BAMS
Meeting Summary

Advances in Precipitation Retrieval and Applications from Low-Earth-Orbiting Satellite Information

Vesta Afzali Gorooh, Kuolin Hsu, Ralph Ferraro, Joe Turk, Huan Meng, Phu Nguyen, Claudia Jimenez Arellano, Satya Kalluri, and Soroosh Sorooshian

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Virtual NOAA Workshop on "Precipitation Estimation from LEO Satellites: Retrieval and Applications"

What: Scientists and stakeholders from precipitation sensor developers, remote sensing algorithm developers, and data users gathered to discuss the state of the science and users' needs for operational precipitation algorithms and products from current and future meteorological satellites.

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Where: Online

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Corresponding author: Vesta Afzali Gorooh, vafzaligorooh@ucsd.edu
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AFFILIATIONS: Afzali Gorooh—Center for Western Weather and Water Extremes, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California; **Hsu, Nguyen, and Jimenez Arellano**—Department of Civil and Environmental Engineering, Center for Hydrometeorology and Remote Sensing, University of California, Irvine, Irvine, California; **Ferraro**—Earth System Science Interdisciplinary Center, University of Maryland, College Park, College Park, Maryland; **Turk**—Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California; **Meng**—National Oceanic and Atmospheric Administration/Center for Satellite Applications and Research/National Environmental Satellite, Data, and Information Service, College Park, Maryland; **Kalluri**—National Oceanic and Atmospheric Administration/Joint Polar Satellite System Program Office, Greenbelt, Maryland; **Sorooshian**—Center for Hydrometeorology and Remote Sensing, Department of Civil and Environmental Engineering, and Department of Earth System Science, University of California, Irvine, Irvine, California

Satellite precipitation retrieval provides essential data over regions where in situ measurements are limited. Low-Earth-orbit (LEO) meteorological satellites operated by the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), the Japan Aerospace Exploration Agency (JAXA), the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), and other agencies worldwide have been the primary source of remotely sensed information used in global and regional precipitation estimation algorithms. The office of LEO Observations (LEO) at NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) sponsored a workshop by the Center for Hydrometeorology and Remote Sensing (CHRS) at the University of California, Irvine, to bring together remote sensing precipitation experts. These experts comprise sensor and algorithm developers and operational data users. This effort aimed to review the existing and future requirements of LEO meteorological satellites. By bringing together a diverse range of expertise, the aim was to identify the current and emerging needs in this field for enhanced satellite-based precipitation monitoring and analysis.

This workshop presented recommendations for addressing various aspects of precipitation sensing from LEO satellites in different areas: (i) Observation system requirements and data delivery, which consider the need for the satellite constellation or other platforms to ensure comprehensive coverage and data collection. Data delivery requirements ensure efficient and effective data delivery. The workshop offered insights into factors like latency and availability that should be considered. (ii) Value/impact studies are critical for understanding the potential value and impact of the observation system. The workshop demonstrated the benefits and implications of implementing satellite-based precipitation estimation and analysis uncertainty. (iii) Measurement requirements, which cover measurement criteria, such as the required channels or sensors, should be addressed in the observation system designs. (iv) Algorithm development and applications, which explore various applications by leveraging the observation system's capabilities. The workshop highlighted the importance of algorithm development for processing and analyzing the collected data. Considering the above areas, the workshop was organized into four major themes: theme 1: NOAA and international communities' plan on LEO satellites and sensors; theme 2: precipitation estimation and algorithms from LEO and combined satellite sensors; theme 3: precipitation estimation and uncertainties; theme 4: users and applications.

International communities' plan on LEO satellites and sensors

Participants in theme 1 highlighted the crucial role of diverse passive and active remote sensing techniques, ranging from ground-based observations like rain gauges and weather radars to satellite systems encompassing visible, infrared (IR), and microwave (MW) spectrums. Notably, the historical development of precipitation instruments (Kidd et al. 2021) was discussed, tracing back to the late 1960s and leading to groundbreaking joint NASA–JAXA missions like Tropical Rainfall Measuring Mission (TRMM; Kummerow et al. 2000, 1998; Simpson et al. 1996) and Global Precipitation Measurement (GPM; Hou et al. 2014; Skofronick-Jackson et al. 2017). JAXA's significant contributions were underscored, emphasizing their passive MW (PMW) and active MW (AMW) sensors. Their forthcoming advancements, such as the launch of Advanced Microwave Scanning Radiometer (AMSR-3) on Global Observing Satellite for Greenhouse Gases and Water Cycle (GOSAT-GW) and Earth-CARE W-band radar observations, promise improved capabilities in monitoring cold-season precipitation (Fig. 1). EarthCARE will continue NASA's *CloudSat* observations that were found informative to enhance high latitude precipitation estimates (Behrangi et al. 2014; Behrangi and Song 2020). EUMETSAT's Polar System–Second Generation (EPS-SG) mission was also highlighted, introducing novel sensors like the Microwave Sounder (MWS), Microwave Imager (MWI), and the Ice Cloud Imager (ICI) sensors to enhance global precipitation observation (Mattioli et al. 2019). One of the most exciting discussions revolved around the Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats mission (TROPICS; Blackwell et al. 2018; Kidd et al. 2022) investigation, which involves small satellites providing imagery near 90 and 205 GHz, a temperature sounding near 118 GHz, and a moisture sounding near 183 GHz. These satellites, deployed in inclined orbit planes, aim to improve global revisit times, particularly addressing critical questions regarding tropical cyclone intensification. The workshop's discussions culminated in recommendations for prioritizing low-latency data for precipitation analysis, maintaining collaborations for PMW advancements, and investing in small satellite missions to improve precipitation retrievals.

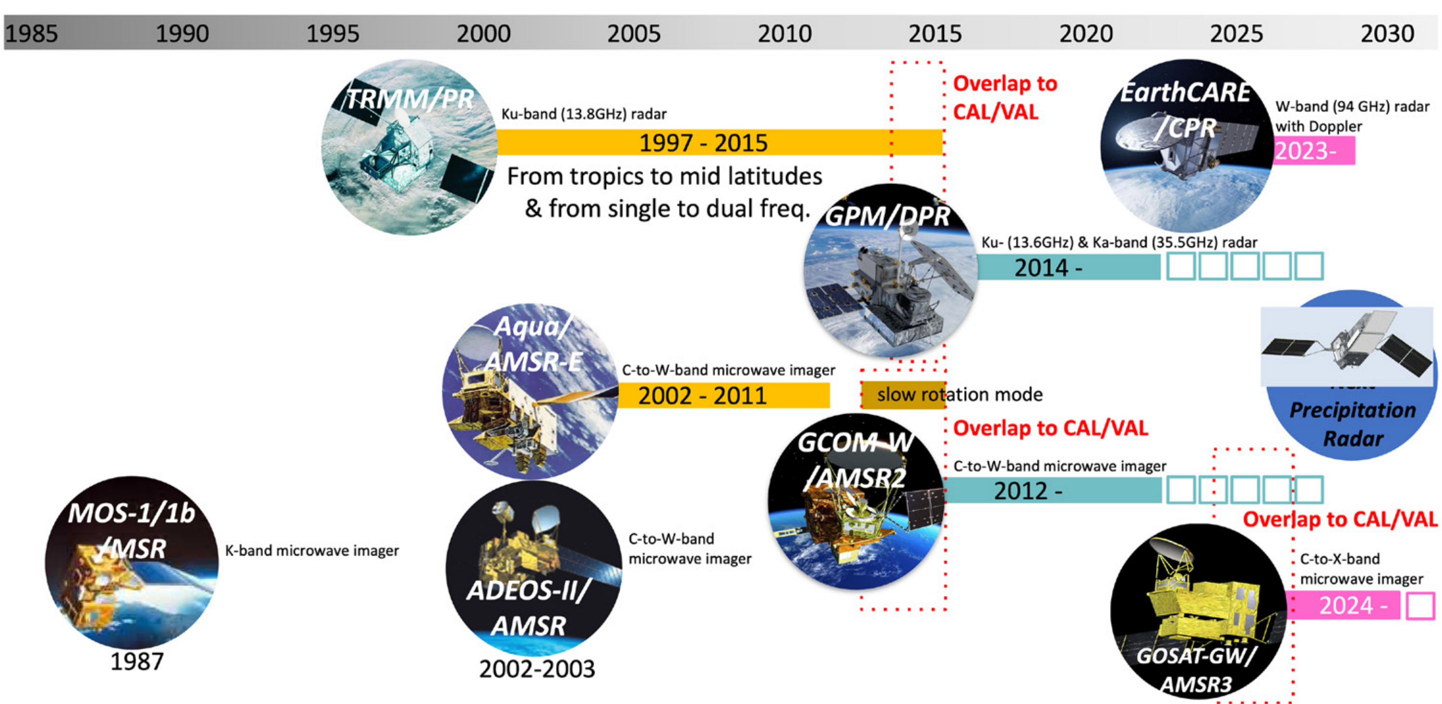

Fig. 1. Precipitation-related missions in Japan (source: Misako Kachi and Takuji Kubota presentations).

Insights into precipitation estimation algorithms from LEO and combined satellite sensors

Several discussions in theme 2 shed light on various aspects of satellite-based quantitative precipitation estimation (QPE) algorithms. Notable presentations included those on established PMW algorithms like Goddard profiling (GPROF; Kummerow et al. 1996, 2015; Pfreundschuh et al. 2022) and Microwave Integrated Retrieval System (MiRS; Boukabara et al. 2011, 2013). The GPROF algorithm uses a Bayesian framework to estimate precipitation rates, adapting to different PMW sensor capabilities, and a machine learning (ML) version is being investigated. MiRS, on the other hand, employs a variational approach and is adaptable in accommodating various satellite sensors. It offers promising performance, particularly during the cold season, and ongoing research aims to improve its accuracy. The meeting also focused on challenges in PMW snowfall techniques. Accurately detecting and quantifying snowfall from satellite observations remains complex due to microphysical variations and radiometric surface interactions. Efforts are being made to enhance snowfall detection algorithms and incorporate ML techniques (Adhikari et al. 2020; Yan et al. 2023; Fan et al. 2023, manuscript submitted to *J. Geophys. Res. Atmos.*). The presentations highlighted the limitations of current approaches in extreme cold conditions, orographic snowfall, and mixed-precipitation scenarios. Another discussion area centered around the Climate Prediction Center morphing (CMORPH; Joyce et al. 2004; Joyce and Xie 2011) algorithm and its recent improvements. CMORPH integrates data from various satellite sources, including IR data, to provide high-resolution precipitation analyses. While the update offers enhanced latency and coverage, challenges persist in accurately estimating orographic rainfall, snowfall, and mixed-phase precipitation.

Based on the presentations and discussions, several key recommendations emerged. There is a need for a methodology to assess the impact of changes to the satellite observing system and how they impact global precipitation products. Collaboration with the International Precipitation Working Group (IPWG) was emphasized to refine techniques, address challenges, and develop innovative methodologies. Sustaining joint radar and radiometer capabilities, improving precipitation evaluation for precipitation regimes outside those found in the contiguous United States (CONUS), and enhancing training datasets for diverse conditions were also highlighted. The meeting provided valuable insights into the state of satellite-based precipitation estimation and its challenges. It highlighted the need for ongoing research, collaboration, and advancements in algorithms to improve the accuracy of global precipitation products.

Unveiling precipitation estimation uncertainties

During the theme 3 of the workshop, which centered on understanding QPE's uncertainties and errors, several critical points were discussed by participants. One key takeaway was the importance of understanding the uncertainties associated with satellite data, particularly considering that datasets with higher temporal resolution tend to carry higher uncertainties (Hartke et al. 2022). Notably, due to their short latency, IR data from geostationary satellites were highlighted as essential for near-real-time satellite precipitation products. However, it was acknowledged that datasets derived from PMW sensors provide higher-quality precipitation data, albeit intermittently. Participants underscored the significance of integrating data from past and current satellites to ensure consistent and reliable Climate Data Records (CDRs; Ashouri et al. 2015; Behrangi et al. 2022; Joyce et al. 2004; Huffman et al. 2023). The challenges of integrating new instruments into long-term precipitation products were addressed, along with the importance of validating these products against various ground-based observations, particularly over challenging environments like oceans. The session also delved into the uncertainties associated with spaceborne radar observations, which are used to calibrate and verify global satellite precipitation estimates. The sources of uncertainty in radar observations were detailed, including radar reflectivity factor–rain rate relationship variability, attenuation, snow issues, ground clutter, and beam footprint variability (Battaglia et al. 2020). Strategies to minimize these uncertainties through parameterizations and a priori information from ground-based observations were proposed. The importance of accurate error modeling was highlighted for the appropriate utilization of satellite products in various applications. The participants stressed the need to consider location-specific error models and accurately model uncertainties to effectively utilize satellite products in various applications, including hydrological modeling, water resources management, and climate studies. The discussion also covered probabilistic QPE algorithms (Kirstetter et al. 2015), which consider uncertainty an integral part of estimation. These algorithms were presented as valuable tools for characterizing extreme weather events and enhancing hazard and risk analysis.

Precipitation estimation users and applications

Discussions in theme 4 highlighted the significance of satellite-based precipitation and water vapor products in enhancing weather forecasting and societal applications over challenging terrains like Alaska. The value of various LEO precipitation products for forecasters was emphasized, including the Advected Layer Precipitable Water (ALPW; Gitro et al. 2018) product, which provides insights into atmospheric water vapor distribution. The insights from the National Weather Service (NWS) Weather Forecast Offices (WFOs) and Weather Prediction Center (WPC) shed light on the critical role of low-latency precipitation products in situational awareness and short-term forecasting. The discussions outlined the needs of forecasters, emphasizing the importance of a high-spatiotemporal-resolution and low-latency satellite constellation to support real-time extreme precipitation prediction and nowcasting. For tropical cyclone monitoring, the workshop highlighted the essential role of LEO satellites' PMW window channels in observing convective structures and physical attributes of cyclones, aiding in intensity assessment. The Aviation Weather Center (AWC) presented their use of satellite-derived precipitation products for aviation Significant Meteorological Information (SIGMETs), indicating that enhanced products highlighting stratiform precipitation under nonglaciated clouds and supercooled cloud water could greatly benefit forecasting operations. Moreover, the workshop showcased that CDRs derived from satellite precipitation products have numerous applications, such as extreme precipitation studies, flood forecasting, and drought monitoring. The key recommendations arising from the discussions were the need for high-spatiotemporal-resolution, low-latency products for NWS users, and optimizing the satellite constellation configuration.

Concluding remarks

This workshop offered valuable recommendations to address the requirements and considerations associated with the satellite observation system, specifically emphasizing precipitation sensing. The participants and stakeholders have contributed key insights and recommendations presented in detail after each theme session in this document. Four primary conclusions emerged overarching the workshop:

- The best precipitation product that NOAA generates now, which can be improved upon in the future, is from an integrated GEO and LEO satellites and surface observation approach; no single observation method can accomplish this on a global scale.
- LEO PMW imagers serve as the backbone of the global satellite precipitation observation system, complemented by an expanding number of PMW sounders. This sensor diversity requires accurate intersensor calibration with similar class sensors, complemented with spaceborne radar and ground-based radars for training and validation.

- Frequent and low-latency observations are required to fulfill many NOAA operational responsibilities, such as weather, water, climate, and aviation hazards.
- Scientific advances are needed to optimize the information content provided by satellite and surface observations; approaches such as artificial intelligence and ML should continue to be pursued.

A summary of the recommendations that emerged from each theme considering various aspects of precipitation sensing from LEO satellites are listed below:

Observation system and data delivery requirements.

- NOAA should actively engage with national and international partners to ensure the continuity and expansion of sensors with precipitation-sensing microwave capabilities to achieve hourly to subhourly refresh rate. Such capability is crucial for NOAA operations and the application communities at large.
- Operational users require timely access to low-latency satellite data (1 h or less) for nowcasting and short-term forecasting. NOAA should prioritize the efficient acquisition of sensor data by developing capacities for near-real-time data downlinks through ground stations or expanding the direct broadcast networks from both NOAA and partner agencies. This includes the acquisition of legacy sensor data.
- Sustaining a joint satellite precipitation radar and conically scanning PMW radiometer reference capability, currently provided by the GPM core spacecraft in sun-asynchronous orbit, is critically essential for the intercalibration of constellation radiometers used in level-3 global precipitation datasets.

Value/impact studies.

- NOAA should routinely invest in performing sensor impact studies on precipitation products whenever new observation capabilities emerge from domestic, international, and private sector partners. Additionally, such impact studies should be performed before existing observation capabilities are considered for decommissioning by NOAA.
- IPWG is a central platform for the scientific community to collaborate on issues related to precipitation retrievals, supporting the future of precipitation-oriented missions. NOAA should continue its engagements with IPWG activities to refine existing techniques, develop innovative methodology, and, most importantly, address the challenges in the field.

Measurement requirements.
Use satellite/sensor impact study results to define and specify desired channel requirements including resolution and polarization for PMW-based rainfall and snowfall retrieval, including window channels near 6, 10, 19, 37, and 89 GHz, together with temperature and water vapor sounding bands near 23, 50, 118, 166, and 183 GHz and higher (Table 1).

Algorithm development and applications.

- Assessing uncertainty using prognostic approaches, employing probabilistic methods, leveraging global radar and ground observations beyond the continental United States, and considering robust data-driven techniques (e.g., ML) are strongly recommended to enhance satellite precipitation estimation.

Table 1. Recommended channels for PMW-based rainfall and snowfall retrievals

Frequency (GHz) / Characteristics	10 H/V	19 H/V	23 H/V	31-37 H/V	50-55 H/V	89 H/V	166 H/V	183 H/V
Light rain over land					x	x	x	x
Heavy rain over land	x	x	x	x	x	x	x	x
Light rain over ocean	x	x	x	x	x			
Heavy rain over ocean	x	x	x	x	x	x	x	x
Snowfall detection over land		x	x		x		x	x
Snowfall detection over ocean		x	x	x	x		x	x
Snowfall rate over land		x	x	x	x	x	x	x
Snowfall rate over ocean				x	x	x	x	x

- Collaboration with the user community is essential to define requirements for establishing a robust climate data record using precipitation radar reference, considering the long duration of operational PMW satellites extending back to 1987 with the Special Sensor Microwave Imager (SSM/I) series.
- Using spaceborne radars for calibrating passive sensors and integrating ground-based observations are essential for diagnosing errors and improving the accuracy of precipitation retrievals. It is advisable to incorporate precipitation parameterizations and prior information from ground observations to mitigate uncertainties in spaceborne radar observations, leading to more accurate and reliable multisatellite precipitation retrievals.
- To effectively utilize satellite products in hydrological modeling, water resources management, and climate studies, incorporating location-specific error and uncertainty models that account for regional variability, time frames, precipitation events, and application domains is recommended.

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