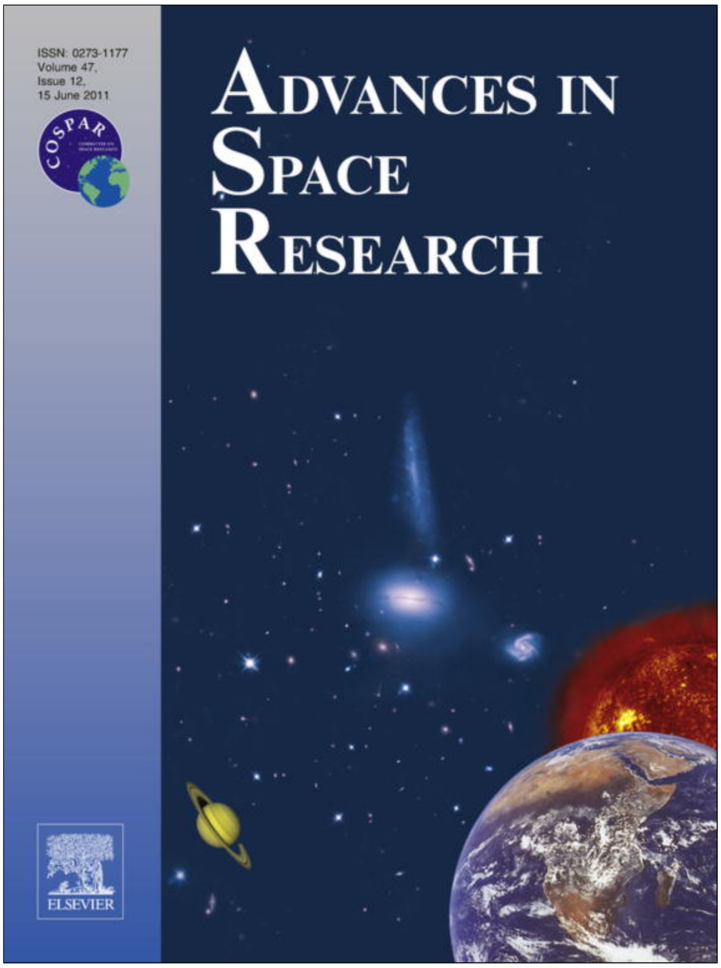
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Distributed networks enable advances in US space weather operations

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Abstract

Space weather, the shorter-term variable impact of the Sun's photons, solar wind particles, and interplanetary magnetic field upon the Earth's environment, adversely affects our technological systems. These technological systems, including their space component, are increasingly being seen as a way to help solve 21st Century problems such as climate change, energy access, fresh water availability, and transportation coordination. Thus, the effects of space weather on space systems and assets must be mitigated and operational space weather using automated distributed networks has emerged as a common operations methodology. The evolution of space weather operations is described and the description of distributed network architectures is provided, including their use of tiers, data objects, redundancy, and time domain definitions. There are several existing distributed networks now providing space weather information and the lessons learned in developing those networks are discussed along with the details of examples for the Solar Irradiance Platform (SIP), Communication Alert and Prediction System (CAPS), GEO Alert and Prediction System (GAPS), LEO Alert and Prediction System (LAPS), Radiation Alert and Prediction System (RAPS), and Magnetosphere Alert and Prediction System (MAPS).

Keywords: Space weather operations; Distributed network; SIP; CAPS; GAPS; LAPS; RAPS; MAPS

1. Background

1.1. 21st Century challenges relevant to space weather

An emerging international discussion considers that space systems and space assets can be used to help solve the big 21st Century problems such as climate change, energy access, fresh water availability, and transportation coordination (Tobiska, 2008a,b; Tobiska et al., 2009). If this is to occur, then the effects of space weather on mission-critical space systems and assets in low Earth orbit (LEO) and geosynchronous orbit (GEO) must be mitigated.

Space weather is the shorter-term variable impact of the Sun's photons, solar wind particles, and interplanetary magnetic field upon the Earth's environment that can adversely affect our technological systems. It includes, for example, the effects of solar coronal mass ejections, solar flares, solar and galactic energetic particles, as well as the solar wind, all of which affect Earth's magnetospheric particles and fields, geomagnetic and electrodynamical conditions, radiation belts, aurorae, ionosphere, and the neutral thermosphere and mesosphere. Disturbances to these regions cause unwanted effects on technological systems that have components sensitive to these regions. As solar cycle 24 begins after several years of quiet conditions, many new advanced technologies have been deployed, and it is likely some of these systems will be exposed to additional unanticipated space weather vulnerabilities.

Active or passive mitigation of space weather effects can most effectively be done when quality space weather information is produced automatically and then integrated into larger systems that manage global energy, water, and transportation activities. The highest priority systems susceptible to space weather are communication, navigation, LEO satellite, and GEO satellite operations.

Operational space weather is, in essence, a supply chain. It is a system of organizations, people, technology, activities, information and resources that move space weather products or services from suppliers to customers. The

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raw material of space environment data is processed by models into information and then refined into specialized products for delivery to end customers. Space weather's greatest value is when it is an integrated information layer within broader systems. Because of a growing number of space weather stakeholders, no single organization can fully identify, much less organize, the universe of operational space weather activity. A particularly severe challenge has been to fund the resources (people, models, operational expertise, and organizations) that can enable operational space weather systems, including the transitioning of models into operations.

1.2. Effects of space weather on operational systems

We know that space and ground operational systems are affected by space weather and include, for instance, telecommunications, Global Positioning System (GPS) navigation, and radar surveillance. As an example, solar coronal mass ejections produce highly variable, energetic particles embedded in the solar wind while large solar flares produce elevated fluxes of ultraviolet (UV) and extreme ultraviolet (EUV) photons. Both sources can be a major cause of terrestrial ionospheric perturbations at low- and high-latitudes. They drive the ionosphere to unstable states resulting in the occurrence of irregularities and rapidly changing total electron content (TEC).

High Frequency (HF) radio propagation, trans-ionospheric radio communications, and GPS navigation systems are particularly affected by these irregularities. For GPS users in perturbed ionospheric regions, the amplitude and phase scintillations of GPS signals can cause significant power fading in signals and phase errors leading to receivers' loss of signal tracking that translates directly into location inaccuracy and signal unavailability.

For example, users of containerized transport systems often desire up-to-the-minute knowledge of a container's location for planning, liability, and security purposes. At present, remote access knowledge is limited to the general location of the vehicle that is carrying the container. Its positional uncertainty can be larger than 100 m. While this moderate level of location accuracy may be sufficient for low priority cargo, it is not adequate for high priority, high-value, or time-critical assets.

1.3. Space weather operations are evolving

During the past decade and a half, starting with the publication of the US National Space Weather Program (NSWP) Strategic Plan (1995), there has been considerable progress made towards developing operational space weather systems. At first, few models existed that could be considered for operations. However, spurred by community interest in space weather, 73 candidate models were identified that characterized 15 space environment domains (NSWP Implementation Plan 2nd Edition, 2000).

During the last decade some of these models were implemented operationally (Tobiska, 2008a, 2009a,b). Early examples were the *Magnetospheric Specification Model* (MSM by NOAA in 2000), *SOLAR2000* (S2K by NOAA in 2001), and *High Accuracy Satellite Drag Model* (HASDM by US Air Force Space Command (AFSPC) in 2004). More recently, coupled-model systems have been created including the *Global Assimilation of Ionospheric Measurements* (GAIM by US Air Force Weather Agency (AFWA) in 2006), *Hakamada-Akasofu-Fry* (HAF by AFWA in 2007), and *Communication Alert and Prediction System* (CAPS by Space Environment Technologies (SET) and Space Environment Corporation (SEC) in 2008). Coupled-model systems currently being implemented include the *Jacchia–Bowman 2008* (JB2008 by SET in 2009–10), the *Nowcast of Atmospheric Ionizing Radiation for Aviation Safety* (NAIRAS by SET in 2009–10), *USGS Dst* (USGS Dst by US Geological Survey (USGS) and SET in 2009–10), commercial GAIM (GAIM by Utah State University in 2009), and *ENLIL with Cone* (ENLIL by NOAA in 2009–10). In addition, the *Space Weather Modeling Framework* (SWMF) and *Center for Integrated Space Weather Modeling* (CISM) systems represent the Sun-to-Earth domain and have linked components with some parts now running for years.

In the first decade of the 21st Century it has been estimated that in the US alone there was sizable funding (~\$1B) for model development provided through directed agency research opportunities (NASA, NSF, DoD, NOAA, DoE). These efforts resulted in mature models throughout five broad domains including solar, heliosphere, magnetosphere, ionosphere, and thermosphere. Yet, while model development was well funded, there was almost no support for transitioning models into operations with the exception of US Air Force projects that moved GAIM, HAF, and HASDM systems into operations. The Community Coordinated Modeling Center (CCMC) was also able to acquire funding to test and compare systems of models. Thus, there existed highly asymmetric agency funding profiles between model developments versus model transitions into operations.

The need for operations implementation did not disappear and this funding asymmetry led to pressures to find new ways of moving models into operations. The emergence of an innovative architecture for operational systems occurred and it is called a distributed network. A distributed network links automated systems of models across dispersed geographical locations. Small businesses, universities, and the CCMC worked during the last 10 years in innovative partnerships to test coupled systems. As a result, the efforts of these groups have resulted in the creation of distributed networks that have helped to close the Technology Readiness Level (TRL) 7–9 gap. Outputs from one system were linked to the inputs of another system to form integrated, but geographically dispersed operational networks. Distributed networks allow developers to maintain versioning and proprietary control over their models while exchanging data via common servers and databases. The also enable consistent, expandable delivery of data products. CAPS, created by SET and SEC, is the best-known example of a distributed network with commercial applications (http://www.spacewx.com "Products:CAPS" menu link). The ES4D application using Google Earth and the Space Wx iPhone/iPod Touch application are examples of product expansion from the original CAPS capability. Although multiple distributed network examples can be found at the SET operational system site (http://www.spacewx.com "SpWx Now" and "Innovations:SET Space Weather Forecasts" menu links) and at the CCMC Integrated Space Weather Analysis System site for prototype space weather (http://www.iswa.gsfc.nasa.gov/iswa/iswa.html), these are simply representative of the breadth of systems now being contemplated.

In relation to space weather's effects upon the ionosphere there are operational challenges resulting from electric field disturbances, irregularities, and scintillation that the CAPS and GAIM systems have sought to address and are working to solve. Ionospheric perturbed conditions can be recognized and specified in real-time or predicted through linkages of models and assimilated data streams. Data from linked systems must be based upon multi-spectral observations of the Sun, solar wind measurements by satellites between the Earth and Sun, as well as by measurements from radar and GPS/TEC networks. Models of the solar wind, solar irradiances, the neutral thermosphere, thermospheric winds, joule heating, particle precipitation, substorms, the electric field, and the ionosphere are able to provide best-estimates of non-measured current and forecast parameters; however, it is clear from experience that the model results are significantly improved by assimilated near real-time data. Thus, a major milestone toward mitigating space weather risks will be met when operational space weather systems such as CAPS and GAIM can demonstrate a seamless energy-effect characterization from the Sun to the Earth.

The process toward solving operational space weather challenges has been evolutionary in defining the solutions, developing the coupled system concepts, integrating the models and data into systems, and validating the outputs. A result of this process is the self-consistent, accurate specification and reliable forecast of major elements of space weather as demonstrated by CAPS and GAIM, which, along with other systems mentioned above, form distributed networks.

1.4. The distributed network architecture

The distributed network concept described here is based on the experience of SET in developing a broad variety of space weather operational systems. We describe the overall architecture concept, the use of redundancy and a unique perspective of time domain definition, and then follow with a description of lessons learned from our experience over the past decade. In Section 2, we provide high-level examples of systems we have built using these concepts. A specific example of how a distributed network is used is described below in Section 1.4.

A distributed network is based upon an architecture called Operational Database Management System (ODBMS). The key elements are (1) an input data stream from third parties; (2) a client server that handles asynchronous file exchanges between geographically separated models hosted on separated prime and backup computers; (3) a real-time repository database for dynamic data sets; and (4) a customer server interface for access to real-time and forecast space weather data. Strengths include fault-tolerance and system flexibility for prototype development. Risks can include susceptibility to network disruptions, unplanned format changes in third-party data streams, and management complexity.

A distributed network is distinguished from the more common rack-mount, clustered operational system consisting of a central server and database at one physical location that is linked to other local computers where models reside. The strengths of the clustered system include information security and control at a single site. Risks can include component failures in highly-coupled systems, limitations to system upgrades, and susceptibility to environment failures at the clustered system location.

In the distributed network, a client server collects the raw operational input data from third parties. The server's software creates metadata tags for all data objects and deposits the data object, combined with its metadata as a "data suitcase", into the dynamic section of the database for use by models or users. Models, running at their appropriate geophysical cadences, are developed and hosted by partnering institutions at remote locations. Requests for data inputs by the models are made to the client server, which then extracts and forwards the requested past, present, or future data suitcase to the requestor across a network. Outputs from the models are collected by the client server and stored in the dynamic database for use by other models.

The use of dynamic metadata allows traceability for all I/O requests from models, customers, or users. Customers access the data products by making requests to the server using either operational application software for automated server connections or browsers for manual, interactive sessions. For example, a customer may want electron densities for a particular time, latitude, longitude and the information content of these data objects would be provided "just-in-time". The iPhone application developed by the Utah State University (USU) Space Weather Center (SWC – http://www.spaceweather.usu.edu/) and SET (http://www.spacewx.com "Innovations:Space Weather on Apple's iPhone/iPod" menu link) is an example of a fully distributed network for a commercial product that has been developed by a university and small business partnership.

As a detailed example of how a distributed network was used for the iPhone app, we describe several of the processes here. First, real-time X-ray data are measured by the GOES satellite; the raw data are processed, then distributed, by

NOAA SWPC. Every 2 min, the SET server in Denver, Colorado extracts the most recent SWPC binary data from the NOAA ESWDS operational server and uses it to create a hybrid solar spectrum with a 2-min cadence, 1-min time granularity and about 3-min latency. The GOES X-ray data are used by the SET SOLARFLARE system, which incorporates the physics-based Mewe model to create a 0.1 nm spectrum from 0 to 30 nm and then runs a flare evolution prediction algorithm. These irradiances are then concatenated with the hourly updated, daily time granularity, 0.1 nm spectrum above 30 nm created by the empirical SOLAR2000 model. SOLAR2000 uses Penticton F10.7 and NOAA, SORCE, and GOME Mg II core-to-wing ratio data to create a solar spectrum. The irradiance file is generated by the SETSYS operational system software and formatted in a file that can be used by the SEC IFM model. The SEC server in Providence, Utah extracts from the SET server every 15 min the solar irradiance spectrum that contains flare information and 1-min forecasts out to 3 or 6 h. SEC uses the file to generate a physics-based global ionosphere at the current epoch, depending upon time-tags in the irradiance file. The SEC ionosphere file is then retrieved at a regular cadence by the SET CAPSOPS system. CAPSOPS creates jpegs and user files for the CAPS, ES4D, and *Space Wx* iPhone app systems. The generic-named files are placed in the proper delivery directories and overwritten at regular time steps. An iPhone app user, with the push of a button on the app, retrieves the information via WIFI or telephone link at any global location, almost instantly. The total latency from data measurement to iPhone app information retrieval can be as low as under 4 min or as high as 30 min, depending upon timing of when *Space Wx* information is requested. In addition, a unique feature of this distributed network is that for some information, no files have been transferred with the exception of the final jpeg seen by the *Space Wx* user. For example, the ACE real-time data is extracted every couple minutes as binary data from the NOAA ESWDS server by the SET server and inserted into a SQL database. A *Space Wx* user in Australia sends a request from their iPhone for the ACE solar wind speed. The request is received at the SET server via the network, these data are extracted out of the database, and formatted immediately into a jpeg file that is sent to the iPhone app. This distributed network process has been optimized to quickly speed information to the user.

It is apparent there would be an unmanageable risk in a system if one were to try running models in a synchronized, end-to-end manner. There are numerous potential single points of failure that can lead to system execution times longer than the anticipated cadence. In addition, with synchronized runs, there is a susceptibility to catastrophic failure in the event of component failure. A distributed network, with "just-in-time" data that are decoupled in time and production location from one another, removes this risk and uses a key design philosophy, i.e., *models are run asynchronously and linked through dynamic data input and output.*

Using the philosophy of asynchronously linked models within a dynamic data flow, the distributed network architecture embodies an additional guiding concept, i.e., *produce accurate real-time and forecast parameters while maintaining output data integrity even when components fail, data drops out, or there is high component latency.* A corollary design practice is used where *no single points of failure, data dropouts or latency will stop the operational generation of real-time and forecast information.* These concepts imply that component failures, data dropouts, and data latency are identified, reported, and corrected where necessary such that the largest risk for data quality is its graceful degradation. Graceful degradation is when climatologically valid data continues to be produced but the enhancements of time resolution, spatial detail, and reduced error have been sacrificed due to component failures. In other words, component failures and data communication interrupts do not produce catastrophic system failure.

A distributed network often has a four-tier architecture encompassing the major components of the system, including Tier 1 database, Tier 2 client server, Tier 3 client (model host), and Tier 4 customer access. The core component is the *tier 1 database* where all relevant information for all models is stored and accessible at any time. It is not an archival database but an operational one, dynamically maintaining real-time I/O capability with metadata wrapped data objects that come from remote data sources or from the most recent models' outputs. Geophysical information of any time domain is extracted from a data object using a "just-in-time" access philosophy to ensure that the most up-to-date information is passed to the requesting user. As data age, e.g., those data older than 72-h, they are removed from the operational database to off-line storage in a separate archival facility. The existence of this database and its guaranteed accessibility is one of the key components to making this operational system work. By employing a Database Management System (DBMS) for organizing the data, the problem of concurrent data operations, such as file read and write from two systems at the same instant, is mitigated and asynchronicity is achieved.

The *tier 2 client server* is usually a set of prime and backup computers controlling all access into and out of the core database and the client tier. These are often the compute engines for the models regardless of their physical location. The client server executes software that receives and transmits data objects to and from the requesting models. Java software on both client and server subsystems is often used to produce metadata tags that are attached to the data objects and this practice enables unambiguous identification of data in past, present, or future time domains as well as data type definitions, sources, uses, uncertainties, and validations. As a result, validation tests can be built into the software to permit automated alternative actions to be performed in the event of exceptions to normal operations. The client server also tracks, logs, and reports on the operational state of the entire system. Tight control on external access to the database through the client server alone minimizes system security risks.

The *tier 3 clients* are the ensemble of partnering institutions' prime and backup model host computers. These machines are dedicated to operationally running specific models and to requesting input data from the client server tier. The output data objects from this client tier are transmitted to the server tier for deposit into the core database tier. Compute engines can also reside at the same location as the server and database; these computers run scientific models that have been developed by team members where the latter do not desire to host a separate operational system themselves.

The *tier 4 customers* are customer user computers that are permitted to query the server tier for information regarding past, present, or future space weather parameters. Customer computers can be sophisticated remote servers, desktops, or even cell phones and PDA's.

When new technology, e.g., satellite sensors, computers, communication options, is introduced, when customer needs change, or when physics-based models improve, a new set of requirements must be addressed. The duration and cadence of code execution drives the hardware requirements, which include machine speeds, memory and network performance, and the number of servers and subsystems. The distributed network architecture influences the requirements for data exchange protocols, exception handling, interface format specifications, and file sizes. The development staff, operations staff, and end-user product requirements affect the design that will integrate all the servers, software, and subsystems. To complete a final system integration, a systems development lifecycle definition is often needed that addresses unit designs, ODBMS, modularity concepts for parameter or model substitution, software quality assurances, maintenance procedures, test plans, and upgrading protocols.

1.5. Data objects are critical components within a distributed network architecture

Data from external sources, measurements, or models can be thought of as objects. Data or model objects are often *encapsulated*. A data object, for example, can contain a scalar, vector, or tensor that represents a past, present, or future time domain. Metadata provides summarized information about the data or model and can be examined by system components to determine if there is a need to unpack a data object.

Persistence of a unique data object means that it remains unchanged during its path through the entire system. Data objects will often have the property of *persistence* since common operations are performed on them such as query functions, i.e., obtaining the time the data were created, determining which time domain they represent, and deciding whether or not they contain valid data. For example, a daily F10.7 value may be associated with a 20:00 UT creation time at the Penticton observatory. In addition, a forecast F10.7 representing the same day's 20:00 UT Penticton value may have been created the previous day by a forecast model. The properties of forecast or measured F10.7 must be identified, and the times associated with these two values will also differ from the storage time when it is written into the database or the time when it is used by a model. Thus, a central server is needed to dynamically maintain the states of the data or model objects' properties that are common to the ensemble of client models.

The *activities* of the central, client server are oriented to data and model object management. At any given instant each data object has several types of times associated with it, e.g., the time the data represents and the time the object was created. The central server is often designed to use a top-level "daemon", i.e., a process that is always running in memory, that sends and receives data objects, dynamically validates data objects, and assigns data stream identifier tags to the data objects based on their time properties.

Finally, a data or model object often has the property of *universality*. A data or model object may be used or contained by nearly all components of the system and a central server is needed to maintain traceability of the data and model objects' properties that are common to the ensemble of client models. Universality for data objects also means that a data object's changing characteristics can be incorporated as they are used or modified by each model. The input or output use of a data object is not a property; instead, it may be either depending only upon how a particular model relates to it.

1.6. Redundancy in a distributed network

Redundancy is an important part of an operational system design since it addresses risks. A first implementation of redundancy that addresses the operational risk of forecast data unavailability is to ensure the *data stream flow*. There are usually two data streams flowing through the system and the system must recognize a data object as belonging to either a primary "A" or secondary "B" data stream. The primary "A" data stream contains enhanced data by virtue of its finer time resolution, spatial detail, or reduced uncertainty. The drawback is that some of these data sets may become unavailable for a variety of reasons. The secondary "B" data stream contains core data that is fundamental to maintaining space weather climatology information flow. This type of information stream is usually easier to produce and, while the uncertainties may be larger, it still represents a valid data solution. These data are always available, either as measured (past or current data) or modeled (current or future data). The redundant data stream attribute is a major design feature of the entire system and all data objects belong to either the "A" or "B" stream.

The data stream concept is separate from the redundancy concept of *primary and backup computers*. Just as two data streams mitigate the risk of losing space weather output data by providing climatologically valid output in the event that enhanced data is not available, the risk of network communications errors from component failures, data outages, latency, or concurrency is mitigated by using a *network switch* between primary and backup computers. This feature ensures that the communication lines are open between primary and backup systems at both the server and client tiers. The network switch is physically separate from both the primary and backup systems, dynamically maintains URL pointers, and has the single function of determining what systems are running and then routing the client/server communications accordingly. Additionally, customer and client machines can have their own logic to select an alternative system. The network switch redundancy option is most applicable to a distributed network. For the central clustered system, an alternative option for maintaining open communication lines is to utilize dedicated T1 lines with external data sources. This expensive solution is often used for mission-critical operations.

A third system-level redundancy implementation that mitigates the operational risk to data quality and availability is the concept of *dual models*. Some space weather models may provide similar data sets and one model may be most useful for the climatology "B" stream while another model may be more useful for the enhanced "A" stream. Dual models (along with similarity of data types) are a type of redundancy often provided in conjunction with the two-stream concept.

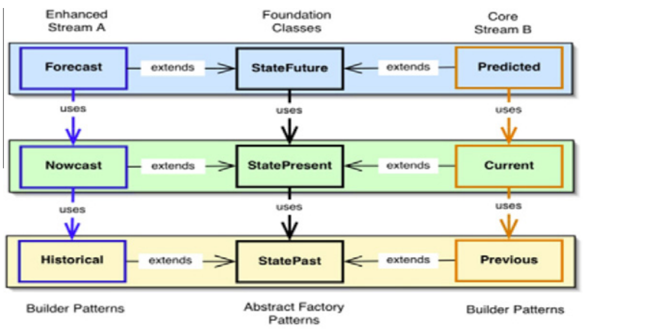
1.7. Time domains in a distributed network

A key element in achieving accurate nowcasts and reliable forecasts is the organization of *time* into operationally useful domains. In distributed networks, an operational time system has been defined that has a heritage in three decades of space weather characterization. Time *domains* are used to operationally designate the temporal interdependence of physical space weather parameters that are relative to the current moment in time, i.e., "now". The current moment in time is the key time marker in our system and is called the *current epoch* in the aerospace community; that usage is adopted here.

Relative to the current epoch, data contains information about the past, present, or future. In addition, data can be considered primary or secondary in an operational system that uses redundant data streams to mitigate risks. Past, present, or future state information that is contained within data is separated with the nomenclature of *historical, nowcast, or forecast* for primary (enhanced) data stream information. Table 1 shows a diagram of these relationships. *Previous, current, or predicted* nomenclature is used for secondary (climatological) data stream information. Using these time domains, failures in the primary (enhanced) data stream result in the use of secondary data stream (climatological) values; the overall effect is to maintain operational continuity in exchange for increased uncertainty. This concept is also known as "graceful degradation".

Historical or previous data are operationally defined as that information older than 24 h prior to the current epoch. These data have usually been measured, processed, reported (issued), and distributed by the organization that creates the information. Their values are unlikely to change significantly and they are ready for transfer to permanent archives. Exceptions such as the definitive Kyoto Dst, for example, take longer to transfer to archives.

Table 1
Stream A and Stream B time domains derive from same classes.



Nowcast or current data are operationally defined as that information for the most recent 24-h period, i.e., 24 h ago up to the current epoch. Some measured data has been received by an operational system but it is likely that not all inputs for all models are yet available. Modeled data are often produced using multiple data sources that can include the most recently received input data and estimated (recently forecast) data. Their values are likely to change and they are not ready for transfer to permanent archives. However, there is value in retaining some of these data for validation and verification exercises.

Forecast or predicted data are operationally defined as that information in the future relative to the current epoch. Forecast data have not been measured but only modeled from either first principles or empirical algorithms. Their values are extremely likely to change and they are not ready for transfer to permanent archives. As with the nowcast data, there is value in retaining some of these data for validation and verification exercises.

Hence, the values for particular types of data can be in a state of constant change. For operational purposes, the data creation date is not related to its designation as historical/previous, nowcast/current, or forecast/predicted. Historical/previous data tends to be measured, static, and ready for archival, nowcast/current data tends to be either modeled or measured but transitional, and forecast/predicted data tends to be modeled and mutable.

The terms "Forecast" vs. "Predicted," "Nowcast" vs. "Current", and "Historical" vs. "Previous" are used to distinguish the different Java builder patterns based on past, present, and future time states. They are all extensions of the same foundation class but represent distinctly different subclass families for the Enhanced ("A") and Core ("B") data objects. Java is used in this discussion as an example although other programming languages can be used in a similar fashion.

In object-oriented terminology the word "extends" means an inheritance property ("is-a" type of relationship).

For example, a Forecast class is a State Future class and it extends (employs) the methods of the parent level State Future class. The word "uses" is a composition property, i.e., a class can be a composite of other classes ("has-a" type of relationship). For example, a Predicted class has a Current class which has a Previous class.

1.8. Lessons learned from distributed network implementation

There have been lessons learned in building integrated, automated space weather systems that can provide effective, timely mitigation of space weather risks to our technological systems. If we coordinate stakeholder participation, build on the positive legacy of the NSWP, and leverage the expertise, capabilities, and national resources that already exist, then progress can be made. Additionally, by emphasizing a business model that is "light and fast" in development and deployment, as opposed to adding new systems into a large, centrally located infrastructures, innovation results with a faster evolution of solutions to meet end-user requirements.

General implementation lessons learned include using a defined systems development lifecycle, developing accurate cost estimates for research and development, employing agile software development, designing automated systems that can react to exceptions and component failures, archiving of validated historical, current epoch, and forecast data, generating anomaly databases, and provide alerts and predictions tailored to actionable responses for changing space weather conditions.

A lesson for the state-of-readiness classification is the example of the Technology Readiness Level (TRL – see http://www.en.wikipedia.org/wiki/Technology_readiness_level). The TRL system is useful when applied to space weather systems because it provides an estimate of the maturity of a model or system on its transition to operations. Working definitions that have been found to be most useful include TRL 6 where the model or system/subsystem prototype has been demonstrated in a standalone environment, TRL 7 where a system prototype has been demonstrated in an operational environment, TRL 8 where an integrated system has been completed and qualified through test and demonstration, and TRL 9 where an actual system is operationally proven through successful mission operations.

Stakeholder coordination is an important lesson for operational space weather progress. Stakeholders include model and data developers who provide innovative physics-based, hybrid, and empirical models as well as observational or virtual observatory data products to improve upon the current data products. Government laboratories are stakeholders and can provide programmatic direction for the development of models and systems. Universities are stakeholders and can provide advances in modeling. Industry is a stakeholder and can provide implementation support to operational users. Small businesses are stakeholders and can provide quick evolution of innovative transitional technologies that link data and models into operational systems.

If space weather information production is a supply chain, then its organization and management must include:

- ensuring uninterrupted, quality data from space and ground assets; this is a traditional task of government but data sale by the private sector will likely emerge;
- supporting ongoing research to improve data gathering and modeling; NASA LWS TR&T, NSF space weather, AFOSR MURI, and ONR MURI funding activities have been very useful but new funding sources, including revenue from customers will likely appear;
- maintaining a cross-TRL prototyping methodology for transitioning lower TRL components to higher TRLs; these were formerly called Rapid Prototyping Centers but were organizationally unsuccessful; private sector and CCMC prototyping processes use distributed networks that have now successfully evolved to provide a significant cross-TRL capability; distributed networks will likely grow;
- validating high TRL components that are ready for operations; funded, independent assessment organizations are continually needed and CCMC or other organizations that are independent of the developers can be used;
- identifying customer needs and requirements for specialized products; this is an iterative process from beginning to end of the supply chain and there is a constant need to bring in customers into active discussions through conferences, private forums, and contractual relationships; and
- summarizing best practices in developing state-of-the-art systems; this continues through the development of professional society (AIAA, IEEE, ASTM), agency (NASA, DoD), national (ANSI, GOST), regional (ECSS), and international (ISO) standards, guidelines, and technical reports.

2. Examples of distributed network applications

Space Environment Technologies provides several examples of data products based on active distributed networks. Short descriptions of each system, their use and customer base, website locations, and partner organizations are listed. It should be noted that each of these systems relies on data streams and/or models that are located at external sites and that are not administered by SET. The fact that a system can be organized across a distributed network of diverse servers and can be run operationally is the key point of this paper and represents a remarkable step towards maturity in the architecture of operational systems.

2.1. Solar Irradiance Platform (SIP)

The Solar Irradiance Platform (SIP) (Fig. 1) Professional Grade (PG) and Research Grade (RG) application

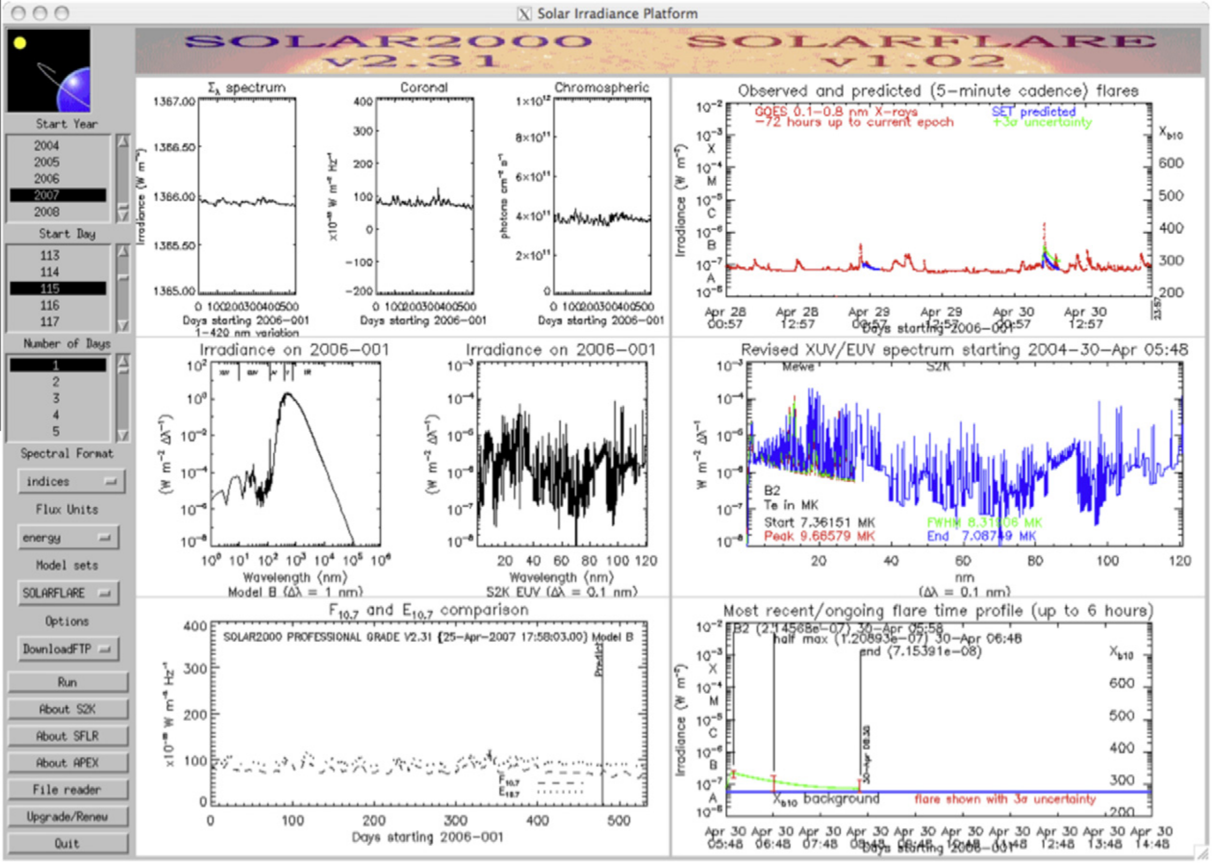


Fig. 1. SIP solar irradiances and indices from Space Environment Technologies at http://www.spacewx.com "Products:SIP" menu link. The screenshot shows the GUI menu bar at the left. The left panel column provides the SOLAR2000 input (top row) and output (middle and bottom rows) parameters. The right panel column provides the SOLARFLARE input (top row) and output (middle and bottom rows) parameters.

is a hybrid solar irradiance system (reference data, real-time data, empirical models, physics-based models) that produces the variable, full solar spectrum in assorted spectral formats, proxies, and indices for historical, nowcast, and forecast applications. SIP incorporates automated forecast updates, including warnings and forecasts, of JB2006/JB2008 and SOLARFLARE parameters useful for satellite and communication operational users. Real-time GOES XRS, SOHO SEM, and TIMED SEE data download capabilities exist. Flexible user tools for analysis, plotting, and data inspection of space weather related solar photon phenomena related to satellite drag, HF signal loss, navigation precision loss, and surface charging are provided in a desktop PC environment. SIP is also provided as a System Grade (SY) application utilizing a configuration file for use by physics-based ionosphere and thermosphere algorithms that require a solar irradiance subroutine. The SIP capabilities continue to expand an overarching SET objective of providing system-level risk mitigation of dynamical space weather phenomena. SIP is at the user-end of a distributed network of cross-linked systems that *create quality data products rapidly*, enable them to be *interpreted quickly*, and foster *appropriate reactions to real-time and predicted information with timely actions*. SIP provides historical, real-time current epoch, and forecast solar data for:

- research and operational applications on standalone, modular, and server-based platforms;
- historical measurements, current observations, and future predictions;
- multiple physics-based and observation-based models as well as historical and real-time data-driven algorithms;
- self-consistent solar energy across the full solar spectrum in high spectral and time resolution formats as well as through solar indices;
- irradiances across all heliophysical time scales (flares, solar rotation, solar active region evolution, and solar-cycle); and
- compliance with the ISO International Standard 21348.

SIP, which was developed by Space Environment Technologies, can be downloaded from the http://www.spacewx.com "Products:SIP" menu link.

2.2. Communication Alert and Prediction System (CAPS)

CAPS (Communication Alert and Prediction System) provides up-to-the-minute current epoch and forecast global and regional communication conditions. Communication frequencies are affected by space weather, which changes dynamically and unexpectedly. Risks to communication systems and information transmittal can be reduced by accurate, operational space weather systems designed specifically for use in communication activities.

CAPS was developed as a collaborative project between Space Environment Technologies (SET) and Space Environment Corporation (SEC). SET provides accurate specification and forecast of solar spectral irradiance variations and makes that information accessible as a time-tagged solar energy input into the physics-based Ionosphere Forecast Model (IFM) developed by SEC. SET and SEC both run operational servers to link the data streams and SEC provides a final IFM output that includes TEC (Fig. 2), electron density, and HF communication frequency data. The Air Force Research Laboratory (AFRL) has provided the PBMOD physics-based scintillation model to SET and it is also run to produce real-time and forecast scintillation S4 data at the CAPS website located at http://www.spacewx.com "Products:CAPS" menu link.

A derivative application called Earth–Space 4D (ES4D) (Fig. 3) provides KML files for use by Google Earth using real-time CAPS data. The result is a real-time visualization of the ionosphere and HF communications availability as driven by space weather and access can be found at the above site. In addition, an iPhone/iPod Touch application called *Space Wx* (Fig. 4) has been developed by SET and USU/SWC. It is available through Apple for download via iTunes as an educational tool showing real-time space weather's effects on the ionosphere. These applications use CAPS data as end-users in a distributed network based on satellite- and ground-based real-time data streams.

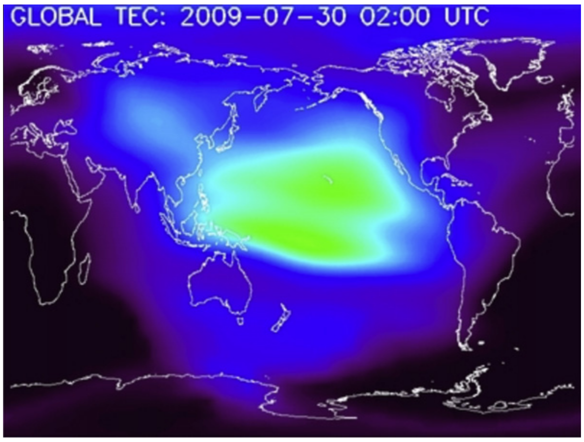


Fig. 2. CAPS from SET and SEC at http://www.spacewx.com "Products:CAPS" menu link. This figure shows the real-time SEC IFM global ionospheric TEC conditions that are derived from the SET flare irradiances.

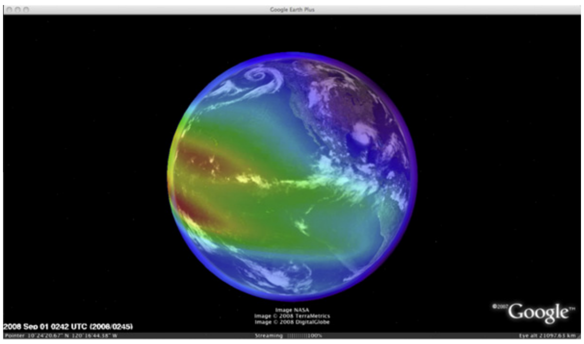


Fig. 3. ES4D from SET and SEC at http://www.spacewx.com "Products:CAPS" menu link. This figure shows the real-time, continuously updating SEC IFM TEC mapped onto the Google Earth globe.

2.3. LEO Alert and Prediction System (LAPS)

AFSPC and SET have produced an empirical thermospheric density model called JB2008 for providing mass densities in LEO satellite operations. SET runs this model in real-time and generates the current thermosphere from 120 to 1500 km in 5 km altitude increments. JB2008 is an improved revision of the JB2006 model, which is based on Jacchia's diffusion equations. Driving solar indices are computed from on-orbit sensor data, which are used for the solar irradiances in the extreme through far ultraviolet, including X-ray and Lyman-α wavelengths. New exospheric temperature equations were developed to represent the thermospheric EUV and FUV heating. New semiannual density equations based on multiple 81-day average solar indices are used to represent the variations in the semiannual density cycle that result from EUV heating. Geomagnetic storm effects are modeled using the Dst index

Fig. 4. *Space Wx* from SET and USU Space Weather Center at http://www.spacewx.com "Innovation:iPhone" menu link. This screenshot shows the home screen of the *Space Wx* v1.3 app with global TEC from IFM. Menu options are for regional TEC maps and for space weather drivers to the ionosphere.

as the driver of global density perturbations initiated by high-latitude processes. JB2008 is validated through comparisons with accurate daily density drag data previously computed for numerous satellites in the altitude range of 175–1000 km. Model comparisons were computed for the JB2008, JB2006, Jacchia 1970, and NRLMSIS 2000 models. Accelerometer measurements from the CHAMP and GRACE satellites were also used to validate the new geomagnetic storm equations. JB2008 is a component of the new COSPAR International Reference Atmosphere 2008 (CIRA08) and of the developing ISO International Standard 14222 for Earth atmosphere densities above 120 km.

The thermospheric densities products by the LEO Alert and Prediction System (LAPS) are from JB2008 (Fig. 5) and can be found at http://www.spacewx.com "Products:LAPS:JB2008" and "SpWx Now" menu links. LAPS is an example of a distributed network incorporating solar and thermospheric density data for use by LEO satellite operators.

2.4. GEO Alert and Prediction System (GAPS)

SET provides the GEO charging and deep dielectric discharging environment at the GEO Alert and Prediction System (GAPS) site. The GEOsynchronous Plasma envirOnmenT model (GEOPOT08) calculates the surface charging on a shaded non-lit GEO spacecraft and the surface charging on a sunlit GEO spacecraft using photoemission on aluminum (Al). Time intervals range from −48 h in the past, through the current epoch, to +72 h in the future. The charging code incorporates a two-Maxwellian energy distribution (cold plasmasphere, hot plasma sheet particles) for electrons and protons and is driven by the 3-h ap index. The model is based on the relationship between ap and SCATHA satellite charging data. The seasonal eclipse duration at current epoch is calculated and displayed and an example of the shaded GOES 10 spacecraft is shown (Fig. 6).

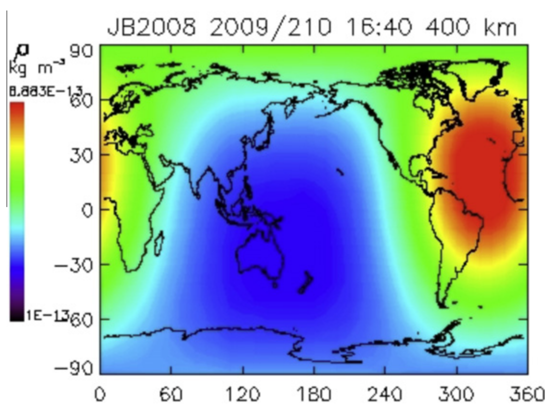


Fig. 5. JB2008 densities from SET and AFSPC at http://www.spacewx.com "Products:LAPS:JB2008" and "SpWx Now" menu links. This figure shows an example snapshot of the real-time global neutral density field at 400 km.

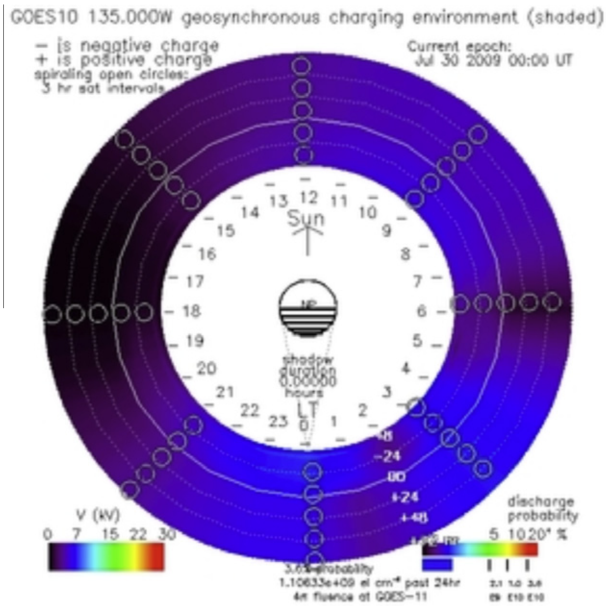


Fig. 6. GAPS GEO charging on a shaded GOES 10 and deep dielectric discharge probability from SET at http://www.spacewx.com "Products:GAPS" menu link. This figure shows the surface charging (color-coded in kV units) for the selected satellite of GOES 10. The lower right bar shows the deep dielectric discharge probability based on the past 24 h of measured GOES 0.6 MeV electrons.

The deep dielectric discharge probability is shown in the bar (lower right of Fig. 6) and is derived from an empirical relationship between 0.6 MeV electrons over a 24-h period and the historical discharging events. The GAPS data can be found at http://www.spacewx.com "Products:GAPS" menu link and this system is an example of a distributed network using historical, real-time, and forecast geomagnetic as well as satellite particle data for the benefit of satellite operational users in geosynchronous orbit.

2.5. Radiation Alert and Prediction System (RAPS)

The Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) project is funded by the NASA Applied Sciences Program. Its objective is to develop a prototype global, real-time, data-driven prediction of atmospheric ionizing radiation dose for archiving and assessing biologically harmful radiation exposure levels at commercial airline altitudes. The sources of the biologically harmful (i.e., ionizing) radiation are galactic cosmic rays (GCR) and solar energetic particles (SEP), which can accompany disturbances on the Sun's surface. The sources, composition, and energy-spectra of atmospheric ionizing radiation are linked to sources and variability of space weather phenomena. As such, the NAIRAS system provides a space weather decision support tool related to radiation impacts on crew and passengers of long-range aircraft, an area of national priority for NASA's Applied Science Program.

The NAIRAS system will enhance the performance of the decision support tools provided by the NOAA Space

Weather Prediction Center (SWPC) and by commercial aviation weather providers, since these decision support systems do not currently monitor or estimate the ionizing radiation present in the atmosphere at commercial airline altitudes. The end-user communities that will benefit from the NAIRAS system are the commercial airline industry (airline corporations and aircrew professional associations), the FAA, the National Institute of Occupational Safety and Health (NIOSH), and NOAA/SWPC. Results from the NAIRAS system will provide tools for its end-user organizations to develop policy and procedures for mitigating biologically harmful radiation exposure and aircrew career planning – especially during SEP events. NAIRAS results will also aid in the formulation of recommended aircrew annual and career radiation dose limits, and will enhance epidemiological studies conducted to better understand the biological effects of atmospheric ionizing radiation on passengers and crew.

SET is the NAIRAS operational implementation partner and provides a Radiation Alert and Prediction System (RAPS) site at http://www.spacewx.com "Products:RAPS" menu link. Fig. 7 provides an example of the NAIRAS dose at altitude output during the October 2003 Halloween storm period. The NAIRAS system is part of the RAPS distributed network using satellite, NWS weather, and ground-based data to provide radiation dose information to aviation end-users.

2.6. Magnetosphere Alert and Prediction System (MAPS)

SET has teamed with the USGS to provide a new real-time USGS Dst index with improve cadence, latency, reliability, accuracy, and forecast ability compared to the existing Dst. Because the Dst is an indicator of space weather disturbances by the solar wind upon the coupled magnetosphere–ionosphere–thermosphere system, there is a strong interest for having an operational index based on ground magnetometers located near the equator. The SET–USGS team has created and is implementing a US-based real-time Dst index using ground-based magnetometers. It will be made publicly available in real-time through the USGS and mirrored by SET. The real-time data will be used to create both 1-h and 1-min Dst near-term forecasts for operational use while solar wind data will provide an estimate of longer-term Dst forecasts to be available through SET servers. The USGS Dst index is nearly identical to the Kyoto Dst (Fig. 8), the defacto world standard, but with improved reliability and accuracy along with higher cadence and lower latency. The real-time and forecast Dst index is an example of a distributed network that

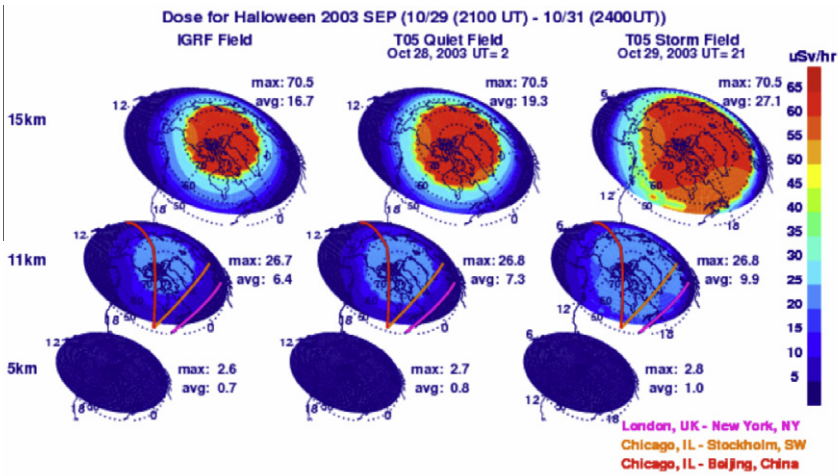


Fig. 7. NAIRAS dose at altitude during October 2003 storms from NASA LaRC and SET at http://www.spacewx.com "Products:RAPS" menu link. This figure shows example time and tropospheric altitude slices for the commercial aviation radiation environment due to SEPs.

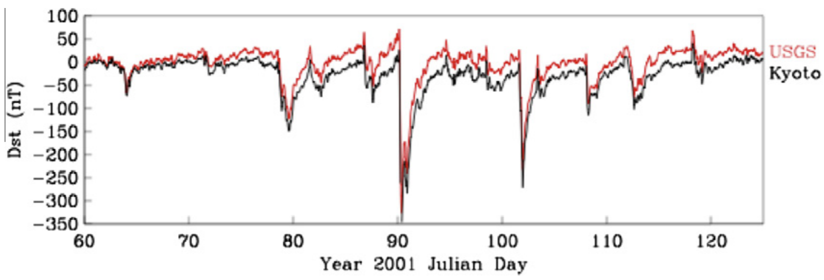


Fig. 8. MAPS (USGS Dst) comparison with Kyoto Dst and USGS at http://www.spacewx.com "Products:MAPS" menu link. This figure shows the comparison between the two data sets for the active storm period before and after the end of March 2001.

will be used for operational space weather support. End-users include commercial aviation for HF availability and for radiation environment, LEO satellite operators for orbit determination, and GEO commercial satellite operators for satellite charging environment specification. SET provides the Magnetosphere Alert and Prediction System (MAPS) site that highlights the USGS Dst at the http://www.spacewx.com "Products:MAPS" menu link.

3. Conclusion

The effects of space weather on space systems and assets must be mitigated and operational space weather using automated distributed networks has emerged as a common operations methodology. This is in part due to innovation by small businesses, universities, and the CCMC to overcome lack of agency funding for model transitioning to operations.

The evolution of space weather operations is described during the decade and a half since the inception of the National Space Weather Program. Distributed network architecture is described, including its use of four tiers (database, central server, client servers, customers), data objects, redundancy methods, and multiple time domains.

There are several existing distributed networks that now provide historical, real-time, and forecast space weather information. The lessons learned in developing those networks are discussed from the perspectives of stakeholder coordination, implementation, TRL classification, and supply chain organization and management. Examples and details of distributed network applications are provided for SET-related systems, including the Solar Irradiance Platform (SIP), Communication Alert and Prediction System (CAPS), GEO Alert and Prediction System (GAPS), LEO Alert and Prediction System (LAPS), Radiation Alert and Prediction System (RAPS), and Magnetosphere Alert and Prediction System (MAPS).

Acknowledgment

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