Transdisciplinarity and the Future of Engineering
B.R. Moser et al. (Eds.)

doi:10.3233/ATDE220664

Conceptual Design of Space Missions Integrated with Real-Time, In Situ Sensors

Brian CHELL[1], Matthew J. LEVINE, Leigha CAPRA, Jerry J. SELLERS, and Paul T. GROGAN

Stevens Institute of Technology, Hoboken, USA

Abstract. Technological advances have enabled new types of distributed space missions (DSMs) that can improve the data resolution along many dimensions over monolithic, “flagship” spacecraft. Future DSMs will fuse data from a wide variety of sensors including other spacecraft and various ground- and air-based in situ platforms. The New Observing Strategies Testbed (NOS-T) is a new digital engineering environment based on systems engineering principles for simulating DSMs using a loosely coupled, event-driven architecture that manages communication between logically and geographically distributed user-developed applications. This paper demonstrates how NOS-T can evaluate new operational modes for satellite constellations using real-time stream gauge data from the U.S. Geological Survey (USGS) National Water Information System (NWIS) to decrease the latency of targeted spacecraft observations of flooded areas. The test case uses real-time data from NWIS stream gauges in the U.S., artificially triggers a flooding event, subsequently tasks satellite observations, and downlinks data to a ground station. It demonstrates how NOS-T enables the transfer of information between in situ and space-based sensors in a digital engineering environment to aid conceptual design of future DSMs across organizational boundaries.

Keywords. Decision support tools and methods, methods for transdisciplinary engineering, collaborative design environments

Introduction

Recent and ongoing improvements in communications infrastructure and electronics miniaturization have allowed for new types of Earth-observing missions with multiple spacecraft, or distributed space missions (DSMs), which provide improved capabilities compared to single-spacecraft missions [1]. DSM observations can be combined with Earth system data from various sources, including in situ sensors on the ground or in the air, allowing for a better understanding of important phenomena, such as floods and fires. The NASA Earth Science Technology Office (ESTO) Advanced Information Systems Technology (AIST) program has an ongoing thrust into New Observing Strategies (NOS), researching how to best leverage DSMs with existing and future sensors to enhance Earth science [2]. These various sensors will not always be under the same organizational or even national umbrella and require new methods of governance and information exchange to reach their potential.

[1] Corresponding Author, Mail: bchell@stevens.edu.

This paper describes a conceptual design study of a NOS mission using real-time, in situ stream gauge data to task simulated spacecraft observations. The study varies the number of satellites in a constellation to see the effect on the time required to downlink high-resolution images of a flooded area. The experiment is conducted with the New Observing Strategies Testbed (NOS-T) [3], a digital engineering environment developed to integrate and orchestrate NOS missions. NOS-T provides infrastructure for applications to publish and subscribe to messages on specific topics. These applications serve as the nodes of a DSM. For example, in this work one of the nodes collects water level data from stream gauges and publishes these gauge heights to the testbed while another subscribes to those messages and uses the gauge height data to create a visual dashboard. Integrating real-time data into a NOS-T test campaign is an important step to prove that the testbed is capable of NOS mission demonstrations.

NOS-T supports transdisciplinary test campaigns by providing a "chat room" for a wide variety of simulation tools, real-time data, and hardware. A major part of NOS-T will be user-developed applications to represent these DSM nodes and evaluate the efficacy of novel observation strategies with truly distributed control. The NOS-T architecture is designed for ease of use and to require a low cost of participation, allowing principal investigators (PIs) to focus on leveraging sensing platforms to further their science objectives. Facilitating the interface between scientists and engineers is a major focus of this development thrust.

1. Background

This section gives background information on DSMs, how they fit into a NOS mission, and adjacent information systems which communicate data from terrestrial sensing networks to improve our knowledge of the Earth system. It finishes by scoping the research objectives for this work.

1.1. Distributed space missions and the New Observing Strategies Testbed

DSMs combine observations from more than one spacecraft to accomplish a common task [4]. By providing more vantage points, these constellations of spacecraft provide unique capabilities, such as improving the temporal resolution of observations with more frequent overflights of points of interest [5]. An example of a DSM is the soon-to-be-launched Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) mission [6]. TROPICS will consist of six identical CubeSats with microwave-band electromagnetic sensors to capture the thermodynamic characteristics of tropical storms. As opposed to a more established, "monolithic" space system architecture, the six spacecraft improve spatial and temporal resolution of cyclone structures anywhere in tropical regions on a global scale. The increased dynamism of these observations will provide opportunities for more intelligent and targeted observations.

While DSMs have promising capabilities, their novelty and complexity introduce challenges. For example, the TROPICS mission consists of six satellites under the control of one entity, MIT's Lincoln Laboratory. However, for missions with federated control of spacecraft, new methods for tasking observations need to be defined [7]. Also, existing cost models are too focused on existing missions, and are insufficient to capture the differing costs of a DSM due to increases for rework and manufacturing errors, spacecraft becoming cheaper after development iterations, and changes from novel operational concepts [8]. These drawbacks have driven the development of NOS-T, where DSM concepts can be demonstrated in a low-cost environment.

NOS-T uses an event-driven architecture where user-developed applications communicate state changes with one another via “events,” or messages published and subscribed to a common message broker. Importantly, it supports loosely coupled connections between applications, where applications can be added and removed without changing other applications or the NOS-T infrastructure. Also, because all events pass through a broker, the connections between computers hosting applications are not direct, allowing for increased modularity, scalability, and security. This loose coupling between applications across organizational and geographical boundaries, simulating the real-world behavior of a NOS. The authors developed NOS-T with systems engineering principles in mind, not only to support NOS technology demonstrations in an easy-to-use environment, but also to socialize new types of missions.

1.2. Adjacent Earth science information systems

The general goal of Earth-observing missions is to improve knowledge about the Earth system. Of course, space-based platforms are not uniquely required to gather this information, as there are myriad sensors on Earth that provide vast amounts of data. Leveraging these existing platforms and data to better target space observations is an important goal of the NOS thrust. This subsection focuses on adjacent ground-based sensors which could supplement NOS missions.

Government agencies are a large provider of accessible Earth science data. One such information system is the National Oceanic and Aerospace Administration's National Weather Service system, which provides current and historical weather data. The European Space Agency (ESA) also has a large database of publicly accessible data, including the high-resolution imaging Sentinel 2 DSM [9].

Other large repositories of Earth science data are available for researchers through the United States Geological Survey (USGS). The Advanced National Seismic System consists of globally distributed seismometers that provide data on significant earthquakes [10]. The USGS also collects data on water resources at more than 1.5 million sites throughout the country which is communicated via its National Water Information System (NWIS) [11]. The USGS provides both sensor networks and related communications and data handling infrastructure to keep these measurements updated in real time and is accessible from visual dashboards and online data requests. This study uses real-time data from NWIS stream gauges.

While government agencies maintain large repositories of publicly available data, crowdsourcing provides an alternative approach to collecting relevant information. Crowd-sourced data include self-reported automobile accidents to help predict traffic [12], self-reported weather conditions bolstered by embedded Internet of Things sensors to improve weather reports [13], and social media posts during an emergency to aid in disaster management [14]. However, crowdsourcing data can be inaccurate [14] and is difficult to mature for Earth science applications [15].

1.3. Research objectives

The main objective of this research is to demonstrate the capabilities of NOS-T to support the prototyping and testing of NOS-style missions. One of the important capabilities for these types of missions includes using real-time, in situ data to better focus observations from space and achieve a more thorough understanding of the relevant phenomena than either space- or in situ sources can offer on their own. This study uses real-time NWIS data from USGS as triggers to task simulated high-resolution spacecraft observations.

Other objectives are to explore application case formulation and execution strategies for future work. NOS-T is a novel tool and maturing these strategies is necessary for future applications with anticipated increases in complexity. The final objective for this study is to communicate NOS-T to a broader community of transdisciplinary engineers. NOS missions are inherently transdisciplinary, and the development team is interested in feedback for future refinements and extensions.

2. Model Development

The scientific objective for this technology demonstration is to capture high-resolution images of flooded areas near major population centers. These images are assumed to be most useful if they can be captured and downlinked in a timely fashion for two major reasons. First, if these images can be relayed to relevant emergency authorities, then perhaps they can aid in disaster relief. Second, if the image is taken while the flooded area is at its greatest, then it will provide the best information for future predictive flooding models.

2.1 Concept of operations

The operational concept for this study is to capture real-time stream gauge data from NWIS, and then periodically trigger floods at one of the stream gauges. This artificial flood trigger will task a spacecraft observation at the flooded stream gauge location. After an image is taken at this location, the spacecraft continues in its orbit until it is in view of a ground station, at which point it downlinks the image data. The latency time between the flood trigger and the image downlink is the key metric for constellation evaluation.

This model has some key differences from an actual flood imaging mission. Speeding up the time required for a test case with the artificial flood trigger is a major difference. The Earth-observing spacecraft being modeled have an orbital period of around 100 minutes and the stream gauge data generally do not fluctuate much on these time scales, as updates are usually given on the order of ten minutes and the gauge heights remain quite consistent unless there is an extreme weather event. Therefore, combining the flood triggers with scaled-up simulation time is essential for this type of workflow verification and serves the technology demonstration purposes of this study to support ongoing fully real-time workflows. Communications between the different sensors are simplified, so that floods are instantly reported to the constellation. Also, cross-link communications between spacecraft are not considered, therefore the spacecraft that observes the flood must wait until it is over the ground station to downlink the image. The spacecraft are limited to pointing their sensors in the nadir direction only, and therefore pointing requirements and attitude control systems are out of scope.

2.2 Application case

The mission is comprised of five user applications communicating over the NOS-T infrastructure, denoted for the balance of this paper by bold text.

Stream Gauges pulls gauge height data from NWIS for stream gauges near the twenty largest metropolitan statistical areas in the United States via HTTP requests. It includes a fictional flood trigger which sends a flood warning to task an observation from a space platform at random intervals. These warnings also include an artificial increase in gauge height at the flood warning location.

Satellites models a constellation of identical spacecraft with high-resolution cameras to capture images of the flooded area. The imaging sensor's field of regard is modeled by an angle which determines how much of the Earth's surface is visible at each point. When the mission design has more than one spacecraft, they are placed in a Walker-Delta constellation, which evenly spaces otherwise identical orbits around the Earth [16]. Orbit propagation uses two-line elements generated by the TAT-C tool [4], with simulation time directed by subscribing to timing messages published by the NOS-T manager application. The NOS-T manager is an application that sends control messages for user applications that require events to initialize, start, execute, and stop. In contrast to the "unmanaged" **Stream Gauges**, the behavior of **Satellites** in response to NOS-T manager messages make it a "managed" application. It is necessary to use managed applications in NOS-T for scaling time faster than real time.

Ground represents a ground station which can receive the flood image data once the spacecraft is in view of its antenna. This application case uses a single representative ground station located at the Svalbard Satellite Station in Norway. This application reports the latitude and longitude of the ground station as well as a minimum elevation angle, the angle with respect to the horizon from which they can receive communications from **Satellites**. A minimum elevation angle of five degrees is used here.

Data is an application which aggregates information to compute downlink latency results in this study. It does not publish any events but subscribes to the flood warning messages as well as the detection and imaging times from the **Satellites** application. **Data** appends these data in a Python list to ensure speed, and then a .csv file is later saved manually for analysis.

Finally, there are two more applications which do not publish any messages to the testbed, rather they subscribe to relevant topics and create visual representations of important mission data. The first is a **Dashboard**, created with the Python Dash library [17], that outputs a real-time plot of the gauge height at all stream gauge locations. Figure 1 is an image of this dashboard with visible flooding spikes in the gauge height.

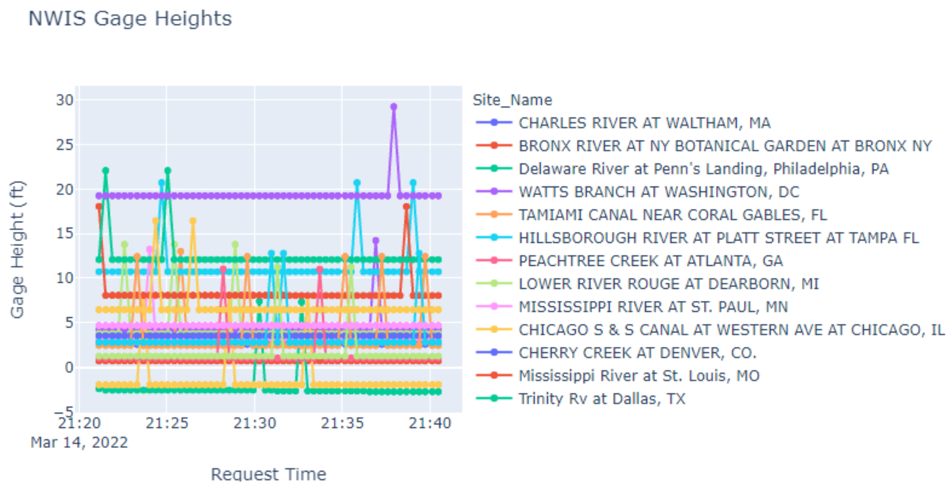

Figure 1. Real-time gauge height results with random flood triggers output by the Dashboard application.

The second visualization application is a **Scoreboard,** developed with the Cesium tool [18], which gives a geospatial view of the overall mission. **Figure 2** is an image of the Earth with an eight-spacecraft constellation, floods in their various states of started, detected, and imaged, and the ground station at Svalbard, near the North Pole. The visualizations from **Dashboard** and **Scoreboard** provide face validity and are essential during test campaign development to verify correct operation.

Figure 2. Geospatial view with Scoreboard application. Blue dots are spacecraft with their sensing footprint below, red dots are locations with flood warnings, orange dots are locations which have been imaged, and yellow dots are locations for which the image has been downlinked. The pink dot is the Svalbard ground station with a cone of visibility above.

Figure 3 depicts a graphical representation of the data flow for this mission. The larger boxes with rounded corners show the applications and the smaller dashed boxes with sharp corners show messages and contents. The arrows signify the direction of data flow, for NOS-T this means which application is publishing which are subscribing.

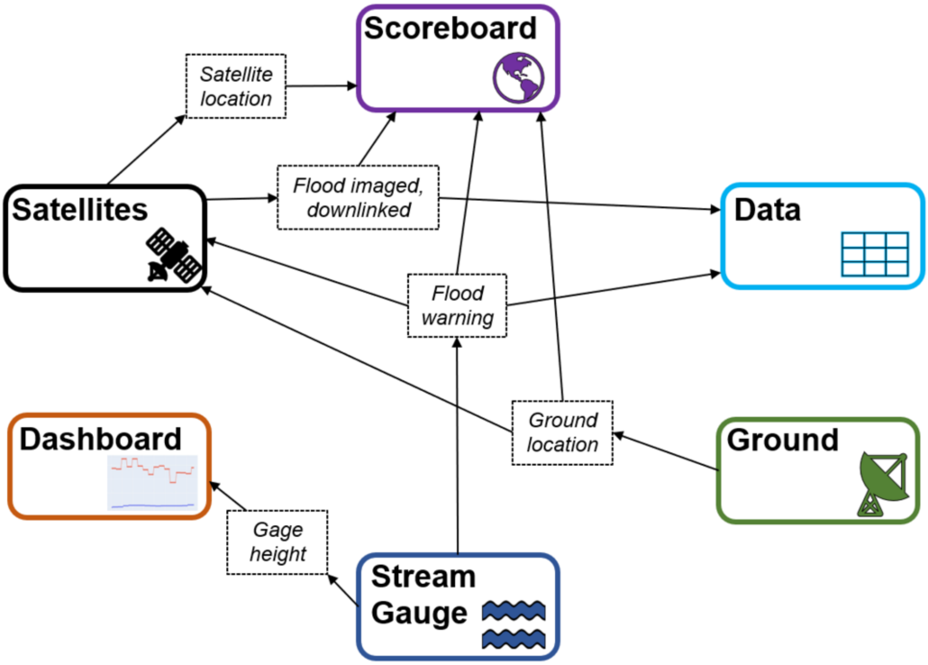

Figure 3. Graphical representation of data flow between applications.

3. Methodology

3.1 Procedure

To run a test case, all the applications must be started before the NOS-T manager. When the manager application is started, it begins to send out timing messages which **Satellites** uses as a heartbeat to respond to by publishing updated spacecraft locations. At the same time, **Stream Gauges** publishes the gauge heights for each location and **Dashboard** is the only subscriber to these events. When a flood is randomly triggered, the spacecraft are automatically tasked to take an image once one of their cameras are in view of that location. After the flooded area has been imaged, **Satellites** publishes a message with a timestamp and flood ID number which is subscribed to by **Data** and **Scoreboard.** **Scoreboard** uses this message to change the flood color from red (warned) to orange (imaged). Next, a similar message is published when the imaging satellite is in view of **Ground** to downlink the data. Once this message is published, **Data** has the timestamp required for the key metric of downlink latency, and **Scoreboard** is updated with the flood color going from orange to yellow (image downlinked).

3.2 Experiment Design

Flood imaging data latency, defined as the time from flood trigger to data downlink, is the key metric for evaluating the various constellations in this study. The input variable is the number of spacecraft in the constellation. For this set of tests, the number of spacecraft is varied between one and ten, with only one satellite per orbit and no phasing between satellites. Using a single, discrete input variable with clear effects on latency is a simple method to demonstrate the integration of real-time data. The ESA's Sentinel 2A high-resolution imaging spacecraft is used as the reference orbit. Sentinel 2A has an orbital inclination of 98.62 degrees and an altitude of 786 km. The sensor field of regard is assumed to be 112 degrees.

For each test case, the simulation is started, and the flood trigger, imaging, and downlink times are collected by **Data** until 33 floods randomly occur. The constellations are evaluated on their mean and maximum downlink latency. The experiment uses a single replication for each test case with a random seed. With 33 flooding events in each test case, the mean downlink latency is assumed to not be greatly affected by stochasticity, however the maximum downlink latency could have some random effects.

4. Results and Discussion

Figure 4 is a plot of the results for mean and maximum reporting latency. All timing results are given in hours of simulation time.

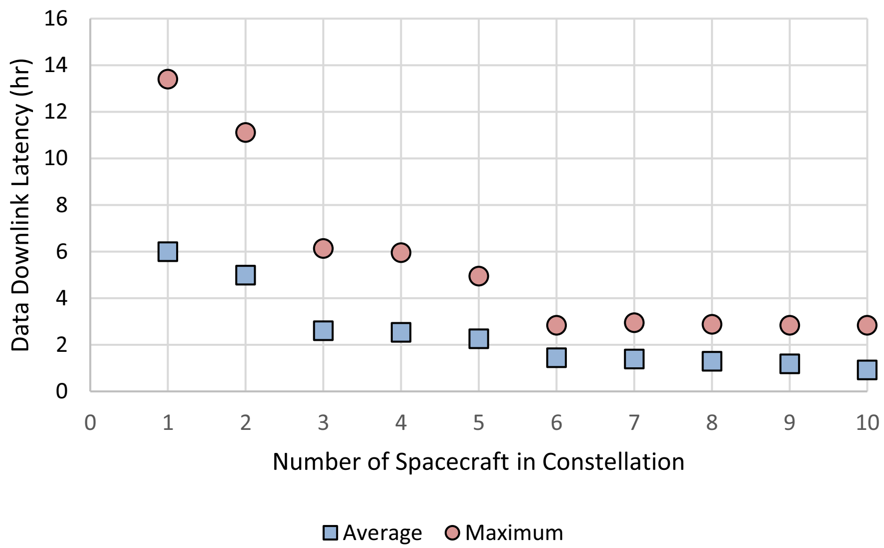

Figure 4. Average and maximum image downlink latency times for all constellations.

The results show that increasing the number of spacecraft in the constellation improves image downlink latency. The only exception is the maximum latency increases between six and seven satellites, this is likely due to stochasticity in the flood locations. The latency times largely level off beyond three-satellite constellations, and while this study does not explicitly consider costs, there is clearly less value in adding additional spacecraft beyond three. Furthermore, the average and maximum latency are highly correlated. This is due to the strategic placement of the Svalbard Satellite station for sun-synchronous orbits. Spacecraft in these orbits will be in view of the polar regions during every orbit, and therefore the Svalbard location allows for downlinking images soon after they are taken. While these results are not surprising, this application case verifies the ability of NOS-T to support a test involving real-time data from in-situ sensors.

It is important to consider how this mission would be different without using stream gauge data to task the space observations. With only space-based assets, the floods would need to first be detected, requiring either many smaller, or larger, more expensive spacecraft to provide coverage over a wide area. Either of these solutions would cost more than the already existing NWIS which provides free, regularly updated data. Furthermore, space-based flooding observations require models that can be inconsistent over differing environments, resulting in less reliable measurements compared to a simple gauge height sensor. Timeliness is another factor, manually identifying and scheduling images could take several hours, compared to the automated workflow demonstrated here.

Through the development of this application case and others for NOS-T, some lessons have been learned that could aid future users. An important lesson suggested to all users is the use of visual mission representations like the Scoreboard. They have been essential for both debugging and giving the test campaigns face validity. The ability to track messages by topic and all together, supported by the NOS-T online manager GUI, is similarly useful for these purposes.

5. Conclusions and Future Work

This study demonstrates how the NOS-T supports theconceptual design of a DSM. Real-time data from the USGS NWIS is used in concert with simulated spacecraft and ground communications infrastructure, with visualization tools to verify and communicate results. In practice, NOS-T will facilitate PIs in science and engineering domains to perform similar mission trade studies. Some of the strengths NOS-T has for simulating NOS include a low cost of entry for PIs and the loose coupling scheme between user applications which allows for the federated control envisioned in these types of missions. Performing complex studies with more applications modeled with fewer simplifying assumptions than this flood imaging application case is important for future development. In particular, orchestrating complex missions in NOS-T with the ability to automate designs of experiments is an important capability that future studies will help to mature.

Acknowledgement

This material is based on work supported, in whole or in part, by the U.S. Department of Defense and National Aeronautics and Space Administration Earth Science Technology Office (NASA ESTO) through the Systems Engineering Research Center (SERC) under Contract No. W15QKN-18-D-0040. SERC is a federally funded University Affiliated Research Center managed by Stevens Institute of Technology. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the United States Department of Defense.

References

[1] J. Le Moigne, Distributed spacecraft missions (DSM) technology development at NASA Goddard Space Flight Center, *Int. Geosci. Remote Sens. Symp.* , 2018, Vol. 2018-July, pp. 293–296.

[2] J. Le Moigne, M.M. Little, M.C. Cole, *NEW OBSERVING STRATEGY (NOS) FOR FUTURE EARTH SCIENCE MISSIONS*, NASA Earth Science Technology Office Science Mission Directorate , NASA Headquarters, 2019, pp. 5285–5288.

[3] NOS-T Team, *NOS-T GitHub Repository*, 2022. [Online]. Available: https://github.com/code-lab-org/nost-tools.

[4] J. Le Moigne, P. Dabney, O. De Weck, V. Foreman, and P. Grogan, *TRADESPACE ANALYSIS TOOL FOR DESIGNING CONSTELLATIONS (TAT-C)*, Software Engineering Division , NASA Goddard Space Flight Center , Greenbelt , MD 20771 , USA Massachusetts Institute of Technology , Cambridge , MA 02139 , USA Stevens Institute of Technology, 2017, pp. 1181–1184.

[5] S. Nag, J. Lemoigne, D. W. Miller, and O. De Weck, A framework for orbital performance evaluation in Distributed Space Missions for earth observation, *IEEE Aerosp. Conf. Proc.*, vol. 2015-June, 2015.

[6] W. J. Blackwell *et al.*, An overview of the TROPICS NASA Earth Venture Mission, *Q. J. R. Meteorol. Soc.*, 2018 , vol. 144, no. November 2017, pp. 16–26.

[7] J. Mason and S. Chien, Automated Scheduling of Federated Observations in the NOS Testbed, In *International Workshop on Planning & Scheduling for Space (IWPSS)*, July, 2021.

[8] V. L. Foreman, J. Le Moigne, and O. L. De Weck, A survey of cost estimating methodologies for distributed spacecraft missions, *AIAA SPACE 2016*, pp. 1–17.

[9] M. Drusch *et al.*, Sentinel-2: ESA's Optical High-Resolution Mission for GMES Operational Services, *Remote Sens. Environ.*, 2012 , vol. 120, pp. 25–36.

[10] H. Benz, R. Buland, J. Filson, A. Frankel, and K. Shedlock, The Advanced National Seismic System, *Seismol. Res. Lett.*, 2001, vol. 72, no. 1, pp. 70–75.

[11] J. L. Goodall, J. S. Horsburgh, T. L. Whiteaker, D. R. Maidment, and I. Zaslavsky, A first approach to web services for the National Water Information System, *Environ. Model. Softw.*, 2008, Vol. 23, no. 4, pp. 404–411.

[12] T. H. Silva, P. O. S. Vaz De Melo, A. C. Viana, J. M. Almeida, J. Salles, and A. A. F. Loureiro, Traffic condition is more than colored lines on a map: Characterization of Waze alerts, *Lect. Notes Comput. Sci. (including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics)*, 2013, vol. 8238 LNCS, pp. 309–318.

[13] Y. Zhu, S. Zhang, Y. Li, H. Lu, K. Shi, and Z. Niu, Social weather: A review of crowdsourcing-assisted meteorological knowledge services through social cyberspace, *Geosci. Data J.*, 2020, vol. 7, no. 1, pp. 61–79.

[14] S. Luna and M. J. Pennock, Social media applications and emergency management: A literature review and research agenda, *Int. J. Disaster Risk Reduct.*, 2018, Vol. 28, no. January, pp. 565–577.

[15] C. S. Lowry, M. N. Fienen, D. M. Hall, and K. F. Stepenuck, Growing pains of crowdsourced stream stage monitoring using mobile phones: The development of crowdhydrology, *Front. Earth Sci.*, 2019, vol. 7, no. May, pp. 1–10.

[16] C. J. Wang, Structural properties of a low earth orbit satellite constellation - the walker delta network, *Proc. - IEEE Mil. Commun. Conf.*, 1993, Vol. 3, pp. 968–972.

[17] "Dash Documentation & User Guide | Plotly." [Online]. Available: https://dash.plotly.com/. [Accessed: 15-Mar-2022].

[18] "Cesium: The Platform for 3D Geospatial." [Online]. Available: https://cesium.com/. [Accessed: 15-Mar-2022].