The Future of Instrument Technology for Space-based Remote Sensing for NASA's Earth Science Enterprise

Frank Peri, Jr.
Earth Science Technology Office
NASA Goddard Space Flight Center
Code 711
Greenbelt, MD 20771

Jonathan B. Hartley
Earth Science Technology Office
NASA Goddard Space Flight Center
Code 711
Greenbelt, MD 20771

James L. Duda
Integrated Program Office
NASA Goddard Space Flight Center
Code 402
Greenbelt, MD 20771

Abstract-**The vision of the Earth Science Enterprise (ESE) of the National Aeronautics and Space Administration (NASA) established a variety of science challenges for the next 25 years, relating to predictions of weather, climate, and foreseeable changes in the Earth's environment. In this paper, we discuss the attendant needs for space-based remote sensing technologies. In addition, we suggest some strategies for deploying the necessary assets.**

I. Introduction

Presently, the ESE collects data from a number of sources, via remote sensing from space, airborne missions, shuttle missions, in situ data sources, field campaigns, sub-orbital missions, data buys, and collecting data from operational and international missions. Several of these parameters have been measured more or less continuously over the last few decades. These measurements have been supplemented by periodic competitive opportunities for focused measurements to investigate emerging scientific phenomena. These periodic, focused investigations are scheduled according to the accrual of scientific knowledge attained from prior investigations. For example, as the general trend of global warming has been recognized, missions were specifically targeted to better understand the carbon cycle, and to measure radiation effects from clouds, vegetation canopy heights and other phenomena. Similarly, future measurements are planned in other aspects of Earth science.

The primary limitation in this strategy is the length of time to develop and deploy space-based measurement assets. Considerable forethought must be paid to assuring continual measurements of certain phenomena in order to maintain a statistical base of scientific data. This period is additionally lengthened by the planning, development and deployment of space-based instruments for periodic focused measurements. The result is that a decade may pass between the theoretical identification of a phenomenon and when the space-based asset to measure the phenomenon is deployed. Finally, limited budgets preclude continually launching unique instruments targeted toward specific measurement needs.

To enable NASA's Earth Science vision, the future paradigm of remote sensing instruments may need to employ large numbers of frequency-agile instruments capable of multi-scene observations. Real-time, autonomous adaptive sensing and taskability will be critical. Advanced capabilities will include:

- Miniaturized observatories
- Robust, compact instrument architectures
- Miniaturized/programmable components
- Aperture synthesis
- Deployable apertures
- Low cost production

The path to the future will comprise incremental, yet revolutionary advances in measurement capabilities and instrument technologies. Table 1 summarizes the key technologies and their science relevance's in each of the instrument classes.

TABLE 1
SUMMARY OF KEY TECHNOLOGIES

Instrument Class	Key Technologies	Relevant Science
Passive Optical	16K by 16K focal plan array detectors High sensitivity, frequency agile, broadband detectors	Land cover use/change Vegetative 3D structure
Active Optical	Reliable, efficient, 1-micron laser transmitter Reliable, efficient, 2-micron laser transmitter Efficient non-linear optics	Tropospheric wind/chemistry, topography Tropospheric wind, CO_2 Tropospheric chemistry, water vapor
Microwave Imagers/Radiometers	Large, lightweight deployable antennas Monolithic Microwave Integrated Circuits (MMICs) High speed, low power, digital correlators	Soil moisture, ocean salinity, precipitation rate, temperature and water vapor profiles, stratospheric chemistry
Radar	Large, lightweight deployable antennas MMICs Compact, efficient transmitters	Weather and climate, erosion, volcano, earthquake monitoring
Onboard Data Processing	High speed, low power field programmable gate arrays Real-time spectral band aggregation, spatial averaging, data compression, event detection	Land surface properties, tropospheric chemistry, topography, solid Earth, ocean productivity

II. Passive Optical Instruments

Optical instruments are the foundation of Earth science measurements and will continue to play a significant role in the future of Earth science. These instruments address a variety of Earth science measurements including: atmospheric ozone and aerosols, cloud properties, ocean color, water quality, land surface properties, soil type, volcano prediction and activity, vegetative 3D structure, and others. Expectations in the next 25 years include improved temporal, spatial and frequency coverage and smaller, less resource intensive instruments resulting from advancements in detector technologies, optics and calibration.

The future of measurements in the visible and IR regions will require advances in focal plane array (FPA) detector technologies, include the use of advanced materials beyond the state of the art in HgCdTe, advances in cooler technology such as solid-state coolers and advances in optics materials including use of silicon carbide and other innovative materials for lightweight, thermally stable mirrors and refractive devices.

The state of the art in FPAs is passively cooled thermal infrared (TIR) detectors of 256 by 256 pixels operating at 100K and for microbolometer arrays of 240 x 360 pixels operating at room temperature. Within the next 25 years, pixel capability is envisioned to increase to 16K by 16K for passively cooled FPAs operating at 150K and to 4K by 4K for uncooled arrays. Detector arrays capable of detecting multiple frequency bands, so-called three-dimensional detector arrays, are currently available in 256 x 256 for IR and 1024 x 1024 for visible wavelengths. Within 20 years pixel capabilities for these arrays are expected to increase to 16K by 16K with spectral response extending continuously from the near ultraviolet (UV) to TIR. These arrays will enable a compact instrument design achieving simultaneous spatial, temporal and frequency content with a high signal-to-noise ratio. Current technology for band selectivity includes the use of fixed band filters and detector architectures. Future frequency agile detector systems will employ high sensitivity, broadband detectors and non-linear optics designed in the range from sub-mm (far IR) to thermal and short wave infrared and ultimately ultraviolet. Quantum Well Infrared Photoconductive (QWIP) focal plane arrays based on GaAs are currently being used in broadband and narrowband IR and TIR applications from 4 to 20 microns. Expected improvements in QWIPs will include greater array size, approaching 2K by 2K, quantum efficiency greater than 20 percent, and multiple/selective frequency bands.

Hyperspectral imagers (HSI), capable of imaging many spectral will find increasing uses in agriculture, forestry, land use and mapping, geology, coastal resources and others. Current HSI systems employ onboard calibration and data processing in complex electronic systems. Future HSI systems will employ high density field programmable gate arrays (FPGAs) that, in combination with light weight optics and self-calibrating systems, will enable smaller, more compact instruments.

Improvements in air temperature, humidity, clouds, and surface temperature measurements will be realized by way of advances in grating spectrometers such as high dispersion gratings and lightweight, wide field optics. Advances in both imaging and sounding Fourier Transform Spectrometers (FTS) will include lightweight composite structures with integrated mirrors, innovative optical path routing, adaptive stroke control and low power actuators. Critical to these instruments is the need to perform precise onboard spectral calibration. Developments such as these will allow spectrometers to be smaller and more capable, with the resultant improvement in global coverage.

III. Active Optical Instruments

An area of Earth science instrument technology that will see increased technology advancement is lasers, specifically, lasers for light detection and ranging (lidar) and differential absorption lidar (DIAL). These measurement techniques are finding uses in several Earth science areas, including: atmospheric chemistry, water vapor, aerosols and clouds, wind speed and direction, pollution, oceanic mixed layer depth, land-locked ice, sea ice, vegetation canopy and crop status, biomass, vegetative stress indicator, surface topography, and others. While much of this science has been ongoing over the past decade using lasers, the measurements have been made almost exclusively from the ground or from aircraft. Advancements in the science could benefit from improved spatial and temporal coverage by the use of space-based deployment of lasers.

The state of the art in lasers for remote sensing instruments requires significant platform resources (primarily power and volume) while also suffering from low reliability and consequently short operational lifetimes. Technology advancements in this area will be necessary to enable long-term, space-based operation of lasers. For the measurement of tropospheric winds, the coherent detection approach will make use of a joule-class, 2-micron laser pump source while the direct detection method will use a joule-class, 1-micron laser pump source with a third harmonic generator to detect at 0.355 microns. The measurement of tropospheric CO_2 can also use a 2-micron laser operating in a low pulse repetition rate DIAL mode for a profile measurement and a 1.6 micron Integrated Path Differential Absorption lidar to provide a high pulse repetition rate lower resolution column measurement. Tropospheric chemistry measurements can use a joule-class, 1-micron laser with frequency doublers and optical parametric oscillators to make a DIAL instrument that will detect in the range of 0.30 to 0.32 microns. Vegetation canopy and surface topography measurements at 0.532 microns can be made by measuring backscattered reflections from a millijoule-class, 1-micron laser transmitter with frequency doubling operating at a pulse repetition rate approaching 10kHz.

Strategies for developing laser technologies will focus on the development of reliable, efficient laser pump sources at 1- and 2-microns, efficient frequency conversion devices such as second and third harmonic generators and optical parametric oscillators and a variety of elements common to all measurement techniques including: improved heat rejection using high thermal conductivity materials, improved laser diode lifetime and reliability, improved frequency control and strict contamination control. Future enhancements may also include the capability to scan the laser transmitter and the development of a high spectral resolution lidar.

In addition to laser technologies, advancements in receiver technologies will be necessary to help mitigate laser transmitter power requirements. These improvements will include, large (3-meter class), lightweight (1-10 kg/m^2), deployable telescopes and high efficiency detectors. Finally, improvements in filter technologies, including narrowband linear variable etalon filters will be necessary for many multispectral measurements.

IV. MICROWAVE IMAGERS/RADIOMETERS

The many Earth science measurements made today with passive microwave instruments will continue into the future and will be significantly enhanced. These instruments address various science questions regarding clouds, precipitation, ocean winds, water vapor profiles, temperature profiles, atmospheric chemistry, soil moisture, ocean salinity, and others. The major improvements expected in the 2020 timeframe include improved temporal coverage resulting from new vantage points and multiple copies of smaller instruments, and higher spatial resolution resulting from large antennas in the lower frequency bands.

Numerous applications exist for imaging and sounding radiometers. Key measurements include cloud sensing, rainfall characterization, sea surface temperatures, sea surface winds, water vapor and temperature profiles, snow and ice. With frequencies ranging from about 5 to 90 GHz and ground resolutions of 3 km or better, these microwave instruments will benefit from new technologies in early development stages now. For applications where improved temporal coverage is required, such as precipitation rate, very compact instruments will be developed to enable constellations of 10's, or even 100's, of sensors. Enabling technologies include widespread use of monolithic microwave integrated circuits (MMICs). MMICs will be widely applied to the whole frequency range of interest and will become more manufacturable. They will be applied to low noise amplifiers, local oscillators, and mixers, ultimately resulting in single MMIC implementations of many of the receivers. Digital conversion and processing, e.g., correlators, will be significantly reduced in size and power. Wide use of "passive" remote sensing using GPS signals is expected as receivers continually gain in processing power and algorithms are further developed to measure and exploit atmospheric occultations and surface reflections.

Significant improvements in hydrology studies and weather prediction will result from better soil moisture measurements. These improvements are dependent on making L-band radiometer measurements with a spatial resolution significantly better than 10 km. In order to do this, large aperture antennas (10's of meters in diameter with areal densities of less than 1 kg/m^2) will be required. Relevant technologies include large deployable systems, inflatable structures, and synthetic aperture systems. Improvements in size and power reduction for RF receivers and digital systems are also desirable. Salinity measurements, while less demanding in spatial resolution, will require significant advances in signal-to-noise ratio resulting from improvements in low noise amplifiers, local oscillators, mixers, and calibration systems.

Physical studies of atmospheric water vapor and temperature for weather prediction and other applications could benefit greatly from continuous diurnal observations of the Earth from geostationary orbit (GEO) at frequencies of 37 to 183 GHz with one-kilometer ground resolution. Current limitations on antenna size severely limit the spatial resolution and signal level which could be obtained with passive microwave measurements. However, technology for very large aperture antennas (100's of meters in diameter) will be available in 15 to 20 years, allowing a GEO instrument to make these observations. Technology for inflatable structures, lightweight reflector materials (areal density of much less than 0.1 kg/m^2), and multifunction membrane structures will be needed.

Limb sounding of the upper atmosphere for temperature, pressure, water vapor, ozone, and trace species has relied heavily on passive microwave measurements in the frequency range from 118 GHz to 2.5 THz. Great improvements are expected in these receivers across the frequency range, enabling lower cost, size, and mass, and enabling greater receiver sensitivity. These reductions will enable an array sounding instrument that will provide vastly improved global coverage.

V. RADAR INSTRUMENTS

Radar technology, as it continues to evolve since its first use in the late 1930s, has found many applications in Earth science. Dual-polarization radar, dual-frequency radar, bistatic system, and synthetic aperture radar (SAR) technologies have exploited the basic physics in different ways to provide a range of exciting possibilities. Improved measurements needed in the longer term include 1.5 km resolution cloud and precipitation profiling at 14, 35, and 94 GHz; advanced Ku-band ocean altimeters that make wide swath measurements; and SARs and interferometric SARs from P to K band with several meter level resolution to characterize vegetation, soil moisture, and ocean salinity, as well as the solid earth, for better understanding and possible future prediction of volcano eruptions, landslides, soil transport, and earthquakes.

Strides have been made in signal processing, in assimilation of radar data into numerical models, in uses of refractivity, cross correlation techniques, and in analysis of temporal data. These new capabilities are enabling the prediction of river flow, reproduction (accurate modeling) and understanding of storm evolution, plant growth and pest control, wind shear, detection of meteorological conditions that lead to icing on aircraft, archeology, and creation of maps of relative humidity. Radar can be used to assist city planners and farmers better manage water storage and storm sewers and improve crop productivity.

The three principle drivers for radar systems are power, antenna size, and signal processing. Radar is an active technique, thus requiring more power, a scarce resource in space. Large radar antennas are required to improve radar data quality. For some remote sensing applications of radar, the spacecraft's motion can be combined with advanced signal processing techniques to simulate a larger radar antenna, thus Synthetic Aperture Radar (SAR). Interferometric SAR (InSAR), in addition, makes use of phase information to produce three-dimensional images. Radars generate large data streams. More and more manipulation of this data will be done on board the spacecraft as signal-processing power increases.

Significant technology advances will continue through the next 25 years in all of the components of the radar systems, with improved antennas, continued reduction in mass, power, and volume of microwave transmitters and receivers, and greatly improved signal processing. Technologies will include microwave receiver miniaturization through the use of MMICs; compact efficient transmitters from P to W band; high-density electronic packaging; high-throughput digital processing through application of high-density, high-speed, low-power processors and special hardware; and large lightweight deployable antennas, using inflatable structures and membrane surfaces.

Advances are expected in mesoscale and microscale collection and processing of radar data from multiple sources, including ground, airborne, and space systems. Substantial advances in radar modeling will feature new signal processing algorithms for holographic impulse radar arrays and synergistic applications of input signals from multiple sensors. This greatly improved assimilation of radar data from linked ground based, airborne, and space-based systems will provide substantially more accurate modeling and prediction applications.

VI. On-Board Processing Considerations

Much of the flexibility of the sensor web will come from the ability to process data in or near the instrument. While broader issues of higher-level science processing, data transmission, network connectivity, and data archiving are discussed elsewhere in the context of information systems, there is significant potential for improved processing within the sensor itself. This on-board processing may include real-time adaptive operation, spectral band aggregation, spatial averaging, data selection, compression, and event detection. As on-board processors and special hardware accelerators, e.g., radiation-hardened, high speed, high density, low power FPGAs, approach gigaflop and teraflop speeds, the flexibility of highly capable instruments that operate in lower resolution monitoring modes and switch to higher resolution probing modes will be realized. Ultimately, applications of quantum and biological computing and holographic memories may allow all processing in real time in the instrument, including full resolution Earth models with full data assimilation.

VII. Conclusions

The science needs established by the vision of NASA's Earth Science Enterprise challenge the state of the art for instrument technologies. Incremental, yet revolutionary advances in measurement capabilities and instrument technologies will be necessary to accomplish this vision. Advancements will be necessary in detectors, optics, lasers, large deployable antennas, and low power, high-speed electronics. Future remote sensing instruments, more compact, economical and more capable by today's measures, with frequency-agility and multi-scene observation capability, will scarcely resemble their contemporary counterparts.

Partnerships between NASA and interagency, international, commercial and academic organizations will be essential to achieving this vision. The economic benefits will be shared across the globe.

VIII. Acknowledgments

The authors acknowledge the efforts of the participants of the Earth Science Vision Workshop conducted in April 2000 for their contribution to many of the concepts discussed in this paper.