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Unlocking the full potential of Earth observation during the 2015 Texas flood disaster

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Abstract Intense rainfall during late April and early May 2015 in Texas and Oklahoma led to widespread and sustained flooding in several river basins. Texas state agencies relevant to emergency response were activated when severe weather then ensued for 6 weeks from 8 May until 19 June following Tropical Storm Bill. An international team of scientists and flood response experts assembled and collaborated with decision-making authorities for user-driven high-resolution satellite acquisitions over the most critical areas; while experimental automated flood mapping techniques provided daily ongoing monitoring. This allowed mapping of flood inundation from an unprecedented number of spaceborne and airborne images. In fact, a total of 27,174 images have been ingested to the USGS Hazards Data Distribution System (HDDS) Explorer, except for the SAR images used. Based on the Texas flood use case, we describe the success of this effort as well as the limitations in fulfilling the needs of the decision-makers, and reflect upon these. In order to unlock the full potential for Earth observation data in flood disaster response, we suggest in a call for action (i) stronger collaboration from the onset between agencies, product developers, and decision-makers; (ii) quantification of uncertainties when combining data from different sources in order to augment information content; (iii) include a default role for the end-user in satellite acquisition planning; and (iv) proactive assimilation of methodologies and tools into the mandated agencies.

1. Challenges

1.1. Delivering Actionable Information

An increasing abundance of remotely sensed data, from satellite and airborne sensors, as well as other types of geospatial data can describe and quantify major flood events. New and ongoing Earth-observing missions are now providing a large, near-real time quantity of valuable, globally consistent and coherent geospatial data that can potentially deliver accurate information at the appropriate temporal and spatial resolution for disaster management and emergency response. Such data span most of the natural life-cycle of a flood event, from initiation though to peak inundation, and then eventual waning and drying to states resembling preflood conditions. Time scales vary from a few days to a few months.

The recently launched GPM, SMAP, GCOM-w, and SMOS missions provide useful information concerning precipitation and soil moisture and also surface water conditions. Satellites and sensors such as MODIS, Landsat, EO-1, Sentinel, TerraSAR-X, and COSMO-SkyMed can document regional floodplain inundation, and commercially operated very high resolution sensors from the air and space (e.g., WorldView and GeoEye satellites operated by DigitalGlobe) provide cadastral-level data including damage assessment capability; note that the latter has also been demonstrated with high-resolution satellite SAR sensors (http://www.jpl.nasa.gov/spaceimages/details.php?id=PIA17687), such as COSMO-SkyMed, TerraSAR-X, and Radarsat-2. Figure 1

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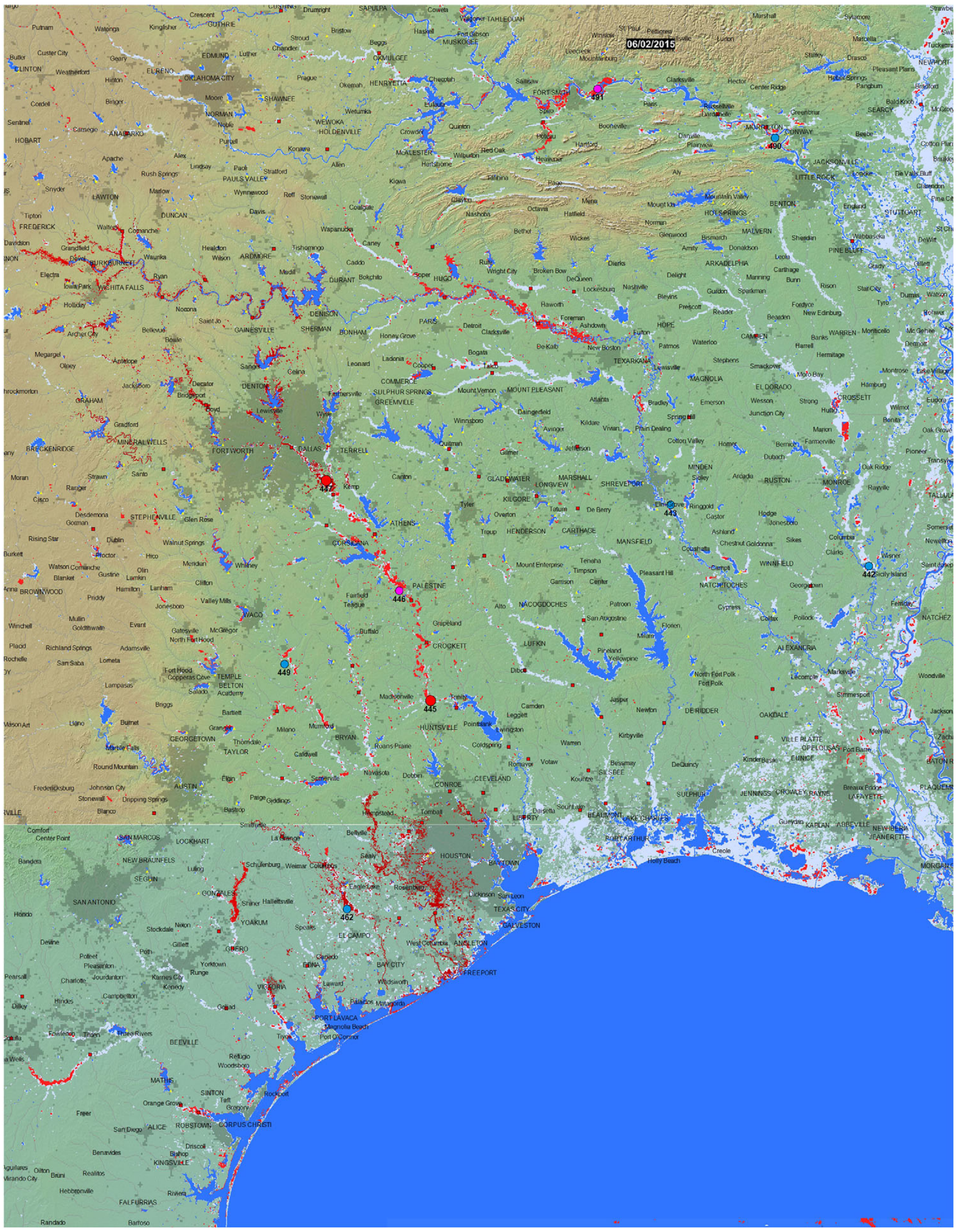

Figure 1. Composite flood map put together in real-time during the recent Texas flood disaster using only satellite observations. This particular map was generated by the Dartmouth Flood Observatory (DFO) from individual flood maps produced by DFO (MODIS (2X daily at 250 m resolution), EO-1 (four images at 30 m resolution), Landsat 7/8 (50+ images at 30 m resolution)) and LIST (CSK (10 images at variable resolutions, 30 m in wide swath) and Sentinel-1(5 images at variable resolutions)) and shows rivers in flood and maximum flood extent for Texas, Oklahoma, and Arkansas up to 6 June. (Red: flooding within past 14 days, includes MODIS automated product. Light red: flooded during this event, from earlier MODIS coverage or nonautomated MODIS mapping, now dry land. Darker red: flooded areas from high-resolution Sentinel 1, Cosmo-SkyMed (radar sensors) or Landsat or EO-1 data. Dark blue: permanent water, February, 2000 (SWBD). Very light blue: all flooding mapped by DFO since 2000.) See *Brakenridge et al.* [2015] for full details and a higher-resolution version of this map. Note that many snapshots of aerial photos are available for free through USGS HDDS (http://hddsexplorer.usgs.gov).

illustrates flood maps from various satellites for the recent Texas May–June 2015 flood disaster. Satellite data sets and maps can also be complemented by model simulations of an event (e.g., NOAA's AHPS, "Advanced Hydrologic Prediction Service" flood forecasting, NOAA's FLASH, "Flooded Locations and Simulated Hydrographs" flash flood forecasting project, the European Commission's GLOFAS, "Global Flood Awareness System," and the University of Maryland's GFMS "Global Flood Monitoring System"). The challenge is how to compare, integrate, and transform these disparate sources of disaster-related products into information useful to decision-makers (which may include the general public, and all levels of government and non-government disaster responders).

While these are great advances, it is worth noting that oftentimes known technological and data analysis limitations may lead to a lesser desirable map product. For instance, the optical-based inundation estimations are very useful but are usually limited to later flood stages after precipitation (and clouds) has dissipated. They also are limited by dense vegetation, shadows, etc. Radar-based inundation estimates are not limited by clouds but in many cases by limited overpasses, unless in constellation where repeat passes can be within a few hours (e.g., the COSMO-SkyMed series). Limits to access of data as well as data processing limitations present challenges to the use of this type of data. Also, calculations of inundation estimations using rainfall (satellite or ground-based) and hydrological routing as well as inundation models offer significant potential but are dependent on accurate rainfall information, knowledge of man-made features (e.g., dams and flood defense structures), and successful parametrization of hydrological processes. Over the last two decades, there are numerous examples in the scientific literature integrating both observations and models to achieve a "best estimate" of inundation as a function of time during and after an event. This could indeed lead to a better and more efficient use of the results of the techniques currently being explored.

1.2. Decision-Making in the Age of Open Geospatial Data

The abundance of open geospatial data and information appears to be presently underutilized by decision-makers, due to a number of reasons, most of which relate to the relative novelty of these resources. There is: (1) limited time and personnel capacity to understand, process, and handle new types of geospatial data sets; (2) limited near-real time data accessibility, bandwidth, and sharing capacity; (3) incompatibility between user platforms and geospatial data formats; (4) data availability may be simply unknown and/or data latency (lag from acquisition to delivery) may be inadequate; and (5) limited understanding by scientists and engineers about end user product and timing needs, i.e., data products which could be produced are not created.

2. Limitations in Fulfilling the Needs of Decision-Makers

Advanced geospatial technologies allow improvement of situational awareness for decision-makers. In the Texas case, these advances enabled satellites to be tasked, data products to be created and distributed, and feedback loops to be developed between the emergency authorities, satellite operators, and mapping researchers. This allowed delivery of a daily stream of relevant products that informed deployment of emergency resources and improved management of this major event across local, state, and national levels. This collaboration was made possible through a lot of domestic support that occurred for this event with coordination through the U.S. Department of State, FEMA, USGS, DoD/NGA, USAF EagleVision, USAF CAP, and also through the Committee on Earth Observation Satellites (CEOS) Flood Pilot activity that is supported in the USA by NASA, NOAA, and USGS and includes numerous civilian space agency assets from the European Space Agency along with national agencies from Italy, France, Germany, Japan, and others.

Despite these notable efforts, it became apparent that one important need, from the decision-making standpoint, is not yet directly met by existing satellite technology, or at least not by any one single data product. The major flooding occurred over a period of many weeks, and a geographic area of more than 40,000 km^2. Some decision-makers desired at least daily status updates over the region. However, the best available synoptic coverage via actual flood imaging covering such a wide area was via NASA's two MODIS sensors, which provided twice-daily imaging over the region at a spatial resolution of 250 m. This spatial resolution is adequate for the larger floodplains, such as that of the Red River, but not for many tributary streams. Also, clouds frequently obscured for several days any coverage by remote sensing at optical wavelengths. Synthetic aperture radar (SAR) satellites, such as Sentinel-1A and COSMO SkyMed, are not hindered by clouds, and operate at much better spatial resolutions, but they are also often not truly configured to provide wide-area repeat coverage. However, this said, the present constellation of COSMO-SkyMed with a revisit capability of only several hours if programmed accordingly, and in the near future with the full constellation of the Sentinel-1 satellites (mid 2016) and also the upcoming NASA/CNES Surface Water Ocean Topography (SWOT, http://swot.jpl.nasa.gov) mission (current launch date of 2020), orbital and repeat cycles to map flooding will be considerably better than at present, for many rivers in flood being imaged at least every few days and with large swath widths (>100 km). In the case of SWOT, this applies globally but may vary according to track orientation and for the Sentinel-1 constellation this is true for Europe and specific regions of interest outside Europe.

Of course the potential of such systematic, high-resolution, and wide area observations could not be tested in the context of the Texas flood disaster but many believe that the “full potential” of EO data is unlocked when many different missions and sensors (e.g., MODIS, Sentinel-1, and COSMO-SkyMed) are combined in an intelligent way, for example, through the inclusion of uncertainties (see approaches proposed by, e.g., *Schumann et al*. [2009], *Pulvirenti et al*. [2011], *Westerhoff et al*. [2013], and *Giustarini et al*. [2015]). This major challenge was clearly posed by the Texas event and was, in part, the assembly of data from a variety of sources, and to embed any local higher-resolution flood images within the larger and time-extended regional context of an expanding regional flood event.

While the current situation represents a clear limitation in fulfilling the needs of the decision-maker, it creates an opportunity and room for innovation to develop products that deliver better actionable information. In this context, quantification of uncertainties when combining data from different sources could augment information content for end-users [*Pappenberger and Beven*, 2006].

3. Utilization of the Data in the Texas Case

Many of our team were directly involved in this flood event of May–June, 2015, the severity of which was further reinforced by a Presidential Disaster Declaration (opening up public assistance) issued for the Red River portion of this event in Louisiana (http://www.fema.gov/news-release/2015/07/13/president-declares-disaster-louisiana), which was still only slowly falling at the end of July. As postevent engagement, the involvement of our team has included teleconference calls with the Texas state government disaster response managers. The following paragraphs give an account of the utilization of the many different satellite flood maps delivered to the disaster response team, according to their feedback. In the next section, we will describe how this feedback will further help guide our work, and we conclude this Commentary with a set of recommendations.

State and local response coordinators know where current and predicted flooding conditions are likely to cause the greatest impacts. These do not necessarily coincide with the locations of the highest measured flood crests, but occur at sites that contain vulnerable features or large assets. Knowledge of where orbital sensor collections can be scheduled helps to coordinate other data collection efforts, such as aerial photographic surveys, and leads to a better prioritization of available resources. Awareness of the collection schedule and the possibilities for future near-term acquisitions by satellites that can still be scheduled also contributes to decisions made by response teams who seek the latest available information as they operate in new areas. In this context, having access to the source imagery data would also permit the creation of different products based on specific applications and user feedback from previous events. Readymade data products, such as the flood maps described here, provide rapid assessment information, while the source data could be used to generate products that answer event-specific questions, if the expertise to do so is available.

In our case, the response teams were continually being delivered the latest satellite images and map products (for flood mapping from the optical imagery, the reader should refer to *National Aeronautics and Space Administration* [2015] and for flood mapping from SAR, please refer to *Matgen et al*. [2011]) while being kept informed of upcoming in-views from the array of satellites available through the CEOS Flood Pilot project. This stream of information provided the response team with situational awareness of what had just been delivered and what was still upcoming and available so decisions could be made to allocate different satellites to cover different parts of the flooding to maximize visibility into the progression of the event.

Primarily, the maps were used to provide a strategic overview of the extent of flooding simultaneously affecting six major river basins over an 800 km range from the Red River and its tributaries in North Texas and Oklahoma to the Nueces River in South Texas. The maps offered a detailed view of inundation impacting agriculture in rural areas (note that in the Texas case no urban areas where mapped with a very high resolution SAR mode, though this has been shown to be possible [e.g. *Mason et al*., 2010]), which is information that can be difficult to obtain from other sources. The maps also help to fill in the coverage gaps between stream gauges that are monitored for current and forecast conditions. Satellite and aerial observations allow monitoring the rise and spread of floodwater through time from the main channel into vulnerable areas. Knowing the rate of inundation throughout the floodplain allows the responding agencies to prioritize and target their resources toward the locations where impacts will occur next and cause the greatest threats to life, property, and important infrastructure. Floodplain inundation dynamics cannot be inferred from a stage height at a stream gauge and so using the flood maps in concert with USGS stream gauge observations and forecasts, the need to fill voids in areas that have few surface observations was highlighted.

4. Reflections

Each major storm, flooding, or other natural hazard event has its own peculiar flavor and impact, depending on where disaster strikes, how large the impact area may be, and the resilience of the built environment, its inhabitants and those called to respond. The case of a broad area event, such as persistent flooding that impacted many of Texas' largest river basins simultaneously in May 2015, is useful for better understanding the needs of emergency managers and responders for actionable information to support strategic planning and tactical decision-making.

Scientists and engineers who seek to develop useful geospatial information products will benefit from a more detailed look at the challenges facing decision-makers as the latter seek to understand what will happen in the next days all the while reacting to specific problems, emergencies, and questions that arise day-to-day, sometimes hour-to-hour. Even those who are experts in map interpretation or familiar with geospatial information do not necessarily have the time to digest that information.

The recent Texas flood events of May and June 2015 provide a window into the day-to-day requirements and unmet strategic and tactical needs of an organization responding to events unfolding across an area of significant size and population. The Texas case described here was a special case where the Italian Space Agency (ASI) wanted to assist with the COSMO-SkyMed constellation, and using the CEOS Flood Pilot presented the easiest vehicle. This is not the norm and should not be since such pilots have a limited life span and certain results they are trying to achieve (for instance, Texas is not one of the CEOS pilot regions), and there is of course also the danger of sidestepping official response teams or other authorities, which cannot be standard operating procedure.

However, there are a number of things that can be done to assist in the long term. Interactions between different expert groups should be strengthened and close collaboration and interaction with emergency responders to identify needs should be encouraged. Such collaborations and interactions allow leveraging existing scientific expertise and state-of-the-art tools to extract actionable information (in the case of flood disaster, this can be automated flood mapping tools, flood detection tools such as UMD's GFMS, and computer simulations). However, these actions need to be done outside of the response window or cycle since, in many cases, product developers or research institutions may not have a response or distribution mandate and so oftentimes technology and products need to be passed on to an agency that does have that mandate. Last but not least, coordination of satellite data acquisitions needs to happen in such a way that available EO data resources can be optimally combined to deliver the best product for actionable information and to this end, the role of official response teams in data acquisition (e.g., satellite tasking) should be enlarged.

In the following section, we provide a short set of recommendations drawn up by the group of authors of how to move forward and what immediate steps are needed to ensure this type of coordinated effort is repeatable, sustainable and viable from a resources point of view. The authors wish to note that this list is nonexhaustive and does not reflect any state or federal government position.

5. Call for Action

Largely drawing on the reflections reported in this Commentary, we suggest the following near-term action items in order to unlock the full potential for Earth observation data in flood disaster response:

1. Stronger collaboration from the onset between agencies, product developers, and decision-makers;
2. Quantification of uncertainties when combining data from different sources in order to augment information content;
3. Definition and inclusion of a default role for the end-user in satellite acquisition planning; and
4. Proactive assimilation of methodologies and tools into the mandated agencies.

A very similar set of actions has been advocated by *Hossain et al*. [2016] for remote sensing and applications in a much broader sense. In order to move forward on the set of action items recommended here, we suggest that in a first instance a small group of space agency program managers as well as experts from the science and decision-making arena hold a scoping workshop. This meeting should address lessons learned from the presented and similar events and define the next steps required to turn flood mapping science into practical and actionable information for a more effective disaster response.

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