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Reimagining the Surface Water and Ocean Topography Mission as the "Landsat" of Surface Water

The Surface Water Ocean Topography (SWOT) mission, jointly developed by NASA and French Space Agency (CNES) with contributions from the Canadian and U.K. space agencies, and planned for launch in 2022, is designed to provide a spatially distributed and high-frequency measurement of water elevation data for the hydrology and oceanography communities for the first time [1], [2]. By virtue of its novel observational capability and stated scientific goals, SWOT satellite data are expected to have a profound impact on our understanding of global surface water. Although there have been many satellite missions that can either map water extent or water elevation, SWOT is the first mission that will measure extent and elevation concurrently regardless of cloud cover conditions and with a higher degree of precision.

Given SWOT's unique capability, we can probably expect SWOT to play a leading role in building the world's space-based gauge network for surface water similar to what the Global Precipitation Measurement mission precipitation radar currently plays for the constellation of passive precipitation sensors [3]. The evidence gleaned from current literature indicates that SWOT data should be able to quantify the surface water fluxes more accurately compared to what is possible with the current suite of altimeters [4]. SWOT is expected to improve global water budget calculations in collaboration with other models and satellite observations [5]–[7]. SWOT data will also be a pathfinder to understanding the human footprint in surface water storage variability due to water management infrastructures [8], [9]. Finally, SWOT should also have a positive societal impact in the water sector, such as disaster management, reservoir operations, water management, ecosystem services planning, hydropower and navigation, fisheries (freshwater and marine), and marine shipping to name a few [10], [11].

Amid the exciting prospects for scientific discoveries and societal applications, one topic that has not received much attention is the enduring nature of the SWOT mission to become a continuous mission similar to Landsat's (which will soon celebrate its golden jubilee). The SWOT mission could potentially experience a similar rite of passage as the Landsat mission whose journey began in 1972 (when it was called *Earth Resources Technology Satellite*) *Earth Resources Technology Satellite* and is currently in its ninth launch. The SWOT mission has the potential to become a continuous mission for Earth's surface water, which is indispensable for the global water resources community. In other words, we can reimagine a future for SWOT akin to the "Landsat of Surface Water."

THE HISTORY AND IMPACT OF LANDSAT MISSIONS

To understand this vision for SWOT, let us review passage of Landsat when it was first launched in 1972 as *Earth Resources Technology Satellite*. Incidentally, when *Landsat-1* was proposed in the 1960s, it was met with intense opposition from those who argued that high-altitude aircraft would be the fiscally responsible choice for Earth remote sensing [12]. The rest is now history. Today, the Landsat program provides the longest continuous record (50 years) with global coverage for both space- and ground-based observations of Earth's land. In 1972, no one could have predicted that Landsat would be such an enduring mission nor last long enough for their grandchildren to witness mission continuity into the 2020s.

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Lauer et al. [12] report that, after the launch of *Landsat-1* in 1972, NASA's Goddard Space Flight Center (GSFC) hosted a series of symposia designed especially for Landsat-sponsored investigators to report "user-identified significant results." The application categories comprised agriculture, forestry, geology, land use, land cover, water, and marine science. The proceedings from the symposia revealed very clearly that Landsat had a powerful impact on many application areas that made the urgent need for continuity very obvious.

For example, in a customer-oriented investigation involving 11,275 Landsat data users, it was reported that the economic benefit of Landsat data for the year 2011 alone was estimated to be US$1.7 billion for domestic users and US$400 million for global users, resulting in a total annual value of US$2.19 billion (in one year). In 2015, the Landsat Advisory Group of the National Geospatial Advisory Committee reported that the top applications of Landsat imagery produced savings of approximately half a billion dollars each year for federal and state governments, nongovernmental organizations, and the private sector. This estimate discounts the additional savings from other uses beyond the top categories. The interested reader is referred to [19] for more information on the clear economic impact from Landsat.

WHAT IS NEEDED TO MAKE THE SWOT MISSION ENDURING?

Today, the SWOT mission has the necessary ingredients to become a similarly enduring mission as Landsat. Now what is required is articulation and amplification of its impact during the initial years after launch similar to the GSFC-hosted symposia in the 1970s on *Landsat-1*. Although scientific discoveries from SWOT on Earth-critical issues will play an important role, we believe an equally vital role that will be necessary to guarantee SWOT's continuity are the profoundly impactful societal applications enabled or accelerated by SWOT data. These societal applications of SWOT data will need to clearly convey to the world the positive impact on the bottom line of the user community in terms of cost savings, improved decision making, and in developing the previously impossible capability to manage water resources. In other words, these applications will need to articulate clear and compelling stories that drive the broader community to demand continuity of the SWOT mission.

SWOT DATA WILL ALSO BE A PATHFINDER TO UNDERSTANDING THE HUMAN FOOTPRINT IN SURFACE WATER STORAGE VARIABILITY DUE TO WATER MANAGEMENT INFRASTRUCTURES.

THE SWOT EARLY ADOPTER PROGRAM

Fortunately, SWOT is uniquely poised to deliver these compelling stories on societal applications with the launch of the SWOT Early Adopter Program (EAP), managed under NASA's Applied Sciences Program (ASP). To maximize the value of satellite data for planned missions, the ASP

1	Alexandria University
2	Asian Disaster Preparedness Center/SERVIR-Mekong
3	BRL Ingénierie
4	Centre for Water Resources Development and Management, Kerala, India
5	*Collecte Localisation Satellites*
6	Compagnie Nationale du Rhône
7	Consortium of Universities for the Advancement of Hydrologic Science, Inc.
8	Environment and Climate Change Canada
9	FM Global
10	Indian Institute of Technology Bombay
11	Indian Institute of Technology Delhi
12	Mercator Ocean
13	NASA Short-Term Prediction Research and Transition Center, University of Alabama
14	National Oceanic and Atmospheric Administration/Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder
15	The Ohio State University
16	Pakistan Council of Research in Water Resources
17	Stantec Inc.
18	Texas Water Development Board, Austin, Texas
19	University of Bonn and Helmholz–Zentrum Geesthacht
20	U.S. Air Force Weather's Land information System, Offutt Air Force Base, Nebraska
21	United States Geological Survey
22	vorteX.io

has developed this prelaunch protocol for engaging with the broader user community [13]. In the vision of the EAP, each selected Early Adopter (EA) proposes an activity for the use of planned satellite data using either proxy data sets or simulated data that mimic the anticipated mission during the postlaunch era. *EAs* are defined as those groups and individuals who have a potential or clearly defined need for data from the planned mission, and who are planning to apply their own resources to demonstrate the utility of planned satellite mission data for their application, system, or model.

Today, the SWOT EAP boasts more than 20 EAs from public, private, national, regional, and international stakeholder entities (see Table 1). These EAs have been building technical literacy on the SWOT mission, learning SWOT's data structure, and exploring how exactly SWOT data can add value or solve a previously unsolved societal challenge. Finally, these EAs are also preparing to lay the software and hardware infrastructure necessary for ingesting anticipated SWOT data in their operations or decision-making environment [10], [11], [14]–[17]. The societal challenges addressed by the EAs cover such diverse topics as flood and reservoir management, fisheries and marine science, transboundary water resources, statewide water supply, and marine navigation. The EAs span the continents of North America, Africa, Europe, and Asia (Figure 1).

TODAY, THE SWOT EAP BOASTS MORE THAN 20 EAS FROM PUBLIC, PRIVATE, NATIONAL, REGIONAL, AND INTERNATIONAL STAKEHOLDER ENTITIES.

Since its launch in 2018, the SWOT EAP has produced five workshops with three virtual training hackathons (both during the COVID-19 pandemic). These workshops have led to the development of user-ready, EA-specific tools for SWOT data, with dozens of peer-reviewed publications showcasing the expected impact of SWOT data on the EA's baseline operations. With support from the SWOT science community, the program has built a formidable archive of freely available multimedia tutorials, education materials, and self-help resources for any user interested in exploring SWOT applications, akin to the Khan Academy or Coursera on SWOT. This archive continues to grow because of EAP's communal spirit, where fellow EAs help each other overcome their respective project hurdles in a "hack" manner [11]. The SWOT EAP has developed consistently because of continuous support from partnering space agencies CNES, NASA, and their respective data-hosting programs such as PO.DAAC and AVISO. In other words, the SWOT EAP has increased user readiness of SWOT data in anticipation of mission launch for the broader application community. This proactive approach is the hallmark of the EAP, namely, to boost a return in public investments of global satellite missions. Detailed information on the SWOT mission on application-related activities and SWOT EA projects can be found at http://swot.jpl.nasa.gov/applications or http://depts.washington.edu/saswe/swot.

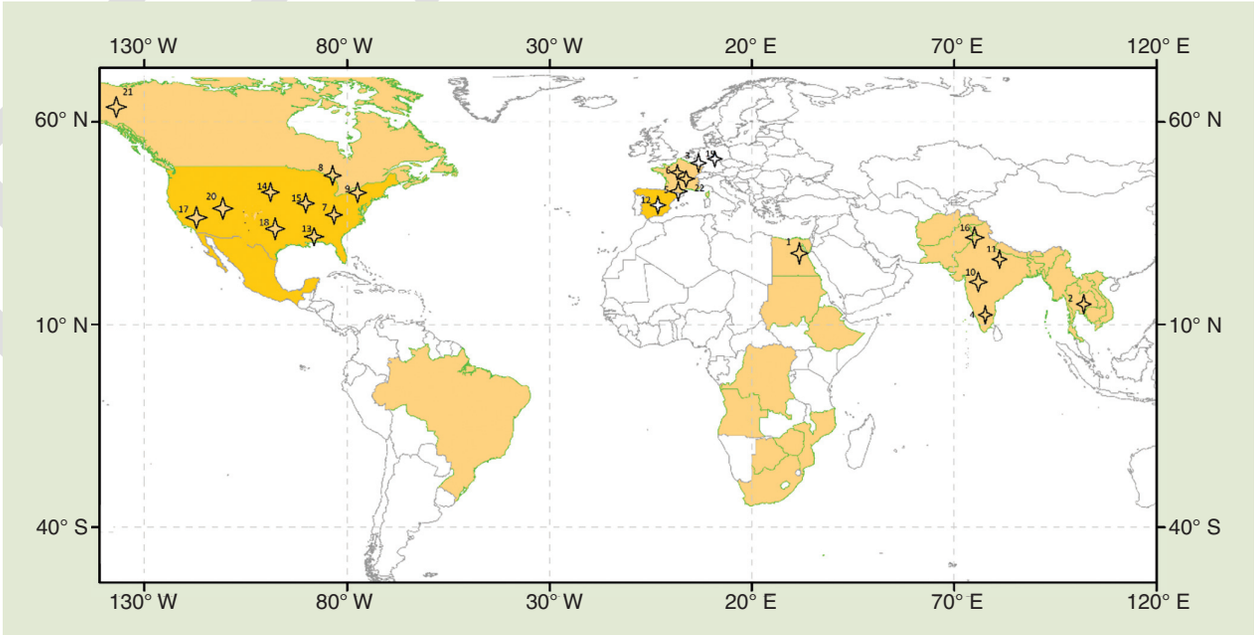

FIGURE 1. A map of current SWOT EAs showing the approximate location of their headquarters. The numbers pertain to numbering of the EAs shown in Table 1. The colored region shows the approximate countries of focus covered under the EA projects.

We are aware that the current state of the SWOT EAP and anticipated scientific breakthroughs and societal applications during the initial years after launch may not be a sufficient guarantee for SWOT to become a continuous mission like Landsat as there are many other factors beyond the control of the scientific community. However, we are inspired by the history of Landsat. We believe that when the real-world value of a mission is relentlessly demonstrated through a proactive program like the EAP, which sheds light on the value of scientific discoveries, societal applications, and tells compelling stories, SWOT too may one day enjoy a golden jubilee similar to Landsat's during the lifetime of our grandchildren.

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