The Virtual Wave Observatory (VWO): A VxO for Heliophysics Data

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Scientific/Technical/Management

1. Objectives and Expected Significance

We propose a Virtual Wave Observatory (VWO) to provide uniform and robust access to distributed space plasma wave and radiation data, metadata, and services for the wave-oriented Heliophysics research community. VWO will extend Heliophysics Virtual Observatories into wave-specific datasets that span most Heliophysics domains: solar wind, interplanetary space, terrestrial magnetosphere and ionosphere, and planetary magnetospheres.

1.1 Introduction

Heliophysics plasma wave and radiation data are currently not easily computer-searchable, making the identification of pertinent wave data features for analyses and cross comparisons difficult and laborious, if not impossible. Since wave analyses span the spectrum of microphysics (kinetic scales) to macrophysics (MHD scales or longer), researchers and students with varied training or expertise may not be able to easily use wave data. In order to resolve these difficulties, and to allow wave data to contribute more fully to Heliophysics research, we propose to develop a Virtual Wave Observatory (VWO) *whose goal is to make all Heliophysics plasma wave and radiation data searchable, understandable and usable by the Heliophysics community*.

For the proposed VWO development, our objective is to enable the search of *multiple* and *distributed* wave data (from both *active* and *passive* measurements) by UT, local time, location, phenomenon (e.g., continuum radiation, whistlers, …), etc. To this end, we will:

1) define the wave-relevant terms for the *Space Physics Archive Search and Extract* (*SPASE*) data model and thereby contribute to *SPASE* development,
2) convert existing Heliophysics wave metadata into the SPASE data model, and enter them into VWO so as to become *accessible* and *searchable* by all VxOs,
3) develop a VWO user interface for both the wave and general Heliophysics communities,
4) adapt, test, and modify existing VHO/VMO middleware and implement context-search capability for *SPASE*-compliant wave datasets, leverage existing investments so as to minimize VWO development costs, and
5) develop an annotation service to capture wave research community knowledge to make the wave data (a) *understandable* and (b) searchable by *phenomena*.

With the VWO, researchers and students will be able to search and access Heliophysics wave data *without* having to separately contact multiple data providers and data centers, although it may still be necessary to obtain guidance on the proper use of data from instrument teams. The VWO capability to search all wave data (active and passive) by phenomena, in addition to other parameters such as UT, location, magnetospheric activity, etc., and the associated annotation service will provide a powerful educational tool for non-wave specialists and a versatile research tool for wave researchers. This capability and service will benefit the entire Heliophysics research community because of the important plasma diagnostic capabilities of space plasma wave and radiation processes.

VWO development will be guided by the needs of the community it serves in addition to the general VxO requirements (see 4.1). The following sections describe the wave research community, the uniqueness of wave data, science examples, and their respective needs. Section 2 shows how these needs will be addressed.

1.1.1 The Heliophysics Wave Research Community and Needs

We identify the wave research community as the community that is concerned primarily with the generation, propagation and reception of plasma waves and radiation in space plasmas as reflected in the goals of *Commission H* of the *International Union of Radio Science* (*URSI*): “(a) to study waves in plasmas in the broadest sense, and in particular in: (i) the generation (i.e. plasma instabilities) and propagation of waves in plasmas, (ii) the interaction between these waves, and wave-particle interactions, (iii) plasma turbulence and chaos and (iv) spacecraft-plasma interaction, and (b) to encourage the applications of these studies, particularly to solar/planetary plasma interactions, space weather, and the exploitation of space as a research laboratory”. Also included are nonlinear wave phenomena such as solitary waves, ponderomotive forces, and nonlinear wave-particle interactions. Wave researchers present the results of their research at national and international meetings convened by the American Geophysical Union (AGU), URSI, and other international scientific organizations and publish scientific papers in a wide variety of journals including AGU's *JGR*, *GRL* and *Radio Science*.

In order to support its research efforts, the ***Wave Community Needs:***

(A) A simple web interface to

(1) search and access a reliable, up-to-date and diverse set of wave data,
(2) access the most recently available mission wave data,
(3) interact with data services, such as VWO, CDAWeb, PDS, etc., and
(4) access data sets concerning particles, fields, space environmental conditions and models so as to understand the context under which emissions are generated;

(B) Community involvement to

(1) provide community-specific requirements to guide VWO development,
(2) register their data with VWO,

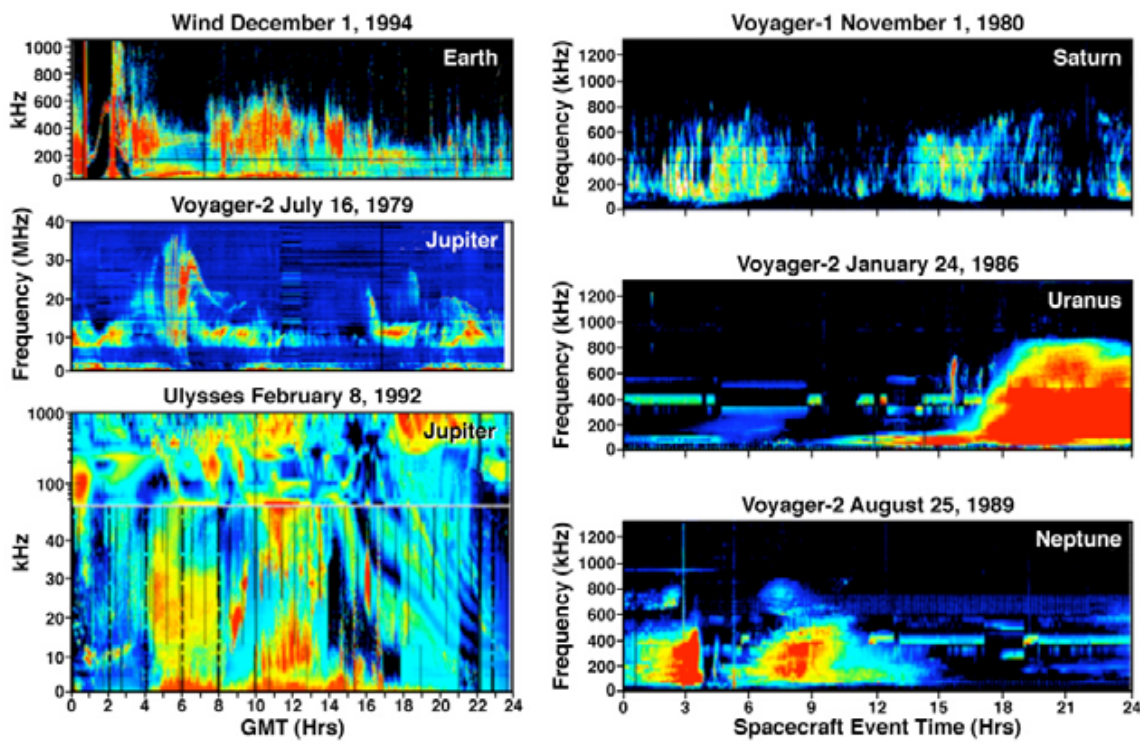

Figure 1. The Virtual Wave Observatory will enable cross-comparison of wave emissions throughout the heliosphere [Kaiser and Weiler, 2000].

(3) encourage wave data providers to use the VxO framework and *SPASE* standards,
(4) provide domain-specific knowledge to annotate wave data and describe wave metadata,
(5) provide feedback to VWO directly by using its web interface and at wave domain-specific symposia and conferences,
(6) inform other Heliophysics communities and VxOs about VWO services and benefits, and
(7) learn together as all of our VxO services develop and mature.

1.1.2 Unique Characteristics of Wave Data and Needs

Heliophysics wave data span most Heliophysics domains: solar wind, interplanetary space, Earth's ionosphere and magnetosphere, and planetary magnetospheres, and are thus inherently of multidisciplinary interest. Figure 1 shows observations of radio emissions from different planetary magnetospheres. Cross comparisons of these datasets will help determine, for example, which radio emissions have common emission mechanisms. Wave propagation studies are also important for elucidating plasma structures in various planetary magnetospheres.

Radio emissions observed in the different planetary magnetospheres, illustrated in Figure 1, result from remote sources (e.g., solar radio bursts, terrestrial auroral kilometric radiation, and Jovian decametric and hectometric radiation) as well as from local (*in situ*) plasma oscillations (e.g., the upper hybrid resonance band), depending on the frequencies of

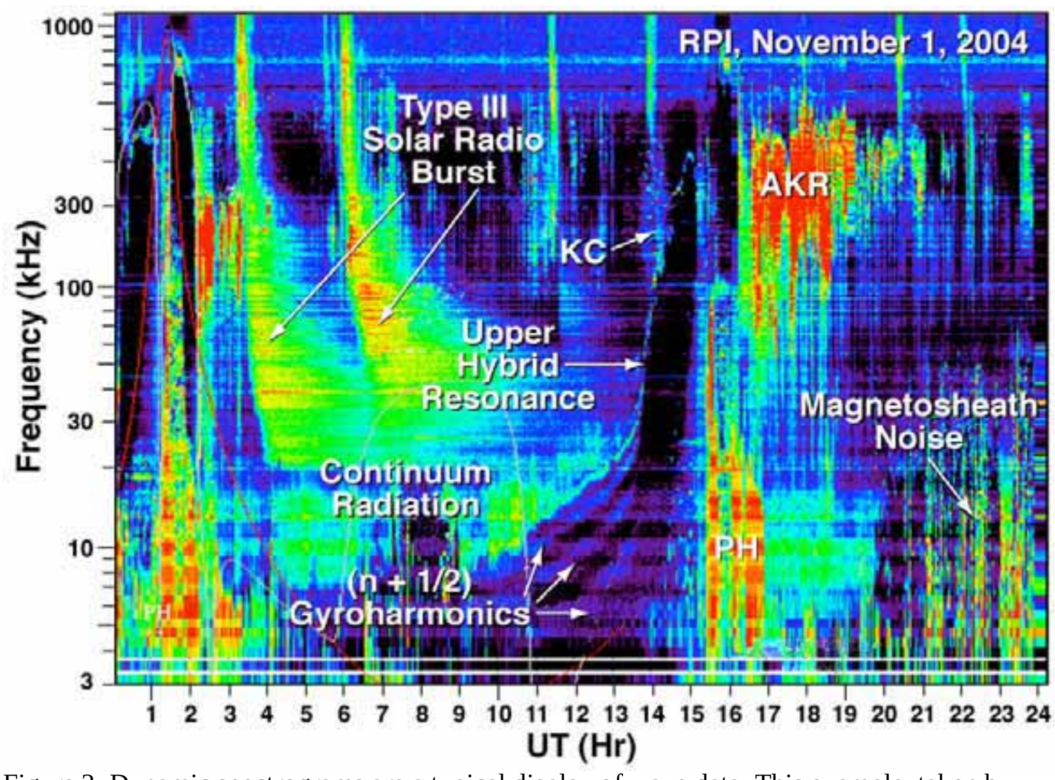

Figure 2. Dynamic spectrograms are a typical display of wave data. This example, taken by IMAGE/RPI, shows different electromagnetic free-space mode wave components: type III solar radio burst, auroral kilometric radiation (AKR), kilometric continuum (KC), and non-thermal continuum radiation, as well as a number of localized plasma wave components: plasmaspheric hiss (PH), (n+1/2) gyroharmonic and upper hybrid resonances, and magnetosheath noise, observed inside and outside Earth's magnetosphere.

measurements and the local plasma conditions. Each panel in Figure 1 was obtained from a passive plasma wave instrument and the individual frequency vs. time records are called dynamic spectrograms. A dynamic spectrogram recorded in the Earth's magnetosphere, with many of the emissions identified, is presented in Figure 2.

Active radio sounding measurements can also yield wave data on plasma resonances and echo traces due to reflections of transmitted signals in different wave modes [e.g., Fung et al., 2003; Green and Fung, 2005; LaBelle and Treumann, 2006]. Figure 3(C) presents an example, called a plasmagram, of data resulting from radio sounding in the Earth's magnetosphere. The other panels in Figure 3, and also Figure 2, illustrate the wide variety of *passive* wave data just in near-Earth space environment. *They illustrate the cross-domain nature and some of the unique multi-dimensional characteristics of the data (frequency, time, location, multi-component intensities, etc.). They also emphasize the need for a separate discipline VxO to serve the wave-research community, and the Heliophysics research community in general.* The development of the VWO will require close collaboration with all existing *and* future Heliophysics virtual observatories (see 2.1 and 2.2).

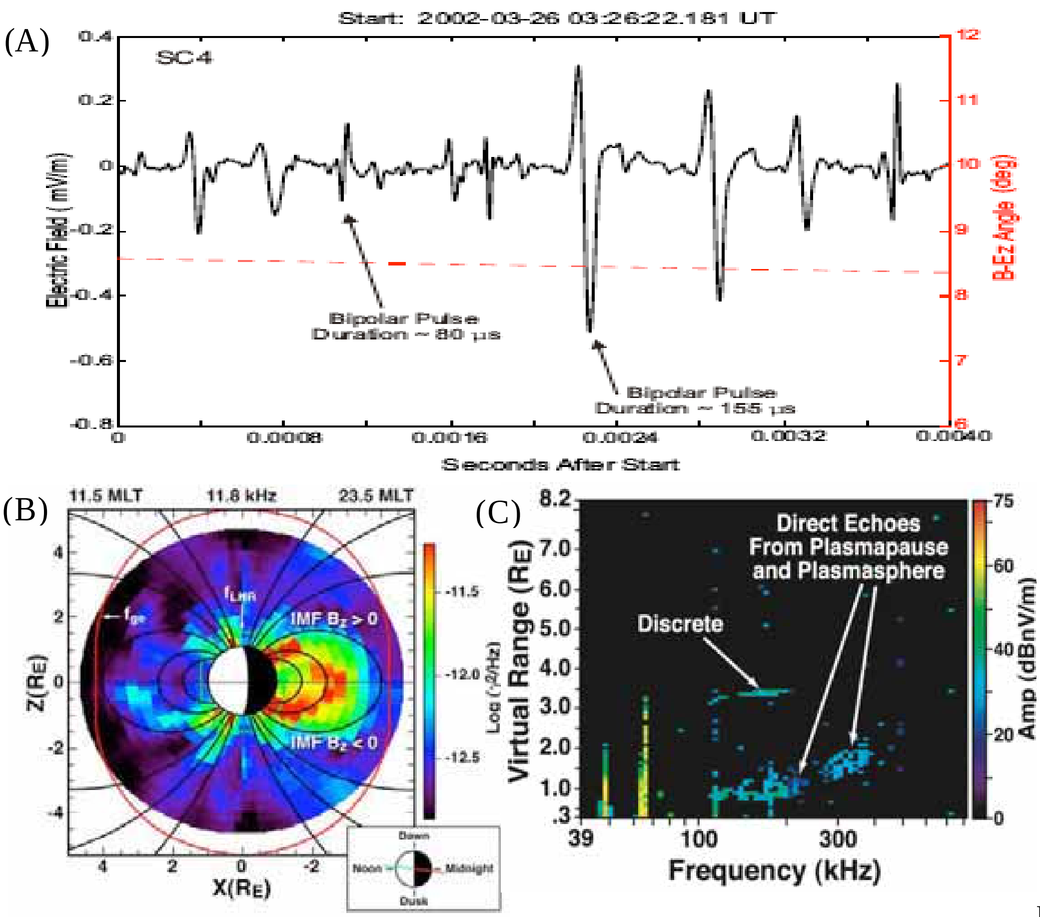

Figure 3. A variety of wave data products showing examples of (A) a high time resolution 4 ms sample of waveforms by Cluster Spacecraft 4, showing the isolated, short duration bipolar pulses in broadband electrostatic noise (BEN) observed during bow shock crossings and well into the magnetosheath [Pickett et al., 2005]; (B) a wave map of wave intensity distribution at 11.8 kHz taken from DE1 observations near the noon-midnight meridian plane [Green et al., 2005]; and (C) active radio sounding data from IMAGE /RPI showing plasma resonance (e.g., vertical traces at lower left), discrete guided echoes and diffuse direct plasmapause echoes [Fung et al. 2003].

A unique aspect of active wave data, is the complex, discipline-specific metadata. For example, active radio sounding IMAGE/RPI data have extensive metadata associated with each sounding measurement regarding: radiated power, frequency range, frequency step size, time per measurement, minimum and maximum virtual range, range increments, pulse repetition rate, pulse width, receiver bandwidth, receiver sensitivity, coherent integration time, Doppler resolution, receiver saturation recovery, Doppler range, amplitude resolution, angle-of-arrival resolution, antenna length, and processing gain [Reinisch et al., 2000]. This uniqueness, and the lack of a metadata standard description within the wave community, warrants a separate focus to develop a *SPASE* description of active and passive wave data.

The wave data products shown in Figure 3 are different than the usual dynamic spectrograms of Figures 1 and 2. Figure 3(A) is a 4 ms sample of the waveform data taken on Cluster Spacecraft 4 when broadband electrostatic noise (BEN) was being observed at a bow shock crossing and well into the magnetosheath [Pickett et al., 2005]. Figure 3(B) is a wave map, created from three years of DE-1 wave data, that shows the spatial distribution of wave intensity at a give frequency [Green et al., 2005]. It was based on selecting data in restricted location and time intervals corresponding to a specific frequency. *The proposed VWO would greatly facilitate such searches and selections of wave data, allowing the construction of wave maps nearly instantaneously*. By comparing wave maps at different frequencies, one can determine how wave activity varies spatially and with frequency, under different geophysical conditions. The IMAGE/RPI plasmagram shown in Figure 3(C) illustrates local plasma resonances and discrete (guided along the magnetic field) and diffuse (direct) echo signatures from different plasma boundaries.

In order to support wave research efforts, there are **needs for *(A) the availability and accessibility of wave and ancillary data, and (B) effective data search and retrieval mechanisms to handle the diverse wave-data products***, as demonstrated by Figures 2 and 3**.** The wave community already has heterogeneous (instrument-specific) metadata for many of their publicly available, but distributed [e.g., in NASA's *CDAWeb* <http://cdaweb.gsfc.nasa.gov> and *Planetary Data System* (*PDS* <http://pds.nasa.gov/>)], wave datasets, but they have no metadata standards to enable effective searches and inter-comparisons of data. Although wave data providers have made great strides in documenting their data sets and storing many of them online or near-line (see Table 1) in self-describing data formats (e.g. the NASA Common Data Format, CDF), the lack of metadata standards has crippled the ability of wave researchers to effectively draw together diverse data sets, including those from the particle and field communities.

(A) Availability and accessibility of data

(1) Wave researchers require the availability and accessibility of diverse sets of reliable and up-to-date (calibrated) wave data from past and future missions that are crucial for wave event studies and inter-comparisons in order to understand wave generation and propagation mechanisms, and to verify theoretical predictions.

(2) Wave researchers require the availability and accessibility of local plasma, particle and field information, under different conditions, in order to interpret and model wave data.

(B) Data search and retrieval

(1) A unique aspect of wave data is that data recorded at the *same frequency but different locations* can pertain to substantially different physical phenomena, depending on the local plasma and magnetic field conditions. As shown in the example dynamic spectrogram in Figure 2, RPI detected different types of electromagnetic emissions, i.e., different wave modes, in the frequency range of 50-500 kHz, at different times (different orbital locations),

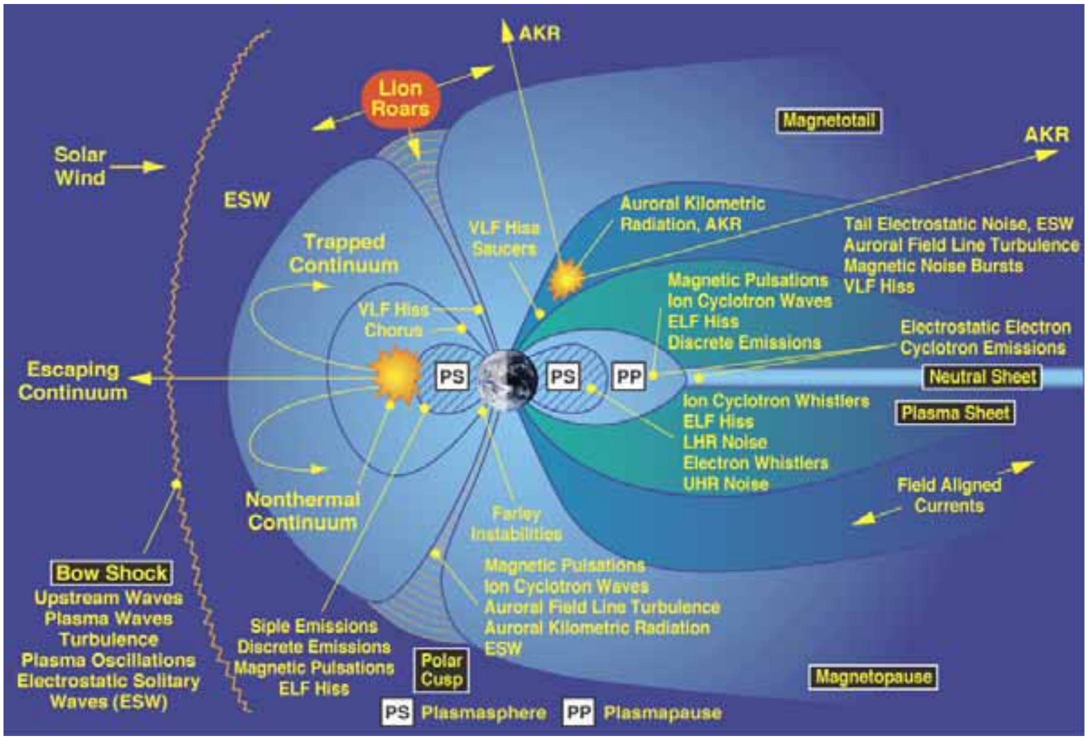

Figure 4. The VWO will provide researchers with sophisticated query tools tailored to this complex environment to better enable science discovery, as illustrated by the abundance of distinct waves phenomena observed in Earth's magnetosphere [adapted from Shawhan, 1979].

such as Earth's intense auroral kilometric radiation (AKR), kilometric continuum (KC) radiation, and solar Type III radio bursts. At lower frequencies RPI detected in situ electrostatic plasma waves below the local electron gyrofrequency during its passage within the Earth's plasmasphere. A wave dynamic spectrogram can contain a wealth of different plasma and electromagnetic wave phenomena covering a large spatial volume that may include vastly different heliophysics domains. Hence tools developed primarily for time-series particle and field data do not work well in serving the needs of the wave community. As shown by the example in Figure 2, wave data cannot be selected by frequency alone in the same way particle data are selected by energy. Data tools for particle and field data must be suitably modified in order to be applicable to wave data. Because of the context-dependent nature of wave observations, it is desirable to be able to select wave data based on geophysical conditions (solar wind, IMF, geomagnetic activity, etc.) and wave phenomena. These phenomena and their magnetospheric source locations are illustrated in Figure 4.

(2) In order to support proper search for wave data, ***there needs to be proper capture and organization of wave metadata and documentation***.

The wave community needs a means of capturing domain knowledge and linking this information to data sets that can then be processed using more sophisticated techniques of search and analysis. We have already noted in the previous sections the complex nature and context-dependence of wave data and the limited utility of simple searches on frequency and time for extracting wave modes of specific types. The scientific analysis of wave data must begin with domain-specific knowledge in order to correctly identify the observed wave phenomenon to be analyzed. Once this identification takes place then a variety of different research approaches may proceed. Event lists, statistical surveys of spatial or temporal distribution of wave modes, and other analysis methods depend on this first stage of domain knowledge applied to the data. If the effort exerted by a domain expert in applying his or her knowledge to a particular data set were forever captured and linked to the data, it would provide a tremendous added value to the data and enable a much wider community involvement in the data analysis.

1.1.3 Science Examples Illustrating the Need for VWO

Wave research tends to focus on the physical mechanisms of generation and propagation of plasma waves and radiation. *The physical context in which these processes occur is therefore of great importance*. In fact, most terrestrial wave phenomena are related to geomagnetic activities, e.g., AKR to AE and ULF waves to Kp. Comparisons of dynamic spectrograms, such as the one in Figure 2, from multiple locations or spacecraft enable determination of source locations, beam patterns and possible emission mechanisms. The information obtained will help elucidate the overall magnetospheric plasma conditions. Active radio sounders on Alouette, ISIS, Ulysses, IMAGE, and Cluster are capable of characterizing the plasma environment in ways that are complementary to particle and field instruments, and such wave measurements often serve as the only means of accurately measuring very low plasma densities [Benson et al., 2003]. Comparison of the RPI active and passive wave measurements, for example, enables accurate determination of local plasma and gyro frequencies, allowing for identification of wave propagation modes [Benson et al., 2004]. The propagation of the wave signals, actively or passively produced, will also depend on the context conditions of the propagation medium, i.e., the magnetospheric plasma conditions. *To allow the wave community to more fully contribute to Heliophysics research, they will require context-based query tools designed with recognition of the unique characteristics of wave data*.

An example of the benefits to be gained by the wave community from the proposed VWO is provided by recent research on KC radiation. This radiation is illustrated in Figure 5a. It corresponds to the indicated nearly horizontal filaments of radiation that slowly increase in frequency with increasing UT. (The term "continuum" is a carry-over from earlier research using receivers that lacked the frequency resolution to detect the fine frequency structure

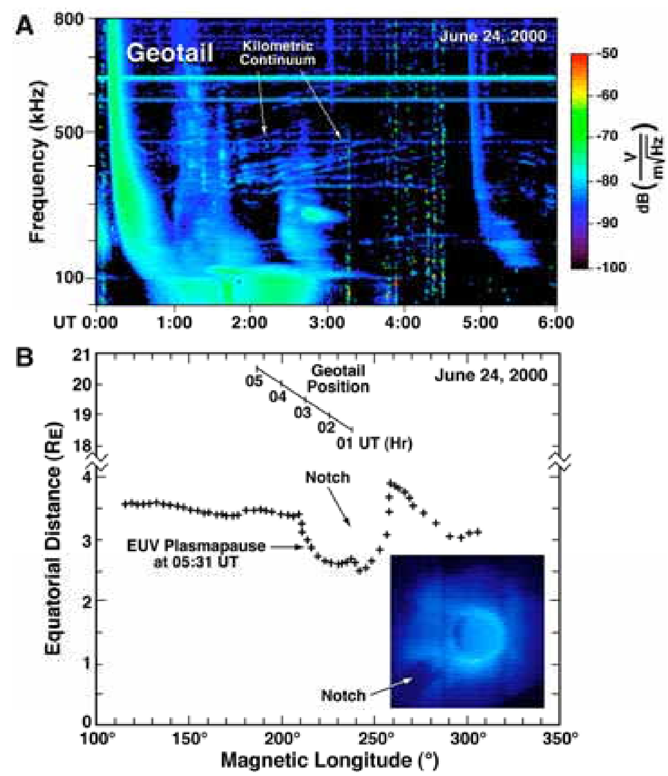

Figure 5 The KC wave observations from Geotail/PWI (panel A) map to a plasmaspheric notch structure as observed by IMAGE/EUV (panel B) [adapted from Green and Fung, 2005]

visible in Figure 5a.) The more intense (nearly vertical) emission features in Figure 5a with rapidly decreasing frequency with increasing UT are solar type III radio bursts. KC has been investigated for more than three decades, has been observed at every planetary magnetosphere visited by spacecraft with plasma-wave detectors, and has been the subject of several review articles [Kaiser, 1989; Green and Boardsen, 2006; Green and Fung, 2005; Hashimoto et al., 2006]. It has long been believed that KC is generated in regions of sharp density gradients, such as in the plasmapause and that it occurs at all local times. Recent work [Green et al., 2004] indicates that it originates in density bite-outs in the equatorial plasmasphere, called notches, as illustrated in Figure 5b. This conclusion was possible because IMAGE/EUV data defined the notch (see insert in Figure 5b) and allowed the plasmapause boundary to be displayed in equatorial distance vs. magnetic local time so as to be compared with the track of Geotail during the KC reception in Figure 5b. Ray tracing indicated that the KC was generated deep within the notch and that the radiation beam was constrained by the notch structure in a manner consistent with the Geotail observations. The VWO will be extremely valuable in (1) locating KC observations by two or more spacecraft during IMAGE/EUV notch determinations, (2) enabling a seamless interface to other VxOs to locate notch determinations during KC events, and/or (3) locating simultaneous multi-satellite KC observations of emissions from the same source region. Such capability will greatly facilitate the investigation of long-standing questions concerning all aspects of a wave research problem, i.e., wave generation, propagation, and reception, that is of fundamental importance to the wider Heliophysics community as well as to the wave community since information concerning the KC fine structure will also provide information on the dynamics and fine structure of the plasmapause source region.

Another example, that illustrates the benefits to be gained by the wave community from the proposed VWO, comes from a recent publication by Muldrew [2006]. In this work, a theoretical model was presented for a fundamental plasma emission, stimulated by ionospheric topside sounders, that has defied explanation for four decades. The confirmation of the model was crucially dependent on obtaining data combining a particular instrument mode of operation, specific operating parameters, and a narrow window of values of ambient magnetic-field strength. Several data intervals, satisfying these conditions, were provided to Muldrew by one of the Co-Is (Benson). These intervals were located by using the limited search capabilities available for use with a subset of the digital topside-ionogram database available from the *National Space Science Data Center* (*NSSDC*). One of the goals of the proposed effort is to expand this type of search capability, so as to be applicable to all available digital topside ionograms, and make it available to the scientific community through the VWO.

The wave community spans nearly all Heliophysics domains. *The community will need to make coordinated searches among multiple datasets to enable the study of universal radiation processes.* The generation mechanisms for wave phenomena are scalable. A single theory may be applicable for wave generation in seemingly quite different environments. Earth's AKR, Jovian decametric emission (DAM), Saturnian SKR and similar emissions from Uranus and Neptune (examples are shown in Figure 1) are all thought to be forms of electron cyclotron maser emission (ECME) [Zarka, 1998 and references therein]. Even solar millisecond-spike bursts are thought to be due to ECME [Holman, Eichler and Kundu, 1980; Melrose and Dulk, 1982]. Moreover, a wave mode may be generated or propagate in a certain way in space plasmas characterized by certain ratios of the plasma and gyro frequencies. A search capability that can allow inter-comparisons among diverse datasets is crucial for greater understanding of wave-generation mechanisms.

Wave research needs access to the latest datasets from new missions on the observations of the numerous wave types throughout the magnetosphere (Figure 4) and beyond in order to provide the greatest benefit to Heliophysics research. Researchers also use and compile for themselves higher order data products such as event lists of various wave phenomenon (for example, Type II and III solar bursts, low frequency AKR) and coordinated observation lists (for example, times when IMAGE and Geotail were at nearly the same local time).

1.2 Relationship to NASA strategic plans and the HP Data Policy

The VWO will enhance the effectiveness of all areas of Heliophysics wave research, and thus will provide important support for NASA Strategic Goals 3B, 3C, and 3F pertaining to Heliophysics, solar system studies, and space environment impacts. VWO will directly support user access for wave data arising from NASA spaceflight missions in a way compatible with complementary VO groups, as specified in the Heliophysics Science Data Management Policy (25 June 2007).

2. Technical Approach and Methodology

The proposed VWO aims to provide uniform and robust access to distributed plasma wave and radiation data, metadata and services for the wave-oriented research community. To avoid duplication of effort, and to economize on development effort, the VWO will leverage extensively on the tools and middleware already in development by other VxOs (Sections 2.2, 2.5), the Virtual Heliospheric Observatory (VHO) < http://vho.gsfc.nasa.gov/> and the Virtual Magnetospheric Observatory (VMOs) at *NASA Goddard* <http://vmo.gsfc.nasa.gov/> and the UCLA <http://vmo.igpp.ucla.edu/index.jsp>, and data providers, taking advantage of the co-location of the nascent VxOs. In collaborating with our data providers and partner VxOs (see section 5.1), the VWO will contribute to the development of *SPASE* with terms that better reflect the complexity of wave data and phenomena (Tasks 1 and 5) and to better enable the user community to search and compare wave data sets (Tasks 2, 3 and 4) that cover the breadth of the Heliophysics domains. We will work with data providers to enhance metadata layers at their sites using standard SPASE-compliant attributes (Tasks 1, 2, 5). VWO evolution will be guided by the VxO requirements (Section 4.1), the needs of our data providers, the best practices of other VxOs, and feedback from VWO users through the website and interactions at discipline-specific conferences (e.g., URSI, AGU, COSPAR, EGU).

In order to meet the needs of the wave researchers and Heliophysics community (1.1.1–1.1.3), five tasks have been defined in Section 1.1 for the proposed development of the VWO. We will first describe in Section 2.1 below the VWO architecture, in Section 2.2 our working relationships with the SPASE consortium and other VxOs, and then describe how we will accomplish each of the stated tasks.

2.1 Architecture and Implementation Approach

Users typically prefer a common data discovery and access tool that absolves them from the need to interact with many different tools and to spend time and effort searching for data sources, documentation and analysis tools. The VWO will provide such a common (one-stop) web browser interface to the VWO Middleware (see Section 2.5) through which users will send queries (see Figure 6). To this end, the VWO architecture will largely be based on the existing VHO and VMO architecture. However, existing virtual observatories provide data searches geared towards time-series and image data. As an example, the VHO and VMO provide statistical summaries of time-series magnetic field and thermal plasma data in addition to spacecraft ephemeris data. Similarly, VITMO provides solar and geomagnetic indices and coincidence restrictions. While this provides some benefit to the wave researcher it is not a full suite of tools for finding and accessing wave data. As such, the VWO middleware will provide a wave research-oriented interface to the wave datasets from the VHO, VMO and VITMO. The Middleware will store and have access to context (such as solar wind, IMF and geomagnetic indices information) and orbit information, and event catalogs from which appropriate time and spatial constraints can be determined. Queries to the VWO will result in the appropriate restrictions being determined from user queries. These restrictions will be sent as appropriate to domain virtual observatory (VHO, VMO or VITMO) to query for data availability. Pointers (hyperlinks) to data granules (files), not the actual data, will be returned to the VWO and hence, the user. The VWO architecture for supporting uniform and robust access to distributed space plasma wave and radiation data is illustrated in Figure 6.

In order to implement this architecture, we have identified five tasks as well as the

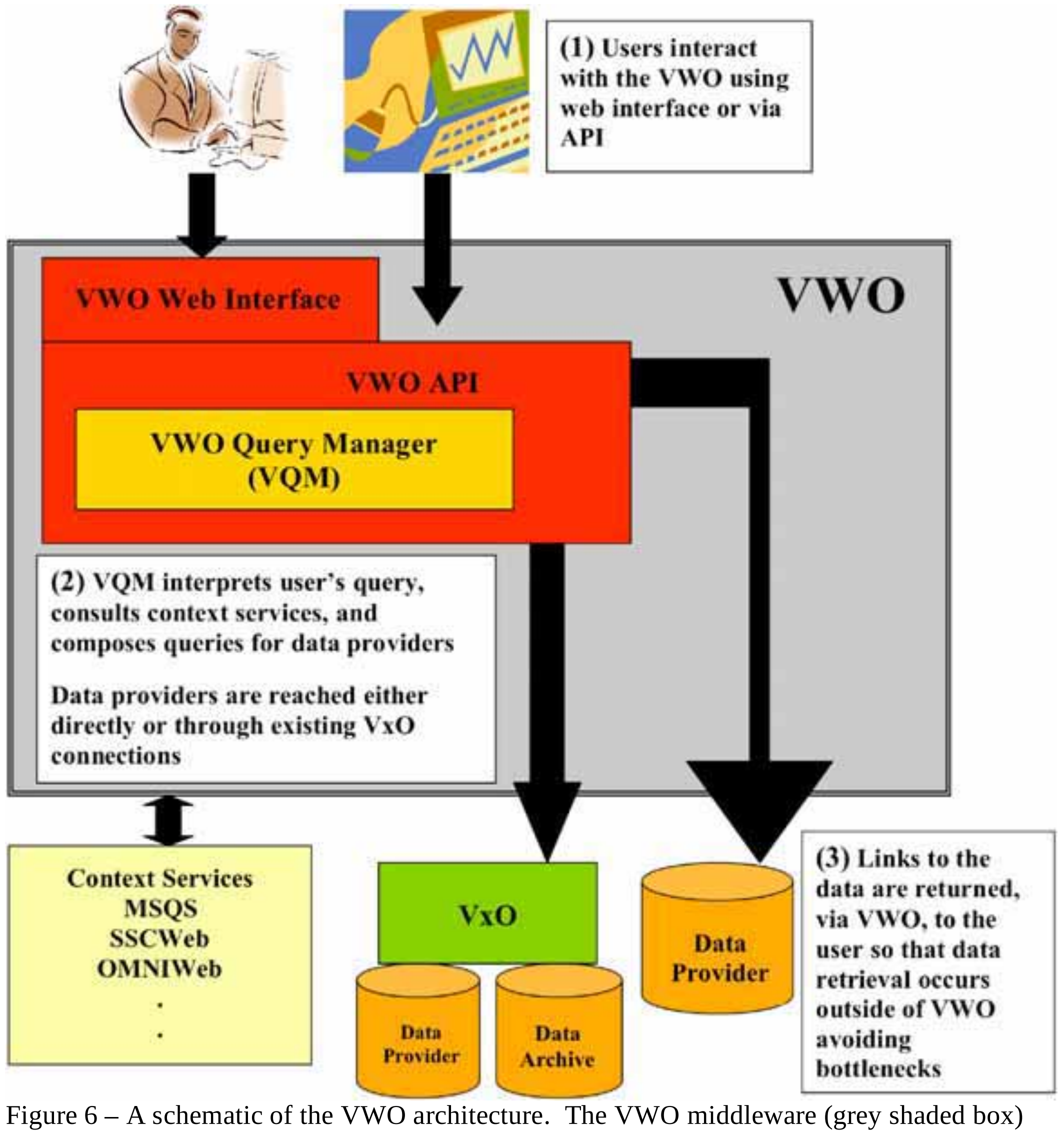

Figure 6 – A schematic of the VWO architecture. The VWO middleware (grey shaded box) will contain a complete set of tools to provide both context and content-based searches for the waves research community. In addition to its own data providers the VWO will leverage existing VxOs, and their data providers, whenever applicable.

overarching need to work with other VxOs and the SPASE community. These detailed tasks and our plan to implement them are discussed in the following sub-sections.

2.2 Working with VxOs and Enhancing the SPASE Data Model

The VWO will interact with other VxOs in terms of people, data, tools and SPASE, as described below:

Personnel — We have on our team staff from all the other Heliophysics VxOs (VHO, VMO-GSFC, VMO-UCLA, VITMO, ViRBO) that have undergone significant development in the past couple of years. This close association among VxO teams ensures that VWO will be developed to be interoperable and compatible with other VxOs *without* much duplication of effort. We will also be participating in all Heliophysics VxO workshops to enable sharing of new results and best practices.

Data — Several of the existing VxOs have planned to serve some wave data sets. A user coming to the VWO for wave data served by another VxO will find easy search and access to these data as well. This capability will be enabled through the collaboration with the other VxOs and the ability to send queries between VxOs using recognized and well-established formats. In addition, wave data served by other VxOs will also be described by the VWO annotation services (see Sections 2.1 and 2.5).

Tools — In order for the wave community to make effective use of the VWO, it will inevitably also need to access data outside of the wave-domain. This will require seamless and transparent interactions with other VxOs. Early in the development of the VWO, we will establish *SPASE*-compliant metadata formats that are compatible with the other VxOs and will utilize SOAP-based APIs allowing coordinated queries to be sent and results received back from any of the other VxOs. This transparent operation will require coordination of efforts with the other VxOs.

SPASE — For the VWO users to be able to make successful searches across all of the wave data sets we will provide, we will need descriptions of the holdings of our data providers that are uniform and complete to a sufficient resolution. The model used by other successful Heliophysics VxOs, and the one we will implement, is the *SPASE* data model. We will initially use the *SPASE* dictionary for the description of the data in order for the VWO to begin registering data sets but will inevitably find areas where we can enhance the dictionary with wave-domain specific terms. With our close collaboration with other VxOs, we will enable these services to also enhance their metadata with the terms that the VWO and the data providers have developed.

2.3 Task 1: Defining wave-relevant terms for the *SPASE* Data Model

We will work with our collaborating data providers and VxO partners (see 5.1), the *SPASE* consortium (http://www.spase-group.org/) and community wave researchers to define the standard *SPASE* terms to describe wave metadata. For creating and defining SPASE terms, we will utilize the *SPASE* description tool developed by the VHO/VMO, available at http://vmo.nasa.gov/content/view/51/72/. Since the IMAGE/RPI data set [Reinisch et al., 2000], containing both active and passive measurements, is the most complete set of general wave data, we will base our design and definition of SPASE terms on the RPI data set. We will then apply the SPASE descriptions to other data sets as prioritized in Table 1, and refine the SPASE definitions. Standardized SPASE terms will then be submitted to the *SPASE* consortium for approval to become a community standard.

2.4 Task 2: Converting metadata of wave datasets into the *SPASE* Data Model, and registering the datasets with VWO

We will utilize and adapt a suite of tools already developed or being developed by the VMO and VHO to enable efficient capturing and publishing of metadata. We will begin by collecting the wave data descriptions that already exist online for most of the data this proposal will immediately support (see Table 1). We will then use the CDF-to- *SPASE* metadata converter developed by the VMO-GSFC team (http://vmo.nasa.gov/vxo/tools/cdf2spase/cdf2spase.php) to cast the wave metadata into the SPASE data model. This tool will save time by populating the *SPASE* Numerical Data Resource from data in CDF format. For datasets in other formats, we will use the *SPASE* Validator developed by the VMO-UCLA to confirm their *SPASE* compliance.

Initially we will be providing value-added search services to the data mostly from NASA space missions or missions with NASA-sponsored instruments on board. Table 1 is a list of most of the available wave data we intend to serve through the currently proposed VWO. The VWO will be working closely with the collaborating wave data providers and the other VxOs that are serving some of these data (middle column of Table 1) to ensure that the interoperability is seamless. We will also be working with current and upcoming missions (THEMIS, RBSP) to assist them in serving their wave data and developing metadata such that they will be compatible with other data sets in the Heliophysics Data Environment. In future work the VWO intends to include serving the wave data from other NASA and international missions such as AMPTE, FAST, Akebono, Demeter and MMS, as well as ground-based active transmitter and passive wave (e.g., VLF and ULF) measurements.

Table 1. VWO wave data sets and providers

Mission (Experiment/Data types)	**Time Span**	**VxO cross reference**	**Availability status / Source**	**Processing* priority**
Alouette 2 (Sounder / digital ionograms in cdf & OS 2 binary)	1965 – 1975	VITMO	Online from CDAWeb & NSSDC / Benson	1
ISIS 1 (Sounder / digital ionograms in cdf & OS 2 binary)	1969 – 1984	VITMO	Online from CDAWeb & NSSDC / Benson	1
ISIS 2 (Sounder / digital ionograms in cdf & OS 2 binary)	1971 – 1984	VITMO	Online from CDAWeb & NSSDC / Benson	1
DE 1 (PWI / spectrogram)	1981 – 1990		Online from NSSDC FTP	1
Polar (PWI / waveform, spectrogram)	1996 – 1997		Online from CDAWeb / Pickett / Anderson	1
IMAGE (RPI / spectrogram, plasmagram)	2000 – 2005		Online from CDAWeb, NSSDC/Reinsich/Benson/Fung	1
Cluster (DWP, EFW, STAFF, Whisper / spectrogram)	2001– present		Online from CAA / Pickett	1
Cluster (WBD / waveform, spectrogram)	2001– present		Online from CAA, Iowa and SWRI/Pickett	1
Ulysses (URAP/ spectrogram, waveform, direction)	1990 – present	VHO	Online from CDAWeb, NSSDC, ESA/MacDowall	1
Wind (Waves / spectrogram)	1994 - present	VHO	Online from CDAWeb/Kaiser	1
STEREO (Swaves / spectrogram)	2006 – present	VHO	Online from CDAWeb/Kaiser	1
Voyager 1 & 2 (PRA / spectrogram)	1977 – 1989		Online from PDS / Walker/ Kaiser	2

Voyager 1 & 2 (PWS / spectrogram)	1978 – 2000		Online from PDS / Walker/ Menietti	2
Galileo (PWS / spectrogram)	1989 – 2003		Online from PDS / Walker / Menietti	2
Cassini (RPWS / spectrogram)	1997 – present		Online from PDS / Walker / Menietti	2
Hawkeye (ELF-VLF / spectrogram)	1974 – 1978		Online from CDAWeb	2
ISEE 1 & 2 (Plasma wave, VLF)	1977 – 1987		Anderson	3
ISEE 3/ICE (Plasma waves spectrum analyzer)	1978 – 1997		NSSDC off line	3
ISEE3/ICE (Radio Mapping of solar wind disturbances)	1978 – 1997		MacDowall	3
CRRES (Plasma wave)	1990 – 1991		Anderson	3
Geotail (PWI)	1992 – present		Anderson	3

*The processing priority: 1 (high), 2 (medium) or 3 (low) in the right-hand column gives the order in which the metadata of the data sets will be processed into *SPASE* format, depending on their readiness for conversion. Within the priority 1 category, the IMAGE/RPI data will be done first as discussed in Task 1 (Section 2.3). The data sets with priority 3 will first have to be promoted to become online accessible (e.g., from CDAWeb or other online archives) before they can be converted; hence they have lower priority.

2.5 Task 3: Developing VWO user interface and expansion/modification of VHO and VMO tools

A wave-oriented researcher is more likely to sort and search in frequency and spatial location, or by wave mode in the future, rather than in time, and often will not want data pre-sorted or fixed according to conventional data catalogs that are mainly time or mission-centric. Thus, a wave researcher will not find a data-search engine oriented toward time series data very useful. *The VWO will custom design its user interface to optimally meet the needs of researchers who enjoy wandering around in frequency space, but who most often are found tripping over imposed time or spatial boundaries, or who require high-time resolution time-series data for the study of nonlinear waves* (Figure 3A).

The VWO web interface will be user-oriented, presenting various choices depending on who the users are and what they might be looking for. The user could be a researcher looking for data, a data provider looking to contribute to the VWO registry or an educator or student looking for explanations of wave phenomena and data examples. The user might want to search for data by mission, by context (state), by wave phenomena or by type of measurement (active vs. passive). We will provide options for each of these and enable the interface to be tailored to their needs. The VWO team will also develop an API (see Figure 6) suitable for Power Users who may wish to develop graphing or analysis applications in IDL or MatLab that will use the VWO as the behind-the-scenes data provider.

The VWO will work closely with existing VxOs (Section 2.2) and leverage the tools and middleware (Tasks 1, 2, 4) being developed by those VxOs in order to economize on development effort and cost, and to avoid duplication of effort. In particular we will rely heavily on close collaboration with Goddard's VMO and VHO. These two VxOs share a common architecture and as such allow us to work with two diverse sub-disciplines while minimizing the technical implementation challenges. In particular, both VHO and VMO plan to offer searching of data based on user contributed event lists. This capability fits naturally with the VWO plan to convert context queries (Task 4) into lists of times suitable for other VxOs. As key personnel from VHO and VMO are Co-Is and Collaborators (Section 5.1) on this proposal, we plan to monitor the development of the event list capability and where necessary augment and modify it to better serve the waves community. For example, the VMO (and soon VHO) offers searches over summary statistics for field and thermal plasma data sets. We propose to work closely with these two VxOs in this area as well with the intent to expand this capability to waves researchers.

2.6 Task 4: Adapting, testing, and modifying VHO/VMO middleware and implementing context-search capability

The key-organizing element for most space physics data services is time: times when "something" happens or time spans when some measurements are made. Scientists currently manually generate, manage, and share lists of observations (times and locations of e.g., CMEs, bow shock crossings, storms, etc). Creating VWO will require development of the VWO Query Manager (VQM) server to work with the various lists (merging and intersecting them) and providing that information to other VxOs where appropriate (see Figure 6). The VQM will be a major component of the VWO Middleware. Figure 7 shows a more detailed view of the various query types and services that the VQM will have to manage and be accessed by other services.

As mentioned in Section 1.1.2 (B) (2), in order to support proper search of wave data, the concept of event lists needs to be expanded to include lists of time intervals that result from context queries of state parameters by using the magnetospheric state query system *MSQS* [Fung, 2004]. In studying the AKR (Figure 2), for example, a scientist might query the *MSQS* for time intervals when a particular set of space environment conditions or magnetospheric state [Fung and Shao, 2007] occurs, including when solar activity is high

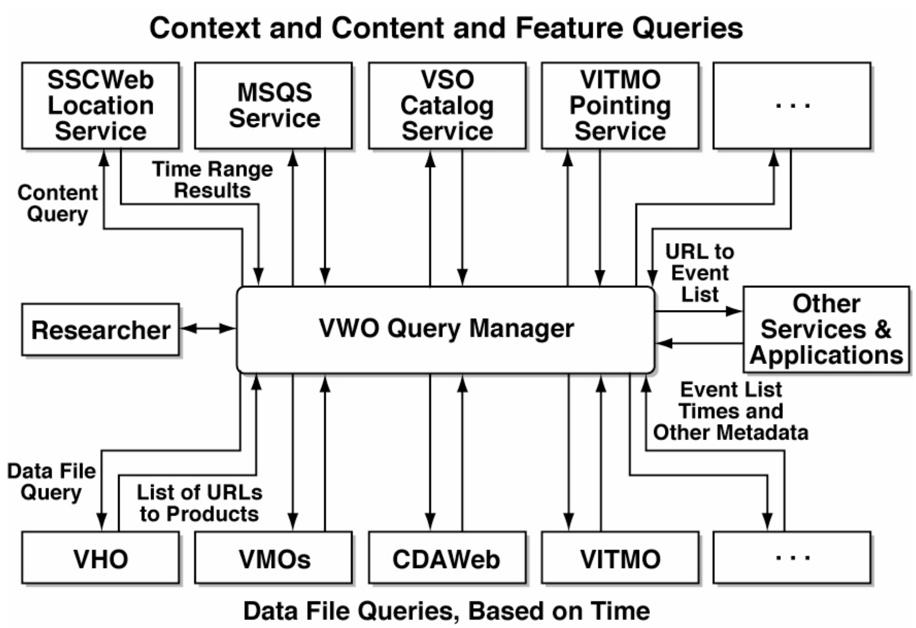

Figure 7. Schematic of VWO's Query Manager system interacting with various VxOs and distributed data services to enable content and context queries (top row) as well as queries for data files (bottom row).

(and low, for comparison), and query SSCWeb for times when Cluster, Geotail and Polar/IMAGE are in strategic positions to observe AKR at various longitudes and latitudes, respectively, in order to determine the variations of AKR emission patterns under different conditions. It may also be needed to find times when Polar and magnetometer ground stations are on the same field lines. Each of these queries generates an event list at VQM, and the lists can then be intersected to find times meeting all criteria. Using this combined list of times, one can query CDAWeb, VxOs and other wave data providers for data during the specified high (low) activity events and browse data plots from these spacecraft, along with Wind and ACE field and plasma data, if needed, to identify inter-planetary shocks from these events arriving at Earth.

Since the VWO will be a heavy user of other VxOs and services (like *MSQS*) listed in Figure 7, the VWO team, whose members are principals of the various services, will work with the community to define and standardize methods for calling to these services, effectively utilizing these services as components of the VWO middleware. This chaining of VxOs demonstrates future uses of the Heliophysics data environment and underscores the need for active collaboration between VWO and other VxOs. Initial work in this area has begun [Narock et al., 2007a, 2007b] and the VWO will stand in a prime location to continue and expand these efforts.

2.7 Task 5: Developing a VWO annotation service to (a) make the wave data *understandable* and (b) enable searches of wave data by *context conditions* and *wave phenomena*

One of the additional services mentioned in Section 2.1 is our annotation service that will capture and store the wave expert knowledge, and put in form of searchable metadata. We expect the annotation service to become an influential technology that shall expand the VWO user base to the scientists who are not wave experts. Domain experts who have retrieved wave data for analysis will be requested to interpret and annotate their wave data. *Their annotations will help identify the wave phenomena and wave modes in the data*, and will be compiled and organized within the VWO framework as part of the documentation and metadata of the pertinent datasets. In order to ensure that accurate information is captured properly, this metadata gathering procedure has to be an iterative process. Once organized, the annotations will become available as additional search parameters for data queries that will allow VWO data searches and retrievals to be based on space environmental context information or on particular wave phenomena. Such context-base data search and retrieval from the VWO data registry will help achieve the optimal exploitation of the data that otherwise lack an intuitive semantic description.

A very similar "expert rating service" has already been implemented by our investigation team members (Galkin and Reinisch) for the IMAGE/RPI radio sounding data [Galkin et al., 2007]. The visualization and analysis software for the IMAGE/RPI is mated to a remotely accessible catalog server holding the data annotations in a relational database. The annotations are directly available as additional constraints in the SQL queries to the catalog. A simple interface allows users to annotate retrieved data as they go along and seamlessly submit new annotations from their remote workstations to the master database over the Internet.

We will extend and implement RPI annotating capability to other wave datasets to be served by the VWO. In this configuration, the VWO query manager will make existing annotations available as the search criteria and allow submission of new annotations for the local centralized storage. Thus the external data providers affiliated with the VWO will not be responsible for read/write management of annotations. This and other additions we propose (see section 2.1) will be rigorously tested by our team and our data providers to ensure that changes made enhance the linkage between wave data sets and other data and services provided through partner Heliophysics VxOs.

Comparison purposes, we will also investigate designing and developing an annotation system more generally for the wave research community. This system will in the future provide data analysis tools allowing wave experts to visualize data sets and provide annotations to reference specific events and features they see in those data sets. These annotations, like those from the RPI-based system above, can then be sent to the VWO, via the tools, where they may also be stored in RDF (http://www.w3.org/RDF). Storing the annotations will provide the ability for more detailed and descriptive searches using semantic web technologies. Our motivation is that annotations have been successful with IMAGE/RPI data (see above) and semantic web technologies have been applied successfully with art images [Hollink, 2003] and nature images [Benitez 2002]. These technologies are also beginning to pervade the biology community (http://biodas.org) and also in heliophysics (http://www.lmsal.com/helio-informatics/kpkb). For the wave community, dynamic spectrograms, wave maps and plasmagrams like the ones in Figures 1, 2, and 3 can be treated as simply images. Thus, we propose to bring this capability to the wave research community meeting the aforementioned needs 1, 2, 3 and 5 and satisfying Tasks 1 and 5. In addition, we propose to use the standard Ontological Web Language (http://www.w3.org/TR/owl-features) to develop a wave ontology to facilitate the annotation searches. In addition, this ontology will compliment existing ontologies in space physics [McGuinness et al. 2007] and astronomy [Derriere et al., 2006] and position the wave community at the forefront of applied information systems research.

2.8 Involving Our Community

As previously mentioned, our targeted community initially will be the wave research community. Members of the VWO team will present their work and receive feedback at wave domain-specific symposia and conferences (AGU, COSPAR, URSI, the International Workshop for Solar and Planetary Radio Emissions (PRE) for examples).

We will develop VWO closely with the wave-research community and other Heliophysics VxOs, and forge closer bonds with the broader research community by soliciting their input. **We seek to enable all researchers in the Heliophysics community to productively use wave data as part of their research investigations.** We have shown that wave data spans most Heliophysics domains and provides unique insights into the physical phenomenon present in these regimes. To enable the broader use of wave data we will develop outreach tutorials on the use of wave data. We will develop a Users Guide with examples of how wave data has contributed to various Heliophysics domains to enable the broader Heliophysics community to begin working effectively with wave data. The VWO website will also contain the means for users to request changes or additions to the VWO website or APIs that we serve. We will also be actively involved in meetings and workshops for the Heliophysics Virtual Observatories and maintain close contact with our partner VxOs.

The wave data providers have already made great strides in documenting their data sets and storing these data in self-describing data formats (e.g., CDF). The VWO will not duplicate these efforts but rather will, when necessary, ensure that the data files have SPASE-compliant descriptions or can be mapped to such descriptions (see App. C of NASA Heliophysics Science Data Management Policy, 25 June 2007). As the VWO project proceeds, we will be working with wave data providers and other VxOs to enhance the SPASE Data Model to better serve the community and allow for greater interoperability.

3. Impact of Proposed Work

On state of knowledge in the field In order to enable more productive science from the wave community, unique relationships must be built between multiple data sets and services. It is often not sufficient to identify data products that are coincident in time but *often analysis of wave phenomenon requires identifying data taken under similar environmental conditions* to better identify the generation mechanisms and propagation effects of the wave phenomenon being observed. The VWO will be ideally suited for coordinated searches across distributed data providers and partner VxOs for the specific context under which these observations were made. Using a consistent set of rich *SPASE*-compliant metadata, a robust search capability (Task 5) and useful software tools (Tasks 1, 2, 3, 4) will better enable the wave community to contribute to heliospheric science.

On technology readiness Our proposed leveraging and adaptation of the tools and middleware being developed by the VHO and VMO (Section 2.2, Tasks 1, 2 and 3) will minimize duplication of effort and streamline access to data and other services from our partner VxOs. As the VHO/VMO middleware matures our means of effectively serving the community will increase. In addition, the proposed adaptation of the operational IMAGE/RPI "expert rating service" (Task 5) will shorten the VWO annotation service development time.

On datasets from related planned missions We will be developing standards that future missions will seek to incorporate into their data descriptions and software. It will be to their advantage to rapidly and cost-effectively incorporate their data sets into this environment. Future providers of data services upgrades will also be able to more effectively develop new tools for the wave community once our work has been completed.

On NASA community research efforts NASA's heliospheric science community has long sought to answer fundamental questions through the use of multi-disciplinary, multi-spacecraft analysis. From the early Coordinated Data Analysis Workshops (CDAWs) to event campaigns the power of uniting the community to address outstanding problems has been recognized and to varying degrees has been successful. Our effort will draw on this legacy, bringing to bear the latest computer technologies to draw distributed data sources together, providing a uniform interface, powerful data search tools and rich metadata descriptions to bring about a true coordinated view of the heliosphere as a system.

A dedicated VWO will be highly beneficial to the wave community by enabling data comparisons, searches, and other services in ways that cater to the unique needs of wave data, which are often in frequency space versus real space, or focused on comparison between datasets based on the same plasma conditions, independent of location. VWO will serve the wave-oriented Heliophysics research community and the greater Heliophysics community through our web site and web services, and provide unique capabilities (typically not available from other domain-oriented VxOs) to query and search for plasma wave and radiation data.

In addition, the proposed VWO tasks will contribute to *SPASE* development, allow Heliophysics wave data to become *accessible* by all Heliophysics disciplines using only a single VWO interface and *searchable* by all VxOs. The VWO annotation service will also to make the wave data *understandable* and usable the Heliophysics community.

4. Relevance to Heliophysics VxO Program and NASA

4.1 Satisfying VxO Requirements

As stated in the "VO Framework" document [Roberts, 2004], "a Virtual Observatory (VO) is a suite of software applications···that allows users to uniformly find, access, and use resources (data, software, document, and image products and services using these) from a collection of distributed product repositories and service providers. A VO is a service that unites services and/or multiple repositories." The proposed VWO meets all requirements of the VO Framework and the VxO requirements as stated on page B. 9-5 (see Table below). It is also designed to meet all wave research community needs (Section 1.1.1 – 1.1.3).

Heliophysics VxO Requirements from 2007 ROSES B.9-5	***VWO Responses***	***Section reference***
What is your focus area and science? Why will a VxO be beneficial?	VWO will serve the wave community. Wave community has no means of easily searching data. Wave data are underutilized by general Heliophysics community	1.1.1; 3.0
What are the data products and resources?	Initial set of data products listed in Table 1.	1.1.2; 2.4; 5.1
How will the data be served? Why will this be better than current access? How will you work with data providers? What is the user interface? What value-added services will you provide?	We will use VHO/VMO Middleware and develop an interface based on VMO, providing a single interface to potentially all Heliophysics wave data. Our data providers are team members. We will develop an annotation service for domain-knowledge capture and search. We will promote off-line data to online; providing one-stop search and access to online wave datasets.	2.4; 2.5; 2.6; 2.7; 2.8; 3.0
What are the metadata to be produced? Who will produce them?	The VWO team will develop and define standard SPASE terms for wave data. We will work with future data providers to use and populate the SPASE-compliant metadata for their data sets.	2.3, 2.4
How will you interact with other VxOs?	We will use and enhance VHO/VMO Middleware and *SPASE* description tools, and cooperate with VxOs to develop standard wave terms for the SPASE Data Model, ensuring interoperability between all VxOs. VxO personnel are also VWO team members.	2.2, 2.3, 2.4, 2.5, 2.6
How will you implement your VxOs within the proposed time?	We will leverage existing VxO tools and middleware to minimize development time, cost and duplication of effort. VWO annotation service will also be developed from an existing operational "expert rating service" developed for the IMAGE/RPI data set	2.0; 2.1; 2.2, 2.3, 2.4, 2.7 5.0
How will you interact and receive feedback from the community?	We will participate in conferences, have a feedback option on interface and capture the domain knowledge of the community in our annotation service.	2.5, 2.8

4.2 Satisfying NASA Strategic Goals and Objectives

Our proposed Virtual Wave Observatory (VWO) directly addresses the highest level requirement of NASA LWS program to attain "unprecedented integration of data and models across many missions, data centers...;" to provide a "coordinated effort to link data and service providers to scientific users;" and finally to enable a "uniform face to an underlying heterogeneous and distributed set of sources." With its focus on wave phenomenon that by their nature cut across discipline-oriented VxOs, and by collaborating with all existing VxOs, our proposed work will be uniquely positioned "to foster communication amongst the nascent VxOs." In addition, while VWO will mainly serve NASA's Heliophysics mission data, some of the data and data systems linked through VWO will reach out to ground-based systems or international partners directly or via various VxOs. The VWO program would contribute directly to NASA's Strategic Goal 3 to "Develop a balanced overall program of science, exploration, and aeronautics...” and its sub-goals 3B (“Understand the Sun and its effects on Earth and the solar system”), 3C (“Advance scientific knowledge of ... hazards and resources present as humans explore space”) and 3F (“Understand the effects of the space environment...”).

4.3 Services to missions

The VWO will provide a versatile data environment for searching and accessing wave data, including those from recent and future Heliophysics missions, such as THEMIS and RBSP, respectively.

5. Plan of Work

The following table gives the work plan for the proposed VWO development. We will present in conferences (AGU meetings and VxO workshops) and publish results yearly in refereed journals, as appropriate, to document the progress, lessons-learned and success of VWO.

VWO Task	**Task Leader and Members**	**Year 1**	**Year 2**	**Year 3**
1. Developing *SPASE* terms for wave metadata	Fung, Anderson, Benson, Galkin, Garcia, Kaiser, MacDowall, Menietti, Narock, Pickett, Reinisch, Walker	Collect metadata; Design & develop SPASE terms for wave data based on IMAGE/RPI active and passive data	Refine, adapt and extend SPASE terms to describe Alouette/ISIS and other datasets in Table 1	Standardize SPASE terms for wave data; Submit standards to SPASE consortium for approval; Publish wave data standard descriptions
2. Convert or Populate wave metadata into SPASE Data Model, and registering data sets	Fung, Anderson, Benson, Candey, Galkin, Garcia, Kaiser, MacDowall, McGuire, Merka, Menietti, Narock, Pickett, Reinisch, Szabo, Walker	Prioritize wave datasets for VWO; Provide up-to-date metadata and documentation of data sets; Populate wave metadata into SPASE data model	Registration of designated wave data sets; Test data registration and interoperability between VWO and VxOs; Promote off-line datasets to online status	Continue registration of data, etc; Publication of data access via VWO
3. Developing VWO interface	Fung, Benson, Candey, Eastman, McGuire, Merka, Morrison, Narock, Reinisch, Shao, Szabo, Walker, Weigel	Announce development of VWO; Seek VxO and Heliophysics community input at meetings; Design VWO architecture and interface using VHO/VMO API & Web services; Design user web interface	Develop web and API interfaces	Implement and test VWO interfaces; Test VWO interoperability with other VxOs, CDAWeb and PDS

4. Adapting, testing, and modifying VHO/VMO middleware to operate on wave datasets	Narock, Benson, Candey, Fung, Galkin, Garcia Merka	Design and develop VWO middleware by adapting VHO/VMO middleware to operate on RPI and other wave data	Test and modify VWO middleware with different wave data sets and data products	Release and document VWO middleware
5. Developing annotation service to (a) make wave data *understandable* & (b) enable wave data searches by *context conditions* & *wave phenomena*	Galkin, Benson, Eastman, Fung Garcia, Kaiser, MacDowall, Menietti, Narock, Shao, Pickett, Reinisch	Design and develop VWO annotation services based on RPI "expert rating service; Implement context search capability	Work with wave community to annotate data; Compile and organize annotations into SPASE-compliant metadata	Continue data annotation; Design and implement data search by phenomena; Test search capability

5.1 Personnel Responsibilities

Proposal team members' expertise and experience are given in their biographical sketches provided after the References. In accordance to the task assignments in the work plan table in Section 5 above, team members' roles and responsibilities are given as follows:
Shing F. Fung (PI), overall project success, budget, staffing, *SPASE* terms development
Roger Anderson, (Collaborator), provide CRRES, ISEE 1&2, Geotail wave data
Robert Benson (Co-I), provider of Alouette and ISIS wave data
Robert Candey (Collaborator), CDAWeb and VITMO interface with VWO
Timothy Eastman (Collaborator), VWO user interface design
Ivan Galkin (Co-I), adapt IMAGE/RPI expert rating service for VWO annotation service
Leonard Garcia (Co-I), Development and population of *SPASE* terms for wave data
Michael Kaiser (Collaborator), provide Voyager/PRA, Wind/Waves and S/Waves data
Robert MacDowall (Collaborator), provide Ulysses/URAP and ISEE-3 wave data
Robert McGuire (Collaborator), CDAWeb & SSCWeb Lead, interoperability with VWO
Doug Menietti (Collaborator), provide expertise on Galileo and Cassini data
Jan Merka (Co-I), VMO-G Lead, middleware development, interoperability with VWO
Daniel Morrison (Collaborator), VITMO Lead, interoperability with VWO
Tom Narock (Co-I), VHO & VMO technical lead, middleware development
Jolene Pickett (Collaborator), provide Polar and Cluster data
Bodo Reinisch (Co-I), provide IMAGE/RPI data
Xi Shao (Co-I), MSQS technical lead, implement context-based data search
Adam Szabo (Collaborator), VHO Lead, interoperability with VWO
Ray Walker (Collaborator), VMO-U and PDS Lead, interoperability with VWO
Robert Weigel (Collaborator), ViRBO Lead, interoperability with VWO

In addition, collaborating data providers will work with the VWO PI and Co-Is to register their datasets, making them searchable, accessible and retrievable (using the SPASE protocols) by users of the VWO. They will also serve as discipline experts on the use of wave data, providing ***documentation and annotation*** as appropriate.

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