Assessing Carbon Properties in Coastal Waters with a New Observing System Testbed

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***Abstract*— Large rainfall events over land can lead to a substantial flux of carbon and nutrients to estuaries and the coastal ocean. In the mid-Atlantic on the east coast of North America (35° - 42° N), these events often happen due to tropical storm activity as well as less predictable anomalously large midlatitude storms or abrupt spring snow melt runoff. Storms can directly impact the coastal carbon cycle via export of carbon from land to sea, while also stimulating phytoplankton production due to the influx of nutrients to the coastal ocean. To assess the impact of high precipitation and river flow events on the coastal carbon cycle, we have integrated multiple observing platforms in an analytical framework to dynamically observe carbon-related properties. The new observing system testbed (NOS-T) allows for an estimate of phytoplankton and organic carbon stocks in the surface ocean, with a goal of providing near real time analytical capability. A case study of high river discharge in the mid-Atlantic in the summer and fall of 2018 and 2021 were used to examine how riverine carbon manifests along the land-estuary-ocean continuum particularly in Chesapeake Bay.**

Chesapeake Bay was chosen as the study site because of long-term monitoring by the Chesapeake Bay Program and a robust and well-developed regional biogeochemical modeling system, the Chesapeake Bay Environmental Forecast System (CBEFS), that is publicly available. There is also new capability in Chesapeake Bay to combine hyperspectral radiometric data from the Aerosol Robotic Network site that is online in 2022 with in-water observations of optical properties. Precipitation data from the Global Precipitation Measurement IMERG data set was used to establish triggering criteria for storm carbon flux observation. USGS and in-water carbon data were used to establish statistical models to estimate the mass flux of organic carbon into Chesapeake Bay using measured river discharge. The year 2018 was examined as there was record rainfall and near record river flow in the late summer. The CBEFS modeling was compared with in-water estimates of dissolved organic carbon (DOC) to assess the model's ability to capture storm fluxes of carbon to the ecosystem.

Multiple satellite platforms were also used to assess how remote sensing using passive Earth orbiting sensors can be used to observe carbon in this complex coastal region. A set of recommendations have been established to improve sensing capability to measure aquatic carbon during storm events. A unique challenge in these dynamic inland waters is how rapidly carbon fluxes can evolve in space and time, with many sources contributing to the water leaving reflectance that satellites can observe. To improve our ability to quantify carbon stocks and fluxes in near real time, a suite of satellite sensors and high-resolution modeling capability is needed, all supplemented by in-situ monitoring. Future inclusion of in-water observations that would be deployed when the system reaches triggering criteria, as well as taskable orbital instruments, will improve estimates of ocean carbon properties and provide the ability to calculate major carbon stocks and fluxes in near real time following episodic storm events.

Keywords—land-ocean continuum, carbon cycle, distributed sensing, data fusion, satellite remote sensing

I. Science Motivation

The transport of carbon from land to sea is recognized as an important yet uncertain term in regional and global carbon accounting, with the annual carbon land to sea carbon flux on the order of terrestrial and marine net production (IPPC-AR6). The uncertainty is due to several factors, not limited to the dynamic physical environment, large environmental gradients, and multiple interacting carbon sources and sinks across the land-ocean continuum. Particularly challenging and unique to coastal ecosystems are the many impacts that human population centers can have on coastal biogeochemistry and water quality.

In addition, pulses of carbon from land to sea during large storms can have direct and indirect impacts on the annual carbon flux that occur on short time scales.

Visible short-wave infrared (VSWIR) satellite remote sensing of the world's oceans has yielded profound insights into the global marine carbon cycle, but significant challenges remain in applying such technologies in estuarine and coastal waters given the complexity of their optical signatures. There are three main challenges to remotely sensing coastal systems: 1) The spatial and temporal resolution required is often finer than what traditional ocean color instruments with daily revisit (e.g. 500 m - 4 km MODIS) offer; 2) The water can be turbid and optically complex with high levels of absorption and scattering by suspended and dissolved material, or the sea floor can reflect light back into the atmosphere from the surface; and 3) Complex interacting biogeochemical processes with multiple carbon sources and feedbacks make the quantification of carbon flow and fluxes very difficult with current observational capability. There is no doubt that the fleet of earth observing satellites has led to improvement in the observation of coastal systems and that advancing technology will improve that capability. However, the augmentation of satellite observations with real-time in-situ data collection and modeling will be crucial for continued understanding of coastal biogeochemistry. Data acquisition from multiple observing platforms has the potential to reduce uncertainty and revolutionize how earth-system observations are integrated for a holistic approach to quantifying the coastal carbon cycle.

An "upstream" factor that can play a large role in carbon accounting is the frequency and intensity of episodic storms and large runoff events from rivers. These events can alter the local and regional carbon budgets, ecosystem structure, and water quality for weeks to months and can play a disproportionate role in the total flux of material from land to sea [1, 2, 3, 4]. In temperate latitudes, runoff associated with large storms can export a large portion of the annual land-ocean flux in a short period of time. While these events occur with some regularity and predictability, often with a one-to-two-week lead time, preparing large scale sampling efforts quickly can be costly and hazardous due to the often inclement conditions. This makes it impractical to capture the spatial and temporal variability necessary to quantify carbon fluxes with in-water observations alone. Furthermore, sustained observations are needed to truly quantify the direct export of carbon from land to sea and secondary effects that may arise such as a shift in the net carbon flux in coastal waters. These changes will occur on short (days to weeks) and medium (weeks to months) time scales. A network of integrated modeling and observational tools is necessary to resolve the bulk of the carbon transport and transformation from land to sea.

The NASA Earth Science Technology Office New Observing Strategy Testbed - Oceans supported an initial exploration and development of a scientific and analytical framework for the integration of multilayer observations of the coastal ocean. The overall goal was to develop capability to proactively detect and observe large carbon flux events in near real time because of the outsized influence these events can have on regional and global carbon budgets. This was done to assemble and better understand current capabilities for Earth observation and algorithm integration in support of a coastal ocean carbon observatory NOS-testbed. Specifically, we wanted to see what kind of information could be acquired from current observational and modeling capability in the mid-Atlantic region of the United States and how products could be analytically linked for coastal carbon quantification. From this, we have identified necessary lines of research and technology development to leverage New Observing Strategies to maximize the scientific and societal use of the next decade of Earth observations.

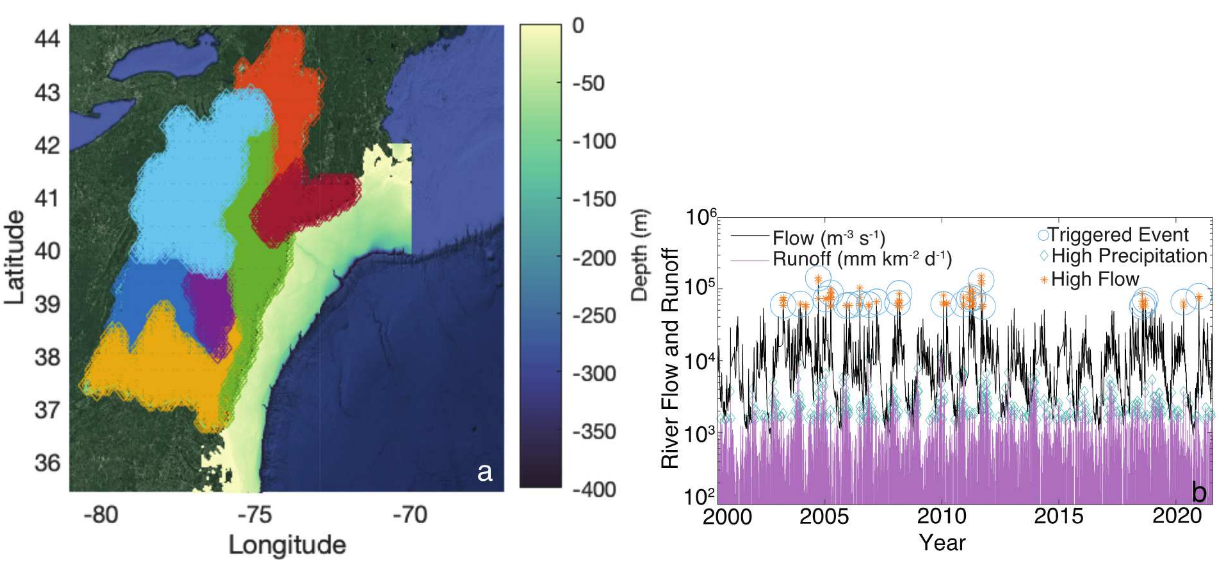

Fig. 1 (a) The Mid-Atlantic region and Chesapeake Bay watershed showing the major river polygons used in the Global Precipitation Measurement (GPM) analysis. GPM data was combined with USGS river flow to identify anomalously high precipitation and river flow events since 2000 (b).

II. USING SATELLITE OBSERVATIONS TO IDENTIFY HIGH RIVER FLOW

The Global Precipitation Measurement IMERG precipitation data product [5] was combined with USGS river flow over the Chesapeake watershed (Fig. 1a) to identify when large river flow events occurred. The framework was designed to utilize GPM observations as the only data processed continuously to identify when precipitation events may drive high river flow. GPM early precipitation data is readily available in standard formats from the NASA GES-DISC repository so integration into an open-source framework for continuous data processing was relatively straightforward. The initial triggering criteria were set using 5-day accumulated rain-flow exceeding the 95th percentile for each watershed polygon (Fig. 1b). The historical data record was used to set the distribution that each sliding window of observations were compared against. This methodology reliably identified time periods when high river flow occurred while also not being too strict to allow for identification of potential storm events when extremely high precipitation and high river flow were uncoupled.

III. ESTIMATING ORGANIC CARBON EXPORT FROM RIVERS INTO CHESAPEAKE BAY

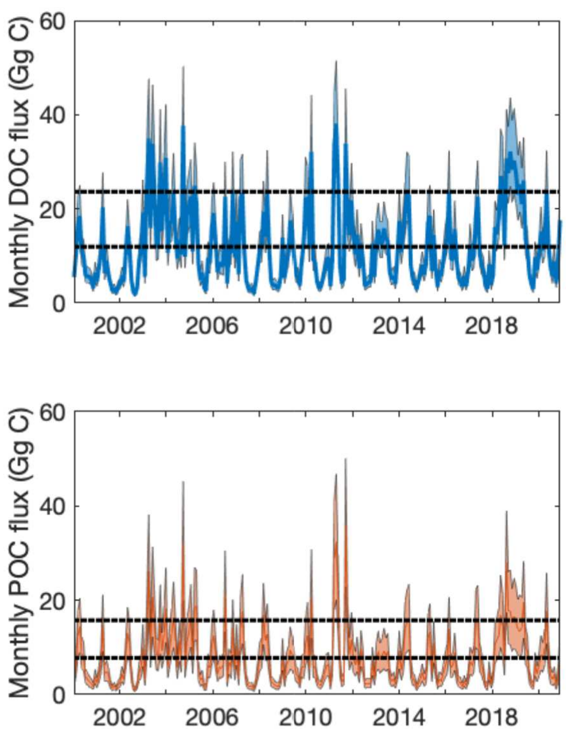

Fig. 2 Monthly estimated dissolved organic carbon (DOC) and particulate organic carbon (POC) flux for the major rivers into Chesapeake Bay. These estimates were produced combing Chesapeake Bay Program observations with the USGS Load Estimator software. The shaded area represents the mean ±1 standard deviation and the two dashed lines represent the mean (lower) and the 95th percentile (upper).

Long term trends of dissolved organic carbon (DOC) and particulate organic carbon (POC) inputs to Chesapeake Bay from the major rivers were estimated using combined in-water measurements and observed river flow. The USGS Load Estimator [6] software was utilized to constructed a statistical model of carbon mass export as a function of time. From these models, time series with uncertainty were generated and periods of high organic carbon inputs were identified above the 99th percentile (Fig. 2). The statistical model used to relate water chemistry to river flow can be used to estimate total mass inputs in near-real time as river flow is constantly measured at major rivers. This allows an upstream input to the system setting the landward boundary of a carbon budget during normal-flow and storm-flow time periods. More high-quality observations of carbon species such as dissolved inorganic carbon, alkalinity, DOC, and particulate carbon are needed to further constrain the carbon estimates. This statistical methodology is well tested and can be used in regions where observations are available to establish the statistical relationship. Extrapolation to un-gauged rivers or regions with a lack of water chemistry measurements requires careful consideration but is possible using other geographical metrics. Machine learning techniques to relate water chemistry to river flow are being tested and may be more widely applicable across regions. A specific series of high river

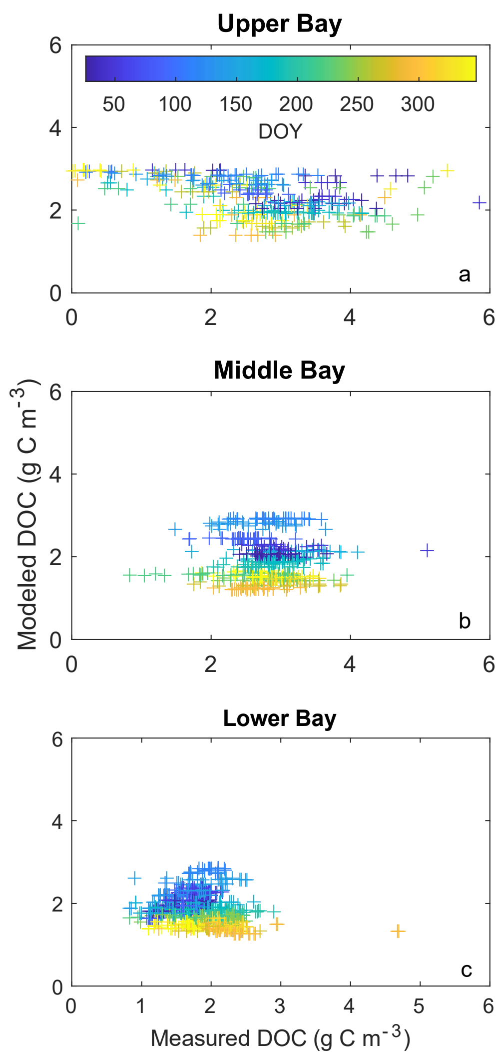

Fig. 3 Chesapeake Bay Environmental Forecast System modeled vs. measured dissolved organic carbon (DOC) for the upper, middle, and lower Chesapeake Bay regions for 2018. The color of each mark represents the day of the year (DOY). The measured DOC is estimated by using the mean of the historical DOC:DON ratio and the measured DON from 2018.

flow events in 2018 were used below to show the potential of integrated observations in estimating carbon stocks and fluxes in Chesapeake Bay.

IV. Regional Biogeochemical Model Estimates of In-Water Carbon at High Temporal Resolution

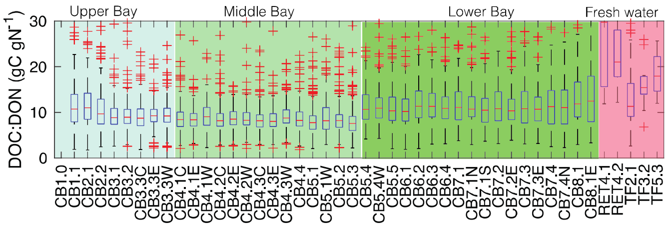

Fig. 4 Historical measurements from the Chesapeake Bay Program of the dissolved organic carbon (DOC) to dissolved organic nitrogen (DOC) ratio. The edges of each box are the 25th and 75th percentile while the red marks represent statistical outliers.

The Chesapeake Bay Environmental Forecast System (CBEFS) provides a daily real time, publicly available estimate of many biogeochemical variables in Chesapeake Bay [7]. The model is highly tested and specifically designed to simulate processes related to the cycling of carbon and nutrients within the bay. Here we did an initial evaluation of the model against in-situ observational estimates of DOC down the bay in 2018 to assess the ability of the model to capture high river flow events. DOC was used because in coastal regions much of the DOC is optically active as colored (or chromophoric) dissolved organic matter making remote sensing of DOC concentration possible. The next section will show initial results of satellite-estimated DOC during the 2018 storm compared to model estimates. The model captures the mean condition quite well in the upper middle and lower bay, but the temporal variability is not well captured (Fig. 3). The observation-model residuals are significantly negatively correlated with time for the middle and lower bay (R^2=0.24, p<0.001 and R^2=0.45, p<0.001). This indicates that seasonal variability is muted within the model and some processes that act as sources of DOC later in the year were not captured by the model configuration. The high discharge inputs of DOC occurred later in the year which likely drives some of the model-data mismatch. CBEFS generally predicted a decline in DOC throughout the year while the observational estimates show a flat temporal response or an increase in DOC in the lower bay stations.

The in-situ estimates do not provide a perfect comparison for model predictive accuracy because they are based on the historical record of DOC:DON ratio which is highly variable (Fig. 4). The lack of contemporary observations of DOC is a serious hindrance to making an accurate model data comparison. Opportunities for future improvements include increasing observations of carbon concentrations to 1) Provide an accurate baseline for carbon concentration assessment in contemporary years and 2) Improve model parameterization and estimates of carbon during base conditions and especially during storms.

V. Towards Satellite Observations of Coastal Carbon Stocks and Fluxes

The optical properties of organic carbon make remote sensing via earth observing optical platforms possible. This is because both POC and DOC absorb Ultraviolet and Visible (UV-Vis) light in measurable ways that the satellite remote sensing reflectance (Rrs) can be used to estimate. Here we will focus on DOC because it is generally higher in concentration, is globally ubiquitous, and has a strong optical signature in coastal systems. Historical satellite observations of Rrs and estimated CDOM and DOC show reliability in estimating in-water DOC concentration from satellite instruments. Specifically, MODIS-Aqua has been used in the mid-Atlantic to predict DOC concentrations [8,9]. On longer time and space scales, satellite organic carbon concentration estimates have high value because of the ability to decrease noise by temporal averaging. Interference from clouds, high turbidity, and poor atmospheric correction lessen as more images can be included into an average composite.

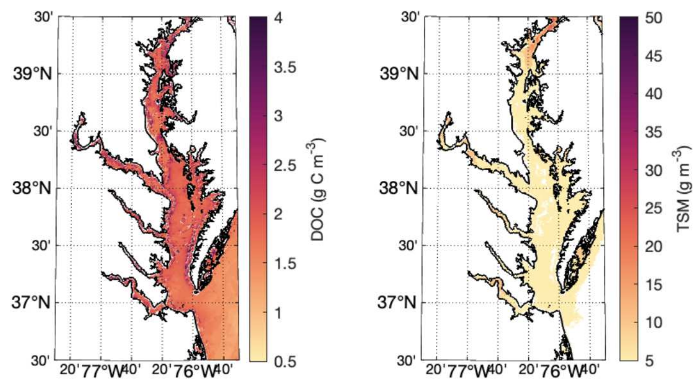

Fig. 5 MODIS-Aqua estimated dissolved organic carbon (DOC) and total suspended matter (TSM) for the Chesapeake Bay averaged from July 21 to August 10th, 2018. DOC was estimated using the Mannino et al. 2015 algorithm and TSM was estimated using the Ondrusek et al. 2012 algorithm.

Over the short time and space scales that storm event observations are needed, satellite images become more difficult to reliably use in aquatic carbon estimation. This is because of cloudiness, individual image noise, and difficult atmospheric correction in coastal waters. MODIS-Aqua images were processed for a three-week period in 2018 around the high river flow event and were atmospherically corrected specifically for high turbidity waters [10]. A regional algorithm was used on the corrected reflectance to estimate total suspended matter (TSM) concentration [11] and DOC [8,9]. While the satellite predictions offer a spatially distributed estimate that can occur at relatively high spatial and temporal resolution, clouds and image noise can substantially decrease image utility. Images can be assembled into composites that yield valuable information about the surface concentrations of optically active constituents such as DOC and TSM (Fig. 5). Using a moving average can provide a continuous data product with decent coverage, but more advanced methods using image generation are needed to interpolate images through cloud cover during storm events. In the three-week period in 2018, only 7 of the 21 days had satellite coverage > 25 % of the pixels within Chesapeake Bay (Fig. 6). Developing technology to fuse model and satellite estimates more realistically with mass conservation will yield a composite product at a spatial and temporal scale that is useful for carbon accounting.

Satellite observations (moderate resolution, moderate accuracy) offer an intermediate estimate between in-situ

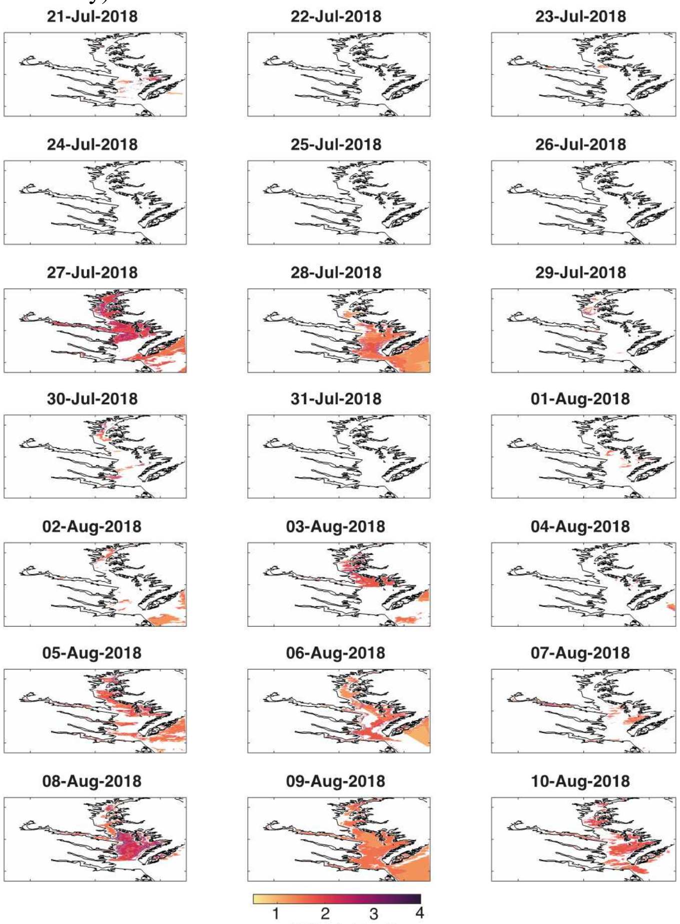

Fig. 7 Satellite estimated dissolved organic carbon (DOC) estimated for the 2018 anomalous precipitation and river flow event. Lack of color indicates satellite derived data are missing, e.g., due to clouds or sunglint.

observations (high accuracy, low resolution) and regional biogeochemical models (high resolution, low accuracy). Beyond the issue of clouds, there needs to be a standardization across satellite sensors to allow for a seamless prediction of algorithmically estimated concentration. Sensors on satellites such as Landsat-8/9 and Sentinel-2a/b provide high spatial resolution, but generally lower signal-to-noise ratio (SNR) and lower revisit times over the same place on Earth. These satellites can provide valuable spatial information that can be combined with other higher revisit satellites to provide a high-dimensional fused image. Utilizing more spectrally diverse sensors in a cohesive methodology is needed to have consistent Rrs-derived estimates of DOC across datasets. Upcoming missions such as the Plankton, Aerosol, Cloud, and ocean Ecosystem satellite (PACE; https://pace.oceansciences.org/home.htm) with its hyperspectral Ocean Color Instrument (OCI) will provide unprecedented spectral resolution at moderate spatial resolution (1km) and nearly daily global revisit. Geostationary satellites such as the Geostationary Littoral Imaging and Monitoring Radiometer (GLIMR; https://eos.unh.edu/glimr) can provide the temporal resolution needed in coastal regions where tides and storms evolve over hours. Cloud cover will always be an issue with passive satellite sensors making in-situ data, remotely operated vehicles, and high-resolution models crucial to capture these transient carbon flux events.

VI. Concluding Remarks

The need for sustained observations to accurately estimate carbon fluxes in coastal waters is increasing with carbon budget assessment goals, e.g., United Nations Framework Convention on Climate Change Global Stocktake. As storm events become larger and more frequent, the influence they have on regional and global carbon budgets will increase. Carbon accounting on an international, regional, and global scale is now routinely done and the more granular the required carbon budget, the more accuracy that is needed. This requires a seamless integration using regional biogeochemical models and in-situ observations (where available), and the fleet of earth observing satellites. Particularly important is to develop the ability to reliably deploy instruments and sensors during large runoff events. We have seen just this last summer catastrophic flooding in Pakistan coinciding with historic drought in Europe all while the largest reservoir in the United States continues to decline. The tools and automated workflows to reliably observe the flux of carbon must be developed now to be prepared for a highly variable and uncertain hydrologic future in the coastal ocean. Much of the technology development, specifically in computer software and open-source science, requires continued investment to get to the point of applicability for regulatory or economic purposes, and to apply this technology to future satellite missions.

Acknowledgment

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