EMSCOPE: A CONTINENTAL SCALE MAGNETOTELLURIC OBSERVATORY AND DATA DISCOVERY RESOURCE

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ABSTRACT

EMScope, a component of the NSF Earthscope project, is installing a 70 km-spaced grid of long-period magnetotelluric stations across the USA. Rapid data quality control and generation of derived data products provides an accessible resource openly available without charge or restriction through the IRIS Data Management Center and EMScope data portals via a set of data discovery tools. These data are available typically within two weeks of acquisition. Initial 3-d inversion of such EMScope data from the US Pacific Northwest shows substantial coherence between crust and mantle electrical conductivity variations, the boundaries of major physiographic provinces, and seismically delineated features.

Keywords: Geophysics, Crust, Mantle, Electrical, Conductivity, Inversion, Data, Discovery

1   INTRODUCTION

The EMScope project is an infrastructure and data acquisition and dissemination activity supported by the US National Science Foundation EarthScope Program. EarthScope represents a $200M investment in geophysical instrumentation and cyberinfrastructure to enable the exploration of the four-dimensional structure and evolution of the North American continent. EarthScope promotes broad, integrated studies of:

- Fault properties and earthquake processes
- Crustal strain transfer
- Magmatic and hydrous fluids in crust and upper mantle
- Plate boundary processes
- Large-scale continental deformation
- Continental structure and evolution
- Deep-Earth structure

The concept of EarthScope follows closely that of shared "big science" infrastructure investments more typically associated with fields such as particle physics (large accelerators) and astronomy (large optical telescopes, radio telescope arrays, the Hubble and Spitzer space telescopes). EarthScope provides such a resource to a community not previously accustomed to operating with large, shared infrastructure investments. EarthScope departs from long-standing tradition in academic geophysics; data and derived data products are distributed rapidly and freely without the proprietary data access restrictions that are typically associated with Principal Investigator-led academic research programs.

In order to investigate the broad range of Earth processes highlighted above, EarthScope has been organized into three primary activities. The first is the San Andreas Fault Observatory at Depth (SAFOD), which is centered on a series of deep boreholes drilled through the eponymous California fault zone. SAFOD carries out sampling, down-hole measurements, and long-term monitoring directly within this seismically active fault zone, at seismogenic depths. The keys aims of research supported by SAFOD include determining the composition of fault zone materials and the constitutive laws that govern their behavior; the direct measurement of the state of stress that initiates earthquakes and control their propagation; and the testing of models that link the dependence of the recurrence of earthquakes to pore fluid pressure and to chemical reactions that modify the nature of the materials within the fault zone (International Continental Drilling Program, 2008). The SAFOD site at Parkfield California is located within arguably the most intensely instrumented seismically active region on Earth and one in which the outcome of monitoring will have a direct impact on seismic hazard assessment to a densely populated, urban, and industrialized area of North America.

The second component of EarthScope is the Plate Boundary Observatory (PBO). PBO was designed to examine the forces that drive tectonic plate boundary deformation; to determine the spatial distribution of plate boundary deformation and the relationship to earthquake nucleation and occurrence; to examine how such deformation changes as earthquake occurrence evolves; to examine the dynamics of magma rise, intrusion, and eruption; and finally to assess means by which these hazards can be reduced. To examine these questions, (at the time of this writing) PBO had installed 852 GPS receivers, 103 borehole strainmeters, and 5 laser strainmeters throughout the USA but most intensely concentrated in the western third of the continental US (i.e., within the region of "tectonic North America") and along the southern coastal region of Alaska (UNAVCO, 2009).

USArray is the final leg of the EarthScope *tripus*, a continental-scale seismic and electromagnetic (magnetotelluric) observatory designed to provide the first multi-scale 3-d/4-d geophysical models of the continental US crust and upper mantle. USArray comprises (at the time of this writing) a transportable array (TA) of 400 broadband seismometers and 20 long-period magnetotelluric (MT) systems that are deployed in a uniform, rolling, 70 km grid sweeping west to east across the continental USA in a series of regional bands of finite temporal duration and a quasi-permanent backbone array (BB) of 39 EarthScope and 70 ANSS (Advanced National Seismic System) broadband seismometers and 7 ultra long-period magnetotelluric systems designed to provide a long-term reference frame and deep anchor in which to place regional geophysical models into context. Finally, USArray also includes a flexible array (FA) of 291 broadband, 120 short period, 1700 active-source, and 25 magnetotelluric systems (provided by the EMSOC consortium of US universities active in MT research), to permit high-resolution principal investigator-led studies within the aperture of the broader-spaced transportable array, to focus on specific geodynamic targets (IRIS, 2009a; EMSCOPE, 2009).

The three principal components of the EarthScope program are summarized here because they share a common cyberinfrastructure, with common objectives. The aim of this activity is to generate multi-scale multidisciplinary data sets, to pass them through quality control as rapidly as possible, to provide a set of data discovery tools of wide use both to expert researchers in the respective disciplines but also to educators as well as the general public, and to provide a secure archiving strategy to preserve these data sets and derived data products for posterity. While each of the components of EarthScope is distinct, the commonality of the data discovery resource is such that present and future researchers will be able to identify hitherto unexpected processes linking observed geophysical phenomenon on scales ranging from millimeters to thousands of kilometers and from milliseconds to years.

For the remainder of this paper we shall focus in on USArray, and specifically its magnetotelluric component, EMScope (**E**lectro**M**agnetic Earth**Scope**). The reader is encouraged to consider this single disciplinary activity as part of a greater whole, i.e., one where the electrical properties of the crust and upper mantle beneath the North American continent is linked to a range of processes, complementary aspects of which are simultaneously viewed by seismic and geodetic observers also operating within the EarthScope framework.

2   THE MAGNETOTELLURIC METHOD

EMScope seeks to build a set of increasingly comprehensive 3-d reference models of crustal and upper mantle electrical conductivity structure over broad areas of the continental USA. The property of electrical conduction is intrinsic to the rocks and minerals that make up the crust and upper mantle, and determination of this property and its variations with depth and geographical position within the Earth's interior is diagnostic of several key material properties: rock composition and pore fluid content (both aqueous and magmatic fluids), porosity and permeability of the rock matrix, temperature, the presence of metallic conductors as well as carbon, and the degree to which the upper mantle contains water, partial melt, and volatile compounds that may be related to the history of subduction of tectonic plates into the Earth's mantle (Karato & Jung, 1998; Toffelmeir & Tyburczy, 2007).

The geophysicist seeks information about the state and composition of the Earth's interior through remote sensing methods. Seismologists and MT researchers observe the effects on the Earth's surface of elastic or electromagnetic wave energy (respectively) as it propagates or diffuses through the Earth's interior. They share a goal in common with that of medical diagnosticians who employ radiological imaging methods such as CT (x-ray computerized tomography) and MRI (magnetic resonance imaging) to reconstruct approximate images of the interior of solid bodies in order to determine the nature of that body. Magnetotellurics is such a remote sensing technique, comprising a method of imaging variations in the electrical conductivity of the materials making up the Earth's crust and mantle. The method works by measuring the response of the Earth to the

magnetic fields variations that are associated with electric currents that flow in the Earth's magnetosphere and ionosphere in response to modulations of the solar wind, as well as the electromagnetic fields related to global lightning discharge as these propagate around the global ionosphere. The Earth and oceans below contain electrical pathways in which secondary currents are set up in response to these external source currents through the laws of mutual induction. The MT observer records the simultaneous variations in electric and magnetic fields as measured at Earth's surface that have arisen in response to these external fields (Price, 1962).

By measuring orthogonal horizontal components of the geoelectric and geomagnetic field variations at an MT station, the electromagnetic impedance tensor **Z** may be calculated (Eq. 1), which is a complex and frequency-dependent quantity:

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix} + \begin{bmatrix} U_x \\ U_y \end{bmatrix}, \tag{1}$$

where E is the electric field, H the magnetic field, U represents uncorrelated noise, and the subscripts x and y refer to the north-south and east-west directions, which are typically taken to be aligned with geomagnetic rather than geodetic coordinates. The electric and magnetic fields so represented are typically taken to be in their frequency domain representation, i.e., a function of radian frequency ω, so the harmonic time dependence of $\exp(-i\omega t)$ is implicit. The MT impedance tensor is usually calculated through application of statistically robust estimators (Chave et al., 1987), so that the statistically stationary fields most closely attributable to plane-wave source fields may be extracted.

It should be noted that for an Earth whose conductivity structure varies only with depth, i.e., a 1-d Earth, the impedance tensor reduces to a simple frequency-dependent scalar relationship between the electric and magnetic fields. In such a case, the depth of penetration into the Earth's interior of magnetic fields originating above the Earth's surface is found to be related simply to the frequency of the harmonic variations of those fields such that lower frequency variations diffuse more deeply into the Earth before the energy (which is converted into induced electrical currents throughout the volume in which it is diffusing) is dissipated. Below a critical depth of penetration (typically known as the electromagnetic skin depth (Eq. 2)) little energy remains available for currents to be induced. If such a 1-d Earth is simplified further to be a constant property half-space, the skin-depth may be expressed as:

$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}}, \tag{2}$$

where δ is the skin depth (the depth within the Earth's interior at which harmonically-varying external magnetic fields incident on the Earth's surface have been attenuated to $1/e$ of their surface value), ω is the radian frequency (i.e. $\omega = 2\pi f$ where f is in Hz), μ is the magnetic permeability of the materials making up the half-space, and σ is the electrical conductivity of those materials. For geological materials, the magnetic permeability is generally taken to be a constant equal to its free-space value, the frequency is known, so only the electrical conductivity of the medium is usually considered to be a free parameter.

For the case where the underlying Earth is represented as a set of stacked horizontal layers each of constant conductivity, the skin-depth concept still applies, i.e., the lower the frequency of the source field and/or the lower the value of the conductivity of each of the layers within the Earth, the deeper the penetration into the Earth. Frequency may therefore serve as a proxy for depth of penetration. For the case where the Earth's conductivity structure varies horizontally as well as vertically (i.e. 2-d or 3-d models), then the relationship between electric and magnetic fields takes on increasingly complex tensor form as in Eq. (1). Despite this added complexity, the scaling between frequency and depth (as well as horizontal extent) of penetration into the geological media remains, albeit in the form of a set of partial integro/differential equations, i.e., Maxwell's equations. In practice for these more complicated scenarios, one solves for the fields induced in such an Earth by solving a boundary value problem using finite difference, finite element, or other numerical approximation methods.

In order to acquire such data, EMScope makes use of several variants of MT receiver instrumentation consisting of the following elements: a sensor to measure time variations in the three orthogonal components of the geomagnetic field; a set of electric field amplifiers and electric dipole receivers to measure concurrent variations

in the two orthogonal horizontal electric field components; a data logging system with time referenced to GPS; and optionally, telemetry and solar power units for backbone MT stations. EMScope uses the Narod Geophysics NIMS MT system equipped with triaxial ring-core fluxgate magnetometer sensor with a noise floor of better than 20 pT/√Hz at 1 Hz (Figure 1). Electric field dipoles comprise 100 m long (for transportable stations) and up to 4,500 m long (for backbone stations) orthogonal electric cables terminated at each end by non-polarizing Pb-PbCl$_2$ electrodes. Backbone instrumentation in most cases is installed in 2 m deep, insulated underground vaults (Figure 2). One EMScope backbone station operates with a LEMI MT instrument acquired from the Center for Space Research of Lviv, Ukraine, which has a noise floor of ~7 pT/√Hz at 1 Hz.

Figure 1. Transportable MT Array field equipment. Triaxial ring core fluxgate magnetometer sensor (left), data acquisition system (center), non-polarizing Pb-PbCl$_2$ electrodes (center, top). 2-3 week instrument deployment yields data in period range of 10 s to 20,000 s. Longer periods -> deeper penetration into Earth's interior.

In all cases, the MT data are sampled at 1 Hz. For transportable array operations, installations are left in place at field sites typically for three weeks, following which the MT data are recovered by a field crew and transmitted, usually via ftp, from internet access points near the field stations. The backbone installations are presently transitioning to a real-time telemetry system rather than data recovery through periodic site visits and manual extraction of flash memory cards. In all cases, our target is to carry out data quality assurance and to generate MT impedance functions as a primary data product within 2 weeks of receipt of the original time series by the EMScope data quality control group, presently led by Dr. Gary Egbert of Oregon State University. Upon completion of that task, the time series and data products are then transmitted directly to the Incorporated Research Institutions for Seismology (IRIS) Data Management Center (IRIS-DMC) for archiving and wider distribution.

Figure 2. Backbone MT Array field equipment installed in NW Minnesota, USA. Magnetometer and data acquisition systems are buried in 2-m deep underground vaults; electric dipoles are typically 500 m long, terminated in electrodes buried 1 m deep in large volume of double-saturated NaCl/kaolinite paste. Systems are solar powered and telemetry is being implemented. The backbone installations are planned for 5-year deployments or longer, yielding a period range of 10 s - 100,000 s.

3   THE EMSCOPE ARRAY CONFIGURATION

The EMScope program has completed the installation of 7 backbone stations distributed across the continental USA. The elements of the array were positioned to provide information on the variations in electrical conductivity with depth beneath distinct geological provinces, each representing a different stage in the accretion and evolution of the North American continent. By the close of the 2008 field season, the EMScope transportable array consisted of 170 completed stations in the northwest of the US, spanning the territory of the states of Washington, Oregon, Idaho, western Montana, and Wyoming. The present configuration of both backbone and transportable arrays is seen in Figure 3. In addition to the EMScope-installed stations, the University of Alberta under the direction of Dr. Martyn Unsworth is coordinating installation of equivalent MT stations in the Canadian province of Alberta using a grid approximately aligned with the EMScope grid.

In 2009 an array of 50 additional stations is planned for installation in the states of Montana and Wyoming, to bound the Yellowstone area as far north as the Canadian border and as far south as southernmost Wyoming. By the end of the 2009 field season, the transportable array will have provided MT data over the geodynamically and tectonically active regions of the Cascadia subduction zone magmatic arc, the northwestern part of the Basin and Range province, the volcanic Snake River Plain region, and the Yellowstone super-volcano. The data so returned and made available for free distribution will provide important new information on the electrical conductivity structure, which in turn can be used to constrain melt and fluid processes, to determine the locations of suture zones between micro-plates, and to investigate the locations and geometry of putative mantle (magma) plumes that have been associated with surface expressions of volcanism throughout the Pacific Northwest and the Yellowstone region (Hanan et al., 2008). From 2010 onward, EMScope will carry out a set of

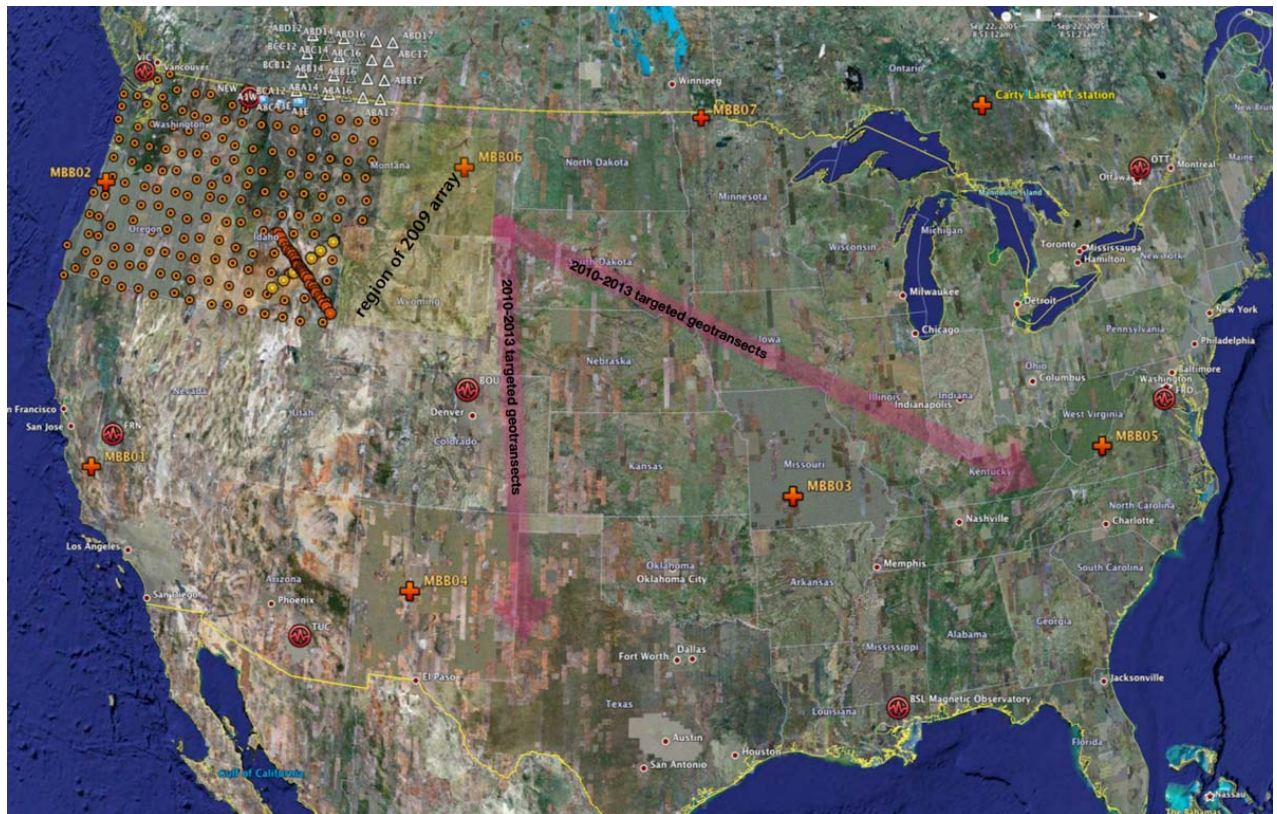regional geotransects throughout the continental USA in other areas of substantial geodynamic and tectonic interest.

Figure 3. Transportable MT Array stations (orange dots) and Backbone MT stations (orange crosses) as of October 2008. Red waveform symbols are permanent magnetic observatories. Cross-shaped pre-EMScope Flexible Array in Snake River Plain area operated by C. deGroot-Hedlin and made available through EMScope/IRIS DMC. University of Alberta MT stations coordinated with EMScope appear as white triangles.

4   EMSCOPE DATA DISCOVERY

EMScope has been designed as an open community data resource. By providing data discovery tools as well as derived data products, the intent is to foster the democratization of electromagnetic geoscience. For instance, few groups exist with the technical expertise or instrumentation to acquire large arrays of MT data. Few groups are proficient in the signal analysis methods required to extract unbiased impedance functions from such data. By providing both post-quality controlled time series as well as the primary data products (MT impedances and other derived quantities such as apparent resistivity and phase functions) following algorithms widely trusted by the MT community (Egbert & Booker, 1986), EMScope hopes to enable researchers and others to gain access to information that they can easily incorporate into their own geophysical modeling, interpretation, and educational activities.

Furthermore, by co-registering electrical conductivity models derived from EMScope data with seismic models (Roth et al., 2008) and/or models of dynamic crustal deformation derived from other USArray or EarthScope data sets, the possibility of joint interpretation by experts crossing disciplinary boundaries is made easier.

The primary point of contact for EMScope is the project web site and data portal: www.emscope.org. A view of the current home page appears in Figure 4. One may access the project data portal either from this page or alternatively through the IRIS-DMC, which can also be found either through the EarthScope project home page www.earthscope.org or through the URL www.iris.edu/SeismiQuery/virtual_net.htm. EMScope employs MINISEED format as the primary means of archiving and distributing MT time series. MINISEED was created as a seismic waveform transmission and archiving model (IRIS, 2009b), and the IRIS-DMC has developed a large number of data discovery tools built on accessing data in this format. EMScope has adapted MT time

series to fit within this data standard in order to provide uniform access to MT data for both MT researchers and seismologists.
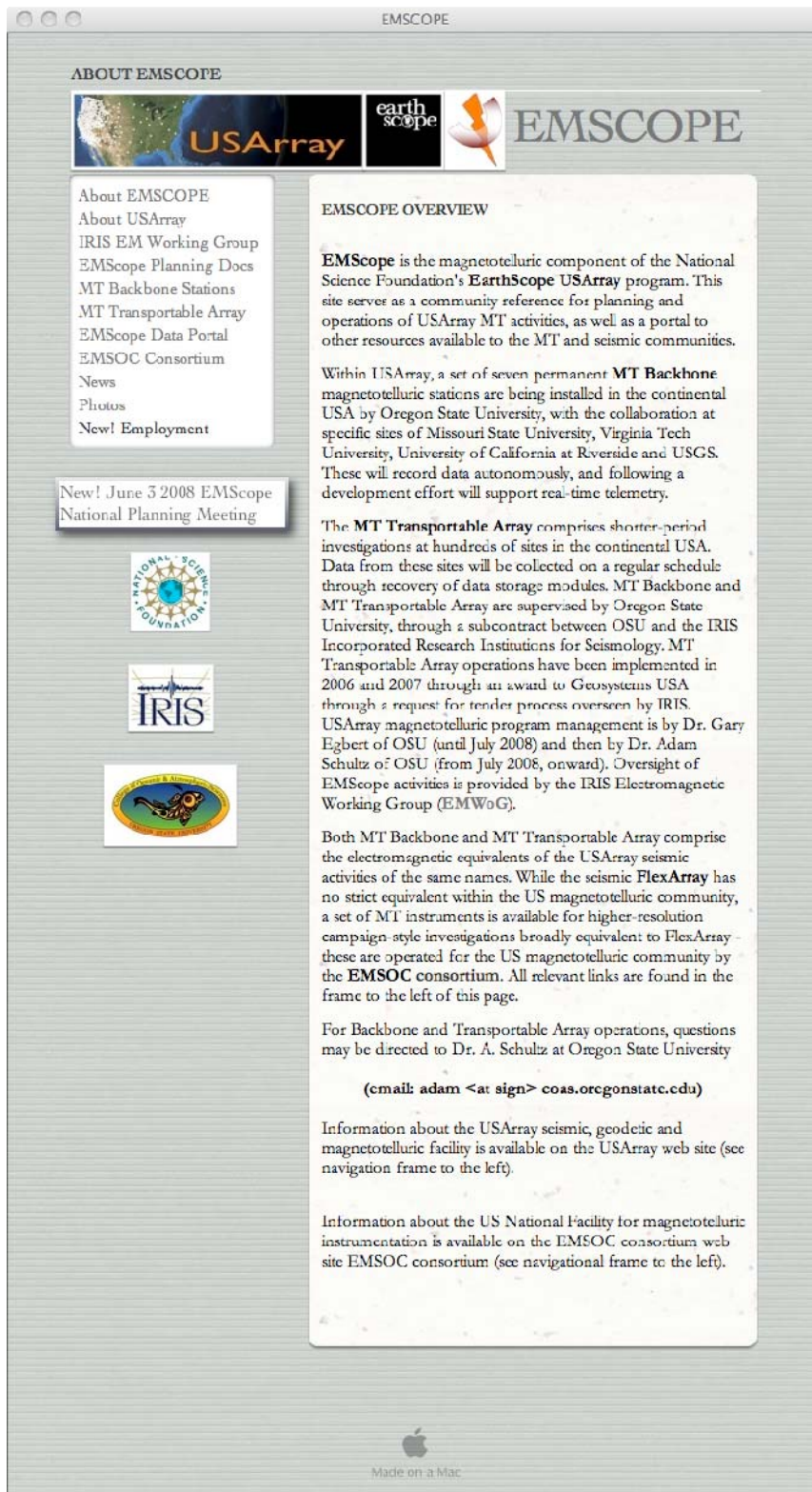

Figure 4. The home page for EMScope www. emscope.org showing relevant links include (top left frame) the EMScope data portal.

Figure 5. A query submitted to IRIS-DMC requesting station information about all USArray MT (i.e., EMScope) stations contained within the IRIS data archive that were operating during the period 1 April 2006 through 3 November 2008 (UT – Universal Time).

Figure 5 displays an IRIS-DMC data availability hierarchical query organized by "Virtual Network". A virtual network is a meta-description of a set of one or more networks of physical instruments. For instance, to query all EMScope MT data available, the "_US-MT" virtual network has been defined. The example in Figure 5 shows a query to display the station information for all EMScope data acquired during the period 1 April 2006 – 3 November 2008.

The result of such a query is a description of the station names as well as the name of the network of which that station was a part, as well as the UT dates and times during which the DMC has time series data archived. Such a query outcome is displayed in Figure 6. The station names within the network displayed (for transportable array sites) follow a precise convention, where the first two characters represent the name of the US state in which the data were collected, the next letter (A-Z) represents a row running approximately parallel to a line of latitude within the quasi-regular 70-km grid of MT stations, and the next two digits represent the longitude or column within the station grid. A query for MT backbone stations would produce similar information, although the station naming convention differs, with MT backbone stations using the convention MBB0x, where x represents one of the digits 1-7.

In order to foster interdisciplinary interpretation and collaboration, the EarthScope project data discovery portal provides a convenient means by which data from different parts of EarthScope (e.g., SAFOD, PBO, and USArray) and different parts of each of these sub-activities (e.g., seismic, geodetic, and magnetotelluric) may conveniently be accessed, cross-referenced, and co-registered. A view of the EarthScope data portal is seen in Figure 6.
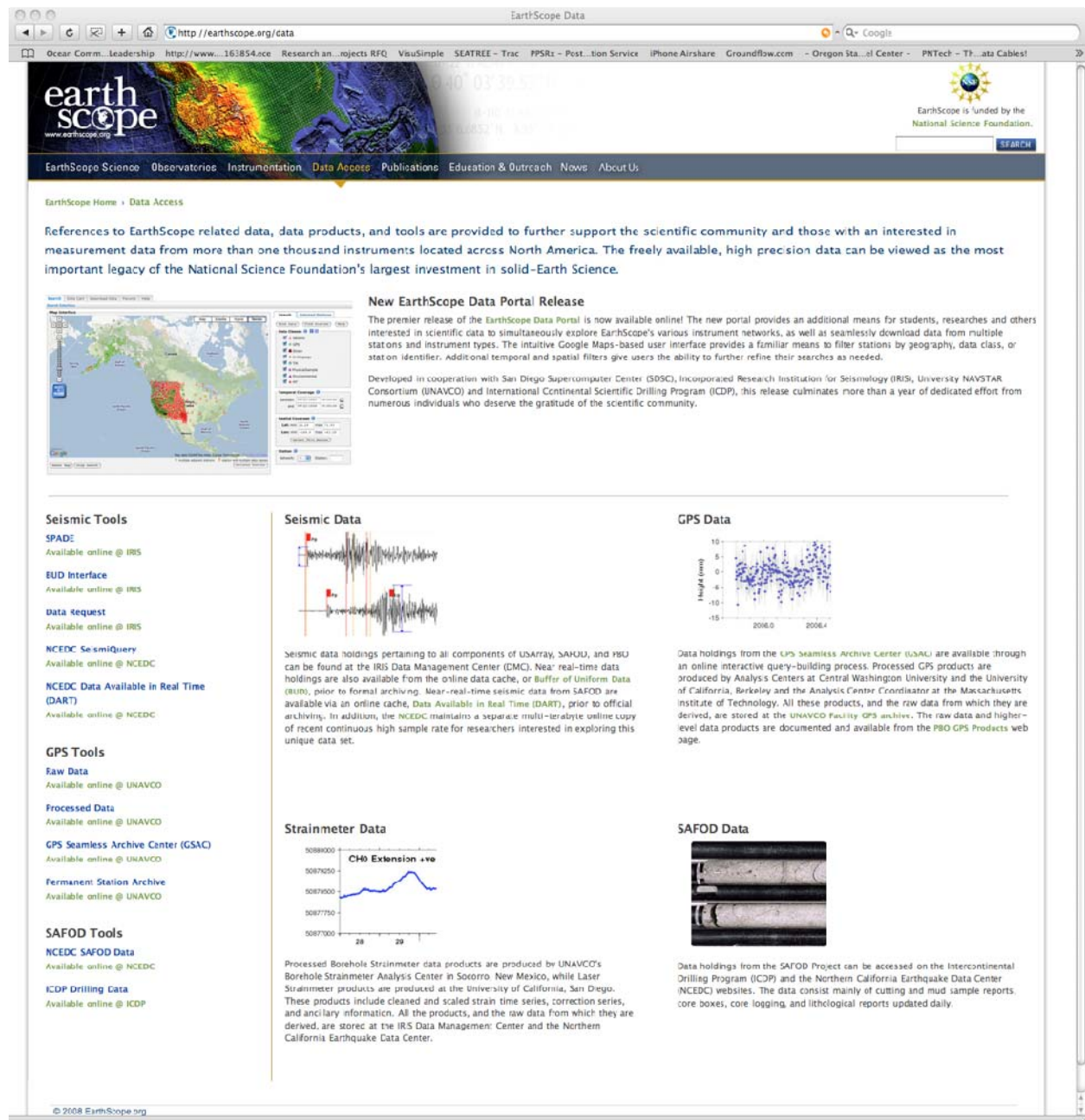

Figure 6. Within EarthScope, "Seismic Data" has come to mean seismic and MT data because these both use identical data discovery and retrieval tools.

The EarthScope data portal has limited GIS capability, such as the provision to overlay maps of data availability tagged by data type (e.g., seismic, MT, strain, etc.) on map overlays, where each data tag is a hot link to metadata. This is seen in Figure 7.
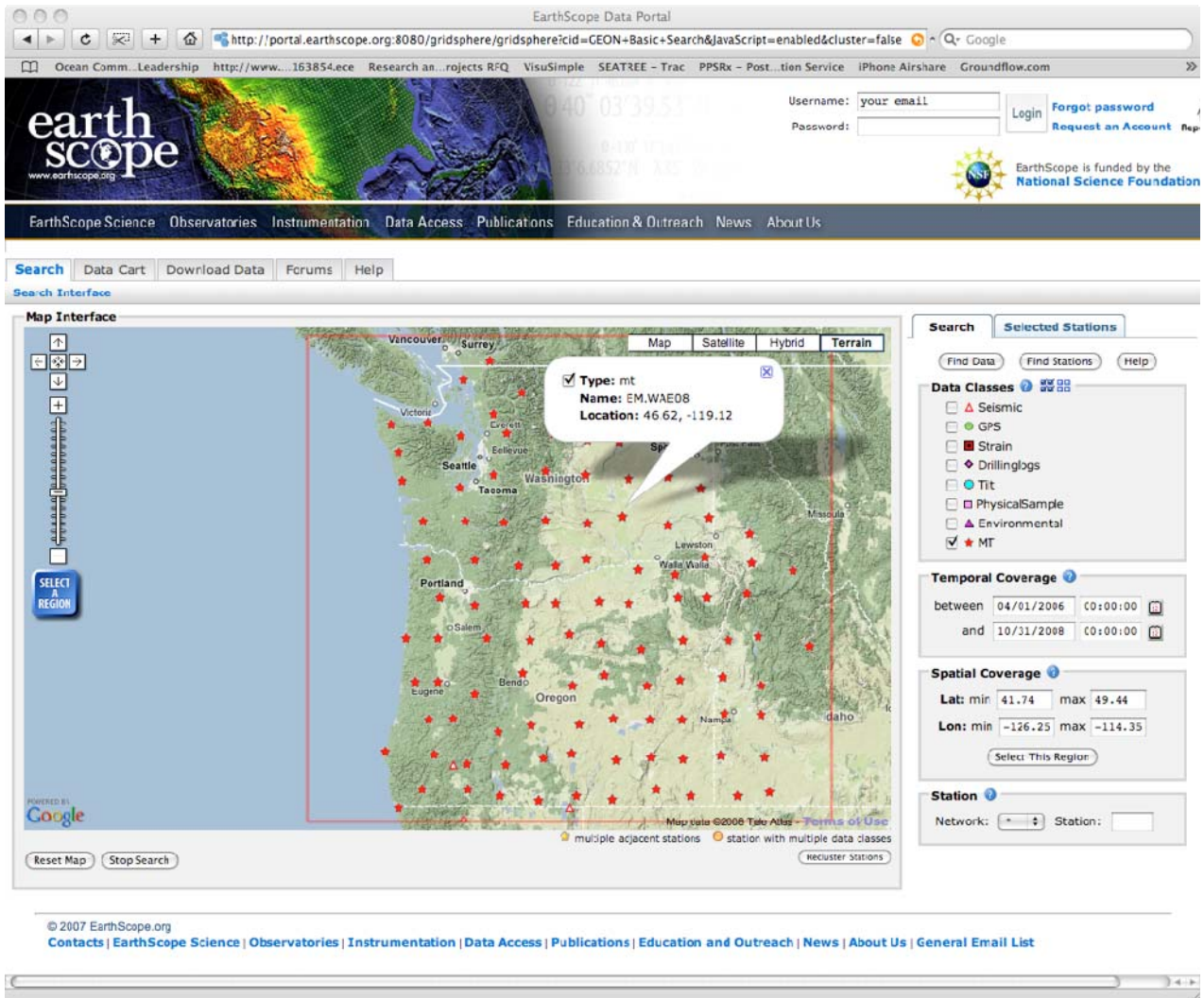

Figure 7. Geo-referenced map overlay of sites in the US states of Washington and Oregon at which the IRIS-DMC contained MT data during the period 4 April 2006 through 31 October 2008.

By selecting one or more sites, a list of data availability is generated, and a "shopping cart" can be built up of data products to be requested. Metadata containing geographical and engineering information is then displayed. A typical "channel summary" display is seen in Figure 8. Once the request is submitted to retrieve the indicated data products, MT time series are then transmitted to the requesting party and available for display and interpretation. A typical EMScope MT time series is seen in Figure 9.
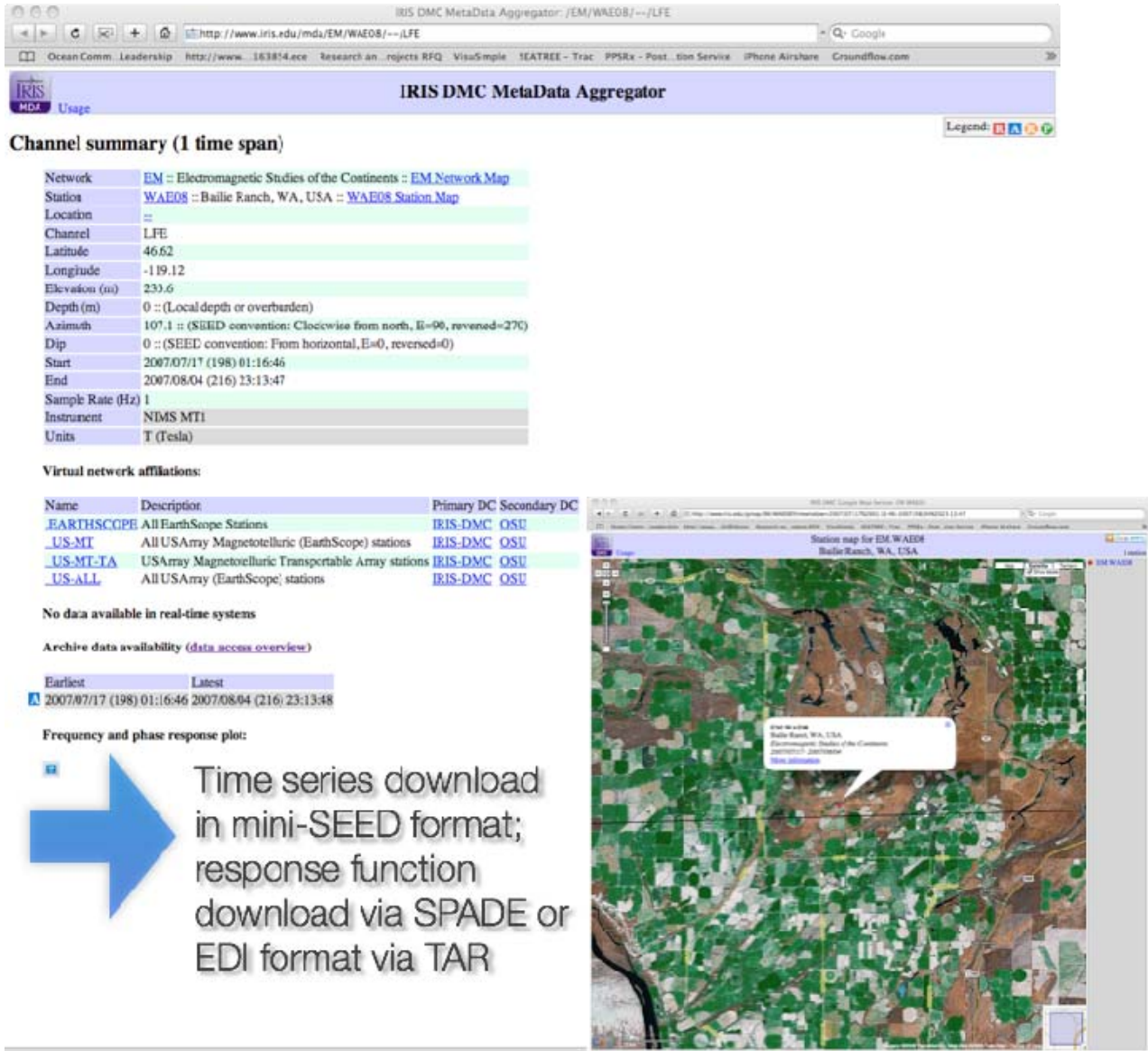
Figure 8. Display of IRIS DMC MetaData Aggregator showing metadata for the east-west magnetic field component measured at EMScope station WAE08 located at the Bailie Ranch, Washington, from 17 July 2007 to 4 August 2007. This data set is part of the virtual network "_US-MT-TA", i.e., the MT transportable array. The station map showing the geo-referenced location of these data appears on the bottom right of the figure.
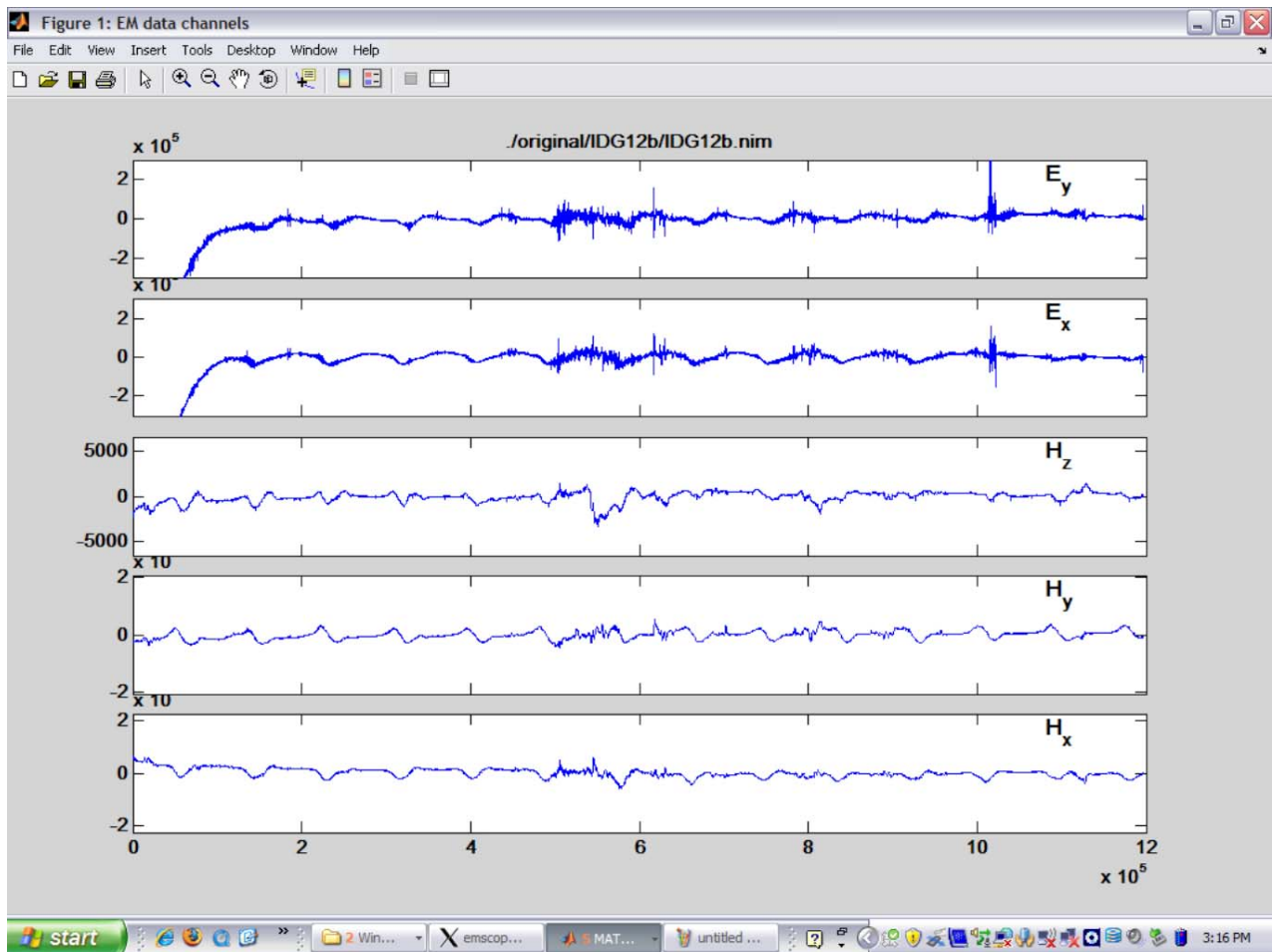
Figure 9. Time series record of approximately 13.9 days duration, showing (from top to bottom) the east-west and north-south electric fields and the vertical, east-west and north-south magnetic fields recorded at EMScope Idaho station IDG12. The periodic diurnal variations in the fields are evident as are a series of shorter duration geomagnetic pulsations.

The EMScope end-user may extract MT impedance functions (Eq. 1) from the IRIS DMC, either in an XML-based format through the IRIS SPADE data discovery resource or in the more familiar (to the MT community) EDI (electronic data interchange) format via ftp of one or more TARballs available through the IRIS DMC. An example of two complex-valued MT impedance tensors subsequently rotated and scaled into the form of real-valued apparent resistivities and phases is seen in Figure 10. In this form, the impedances have been decomposed into values in two principal directions, one of which appears in red and the other in blue. The curves displayed on the left hand side of Figure 10 are from a site in the SW corner of the Snake River Plain. These show the signature of a typical conductive zone in the lower crust of the sort seen widely in the US Great Basin and other areas of active basaltic under-plating of the crust. The curves on the right hand side of the figure are from the Montana plains and show essentially no evidence of a lower crustal conductor or of basaltic under-plating.
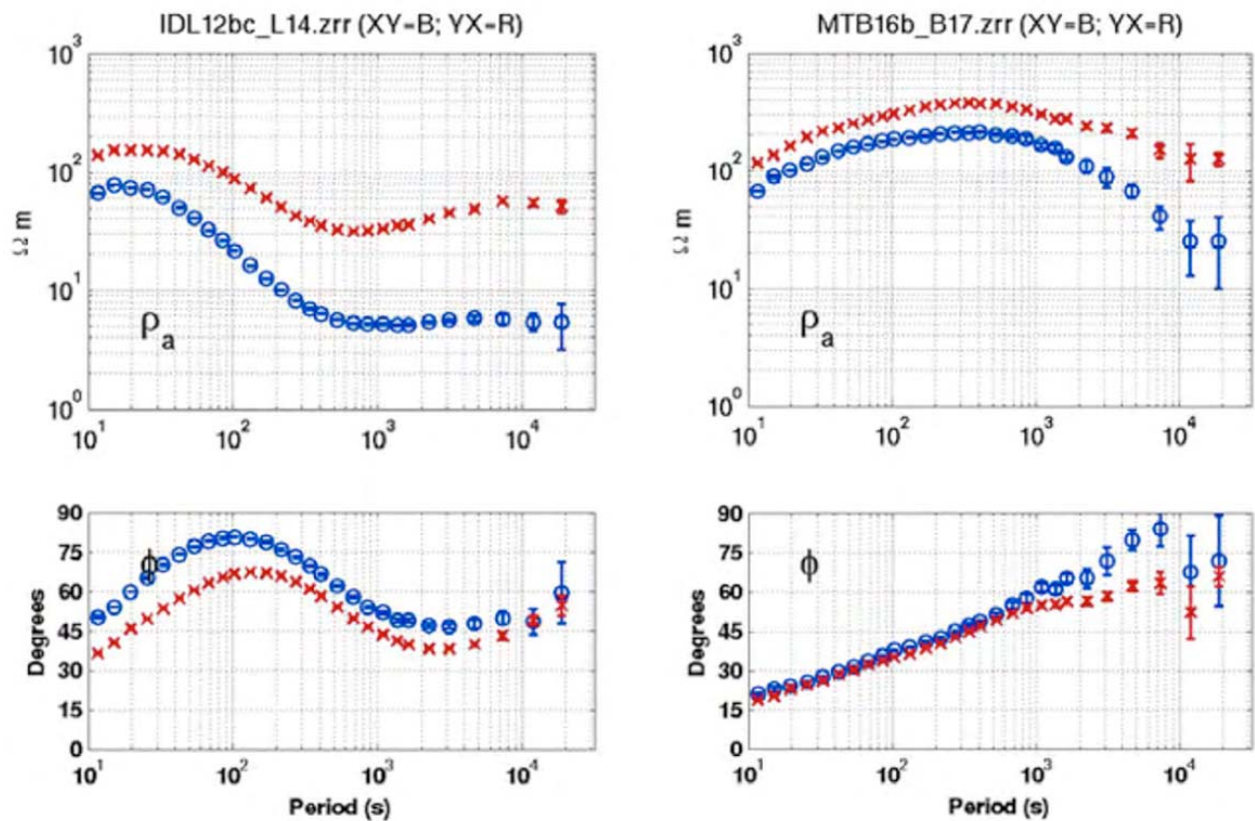
Figure 10. Transportable Array MT response functions (complex-valued impedance tensors scaled into real-valued apparent resistivities and phases in each of two principal directions). Site L12 is in the SW corner of the Snake River Plain and shows a typical conductive lower crustal signature as seen widely in the Great Basin and other areas of active basaltic underplating. Site B16 is in the Montana plains and shows essentially no lower crustal conductor.

The corpus of MT data and derived data products illustrated above is the foundation for a steadily-expanding collection that can be used to provide information on the structure, composition, and physical state of the Earth's crust and mantle. The spatial aperture of this data set will, over time, expand to the scale of the North American continent. EarthScope, having provided this resource, depends on the community of research geophysicists to transform these data into models. Initially the models will be of the variations in electrical conductivity with position within the aperture of the array. An initial set of 3-d models of conductivity structure beneath the 110 transportable array MT stations collected in the states of Washington and Oregon in 2006-2007 has been derived by Patro and Egbert (2008), revealing robust and spatially-coherent lower crustal structures, including a region of high conductivity beneath SE Oregon and beneath the Cascade volcanic mountain range and a very resistive region of crust to the NW of this region, associated with mechanically-rigid crustal blocks. Conductive mantle is revealed beneath the volcanic arc associated with the subduction of the Juan de Fuca plate beneath Washington State.

5   CONCLUSION

The adoption of the magnetotelluric method for wide-scale reconnaissance and exploration for regional-to-continental scale Earth structure has been limited by a paucity of instrumentation that has been available for such purposes, the relatively limited expertise in reducing MT data sets to an unbiased and interpretable set of MT responses, the academic tradition of restricting access to such data sets to the group responsible for their acquisition for periods of proprietary use, the *ad hoc* manner in which the existence of such data sets has been made known to the greater community, and the difficulties inherent in 3-d inversion of such data sets. Compounding these barriers is the recognition that co-registration of MT data sets with complementary data is required in many cases in order to advance from modeling efforts of interest to a small specialist community, to multi-disciplinary interpretations of geological or geodynamic importance to a much larger community of scientists and other interested parties. The EMScope component of the EarthScope/USArray project is addressing a number of these concerns. Rapid turn-around of raw data sets into

post-quality controlled archival quality distributions and the rapid generation of derived data products such as MT response functions, coupled with the use of widely-known data discovery tools originally created for seismology enhances the ability of the MT community to access and make available such data. The co-registration of MT and other data sets is made far easier by such tools, thus promoting joint interpretation of these data with, for example, seismic and geodetic data products. Formidable barriers to the wider adoption of MT data and models have been lowered by eliminating all proprietary data restrictions and making access to these resources free of charge to the receiving party.

6   ACKNOWLEDGEMENTS

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(Article history: Received 31 January 2009, Accepted 7 June 2009, Available online24 October 2009)