THE *MINIATURIZATION* REVOLUTION *IN* EARTH OBSERVING

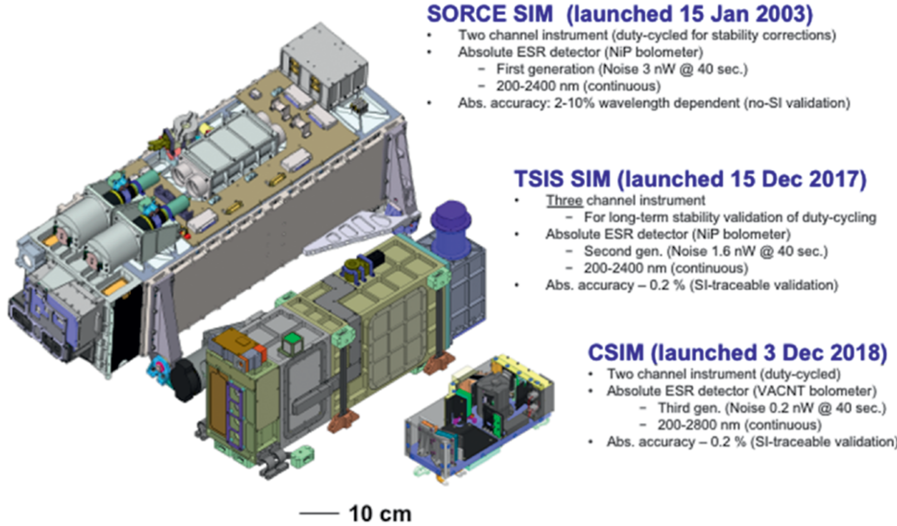
Adapted from "The Emerging Technological Revolution in Earth Observations," by **Graeme Stephens** (JPL/California Institute of Technology), **Antony Freeman**, **Erik Richard**, **Peter Pilewskie**, **Philip Larkin**, **Clara Chew**, **Simone Tanelli**, **Shannon Brown**, **Derek Posselt**, and **Eva Peral**. Published in BAMS online, March 2020. For the full, citable article, see DOI:10.1175/BAMS-D-19-0146.1.

Routine observations of Earth from space are essential in the prediction of weather and warnings of hazards. At the World Weather Open Science Conference in 2015, the director of one of the world's leading weather prediction centers was asked which of the many streams of data coming from Earth orbiting satellites and in situ observing networks has the greatest impact on forecasts. The simple answer was "all of them." Indeed, many streams of observations, together with advances in models that use the observations, have fueled advances in numerical weather prediction.

Predictions of weather on short time scales or of climate change on longer time scales require observations of the entire interconnected Earth system. For example, advances in the prediction of any specific aspect of environmental change, such as sea level, are dependent on many variables not directly connected to it.

The high cost of most Earth observing systems today has, out of necessity, driven a narrow observing strategy built around measurements of a small number of "essential" variables. Consequently, the broad picture tends to be lost. The rising costs of operational observing systems in times of flat or declining budgets serve only to exacerbate the problem. Added to these pressures is the need for a sustained Earth observing system both to monitor global change and to determine what drives it.

Somewhat independent of these challenges, but ultimately part of the solution to them, is the revolution in spacecraft miniaturization, which offers affordable access to space. The miniature CubeSat is just one important factor in this revolution, but perhaps more important is the parallel miniaturization of sensors that is also occurring. It helped set design standards for volume and power for miniaturized sensors. Sensor miniaturization is critical for advancing Earth sciences, and the revolution described has benefitted directly from CubeSat design standards that establish sensor volume and power requirements. While CubeSat or small satellites with these small sensors are not yet a replacement for larger systems, we illustrate the state of sensor miniaturization and its role in revolutionizing future satellite observations.



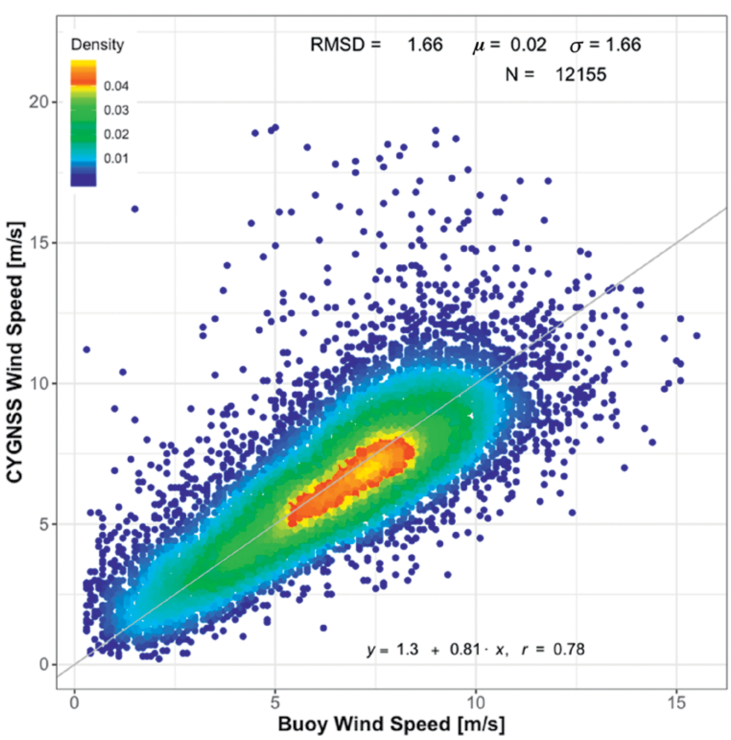
The evolution of the solar spectral irradiance monitor (SIM) from SORCE to TSIS to CSIM where the size and mass of the latter were reduced to fit into a 6U CubeSat.

Important tradeoffs must be taken into account when considering the extent to which the advantages of small, relatively low-cost sensors outweigh those of larger and more expensive counterparts. We offer preliminary results from ongoing assessments of small sensor systems.

Miniaturization examples

A survey of CubeSat sensor technology researcherswas conducted in 2012 and again in 2019. The respondents binned their perceptions of the state of the art in miniaturization into three categories: "feasible," meaning technology compatible with CubeSat standards; "infeasible" for technologies clearly incompatible with CubeSat; and "problematic" for instruments that could be developed to fit CubeSat standards, but with significantly reduced data quantity and/or quality. With one exception, all instrumentation and capabilities deemed infeasible or problematic in 2012, such as rain radar, are feasible in 2019. Given the lower cost offered by miniaturization, these advances offer the realistic potential adoption of entirely new approaches for observing Earth.

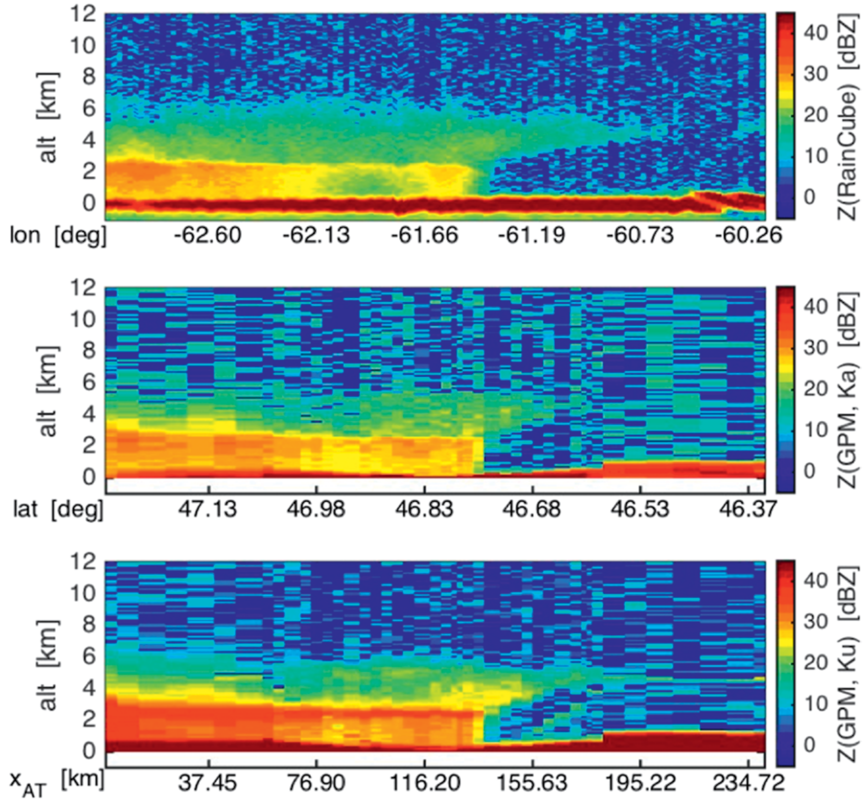
Four examples illustrate the degree and scope of the miniaturization underway. They represent measurements designated as high



Comparison between CYGNSS derived winds and in situ buoy measurements (from Crespo et al. 2019).

priority by the National Research Council and underwritten by the NASA's Earth Science Division.

The measurement of solar spectral irradiance from a CubeSat (Compact Spectral Irradiance Monitor). Continuation of the essential long-term record of solar spectral radiation (SSI) now relies on the Total and Spectral Solar Irradiance Sensor (TSIS-1) on the International Space Station, which overlapped the aging Solar Radiation and Climate Experiment (SORCE). To ensure ongoing SSI measurements, the Compact Spectral Irradiance Monitor—Flight Demonstration (CSIM-FD) was launched on 3 December 2018 as part of a CubeSat demonstration flight. CSIM is an ultracompact SSI monitor covering the 200–2,800-nm spectral range and was integrated into a 6U CubeSat. CSIM has one-tenth the mass and one-twentieth the volume of the currently operational Total and Spectral Solar Irradiance Sensor instrument aboard ISS, which in turn is smaller than the equivalent SORCE instrument. Instrument size reduction was driven in part by micromachining and carbon nanotube technology. This resulted in a miniature CSIM Electronic Substitution Radiometer with lower noise and faster response than the previously launched instruments. The CSIM-FD instrument agrees within 1% and within the radiometric accuracy of the TSIS-1 instrument across the spectral range from 200 to 2,400 nm—96.2% of the total solar irradiance output from the sun.



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.

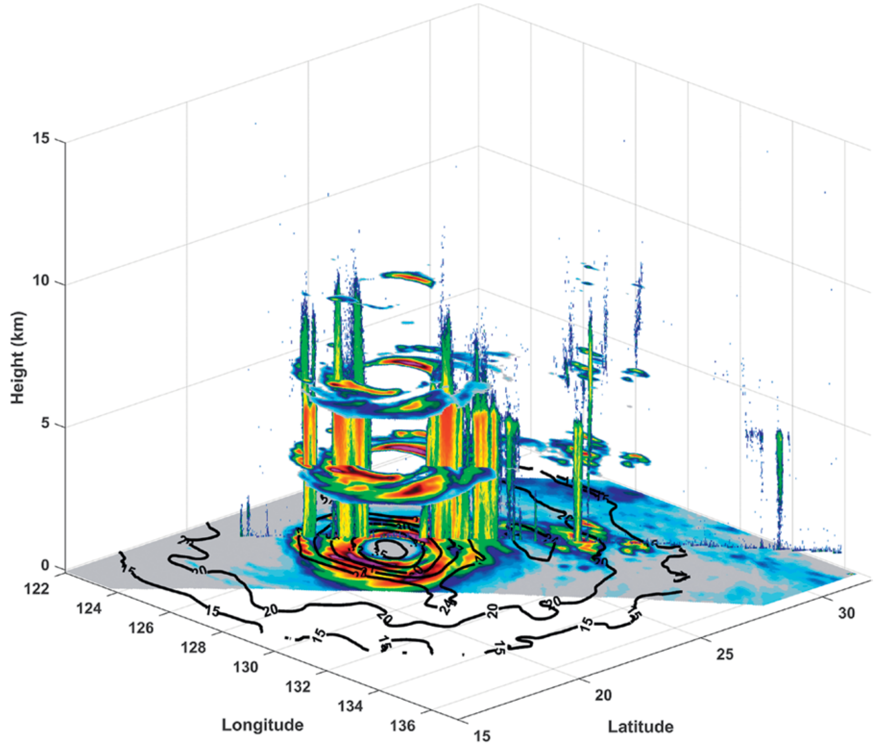
CYGNSS. The Cyclone Global Navigation Satellite System (CYGNSS) mission, managed by the University of Michigan, measures oceanic wind speed using reflected Global Navigation Satellite System signals with an approximate 3-h revisit time. CYGNSS aims to improve intensity forecasts of tropical cyclones. One hypothesis was that frequent revisits by eight small spacecraft better samples the rapid genesis and intensification of a tropical cyclone.

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 GPS reflections. The DDM relates to surface roughness, which is dependent on the near-surface wind speed. As a signal of opportunity measurement, the GPS signals are not necessarily optimized for ocean wind sensitivity, especially lighter winds.

For validation, the surface wind speeds derived from CYGNSS are compared to wind speeds from the Pacific Marine Environmental Laboratory Global Tropical Moored Buoy Array. 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 provide primarily a low-wind-speed evaluation of the CYGNSS flux estimates. Comparison between the CYGNSS-retrieved LHF estimates and estimates from in situ buoys shows a strong correlation.

Both wetland waters and soil moisture—crucial to projecting changes in atmospheric methane and terrestrial water storage—provide clear reflection signatures in Global Navigation Satellite Systems Reflectometry measurements. On any given day, an estimated 80% of the soil moisture active passive (SMAP) (Equal Area Scalable Earth-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 the multiple CYGNSS satellites is possible, an immense improvement over measurements from a single standard satellite with a 16-day repeat cycle. The unbiased root-mean-square (RMS) error between in situ data from more than 200 soil moisture stations and CYGNSS soil moisture retrievals is equivalent to the 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, largely 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.



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.

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 is a 6U CubeSat for demonstration of the mission, launched in 2018 and designed and built through a partnership between Colorado State University and the Jet Propulsion Laboratory (JPL). TEMPEST-D carries a cross-track imaging, five-channel passive microwave radiometer, intended to be comparable in terms of sensor design and data quality to the much larger Advanced Technology Microwave Sounder (ATMS) on NOAA polar satellites.

The radiometer has operated nearly continuously since 11 September 2018. TEMPEST-D and NOAA ATMS data for 11 December 2018 from the near 90-GHz channels show remarkable qualitative agreement. Detailed intercomparison is

The evolution of small sensor capability between 2012 and today.

Technology	Status in 2012 (from Selva and Krejci 2012)	Status Today (from 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 is scheduled to launch in 2020.
Atmospheric temperature and humidity IR sounders	Feasible	Feasible	CIRAS &3D Winds, CubeSat IR Atmospheric Sounder (CIRAS) is a 4U cryocooled grating MWIR spectrometer for sounding atmospheric water vapor and temperature, and some constituents (e.g., CO and CO_2. 3D Winds is a proposed constellation of 12 6U CubeSats, each carrying a passively cooled midwave infrared hyperspectral FTS sensor tracing water vapor features.
Cloud profile and rain radars	Infeasible	Feasible	RainCube and CloudCube—CloudCube is a W-band concept under development employing related technology to RainCube.
Earth radiation budget radiometers	Feasible	Feasible	RAVAN, CSIM, PREFIRE—RAVAN is a technology demonstration of nanotube detectors targeting Earth's radiation budget. CSIM—See text. PREFIRE (Polar Radiant Energy in the Far-Infrared Experiment) is a miniaturized 3U thermal IR spectrometer exploiting thermopile detector technology.
High-resolution optical imagers	Infeasible	Feasible	The company Planet has deployed hundreds of 3U Dove satellites, each carrying a multispectral, optical imager capable of 3–5-m spatial resolution.
Imaging microwave radars	Infeasible	Feasible	A Ka-band SAR that fits in a 12U volume has been conceptualized.
Imaging multispectral radiometers (visible–shortwave infrared) and hyperspectral spectrometers	Problematic	Feasible	Astro Digital has developed and flown a small constellation of 6U CubeSats each carrying a three-band (red, green, near-infrared) multispectral imager; Snow and Water Imaging Spectrometer (SWIS) is a 6U compact imaging spectrometer measuring radiances between 350 and 1,700 nm
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.
Lidars	Infeasible	Problematic	TOMCAT—A SmallSat lidar concept operating at 1,064 nm. TOMCAT 1,064-nm clear-sky SNR is similar to CALIOP during daytime, 8 times better than CALIOP at night.
Lightning imagers	Feasible	Feasible	RaioSat—Brazil's RaioSat project 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 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.
Scatterometers	Infeasible	Feasible	GNSS reflectivity (CYGNSS)—Refer to text.

ongoing to document the quality of TEMPEST-D relative to larger operational sensors such as ATMS.

RainCube. Until recently, radars have typically been considered too large and heavy and as requiring too much power for small satellite platforms. A novel miniature Ka-band atmospheric precipitation radar (mini-KaAR) architecture developed at JPL substantially reduces the number of components and mass by over an order of magnitude. It is comparable to low-cost miniature platforms such as CubeSats and SmallSats. A CubeSat version of the mini-KaAR radar electronics was launched in 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 electronics. The antenna size for RainCube, once deployed, is 0.5 m, with a gain of 42.6 dB and a resulting footprint of approximately 8 km from the nominal 400-km orbit.

As both RainCube and the dual-frequency precipitation radar of the Global Precipitation Mission (GPM) passed over a portion of a large stratiform rain system, the RainCube Ka-band radar displayed a remarkably similar capability for measuring precipitation as GPM.

The outlook

Prediction across the time scale from weather to climate is a huge challenge that, in part, requires affordable, connected observing systems. The revolutionary miniaturization of satellites and sensors we are now witnessing offers some hope for addressing this formidable challenge. With the miniaturization of sensors, together with advances in small satellites, comes the expectation of affordable integrated observing systems, either as a multiple payload on single spacecraft, or in the form of a constellation such as popularized with the A-Train. Mega–small satellite constellations or a constellation of closely clustered systems in formation can offer new dimensions to our observing strategies. Confirming the extent to which small sensors can indeed replace or provide capabilities similar to their larger, more expensive counterparts remains an ongoing a topic of study.

METADATA

BAMS: What would you like readers to learn from this article?

Graeme Stephens (JPL/California Institute/ of Technology): *Much has been written, said, and even promised about advances that have occurred with small satellites and, notably, CubeSats. These technological advances are important in their own right, but if technology is to advance Earth science generally, and atmospheric sciences specifically, then it is critical that we evolve our sensors not only to match these platform capabilities but offer entirely new ways to think about making observations. I wanted to convey to the reader a sense of how this sensor development has quietly advanced over the past decade and why this might be important.*

BAMS: How did you become interested in the topic of this article?

GS: *I have felt that the dialogue on the spaceborne technology developments has been a little lopsided, focusing more on the platform and less on what it is we want to measure. As a scientist I perhaps care more about what than how. I know that even in the Earth observational community there has been a lack of appreciation or awareness for the sensor technology revolution, as I call it , that has occurred.*

BAMS: What surprises/surprised you the most about the work you document in this article?

GS: *I think the big surprise is reflected most in the table and the rapid advance of technology such that we have gone from ideas that were not feasible to feasible in a short period of time.*

BAMS: How will you follow up?

GS: *I am in engaged in planning and designing new observing systems for the coming decade that is to exploit these sorts of new capabilities introduced in the paper.*