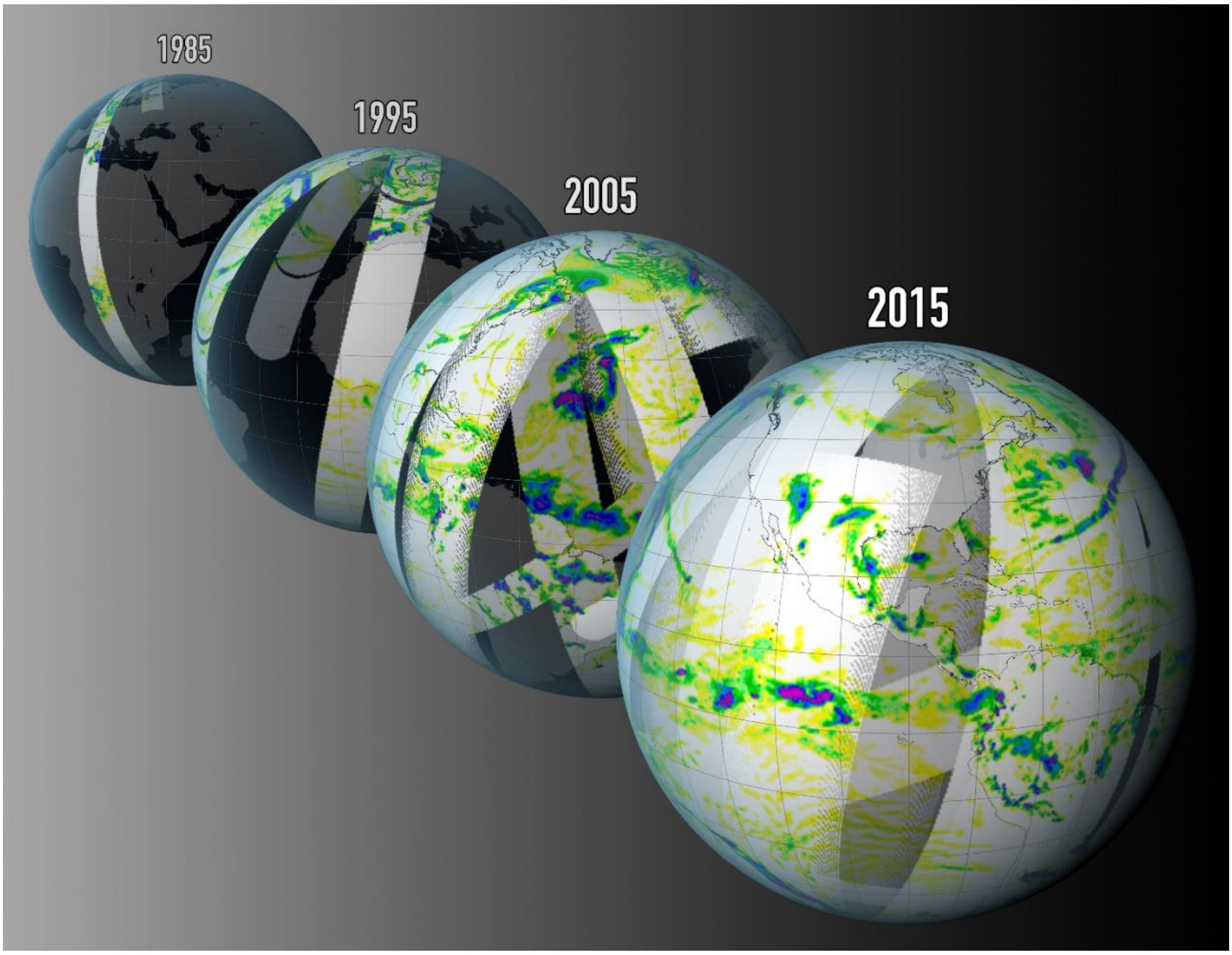
Committee on Earth Observation Satellites

Precipitation
Virtual
Constellation

The Global Satellite Precipitation Constellation: current status and future requirements



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Chris Kidd[1,2]
George Huffman[2]
Viviana Maggioni[3]
Philippe Chambon[4]
Riko Oki[5]

[1] *Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD. USA*
[2] *NASA/Goddard Space Flight Center, Greenbelt, MD. USA*
[3] *Sid and Reva Dewberry Department of Civil, Environmental, and Infrastructure Engineering, George Mason University, Fairfax, VA, USA*
[4] *CNRM, Université de Toulouse, Météo-France, CNRS, Toulouse, France*
[5] *Earth Observation Research Center, Japan Aerospace Exploration Agency, Ibaraki, Japan.*

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Revision History

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1.0	CEOS P-VC and community acceptance	xxxxxx 2021	

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Glossary

ABI	Advanced Baseline Imager (GOES)
ACCP	Aerosols, Clouds, Convection and Precipitation
AHI	Advanced Himawari Imager
AMSR	Advanced Microwave Scanning Radiometer
AMSR-E	AMSR-EOS (NASA)
AMSU	Advanced Microwave Sounding Unit (A/B)
AMW	Active MicroWave (radar)
ATMS	Advanced Technology Microwave Sounder
AWS	Arctic Weather Satellite
CGMS	Coordination Group for Meteorological Satellites
CIMR	Copernicus Imaging Microwave Radiometry mission
CMA	China Meteorological Administration
CMORPH	CPC MORPHing algorithm
CNES	Centre National d'Études Spatiales
COWVR	Compact Ocean Wind Vector Radiometer
CPC	Climate Prediction Center
CPR	Cloud Profiling Radar
DMSP	Defense Meteorological Satellite Program
DoD	Department of Defense
DPR	Dual-frequency Precipitation Radar (GPM)
EarthCARE	Earth Clouds, Aerosols and Radiation Explorer (ESA-JAXA)
EPS	EUMETSAT Polar System
EPS-SG	EPS-Second Generation
ESA	European Space Agency
ESMR	Electronically Scanned Microwave Radiometer
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FY	Feng-Yun (satellite series)
GCOM-W	Global Change Observation Mission-Water
GEO	Geostationary or Geosynchronous
GMI	GPM Microwave Imager
GOES	Geostationary Operational Environmental Satellite
GOSAT-GW	Global Observation SATellite for Greenhouse gases and Water cycle
GPM	Global Precipitation Measurement mission
GPM-CO	GPM-Core Observatory
GSMaP	Global Satellite Mapping of Precipitation
ICI	Ice Cloud Imager (EUMETSAT)
IMERG	Integrated Multi-satellitE Retrievals for GPM
IPWG	International Precipitation Working Group (CGMS)
IR	InfraRed
ISRO	Indian Space Research Organisation
ISS	International Space Station
JAXA	Japan Aerospace eXploration Agency
JPSS	Joint Polar Satellite System
LEO	Low Earth Orbit satellite

MetOp	Meteorological Operational satellite
MHS	Microwave Humidity Sounder
MWI	MicroWave Imager (EUMETSAT)
MWHS	Microwave Humidity Sounder
MWRI	Microwave Radiometer Imager
MWS	Microwave Sounder
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NPP	National Polar-orbiting Partnership
OSCAT	Oceansat Scatterometer
OSSE	Observing System Simulation Experiments
PMW	Passive MicroWave
PR	Precipitation Radar (TRMM)
RFI	Radio Frequency Interference
SAPHIR	Sondeur Atmosphérique du Profile d’Humidité Intertropicale par Radiométrie (Megha-Tropiques)
SEVIRI	Spinning Enhanced Visible and InfraRed Imager
SMMR	Scanning Multichannel Microwave Radiometer
S-NPP	Suomi National Polar-orbiting Partnership
SSM/I	Special Sensor Microwave/Imager
SSMIS	Special Sensor Microwave Imager Sounder
STP-H8	Space Test Program - Houston 8
TEMPEST	Temporal Experiment for Storms and Tropical Systems
TMI	TRMM Microwave Imager
TRMM	Tropical Rainfall Measuring Mission
TROPICS	Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (NASA)
UTC	Universal Time Coordinated
VIS	Visible
WSF-M	Weather Satellite Follow-on -Meteorology
WMO	World Meteorological Organisation

Synopsis

Maintaining a robust constellation of precipitation-capable satellite sensors is crucial to capture and map the spatial and temporal variability of precipitation across the Earth's surface.

Executive Summary

Precipitation is the primary source of freshwater across the world. As such, the availability of precipitable water is vital to our society and the environment around us. Furthermore, precipitation is a key component of the global water and energy cycle affecting our weather and climate. Mapping precipitation on a global scale is therefore of great importance and has been addressed through surface measurements and more recently, through a series of satellite programs. A core collection of satellites, carrying passive microwave (PMW) radiometers, has grown over the last 30 years to form a constellation of about 10-12 sensors. Meanwhile, a broad range of science and user communities has become increasingly dependent on the precipitation products provided by these sensors. The present constellation consists of both conically scanning and cross-track scanning precipitation-capable multi-channel instruments, many of which are beyond their operational and design lifetime but continue to operate through the cooperation of the responsible agencies. A number of groups, including the Group on Earth Observations and the Coordinating Group for Meteorological Satellites (CGMS), have raised the issue of how a robust precipitation constellation of the future should be constructed. The key issues of current and future requirements for the mapping of global precipitation from satellite sensors can be summarised as providing: 1) observations at sufficiently fine spatial resolutions to capture precipitation-scale systems and reduce the beam-filling effects of the observations; 2) a diverse channel selection for each sensor to cover the range of precipitation types, characteristics, and intensities observed across the globe; 3) an observation interval that allows temporal sampling that is commensurate with the variability of precipitation; and 4) precipitation radars and radiometers in low inclination orbit to provide a consistent calibration source, as demonstrated by the first two spaceborne radar/radiometer combinations on the Tropical Rainfall Measuring Mission (TRMM) and Global Precipitation Measurement (GPM) mission Core Observatory (CO). These issues are critical in determining the direction of future constellation requirements, while preserving the continuity of the existing constellation necessary for long-term climate-scale studies.

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Recommendations

Considering the current and planned precipitation missions, the following actions are deemed necessary to ensure the long-term continuity of global satellite precipitation observations:

i) continued commitment and support by the appropriate agencies and organisations for current and planned precipitation-capable missions together with free and open data sharing;

ii) development of a long-term, sustainable strategy for a constellation of precipitation-capable sensors that meet the scientific and user requirements, including,

  - passive microwave sensors with diverse channels covering the primary precipitation-sensitive frequencies with good spatial resolution[1], and
  - operational precipitation radars in non-Sun-synchronous orbit to provide calibration and reference standards for the passive microwave (and infrared) precipitation estimates[2];

iii) continuation of precipitation-capable missions beyond nominal mission lifetime operations, with due regard for the limitations imposed by deorbiting/sensor degradation considerations;

iv) integration of new technologies (such as smallsats and cubesats) and data sets where these meet the necessary scientific and user requirements; and

v) implementation of mitigation strategies to maximise the use of observations and retrievals from sub-optimally performing sensors (e.g., failed/noisy channels) to help maximise temporal sampling.

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[1] as exemplified by the Advanced Scanning Microwave Radiometer (AMSR) and GPM Microwave Imager (GMI) class of sensors.

[2] as exemplified by the mapping capabilities of the TRMM Precipitation Radar (PR) and GPM Dual-frequency Precipitation Radar (DPR), together with the sensitivity of the CloudSat Cloud Profiling Radar (CPR).

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1 Introduction

Water is a fundamental element of the Earth system and is vital to all life on Earth. Consequently, the observation and measurement of precipitation (rainfall and snowfall) on a global scale is crucial to our understanding of the Earth system and the impact it has across many levels of our society (Kirschbaum et al. 2017; Skofronick-Jackson et al. 2017). Precipitation directly links the global cycles of energy and water through constraining and enabling the exchange of energy (Trenberth et al. 2009). While precipitation controls many natural hazards such as droughts and floods (Vicente-Serrano et al. 2010; Kundzewicz et al. 2014), it is also the crucial input to water resources on which agriculture, industry, and society depend.

Measuring precipitation at the local through to global scales is therefore of great importance to understanding water and energy interactions within the Earth System as a whole, as well as being able to monitor, assess, and manage the environment around us. While local measurements of precipitation have been made intermittently over thousands of years, the current global precipitation record based upon rain gauges, which are essentially limited to land areas, effectively covers the last 150 years or so. Truly global measurements of precipitation rely upon satellite observations which are only available over the last 40 years or so. However, to fully observe and measure precipitation it is necessary to understand its characteristics.

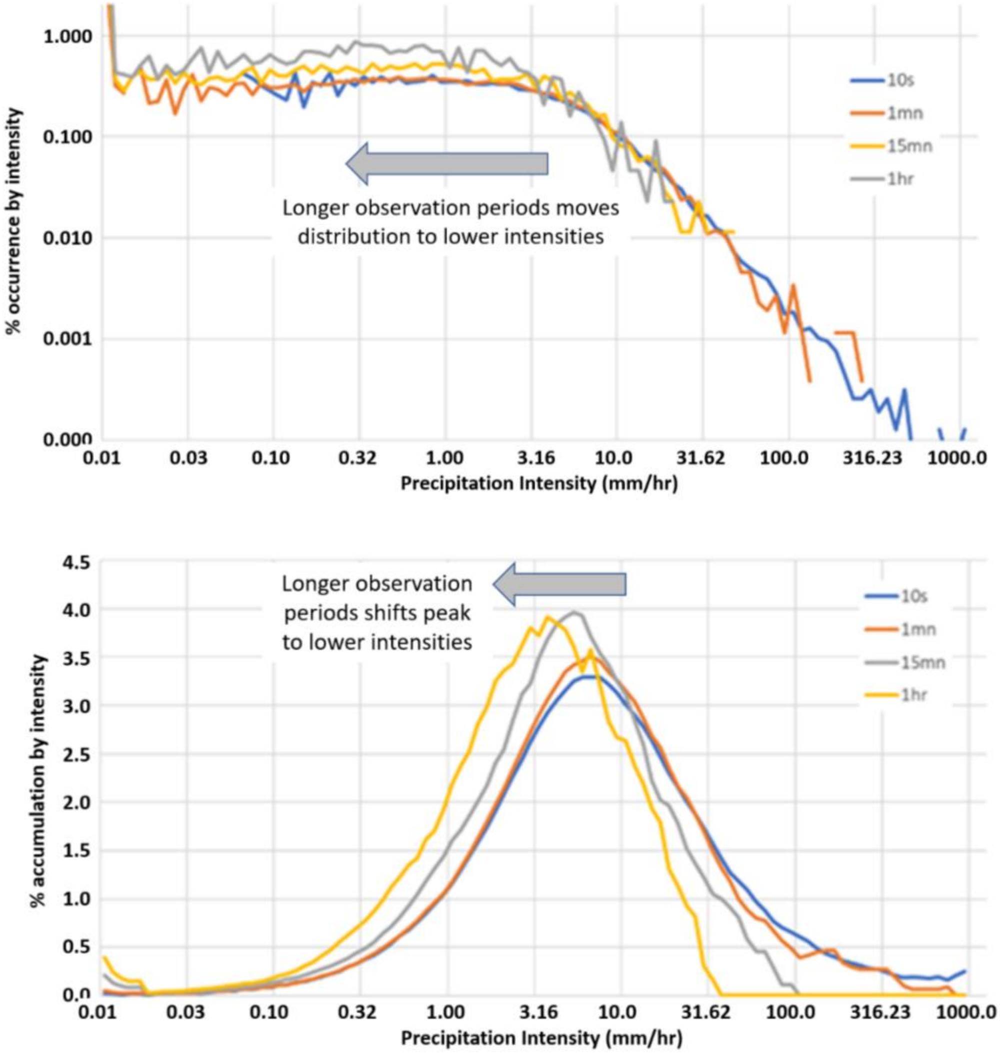
Characteristics of precipitation.

The variability of precipitation, both temporally and spatially, makes it difficult to comprehensively capture the characteristics of precipitation from any particular sensor or instrument. Indeed, the requirements for observing precipitation are determined by the scales and characteristics that precipitation exhibits: these characteristics create a challenging statistical problem.

At the micro-physical scale, water is the only element that co-exists in all three phases, namely vapour, liquid, and solid, a situation that is common in many precipitation systems. Liquid-phase water starts with the formation of water droplets (about 10 µm), usually on cloud condensation nuclei (c.0.1 µm), through the growth of cloud droplets to precipitation-sized particles (c.100 µm, up to 4-5 mm; Ma et al. 2019). Smaller droplets are spherical, but large droplets become flatter or even umbrella-shaped due to air resistance prior to breakup. Pristine ice-phase water particles have similar growth, except physical aggregation of particles and interactions with liquid (riming) may also occur. The resulting icy particles exhibit a vast range of shapes, sizes and densities, with significant implications for the retrieval and estimation of (frozen) precipitation.

At the precipitation system scale, the mechanisms driving the microphysical processes that form clouds and falling precipitation result in variations in precipitation characteristics that range from a few metres to 1000 km or more, and from a few seconds through to days, weeks, and longer (Trenberth et al. 2009). Thus, the observations of precipitation are very much dominated by the interaction between the time/space scales of the precipitation being observed and the resolution/sampling of the observing system (Luini and Capsoni 2012).

Statistically, precipitation in space/time is unusual in that the modal value is zero, i.e., for most of the time and for the majority of the globe, it is not raining or snowing. Furthermore, when precipitation does occur, the intensities are heavily skewed towards the low intensities, while the accumulation of precipitation (being a function of occurrence × intensity) is more log-normally distributed (see Figure 1). Furthermore, as instantaneous samples are accumulated over time and space, the distribution shifts towards a more normal distribution. This complicates any statistical evaluation and requires extreme care when analysing or evaluating precipitation data sets, particularly those with different temporal or spatial resolutions, and from instrumentation with different sampling characteristics. Specifically, the distribution of precipitation intensities is very much dependent upon the spatial and temporal scales being considered (Luini and Capsoni 2012), such that observing a precipitation system at the same time with sensors with different spatial resolution will yield different results. Similarly, comparing instantaneous precipitation with precipitation accumulated over a few minutes, days, or months will reveal very different characteristics. The practical implication is that instantaneous point measurements cannot be directly compared with those collected over an area and/or over time. This issue in compounded by the fact that precipitation events may last from just a few minutes to many hours or even days.


Longer observation periods moves distribution to lower intensities

Longer observation periods shifts peak to lower intensities

Figure 1: Distribution of precipitation characteristics by intensity for the occurrence (top) and accumulation (bottom) derived from ground-based Micro Rain Radar measurements.

2 Conventional precipitation measurements

Conventional measurements made by rain gauges and snow gauges are generally representative of a very small area close to each gauge (Kyriakidis et al. 2001; Lundquist et al. 2019). Surface-based weather radar observations provide valuable spatial measurements over large areas (Harrison et al. 2000; Ciach and Krajewski 1999), although they have limitations and often complement the global coverage provided by gauge measurements. Crucially, over the oceans few or no observations are available (or possible) through conventional means (Kidd et al. 2017). Even basic questions, such as addressing the amount and occurrence of precipitation, are generally limited to land regions (e.g., Sun et al. 2006; Herold et al. 2015).

Gauge measurements

The *de facto* device for measuring rainfall is the rain gauge. The basic gauge consists of a funnel and a collection vessel, with the amount of water collected usually measured daily, although less often in more remote regions (Strangeways 2004; Sevruk and Klemm 1989). A wide range of designs have evolved over time, including ones that allow the automatic recording of the rainfall. Tipping bucket rain gauges, for example, record the time/date (or number of tips per unit time) that a known quantity of rainfall tips a small bucket (Sevruk 2005). Rain gauges are often used to measure snowfall through the use of a small heater to melt the snow and therefore measure the liquid equivalent. Gauges are however subject to errors and uncertainties in their measurements (Ciach 2003; Villarini et al. 2008). The primary source of these errors result from turbulence around the gauge orifice (Duchon and Biddle 2010) which may cause significant under-catch in light rain and/or strong winds (Kochendorfer et al. 2017). This under-catch is a significant source of error in measuring snowfall due to the lower fall speeds of snowflakes (Thériault et al 2012). Consequently, snow gauge use of ‘shields’ to reduce the wind speed around the gauge orifice (Duchon and Essenberg 2001). Despite issues relating to their accuracy, gauges remain the mainstay of conventional global precipitation measurements, particularly when corrections are applied (Michelson 2004). Even so, their coverage across the globe is extremely variable. Over land, some regions have what could be considered adequate coverage, while other regions have none. Measurements over oceans are only available from a few atoll or island locations and a very small number of moored or drifting buoys. Overall, the global surface represented by gauge measurements is pitifully small (Kidd et al. 2017).

Weather radar measurements

The development of weather radar systems has created an important source of precipitation information at local to regional scales (Whiton et al 1998a, 1998b). Unlike the point-measurements of gauges, radars can provide frequent, 3-dimensional observations of precipitation up to about 250 km from the radar location (Zhang et al. 2011). Weather radars now provide national and international coverage over many regions of the world, including the United States (e.g., Zhang et al. 2016), Europe and large parts of Australasia. However, radars rely upon several assumptions to convert the backscatter signal from the rain and/or snow particles to an equivalent precipitation intensity (Campos and Zawadzki 2000; Uijlenhoet 2001; Uijlenhoet et al 2003) with the final precipitation product being reliant upon calibration against surface gauge data, where available. Furthermore, to avoid surface clutter the radar beam is usually elevated resulting in the altitude of the beam increasing with range, thereby no longer measuring the at-surface precipitation and making the detection of the near-surface phase (rainfall vs snowfall) difficult (Mimikou and Baltas 1996). Weather/precipitation radars are also essentially confined to land areas, while the expense of installation, operation, and maintenance limits their deployment to the more developed countries.

Emerging technologies

Several alternative surface-based instruments and techniques have shown merit for measuring precipitation and augmenting conventional measurements, particularly in regions with few or no surface observations. Information on precipitation is particularly scarce over the oceans, being largely limited to observations made by island-based gauges, buoys, or ships which are typically not representative of the open ocean precipitation (Khan and Maggioni 2019). Estimating rainfall through the use of underwater hydrophones is presented by Pumphrey et al. (1989), Medwin et al. (1992) and Forster (1994). More recently Ma and Nystuen (2005) found an excellent agreement between acoustic, gauge and TRMM satellite measurements, particular at higher rain rates. While such instruments are very promising, their deployment and maintenance is often difficult and expensive, although the rewards are potentially great. Over land, the attenuation of microwave communication signals by rainfall has been studied since the late 1960’s (e.g., Semplak and Turrin 1969). The development of the current mobile phone infrastructure allows the characteristics of this path attenuation to be fully exploited, as exemplified by the work by Leijnse at al. (2007) over The Netherlands. Since the microwave paths are close to the ground, they tend to be more representative of surface rainfall than weather radars. A more comprehensive study by Overeem et al. (2011) showed very good correlations between the link-derived estimates and those from the weather radar. Further development would complement and augment existing precipitation measurements in regions where few precipitation observations exist.

3 Satellite Precipitation Measurements

Observations provided by satellite sensors are therefore essential for measuring precipitation across the globe (e.g., Adler et al. 2003). Since no single satellite can achieve this coverage alone, a stable and robust constellation of satellite-based sensors is critical to provide sufficient temporal sampling to capture the vagaries of precipitation, particularly over surface-data sparse regions such as over the Poles or oceans, to provide consistent global precipitation products to the user community (Huffman et al. 2007). Furthermore, maintaining such a constellation is crucial for long-term climate studies into changes in precipitation across the Earth’s surface (Adler et al. 2017; Levizzani et al. 2018).

Satellite systems and retrievals

Precipitation-capable satellites may be classified by their orbital characteristics and sensing frequencies. Low Earth Orbiting (LEO) satellites typically orbit the Earth at altitudes between 400-800 km providing about 14-16 orbits per day, with most operating in a Sun-synchronous orbit. Some low-inclination orbiting satellites provide non-Sun-synchronous observations at different times of day as their orbits precess over periods of weeks or months. LEO satellites sensors generally provide broad sub-satellite swaths of data, although some provide data across only a narrow swath or only at nadir. The LEO satellites most relevant for precipitation studies carry visible (VIS), Infrared (IR), passive microwave (PMW) and active microwave (AMW) instrumentation (Kidd and Levizzani 2011). Geostationary (or geosynchronous) (GEO) satellites occupy a much higher orbit at about 35,800 km above the Earth's surface. These orbits are synchronised with the Earth's rotation so appear stationary over a fixed location at the Equator, allowing frequent and regular observations. However, their observations are largely limited to VIS/IR sensors, although mission concepts have been developed for geostationary PMW sensors (e.g., Tanner et al. 2007; Lambrigtsen et al. 2007; Duruisseau et al. 2017; Lambrigsten 2019). GEO-PMW observations would also be constrained by the frequency/wavelength of observations and their spatial resolution and typically would only provide limited coverage at any one time. Table 1 summarises the range of both LEO and GEO

Table 1: Characteristics of present-day LEO and GEO satellites and their observational capabilities.

			Orbit	
			LEO[1]	**GEO[2]**
		Characteristics	400-800 km altitude orbits c.14-16 orbits/day Polar orbiting Sun-synchronous (up to 2 overpasses/day), or Low inclination precessing orbits	c.36,000 km altitude orbits Geosynchronous satellites remain stationary relative to sub-satellite point.
Band	**Vis/IR**	Cloud top properties Reflection (VIS), emission (IR), texture & particle sizes	Multi-spectral observations Orbital swaths ca 2900 km wide Resolutions <1 m to 1 km	Multi-spectral Frequent/regular samples over sectors or full disk coverage Resolutions <1-4 km sub-satellite footprints
	PMW	Hydrometeor column Emission or scattering from liquid, ice and water vapour	Multi-channel observations Orbital swath (sensor specific) c.5 – 70 km footprints	*Not possible at present* *Several feasibility studies*
	AMW	Vertical profiles of hydrometeors Backscatter from liquid and ice particles	Single/dual frequency (13.6/35/94 GHz) Single beam (CloudSat with 1.4x3.5 km footprints) or narrow swath (DPR 245 km with 5.4x5.4 km footprints)	*Not possible at present* *Some feasibility studies*

[1] LEO: Vis/IR observations provided by a large group of sensors ranging from land surface monitoring missions (e.g. Landsat) through to meteorological missions (e.g. AVHRR) with resolutions typically matched to user requirements. PMW channels used for the retrieval of geophysical and meteorological parameters, including precipitation.

[2] GEO: constellation of GEO satellites provides global coverage with frequent/regular observations, disseminated at a nominal 3 hourly interval, but with sensors typically providing operational 10-15 min. data collection, and rapid scans <1 minute.

satellite observing systems with precipitation capabilities. The use of satellite observations for precipitation estimation extends back over 40 years, with the longest data records based upon VIS and/or IR imagery. Early precipitation estimates were based upon empirical relationships between the brightness and/or temperature cloud top characteristics and surface rainfall (Kidd and Levizzani 2011). Despite a degree of success, such relationships are generally poor and inconsistent over time and space (Kidd and Muller 2010; Kidd and Levizzani 2019). PMW radiometers, developed in the mid-1970s, measure the upwelling radiation from the Earth's surface which is largely unaffected by the presence of cloud, particularly at the lower frequencies (below 37 GHz). Sufficiently large liquid and ice particles (as in the case of precipitation-sized particles) affect the upwelling radiation, leading to increased radiation at the lower frequencies due to emission from liquid droplets, while at the higher frequencies ice particles cause a decrease in the upwelling radiation (Kummerow 2020). Despite PMW observations being more direct than those of the VIS/IR, many assumptions are necessary to convert the satellite observations to precipitation estimates, particularly over land, where low frequency observations are impractical for retrieving precipitation. The most direct measure of precipitation from space is obtained from AMW sensors (precipitation radars) that rely upon the backscatter from the precipitation sized particles to estimate precipitation intensity, as their ground-based counterparts do (see Battaglia et al. 2020). Two precipitation-specific radars have flown; the first, the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) operated at 13.6 GHz (Kummerow et al. 1998), while the Global Precipitation Measurement (GPM) mission Dual-frequency Precipitation Radar (DPR) currently operates at 13.6 and 35.5 GHz (Hou et al. 2014). The Cloud Profiling Radar (CPR) on CloudSat operates at 94 GHz (Stephens et al. 2002; Stephens et al. 2018), although not designed to retrieve precipitation and while only providing nadir observations, its increased sensitivity has proved invaluable at providing an additional calibration/validation data source for precipitation retrieval schemes, particularly for light precipitation and snowfall (Battaglia et al. 2020). Nevertheless, as with ground-based radars, the backscatter-to-precipitation relationship is not consistent, and these sensors cannot retrieve precipitation within about 500-2000m of the surface due to ground clutter (Skofronick-Jackson et al. 2019). Other sensors have shown some abilities to identify and retrieve precipitation, such as altimeter data which is primarily used to measure sea surface height. Quartly et al. (1996, 1998), Quartly (2010) and Varma et al. (2020) outlined and evaluated the retrieval of precipitation from such sensors, although like the CPR, such sensors are nadir-only and therefore only provide limited sampling. Radar scatterometers (e.g. OSCAT) with swath and spatio-temporal resolution comparable to the microwave radiometers also show potential for precipitation estimation (Ghosh et al., 2014). More recently Turk et al (2021) showed that radio occultation has the potential to identify precipitation, although with large spatial resolutions.

Critically, on a global scale, satellite-based observations largely address the shortcomings of conventional measurements for observing precipitation while providing more comprehensive data for studying the characteristics and mechanisms of precipitation (Tapiador et al. 2011). However, to measure and map precipitation correctly, satellite systems must provide sufficient sampling to capture the temporal and spatial variability of precipitation.

Current precipitation constellation

The evolution of the constellation of precipitation-capable satellite sensors is shown in Figure 2. Building upon the development work on early PMW sensors (e.g., ESMR-5/6 and SMMR), conically-scanning PMW sensors began in the late 1980's, with cross-track scanning PMW sounding instruments from the late 1990's onwards. The latter, although primarily designed for retrieving temperature and humidity (Mo 1995), have proved invaluable in increasing the temporal sampling necessary for precipitation measurements (Kidd et al. 2016, 2021; Bagaglini et al. 2021). The launch

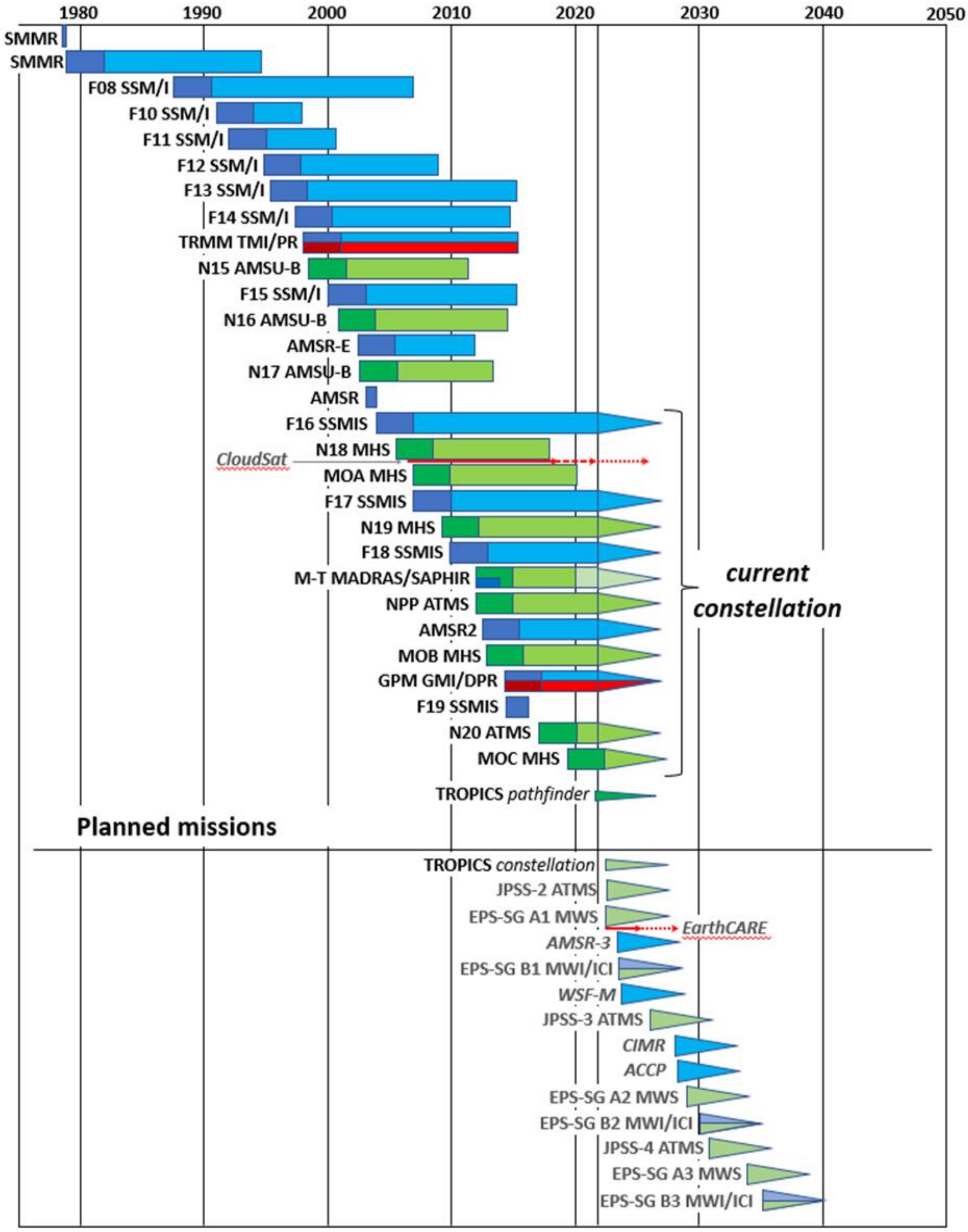


Figure 2: Timeline of PMW satellites and sensors providing analysis-ready data. The wide bars and arrows indicate swath-based or nadir-only observations respectively. Blue bars represent imaging/conical scanning radiometers, green bars represent sounding/cross-track radiometers and red bars indicate AMW (radar) sensors. Triangles indicate those sensors that currently provide data (as of 2021-02-09) and may continue to do so, together with future missions. *(Data source: based upon World Meteorological Office (WMO) Observing Systems Capability Analysis and Review Tool (OSCAR) database and EUMETSAT)*

of TRMM in 1997 (Simpson et al. 1988; Kummerow et al. 1998) facilitated multi-sensor retrievals through the inter-calibration of the then-available PMW sensors with the TRMM instruments. This inter-calibration concept was expanded with GPM launched in 2014 (Hou et al. 2014; Skofronick-Jackson et al. 2017).

The GPM Core Observatory (GPM-CO) carries the DPR and the GPM Microwave Imager (GMI), both of which have been shown to be very well calibrated (Wentz and Draper 2016). The GPM constellation, compromised of about 10-12 PMW-based precipitation-capable satellites is provided by several international agencies (see Table 2). Amongst these are the operational missions of NOAA (with the MHS and ATMS sensors), those of EUMETSAT (MetOp MHS) and the U.S. Department of Defense (DoD) SSMIS sensors (Kidd et al. 2020). In addition, JAXA contributes the AMSR-2, while the Centre National d'Etudes Spatiales (CNES) and the Indian Space Research Organisation (ISRO) contribute SAPHIR onboard the Megha-Tropiques mission (Roca et al. 2015; Varma et al. 2016). Data archives of the observations from all of these and previous PMW missions provide the necessary input for routine global estimates throughout the entire data record. Additional operational precipitation capable PMW missions exist (e.g., Li et al. 2018), but due to data access/usage arrangements these cannot presently be fully exploited by the wider precipitation community. The multi-agency co-ordination of the orbital crossing times of these missions impacts the temporal sampling. At present the EUMETSAT, NOAA and JAXA missions generally use station-keeping to ensure consistent overpass times. The crossing times of other PMW satellites drift over the course of 14-15 years between the extremes of ca.13:30 to 22:30 (ascending node). A number of missions, (e.g. TRMM, GPM and Megha-Tropiques) had, or have, non-sun-synchronous precessing orbits and therefore observe the full diurnal cycle at any one location over the period of a few months, albeit with highly intermittent sampling (Roca et al. 2018).

Table 2: Microwave sensors contributing to the GPM precipitation constellation. The current precipitation constellation missions are highlighted in bold, while previous missions are in italics and grey lettering.

Satellite	Agency	Sensor	number	Channels	Retrieval resolution*
AMW instruments					
GPM	**NASA/JAXA**	**DPR**	**x1**	**13.6/35.5 GHz**	**5.4 x 5.4 km**
TRMM	*NASA/JAXA*	*PR*		*13.6 GHz*	*4.3 x 4.3 km*
PMW imagers					
GPM	**NASA/JAXA**	**GMI**	**x1**	**10.7-183.31 GHz**	**10.9 x 18.1 km***
DMSP F16,17,18,_19_	**US DoD**	**SSMIS**	**x3**	**19.35-183.31 GHz**	**45 x 74 km***
GCOM-W1	**JAXA**	**AMSR2**	**x1**	**6.7-89.0 GHz**	**14 x 22 km***
TRMM	*NASA/JAXA*	*TMI*		*10.7-89.0 GHz*	*20.9 x 34.6 km**
PMW sounders					
NOAA-_18_**,19**	**NOAA**	**MHS**	**x1**	**89.0-183.31 GHz**	**17.12 x 21.64 km***
METOP-_A_**,B,C**	**EUMETSAT**	**MHS**	**x2**	**89.0-183.31 GHz**	**17.12 x 21.64 km***
NPP, NOAA-20	**NOAA**	**ATMS**	**x2**	**23.0-183.31 GHz**	**16.51 x 16.22 km***
MeghaTropiques	**ISRO/CNES**	**SAPHIR**	**x1**	**183.31 GHz (x6)**	**7.34 x 7.27 km**

*(*retrieval resolution is that of the NASA GPROF scheme).*

Complementing the LEO observations, a ring of GEO satellites provide frequent and regular vis/IR observations (see Table 3) that are used to augment the LEO PMW observations. These satellites' IR data are often used for precipitation retrievals in conjunction with the LEO PMW observations through the generation of gridded 'global' IR data, such as the NOAA Climate Precipitation Center (CPC) 4 km 30-minute global IR composite (Janowiak et al. 2001) and the GridSat collection at 10 km 3-hour subsampled data (Knapp and Wilkins 2018). Merged PMW and IR satellite schemes such as the CMORPH (Joyce and Xie 2011), GSMaP (Kubota et al 2020) and IMERG (Huffman et al. 2020) allow precipitation products to be generated at resolutions of 30-minutes/10-km or better, which critically relies upon sufficient high-quality PMW instantaneous retrievals of precipitation.

Table 3: Current GEO VIS/IR sensors: those that actively contribute to the global 30-minute 4 km IR imagery are highlighted in bold. *(All of these provide multi-channel VIS/IR observations with temporal sampling of 15 minutes or better, and < 1km / 4km for VIS/IR at sub-satellite point).*

Satellite	Agency	Sensor	Longitude	Channels/number		Sub-satellite resolution
GOES-13 (Storage)	NOAA	IMAGER	60°W	VIS/IR	x5	1 km / 4 km
GOES-14 (backup)	NOAA	IMAGER	105°W	VIS/IR	x5	1 km / 4 km
GOES-15 (West backup)	NOAA	IMAGER	128°W	VIS/IR	x5	1 km / 4 km
GOES-16 (GOES-East)	**NOAA**	**ABI**	**75.2°W**	VIS/**IR**	**x16**	**0.5 km / 2 km**
GOES-17 (GOES-West)	**NOAA**	**ABI**	**137.2°W**	VIS/**IR**	**x16**	**0.5 km / 2 km**
Meteosat-8 (IODC)	**EUMETSAT**	**SEVIRI**	**41.5°E**	VIS/**IR**	**x12**	**1 km / 3 km**
Meteosat-9 (rapid scan)	EUMETSAT	SEVIRI	3.5°E	VIS/IR	x12	1 km / 3 km
Meteosat-10 (rapid scan)	EUMETSAT	SEVIRI	9.5°E	VIS/IR	x12	1 km / 3 km
Meteosat-11	**EUMETSAT**	**SEVIRI**	**0°**	VIS/**IR**	**x12**	**1 km / 3 km**
Himawari-8	**JMA**	**AHI**	**140.7°E**	VIS/**IR**	**x16**	**0.5 km / 2 km**
Himawari-9 (standby)	JMA	AHI	140.7°E	VIS/IR	x16	0.5 km / 2 km

To provide sufficient observations temporally it is necessary to exploit all available sensors. It is fortuitous that many of the precipitation-capable missions have lasted beyond their designed operational lifetime through support of their respective agencies. However, a pressing issue of the current constellation is the age of the satellite missions: before 2016 the mean age of these satellites was 5-7 years; after 2016 the age has slowly risen and now is over 9 years (see Figure 3). Crucially, satellites fail and sensors fail, often unexpectedly. A practical consequence of the gains and losses of these sensors is the direct impact upon the temporal sampling by the constellation. For example, a failure of the three oldest sensors in the constellation (the SSMISs on the DMSP F16 and F17 and the SAPHIR on Megha-Tropiques) would lead to a loss in the temporal sampling, extending the gaps between successive PMW observations, including the critical longest gaps, as illustrated in Figure 4. Analysis shows that a loss of the oldest satellite sensors would result in a reduction in the number of samples by nearly 15% (see Figure 5). A concerted program of new satellites/sensors is therefore crucial to ensure the continuation of precipitation measurements in a controlled and planned manner necessary to support the user requirements.

Planned precipitation-capable missions

There are a number of planned satellite missions that are capable of providing observations from which precipitation may be retrieved, as summarised in the lower part of Figure 2. At present the planned precipitation-capable missions over the next decade include:

EUMETSAT: The European Polar-orbiting System (EPS) Second Generation (SG) will provide continuity to the current MetOp series of satellites, and so the orbital characteristics are likely to be commensurate with the current missions, including station keeping (Accadia et al. 2020). The SG-A satellites will carry the cross-track MicroWave Sounder (MWS; 24 bands, 23-229 GHz, 40-17 km resolution), while the SG-B satellites will carry the conically scanning MicroWave Imager (MWI; 18-bands, 18.7-183 GHz, 50-10 km resolution; Accadia et al. 2020) and the Ice Cloud Imager (ICI; 11 bands, 183-664 GHz, 16 km resolution; Eriksson et al. 2020). The SG-A and SG-B satellites are likely to be in the same orbital plane but ½ orbit offset allowing adjacent swath coverage. Precise launch dates are yet to be determined, but are likely to be begin in the 2024/2025 timeframe.

NOAA: Additional platforms in the current Joint Polar System Satellite (JPSS) series (JPSS-2/-3/-4) through the 2030's are likely to occupy the same orbit as NPP and NOAA-20 (Goldberg et al. 2013). Each satellite will carry the ATMS sensor (22 band, 23-183 GHz), with resolutions on the order of 16 km at nadir for the higher frequency channels, although the resolution at well-used 88.2 GHz channel is 32 km.

US Department of Defense: The DoD has a long history of precipitation-capable missions (SSMI and SSM/I), and DoD has commissioned Ball Aerospace to build a new PMW imager, the Weather Satellite Follow-on – Microwave (WSF-M) (see Newell et al. 2020). The planned sensor is a 6 frequency, 17 channel radiometer covering frequencies between 10-89 GHz with a finest spatial resolution of 15x10 km. The contractual launch date is set as October 2023.

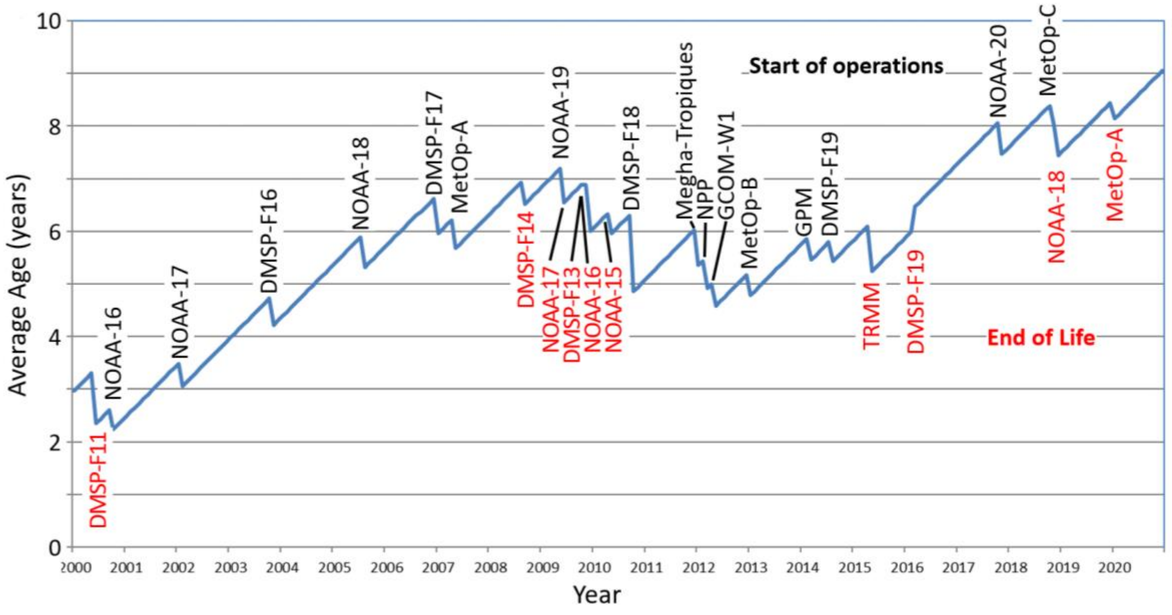


Figure 3: Mean age of the PMW satellites up to 1st January 2021. From 2005-2016 the mean age was around 5-7 years, but now currently exceeds 9 years. Note that the constellation becomes younger both with a new launch and if a long-term mission reaches its end of life.

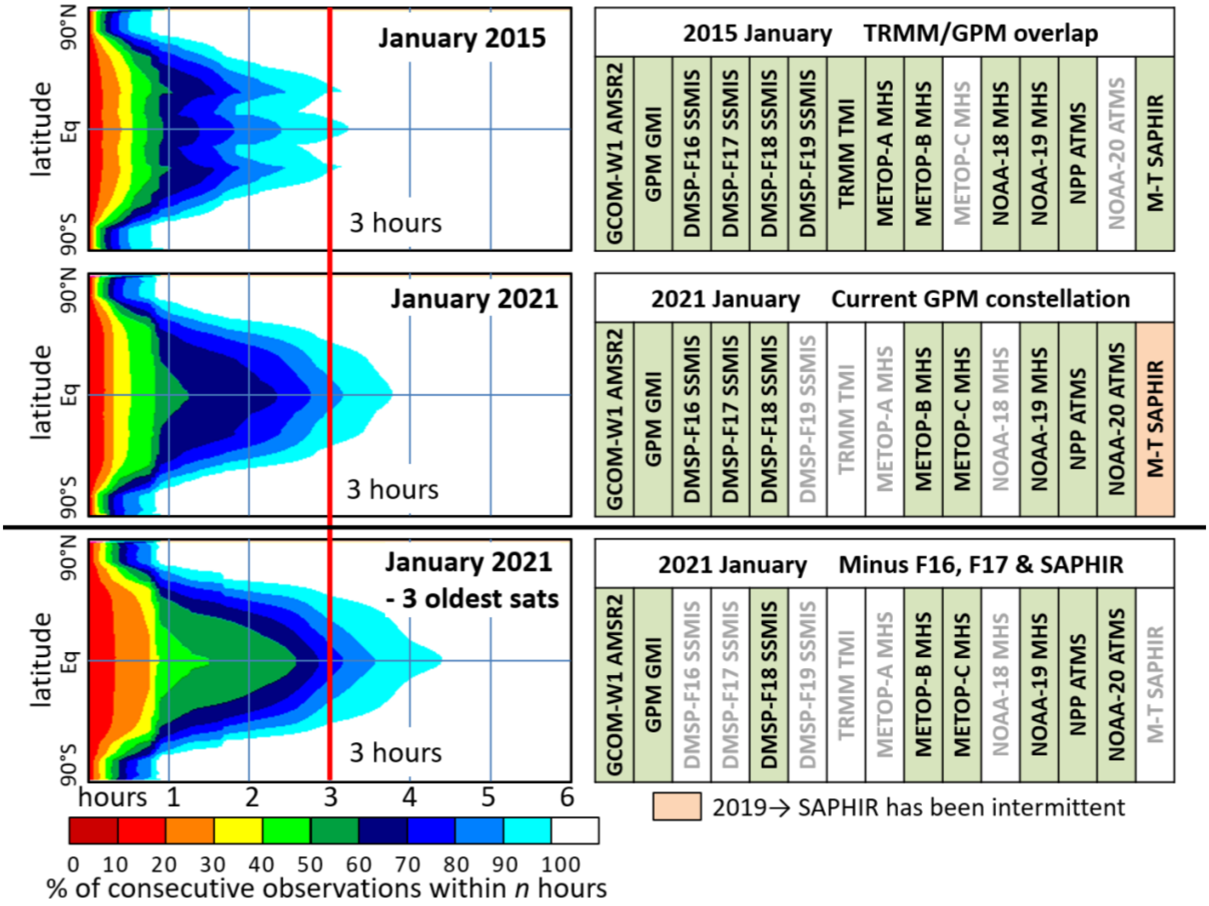


Figure 4: Revisit times by latitude for three selected dates. The baseline GPM sampling is shown at the top for January 2015, while the current sampling is shown in the middle for January 2021. The bottom row shows a possible scenario if the three oldest sensors (SSMIS F16 and F17, and SAPHIR) are not included. The red vertical line represents the widely accepted 3-hour minimum revisit time necessary to adequately capture the accumulation of precipitation at daily, 0.25° scales. While the 3-hour revisit time was attained more than 90% of the time in January 2015, the reduction in the constellation numbers has reduced this to about 80% in January 2021.

JAXA: The third generation of the Advanced Microwave Scanning Radiometer (AMSR-3) sensor (Kasahara et al. 2020) is being built for installation on JAXA's Global Observation SATellite for Greenhouse gases and Water cycle (GOSAT-GW) with a scheduled launch date in 2023-24. The AMSR-3 sensor provides similar channel selection as the other AMSR sensors (12-channel, 6.7-89 GHz), but with additional higher-frequency channels at 166 and 183 GHz. Spatial resolutions will be similar to the current AMSR-2 instrument (Imaoka et al. 2010).

NASA: Time-Resolved Observation of Precipitation structure and storm Intensity with a Constellation of small Satellites (TROPICS) is a NASA Earth Venture Mission, providing 6 (plus one pathfinder) cubesats, primarily focused on the evolution of weather systems across the Tropics (Blackwell et al. 2018). Each cubesat carries a small microwave radiometer operating at frequencies between 90 and 204 GHz with spatial resolutions similar to the MHS/ATMS sensors, and thus should be capable of providing observations for precipitation retrievals. An initial pathfinder mission was launched on 30 June 2021, with the remaining 6 satellites due for launch in 2022.

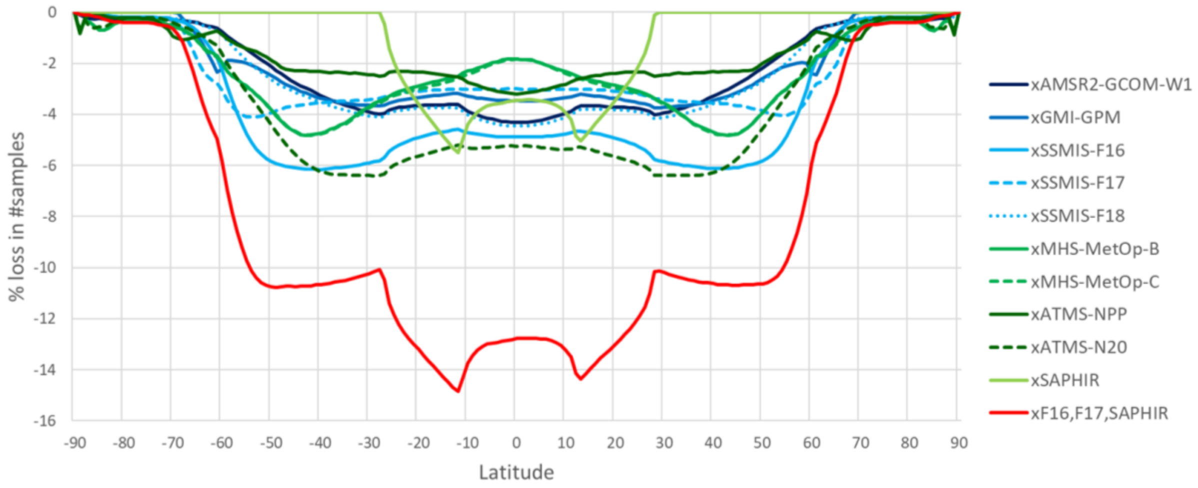


Figure 5: Decrease in the number of samples as a result of a loss of a particular (or multiple) constellation sensor(s). While the loss of a single (multiple) sensor(s) may be calculated for a particular day, the orbital complexities as a result of the uncoordinated nature of the constellation of satellites means that several sensors provide observations within a few minutes of each other, while leaving other periods with extended observational gaps. Importantly, the loss of multiple sensors (e.g. the aging F16, F17 SSMIS's and the partially operating SAPHIR) results in a decrease in the number of samples of 15% (red line). (The asymmetry in the SAPHIR losses are a result of the sensor's partial operation).

Chinese Meteorological Administration (CMA): The FY series of satellites carrying the MWHS-2 and the MWRI instruments (Guo et al. 2015; Lawrence et al. 2018) has a proven record of precipitation-capable missions. The planned Chinese Rain Mapping missions (FY-3I and FY-3J) are expected to have capabilities similar to the GPM core observatory, hosting the PMW MWRI/MWHS-2 sensors and a rain radar providing observations at 13.6 and 35.5 GHz. These missions are currently planned to launch in 2022/2023.

Other missions of interest being developed by the operational agencies include the European Copernicus Imaging Microwave Radiometer (CIMR; Accadia et al. 2020), the ESA Arctic Weather Satellite (AWS) and EarthCARE (Lefebvre et al. 2017), and the NASA-led Aerosols, Clouds, Convection, Precipitation mission (ACCP), which should be available for launch within the next decade. The Russian Meteor-N series also host both PMW imagers and sounders although with limited data access. Many other small satellite missions (cubesats and smallsats) are proposed that could provide precipitation-relevant data (see Stephens et al. 2020). Novel concepts, such as the Space Test Program - Houston 8 (STP-H8) program to be flown on the International Space Station (ISS) from early 2022 with the conically-scanning, lower frequency Compact Ocean Wind Vector Radiometer (COWVR) sensor and the cross-track, high-frequency Temporal Experiment for Storms and Tropical Systems (TEMPEST) sensor, will test and potentially expand the use of multi-sensor retrieval schemes. In addition, there is now interest within the private sector for the development of sensors to provide meteorological observations, including constellations of precipitation-capable sensors, such as that proposed by tomorrow.io (see https://www.tomorrow.io/). However, it is vital that these innovations support the spatial, temporal, channel, and quality requirements to address the needs of the user community, as well as facilitate the integration of their observations into the near real-time production of satellite precipitation products.

4 Defining future mission requirements

User requirements

The main drivers for all new missions are the unavoidable compromises between the needs of the user communities, the engineering/physical constraints, and the available budget. For precipitation, the temporal and spatial resolutions of the observations (and hence derived products) is determined by the capabilities of the observing system and the requirements of the user communities and their respective applications. Polls of the user community found significant variations in their requirements for temporal and spatial sampling, and data latency (observation-to-delivery delay) (see Table 4 and Figure 2, Friedl 2014) reflecting the extensive range of research and application topics. Perhaps the most stringent requirements are associated with emergency managers, who require good spatial resolution (20 km or better), frequent (every few minutes), and immediate (within a few minutes) information. Products from the current constellation, for comparison, using combined PMW and IR observations provide products at ca. 10 km resolution, every 30 minutes, within about 4 hours, although very near real time IR-only products are available with reduced veracity. However, the requirements within each user community are very diverse, and moreover, the scales may vary within a particular application, as demonstrated by Reed et al. (2015), who investigated the temporal sampling of precipitation datasets for hydrological modelling to meet the necessary flood-forecasting requirements. It is therefore crucial to address the most stringent user requirements as these are often those which have the greatest impact on both the physical and human environment. However, the available scales and sampling are often coarser than the physical scales of precipitation which are further constrained by the physical and engineering limitations of the sensors.

Addressing the temporal sampling and spatial resolution.

The spatial resolution at microwave frequencies is essentially limited by the size of the antenna (dish) that can be deployed on the satellite platform, which is determined by the engineering, launch vehicle and budget limitations. For a given antenna size, the best available resolution is inversely related to the observation frequency, consequently high-frequency channels have finer resolution than low-frequency channels for the same sized antenna. At present, the finest PMW resolution is about 3x5 km at 89, 166, and 183 GHz using a 2 m dish (e.g., the GMI). Utilization of a larger dish is extremely problematic, both in terms of launch, and in terms of operation since the dish is continually rotating. Deployments of large (5-6m) mesh antennas are planned, such as the CIMR mission (Accadia et al. 2020) but are limited to the lower frequency channels (<37 GHz) by the current-generation limits to the dish-surface conformance. While GEO-based Synthetic Aperture systems have been studied for precipitation missions (e.g., Lambrigsten 2019), they require significant additional processing, are not truly global, have relatively poor spatial resolution, and envisage having only high frequency channels (which are less directly related to precipitation). Consequently, potential GEO-based systems would not necessarily provide any significant advantage over LEO-based radiometers. Importantly, since the spatial variability of precipitation is on the order of a few km, resolving this variability at 1 km or less would be optimal for satisfying the more-stringent user needs and, as such, remains a significant and unmet challenge.

The temporal sampling from PMW satellites is crucial in capturing the variability of precipitation over time (see Varma et al. 2003 and 2006; Piyush et al. 2012). Temporal sampling of 3 hours is often quoted as a minimum requirement. This was originally based upon a number of requirements, including the number of samples necessary to reduce ambiguities when observing the diurnal cycle of precipitation (by providing at least the first three sinusoidal components), as well as from the WMO-agreed distribution of near-real-time GEO IR imagery at intermediate and Synoptic hours (00 UTC, 03 UTC, etc). However, 3-hourly observations cannot adequately capture the true precipitation accumulation at the daily scale, as illustrated in Figure 6. At 1 km, accumulated precipitation based on 3-hourly sampled data attains a correlation of less than 0.5 against the daily precipitation total and, while coarser resolutions provide higher correlations, even at 25 km resolution this does not exceed 0.8. Crucially, improving the spatial resolution (necessary to capture the spatial variation on precipitation) also requires a large increase in the temporal sampling. This dilemma is further emphasised in Figure 7, which plots the correlation of instantaneous PMW and IR precipitation estimates against surface radar over the course of 1 day (25 July 2015) over the central UK. Each peak in the correlation represents the retrieval at the time of the sensor's observation. While the correlations between the satellite and surface radar products are good across all the satellites at the time of overpass, the correlation (in common with other measures) quickly deteriorates at times away from the time of the overpass. Even when the IR data are directly calibrated with the surface radar, as is done for Figure 7, the PMW products are much better. Despite a reasonable number of PMW overpasses being available (as is currently the situation), there are clear gaps (around 05:00 and 23:00 UTC) on this day where no PMW overpasses occur and satellite precipitation estimates typically have to rely more heavily upon IR data. It should also be noted that the swath over which each sensor collects data is crucial in determining the temporal sampling. For example, the AMSR2 sensor collects data across a 1450 km swath compared to the GMI and DPR with swaths of 885 km and 245 km, respectively: the narrower the swaths, the more sensors are needed to provide a similar temporal sampling.

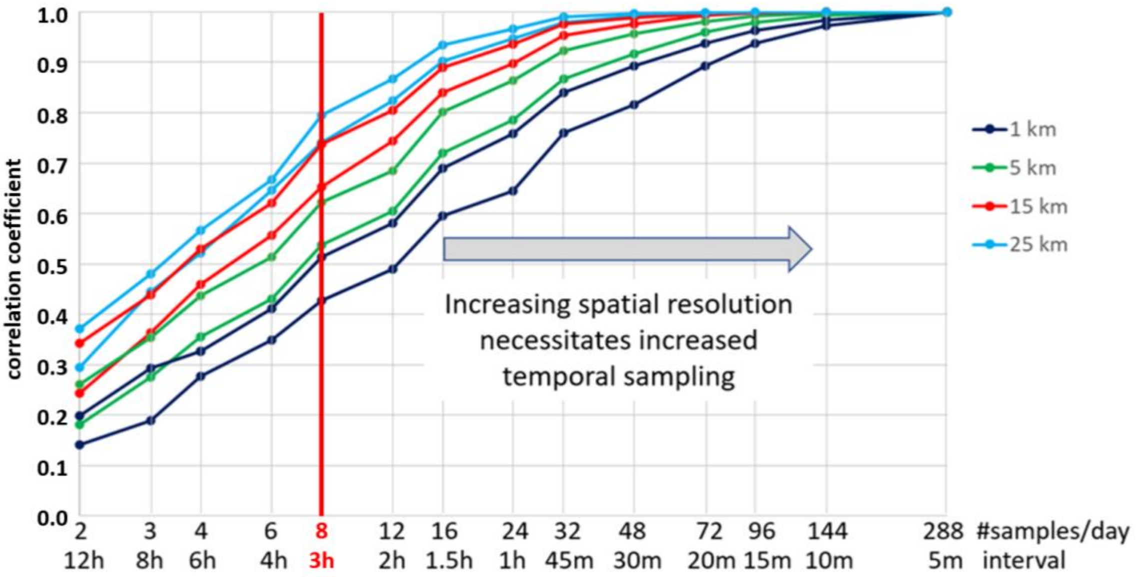


Figure 6: Increasing the spatial resolution requires more samples to attain the same level of statistical performance. For example, a sensor with a 25 km resolution might attain a correlation of 0.8 with 3h sampling, however, a 15 km resolution sensor would need more than 12 samples to attain the same correlation. The oft-quote 3h requirement is highlighted in red.

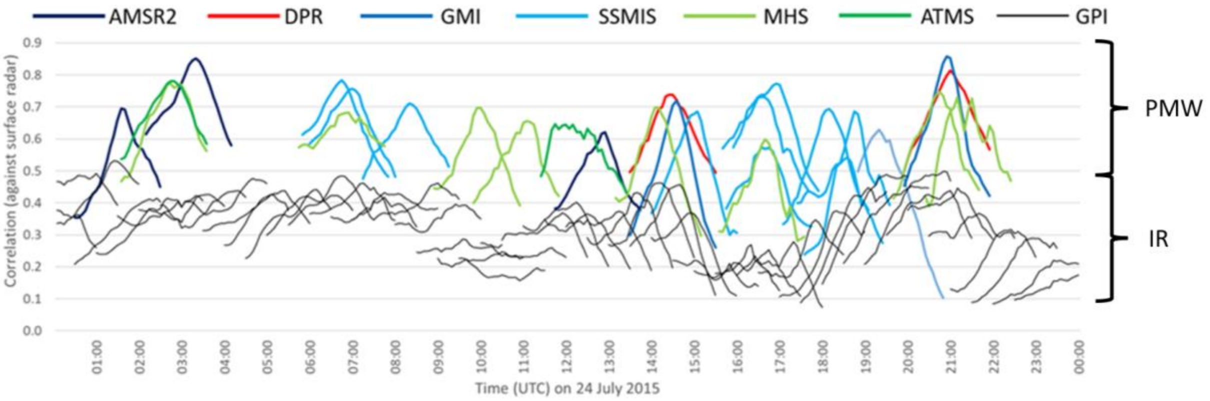


Figure 7: Correlation of precipitation retrievals for 1 day for a sample site in the UK. Note that the correlations between satellite estimates and surface radar peak markedly at time of observation and decline away from time of observation. The IR-only retrievals never match the correlations of the PMW retrievals. Also note the gaps in PMW overpasses and retrievals from 04:00-06:00 and 22:00-01:00.

5 Maintaining a robust constellation

The current precipitation constellation provides a significant number of observations to generate precipitation estimates. However, the continuity of these observations is very precarious. The precipitation community has become very adept at collecting observations from a diverse range of satellite missions and sensors. These include observations from missions not originally designed for the retrieval of precipitation, as well as observations from other water-related missions that can be useful in closing the water-cycle loop (Brocca et al. 2014; Behrangi 2020). However, there is presently no adequate substitute for a steady supply of precipitation-relevant observations. To ensure an uninterrupted stream of satellite precipitation measurements, a number of strategies need to be considered.

Maintaining/strengthening the constellation through new missions

The largest driver for maintaining the capabilities of the precipitation constellation is the provision of new missions. The current constellation is continuously aging, with many current sensors now more than 10 years old and well beyond their anticipated mission lifetime (see Figure 3). Given the time required to design, build, test, and launch new sensors it is imperative that a long-term strategy for the precipitation constellation is devised and implemented. As outlined above, several operational missions are planned (e.g., the NOAA JPSS and the EUMETSAT EPS-SG series), but there are fewer dedicated long-term precipitation-specific missions with mapping capabilities. While many operational missions provide valuable observations for the precipitation community, these missions are not necessarily optimised for precipitation retrievals, either due to the sensor-specific characteristics or through orbital characteristics that do not provide the frequent or uniform sampling necessary for precipitation measurements. Observing System Simulation Experiments (OSSE) could be used (e.g., Chambon et al. 2014) to improve coordination between the satellite agencies to provide an optimal sampling strategy, and to assess the likely impact of the loss of one or more sensors within the constellation (Chambon et al. 2012). As Figure 8 illustrates, many of the operational agency missions duplicate observations, it is therefore crucial that organisations and agencies act upon such studies.

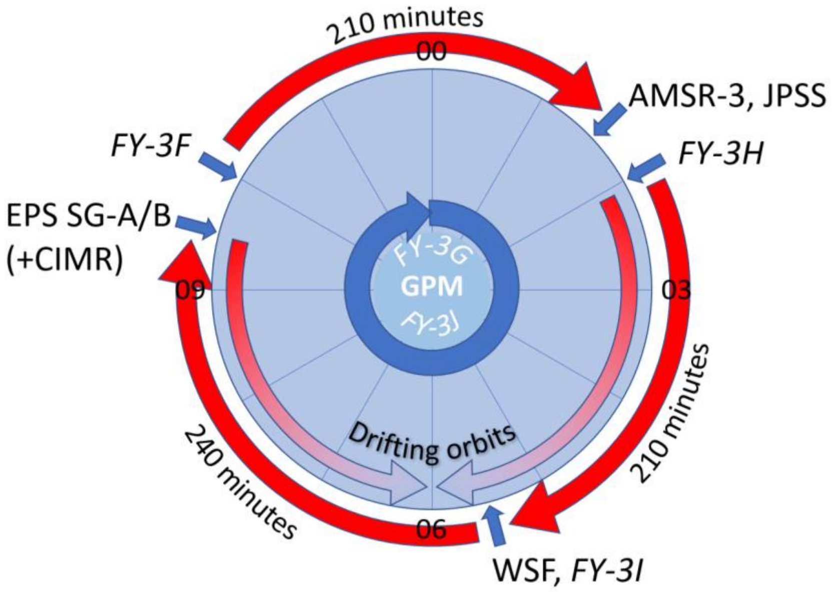


Figure 8: Anticipated composition of the precipitation constellation in the 2028-2030 timeframe. Note that the main operational agency missions are clustered around the 02:30/03:00, 05:30/06:00 and 09:30/10:00 times. The gaps between these times require observations from either satellites in drifting orbits or from those in non sun synchronous low inclination orbits.

Robustness through redundancy

Larger satellites are generally more robust at dealing with failures due to built-in redundancy, thus allowing long-term, if not multi-decadal, records of observations to be collected, as exemplified by TRMM. Meanwhile, the long-term reliability of precipitation-capable cubesats and smallsats has yet to be fully evaluated, but it is anticipated that the orbital characteristics would determine the mission lifetime rather than any system or sensor failure. Furthermore, many operational meteorological satellites, such as the GEO missions (GOES, Meteosat, etc.) and the LEO MetOp and NOAA missions have on-orbit backup sensors. However, it should be noted that the backup satellites generally collect data over the same space/time domains as that of the primary missions and therefore contribute relatively modestly to the overall temporal sampling.

Extended mission lifetimes

Allowing missions to operate past their design lives and therefore continue to provide data as part of the precipitation constellation is a proven concept. However, the extension of missions is often fraught with obstacles, not least being the need to comply with the modern standards for end-of-life disposal of satellites to avoid space junk (Crowther 2002; Witze 2018). Nevertheless, the precipitation community has, in part, been successful in persuading agencies to keep such missions operating after the end of their designed lifetime (e.g., TRMM), with partial failures (e.g. Megha-Tropiques), or after station-keeping fuel was exhausted (e.g., MetOp-A). The extension of mission lifetimes has only been, and likely will be, an issue for the larger satellite systems compared with smaller satellites which have shorter planned lifetimes.

Retrieval scheme resilience

Many precipitation retrieval schemes require a full set of observations to generate a valid estimate. However, such schemes could be adapted to provide useful information with fewer channels. Figure

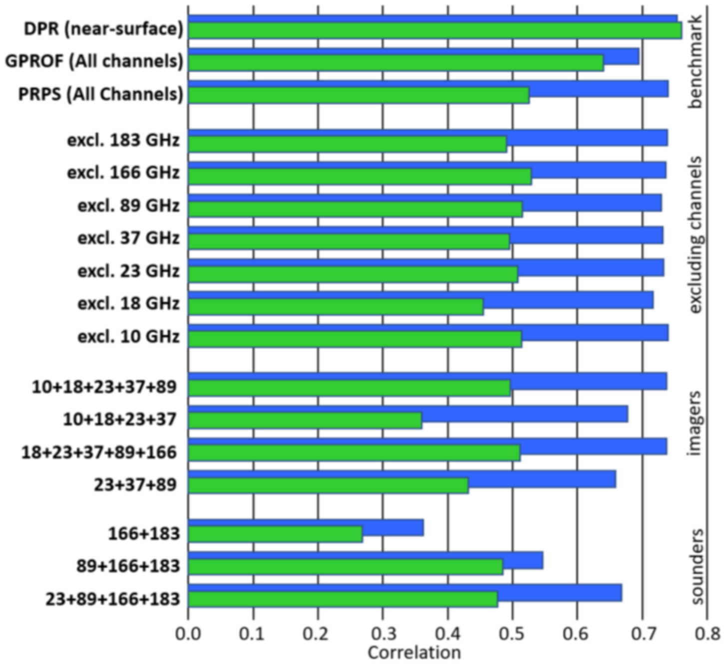


Figure 9: Simulations of channel selection using data using the GMI channels (DPR data is included for comparison). It can be noted that the loss of any particular frequency has relatively little impact relative to any other channel, largely a result of the wide-channel availability on the GMI. Difference channel combinations show more variability, but similar performance with 4 or 5 frequencies. The simulation of the sounder channels (bottom group) shows the merit in including some of the lower frequency channels, particularly the 89 GHz (land and ocean) and the 23 GHz (coean).

9 shows a range of retrieval scenarios using different channel combinations. The loss of a single channel on a diverse-channel sensor (such as the GMI) only degrades the retrieved precipitation marginally. The better performance of precipitation retrievals from the observations gathered over a wide range of frequencies has been shown by Kidd et al. (2018). Additionally, the flexible utilisation of channels in the retrievals has particular merit when dealing with surface-based Radio-Frequency Interference (RFI; Wu and Weng 2011), which necessitates the exclusion of certain channels from retrieval schemes at certain times/locations. Furthermore, the calculation of the errors and uncertainties associated with the retrieved precipitation is urgently needed to allow users to assess the usefulness of retrievals from different schemes. New techniques should also be investigated and developed that merge observational data before the retrieval stage, rather than merging precipitation estimates post-retrieval. The last point might be a longer-term goal, but it is possible to envisage a scenario where two satellites in very similar orbits, both experiencing channel degradation could jointly provide the capabilities of a single sensor.

Data availability and access

Most precipitation-related satellite observations are freely available both in terms of being available and accessible to any particular user. However, there are many data sets that are more restrictive and may not be accessible to all potential users. Furthermore, the access to such data sets in very near real time is somewhat limited, yet is of great importance to ensure timely integration into user's processing systems, such as that used in flood forecasting. Crucially, science works best when such data are accessible to the community, as shown by the open release of the DMSP SSMI data in 1987 by the US Department of Defense, which enabled the careers of many of the current generation of precipitation scientists and the development of their retrieval schemes.

6 Recommendations

Based upon the current precipitation constellation and planned missions, the following actions are necessary to ensure the long-term continuity of global satellite precipitation observations:

i) reaffirm commitment and support for current and planned precipitation-capable missions together with free and open data sharing by the appropriate agencies and organisations;

ii) develop a long-term strategy for a viable constellation of precipitation-capable sensors that meet the necessary scientific and user requirements. Specifically,

- PMW sensors with diverse channels covering the primary precipitation-sensitive frequencies with good spatial resolution (as exemplified by the AMSR/GMI class of sensors), and
- operational AMW sensors in a non-Sun-synchronous orbit for cross-calibration and reference standard for PMW (and IR) precipitation estimates (as exemplified by the mapping capabilities of the PR/DPR and the sensitivity of the CPR);

iii) support for the continuation of precipitation-capable missions beyond nominal mission lifetime operations, with due regard for the limitations imposed by deorbiting/sensor degradation considerations;

iv) integration of new technologies, such as smallsats and cubesats, with access to new data sets where these address the necessary scientific and user requirements; and

v) implementation of mitigation strategies within the precipitation retrieval schemes to maximise use of sub-optimal observations, including failed/denied channels, to help ensure the continuity of adequate sampling.

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