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Sensor Web for Spatio-Temporal Monitoring of a Hydrological Environment. K.A. Delin[1], S.P. Jackson[1], D.W. Johnson[1], S.C. Burleigh[1], R.R. Woodrow[1], M. McAuley[1], J.T. Britton[1], J.M. Dohm[2], T.P.A. Ferré[2], Felipe Ip[2], D.F. Rucker[2], V.R. Baker[2,3] [1]Jet Propulsion Laboratory, M/S 306-336, 4800 Oak Grove Drive, Pasadena, California 91109-8099 (kevin.delin@jpl.nasa.gov), [2]Dept. of Hydrology and Water Resources, University of Arizona, Tucson, AZ 85721, [3]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721.

Introduction: The Sensor Web[1,2] is a macro-instrument concept that allows for the spatio-temporal understanding of an environment through coordinated efforts between multiple numbers and types of sensing platforms, including, in its most general form, both orbital and terrestrial and both fixed and mobile. Each of these platforms, or pods, communicates within its local neighborhood and thus distributes information to the instrument as a whole. The result of sharing and continual processing of this information among all the Sensor Web elements will result in an information flow and a global perception of and reactive capability to the environment. As illustrated in Figure 1, the Sensor Web concept also allows for the recursive notion of a "web of webs" with individual distributed instruments possibly playing the role of a single node point on a larger Sensor Web instrument.

In particular, the fusion of inexpensive, yet sophisticated, commercial technology from both the computation and telecommunication revolutions has enabled the development of practical, fielded, and embedded *in situ* systems that have been the focus of the NASA/JPL Sensor Webs Project (http://sensorwebs.jpl.nasa.gov/). These Sensor Webs are complete systems consisting of not only the pod elements that wirelessly communicate among themselves, but also interfacing and archiving software that allows for easy use by the end-user. Previous successful deployments have included environments as diverse as coastal regions, Antarctica, and desert areas[3]. The Sensor Web has broad implications for Earth and planetary science and will revolutionize the way experiments and missions are conceived and performed.

As part of our current efforts to develop a macro-intelligence within the system, we have deployed a Sensor Web at the Central Avra Valley Storage and Recovery Project (CAVSARP) facility located west of Tucson, AZ. This particular site was selected because it is ideal for studying spatio-temporal phenomena and for providing a test site for more sophisticated hydrological studies in the future.

Deployment: The CAVSARP site includes more than 10 recharge basins that are aligned parallel to one another (Figure 2). The berm heights, which form the margins of the basin, range between approximately 4.5 ft and 7 ft, allowing a maximum water level of approximately 7 ft along the northern berm. The facility provides controlled conditions of soil moisture, from dry (very low moisture) to inundation.

As shown in Figures 2 and 3, the Sensor Web system deployed consists of 16 self-contained, battery-powered pods equipped with solar panels for augmented energy harvesting. All pods have ambient air temperature and relative humidity sensors, as well as light level sensors. In addition, the pods deployed inside the recharge basin are equipped with a soil temperature sensor and two gypsum-style soil moisture sensors, one buried just below the surface and the second

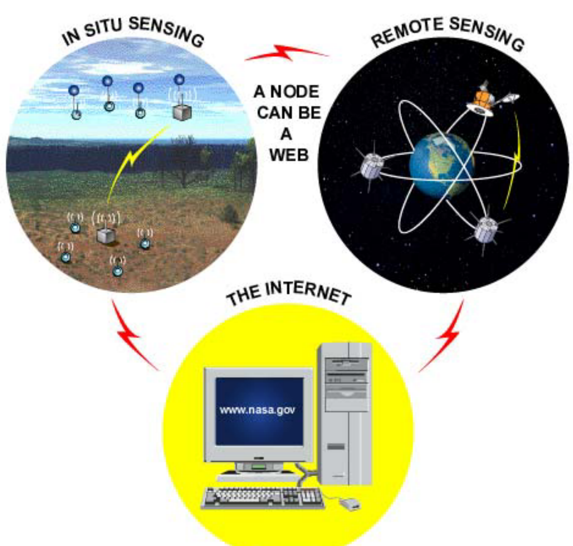

Figure 1: Generalized concept of the Sensor Web, including both orbital and terrestrial platforms.

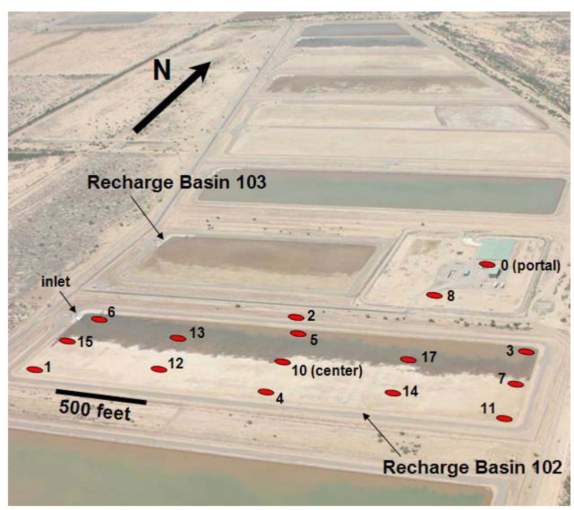

Figure 2: Oblique aerial photograph showing the location of the individual pods of the Sensor Web system at CAVSARP. The portal pod 0 is connected to a local server for Internet access.

buried at a depth of 0.5 m. These soil sensors are attached to the pods via long leads, which allows the pods to stay above water during flood events. (While the pods themselves are water-tight, pod-to-pod radio communication would not be possible if they were submerged.)

The Sensor Web was deployed and activated on November 13, 2003. The deployment topology was determined by the scientific nature of the study and not limited by technology considerations such as radio range. While the Sensor Web is designed to move information pod-to-pod via a hopping algorithm, little hopping was required in this deployment owing to the dense pod placement. Data is taken and transferred around the entire distributed system every five minutes and can be viewed via standard Internet browsers at http://cavsarp.ci.tucson.az.us/webgui.

Implications: Flooding events within the recharge basin are an ideal way to show the ability of the Sensor Web to display changing conditions in both space and time. Figure 4 shows a real-time data stream from the Sensor Web system that includes both soil temperature (surface) and moisture (both at the surface and at 0.5 m depth). During controlled flooding events, for example, it is possible to watch the water spread both laterally across the basin from the inlet point in the northwest corner, as well as infiltrate into the ground. Drainage shows the opposite pattern with the south side of the basin drying out first.

The well-controlled nature of this environment, coupled with the robust Sensor Web system, allows for us to begin our program of having the sensed data interpreted on-the-fly within the Sensor Web. The significance of the Sensor Web system from a hydrological standpoint is that phenomena such as flooding can be mapped and assessed in real time over a broad region, which includes the direction of a moving flood front, rather than a collection of individual soil moisture readings. This development will fulfill the Sensor Web's true potential as an intelligent, distributed instrument with both terrestrial and extraterrestrial applications.

References: [1] Delin, *et al.* (1999) *NASA Tech Briefs* **23**, 80. [2] Delin (2002) *Sensors* **2**, 270-285. [3] Delin, *et al.* (2003) *Space Mission Challenges for Information Technology*, Pasadena, CA.

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Figure 3: NASA/JPL team members deploy a Sensor Web pod in recharge basin 102. Extended stands allow the pods to stay operational (above water) during a basin flooding event.

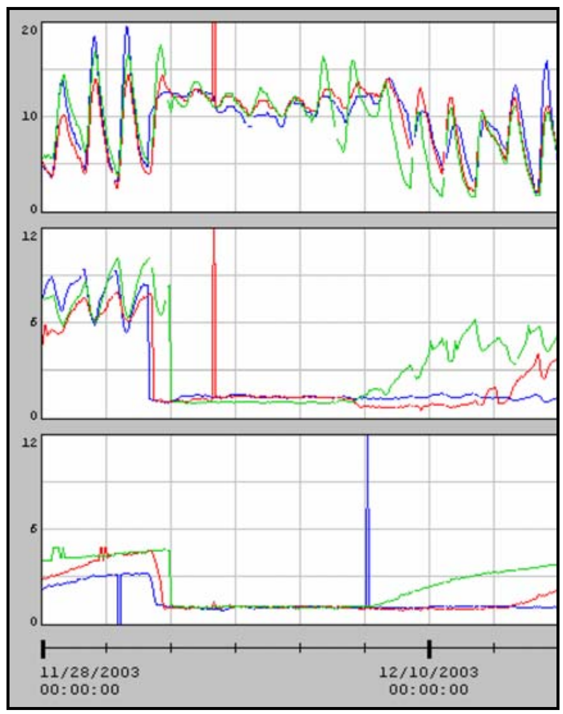

Figure 4: Screen-capture of Internet data from CAVSARP facility. Graphs (top to bottom): surface temperature (°C), surface moisture, and soil moisture at 0.5 m depth (relative units; lower values imply wetter soil). Diurnal cycles in moisture measurements are artifacts and can be corrected with local temperature. Sensor Web pod 6 (inlet) is in blue, pod 10 (basin center) in red, pod 11 (diagonal corner) in green (Sensor Web pod locations indicated in Figure 2). Note direction of inundation can be determined and that the basin dries out in reverse order of flooding. Data correlates with water discharge into basin, inundation, infiltration, drying, and the beginning of another cycle.