# Earth Remote Sensing Technologies in the Twenty-First Century

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***Abstract*— An Earth System Model of increasing capability and predictive power will depend on ever more sophisticated observing systems. These observing systems will require increased resolution in the spatial, spectral, radiometric, and temporal domains. There is a need for improvement of individual system capabilities and for the deployment of large numbers of sensors. Many new technologies will be required to accomplish this. Projecting decades into the future is difficult; however, because fundamental physical limits provides constraints on future progress, it is possible to outline the general form of future remote sensing systems and the technologies they will rely on. Several trends are expected to continue far into the future: miniaturization and integration of electronics, increases in computational power, progress in large apertures, increases in transmitter power for active systems, miniaturization of optics, and increases in frequency tunability and flexibility. Ultimately, the size of an observing platform will be dictated solely by the physics of its parts. These technology challenges for future global Earth observation can best be met through the combined efforts of the international community.**

## I. INTRODUCTION

The Earth is a complex system. There are many benefits which will come from a better understanding of the Earth, not the least of which is the ability to better predict those phenomena that have a major effect on human life: weather, short and long-term climate, atmospheric pollution, fresh water availability, and natural hazards such as hurricanes, floods, droughts, forest fires, volcanoes, and earthquakes.

Although weather models have attained a significant level of accuracy, the models of many other aspects of the Earth system are in their infancy. All of these models will continue to grow in sophistication and will ultimately be merged into an Earth system model that allows accurate modeling of the interactions between all of the Earth's subsystems. The challenge here is two-fold: to create better models themselves and to provide more accurate and more frequent inputs to the models. Providing better data and improving the models both rely on improved Earth remote sensing technology.

A sensorweb concept [1] has been described as a means to provide the spatial and temporal coverage necessary to feed these new Earth system models. The sensorweb is dependent on advances in technology that enable autonomy, heterogeneity, scalability, and affordability of remote sensing systems.

Many changes will be necessary at the level of the individual sensor to enable this vision. While most of the measurements to be made in the future are already being made or have been conceived at some level, great strides in technology are necessary. These changes, some gradual and some, no doubt, revolutionary, will lead to an extensive sensorweb feeding a comprehensive Earth System Model.

## II. REMOTE SENSING CHARACTERISTICS

Future sensors will continue the progression toward more comprehensive and more accurate Earth science measurements. There will be improvements in the spatial, spectral, radiometric, and temporal characteristics of the measurements.

While many measurements are made with sufficient spatial resolution today, such as low-earth orbit (LEO) land cover and land use, with visible and near-infrared observations in the 10's of meters; others, such as LEO ocean salinity and soil moisture, will not have the desired resolution in their first implementations. Future measurements from geostationary orbit (GEO), across the spectrum, will require resolutions that challenge the state of the art. Large antenna and mirror structures will be required to make visible, infrared, and microwave measurements from GEO and from the Lagrange points, L1 and L2, located one and a half million kilometers from Earth on the Earth-sun line. Differential absorption lidar (DIAL) and laser Doppler wind measurements from LEO, and someday GEO, require apertures of several meters. Interferometry from L2 to measure the Earth's atmosphere will require apertures in the 10 m range [2].

Spectral information needs will increase the range of wavelengths measured, the number of bands measured simultaneously, and the resolution of each spectral measurement. New areas, such as the far infrared, will be opened for atmospheric measurements. Hyperspectral measurements of vegetation, ocean color, and minerals will expand. Atmospheric chemical species will be measured more accurately with high resolution spectrometers.

In pursuit of higher accuracy, radiometric resolution will need to increase and noise will have to be reduced. Improved cooling approaches will become available to support this.

Larger apertures, lower noise, and faster optical systems will improve signal to noise ratios.

Finally, temporal resolution must be increased to answer many questions about the Earth system. Wide field of view systems; systems at GEO, L1/L2, and other vantage points; and increased numbers of small sensorcraft will allow continuous observations of diurnal and short time scale changes.

## III. NEW TECHNOLOGY TRENDS

There are themes which are apparent in technology development for Earth remote sensing that will likely continue for decades in the future. Key optical and radiofrequency technologies for future systems have been described [3]. If there is one underlying technology area that governs the rate of progress in all of these areas, it seems to be materials. New materials enable shrinking circuit sizes, they allow lower power operation for 3-dimensional packaging, they extend the spectral range and performance of detectors, they provide the strength with low mass for large structures, they enable higher power, more efficient transmitters, and they enable compact optical systems. Many of these trends are apparent in technology developments being funded today by the Earth Science Technology Office (ESTO) for NASA's Earth Science Enterprise. Examples are provided below in a discussion of remote sensing instrument trends.

### *A. Miniaturization of electronics*

The progress in miniaturization of electronics, particularly digital electronics, is well known. As features size decreases and wafer size increases, more and more gates can fit on a single integrated circuit. This trend will continue for many years and several new trends will become apparent within the next decade. The use of 3-dimensional chip making will become widespread as cooling and connection problems are solved. Overall packaging sizes will dramatically decrease with order of magnitude decreases in volume and mass.

The same trend is occurring in analog electronics, for example, the use of monolithic microwave integrated circuits (MMICs) is enabling significant decreases in the size and mass of radiofrequency circuits. MMICs are still relatively new and higher integration levels will follow in the future. In parallel with the decreases in size of analog electronics, many analog systems will evolve to full digital systems with antennas connected directly to analog-to-digital converters.

Detectors, while increasing in sensitivity and in format size, will be integrated with all of the ancillary electronics into a single 3-D "chip" which could replace all of the electronics of one of today's instruments.

Further in the future the electronics will become simply a part of the structure with no separate packaging. This will happen as membrane and 3-D electronics are attached directly to structural members or as electronic components actually become load bearing elements themselves.

ESTO projects developing a precipitation radar [4], high-frequency MMICs [5], and a photovoltaic long-wave infrared detector [6] have furthered this trend.

### *B. High-performance onboard computing*

Along with the decrease in size of electronics will come further astounding increases in processing speed, both for programmable and general-purpose processors. By the time today's technologies are fully exploited, radical new technologies, such as quantum and biological computing, will be realized. Storage density will continue its steady progression. The ultimate result will be, for all practial purposes, unlimited computing power on orbit within the sensor itself. ESTO-funded development of a holographic memory [7] is a step in this direction.

### *C. Large, lightweight structures*

Measurements with higher spatial resolution will require larger apertures. The technology for large deployable antennas and mirrors will progress steadily. The approaches to large deployable mesh and membrane antennas being pursued today will be extended to larger and larger systems of 10's of meters with lower and lower mass density. Deployable mirror and adaptive optics technology will advance to enable low-mass, multi-meter optical systems. ESTO's work on a 6 meter inflatable radar antenna [4] and large, sparse aperture radiometers [8] are examples of this progress.

### *D. Increased power active sensing*

While a number of LEO active sensors have been successfully deployed, there remain many challenges in increasing the power and efficiency of lasers and radars. Increased power levels are needed for extension of radar and laser measurements to GEO and for challenging DIAL and tropospheric wind measurement applications in LEO. New laser and non-linear, frequency-shifting materials are likely to be a fundamental part of achieving these long-term goals, as are increasing power levels and efficiencies in solid-state radiofrequency amplifiers. ESTO has funded a Laser Risk Reduction Program addressing some of these laser challenges.

### *E. Compact optics*

Increased coverage through multiple copies of sensors can be facilitated by smaller instruments. Many innovative approaches to refractive and reflective optics are under development. Compact Fourier transform and grating spectrometers will allow reductions in overall size and mass of optical instruments. Efficient new coolers will extend these size benefits far into the infrared. Technology for an infrared sounder using compact refractive optics [9] has been funded by ESTO, as well as work on an optical cryocooler [10].

### *F. Frequency flexibility*

Wavelengths and their corresponding frequencies today are carefully selected and are sparse because limited resources constrain system configurations. In the future hyperspectral and tunable systems will be commonplace, allowing much greater flexibility in the spectral domain. Tunable lasers will allow multiple observations with the same instrument and adaptation of wavelengths to provide the most accurate measurements. Hyperspectral systems will allow flexibility through on-board frequency selection, aggregation, and combination. Immediate

Figure 1. Evolution toward smaller and larger satellites.

digital conversion of signals from antennas will allow wider bandwidth RF systems. Detectors themselves will become multispectral, in some cases eliminating the need for spectrometers. ESTO has funded a new hyperspectral infrared imaging detector which images four infrared bands in the 3 to 15 micron range on one detector.

## IV. FUTURE SENSORS: NANO-SATS AND WISP-SATS

Over the course of the next several decades these technology trends lead to a very different picture of the set of remote sensing satellites from that of today's. The sensorweb is a result of the highly connected nature of a large number of affordable, but very capable and flexible, satellites. A number of papers at past IGARSS sessions have discussed the sensorweb, and also the nature of some of the individual future sensors. But how will the general nature of the individual sensor platforms change?

The vast increases in electrical and mass efficiency implied by the technology trends discussed above will lead to a more heterogeneous set of sensor systems. The increasing integration and miniaturization will mean that spacecraft will take on the shape and general characteristics of their largest physical constraint. The overall size of the sensor system will be defined by the aperture required for large-aperture systems and, perhaps, by the solar power collection system for small satellites. The range of sizes of these sensors will far exceed that of today with some very large systems with apertures of many 10's of meters and the smallest systems no bigger than a bread box. From a distance such systems might appear to be flying antennas or flying solar arrays with no traditional spacecraft bus. Everything will disappear except those structures where size is dictated by physics. Rather than today's distribution of satellite sizes which cluster together in the several meter size range, there will be a much more even distribution of sizes from 10's of centimeters to 10's, or perhaps 100's, of meters, depending on the application. This is shown graphically in figure 1. The former are the micro- and nano-sats and the latter, with their very large, lightweight structures, might be called wisp-sats because of their delicate, insubstantial appearance. The figure plots the largest non-solar array dimension versus the spacecraft mass. The scatter plot of points represents today's Earth science satellites including ACRIMSAT, Terra, Aqua, SOURCE, TOMS-EP, ICESat, Landsat 7, GRACE, Jason-1, EO-1,and RADARSAT. The ovals represent areas which will become increasingly populated in the future.

The progression to large numbers of small satellites will depend largely on increases in launch opportunities and decreasing launch cost; the progression to very large satellites will depend on the progress of the enabling large structure technology.

## V. CONCLUSION

These and many other technologies will continue to provide a challenge to the world's space technologists. The trade space is enormous and funds are limited. Broad investments by the international community will enable rapid progress and support the continuing evolution of the Earth System Model.

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