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Autonomous Flood Sensorweb: Multi-Sensor Rapid Response and Early Flood Detection

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Abstract: Extreme floods have been reported to be more frequent partly due to global warming. As such, the necessity for timely detection and mapping of floods is increasingly important in order to protect lives and livelihoods. Floods affect large regions of the Earth and cannot be reliably predicted. Hydrological data from in-situ sensors are sparse and cannot map the full extent of flooding. The use of satellite-based information for assessing floods is not new. However, the problem with satellite remote sensing historically has been both the large areas affected and obtaining timely ground-based reception of satellite data. The Autonomous Sciencecraft Experiment (ASE) experiment overcomes the data size and downlink problems. For flood processes, the ASE includes a satellite-based floodwater classification algorithm (ASE_FLOOD), which reliably detects flooding as it occurs and autonomously triggers further image acquisition to map and track flood changes through time. In addition, the ASE enables more effective and timely monitoring for other dynamic transient events on Earth, which include volcanic eruptions and sea ice breakups. The Flood Sensorweb is an extension of ASE and serves to link different remote sensing assets obtained at different spatial and temporal resolutions for flood detection and monitoring. It is a demonstration in which Dartmouth Flood Observatory's Water Surface Watch (a satellite-based global runoff monitoring system) alerts ASE operations of sites where there is potential flooding. Based on these alerts, ASE autonomously retargets NASA's EO-1 spacecraft to verify flooding conditions at these sites, thereafter acquiring local high-resolution images of these flooded areas. The Flood Sensorweb offers an important asset for the study of transient hydrological phenomena globally, especially at remote locations. The use of autonomous change detection, triggering the needed local high-resolution imaging by automatic systems, provides the critical near real-time data needed for early detection and modeling of seasonal and extreme floods.

Keywords*:* flood detection, near real-time, flood mapping; flood monitoring; spacecraft autonomy; flood sensorweb

1. INTRODUCTION

Because of its devastating nature, flooding poses serious hazards to lives and livelihoods in many parts of the world. According to the Federal Emergency Management Agency (FEMA) of the United States, flooding is one of the most common and widespread of all natural disasters. The economic damages from floods have increased considerably in the last 30 years. For example, it cost the United States $2.4 billions in 2003 (http://www.flooddamagedata.org/national.html). Floods, which affect large regions of the Earth, cannot be reliably predicted. In addition, hydrological data from in-situ sensors are sparse and cannot map the full extent of flooding.

Remote sensing technologies have been used to study flooding for the last 2 decades [Brakenridge et.al, 2003a, 2003b]. Some of the advantages of remote sensing include its near-global and frequent-repeat coverage of large spatial extent (e.g., 1km-AVHRR and 25km-QuikSCAT/RadarSat and twice-daily-repeat MODIS and once-per-16 days EO-1, respectively). Main disadvantages have been cloud cover (especially for optical sensors), the large datasets associated with satellite imagery, low sensor spatial resolution in many case (e.g. 250m-MODIS), lack of timeliness (slow and infrequent satellite-to-ground data downlink, especially in a case of a transient event such as a flood), and complicated processing (e.g., sensor-specific processing requirements).

In the case of flooding, aside from adequate spectral resolution for good land/water separation, different spatial and temporal resolution imagery data are required for specific purposes such as flood detection and monitoring and related damage assessment. For example, high temporal resolution data are required for the early detection of flooding. Dartmouth Flood Observatory (DFO) has demonstrated that the high temporal resolution MODIS instrument (twice daily repeat cycle) with moderate spatial resolution (250m/pixel) is adequate for flood detection [Brakenridge and Anderson, 2005]. However, to delineate the extent of flood inundation, high-spatial resolution imagery (e.g., 30- to 120-m/pixel) is required. The high-resolution imager, HYPERION (30m/pixel), for example, is a useful instrument on the EO-1 spacecraft for mapping the extent of flooding, but is limited with respect to the detection and monitoring of dynamic flood processes because of its low temporal resolution (once every 16 days). Generally, most high-spatial resolution sensors have a low-temporal resolution (typically once every 16 days) due to their flight operation configurations.

Finally, for flood damage assessment, timely high-resolution images are required to detect, monitor, and assess flood events. As a result, it is necessary to combine the two types of satellite imagery. (1) Wide-area, low-spatial, high-temporal data are used to monitor large areas for signs of flooding conditions. (2) In the event of a detected flood, high-spatial but low-temporal sensors are triggered to zoom in and acquire images of areas that are most severely flooded. In addition, the Type 2 sensors must take images from several orbital passes to cover the full extent of the flooded areas because of their narrow imaging swaths. Alternatively, they must produce a composite of images from different sensors. With the combination of sensors, we are able to obtain image data during early flood stages, as well as track the progress and spatial extent of flooding. One challenge has been how to link the different sensors together effectively to achieve this. Here, we present Flood Sensorweb as an innovative solution of detecting and mapping flooding through the linkage of spaceborne and ground-based sensors at varying spatial, temporal and spectral resolutions, and the implications on providing near real time information for flood modeling and mitigation.

2. ASE EXTENDED EFFORT- FLOOD SENSORWEB

The Autonomous Sciencecraft Experiment (ASE) [Chien et. al, 2005] project has reached its primary objectives of both autonomous control of the Earth-orbiting EO-1 spacecraft and spaceborne identification of transient processes such as flooding in near real time [Ip et al., 2006]. The satellite-based floodwater classification algorithm, ASE_FLOOD, has been demonstrated to reliably detect flooding and trigger further data acquisition of the floodwater conditions. Fig. 1 shows an example from an earlier ASE experiment where a detected flood-condition on Brahmaputra triggered a response datatake of the same river 2 days later indicating a progressing flood. The algorithm is able to detect and map the extent of flooding, as well as track its progress without any human intervention or prior knowledge.

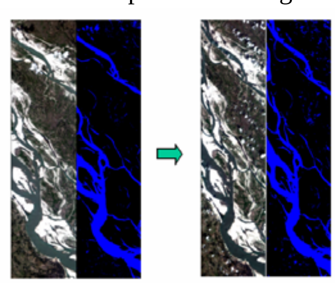

Fig. 1. Results from earlier ASE experiments. Flooding along the Brahmaputra River near Sirajganj Bangladesh on 1/31/05 triggered a

second data acquisition on 2/2/05 (Note: the trigger threshold based on a 1024x256-pixel-area were cloud<50% and water>4.24% or 11115 pixels; the first Brahmaputra scene has a total of 46818 classified water pixels, which exceeded the threshold, thus, triggered the second data acquisition. The second image has 55239 water pixels, indicative of a progressing flood) [Ip et.al, 2006]

The next step will be to integrate ASE_FLOOD with other observational platforms to enhance the capability of flood detection, thereby providing valuable information for flood modeling (including forecasting and mitigation). Though ASE_FLOOD is still evolving, here we show how ASE is being integrated with the Dartmouth Flood Observatory Flood Alert system to form an interactive automated Flood Sensorweb network.

DFO's Flood Alert data (derived from remote sensing sources such as the QuikSCAT, AMSR-E, TRMM, MODIS) alert ASE of locations of potential flooding. The alerts are then inserted into the ASE software flying on EO-1, thereby directing the HYPERION and Advanced Land Imager (ALI) sensors to acquire high-resolution images (30m-hyperspectral and 10m-PAN) at these locations to determine whether flooding is transpiring. If significant flooding is detected, then ASE continues to monitor and map the flood until it subsides.

3. RESULTS

As of early 2006, the Flood Sensorweb has been successful in acquiring images of major rivers triggered by DFO (Table 1). A typical ASE Flood Sensorweb scenario includes the following steps:

1) ASE receives a DFO Flood Alert text file indicating the location (lat/long) of an active flood (new target area). [http://www.dartmouth.edu/~floods/AMSR-E%20Gaging%20Reaches/Summary.htm]
2) ASE responds by autonomously rescheduling EO-1's HYPERION and ALI sensors to take images in and around the new target at the next available orbital passes.
3) ASE takes the first image of the target and analyzes it for significant flood conditions and decides autonomously whether to continue monitoring.
4) If there is significant flooding, ASE re-prioritizes the satellite's resources and retargets its sensors to continue taking images in and around the flooded area. Additional images may cover the original targeted area and/or a new flood-affected area (e.g., downstream and river floodplain). The goal is to have an adequate number of images to cover the full extent of flooding while tracking the flood progress.
5) ASE stops monitoring the area when there is no significant flooding (from pre-determined thresholds).

Below are some of the EO-1 datatakes acquired by the Flood Sensorweb and triggered from flood alerts issued by DFO:

Table 1. List of ASE Flood Sensorweb replacement scenes (Year-doy/hh:mm:ss Location)

2006-036/03:08:36 Lena
2006-036/08:27:21 Zambezi (2/5/06)
2006-036/015438 Fortescue
2006-036/16:28:12-Mississippi
2006-037/04:01:03 Chindwin burma (2/6/06)
2006-037/18:45:23 Sacramento (2/6/06)
2006-038/01:36:11 Fitzroy
2006-038/13:05:35 Sao Francisco
2006-039/03:43:58 Chindwin burma
2006-039/03:45:10 Irrawaddy (2/8/06)
2006-041/06:33:34 Ob (ice-covered)
2006-042/04:07:29 Mu
2006-042/05:44:14 Indus1 (2/11/06)
2006-042/07:17:23 Volga
2006-042/09:07:09 Logone
2006-043/04:47:24 Sapt Kosi Nepal (2/13/06)
2006-043/06:16:28 Ob (ice-covered)
2006-043/16:21:21 Polochic
2006-044/07:05:36 Tigris
2006-044/10:27:21 Niger
2006-045/05:59:24 Huainan Honghe
2006-045/09:20:12 TiszaTiszanana
2006-047/04:13:01 Bihar Ganges
2006-049/03:55:12 Irrawaddy (2/18/06)
2006-049/05:32:04 Indus1 (2/18/06)
2006-049/18:39:04 Sacramento (2/18/06)
2006-050/12:59:02 Sao Francisco
2006-053/08:25:58 Zambezi (2/22/06)
2006-053/16:24:50 Wabash
2006-055/04:39:25 Sapt Kosi Nepal

For instance, on 2/10/06 (day of year 041) ASE received a DFO flood alert for the Sapt Kosi area in Nepal. ASE responded autonomously by reallocating EO-1's image acquisition schedule, and retargeting its sensors to acquire images of the area on the next available orbital pass (2/13/06). The ASE response was in the form of "The following replacement scene has been queued for uplink: Sapt Kosi Nepal [SW/W2] JPL 2006-043/04:47:27 750 25.9498 86.468 [DFO]". A replacement scene takes priority over any image scene that is already on the satellite's data acquisition queue. In the case of Sapt Kosi Nepal, a SW (Sensorweb) image acquisition with view angle W2 (west 2) of Sapt Kosi Nepal (lat 25.9498 long 86.468) was alerted by DFO and ASE responded by inserting (replacing if necessary) the image datatake on 2006-043 at 04:47:27 hours. On day 043, EO-1, controlled by ASE, acquired images (HYPERION and ALI) of the area, and the onboard algorithm ASE_FLOOD analyzed them to verify the flooding conditions. The images and resulting statistics of Sapt Kosi are shown in Figs. 2A-D. Even though the classified image statistics indicated normal flow conditions on both days, we can still see how HYPERION and ALI image data at different spatial and spectral resolutions complement each other. HYPERION's high spectral resolution allows good water/land discrimination while ALI's wide-area coverage allows mapping the full extent of flooding.

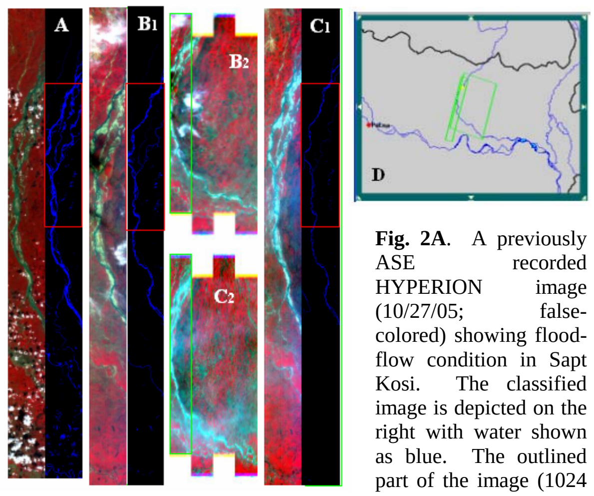

Fig. 2A. A previously recorded ASE HYPERION image (10/27/05; false-colored) showing flood-flow condition in Sapt Kosi. The classified image is depicted on the right with water shown as blue. The outlined part of the image (1024 x 256 pixels) highlighted in red has a total of 32046 water pixels, which is used for change detection. **Fig. 2B.** A HYPERION (B_1) image taken on 2006-033 by the ASE Flood Sensorweb showing normal flow conditions at Sapt Kosi. The outlined part of the image has a total of 17633 water pixels (nearly half that classified in the previous example of Fig. 2A). Because of the non-flood condition detected by ASE, no further datatakes of the area was scheduled. The adjacent ALI (B_2) image taken during the same period shows the downstream condition of the river. The green box outlines corresponding area between the HYPERION and the ALI images. In the false-colored image, the cyan color depicts the exposed riverbeds and is not to be mistaken with the dark-colored sediment-laden river water. **Fig. 2C.** A HYPERION (C_1) image taken on 2006-043 (2/13/06) by the ASE Flood Sensorweb showing another normal-flow condition in Sapt Kosi. The sub-image has a total of 8185 water pixels. The adjacent ALI (C_2) image shows the downstream condition of the river. The green box outlines corresponding area between the HYPERION and the ALI images. **Fig. 3D.** Map showing the corresponding footprints of the HYPERION and the ALI images taken on 2006-043.

Other Flood Sensorweb replacement scenes included the Indus River on 2/11/06 and 2/18/06, the Irrawaddy River on 2/8/06 and 2/18/06, and the Zambezi River on 2/5/06 and 2/22/06 (see Table 1).

4. CONCLUSIONS AND IMPLICATIONS

The Flood Sensorweb has been demonstrated to be effective in autonomous rapid flood response by linking ground- and space-based instruments. In many cases, it can be triggered via a variety of sources (in this case a ground-based DFO Flood alert, which is in turn dependent upon a variety of space-based information).

During our experiment, we were able to capture pre-, peak-, and post-flood flow conditions of major rivers. This information can be readily coupled with any existing flood model to improve our understanding of flooding and flood mitigation. For example, an ASE-derived flood inundation map may be combined with topographic information to derive water levels, which then can be input into a flood model in order to map the full extent of flooding along a river system [Miyamoto et. al, 2006]. Some sensors detect flow changes, while others map where and when such changes are occurring.

Detecting floods as they appear and tracking their evolution provide not only early warnings of potentially hazardous conditions, but also improved understanding of flood evolution. Other autonomous Sensorwebs [Chien et. al, 2005b] that are in progress include those involved in detecting volcanic eruptions [Davies et. al, 2006] and ice breakups (Fig. 3). ASE has flown on EO-1 as the primary mission operations since November 2004.

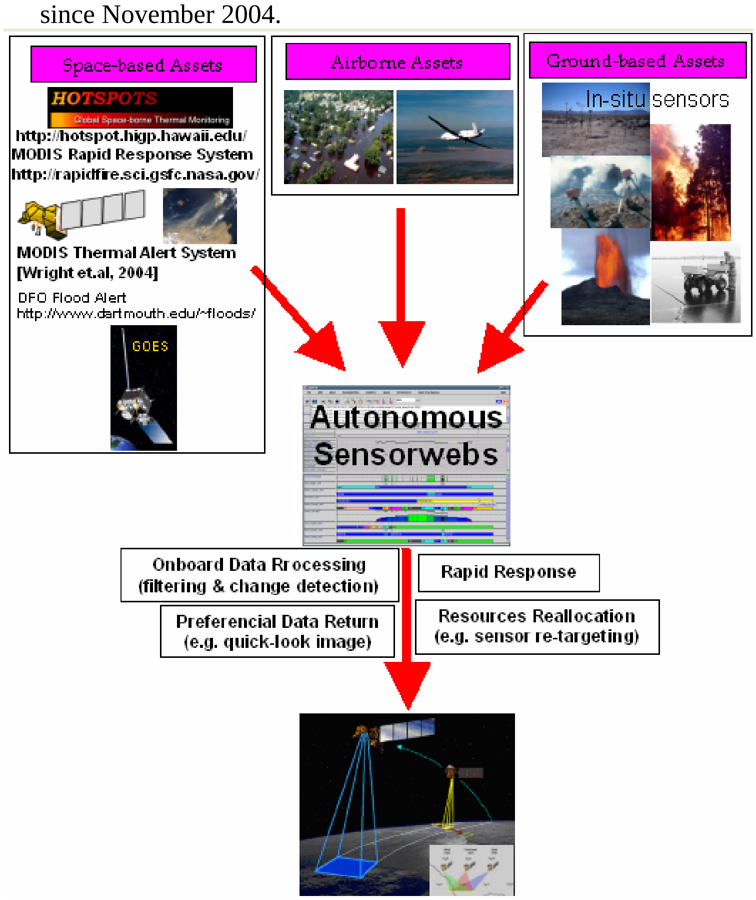

Figure 3. Concepts and data flow in autonomous Sensorwebs involving sensors and triggers from multiple land-, air- and space-based remote sensing assets.

5. ACKNOWLEDGEMENTS

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