The Emerging Technological Revolution in Earth Observations

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ABSTRACT: A technology revolution in Earth observation sensor design is occurring. This revolution in part is associated with the emergence of CubeSat platforms that have forced a de facto standardization on the volume and power into which sensors have to fit. The extent that small sensors can indeed provide similar or replacement capabilities compared to larger and more expensive counterparts has barely been demonstrated and any loss of capability of smaller systems weighed against the gains in costs and new potential capabilities offered by implementing them with a more distributed observing strategy also has not yet been embraced. This paper provides four examples of observations made with prototype miniaturized observing systems, including from CubeSats, that offer a glimpse of this emerging sensor revolution and a hint at future observing system design.

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Observations we routinely make of Earth from the vantage point of space directly impact our lives and our well-being (National Academies of Sciences, Engineering, and Medicine 2018). These observations are essential inputs into the routine prediction of weather and warnings of hazards, are the bedrock of many of the services that support our daily lives, and provide essential information for developing a secure nation and world. Identifying what observations matter most in meeting these diverse needs and developing ways to provide them is, however, not a simple task.

At the World Weather Open Science Conference in 2015, the then director of one of the world's leading weather prediction centers was asked of all the streams of data ingested into their advanced forecast and assimilation system, and many come from Earth orbiting satellites in addition to in situ observing networks, which single measurement stands out as highest priority or has most forecast impact. The answer was “all of them.” The substance of this seemingly evasive answer is well understood in that many streams of observations, together with advances in models into which the observations are assimilated, have fueled the advances in numerical weather prediction witnessed today (Bauer et al. 2015). The fact that a wide range of observations is essential for this purpose (WMO 2016) underscores the real and wider challenge inherent to Earth observations more generally and is a challenge further noted in the decadal study of the National Research Council (NRC) (National Academies of Sciences, Engineering, and Medicine 2018).

Earth is an interconnected system, and prediction of its behavior, either on the short weather time scales or longer time scales of climate change, for example, requires observations of its many interconnected parts. Why this is important is that advances in the prediction of any specific aspect of environmental change, like prediction about sea level rise or about precipitation change over the southwestern United States for instance, is typically affected more by measurements of a range of parameters not obviously connected to observations of sea level or precipitation specifically.

As in all sciences, progress in Earth system sciences, and especially in the area of Earth observations, has not been steady. Most of the ideas, instruments and methods influencing this area of science are conceived around discreet missions or similar narrow concepts. The high cost of most Earth's observing systems today has, out of necessity, also driven a narrow observing strategy built around measurements of a small number of “essential” variables. Consequently, an Earth observing system viewpoint tends to be lost and the rising costs of operational observing systems in times of flat or declining budgets serves only to exacerbate the problem. Added to these pressures is the broad recognition of the need for a sustained Earth observing system both to monitor global change and attribute the causes to it (National Academies of Sciences, Engineering, and Medicine 2015).

Somewhat independent of these great challenges is a technology revolution that is occurring before us. Much of the recent discussion about technology innovation of spaceborne systems has revolved around discussion of CubeSat capabilities (National Academies of Sciences,

Engineering, and Medicine 2016) and the affordable access to space that such capabilities offer. Spacecraft miniaturization, more generally including and beyond CubeSats, is indeed one important factor in the developing revolution. However, this revolution runs much deeper. The aspect of the miniaturization revolution that is critical to Earth sciences is that of sensor design also aided by advances in detector and other system technology. CubeSat development played a role in advancing this development by providing a de facto standardization that, in concrete terms, sets design principles with specifications on the volume and power into which sensors have to fit. This paper does not focus on the evolving CubeSat or small satellite capabilities [e.g., refer to Millan et al. (2019) for a review] and is not meant to imply these small platforms are yet a replacement for larger more capable systems. The intent of the paper is to provide the reader with a genuine sense for what is occurring in sensor miniaturization today that is the ultimate engine of the observational revolution proposed. Although the examples presented in the next section, are, for the most part, from technical demonstration missions currently in orbit, they provide a view of the future of Earth observations.

Critics of miniaturization, however, rightly argue there is much to be proven. The extent that small sensors can indeed provide similar or replacement capabilities compared to their larger and more expensive counterparts has barely been demonstrated and any loss of capability of smaller systems weighed against the gains in costs and new potential capabilities offered by implementing them with a more distributed observing strategy also has not yet been fully embraced. Assessments of these smaller sensor systems are the subjects of ongoing analysis and study and preliminary results from them are offered to the reader.

Miniaturization examples

Perceptions about how sensor miniaturization capabilities have evolved since 2012 are offered in Table 1. Selva and Krejci (2012) published a survey of CubeSat sensor technologies in which they binned the current state of the art into three categories: “feasible,” meaning that a technology, or a sensor is compatible with the CubeSat standard and thus can be expected to provide measurements from that platform; “infeasible” is for a technology determined to be clearly incompatible with the CubeSat standard; and “problematic” are for those instruments that could be developed to fit the CubeSat standard, but at the expense of significantly reduced data quantity and/or quality. Table 1 both summarizes their analysis and updates it for 2019. What was deemed infeasible and problematic seven years ago, like the case of a rain radar, has now been demonstrated to be feasible. Since miniaturization typically is associated with significant reduction in sensor cost, these advances also now offer the potential to adopt entirely new approaches for observing Earth (e.g., Stephens et al. 2019). Four examples that illustrate the degree and scope of effort underway are discussed here. These examples are of measurements identified in the recent decadal study of the NRC as high priority and have specifically benefitted from investments in the Earth Science and Technology Office of NASA’s Earth Science Division to advance the miniaturization of various technologies over time. This table, however, does not reflect on the fidelity of the measurements although some performance characteristics, when known or verified, are provided in the table for reference.

The measurement of solar spectral irradiance from a CubeSat (Compact Spectral Irradiance Monitor). Maintaining the continuity of an accurate, long-term climate data record on solar spectral irradiance (SSI) is essential (National Research Council 2012). The current approach relies on the Spectral Irradiance Monitor (SIM) on the Total and Spectral Solar Irradiance Sensor (TSIS-1) mission that began operations from the International Space Station (ISS) in March 2018 with overlap to the Solar Radiation and Climate Experiment (SORCE) mission that is approaching its end-of-mission life.

Table 1. The evolution of small sensor capability between 2012 and today.

Technology	Selva and Krejci (2012)	Freeman (2019)	Description
Atmospheric chemistry instruments	Problematic	Feasible	PICASSO—Instrument designed to obtain vertical profiles of stratospheric ozone via spectral observation of solar occultation. PICASSO launched in 2019.
Atmospheric temperature and humidity IR sounders	Feasible	Feasible	CIRAS & 3D Winds, CubeSat IR Atmospheric Sounder (CIRAS) is a 4U cryo-cooled grating MWIR spectrometer for sounding atmospheric water vapor and temperature, and some constituents (e.g., CO and CO ₂ ; Pagano et al. 2016). 3D Winds is a proposed constellation of twelve 6U CubeSats, each carrying a passively cooled midwave infrared hyperspectral FTS sensor tracing water vapor features (Glumb et al. 2015). CIRAS (CrIS) spectral range, resolution, and NEDT are 1,950–2,450 cm ⁻¹ (650–2,550 cm ⁻¹), 1,2–2 cm ⁻¹ (0.9 cm ⁻¹), and <0.2 K (0.2 K), respectively.
Cloud profile and rain radars	Infeasible	Feasible	RainCube and CloudCube—Refer to text for RainCube. CloudCube is a W-band concept under development employing related technology to RainCube. RainCube minimum sensitivity <13 dBZ and 120-m vertical and 7.9-km horizontal resolution.
Earth radiation budget radiometers	Feasible	Feasible	RAVAN, CSIM, PREFIRE—RAVAN is a technology demonstration of nanotube detectors targeting Earth's radiation budget. CSIM—Refer to text. PREFIRE (Polar Radiant Energy in the Far-Infrared Experiment) is a miniaturized 3U thermal IR spectrometer exploiting thermopile detector technology, NEDT ~ 0.6 K.
High-resolution optical imagers	Infeasible	Feasible	Commercial company Planet has deployed hundreds of its 3U Dove satellites, each carrying a multispectral, optical imager capable of 3–5-m spatial resolution.
Imaging microwave radars	Infeasible	Feasible	Freeman et al. (2016) describe a concept for a Ka-band SAR that fit in a 12U volume.
Imaging multispectral radiometers (visible–shortwave infrared) and hyperspectral spectrometers	Problematic	Feasible	AstroDigital, SWIS: Astro Digital has developed and flown a small constellation of 6U CubeSats each carrying a three-band (red, green, near-infrared) multispectral imager, capable of 22-m spatial resolution; Snow and Water Imaging Spectrometer (SWIS) is a 6U compact imaging spectrometer measuring radiances between 350- and 1,700-nm spectral range with 5.7-nm resolution
Imaging multispectral radiometers and sounders (microwave and millimeter wave)	Problematic	Feasible	TEMPEST, TROPICS, IceCube; TEMPEST—Refer to text. The TROPICS sensor is two total power radiometers of with eight channels from 90 to 119 GHz, and four channels from 183 to 206 GHz. IceCube is a 3U CubeSat demonstration of an 874-GHz radiometer for cloud ice observations (Wu et al. 2014). TEMPEST-D NEDT* are as follows: 0.13 (0.29), 0.25 (0.46), 0.2 (0.38), 0.25 (0.54), and 0.7 (0.73) K, respectively, for 87-, 164-, 174-, 178-, and 181-GHz channels (ATMS NEDT in parenthesis)
Lidars	Infeasible	Problematic	TOMCAT—A SmallSat lidar concept operating at 1,064 nm (McGill and Yorks 2018). TOMCAT 1,064-nm clear-sky SNR is similar to CALIOP during daytime, 8 times better than CALIOP at night (assuming a 425-km orbit altitude). The duty cycle is dependent on bus capabilities.
Lightning imagers	Feasible	Feasible	RaioSat—Brazil's RaioSat project (Naccarato et al. 2016) is designed to detect intracloud and cloud-to-ground lightning flashes simultaneously, using a 3U optical sensor and a VHF antenna.
Multiple angle/polarimeter	Problematic	Feasible	HARP Polarimeter—A 3U hyperangular imaging polarimeter (Martins et al. 2014) with three channels at 440, 550, and 670 nm, with 2.5-km spatial resolution at nadir, and a degree of linear polarization < 1%.
Ocean color spectrometer	Feasible	Feasible	SeaHawk—Seahawk satellites are 3U spectrometers for ocean color using eight visible–near-infrared bands in the same range as SeaWiFS (402–885 nm), at spatial resolutions from 75 to 150 m, with SNR comparable to its predecessor SeaWiFS.
Radar altimeters	Infeasible	Feasible	SNoOPI—A 6U CubeSat mission, currently under development, using reflectometry to exploit UHF (P band) signals from communication satellites for root-zone soil moisture (Garrison et al. 2017).
Scatterometers	Infeasible	Feasible	GNSS reflectivity (CYGNSS)—Refer to text

Fig. 1. The evolution of the solar spectral irradiance monitor (SIM) from SORCE to TSIS to CSIM where the size and mass of the latter were reduced to fit into a 6U CubeSat.

Challenges remain, however, for maintaining an SSI measurement record into the future and over the long term. To address this challenge, the Earth Science Technology Office (ESTO) supported the development of Compact Spectral Irradiance Monitor—Flight Demonstration (CSIM-FD), which was launched into a sun-synchronous orbit onboard a SpaceX Falcon 9 rocket on 3 December 2018 as part of a CubeSat demonstration flight (Richard et al. 2019). CSIM is an ultracompact SSI monitor covering the 200–2,800-nm spectral range and was integrated into a 6U CubeSat. CSIM has a mass of one-tenth and volume of one-twentieth of the currently operational TSIS-1 ISS instrument with even greater reductions in size and mass compared to the SORCE mission (Fig. 1).

Several technology innovations drove the reduction in instrument size. The Electronic Substitution Radiometer (ESR) offers exacting onboard calibration to meet the accuracy requirements and traceability to a cryogenic radiometer. The size and environmental demands on instrument design have been radically reduced by using micromachining and carbon nanotube technology. These significant technology and design advances resulted in a miniature CSIM ESR with *lower noise and faster response* than the ESR on TSIS or SIM.

The current overlap of CSIM-FD with existing SSI measurements from both the TSIS-1 SIM and SORCE SIM provides the opportunity to validate the performance of this miniaturized sensor as shown in Fig. 2. This figure presents a preliminary comparison between the SSI measured in March 2019 by the TSIS-1 SIM and CSIM-FD. The agreement is within 1% and within the radiometric accuracy of TSIS-1 across the spectral range from 200 to 2,400 nm. The TSIS spectral range represents 96.2% of the total solar irradiance output from the sun. CSIM has a cutoff of 2,800 nm, thus providing a measure of slightly more (97.4%) of the total energy output.

CYGNSS—A small satellite signal of opportunity constellation. OCEAN WINDS AND EVAPORATION. Examples of science returned using signal of opportunity (SoOp) is provided by the Cyclone Global Navigation Satellite System (CYGNSS) mission (Ruf et al. 2016), which measures oceanic wind speed using reflected Global Navigation Satellite System (GNSS) signals with an

approximate 3-h revisit time. CYGNSS was motivated by two hypotheses related to improving the intensity forecast of tropical cyclones (TCs). First, that the better penetration provided by forward-scattered L-band radiation in regions of intense precipitation will enable better observation of the inner core. Second, that the high revisit rate provided by a constellation composed of multiple spacecraft better samples the rapid genesis and intensification stages of the TC life cycle. An example of CYGNSS winds around a tropical storm is presented below (and described in reference to Fig. 7).

Managed by the University of Michigan, CYGNSS is the first science mission utilizing a bistatic radar scatterometer derived from GPS reflections. CYGNSS measures the shape and power of a delay-Doppler map (DDM) of these GPS reflections. The DDM relates to surface roughness, which is then dependent on the near-surface wind speed (Ruf et al. 2016; Ruf and Balasubramaniam 2019). Being a signal of opportunity measurement, the GPS signals observed are transmitted in L band and are reasonably well characterized but not necessarily optimized for ocean wind sensitivity, especially lighter winds. A pair of GPS antennas, mounted on the bottom of each of eight small satellites in a constellation provide high-revisit-rate observations between $\pm 35^\circ$ latitude.

The surface wind speed derived from CYGNSS are compared to wind speeds from matched observations from the Pacific Marine Environmental Laboratory (PMEL) Global Tropical Moored Buoy Array in Fig. 3 (left panel). Latent heating fluxes are derived from these winds with additional inputs that include the surface and air temperature and water vapor obtained from 1-hourly Modern Era-Retrospective Analysis for Research and Applications (MERRA) fields, selecting the nearest grid point to the CYGNSS observation in both space and time. These are used, along with the wind speeds, in the Coupled Ocean–Atmosphere Response Experiment (COARE), version 3.5, algorithm and then compared to estimates of fluxes obtained from the moored buoy array as shown in Fig. 3 (right panel). A complete description of the algorithm, along with an evaluation of the flux products, can be found in Crespo et al. (2019). CYGNSS winds at speeds up to 15 m s^{-1} compare well both to other remote sensing measurements and in situ data. As wind speeds in the buoy dataset rarely exceed 15 m s^{-1} , the latent heat flux (LHF) estimates from these buoys and highlighted in this figure provide primarily a low-wind-speed evaluation of the CYGNSS flux estimates. Validation for higher wind speeds remain challenging in part due to paucity of validation data at higher speeds. Fluxes from both CYGNSS and buoys were computed using version 3.5 of the COARE algorithm (Edson et al. 2013), and comparison between shows a strong correlation between CYGNSS retrieved LHF estimates and estimates derived from in situ measurements.

Fig. 2. Early results from CSIM-FD comparing the solar spectral irradiance measured by both TSIS-1 and CSIM. Both instruments have their prelaunch spectral irradiance calibrations tied to a cryogenic radiometer. The preliminary agreement is with absolute SSI differences $<1\%$ between 400 and 2,400 nm.

Fig. 3. Comparisons (left) between CYGNSS derived winds and in situ buoy measurements and (right) between CYGNSS deduced latent heat flux and the latent heat flux derived from in situ buoy observations (from Crespo et al. 2019).

SOIL MOISTURE. Surface water over land influences a number of important Earth science processes. Information about wetland dynamics is essential to characterizing, understanding, and projecting changes in atmospheric methane and terrestrial water storage and soil moisture has a wide influence including on convective storms (e.g., Betts 2004). Both wetland waters and soil moisture provide clear reflection signatures in Global Navigation Satellite Systems Reflectometry (GNSS-R) measurements (Nghiem et al. 2017; Chew et al. 2018).

Chew and Small (2018a) estimate that on any given day, approximately 80% of the Soil Moisture Active Passive (SMAP) EASE-2 grid cells that fall within the latitudinal band of CYGNSS will be sampled, and the majority of these grid cells are sampled more than once. Retrieving daily or subdaily soil moisture using observations from CYGNSS is shown to be possible, thus being an immense improvement over measurements for a single satellite with a 16-day repeat cycle. An experimental data product using CYGNSS observations to retrieve daily soil moisture exists, and data and an algorithm theoretical basis document (ATBD) are available (<https://data.cosmic.ucar.edu/gnss-r/>) (Chew and Small 2018b). In a validation exercise using data from more than 200 in situ soil moisture stations, the unbiased root-mean-square (RMS) error between in situ data and CYGNSS soil moisture retrievals was $0.047 \text{ cm}^3 \text{ cm}^{-3}$, which is essentially equivalent to the $0.05 \text{ cm}^3 \text{ cm}^{-3}$ RMS error of level 3 SMAP soil moisture retrievals for the same stations.

The spatial resolution of the CYGNSS signal over land, however, has yet to be definitively quantified, in large part because the spatial resolution is not defined by the size of the antenna, but by the roughness of the reflecting surface. Observational and other evidence is starting to show that the majority of the reflecting signal, for relatively smooth surfaces, comes from an area of only a few square kilometers, which makes it comparable in resolution to the now-inactive SMAP radar (Camps 2019; Chew and Small 2018a).

An illustration of the CYGNSS soil moisture measurements performance is provided in Figs. 4a and 4b. These panels show CYGNSS SNR that has been gridded to 9 km and seasonally averaged for JJA 2018 and DJF 2018/19, respectively. The SNR observations were corrected for gain and range assuming coherent reflections, as has been done in previous studies (e.g., Chew and Small 2018a). The change in mean SNR between the two seasons is shown

in Fig. 4c—blue colors indicate areas where CYGNSS SNR was higher in the summer, and red colors are areas where SNR was higher in the winter. Figure 4d shows changes in soil moisture from the SMAP radiometer for the same time period and indicates how CYGNSS SNR is well correlated with changes in SMAP soil moisture. In this case, the global correlation coefficient between CYGNSS and SMAP soil moisture is 0.7.

TEMPEST. The Temporal Experiment for Storms and Tropical Systems (TEMPEST) mission was originally conceived to map the onset of precipitation over the global ocean simultaneously with the surrounding moisture field. TEMPEST-D, a demonstration satellite designed and built through a partnership between the Colorado State University and the Jet Propulsion Laboratory, was launched in May 2018 and deployed from the ISS in July 2018 to reduce the technology risk for the mission (Reising et al. 2018; Padmanabhan et al. 2018). TEMPEST-D is a 6U CubeSat carrying a cross-track imaging, five-channel passive microwave radiometer with bands from 90 to 200 GHz. Critical to the TEMPEST-D design is the ability to resolve the time derivative of the scene brightness temperature. This is facilitated by the inclusion of high-quality blackbody calibration sources viewed through the antenna, end to end. In this way, the sensor design and expected data quality are similar to the Advanced Technology Microwave Sounder (ATMS) on the NOAA polar satellites (Kim et al. 2014).

The TEMPEST-D radiometer comprises a scanning antenna assembly, single multifrequency feed horn and five direct detection microwave receivers. The center frequencies are at 87, 164, 174, 178, and 181 GHz, similar to that of the ATMS. The antenna scans at 30 revolutions per minute in the cross-track direction providing views of the Earth scene and two calibration targets. A blackbody absorber is viewed at the top of the scan in the zenith direction and cold space is viewed at the scan edge. The receivers use indium phosphide low-noise amplifiers, giving the sensor a lower noise temperature than other radiometers on orbit at similar

Fig. 4. (a) Mean 9-km-gridded CYGNSS SNR observations for the summer (June–August) of 2018. (b) Mean 9-km-gridded CYGNSS SNR observations for the winter (December–February) of 2019. (c) Change in SNR between summer 2018 and winter 2019. (d) Change in SMAP soil moisture retrievals between summer 2018 and winter 2019.

frequencies. The sensor mass is 3.8 kg and it operates with 6.5 W of power. The spatial resolution at nadir is 25 km for the 87-GHz channel and 13 km for the 180-GHz channels and the scan has a swath width of 1,400 km. A comparison of the noise-equivalent delta temperature (NEDT) between TEMPEST and ATMS is provided in Table 1. TEMPEST-D NEDT ranges between 0.13 and 0.25 K for the channels between 87 and 178 GHz and 0.7 K for the 181 GHz compared to ATMS documented NEDTs of 0.29–0.54 K for the 87–178-GHz channels and 0.73 K for the 181-GHz channel. This improved performance of TEMPEST-D is a consequence of improved technology that both improves performance while miniaturizing the instrument.

The radiometer has operated nearly continuously since the start of payload operations on 11 September 2018. Figure 5 presents data taken on 11 December 2018 from the near 90-GHz channels on TEMPEST-D and NOAA ATMS (center frequencies at 87 and 88.2 GHz, respectively) showing remarkable qualitative agreement. Detailed intercomparison studies are ongoing to document the quantitative performance quality of TEMPEST-D relative to the larger operational sensors, such as ATMS.

RainCube. Until recently, radars have typically been thought of as a payload that cannot fit small satellite platforms given their perceived large size, weight, and power requirements. A novel miniature Ka-band atmospheric precipitation radar (mini-KaAR) architecture was developed at JPL (Peral et al. 2019). The radar design substantially reduces the number of components, power consumption, and mass by over an order of magnitude with respect to existing spaceborne radars making it compatible with the capabilities of low-cost satellite platforms such as CubeSats and SmallSats. A CubeSat version of the radar electronics, and an ultracompact lightweight deployable antenna were launched in May 2018 as the technology demonstration RainCube mission on a 6U CubeSat. The RainCube radar operates at the center frequency of 35.75 GHz and utilizes offset I-Q, a novel modulation technique for precipitation radars that enables miniaturization of the radar electronics by directly converting to (from) Ka band from (to) baseband, properly selecting the frequency scheme, and using digital filtering to remove spurious signals. The radar also adopts a solid state power amplifier that produces approximately 10 W of RF peak power, and a chirped pulse nominally of 166 μ s (with linear frequency modulation and amplitude tapering) with a duty cycle of 10% principally due to the limited resources of the CubeSat platform that hosts it. The antenna size for the RainCube technology demonstration once deployed is 0.5 m, with an antenna gain of 42.6 dB, resulting in a footprint of approximately 8 km from the nominal orbit altitude of 400 km.

Fig. 5. Global images of brightness temperature from (top) the 87-GHz TEMPEST-D channel and (bottom) the 88-GHz ATMS channel on 11 Dec 2018.

An example of the RainCube performance compared to the dual-frequency precipitation radar (DPR) of GPM is presented in Fig. 6. In this example, both the RainCube radar and DPR passed through about a 130-km segment a large stratiform rain system observed on 25 January 2019 near Prince Edward Island. The radar reflectivities of the two DPR frequencies, 14 GHz (Ku) and 35 GHz (Ka), are matched to within 9 min of the RainCube Ka-band radar observations. These matches were achieved by maximizing feature matching between the RainCube curtain and the DPR 3D volume scans and reveal the remarkable performance of the RainCube Ka-band radar indicating a capability for measuring precipitation similar to that of GPM.

The outlook

Earth is a dynamic planet on which the atmosphere, ocean, land, and ice connect and interact across a range of spatial and temporal scales. We have understood this dynamic perspective at least since the International Geophysical Year (IGY) in 1957/58 that brought together many disciplines in Earth sciences and marked a major change in the way we think about studying Earth. Today's leading science occurs at the Earth system level, with the aim of understanding the linkages between its different components, the processes that connect them, and how variability occurs among them. Characterizing these Earth system interactions is the basis for understanding how the Earth system functions today, how it supports life, how conditions might change in the future, and how humans influence such change.

Predicting across the time scale from weather to climate is a huge challenge that in part requires the development of affordable, connected observing systems that further advance our understanding of subsystem interactions and provide these over a range of time scales typical of weather prediction to understanding and prediction of changes on decadal and longer time scales. As illustrated in this paper, we are now witnessing a revolution in space engineering that offers some hope for addressing such formidable challenges. We now witness the emergence of reusable launchers that are reducing the cost of access to space. The cost of making observations will also potentially reduce with the miniaturization activities like those highlighted in this paper that both reduce cost of sensors and reduce the effective cost of launch by increased potential for shared launches of multiple small platforms.

With the miniaturization of sensors described comes, together with advances in small satellites (e.g., Millan et al. 2019) the expectation of affordable integrated observing systems

Fig. 6. Observations along a ~130-km path through a large stratiform precipitation weather system near Prince Edward Island, Canada, on 25 Jan 2019. The radar cross sections of Ka-band RainCube radar and that of the GPM DPR were within 9 min from each other. The DPR operates at two frequencies: 14 (Ku) and 35 (Ka) GHz. These matches were done by maximizing feature matching between the RainCube curtain and the DPR 3D volume scans.

Fig. 7. A serendipitous observing system built from miniaturized small satellite and CubeSat observations. The black contours are the surface winds observed by GNSS reflections measured by the CYGNSS constellation of small satellites, the vertical profiles of reflectivity are provided by RainCube as it dissected the storm, and the horizontal distribution of microwave brightness temperature from the surface upward, respectively, at 164, 174, 178, and 181 GHz provides the water vapor distribution at different levels notionally characterized by the heights of the peak of the weighting functions that characterize the contributions of absorption/emission at these frequencies.

either as a multiple payload on single spacecraft, or in the form of constellation such as popularized with the example of the A-Train, as mega-small satellite constellations or as a constellation of closely clustered systems in formation that offers new dimensions to our observing strategies like using time difference measurements (e.g., Stephens et al. 2019). Figure 7 is a serendipitous example of such an observing system in this case composed of the three miniature satellite systems highlighted above. This example shows coincident overlying observations of RainCube, TEMPEST-D and CYGNSS that each measure important but different aspects of a major storm system TRAMI that was located at 23.5°N, 127°W and sampled at 0735 UTC 28 September. This figure hints at how a deeper understanding of processes can be obtained when observations are integrated. In this example, the surface winds that are observed by CYGNSS are produced by the internal dynamics of the storm that is driven by the latent heating that is reflected in the radar reflectivity profiles of RainCube that is in turn shaped by the environmental water vapor observed by TEMPEST, that converges into the storms by the winds making the rains observed by the radar. These observations provide a perspective of this connected cycle of processes central to storms that are a fundamental property of the Earth system and a major challenge to Earth system prediction.

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