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# A Web of Sensors: Enabling the Earth Science Vision

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This paper expands a topic presented at the Institute of Electrical and Electronics Engineers' (IEEE) International Geosciences and Remote Sensing Symposium (IGARSS) at Toronto, Ontario, Canada in July 2002.

*Abstract*—**Highly coordinated observations and autonomous decision-making are needed to improve our ability to detect, monitor, and predict weather; climate; and the onset of certain natural hazards. The 'SensorWeb' concept has been proposed as a potential solution to this requirement. This paper presents two candidate uses for the concept, describes its capabilities and unique architectural properties, and outlines challenges to overcome for successful development of SensorWeb architectures. The conclusion proposes that the primary challenge to implementation of SensorWebs—beyond the obvious technical obstacles—will be our ability to develop and execute a long-term strategy that provides for the deployment of a series of compatible missions that deliver the full promise of envisioned SensorWeb capabilities.**
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## INTRODUCTION

Socio-economic benefits are a primary driver for the National Aeronautics and Space Administration (NASA) Earth Science (ES) Enterprise vision for the year 2025. Scientific knowledge and technologies that enable routine prediction of weather, climate, and prediction of the onset of certain natural hazards produce direct economic benefits to the public, industry, and to federal; state; and local governments.[1] Weather and climate forecasts provide advance indication of winds; temperature; precipitation; clouds; humidity; and air quality, and we depend on these data to plan our travel, tourism, and leisure and work activities on a daily basis. In addition, a large segment of our economy includes industries–such as farming, tourism, transportation, and gas; electric; and water utilities–that are affected by climate and thus rely on reliable forecasts to manage their short- and long-term operations. Likewise, information about the onset and severity of hurricanes, tornadoes, floods, droughts, thunder and winter storms, forest fires, earthquakes, and volcano eruptions would allow communities and government agencies to prepare for impending hazards and to manage relief efforts such that loss of life and property is mitigated and scarce resources are effectively utilized.

## VALUE OF SENSORWEBS FOR ES

The SensorWeb concept proposed by NASA defines a virtual organization of multiple numbers and types of sensors combined into an intelligent 'macro instrument' in which information collected by any one sensor can be used by any other sensor in the web, as necessary to accomplish a coordinated observing mission.[2,3] This web configuration allows inter-system collaboration not possible with stand-

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alone sensors and thus provides the foundation needed to develop systems capable of adaptive behaviors. As the technology matures, SensorWeb-observing systems could be combined with software 'agents' that perform real-time analysis and decision-making to implement advanced SensorWeb-enabled systems that autonomously execute complex adaptive observing strategies.[4]

Preliminary work in this emerging field suggests that autonomous SensorWebs have potential to improve the performance of weather and climate predictive systems such that the useful range of forecasts would be extended. Also, SensorWebs could perform focused observations needed to predict, detect, and monitor the development and effects of certain natural hazards. The value of SensorWeb capabilities in these predictive scenarios is illustrated by the two system concepts described below. The first example provides a brief introduction to a hazard mitigation decision-support system concept, whereas the second example describes in detail the structure and key functions of a weather-forecasting architecture concept.

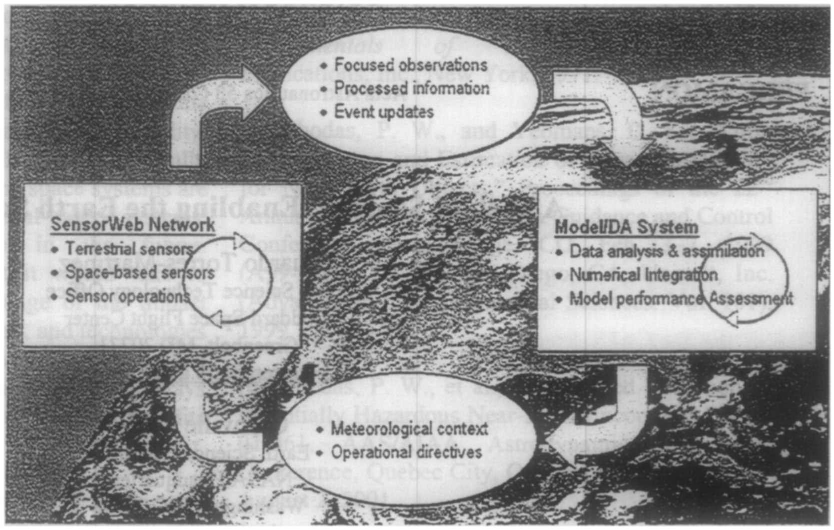


**Figure 1** - Illustrates key system functions and the data types exchanged by the Model/Data Analysis System and the SensorWeb Network to implement closed-loop operations. Data processing and real-time decision-making tasks must occur concurrently to enable fully autonomous operation of

## Hazard Prediction, Detection, and Monitoring

SensorWeb-enabled observations linked with predictive models could drive decision-support systems to provide reliable warnings of the onset of certain natural hazards. Additionally, such systems could perform monitoring of events to provide real-time updates needed to guide rescue and relief efforts in affected areas. A similar approach is being implemented by OK-FIRST, an existing decision-support system that gathers real-time data from Federal and State-wide sources via the Internet and presents it to Oklahoma-state officials who evaluate impending hazards and issue warnings.[6] Since its inception, OK-FIRST has allowed safety officials to take preemptive actions that saved lives.

SensorWeb-based warning systems could predict the likelihood of hazards; estimate the effects of events before they develop; and, when hazards occur, monitor their development to provide real-time updates. Such information would help communities make preparations and guide planners to take actions such as evacuations. A more advanced application would provide forecasts and real-time assessment of the accessibility of areas (e.g. condition of highways, bridges, and waterways) to help planners direct relief efforts that involve delivery of personnel, equipment, and supplies to affected areas.

## Advanced Weather Forecasting

Fundamental weather forecasting improvements could be achieved with an architecture that exploits the adaptive capabilities of the SensorWeb concept.[5] By introducing a feedback path between a Numerical Weather Prediction model and a SensorWeb-based observing system, *future observations* could be tailored to the specific data acquisition needs identified by the prediction model system. Figure 1 illustrates a top-level concept for a closed-loop system where a Model/Data Analysis and a SensorWeb Network exchange data and control information.

Within such architecture, platforms and individual sensors in the SensorWeb would have access to knowledge about what other sensors see, as well as access to information about probable future states of the atmosphere generated by the forecast model. We propose a SensorWeb system in which resides the intelligence to "understand" (and act upon) the meteorological context against which immediate and future observations are to be acquired and used. Such a system would have the ability to flexibly alter default observing scripts in response to observed meteorological change, to targets of opportunity encountered during otherwise routine observing periods, and to guidance from the ground-based modeling system. Individual platforms and instruments in the SensorWeb would autonomously alert other affected sensors spacecraft and the model to meteorologically significant developments.

The system envisioned would need to possess an unprecedented level of semi-autonomous intelligence, such that it would actually be able to formulate observation strategies, weigh options and priorities, and then direct the coordinated tasking of space-based platforms and instruments with guidance based on observational needs identified from a modeling system. Because it will be required to reconfigure itself flexibly and quickly in response to changing mission goals, within the observing system must reside on-board processing that affords a high degree of automated analysis and decision-making capability.

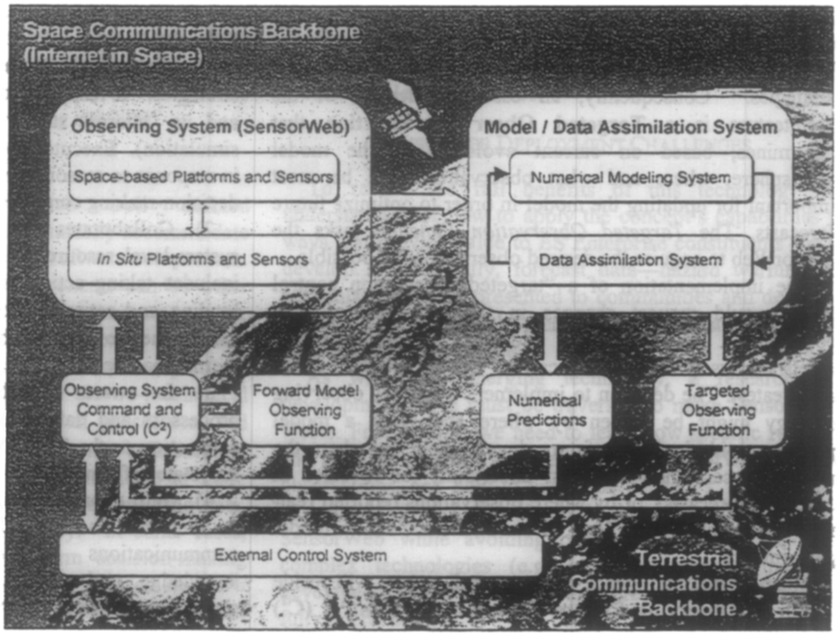


Figure 2 - The External Control System interacts through a seamless real-time communications grid to coordinate interactions between components of the Model and the SensorWeb Network and to enforce policies that govern the "behavior" of the overall system.

Figure 2 shows how the main functional elements of the notional architecture are partitioned and connected. In this concept, system communications would be carried via a high-speed global Earth-to-space network that would use "internet-like" protocols to provide flexibility and seamless operation.

The **Observing System (SensorWeb)** includes space-, airborne-, and ground-based sensors that collect in-situ and remotely-sensed data. The SensorWeb contributes to the near-real time operation of the architecture by automatically performing data processing tasks such as calibration, geo-location, quality-validation, and dissemination to appropriate users.

The *Observing System* must have the capacity to enable multi-temporal sampling and multi-angle viewing opportunities of the same location as needed to detect, confirm, interpret and retrieve certain types of geophysical measurements or processes. Such an *Observing System* must satisfy three functional requirements: First, it must reliably collect, process, and deliver routine global observations that the modeling system needs to produce operational forecasts. Second, it must be able to execute *ad hoc* measurement strategies in response to special needs identified by the modeling system. Finally, it must autonomously respond to needs identified by elements of the Observing System itself.

In addition to providing operational weather forecasts, the **Model / Data Assimilation System (MDAS)** provides the SensorWeb with predictions of what individual platforms (both ground- and space-based) and/or sensors should anticipate at a given time and place during their observing period. Based on ensemble predictions and theoretically-based assessment of optimal future observational needs, the MDAS will able to request behavioral changes within the *Observing System* and among observational network elements. The MDAS would request specific *targeted*, observations whose assimilation would be most likely to improve model depiction and forecasts. Additionally, model predictions will be compared with observations from the Observing System in near real time, and in response to such real-time feedback from the SensorWeb, the model may automatically reconfigure itself, for example by modifying parameterizations, or by adapting its grid resolution in order to better capture what has been actually observed.

Given that differences between the model and observations—whether viewed in geophysical parameter space or a radiance space—are what ultimately get assimilated into the model, an explicit **Forward Model Observing Function** will facilitate an apples-to-apples comparison of what a given sensor observes relative to model predicted geophysical parameters. The *Forward Model Observing Function* would serve to transform MDAS forecast atmosphere into model forecasts of SensorWeb observations that each sensor on each platform should expect to see in its native sensor format throughout its assigned observation period. This includes transforming model data to match various parameter space (e.g. radiance) and sensor viewing geometries. These model data delivered to the platform will be for change detection, quality control or for providing first guess information for on-board geophysical retrieval.

For this conceptual approach to be effective, the proposed architecture must be especially suited to autonomous generation and implementation of targeted observing strategies. Consequently, an essential element of the architecture is a **Targeted Observing Function** that determines, based on current evolution of the model atmosphere, where and what observations will be most important for updating the model in order to optimize future forecasts. The *Targeted Observation Function* tasks the SensorWeb to acquire the desired observations, if possible.

The implementation of a "targeted observation control loop" would request changes in the schedules of data collections to engage additional complementary assets/sensors to observe at locations where perceived needs are greatest. The decision to implement a specific observing strategy might be driven by where and when a model predicts rapid significant future development, by where the model forecast shows greatest uncertainty (as revealed in ensemble forecasts), or by where observations reported real-time from the SensorWeb reveal deficiencies in model performance.

Much of the intelligence of the overall system will reside within an **Observing System Command & Control ($C^2$)** that will coordinate communications among system-wide sensors and between modeling and observing systems. The $C^2$ component autonomously negotiates conflicting demands on system resources based on pre-programmed policies and priorities. It manages and directs all Sensor Web assets based on inputs from the MDAS, from other users, and from the SensorWeb itself. $C^2$ monitors the quality of the data that is being returned by the Sensor Web and automatically schedules additional or corroborating observations that might be needed. Taking into account specific observing requests (whether initiated by the *Targeted Observing Function* or within the SensorWeb), and with knowledge of the future disposition and availability of various observing assets, the $C^2$ decides what each sensor should measure in future observing periods.

An **External Control System (ECS)** performs regulatory functions. It provides the interfaces for humans in the loop, implements security, and provides overall monitoring and control for the combined observing and modeling systems. It governs the implementation of human-directed policy regarding operation, prioritization and allocation of system resources.

## SensorWeb Capabilities

The examples described above are notional observing scenarios where SensorWeb capabilities would enable a unique set of observing behaviors. From a technology-development perspective, knowledge of distinctive system capabilities is the first step towards defining the range of science and technology advancements needed to implement SensorWeb architectures. According to proposed ES Vision scenarios, an advanced SensorWeb system would display the following behaviors:

1) Autonomously implements interactive observing strategies. It responds to changes in both the phenomenon and its 'internal state' (e.g. as depicted within a model simulation). Executes opportunistic and routine observations in response to seasonal or event triggers, or when directed by decision-making components of the observing system.

2) Collaborates at the subsystem level to manage system-level resources and its overall configuration. This includes taking actions such as reconfiguration, temporary binding and retirement of assets, allocation of bandwidth, management of consumables, and maintenance of power and thermal balance.

3) Is aware of what sensors and resources (e.g. processors and databases) are connected, or available for connection to the SensorWeb. Further, it has knowledge of the 'state' of connected assets and can direct them.

4) Will dynamically acquire unique resources as needed to perform tasks. This could be processor time, communications bandwidth, archived data sets or knowledge, and sensors. In addition, it can initiate the generation of data products needed to perform decision-making tasks.

5) Performs secondary system tasks unattended by humans. This includes navigation, formation flying and maneuvering, enforcement of system constraints, self-maintenance (e.g. graceful degradation and repairs), and safing.

## Unique Architectural Properties

The basic infrastructure needed for a notional SensorWeb architecture (e.g. autonomy, collaboration, and distributed assets) has already been prescribed for formation-flying systems.[4] However, SensorWebs expand the formation-flying concept to include unique properties as described below.

### Autonomy

The goal of autonomy is to enable systems that operate without human intervention for extended periods in dynamic environments.[7] Such an environment is characterized by uncertainty, which can be systemic (e.g. component failures) or environmental (e.g. changes in the phenomenon). For both cases, the fundamental requirement is complex decision making without human intervention. In formation-flying architectures, automation is applied to implement planning and scheduling based on high-level goals, and to perform ancillary system functions.[4] *The SensorWeb architecture duplicates these functions but adds an additional requirement: to enable decisions that involve selecting one of several possible high-level goals.* This property applies to SensorWeb systems with assets that can be used to generate more than one data set (i.e. research or applications measurements). The 'intelligence' capability of advanced SensorWebs must deal with uncertainty, react adaptively to changing circumstances, but most importantly, must recognize and exploit opportunities to apply its resources to alternative top-level goals while avoiding conflicts.

### Heterogeneity

Formation flying systems have well defined configurations; SensorWebs must dynamically accommodate a diverse combination of hardware and software components. At the macroscopic level, these components can be other SensorWebs or platforms that host instruments on the ground; sea; air; and space. At the microscopic level they are a wide variety of subsystems such as detectors, platform sensors and actuators, auxiliary electro-mechanical subsystems, embedded analog and digital processors, and control and data processing software.[4] System collaboration requires that assets and components communicate to share information that may include science and engineering data, data products, commands, and telemetry. In some cases, data fusion will be required to perform decision-making tasks. *The SensorWeb architecture must provide standard languages, policies, and protocols that enable transparent communication within and across layers of a system, as well as across systems.*

### Scalability

Unlike typical formation-flying designs, SensorWebs are by definition dynamic structures (e.g. additional wind-measurement platforms may be added only during hurricane season). *The SensorWeb architecture must support incremental addition and retirement of assets while providing commensurate levels of functional performance.* Scalability enables the system to expand or contract with consistency and provides the flexibility needed for dynamic reconfiguration of the web (e.g. attach and release assets on a permanent or temporary basis). In addition to new sensors, assets may include processing or communications components that can be shared to enhance the performance of the system.

### Human-Interface Consistency

Significant human-interface issues must be resolved, most likely by extensive use of visualizations. *The challenge is to develop a human interface that provides a consistent picture across all layers and components of the architecture; some that are physical (e.g. inter-platform data paths), others logical (e.g. collective behavior of assets in response to decision making).* The architecture's interface must decompose the complexity of the system while providing human operators with a consistent view that integrates the reasoning layers, inter-system interactions, and system components down to the subsystem level. In addition, the interface's rendition must be dynamic so that it maintains and presents to the operators a view that reflects the web's configuration. These interface properties are crucial for circumstances that require humans to diagnose and resolve system problems or failures.

## SensorWeb Deployment Challenges

To realize the full benefits of this technology our understanding of how to apply the concept's capabilities in ways that provide value to ES Enterprise constituents has to develop. Specifically, forecast data—hazard warnings in particular—must be presented to communities and decision-makers in ways that help them use the information correctly to generate positive value.

As with any emerging technology, a research and development curve must be traversed to make SensorWebs viable. For instance, we need to learn how specific research and application areas will benefit from SensorWeb-enabled observations, and how to apply the concept's 'intelligence' to optimize various observing tasks that can be shared by one SensorWeb while avoiding conflicts. Finally, the most complex technologies (e.g. intelligent agents) must be developed and proven before they are adopted and become fully operational.

Advanced capabilities such as autonomy and inter-system collaboration require compatibility of components at all levels. As such, successful development of technologies needed to implement SensorWeb architectures would benefit from an integrated systems approach that coordinates the development of architecture-related standards and components across technical disciplines.

Construction of SensorWeb systems will require incremental deployment of assets that serve a stand-alone purpose when deployed and can be subsequently connected to the web by an intelligence layer. On a grand scale, SensorWeb networks could involve the use of inter-agency and international platforms that are shared to collaborate for certain tasks. International participation will require deliberation of topics related to inter-operability standards, intellectual property rights, and technology transfer. Such topics will emerge as we begin to jointly develop the highly integrated systems needed for autonomous collaboration.

## Conclusion

The deployment challenges presented above suggest that to successfully develop SensorWeb systems, NASA must craft and execute a strategy that defines a *long-term systems migration pathway* that allows incremental deployment of ground and space assets across the full range of SensorWeb-capable ES missions. At the technical level this will include developments such as new standards that ensure scalability and homogeneity of the architecture. For the programmatic level this could involve a review of how well our current mission planning, selection, and procurement practices could support this new approach. Finally, at the inter-agency and international level, this will require new levels of commitment for long-term collaboration from all parties.


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