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Key Point:
- Remotely sensed data are core parts of Earth and planetary observation systems

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From planets to crops and back: Remote sensing makes sense

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Abstract Remotely sensed data and the instruments that acquire them are core parts of Earth and planetary observation systems. They are used to quantify the Earth's interconnected systems, and remote sensing is the only way to get a daily, or more frequent, snapshot of the status of the Earth. It really is the Earth's stethoscope. In a similar manner remote sensing is the rock hammer of the planetary scientist and the only way comprehensive data sets can be acquired. To risk offending many remotely sensed data acquired across the electromagnetic spectrum, it is the tricorder to explore known and unknown planets. Arriving where we are today in the use of remotely sensed data in the solar system has been a continually evolving synergy between Earth observation, planetary exploration, and fundamental laboratory work.

1. Commentary

I think it is nothing to reach for my phone, tap on my weather app, and get an instant reading of temperature, pressure, precipitation, and wind. If I need more data, say I am planning on some remote sensing field work in support of my newest research, I can open up an amazing, hourly forecast for the next 48 h detailed to the percent cloud cover, temperature, pressure, and wind. PERFECT!

That simple act to access what is commonly rather mundane information is actually a highly distilled synthesis of a collection of beautiful remotely sensed data (such as produced from Earth-observing satellites, Figure 1) synchronized with sophisticated, global weather, and climate models to generate a prediction of weather. On the bigger stage, beyond what I need to be wearing today, the same synthesis and integration has become essential in global business. For example, prediction of temperature and rainfall conditions for growing seasons across key agricultural regions worldwide is extremely important on a surprising range of economic scales. An individual farmer in the Mato Grosso region of Brazil might seek to maximize profits, but the timing of rainfall is critical. If the rains come early, the farmer can profitably get two harvests from the growing season, a crop of short-cycle soybeans followed immediately by a crop of corn. However, if the rains should be delayed or deliver less water, then one crop of long-cycle soybeans, which result in a greater yield, is the prudent choice [*Spera et al.*, 2014]. This decision has to be made during the dry season, but to make the decision of one or two, the farmer can now heed long-range temperature and rainfall predictions developed by the Brazilian national meteorological institute, Inmet [*Battisti*, 2016].

This prediction is rooted in El Niño monitoring and prediction that takes into account long-term sea surface and subsurface temperature measurements made across the vast expanse of the Pacific Ocean with satellites and networks of buoys [*Tollefson*, 2014]. Interestingly, the seemingly esoteric yet unbelievably precise measurement of changes in sea surface elevation (is it not 0?) is a strong indicator of vast movement of water across the Pacific in response to El Niño. Beyond the interests of an individual farmer in Brazil, climate monitoring and prediction rooted in fundamental remotely sensed measurements of the Earth across the electromagnetic spectrum on monitoring of a developing El Niño to hedge fund managers in London and New York shifting financial resources to also maximize profits [*Mulvany*, 2016]. In terms of important societal impact, these same tools and techniques are used to respond to humanitarian crises brought on by drought, floods, and other extreme weather.

Exceptional fundamental science has been made possible by the steady progress in remote sensing instrument capabilities. The rather rudimentary capabilities at the dawn of the Earth and planetary spacecraft observing era in the 1960s and 1970s have given way today to an international network of satellites integrated to provide daily, and more frequent, measurements of the complex Earth system (Figure 1) and planets (Figure 2). Exciting new developments in commercial remote sensing are turning heads as well

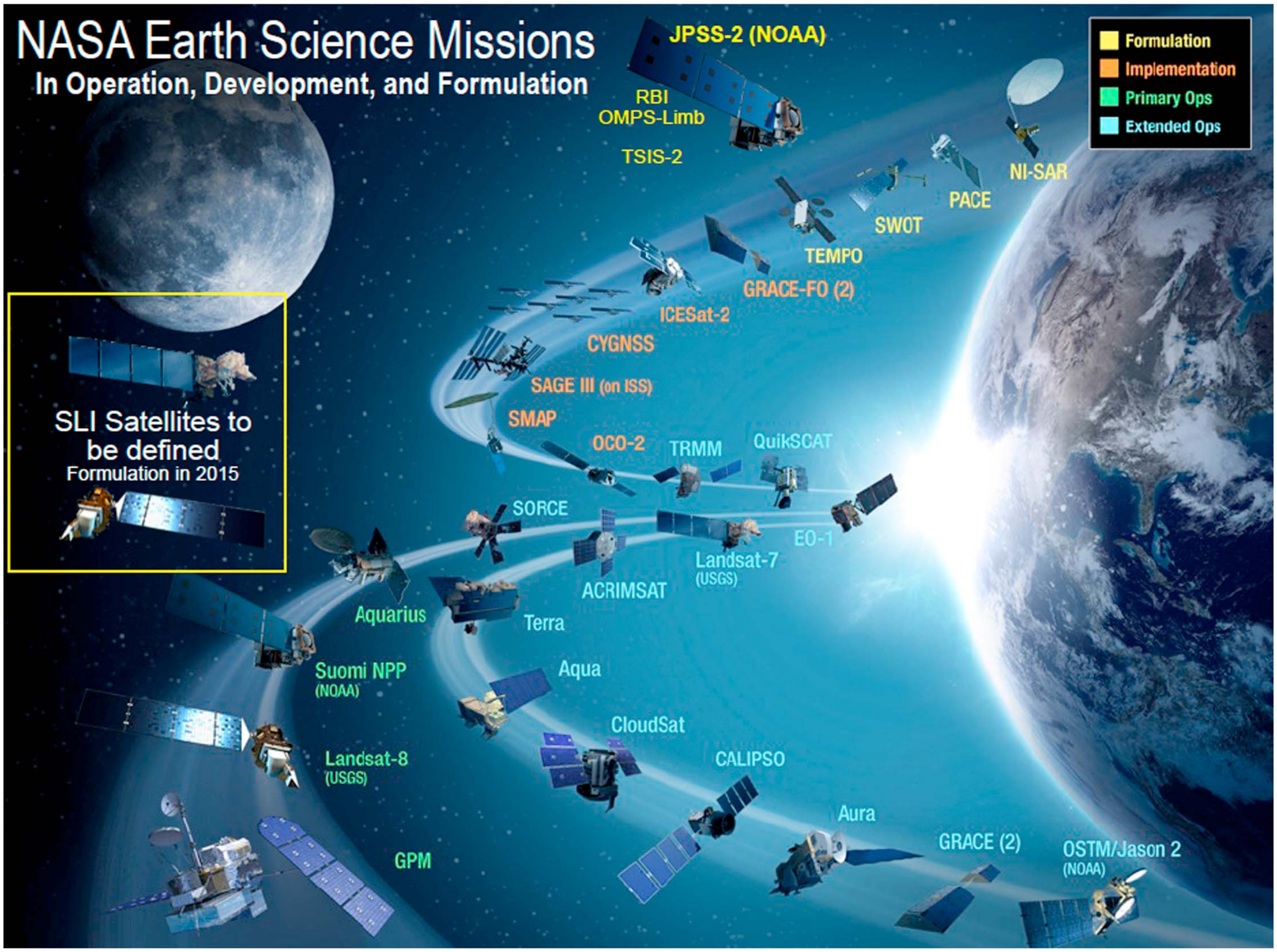

Figure 1. Earth-observing satellites in operation or development. Instruments on this impressive suite of missions provide regular quantitative global measurements of Earth's atmosphere, hydrosphere, cryosphere, and geosphere that are freely available. Data from the suite of international and commercial providers are equally impressive. Image source: NASA.

with the launch of Planet Labs' network of >100 satellites. Instead of a global daily snapshot at hundreds of meters spatial resolution, we are now looking at a global snapshot at meters resolution.

A fascinating example of the interplay and feedbacks between planetary exploration and Earth observation is the development of active remote sensing (where an active signal originates from the spacecraft and is then received after reflecting off gases or particles in an atmosphere or a planetary surface or even subsurface layers) for determination of elevation and vegetation characteristics. Lidar (light detection and ranging) instruments quantify the distance between an observing platform (e.g., satellite) and a surface using laser light pulses. Additional information on the structure of vegetation canopies or the roughness of surfaces is gleaned from the shape of the returned pulse after interaction with the target. Lidar was first flown over the Moon during the Apollo 15, 16, and 17 missions [*Kaula et al*., 1974], but it was not until the technological development of stable, long-lived laser sources and sensitive detectors that orbiting instruments were possible, first with the Mars Observer Laser Altimeter [*Smith et al*., 1998]. Miniaturized long-lived laser sources have led to an explosion in the availability of lidar and similar instruments for routine topographic measurements and the next generation of Earth and planetary sensors for field and rover deployment.

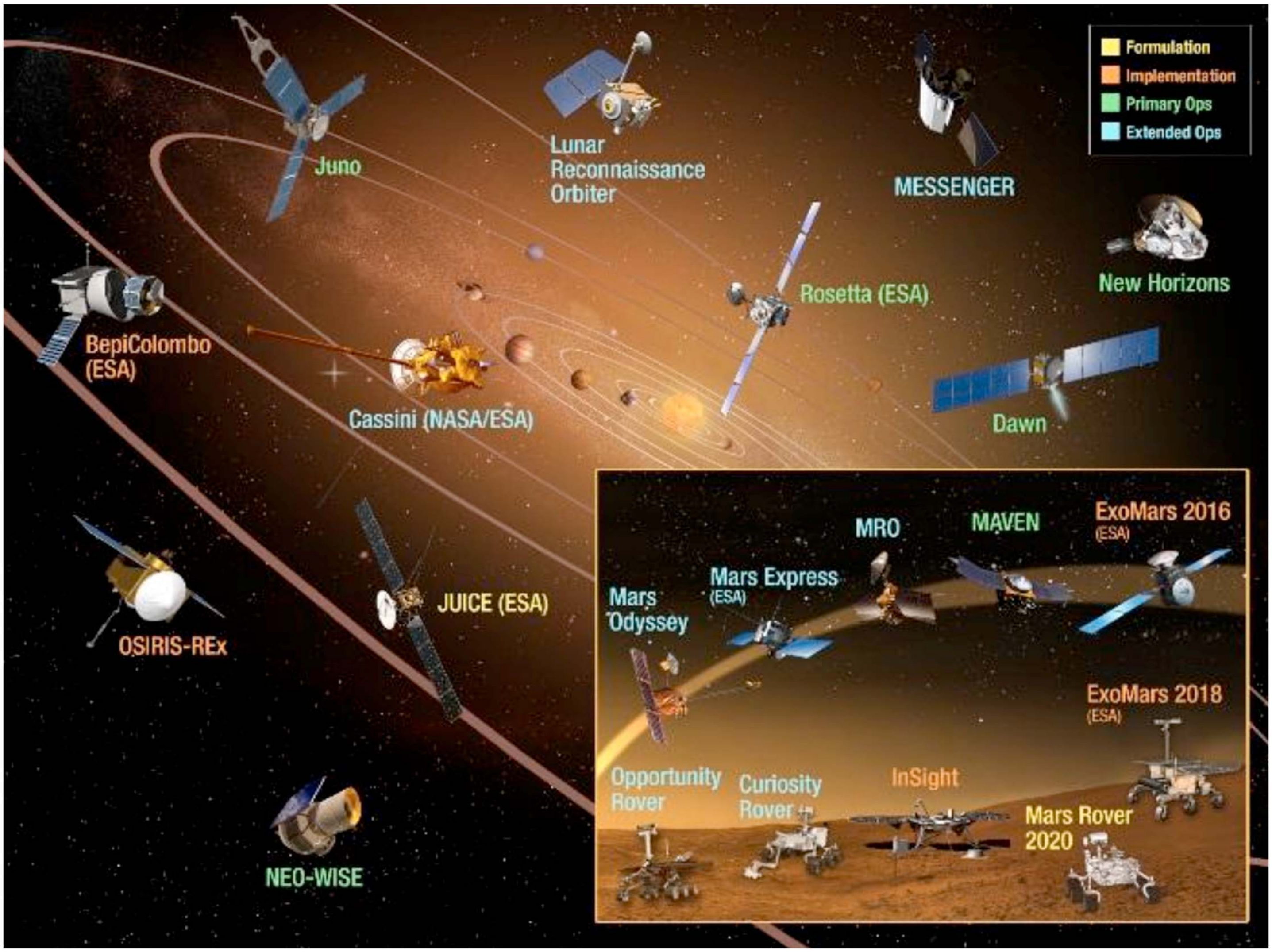

Figure 2. Planetary spacecraft recently in operation or development. Instruments on these missions provide regular quantitative global measurements of a diverse suite of planetary objects and span the electromagnetic spectrum. Data from these mission are freely available. Image source: NASA.

Measurement of the electromagnetic radiation in all its forms on Earth and other planetary bodies is the foundation of remote sensing. The beauty of these measurements is that collectively, they traverse many orders of magnitude in energy, and its generation comes from different sources. This allows an enormous range of science questions to be addressed. The sources of electromagnetic radiation may be from passively measured solar and thermal radiation reflected and emitted from the surfaces, oceans, and atmospheres of planets to the radiation generated and reflected from the many active remote sensing radar and lidar sensors. The number of sensors on orbit around the Earth today is nothing short of stunning where much of the electromagnetic spectrum is now exploited through passive or active methods.

Fundamental basic research supported by international government science agencies, including in the U.S. National Science Foundation and NASA and the key national laboratories, has pushed and pushed the science and technology of these measurements. There is a beautiful synergy between the technology developed for the exploration of the solar system's planetary and small bodies (Figure 2) and that developed to measure the Earth (Figure 1). In planetary exploration, it is a rare thing to hold and bring to the laboratory samples from these bodies. Instead, remote sensing across the electromagnetic spectrum is the "rock hammer," or interrogation tool, of planetary scientists. But more than that, continual advances in the understanding of the interaction of electromagnetic radiation with materials have brought very sophisticated levels of data analysis and algorithms for quantification of material properties of the atmospheres, oceans, and surfaces of the planets. For example, missions to Mars, Venus, Mercury, and the Moon have generated spectacular measurements of the shape, morphology, and surface compositions. Because of the lack of vegetation and atmospheres that are thin to absent (except for Venus), these bodies are pure laboratories for developing the quantitative models for deriving geophysical surface properties from remotely sensed data.

For many years the Moon was considered to be bereft water. However, global hyperspectral mapping with the Moon Mineralogy Mapper (M^3) in 2008 in visible to near-infrared wavelengths showed a surprising absorption feature best explained by water [*Pieters et al*., 2009]. This coincided with reanalyses of lunar samples that also showed a component of water [*Saal et al*., 2008]. The synergy between the sample and remotely sensed data has led to a completely new perspective of the evolution of the Moon. The hyperspectral instrument on M^3 is an excellent example of a remote sensing instrument that has been developed for Earth and planetary observations over the past 30 years. I worked with data from the engineering test bed instrument for the imaging spectrometer, the Airborne Imaging Spectrometer in 1984 [*Mustard and Pieters*, 1987]. The technology continues to be pushed, and now small, affordable yet capable hyperspectral sensors based on these Earth and planetary missions are readily available commercially. They are being used in surprising and unexpected ways including the important work for growers and oenophiles in precision agriculture of high-value wine grapes [e.g., *Haboudane et al*., 2004; *Zarco-Tejada et al*., 2012].

Remote sensing has thus become fully integrated into the service of society, while the symbiosis with planetary exploration and Earth observations with fundamental lab-based science continues to push capabilities even further. Weather is but one small example, yet the impact of accurate knowledge of the weather is worth billions of dollars in commercial enterprises but is of unlimited value to public safety. The innovations in the service of planetary exploration has had profound effects on the development of Earth observation platforms, and vice versa.

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