COMMENTARY

Promoting global surface water monitoring research with the SWOT satellite

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Water resources are among the most precious natural assets on Earth, which are essential for sustaining life on Earth, supporting ecosystem health, and driving socio-economic development. However, water resources are not evenly distributed across the planet, and challenges such as climate change are putting pressure on water resource management. Accurate global water dynamic monitoring is crucial not only for achieving sustainable development goals but also for preventing and mitigating water-related disasters. Satellite remote sensing, with its economic efficiency, rapid data acquisition, and ability to integrate multi-source sensor data for comprehensive monitoring, plays a pivotal role in monitoring global water resources. However, existing satellite missions often face challenges such as limited spatiotemporal resolution, incomplete global coverage, and cross-platform asynchronous 3D observation consistency, making it difficult to accurately capture the seasonal changes and key characteristics of global medium-sized water bodies, such as storage and flow. The Surface Water and Ocean Topography (SWOT) satellite mission will monitor rivers, lakes, reservoirs and oceans with higher precision, thus comprehensively improving the global water dynamic monitoring capability.

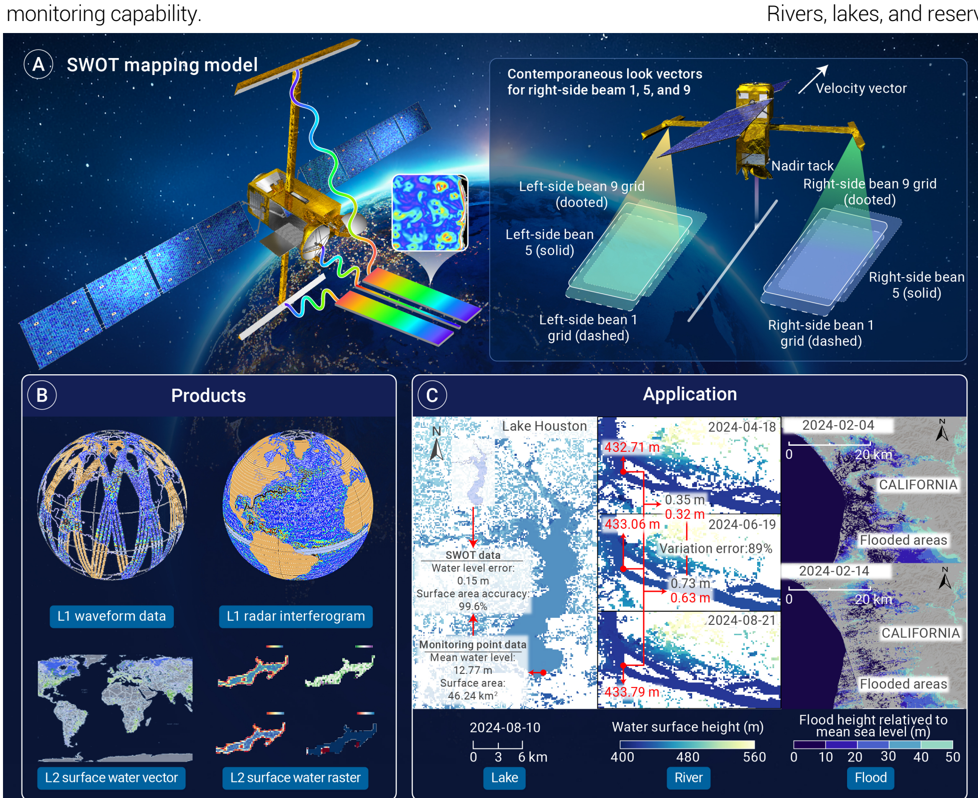

Figure 1. Schematic diagram for the SWOT satellite mapping and applications (A) SWOT Mapping Model illustrating the satellite's measurement principle using radar interferometry; (B) Products generated, including L1 waveform data, L1 radar interferogram, L2 surface water vector and L2 surface water raster; (C) Applications of these products in various scenarios, such as lake water levels, river water surface elevations and flood levels relative to mean sea level.

SWOT SATELLITE OVERVIEW

On December 15, 2022, NASA launched the SWOT satellite, marking a significant milestone as the first satellite designed for hydrological monitoring.[1] Traditional satellite altimeters, such as those on the Jason series, are limited by their narrow beam observations and inability to simultaneously measure water level and width, requiring extensive ground calibration. In contrast, the SWOT employs advanced payloads and data processing technologies to enhance surface water monitoring capabilities, providing high spatio-temporal resolution data on global surface water and ocean topography. The satellite's primary instruments include a Ka-band Radar Interferometer (KaRIn), a nadir altimeter, and radiometers, all of which work in tandem to generate high-resolution digital elevation models of water bodies. KaRIn captures detailed two-dimensional water surface data, allowing SWOT to measure water levels, widths, and slopes simultaneously. This innovative technology allows for comprehensive monitoring of rivers, lakes, reservoirs and oceans, offering invaluable insights into the dynamics of Earth's surface water.

SURFACE WATER DYNAMIC MONITORING

Rivers, lakes, and reservoirs are crucial components of the Earth's water cycle, essential for urban water supply, agricultural irrigation, and industrial production. Advances in remote sensing, like mapping global surface water changes with Landsat over 32 years, have significantly improved water management.[2] However, traditional radar altimetry satellites, with a typical 1 km footprint, struggle to monitor small and medium-scale water bodies accurately, especially in coastal areas. Intensified human activities and climate change have caused significant changes in the hydrology of lakes and reservoirs, necessitating continuous monitoring and analysis. Monthly water body observation is needed, but current satellite limitations in spatial resolution, observation frequency, and atmospheric SWOT's Level 2 products for water surface and elevation and inundation extent provide robust foundations for large-scale hydrological monitoring.[3] SWOT covers latitudes between 78° North and 78° South, revisiting locations every 21 days, typically providing a spatial resolution of 100 m or 250 m. Under certain conditions, the resolution can be improved to as fine as 10 m for nadir measurements and 70 m for the wide swath, allowing for more detailed observation of Earth's surface waters. SWOT's KaRIn enables detailed observation of inland water bodies, mapping global water bodies with surface areas over 0.06 km² and river widths over 100 meters. This supports investigations into dynamic river flow changes and provides comprehensive global inventories of lakes, reservoirs, wetlands, and rivers. Combining SWOT's high-resolution data with Sentinel-1/2, and Landsat observations enhances analyses of water quantity and distribution, supporting effective water resource management and climate change modeling.[4]

To preliminarily assess the accuracy of the SWOT Level 2 HR products in medium and small-sized water bodies, we conducted exploratory works in the application section (Figure 1). We conducted accuracy validation of water surface elevation and water body boundary vectors in the concurrent products by integrating water levels from gauge monitoring on Lake Houston and Landsat-8 images. Our analysis indicates that SWOT can achieve an absolute accuracy of 0.15m for inland large-scale water level observations, with an overall water body boundary accuracy of 99.6%. Additionally, we performed a long-term accuracy evaluation of water surface elevation using in-situ water level observations from gauge stations near the Missouri River. In the evaluation, the red number represents the water level observed by the SWOT of the river and the change value of the river at the adjacent moment, and the black represent changes in in-situ water levels. The final results demonstrate that SWOT can achieve a relative accuracy of approximately 0.1m for small-scale water bodies.

FLOOD DYNAMICS ANALYSIS

Floods cause significant global damage, with annual economic losses reaching $290 billion in 2023 due to natural disasters.[5] Effective flood monitoring is crucial for disaster management and mitigation. Traditional methods, relying on meteorological and hydrological stations, often lack precise topographical data and extensive water level measurements, making them inadequate for high-precision monitoring. Satellite remote sensing using visible and thermal infrared bands helps identify water bodies but fails during cloudy and rainy conditions, complicating the assessment of inundation depths and floodwater velocities. SWOT provides high-resolution, wide-swath measurements of water surface elevations, capable of penetrating through clouds and vegetation. This enables more accurate flood mapping and water flow monitoring, thereby enhancing our capacity to track floods and mitigate risks compared to existing satellites.

Compared with traditional methods, the SWOT satellite can provide comprehensive near-real-time 3D flood information through advanced KaRIn technology. SWOT employs nine KaRIn beams to create detailed 3D images of flood zones, accurately tracking inundation, water level rise rates, and flood propagation. SWOT's high-resolution data can be integrated into advanced hydrological models, enhancing flood prediction capabilities. Traditional stream gauges provide limited data and often fail to capture the full extent of flooding. In contrast, SWOT measures water level, width, and slope across vast areas, offering a comprehensive understanding of flood dynamics and allowing accurate tracking of floodwater movement. These high-resolution measurements reveal dynamic features in flood-prone areas, significantly enhancing our understanding of flood dynamics and associated risks.

The SWOT satellite have shown a large potential in monitoring flooding hazards. In February 2024, California, USA experienced a severe flood threat due to heavy rainfall. During this event, the SWOT mission successfully recorded the flood as shown in Figure 1. Specifically, the SWOT satellite can effectively monitor the entire process of flooding from onset to dissipation, including detailed changes in water levels. Key hydrologic parameters such as streamflow and flood runoff volume can be derived from SWOT, providing valuable insights into flood behavior. In addition, SWOT high-resolution data and continuous measurement capabilities make it particularly well-suited for flood monitoring and hydrologic model calibration, thus playing an essential role in enhancing flood warning systems and improving response strategies.

CHALLENGES AND FLUTURE DIRECTIONS

Despite its advantages, SWOT faces many challenges and future directions:

Water Level Measurement Accuracy: The accuracy of SWOT's radar interferometer and nadir-looking altimeter can be affected by water surface wind speed and scattering characteristics. These factors may introduce errors, necessitating ongoing studies and algorithm enhancements to improve measurement reliability.

Spatial Resolution: SWOT's water surface raster data products have spatial resolutions of 100m and 250m. This resolution might miss finer geographical features and subtle hydrological changes, particularly in small or narrow water bodies, highlighting the need for advancements in spatial resolution to capture these details.

Integration with Other Satellite Remote Sensing Products: By integrating multiple data sources, such as ICESat-2, and Sentinel, with SWOT data, we can refine the accuracy and temporal resolution of surface water level measurements, aiding in more precise monitoring of hydrological phenomena.

Combination with Hydrological Models: Remote sensing can provide snapshot observation when the satellite overpass, while the hydrological models are able to continuously simulate hydrological processes. Integrating SWOT data with these models through data assimilation techniques is able to enhance the depth and continuity of our understanding of water dynamics.

Denoising of Water Surface elevation Raster: Radar layover effects may introduce noises and distortions in SWOT data, particularly in regions with complex topography. Advanced denoising algorithms are required to address these effects, ensuring accurate measurements of water surface elevation and slope, which are critical for reliable river discharge estimates.

CONCLUSION

In summary, the SWOT satellite represents a significant leap forward in global surface water monitoring, offering high-resolution, wide-coverage data that are crucial for understanding and managing water resources in the face of climate change. While challenges remain, ongoing advancements in measurement techniques and data processing are expected to further enhance the satellite's capabilities. By providing critical data on surface water dynamics, SWOT will play a pivotal role in supporting sustainable water resource management and disaster risk reduction.

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AUTHOR CONTRIBUTIONS

Conceptualization: N.X., H.L.. Investigation: J.Y., N.X., H.L.. Writing - Initial: J.Y., M.W.. Writing - Review, Editing: P.G., H.L., Y.C., X.T., F.M.. Funding acquisition: J.Y., N.X.. All authors contributed to and approved the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.