frontiers in Remote Sensing

TYPE Editorial
PUBLISHED 07 October 2026
DOI 10.3389/frsen.2026.1994165

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OPEN ACCESS

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RECEIVED 10 September 2026
REVISED 22 September 2026
ACCEPTED 28 September 2026
PUBLISHED 07 October 2026

CITATION
Lux O and Milinevsky G (2026) Editorial: Instruments and Technologies for Earth Observation Satellite Missions.
Front. Remote Sens. 7:1994165.
doi: 10.3389/frsen.2026.1994165

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Editorial: Instruments and Technologies for Earth Observation Satellite Missions

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KEYWORDS
Earth observation, Falcon Neuro, HARP, satellite missions, Sentinel-3A, Sentinel-3B

Editorial on the Research Topic
Instruments and technologies for earth observation satellite missions

The acquisition of global observations from space has become essential for environmental monitoring, weather prediction, and climate research. Earth observation satellite missions provide measurements across large spatial scales and increasingly high spatial, spectral, and temporal resolutions, enabling the investigation of complex processes within the atmosphere, ocean, and terrestrial environment. Meeting the growing demands of Earth system science, however, requires continuous advances in sensor technologies, observation concepts, retrieval methodologies, and calibration and validation strategies. The Research Topic *Instruments and Technologies for Earth Observation Satellite Missions* brings together contributions that demonstrate recent progress in these areas and highlight opportunities for improving both the quality and scientific exploitation of satellite observations.

A key aspect of current developments in Earth observation is the ability to extract additional physical information from measurements through innovative sensor concepts. Polarimetric observations provide an important example. The contribution from Smith et al. presents the Hyper-Angular Rainbow Polarimeter 2 (HARP2), deployed on NASA's Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission. In addition to measuring aerosols, the instrument provides highly accurate, multi-angle polarized observations of clouds and is particularly sensitive to the polarized cloudbow produced by liquid-water cloud droplets. The angular structure of this feature contains information on cloud droplet size distributions, allowing the retrieval of effective radius and variance. With a spatial resolution of approximately 5 km and a wide observational swath, HARP2 enables these measurements on a global scale. Its capabilities demonstrate how targeted instrument design can provide new links between cloud microphysics and radiative properties and thereby open new avenues for investigating the role of clouds in the Earth system.

The scientific potential of multi-angle polarimetry is further illustrated by the application of cloud tomography to observations from the Research Scanning Polarimeter (RSP). Alexandrov et al. demonstrate the retrieval of two-dimensional distributions of cloud extinction from real airborne measurements acquired during the Cloud, Aerosol and Monsoon Processes Philippines Experiment. The tomographic approach combines information on cloud geometry and directional cloud optical thickness with mathematical inversion techniques to reconstruct the internal structure of clouds. When combined with droplet size information obtained from polarized

measurements, the retrieved extinction fields can be related to droplet number concentration. Comparisons with coincident lidar and cloud-radar observations provide an important basis for evaluating the retrievals. Beyond the specific application, this work demonstrates how advanced measurement geometries and inverse methods can transform remote sensing observations into spatially resolved information about processes occurring inside clouds.

Innovation in Earth observation also extends to fundamentally different approaches to image acquisition. The Falcon Neuro mission explores the use of event-based vision sensors installed on the International Space Station to detect lightning and related atmospheric electrical discharges. Lightning is characterized by rapid temporal evolution, creating demanding requirements for both spatial and temporal sampling. The study from McHarg et al. demonstrates that event-based sensors provide an alternative to conventional frame-based imaging by responding to changes in the observed scene. Initial measurements demonstrate the potential of this technology for space-based lightning observations. This contribution highlights the opportunities offered by emerging sensor technologies and illustrates how concepts initially developed for other applications can be adapted to address specific challenges in Earth system observation.

Another important direction is the optimization of how measurements are acquired. For satellite observations of atmospheric carbon dioxide and methane, clouds can lead to the rejection of a large proportion of measurements. Rather than addressing cloud contamination exclusively after data acquisition, the paper from Nassar et al. investigates the use of real-time cloud information to guide instrument pointing. Simulations of such an "intelligent pointing" strategy show that substantial improvements in the fraction of cloud-free observations can be achieved, particularly for missions in highly elliptical or geostationary orbits. The analysis further demonstrates that field-of-view geometry plays an important role in observational efficiency, with imaging Fourier transform spectrometers offering advantages for scanning irregularly shaped land areas. These findings point toward a more adaptive approach to satellite observations in which environmental information is used to optimize measurements in real time.

The work from Gilerson et al. emphasizes another fundamental requirement for successful Earth observation: the rigorous characterization of measurement uncertainty. Uncertainties in ocean-color remote sensing reflectance directly affect the retrieval of chlorophyll-a concentrations and other water properties. An analysis of measurements from the Sentinel-3A and -3B Ocean and Land Colour Instrument (OLCI) shows that, consistent with findings for other ocean-color sensors, spectral components from Rayleigh scattering and surface effects constitute a major source of uncertainty. Variability associated with water-leaving reflectance is also important in coastal regions, while contributions from aerosols and glint are comparatively smaller. The results emphasize that improvements in satellite data products depend not only on sensor performance but also on a detailed understanding of atmospheric correction, radiometric uncertainties, and the characteristics of different observing environments.

Viewed together, the contributions demonstrate the breadth of technological and methodological advances currently shaping space-borne Earth observation. They encompass novel polarimetric instrumentation, tomographic retrieval techniques, event-based imaging, adaptive observation strategies, and systematic uncertainty analysis. Importantly, these developments address different stages of the observation chain: from how measurements are acquired, through how instruments are operated, to how observations are interpreted and their accuracy assessed.

This combination of technological innovation and methodological development will become increasingly important as satellite missions evolve toward more complex and integrated observing systems. Future instruments are likely to provide measurements with greater angular, spectral, spatial, and temporal information, while increasingly autonomous observation strategies may allow missions to respond dynamically to changing environmental conditions. At the same time, the growing diversity of observations will make robust calibration, validation, uncertainty quantification, and physically based retrieval methods essential for ensuring that increased data volume translates into increased scientific knowledge.

The contributions assembled in *Instruments and Technologies for Earth Observation Satellite Missions* thus provide examples of both current capabilities and future directions in satellite remote sensing. They demonstrate that advancing Earth observation is not simply a matter of developing more sensitive instruments or acquiring more data. Progress also depends on designing measurements around the physical information sought, exploiting innovative observation concepts, optimizing the use of available measurement opportunities, and establishing the accuracy and limitations of the resulting products. Together, these advances will strengthen the ability of Earth observation satellite missions to provide the reliable, detailed, and globally consistent information needed to understand and monitor our changing planet.

Author contributions

OL: Writing – original draft, Writing – review and editing. GM: Writing – original draft, Writing – review and editing.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The authors OL, GM declared that they were an editorial board member of Frontiers at the time of submission. This had no impact on the peer review process and the final decision.

Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. Language editing assistance was provided using ChatGPT (OpenAI).

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