Implementing USAAC Recommendations to Achieve Comparable MT and Seismic Transportable Array Station Density

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**Executive Summary.** In December 2008 USAAC recommended that IRIS develop a plan for a continental-scale USArray magnetotelluric transportable array (MT TA) footprint equivalent to the seismic TA footprint (~1623 stations). The resulting whitepaper was endorsed by USAAC in May 2009. The whitepaper is updated here to reflect progress made during 2009 and to incorporate updated cost estimates based on an additional year of field operations. We provide an overview of the USArray MT program, the impacts and results from MT work to-date, existing financial resources, highlights of community recommendations for future MT TA work, and a discussion of the cost implications and strategy for implementing the USAAC recommendations.

The MT component of USArray includes 7 permanent backbone (MT BB) stations similar in concept to the seismic Reference Network, and 20 MT TA instruments typically deployed for 3 weeks at each site and then relocated in a rolling footprint. From 2006-2009, 221 high quality MT TA stations were completed on a contiguous 70 km station grid in the NW quadrant of the continental US (Fig. 1). Such a large-scale contiguous grid of MT stations is unprecedented and exceptionally well suited to recently developed 3D MT inverse modeling methods. Ongoing work to invert and interpret USArray MT data by a number of research groups, including results presented at national and international conferences and in peer reviewed publications has demonstrated the transformative potential of regional-to-continental scale mid-crustal-to-mantle conductivity images, particularly when co-registered with complementary EarthScope data products such as seismic tomograms.

The USArray MT O&M budget is currently $0.47M/year. This budget supports MT TA and MT BB operations, data quality control, generation of data products and transmission to IRIS DMC, software development, documentation, web services and operation of the MT instrument center at Oregon State University. The current funding level permits continuation of all of these activities, as well as the installation of ~45 additional MT TA stations/year. At the present pace ~401 MT TA stations will be completed by the end of the initial EarthScope O&M period in 2013, providing ~25% coverage of the continental US.

While partial coverage of the US is of great value, this remains far short of the number of stations required to sample the eleven regional-scale targets identified in a 2008 NSF-supported national EarthScope MT planning meeting. Such a sub-sampling also inhibits discovery of new targets not presently contained within identified MT study areas, such as the “mantle drip” features identified by the seismic TA/FA. A more complete MT TA footprint would greatly facilitate joint interpretation of highly complementary seismic, MT and other EarthScope data sets across the continental US.

We consider two approaches to implementing the USAAC recommendation. By moving to year-round field operations we can utilize the full capacity of the existing USArray facility of 20 MT TA instruments, completing 120 stations/year. This requires incrementing the O&M budget by ~$0.60M/year (to $1.07M/year) from 2011 and beyond. ~626 stations would be completed by the end of 2013 (covering 39% of the continental US), and 866 stations would be completed by the planned decommissioning of the last continental US seismic TA stations in 2015 (53% coverage). If additionally we combine the USArray instruments with former EMSOC instruments that will be transferred to OSU in 2010, 270 stations could be completed each year, for an O&M increment of $1.58M/year (to $2.05M/year) from 2011 and beyond. 1076 stations would be completed by the end of 2013 (66% coverage), and 1616 stations by 2015 (~100% coverage).
EMScope Overview. The magnetotelluric component of USArray, EMScope, operates in a manner analogous to its seismic counterpart with both Backbone (MT BB, i.e. the reference network) and Transportable Array (MT TA) sampling modes. The MT BB consists of seven quasi-permanent stations distributed over different physiographic regions of the continental US, each designed to yield MT data in the period range of 10 s – 100,000 s. These fixed sites provide remote reference measurements of the magnetic field as required for processing of MT TA data, and also provide local estimates of MT response functions (broadly similar to seismic receiver functions) that provide deep penetration from the mid-crust through the mid-mantle transition zone. MT response functions are inverted to produce models of the electrical conductivity of the crust and mantle (Fig. 3). These anchor points in California, Oregon, Montana, New Mexico, Minnesota, Missouri and Virginia (crosses in Fig. 1, station and data examples in Fig. 2) provide a deep reference model in which higher resolution regional 3D electrical conductivity models can be placed into context.

Fig 1. Backbone MT stations (orange crosses on map) provide stable, long-period data over months and years of observations to image deep into the mantle; they also provide remote reference magnetic field data used to reduce source field bias effects in MT TA data. Transportable MT stations (dots on map) collect data for 3 weeks then relocate to the next location in a uniform grid shown here for sites in WA, OR, ID, MT, WY, northern CA occupied in 2006-2009.

Whereas seismic TA stations are installed for 18 months, the MT TA stations operate for 3 weeks after which the MT installation is relocated to the next point in the MT TA grid. Data in the frequency range of about 10 s – 10,000 s are obtained providing information on conductivity structure from the mid-crust to the upper mantle. One consequence of this shorter sampling period is that a smaller pool of MT instrumentation is sufficient to achieve an equivalent number of grid points as for the seismic TA. An MT TA site can be installed in half a day by a field crew of two. MT TA operations are more constrained by seasonal considerations than seismic TA, since operations must be restricted to the southern tier of states during the November – April winter weather (snow) period.

As of Fall 2009 and following MT TA seasonal field campaigns in 2006-2009, 221 MT TA stations were completed south of the Canadian border (Fig. 1). Thus far the MT TA array has covered the Cascadia region of Oregon, Washington and Idaho, the Snake River Plain (SRP), Yellowstone and the adjoining areas to the east in Wyoming and Montana north to the Canadian border and south to northernmost Utah and Nevada. 25
MT stations have also been completed thus far in Alberta, Canada on an extended MT TA grid by the University of Alberta as part of an ongoing collaboration with EMScope, using similar NIMS long period MT instruments.

Fig 2. (left). MT backbone station at Agassiz National Wildlife Refuge in Minnesota, showing top of 2 m deep underground, insulated vault containing fluxgate magnetometer, separated by 5 m from 2nd vault containing data acquisition unit. GPS antenna seen in pink cover top of fencepost to left. System powered by 27-W solar panel at rear. All materials used at site are nonmagnetic. Not shown – two crossed trenched and buried 500 m-long N-S and E-W electric dipole receivers used to monitor electric fields. Electrodes are located in 1 m deep underground vaults at each of the four distal points of the electric dipole receiver arrays. (right) MT response functions displayed as apparent resistivity and phase for MT BB site MBB03 in Braden, Missouri. The response is shown displayed in two orthogonal directions – the split between the two modes illustrates the frequency-domain tensor character of EM response functions above non-1D structures. Note that high quality responses are obtained from MT BB installations for periods greater than 100,000 s.

Our present plan for 2010 onward is for the MT TA to occupy a set of regional footprints targeting a subset of key areas of interest identified during a 2008 national planning meeting sponsored by NSF (see MT Community Recommendations section below). The present level of EMScope O&M funding will permit acquisition of approximately 45 MT TA stations per year, permitting construction of a small, discontinuous set of targeted arrays rather than a contiguous array spanning all of the continental US. At this pace we will obtain 25% coverage of the continental US by the end of the initial 5-year O&M period in 2013, and 30% coverage two years later when the last continental US seismic TA station is decommissioned. This is described in more detail below.

Existing resources. The operation of the MT BB array, the MT instrument facility, the acquisition of approximately 45 MT TA sites per year through sub-awards to TA contractors, all MT data quality control, response function calculation and transmission to IRIS DMC, software development, maintenance of documentation, web services and all other functions of EMScope takes place within a budget of $0.47M/year. (Approximately 2% inflationary adjustment has been factored into the current EMScope O&M allocation for the remainder of the initial phase of EMScope operations.) The total inventory of MT TA instruments currently consists of 20 NIMS (Narod Geophysics, Vancouver BC, Canada) long-period instruments. These are stand-alone battery-powered instruments that record data on flash disks. These instruments, support...
equipment, and related hardware and software are maintained at an EarthScope instrument center at Oregon State University.

Management structure. EMScope is managed through a sub-award from IRIS issued to Oregon State University. Bob Woodward is the IRIS project officer with oversight of EMScope; Adam Schultz is PI of the Oregon State sub-award. Gary Egbert at OSU is responsible for data QC and data flow into IRIS DMC. As lead EMScope institution, OSU provides a variety of services to IRIS, following an agreed SOW and defined milestones; weekly, monthly, quarterly and annual reports are filed with IRIS and assimilated with IRIS’s USArray reporting to NSF. The management sub-award is reviewed annually, performance is assessed and renewal is sought based on that assessment.

Scientific Impact. A number of groups around the US and internationally are analyzing, inverting and/or interpreting EMScope data including groups at Woods Hole Oceanographic Institution, University of Utah, Oregon State University, University of Tokyo (Earthquake Research Institute), Scripps Institution of Oceanography, Arizona State University, Missouri State University, and Virginia Tech. EMScope is the first effort of which we are aware to carry out continental-scale 3D electrical mapping of the crust and upper mantle on a uniform grid, and prior to the completion of the Cascadia MT TA array (Washington, Oregon and W. Idaho) it was an open question whether spatial aliasing would present a significant complication to the interpretation of these data. The 3D inversion of the Cascadia data has revealed substantial coherence between the resulting 3D conductivity models and the known boundaries of major physiographic provinces, as well as strong correlations (both positive and negative) with seismically delineated mid-to-lower crustal and upper mantle features. These results indicate that the selection of a 70 km grid, following a similar pattern1 to the seismic TA, has produced a rich and interpretable data set when modern 3D inversion tools are employed in the analysis.

Three-dimensional inversion of this dataset (Fig 3) reveals extensive areas of high conductivity in the lower crust beneath the Northwest Basin and Range, and beneath the Cascade Mountains, contrasting with very resistive crust in Siletzia, the accreted thick ocean crust which forms the basement rocks in the Cascadia forearc and the Columbia Embayment [Patro & Egbert, 2008]. The conductive lower crust beneath the southeastern part of the array is inferred to result from fluids (including possibly partial melt at depth) associated with magmatic underplating. Beneath the Cascades high conductivities probably result from fluids released by the subducting Juan de Fuca slab. Resistive Siletzia represents a stronger crustal block,

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1 The 70 km grid pattern of MT and seismic TAs is equivalent, but sites are very rarely if ever collocated because of different siting/permitting requirements – e.g. the sensitivity of MT to EM fields of anthropogenic origin imposes particular requirements generally absent from seismic.

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accommodating deformation in the surrounding crust by rigid rotation. Significant variations in upper mantle conductivity are also revealed, with the most conductive mantle beneath the Washington backarc in the northeastern part of the array, and the most resistive corresponding to subducting oceanic lithosphere.

Fig 4. Comparison between 3D resistivity (reciprocal conductivity) models of Cascadia, and shear wave tomograms for depths (from left to right) of 50 km, 100 km, 200 km and 300 km. The area of Washington, Oregon and western Idaho for which 3D resistivity model information is provided is shown on the larger area seismic depth sections as a box – thus seismic and electrical models are plotted on a common length scale. The Juan de Fuca slab signature is clear in both models (though different), in both cases exhibiting lateral continuity. The low velocity feature beneath Newberry coincides with a circular zone of enhanced conductivity in the upper mantle. Some features in the MT image, such as the high conductivity zone at shallow depths in SE Oregon, correlate well with structures of similar geometry in the seismic images at mantle depths.

The Juan de Fuca slab is well imaged in body wave seismic tomography models, extending to depths of ~500 km and perhaps deeper [Roth et al., 2008; Fouch et al., 2009]. Significant zones of focused reduced seismic velocities are evident beneath both the Newberry region and the surface expression of the Columbia River basalts (Fig 4). Fouch et al found no evidence for a zone of low velocities beneath the Juan de Fuca slab. Further, the absence of a slab signature beneath central Oregon, interpreted by some groups as a “hole” in the slab, may be an inversion artifact due to imperfect ray coverage and the presence of the reduced velocity zone coincident with Newberry.

The joint interpretation of USAArray magnetotelluric and seismic data sets is just getting started, but there are already clear indications of how these data sets are mutually complementary. The variations in conductivity are sensitive indicators of the presence of aqueous and magmatic fluids, as well as a set of important constraints on temperature, composition and at mantle depths the influence of water and volatiles on upper mantle processes. The seismic tomography models are primarily sensitive to thermal and compositional changes in mantle structure. In particular, the strong reduction in S wave velocities may indicate the presence of partial melt (magmatic fluids) in some regions of lowest S wave velocity perturbations. It is notable that there are zones within Cascadia where both conductivity and seismic velocity anomalies are correlated, but other zones where anticorrelations are seen. The potential that conductive (hot or rich in interstitial fluids) and slow (also hot or rich in interstitial fluids) zones might be identified e.g. with regions of basaltic underplating of the crust is unsurprising; but perhaps even greater insights can be gained where these indicators diverge, e.g. fast (potentially cooler) and conductive (therefore most likely aqueous fluids or
carbon films rather than melt along grain boundaries). As the seismic and MT TAs progress across the continental US we anticipate emphasis will be placed on such joint interpretation efforts and a greater understanding will emerge of how each parameter may be used to constrain the interpretation of the other.

**MT community recommendations.** An NSF-supported MT community meeting was held in June 2008 as a prelude to the IRIS National Meeting at Skamania Lodge, Washington. Approximately 30 MT, seismic and geological specialists attended, with the goal of identifying the highest priority targets that should be investigated with the USAArray MT observatory. The number of identified high priority targets significantly exceeds what is possible to achieve with ESMope’s existing resources.

Prioritization of future MT TA footprints was based on identifying key tectonic processes that formed or modified the US, and determining whether candidate MT footprints of affordable areal coverage could contribute significantly to understanding them. Three main processes where MT can play a very significant role were identified for study: Rifting, Subduction, and Intraplate deformation. Summaries of the questions addressed and the proposed study areas follow below.

**Rifting:** Does the mantle lead the crust when lithosphere is rifted, or is the degree of deformation essentially equal at all levels? Is rifting fundamentally symmetric or asymmetric? What are the relative roles of force versus strength in determining the nature of deformation? To what extent are pre-existing structures reactivated? Where in the domain do fluids influence rock strength and redistribute chemical elements? How do fluids communicate between the upper mantle and the upper crust?

Modern rift areas considered important to illuminate using MT TA include the Rio Grande Rift and the eastern Great Basin. Particularly intriguing is the Northern Rio Grande Rift of central Colorado where surface extension is very slight but strong resistivity and seismic anomalies in the upper mantle are suggested from previous studies. An important fossil example is the Mid-Continent Rift of Wisconsin and upper Michigan, where a Grenville age rifting event nearly separated the continent leaving a volcanic rift section nearly 30 km thick in places. Fossil environments give us a chance to study processes that have gone more to completion. In this case, we may be able to resolve leftover effects of upper mantle modification such as dehydration.

*Rifting processes have not yet been within the aperture of the MT TA program.*

**Subduction:** Where are the major loci of fluid release and melt formation, spawned to a large extent by the hydrated oceanic lithosphere? Does fluid release control the location of slow slip events and seismic tremor? Is there significant slab corner flow? What is the ultimate depth of significant amounts of underthrust oceanic sediments? What are upper mantle properties following oceanic closure and cessation of subduction, including effects of possible slab delamination?

The completed MT TA footprints covering Oregon, Washington, Idaho and western Montana have covered most of Cascadia, the main active subduction environment of the continental U.S., although to investigate Gorda Plate corner flow phenomena the Cascadia array would need to be extended southward into the Mendocino area of northern California. In terms of future work, an important fossil subduction orogen of the United States is the Appalachian mountain chain running the length of the eastern U.S. Because it is somewhat simpler in form and history, has two known major suture zones, and has a higher likelihood of suffering ultimate slab delamination, the Southern Appalachians is of somewhat higher priority than the Northern Appalachians. Graphitization of subducted sediments provides an electrical tracer for MT.

**Intraplate Deformation and Volcanism:** How important is tectonic activity far from a plate boundary in shaping the crust and upper mantle? What can this phenomenon tell us about the relative roles of force versus strength in deformation? Are there volumetrically significant additions of material to the crust through intraplate volcanism?
The Snake River Plain (SNP) was instrumented during the 2008 MT TA field operations. Following this there was essentially unanimous agreement at the workshop that the Yellowstone hotspot area be covered by the 2009 TA footprint and this has since been carried out. More complete imaging of the SRP source magmas would be aided by continuation of the proposed Mendocino region MT TA lines further east. Data from the 2009 MT TA footprint will also be used to examine the influence of lithospheric 'hard spots' (e.g., Billings anomaly) in influencing loci of magmatic input and crustal underplating. Another target area is the New Madrid seismic zone of the south-central U.S. Although far from an active plate boundary or apparent intraplate volcanism, an MT footprint nevertheless could examine the role of distributed fluids in promoting regional-scale deformation driven by far-field forces. The Salton Trough was also noted as a target. Since that time there has been proposal pressure to extend MT operations into Salton Trough and the transpression region of the California borderlands, and it is likely that there would be strong community interest in continuing the MT TA into the entire region of the state.

The workshop did not address PI-led MT investigations akin to EarthScope seismic Flexarray studies. In addition to Salton Trough there has been proposal pressure for an MT CAFÉ experiment (funded), a high-resolution onshore-offshore MT Cascadia Flexarray experiment related to Episodic Tremor and Slip phenomenon (pending), an MT Oregon High Lava Plains experiment that is in the planning stages, and similarly an MT experiment in the Wabash Valley seismic zone in Illinois. These and future PI-led MT Flexarray experiments are likely to be impacted by the lack of a systematic, wide-area background sampling by the MT TA that ensures that high-resolution local models are consistent with large-scale continental structure.

Current O&M levels will support approximately 45 MT TA sites per year. At current O&M levels, the initial 5-year O&M period will permit us to complete the continuous Cascadia through Yellowstone array (221 stations + Canadian contributions), and to implement at most one-to-three of the eleven targets identified in Figure 5. Under this scenario, decisions will have to be made in 2009 to prioritize the following top 7 of 11 proposed candidate footprints for 2010-2013:
1. Continuation of the existing MT TA array to the south (Mendocino) to include plate corner flow, the southern expressions of the Snake River Plain, and putative lithosphere drip features in Nevada.
2. Eastern Great Basin: Active asymmetric rifting, control on modern deformation by Precambrian hinge line.
3. Northern Rio Grande Rift: Active symmetric rifting, test of whether mantle leads the crust in deformation, reactivation of fossil structures.
5. Mid-Continent Rift Zone: Upper mantle modification by nearly complete rift event, especially hydration/dehydration. Subject of a one-day pre-AGU workshop.
7. New Madrid Zone: Large-scale rock strength variations in deformation.

These arrays will have limited aperture, consisting of 45-135 stations at most, i.e. on half the scale or at most on the same scale of the Cascadia array that led to the 3D model seen in Fig 3. This scenario will not permit acquisition of MT TA in much of California, nor will it enable the important exploration/discovery aspects inherent in the continuous/comprehensive coverage of the 1600 station seismic TA footprint. This is a shortcoming that restricts achieving the full potential of MT TA.

**Draft USAAC recommendations.** During the USAAC meeting in San Francisco in December 2008 the USAAC reviewed the current state of EMScope and current MT research results, including the emerging set of 3D inverse models akin to seismic tomograms that are now being published. The USSAC recommended that the MT TA be extended to provide 70 km spacing over the full territory of CONUS, i.e. a seismic TA-like grid of approximately 1600 stations. USAAC asked that a plan and budget be devised to address this goal, ideally over a time frame to coincide with the end of seismic TA operations in the continental US (i.e. by end 2015). This implementation plan has been written in response to the USAAC recommendations. In the remainder of this document we consider costs for implementing these recommendations.

**Implementation.** In the discussion below we assume a TA long-period MT instrument can be deployed as frequently as 6 times each year, each time for three weeks of data acquisition, with up to a week down time between deployments to allow for recovery and relocation, i.e. a 50% duty cycle over each 12 month period. The remainder of the year the instruments would be at the instrument center being reconditioned, and available for EarthScope funded MT Flexarray research projects. Thus the current inventory of instruments has the capacity of achieving 120 MT TA stations/year, not accounting for instrument damage and repair.

The current pace of approximately 45 MT TA stations per year is dictated by the O&M budget rather than the capacity of the MT instrument facility. At this pace by the conclusion of the first five year EarthScope O&M period in 2013 ~401 MT TA stations will have been completed, covering 25% of the area of the continental US. If this rate was sustained during a follow-on O&M period, ~491 MT TA stations would be completed by 2015, providing 30% MT TA coverage of the continental US by the time the final continental US seismic TA footprint was decommissioned. MT TA operations in the continental US could continue past this point, after seismic TA operations had moved to Alaska.

During USAAC discussions in December 2008, it was noted that such a time delay in obtaining MT coverage for areas where seismic TA had completed operations would impede co-registering MT and seismic models in the continental US, inhibiting efforts to integrate and synthesize these data types, and slowing overall progress. This would also impede synchronous seismic and MT TA operations in Alaska. There are advantages to speeding up the pace of MT data acquisition beyond 45 stations/year, to 120 stations/year or even to 270 stations/year so the complementary constraints provided by the different EarthScope data sets could be made available to modelers in as timely manner as possible. These greater installation rates can be accomplished in the first case by moving to year-round operations, and in the second...
An extended MT TA field season is possible, with field operations in southern tier states taking place outside the May-October window. This would require either contracting with commercial crews (as was the case for the 2006-2007 MT TA NIMS operations) since student field crews would be less available in the winter months, or by hiring full time field staff dedicated to MT TA operations (following the seismic TA model). We have budgeted assuming multiple sub-awards are issued each year by OSU to different field crew operators. We have allowed for one academic (summer) and one commercial operator (other seasons) to support 120 completions/year. Up to two additional commercial vendor sub-awards would be required to achieve 270 completions/year. In the latter case costs would likely be reduced if full time MT TA field staff were hired in lieu of subcontracting MT TA operations to commercial survey crews. In either case student E&O objectives could still be achieved e.g. by continuing to use students for summer operations (one of the sub-awards), while using full-time MT TA facility personnel or commercial contractors at other times.

**Equipment considerations.** The existing USAArray MT facility of 20 1-Hz NIMS (Narod Geophysics) MT instruments operated by Oregon State can be used to complete up to 120 MT TA stations/year if year-round operations are undertaken. An agreement is in place to relocate the 25 NIMS MT instruments currently operated by the University of Washington (the former EMSOC consortium pool) to the Oregon State facility, most likely in 2010. The former UW instruments are to be made available for NSF-supported MT operations worldwide. We assume below they will be available no more than 50% of the year to MT TA operations. At this level of availability the combined 45-instrument array can support 270-station completions/year.\(^2\)

**Incremental O&M costs.** The following table shows the *incremental* cost of increasing the MT TA component of EMScope from 45 station completions/year to 120 and 222 per year respectively, including a 2% annual inflationary multiplier. We have assumed the current 45 completion/year pace will continue through 2010 (leading to 266 total stations completed by the start of 2011). We include the incremental cost of sub-awards for the MT TA data acquisition effort, staff costs for data QC, response function calculation and transmission to IRIS DMC, pro rata management costs and indirect costs.

<table>
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<th>45 TA/year</th>
<th>120 TA/year</th>
<th>270 TA/year</th>
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<td>2011</td>
<td>0</td>
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<td>2015</td>
<td>0</td>
<td>$670,400</td>
<td>$1,847,240</td>
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**TOTAL # stations\(^1\) (% coverage of CONUS)**

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<tr>
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<th>491 (25%)</th>
<th>866 (53%)</th>
<th>1,616 (100%)</th>
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\(^1\) incl. 221 acquired 2006-2009

**TOTAL increment**

|         | $0        | $3,223,102 | $8,981,031   |

\(^2\) An MRI-R\(^2\) proposal (pending) has been submitted by Oregon State and collaborators to obtain 30 highly flexible ultra wide-band MT systems to support investigator led MT Flexarray and non-EarthScope MT investigations, potentially making it possible to dedicate the 25 former EMSOC instruments entirely to USAArray operations.
References:


Schultz, A., Earthscope magnetotelluric program – the USAArray Backbone MT Array, *18th EM Induction*


