3.4. Requirements for a constellation of precipitation sensors

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A fundamental requirement for the accurate measurement and representation of any parameter is that the observations made must be commensurate with, or finer than, the variable being measured. This is challenging for satellite-based observations due to the physical and engineering constraints imposed upon the characteristics of the observations being made. Measuring precipitation from spaceborne sensors is no exception.

3.4.1. A constellation for precipitation

For the measurement of precipitation, several key factors must be considered:

Precipitation characteristics: precipitation is temporally very variable with changes occurring over timescales of a few seconds, but which also impact the longer-term accumulations. Furthermore, precipitation varies greatly spatially, from a few tens of metres in intense storms, to over tens of kilometres in synoptic systems. Scale is a key driver of the characteristics of precipitation: at the instantaneous scale, precipitation intensity is heavily skewed towards the normal – zero, although coarser spatial and temporal scales results in more normally-distributed values.

Observing capabilities: Given the variability of precipitation, frequent and regular observations are key to providing representative measurements. However, frequent and regular observations (with reasonable resolution) are only available from GEO VIS/IR sensors, which do not observe precipitation per se but infer it from the cloud tops. Despite many schemes to derive precipitation from multi-spectral VIS/IR observations (some simple, some complex), the fact is that these still rely upon the cloud top properties. Such schemes will not improve upon schemes utilizing PMW data at the time of the PMW observation: however, VIS/IR observations have an essential role in providing information on precipitation when no PMW data is available.

Engineering and physical aspects: The use of PMW observations is key to providing good precipitation estimates. However, there are physical limitations to the engineering achievable and the range of channels that can be usefully employed. In particular, the resolution of PMW sensors is limited by the size of the antenna and the frequencies used. Although it may be possible to utilize higher frequencies to provide finer spatial resolutions, such higher frequencies are less direct to surface precipitation.

User requirements: Ultimately, precipitation is measured for the benefit of the user community, which has a vast range of requirements: spatially from metres through kilometres, temporally from seconds to annual and latency from minutes through seasonal (GEO 2010). Matching the fundamental characteristics of precipitation with the observational and engineering limitations effectively sets the boundaries within which the user community must operate.

Observations from PMW radiometers are therefore seen as *the* sensor for global precipitation measurements from satellites. These sensors, initially developed in the 1970s, have evolved into the suite of sensors that are available to the community today: these now form a constellation of about 10–12 precipitation-capable sensors available at any particular time. A broad range of science and user communities are now dependent upon the precipitation products provided by these sensors for a range of applications, from climate monitoring to

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disease early warning. The current precipitation constellation consists of both conically scanning and cross-track multi-channel instruments, many of which are beyond their operational and design lifetime, but continue to operate through the cooperation of the responsible agencies. The Group on Earth Observations (GEO) and subsequent discussions by the Coordinating Group for Meteorological Satellites (CGMS) have raised the issue of how a robust future precipitation constellation should be constructed. The key factors to be considered can be summarized as:

i. sufficiently fine spatial resolutions necessary to capture precipitation-scale systems and reduce the non-linearity ("beam-filling effect") of the observations;
ii. wide channel diversity for each sensor necessary to cover the range of precipitation types, characteristics and intensities that are observed across the globe;
iii. an observation interval that provides temporal sampling commensurate with the variability of precipitation; and
iv. precipitation radars within the constellation to provide a consistent calibration source across the globe, as demonstrated by the impact of the first two spaceborne radars on the Tropical Rainfall Measuring Mission (TRMM) and Global Precipitation Measurement (GPM) 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.

The current precipitation constellation, as epitomized by the GPM mission, includes 10 or more precipitation-capable missions from several international agencies, including CNES, ESA, the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), ISRO, JAXA, NASA, NOAA and the U.S. DoD. Additional operational precipitation-capable PMW missions exist, but data access/usage arrangements limit their widespread exploitation. The multi-agency aspect affects the coordination of each mission's orbital crossing times. To ensure consistent overpass times, the operational EUMETSAT Meteorological Operational satellite (MetOp)-B and -C, and NOAA Suomi National Polar-orbiting Partnership (SNPP) and NOAA-20 orbits are rigorously maintained, but in doing so, each pair essentially gathers observations at the same time. The overpass times of other missions drift over the course of 14–15 years between the extremes of ca.13:30 to 22:30 (ascending) while the precessing orbits of GPM and Megha-Tropiques provide overpasses across all times over the period of a few months (albeit with highly intermittent sampling). Due to the irregular nature of the PMW observations, the frequent and regular observations made by the GEO satellite sensors are crucial in providing continuous precipitation estimated through the use of merged precipitation retrieval schemes.

Despite the case for the utilization of satellite-based PMW sensors, satellites within the current precipitation constellation are old, with many missions beyond their designed operational lifetime: at present, their average age is just under 10 years old. It is therefore crucial that there is a concerted program of new satellites/sensors to ensure continuity in satellite-based precipitation measurements that meets the needs of the user community. The majority of the sensors in the current precipitation constellation are cross-track scanning sounding instruments, not designed for precipitation retrievals, and this is also reflected in the precipitation-capable sensors proposed in the near future (see below). The gain or loss of these sensors to/from the constellation directly impacts the temporal sampling of the observations together with the ability to accurately retrieve the precipitation. The oft-cited "3-hour" repeat observation time quoted for the GPM mission should be seen as an idealized (statistical) mean revisit time: in reality, there are significant regional temporal gaps of 4 hours or more in global sampling.

Several precipitation-capable missions are currently being planned for launch over the next decade. These include:

3.4.1.1. EUMETSAT: European Polar-orbiting System, Second Generation (EPS SG)

These satellites and sensors will provide continuity to the current MetOp series of satellites, with similar orbital characteristics to current missions. The Second Generation A (SG-A) satellites will carry the cross-track MicroWave Sounder (MWS), while the SG-B satellites will carry the conically-scanning MicroWave Imager (MWI) and the Ice Cloud Imager (ICI).

3.4.1.2. NOAA: Joint Polar System Satellite

The first in the JPSS series (JPSS-1, a.k.a. NOAA-20) is operational and will be joined by JPSS-2/-3/-4, with each satellite carrying an ATMS sounding instrument.

3.4.1.3. U.S. Department of Defense: Weather Satellite Follow-on–Microwave (WSF-M)

The U.S. DoD has two SSMIS/GMI-like sensors as part of their WSF-M with a contractual launch date of October 2023.

3.4.1.4. JAXA: Advanced Microwave Scanning Radiometer-3

JAXA is currently building the third generation AMSR sensor to be flown on their Global Observations SATellite for Greenhouse gases and Water Cycle satellite 3 (GOSAT-3). The sensor will build upon the heritage of the AMSR sensors with addition of high-frequency channels.

3.4.1.5. NASA: Time-Resolved Observation of Precipitation structure and storm Intensity with a Constellation of small Satellites (TROPICS)

The TROPICS mission will provide a total of seven cubesats, one pathfinder to be launched June 2021 in a polar orbit, to be followed by six in a low-inclination orbit to look at the evolution of weather systems across the Tropics.

3.4.1.6. NASA: Aerosols, Clouds, Convection and Precipitation (ACCP) mission

NASA is currently finalizing the ACCP mission architecture with a goal of observing precipitation processes.

3.4.1.7. China Meteorological Administration (CMA)/National Remote Sensing Center of China (NRSCC): Rain mapping missions

The Chinese rain mapping missions are scheduled to be flown from 2023 onwards as FY-3G and FY-3J. Both missions would include PMW and AMW sensors with similar characteristics to the current GPM mission.

The collection of sufficient observations for generating precipitation estimates with reasonable confidence is very precarious, even with the current constellation. The precipitation community has been very adept at exploiting data from a range of satellite missions and sensors not necessarily design for the retrieval of precipitation. A number of strategies needs to be considered to ensure a continuation of adequate precipitation measurements from satellite systems:

i. New missions: These are the largest driver for maintaining the capabilities of the precipitation constellation. However, this requires long-term planning since missions (even cube-/small-sats) take a decade (or more) from formulation to operation. Crucially, there are few dedicated precipitation-specific missions planned, particularly in terms of mapping capabilities, channel selection, orbital characteristics and data latency. Coordination between the satellite agencies is crucial to ensure an optimal sampling strategy.
ii. Redundancy: larger satellite systems tend to provide a better degree of redundancy, allowing multi-decadal records of observations to be collected. The long-term reliability of (precipitation-capable) cubesats has yet to be fully evaluated, but their orbital characteristics are likely to be a main driver of their mission lifetime. While the MetOp and NOAA polar-orbiting missions typically have on-orbit backup satellites, use of their backup missions in the precipitation constellation is limited, since their observations generally cover the same space/time domains of the primary missions.
iii. Extended mission lifetimes: many missions operate beyond their designed operational lifetime, yet within the end-of-life disposal requirements. The utilization of such missions is essential to maintain the number of available satellite sensors. To date, missions such as TRMM and Megha-Tropiques have had extended mission lives, together with post-operation missions such as MetOp-A. The extension of mission lifetimes has been possible for medium to large satellite systems that often carry additional fuel: cubesats do not have this same capability.
iv. Retrieval scheme resilience: retrieval schemes rely upon a set of sensor-specific channels to generate a precipitation estimate. Unfortunately, most schemes will not provide an estimate if one channel is not usable, despite valid data from the other channels. In reality, a single channel loss on diverse-channel sensors (that is, SSMIS/AMSR-type) only degrades the retrieved precipitation very marginally. The flexibility of the retrieval schemes is therefore vital to deal with data loss from one or more input channels or sources. Further, new techniques should be investigated and developed that merge observational data before the retrieval stage, rather than merge precipitation estimates post-retrieval: it is possible to envisage a scenario where two satellites in very similar orbits, both experiencing channel degradation, could between them provide the capabilities of a single sensor.

3.4.1.8. ESA Copernicus Imaging Microwave Radiometer (CIMR)

The Copernicus Imaging Microwave Radiometer (CIMR) is currently being developed by ESA to provide fine resolution observations over frequencies from 1.4 to 37 GHz using a deployable 7m antenna. The anticipated launch date is post-2028.

3.4.1.9. ESA Arctic Weather Satellite (AWS)

The Arctic Weather Satellite (AWS) mission currently under development will provide frequent coverage of Earth for improved nowcasting and numerical weather prediction, carrying a cross-track microwave sounder.

3.4.2. Recommendations

i. Reaffirmation of a commitment and support for current and planned precipitation-capable missions

ii. Development a long-term strategy for a viable constellation of precipitation-capable sensors that meet the necessary scientific and user requirements. Specifically,
  a) PMW sensors with diverse channels covering the primary precipitation-sensitive frequencies with good spatial resolution, exemplified by the AMSR/GMI class of sensors, and
  b) operational AMW capabilities in a non-Sun-synchronous orbit for cross-calibration of all PMW (and IR) precipitation estimates, exemplified by the PR/DPR sensors.

iii) Support for the continuation of precipitation-capable missions beyond their nominal mission lifetime, subject to the limitations imposed by deorbiting/sensor degradation considerations

iv) Exploit new technologies, such as cubesats, where these meet the necessary scientific and user requirements

v) Implement mitigation strategies within the precipitation retrieval schemes to maximize the utilization of sub-optimal observations to help ensure continuity in adequate sampling.