final evaluation and commits HMTF resources.

5.1. TIMELINE

After the funds have been committed to CUAHSI, a solicitation process will begin immediately. An anticipated timeline for development of the HMTF is quite aggressive, showing the expectation for initiation of proposal peer review within 12 months of the call for HMTF proposals. First provision of support to university faculty is anticipated by the middle of Year 2. Key milestones are site selection, building preparation, staff hiring, and instrument purchase and preparation.

Activity	Year 1	Year 2	Years 3 and beyond
Center solicitation	***		
HMTF site selection	*		
Space acquisition and preparation	*****		
Leadership team recruitment	***		
Professional staff recruitment	**	****	
Initial hardware acquisition		****	
Equipment installation, testing, and use protocol development		*****	
Call for proposals for HMTF support services		* *	* *
LTHOs support		*******	********
University PI support		*****	********

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