THE UNITED STATES' NEXT GENERATION OF ATMOSPHERIC COMPOSITION AND COASTAL ECOSYSTEM MEASUREMENTS

NASA's Geostationary Coastal and Air Pollution Events (GEO-CAPE) Mission

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GEO-CAPE will measure tropospheric trace gases and aerosols and coastal ocean phytoplankton, water quality, and biogeochemistry from geostationary orbit to benefit air quality and coastal ecosystem management.

CHARGE OF THE NRC REPORT. The U.S. National Research Council (NRC), at the request of the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Geological Survey, conducted an *Earth Science Decadal Survey* review to assist in planning the next generation of Earth science satellite missions [NRC 2007; commonly referred to as the "Decadal Survey" ("DS")]. The Geostationary Coastal and Air Pollution Events (GEO-CAPE) mission measuring tropospheric trace gases and aerosols and coastal ocean phytoplankton, water quality, and biogeochemistry from geostationary orbit was one of 17 recommended missions. Satellites in geostationary orbit provide continuous observations within their field of view, a revolutionary advance for both atmosphere and ocean science disciplines. The NRC placed GEO-CAPE within the second tier of missions, recommended for launch within the 2013–16 time frame. In addition to providing information for addressing scientific questions, the NRC advised that increasing the societal benefits of Earth science research should be a high priority for federal science agencies and policy makers.

In August 2008, two GEO-CAPE Science Working Groups (SWGs)—one from the atmospheric composition observing community and the other from the ocean color (OC) observing community—convened for the first time to begin formulating a well-defined mission with achievable science and applications requirements. One challenge of putting together such a mission was the cooperation of two scientific disciplines to formulate a set of instruments and observing strategies that would benefit both communities. Subsequent workshops (September

2009, March 2010, and May 2011) have enabled the SWGs to define the science requirements more precisely for each discipline with the intent of working jointly through mission engineering studies to see how these requirements could be achieved most expeditiously. Because of budget constraints since the release of the DS, a GEO-CAPE launch as a single independent satellite was delayed beyond 2020, prompting the SWGs to take a creative approach to develop a realistic mission concept at considerably lower cost and risk that would still meet most of the DS science requirements. Thus, the SWGs now endorse the concept of a phased mission implementation that can be achieved by flying each GEO-CAPE instrument separately as secondary "hosted" payloads on commercial or government-owned geostationary satellites. Other government agencies have already adopted the hosted payload implementation approach because it substantially reduces the overall mission cost [e.g., the Federal Aviation Administration's Wide Area Augmentation System (WAAS) satellite; see http://lefebure.com/articles/waas-satellites/]. Single instrument packages accommodated on planned geostationary communication satellites (COMSATs) will cost a fraction of deploying an independent dedicated GEO-CAPE satellite.

Global constellations of geostationary atmospheric chemistry and coastal ocean color sensors are a possibility by 2020. The European Space Agency (ESA) and the Korea Aerospace Research Institute (KARI) are planning launches of atmospheric chemistry payloads in the 2018 time frame (CEOS Atmospheric Composition Constellation 2011); such a network of geostationary platforms over the Americas, Europe, and Asia would serve as a virtual constellation, fulfilling the vision of the Integrated Global Observing System (IGOS) for a comprehensive measurement strategy for atmospheric composition (IGACO 2004). GEO-CAPE will also contribute to a global effort for geostationary ocean color observations that will include regional efforts by KARI, such as the recently launched Geostationary Ocean Colour Imager (GOCI) with follow-on plans for a GOCI-II launch in 2018, as well as interests by European and Indian space agencies to launch geostationary ocean color sensors by 2020 (Antoine 2012).

We begin this paper with the current expression of GEO-CAPE objectives as developed by the SWGs through the GEO-CAPE Community Workshops. Next we summarize the science traceability matrices that have evolved over the past 2 yr and examine the key measurements that are required. Last, we describe a methodology for the implementation of GEO-CAPE that should meet the science requirements outlined in the DS at low risk while resulting in a cost savings of hundreds of millions of dollars over the life of the mission.

GEO-CAPE SCIENCE QUESTIONS. The SWGs were charged with developing a coherent set of realistic science objectives that could be readily achieved using technology that either currently exists or likely will be available within the next several years, expressed as science traceability matrices (STMs) that describe the flow from GEO-CAPE scientific questions to instrument requirements. The current atmospheric and ocean science traceability matrices are available at the GEO-CAPE website

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(http://geo-cape.larc.nasa.gov), and changes will be posted as development progresses. The scientific questions guiding these STMs are outlined below and the measurement characteristics are discussed in the "Derivation of science traceability matrices" section.

Atmospheric composition science questions. A-Q1: WHAT ARE THE TEMPORAL AND SPATIAL VARIATIONS OF EMISSIONS OF GASES AND AEROSOLS IMPORTANT FOR AIR QUALITY AND CLIMATE? One of the four major objectives of the GEO-CAPE mission defined by the DS is to provide the research and operational air quality (AQ) communities with information on the natural and anthropogenic emissions of ozone (O_3) and aerosol precursors. Emissions inventories are vital for developing effective air pollution mitigation strategies, and the DS emphasizes the fact that the present-day observational system for air quality, based mainly on a network of surface sites, is inadequate for relating pollutant levels to sources and transport. While the DS description of the GEO-CAPE mission focused on air quality applications, the Atmosphere SWG translated the DS emissions objective more broadly in recognition of NASA's increased emphasis on climate and the inextricable linkage between climate and air quality–relevant gases and aerosols.

A-Q2: HOW DO PHYSICAL, CHEMICAL, AND DYNAMICAL PROCESSES DETERMINE TROPOSPHERIC COMPOSITION AND AIR QUALITY OVER SCALES RANGING FROM URBAN TO CONTINENTAL, FROM DIURNAL TO SEASONAL? This science question directly supports the major objectives of the GEO-CAPE mission as defined by the DS:

> The emissions and chemical transformations interact strongly with weather and sunlight including the rapidly-varying planetary boundary layer as well as continental-scale transport of pollution. Again, the scales of variability of these processes require continuous, high spatial and temporal resolution measurements only possible from geosynchronous orbit (NRC 2007).

To quantify and separate the effects of chemical and dynamical processes, it will be critical to probe the planetary boundary layer, which reflects dynamical variations and is the region that is impacted by both emissions and photochemical processes. For that reason, the STM requires two pieces of information in the troposphere for carbon monoxide (CO) and O_3, with sensitivity in the boundary layer. It is expected that this vertical information can be achieved using information from different regions of the electromagnetic spectrum, but the details of which portions of the spectrum are required are still being evaluated, as discussed in the "Improvement to measurement capabilities by GEO-CAPE" section.

A-Q3: HOW DOES AIR POLLUTION DRIVE CLIMATE FORCING, AND HOW DOES CLIMATE CHANGE AFFECT AIR QUALITY ON A CONTINENTAL SCALE? Since the publication of the DS, scientists and policy makers have increasingly recognized the coupling between air quality and climate as a key issue for air quality management. The Intergovernmental Panel on Climate Change (Solomon et al. 2007) finds that emissions of short-lived climate forcers (SLCFs) relevant to air quality may exert a forcing on climate change greater than carbon dioxide (CO_2) emissions over the next 20 yr. The U.S. Environmental Protection Agency (EPA) recently initiated the Climate Impact on Regional Air Quality project to improve understanding of chemistry–climate interactions at the regional scale, and they, along with international bodies such as the United Nations Environment Programme (UNEP), have sponsored workshops or working groups on SLCFs (UNEP 2011a,b). GEO-CAPE is the only mission planned under either the DS or NASA climate initiative that will measure species critical to both air quality and climate, including methane (CH_4), O_3, aerosols, and others, such as CO, that indirectly alter climate by changing the oxidative capacity of the atmosphere.

A-Q4: HOW CAN OBSERVATIONS FROM SPACE IMPROVE AIR QUALITY FORECASTS AND ASSESSMENTS FOR SOCIETAL BENEFIT? This science question directly reflects the air quality objective as stated in the DS, "to satisfy basic research and operational needs for air quality assessment and forecasting to support air program management and public health." The Atmosphere SWG has identified the following four activities that are necessary to meet this objective: integrating new knowledge to improve the representation of processes in air quality models, combining satellite measurements with information from surface in situ networks and ground-based remote sensing to construct an improved AQ observing system, measuring relevant species with the spatial and temporal resolution to improve data assimilation for air quality forecasts, and measuring aerosol optical depth (AOD) and sulfur dioxide (SO_2) with the spatial and temporal resolution needed to monitor large-scale air quality hazards.

A-Q5: How does intercontinental transport affect surface air quality? There has been increasing awareness in the U.S. air quality management community that efforts to meet air quality standards through domestic emission controls could be compromised by intercontinental transport of pollution, an issue that has been stressed by the Hemispheric Transport of Air Pollutants Task Force (Dentener et al. 2010; Dutchak and Zuber 2010; Keating et al. 2010; Pirrone and Keating 2010) of the UNEP. Satellite observations from low-Earth orbit (LEO) clearly identify intercontinental transport, but the poor measurement frequency provides insufficient information for air quality management. Observations from geostationary Earth orbit (GEO) will allow tracking of the arrival of intercontinental pollution over the receptor continent and assessment of its impact on surface sites.

A-Q6. How do episodic events, such as wildfires, dust outbreaks, and volcanic eruptions, affect atmospheric composition and air quality? Unpredictable events, such as wildfires, volcanic eruptions, and industrial catastrophes, can have large impacts on air quality (e.g., Al-Saadi et al. 2005). The continuous high-resolution information afforded by GEO-CAPE will provide a unique resource for monitoring and forecasting the associated pollution plumes. A successful resolution to this question implies an operational aspect for the use of these data and necessarily requires close collaboration with operational agencies (primarily EPA and NOAA), to assist them in understanding and digesting the measurement data from GEO-CAPE.

Ocean science questions. O-Q1. How do short-term coastal and open ocean processes interact with and influence larger-scale physical, biogeochemical, and ecosystem dynamics? The large-scale response of ocean circulation, biogeochemistry, and ecosystems to atmospheric, climatic, and anthropogenic forcing is the integral of processes occurring on smaller scales (Mann and Lazier 2006). Examples include vertical mixing, upwelling, primary production, and grazing, as well as turbulent kinetic energy processes that can occur on inertial and semidiurnal tidal frequencies. Some of these processes are not easily discernible by the current generation of polar-orbiting ocean color satellite sensors. GEO-CAPE, with associated field campaigns, will provide the measurements that show how these small-scale processes operate, allowing for parameterization in larger-scale predictive models. The interplay of these dynamic physical, chemical, and biological processes drives the transfer of matter and energy on regional and global scales, affecting Earth's climate as well as human health and prosperity.

O-Q2. How are variations in exchanges across the land–ocean interface related to changes within the watershed, and how do such exchanges influence coastal and open ocean biogeochemistry and ecosystem dynamics? Exchanges of waterborne materials from land to ocean are a function of seasonal discharge dynamics, atmospheric deposition, and land surface attributes that are influenced by a host of natural and anthropogenic processes (Liu et al. 2010). Wetlands, estuaries, and river mouths at the land–ocean interface are regions of vigorous biogeochemical processing and exchange, where land-derived materials are transformed to other compounds, affecting fluxes of carbon and nutrients to both the coastal ocean and the atmosphere (Mackenzie et al. 2004). Global change impacts on climate, land use practices, and air quality will ultimately influence the delivery of dissolved and particulate materials from terrestrial systems into rivers, estuaries, and coastal ocean waters, and the measurements from GEO-CAPE will provide new insight into the mechanisms that control these processes.

O-Q3. How are the productivity and biodiversity of coastal ecosystems changing, and how do these changes relate to natural and anthropogenic forcing, including local to regional impacts of climate variability? The ways in which climate variability and global change impact the biodiversity and productivity of coastal ecosystems is still the subject of significant debate (Harley et al. 2006; Scavia et al. 2002). Coastal ecosystems account for 15%–21% of the global ocean primary production (Jahnke 2010), and they provide the great majority of marine resources that are harvested for human consumption. Coastal ecosystems also receive the great majority of anthropogenic inputs (except CO_2) resulting from their proximity to human populations. Coastal primary producers, fish, and other consumers all should decrease when i) upwelling or other nutrient supply processes decrease, ii) nutrient stocks above the thermocline/nutricline decrease, and/or iii) the thermocline/nutricline deepens. While these biogeochemical links are currently observable at longer time scales using polar-orbiting sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Medium Resolution Imaging Spectrometer (MERIS), GEO-CAPE will provide critical data linking the inertial and semidiurnal frequency variability in ocean processes to the spectrum of biological response.

O-Q4. How do airborne-derived fluxes from precipitation, fog, and episodic events, such as fires, dust storms, and volcanoes, significantly affect the ecology and biogeochemistry of coastal and open ocean ecosystems? Atmospheric fluxes influence marine ecosystems in two ways, via direct deposition to the surface of marine waters and indirect deposition to the watersheds emptying into those waters (O-Q2). Two key nutrients, nitrogen and iron, are known to have significant airborne vectors that are episodic in time and space. Dust storms are known to deposit significant amounts of iron both to the open ocean and coastal ocean waters via dry deposition of dust aerosol particles (Baker et al. 2003). Similarly, recent work has indicated volcanic ash may also be a significant source of iron in some ocean waters via aerosol deposition (Langmann et al. 2010; Lin et al. 2011). Unlike dust deposition of iron, nitrogen deposition is more important in coastal waters than open ocean areas due to the proximity of coastal ecosystems to anthropogenic source regions (Paerl et al. 2002). In addition to nutrients, the atmospheric deposition of other compounds is expected to be important in marine ecosystems as well. For example, copper from aerosol deposition was found to inhibit the growth of certain marine species, suggesting an influence on marine primary productivity (Paytan et al. 2009). GEO-CAPE's multiple observations per day will provide new insight into the temporal evolution of both coastal and open ocean waters to episodic inputs of nutrients and other compounds.

O-Q5. How do episodic hazards, contaminant loadings, and alterations of habitats impact the biology and ecology of the coastal zone? Episodic hazards of short duration, such as hurricanes and other extreme storms, floods, tsunamis, chemical spills, and harmful algal blooms, which can occur without warning, are especially challenging to observe. Yet it is these same events that have the most severe and lasting effects on coastal ecosystems. Other severe impacts resulting from the loss of coastal marshlands, resulting from development and sea level rise occur so gradually over such long periods of time that they are likewise difficult to observe. In both cases, GEO-CAPE will permit the more detailed assessment of the extent and duration of damage to coastal habitats from disasters. Assessment of impacts on coastal and open ocean communities requires both standing stock and rate measurements over many years.

Effective response and prediction relies on accurate and timely information that is updated frequently. The recent Deepwater Horizon oil disaster, which has both episodic and long-term effects on the environment (Hu et al. 2011), is one example in which data from the GEO-CAPE mission would have provided valuable information about the extent, movement, persistence, and fate of the spill.

Atmosphere–ocean interdisciplinary science. The interconnections between the atmosphere and coastal waters are complex, involving nutrient delivery and bioavailability; deposition and biogeochemical cycling of toxic compounds, trace metals, and persistent organic pollutants; and air–sea trace-gas exchange, with coastal waters functioning both as sources and sinks. There is high potential from combined GEO-CAPE observations of trace gases (e.g., HCHO, CHOCHO, and SO_2), aerosol, and ocean color in quantifying and understanding ocean–atmosphere exchange and biogeochemical cycling. Marine ecosystems may play an important role in urban air quality by providing halogen radicals that influence O_3 production and the oxidative capacity of the boundary layer along coastal margins (e.g., Knipping and Dabdub 2003; Tanaka et al. 2003; Pszenny et al. 2007). By leveraging the measurements made for the primary air quality and ocean color scientific goals of GEO-CAPE, this mission is poised to make a unique contribution to interdisciplinary research on a variety of spatial and temporal scales. GEO-CAPE is anticipated to provide a valuable resource to our international partners in advancing the objectives of the international Surface Ocean–Lower Atmosphere Study (SOLAS; Liss et al. 2004).

DERIVATION OF SCIENCE TRACEABILITY MATRICES.

Beginning with the first open Community Workshop (2008), the development of GEO-CAPE's STMs has occurred through two working groups composed of scientific, remote sensing, and in situ observation experts. Special studies on temporal and spatial variability of observables, the data needs of the science applications communities, and relationships between observables and climate were conducted in support of the STM development. The heritage of measurement techniques and product algorithms already demonstrated from low-Earth orbit through NASA and international Earth-observing programs guided the traceability from science questions to measurement requirements. The recommended measurement and instrument requirements necessary to address the science questions, observational approaches, and measurements are summarized in Tables 1 and 2. The requirements described in this section remain provisional until

Table 1. Atmosphere science traceability matrix.

Science Questions	Measurement Objectives (color flag maps to Science Questions)	Measurement Requirements (mapped to Measurement Objectives)	Measurement Rationale
1. What are the temporal and spatial variations of emissions of gases and aerosols important for air quality and climate? 2. How do physical, chemical, and dynamical processes determine tropospheric composition and air quality over scales ranging from urban to continental, diurnally to seasonally? 3. How does air pollution drive climate forcing and how does climate change affect air quality on a continental scale? 4. How can observations from space improve air quality forecasts and assessments for societal benefit? 5. How does intercontinental transport affect air quality? 6. How do episodic events, such as wild fires, dust outbreaks, and volcanic eruptions, affect atmospheric composition and air quality?	Baseline measurements[1]: O3, NO2, CO, SO2, HCHO, CH4, NH3, CHOCHO, different temporal sampling frequencies; AOD, AAOD, AI, aerosol optical centroid height (AOCH), hourly for SZA<70; all at 4 km x 4 km product horizontal spatial resolution at the center of the domain. Descope options: degrade product horizontal spatial resolution to 8 km x 8 km. eliminate cloud camera. eliminate observations over the open ocean (>250 km from coast). eliminate AOCH. Eliminate HCHO, SO2, CH4, CHOCHO, NH3, AAOD, AI.	**Geostationary Orbital Location:** 100 W +/-10 Viewing North America from 10-60N	Provides optimal view of North American atmospheres over land, coastal waters, and open ocean in support of science questions.
		Column measurements: [A to K]	Continue the current state of practice in vertical; add temporal resolution.
		Cloud Camera *1 km x 1km horizontal spatial resolution, two spectral bands, baseline only*	Improve retrieval accuracy, provide diagnostics for gases and aerosol
		Vertical information: [A to K]	
		Two pieces of information in the troposphere in daylight with sensitivity to the lowest 2 km: O3, CO	Separate the lower-most troposphere from the free troposphere for O3, CO.
		Altitude (+/- 1km): AOCH	Detect aerosol plume height; improve retrieval accuracy.
	A. Measure the threshold or baseline species or properties with the temporal and spatial resolution specified (see next column) to quantify the underlying emissions, understand emission processes, and track transport and chemical evolution of air pollutants [1, 2, 3, 4, 5, 6] B. Measure AOD, AAOD, and NH3 to quantify aerosol and nitrogen deposition to land and coastal regions [2, 4] C. Measure AOD, AAOD, and AOCH to relate surface PM concentration, UV-B level and visibility to aerosol column loading [1, 2, 3, 4, 5, 6] D. Determine the instantaneous radiative forcings associated with ozone and aerosols on the continental scale and relate them quantitatively to natural and anthropogenic emissions [3, 5, 6] E. Observe pulses of CH4 emission from biogenic and anthropogenic releases; CO anthropogenic and wildfire emissions; AOD, AAOD, and AI from fires; AOD, AAOD, and AI from dust storms; SO2 and AOD from volcanic eruptions [1, 4, 6] F. Quantify the inflows and outflows of O3, CO, SO2, and aerosols across continental boundaries to determine their impacts on surface air quality and on climate [2, 3, 5] G. Characterize aerosol particle size and type from spectral dependence measurements of AOD and AAOD [1, 2, 3, 4, 5, 6] H. Acquire measurements to improve representation of processes in air quality models and improve data assimilation in forecast and assessment models [4] I. Synthesize the GEO-CAPE measurements with information from in-situ and ground-based remote sensing networks to construct an enhanced observing system [1, 2, 3, 4, 5, 6] J. Leverage GEO-CAPE observations into an integrated observing system including geostationary satellites over Europe and Asia together with LEO satellites and suborbital platforms for assessing the hemispheric transport [1, 2, 3, 4, 5, 6] K. Integrate observations from GEO-CAPE and other platforms into models to improve representation of processes in the models and to link the observed composition, deposition, and radiative forcing to the emissions from anthropogenic and natural sources [1, 2, 3, 4, 5, 6]	***Product horizontal spatial resolution at the center of the domain,*** (nominally 100W, 35 N): [A to H] 4 km x 4 km: Gases and Aerosols — Capture spatial/temporal variability; obtain better yields of products. 16 km x 16 km: Over open ocean — Inherently larger spatial scales, sufficient to link to LEO observations	
		Spectral region : [A to H]	Typical use
		UV, Vis, TIR: O3	Provide multispectral retrieval information in daylight
		SWIR, MWIR: CO	
		UV: SO2, HCHO	Retrieve gas species from their atmospheric spectral signatures (typical)
		SWIR,TIR: CH4	
		TIR: NH3	
		Vis: AOD, NO2, CHOCHO	Obtain spectral-dependence of AOD for particle size and type information
		UV-deep blue: AAOD	Obtain spectral-dependence of AAOD for aerosol type information
		UV-deep blue: AI	Provide absorbing aerosol information
		Vis-NIR: AOCH	Retrieve aerosol height [3]

Atmospheric measurements over Land/Coastal areas: [A to K]

Species	***Time resolution***	*Typical value* [2]	*Precision* [2]	Description
O3	Hourly, SZA<70	9×10^{18}	0-2 km: 10 ppbv 2km–tropopause: 15 ppbv Stratosphere: 5%	Observe O3 with two pieces of information in the troposphere with sensitivity to the lowest 2 km for surface AQ; also transport, climate forcing
CO	Hourly, day and night	2×10^{18}	0-2 km: 20ppbv 2km–tropopause: 20 ppbv	Track anthropogenic and biomass burning plumes; observe CO with two pieces of information in the vertical with sensitivity to the lowest 2 km in daylight
AOD	Hourly, SZA<70	0.1 – 1	0.05	Observe total aerosol; aerosol sources and transport; climate forcing
NO2	Hourly, SZA<70	6×10^{15}	1×10^{15}	Distinguish background from enhanced/ polluted scenes; atmospheric chemistry

Additional atmospheric measurements over Land/Coastal areas, total column: [A to K]

Species	***Time resolution***	*Typical value* [2]	*Precision* [2]	Description
HCHO*	3/day, SZA<50	1.0×10^{16}	1×10^{16}	Observe biogenic VOC emissions, expected to peak at midday; chemistry
SO2*	3/day, SZA<50	1×10^{16}	1×10^{16}	Identify major pollution and volcanic emissions; atmospheric chemistry
CH4	2/day	4×10^{19}	20 ppbv	Observe anthropogenic and natural emissions sources
NH3	2/day	2×10^{16}	0-2 km: 2ppbv	Observe agricultural emissions
CHOCHO*	2/day	2×10^{14}	4×10^{14}	Detect VOC emissions, aerosol formation, atmospheric chemistry
AAOD	Hourly, SZA<70	0 – 0.05	0.02	Distinguish smoke and dust from non-UV absorbing aerosols; climate forcing
AI	Hourly, SZA<70	-1 – +5	0.1	Detect aerosols near/above clouds and over snow/ice; aerosol events
AOCH	Hourly, SZA<70	Variable	1 km	Determine plume height; large scale transport, conversions from AOD to PM

Open ocean measurements: [F, H, I, J, K] *16 km x 16 km*

O3	1/day	Over open oceans, capture long-range transport of pollution, dust, and smoke into/out of North America; establish boundary conditions for North America
CO	1/day	
AOD, AAOD, AI	1/day	

AOD=Aerosol optical depth, AAOD=Aerosol absorption optical depth, AI=Aerosol index.

The mixing ratio [mole fraction], ppb, of a target gas is number of moles of that gas/mole of air, invariant with temperature and pressure. The number density is the number of molecules of the target gas/unit volume of air; the total column concentrations in the table above are the integral of the number density from the surface to space.

[1] Baseline: Measured quantities deliver the full science requirements for GEO-CAPE.

[2] Typical column amount. Units are molecules cm^{-2} for gases and unitless for aerosols, unless specified. Typical AOD and AAOD values are provided for mid-visible wavelengths over North America.

[3] Retrieval aerosol height from different techniques, e.g. O2-O2 band at 477 nm, O2-A band at 760 nm, O2-B band at 680 nm.

* = background value. Pollution is higher, and in starred constituents, the precision is applied to polluted cases.

Table 2. Ocean science traceability matrix.

GEO-CAPE Oceans STM

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Science Focus	Science Questions	Approach (Maps to Science Question)	Measurement Requirements	Instrument Requirements	Platform Requirem.	Ancillary Data Requirem
Short-Term Processes **Land-Ocean Exchange** **Impacts of Climate Change & Human Activity** **Impacts of Airborne-Derived Fluxes** **Episodic Events & Hazards**	**1** How do short-term coastal and open ocean processes interact with and influence larger scale physical, biogeochemical and ecosystem dynamics? (OBB 1) **2** How are variations in exchanges across the land-ocean interface related to changes within the watershed, and how do such exchanges influence coastal and open ocean biogeochemistry and ecosystem dynamics? (OBB 1 & 2) **3** How are the productivity and biodiversity of coastal ecosystems changing, and how do these changes relate to natural and anthropogenic forcing, including local to regional impacts of climate variability? (OBB 1, 2 & 3) **4** How do airborne-derived fluxes from precipitation, fog and episodic events such as fires, dust storms & volcanoes significantly affect the ecology and biogeochemistry of coastal and open ocean ecosystems? (OBB 1 & 2) **5** How do episodic hazards, contaminant loadings, and alterations of habitats impact the biology and ecology of the coastal zone? (OBB 4)	GEO-CAPE will observe coastal regions at sufficient temporal and spatial scales to resolve near-shore processes, tides, coastal fronts, and eddies, and track carbon pools and pollutants. Two complementary operational modes will be employed: (1) survey mode for evaluation of diurnal to interannual variability of constituents, rate measurements and hazards for estuarine and continental shelf and slope regions with linkages to open-ocean processes at appropriate spatial scales, and (1 2 3 4) (2) targeted, high-frequency sampling for observing episodic events including evaluating the effects of diurnal variability on upper ocean constituents, assessing the rates of biological processes and coastal hazards. (1 2 4 5) *Measurement objectives for both modes include:* (a) Quantify dissolved and particulate carbon pools and related rate measurements such as export production, air-sea CO2 exchange, net community production, respiration, and photochemical oxidation of dissolved organic matter. (1 2 3) (b) Quantify phytoplankton properties: biomass, pigments, functional groups (size/taxonomy/Harmful Algal Blooms (HABs)), daily primary productivity using bio-optical models, vertical migration, and chlorophyll fluorescence. (1 2 3 4 5) (c) Measure the inherent optical properties of coastal ecosystems: absorption and scattering of particles, phytoplankton and detritus, CDOM absorption. (1 2 3 4 5) (d) Estimate upper ocean particle characteristics including particle abundance and particle size distribution. (1 2 3) (e) Detect, quantify and track hazards including HABs and petroleum-derived hydrocarbons. (5) GEO-CAPE observations will be integrated with field measurements, models and other satellite data: (1) to derive coastal carbon budgets and determine whether coastal ecosystems are sources or sinks of carbon to the atmosphere, (2 3) (2) to quantify the responses of coastal ecosystems and biogeochemical cycles to river discharge, land use change, airborne-derived fluxes, hazards and climate change, and (1 2 3 4 5) (3) to enhance management decisions with improved information on the coastal ocean, such as required for Integrated Ecosystem Assessment (IEA), protection of water quality, and mitigation of harmful algal blooms, oxygen minimum zones, and ocean acidification. (3 5)	Water-leaving radiances in the near-UV, visible & NIR for separating absorbing & scattering constituents & chlorophyll fluorescence Product uncertainty TBD **Temporal Resolution:** *Targeted Events:* • Threshold: ≤1 hour • Baseline: ≤0.5 hour *Survey Coastal U.S.:* • Threshold: ≤3 hours • Baseline: ≤1 hour *Regions of Special Interest (RSI): Threshold: ≥1 RSI 3 scans/day* • Baseline: multiple RSI 3 scans/day *Other coastal and large inland bodies of water within ocean color FOR:* • Threshold: ≥4 times/yr • Baseline: ≤3 hours **Spatial Resol. (nadir):** • Threshold: ≤375 x 375 m • Baseline: ≤250 x 250 m **Field of Regard for Ocean Color Retrievals:** 60°N to 60°S; 155°W to 35°W **Coastal Coverage:** width from coast to ocean: • Threshold: min 375 km • Baseline: min 500 km RSI examples: Amazon & Orinoco River plumes, Peruvian upwelling, Cariaco Basin, Bay of Fundy, Rio Plata, etc. TBD)	**Spectral Range:** Hyperspectral UV-VIS-NIR • Threshold: 345-1050 nm; 2 SWIR bands 1245 & 1640 nm • Baseline: 340-1100 nm; 3 SWIR bands 1245, 1640, 2135 nm **•Spectral Sampling & Resolution:** • Threshold: UV-Vis-NIR: ≤2 & ≤5nm; 400-450nm: ≤0.4 & ≤0.8nm (for NO_2 at spatial resolution of 750x750m at nadir); SWIR resolution: ≤20-40 nm • Baseline: UV-ViS-NIR: ≤0.25 & 0.75 nm; SWIR: ≤20-50 nm **Signal-to-Noise Ratio (SNR) at Ltyp(70° SZA):** • Threshold: ≥1000 for 10 nm FWHM (350-800 nm); ≥600 for 40 nm FWHM (800-900 nm); ≥300 for 40 nm FWHM (900-1050 nm); ≥250 and ≥180 for 1245 & 1640 nm (20 & 40 nm FWHM); ≥500 NO_2 band. • Baseline: ≥1500 for 10 nm (350-800 nm); NIR, SWIR and NO_2 bands same as threshold; ≥100 for the 2135nm (50nm FWHM) • Threshold: Aggregate SWIR bands to 2x2 GSD pixels to meet SNR. **Scanning area per unit time:** Threshold: ≥25,000 km²/min; Baseline: ≥50,000 km²/min **Field of Regard:** • Full disk: 20.8° E-W and 19° N-S imaging capability from nadir for Lunar & Solar Calibrations **Error** (as % of nadir pixel) — Threshol / Baselin **Pointing Knowledge LOS** <50% / <10% **Pointing Accuracy LOS** <100% / <25% **Pointing Stability LOS** <50% / <10% **Geolocation Reconstr.** <100% / <10% **Non-saturating detector array(s) at Lmax** **On-board Calibration:** • Lunar: Threshold: minimum monthly; Baseline: same as threshold • Solar: Threshold: none; Baseline: daily **Polarization Sensitivity:** <1.0% **Relative Radiometric Precision:** • Threshold: ≤1% through mission lifetime • Baseline: ≤0.5% through mission lifetime **Mission lifetime:** Threshold: 3 years; Goal: 5 years **Intelligent Payload Module:** Near Real-Time satellite data download from other sensors (GOES, etc.) for on-board autonomous decision making - **Baseline.** **Pre-launch characterization:** to achieve radiometric precision above on orbit **Solar Zenith Angle Sensitivity:** Threshold: ≤70°; Baseline: ≤75°	Geostationary orbit at 95W longitude to permit sub-hourly observations of coastal waters adjacent to the continental U.S., North, Central and South America Storage and download of full spatial data and spectral data.	Western hemisphere data sets from models, missions, or field observations **Measurement Requirements** (1) Ozone (2) Total water vapor (3) Surface wind velocity (4) Surface barometric pressure (5) Vicarious calibration & validation - coastal (6) Full prelaunch characterization (7) Cloud cover **Science Requirements** (1) SST (2) SSH (3) PAR (4) UV solar irradiance (5) MLD (6) Air/Sea pCO2 (7) pH (8) Ocean circulation (9) Tidal & other coastal currents (10) Aerosol deposition (11) run-off loading in coastal zone (12) Wet deposition in coastal zone (13) Wave height & surface wind speed **Validation Requirements** Conduct high frequency field measurements and modeling to validate GEO-CAPE retrievals from river mouths to beyond the edge of the continental margin.

GEO-CAPE Science Questions are traceable to NASA's OBB Advanced Planning Document ....

* Coastal coverage within field-of-view (FOV) includes major estuaries and rivers such as Chesapeake Bay & Lake Pontchartrain/Mississippi River delta, e.g., the Chesapeake Bay coverage region would span west to east from Washington D.C. to several hundred kilometers offshore (total width of 375 km threshold).

NASA approves the mission for development, and thus are subject to revision as mission studies and budgetary guidance continue to evolve.

The basic technology for the atmospheric composition measurements specifically mentioned in the DS already exists and has been successfully demonstrated from LEO platforms. From the traditional meteorological perspective, the use of satellite information made a quantum leap when sensors were placed on geostationary platforms. There is no doubt that similar advancements will be realized when sensors devoted to atmospheric composition measurements are likewise put on a geostationary platform.

The atmosphere STM working group identified a wide range of measurement techniques applied to different spectral regions that are capable of producing the science data products required for GEO-CAPE. In the development of the STM described in Table 1, the resultant requirements were derived with a thorough knowledge of the strengths and weaknesses of current science products derived from the Ozone Monitoring Instrument (OMI), Measurements of Pollution in the Troposphere (MOPITT), Tropospheric Emission Spectrometer (TES), and MODIS. Thus, the Atmosphere SWG took the approach that the measurement precision and accuracy capabilities of these NASA Earth-observing instruments would address GEO-CAPE's frontier science with relatively low risk. On the other hand, the Atmosphere STM remains open to a wide range of measurement implementations (instrument concepts) as requirements for science data products (measurement requirements) are established. The draft atmosphere STM summarized in Table 1 was discussed and adopted at the GEO-CAPE 2010 Science Working Group meeting and the GEO-CAPE 2011 Open Community Workshop.

The ocean measurement requirements shown in Table 2 are consistent with those for GEO-CAPE recommended by the DS (NRC 2007), as well as with those from the geostationary ocean color mission described in the NASA Ocean Biology and Biogeochemistry Program (OBB) planning document

(NASA 2006). An optimal spatial resolution to resolve coastal ocean geophysical features (and hence in-water constituents) would be <200 m [ground sample distance (GSD)] for turbid waters within 10 km of the shore (Bissett et al. 2004; Davis et al. 2007). Because spatial resolution represents one of the principal drivers of instrument size and mass, a compromise must be made between resolving in-water constituents within the nearshore region and developing a geostationary satellite sensor that is both reasonable in size and mass and technologically feasible. A nadir spatial resolution of 375 m could represent a practical compromise to image estuaries and their larger tributary rivers (e.g., the Chesapeake Bay and Potomac River), as well as to resolve eddies, coastal fronts, and moderately sized phytoplankton patches (e.g., Dickey 1991). Studies are underway that will assist in further refinements of the spatial and temporal resolution requirements.

High-frequency satellite observations are critical to studying and quantifying biological and physical processes within the coastal ocean. Current satellite-based products of ocean primary production rely on no more than a single satellite observation per day of chlorophyll and other ancillary products. Because of cloud cover and gaps in coverage of LEO sensors, such as MERIS and MODIS, the number of satellite observations over an ocean region is typically reduced to only a few measurements per week. Because phytoplankton blooms develop over the course of a few days to a week, the complete dynamics of the blooms are not captured by individual LEO sensors. Yet, the in situ–derived primary production (PP) measurements used to validate this satellite product quantify PP over a 6–24-h period. Furthermore, the physiology of phytoplankton cells (chlorophyll content, nutrient uptake, etc.) varies on diel cycles, and this has a significant impact on their growth rate and hence PP (Furnas 1990). Therefore, multiple observations per day over several days would permit more robust satellite-based estimates of PP. Moreover, because tidal currents reverse within ~6 h for semidiurnal (and ~12 h for diurnal) tidal cycles, tracking natural constituents and hazards, such as oil slicks or harmful algal blooms, using a satellite sensor requires a minimum of three observations per day distributed 3 h apart (Davis et al. 2007).

The current set of OC instrument requirements is drawn from a number of sources (e.g., NASA 2006; NRC 2007, 2011; Antoine 2012, and other references in this document) and will continue to be refined based on results from the GEO-CAPE science studies supported by NASA. Requirements specified for spectral range, resolution, and signal-to-noise ratio (SNR) are considered necessary to accomplish atmospheric correction of the top-of-the atmosphere radiances (aerosol properties and atmospheric NO_2) in order to produce the ocean spectral remote sensing reflectances. Furthermore, the spectral range and resolution requirements are also necessary to retrieve products such as colored dissolved organic matter (NASA 2006; NRC 2007, 2011) and phytoplankton functional types (e.g., Bracher et al. 2009). In addition, these requirements will enable retrieval of atmospheric NO_2 (Tzortziou et al. 2010) and aerosol properties [including aerosol layer height (Dubuisson et al. 2009)] for atmospheric correction and for retrieval of phytoplankton functional types by methods such as PhytoDOAS (Bracher et al. 2009) and radiometric inversions to derive phytoplankton absorption coefficients and pigment concentrations (Moisan et al. 2011).

MEASUREMENTS. *Atmospheric composition measurements.* CURRENT MEASUREMENT CAPABILITIES. Table 1 lists the species to be measured by GEO-CAPE, the scientific objectives to which they respond, and the corresponding measurement requirements. Ozone, aerosols, and an ensemble of precursors are included to better understand the related sources, transport, chemistry, and climate forcing. Methane is included because of its importance as a greenhouse gas. CO and O_3 retrievals include two pieces of information in the troposphere, including sensitivity below 2 km, in order to discriminate near-surface pollution and to better characterize pollutant transport. The measurement of AOD is complemented by aerosol absorption optical depth (AAOD), aerosol index (AI), and height [aerosol optical centroid height (AOCH)].

All of the air quality gases listed in Table 1 have now been measured with the required precisions in Global Ozone Monitoring Experiment (GOME), Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY), MOPITT, OMI, and TES with the exception of the O_3 partial tropospheric columns. The required accuracy for AOD is nearly equivalent to the current accuracy of the MODIS aerosol optical thickness (AOT) product, and AAOD and AI are now routinely retrieved from OMI. GEO-CAPE development requires transferring this existing capability from LEO to GEO, considering the necessity for increased optical throughput and the likely need for an instrument configuration different from any of the previous satellite instruments. Spectral resolution requirements, and their trade-off with measurement SNR requirements, are the subject of current studies. One of the advantages of GEO is that the instruments can "stare" for as long as is

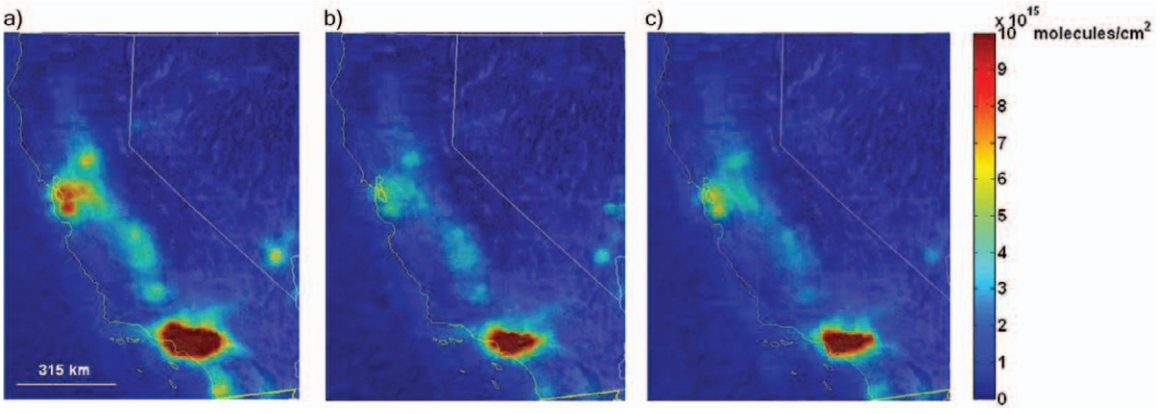

Fig. 1. Average summertime OMI tropospheric NO_2 column concentrations (molecules cm^{-2}) for (a) a weekday (Tuesday–Friday) in 2005, (b) a weekend day (Saturday and Sunday) in 2005, and (c) a weekday in 2008 (from Russell et al. 2010).

necessary to improve SNR and achieve the required precision for the measurement of a specific species. One challenge is to relate retrieved quantities, which are representative of trace gases at some average concentration of a column that also includes surface concentrations, to the actual surface concentrations, which are most meaningful for air quality research.

SCIAMACHY, the GOME instruments [GOME/*European Remote Sensing Satellite* (*ERS*)*-2* followed by the *GOME-2*/Meteorological Operation (MetOp)], and OMI make measurements in the ultraviolet portion of the spectrum to derive O_3, NO_2, SO_2, and HCHO concentrations (Chance et al. 1991, 1997, 2002; Burrows 1999; Bovensmann et al. 1999; Levelt et al. 2006). Glyoxal has now been measured by OMI and SCIAMACHY (Kurosu et al. 2005; Chance 2006; Wittrock et al. 2006). More recently, capabilities have been demonstrated for retrieval of methane from SCIAMACHY (Frankenberg et al. 2006) and direct retrieval of tropospheric O_3 from OMI (Liu et al. 2010).

Figures 1 and 2 illustrate how current satellite capability has already been used to provide useful information on sources that impact regional- and even urban-scale pollution events. Figure 1 compares OMI-derived NO_2 distributions for California in 2005 during weekday (Fig. 1a) and weekend periods (Fig. 1b) during the same year (Russell et al. 2010). The differences in these panels clearly illustrate the smaller emissions during Saturdays and Sundays, primarily resulting from less commuter traffic and industrial activity. Figure 1c likewise suggests that California emission controls for nitrogen oxides put in place in 2005 have reduced the NO_2 burden resulting from these new regulations. Figure 2 compares average SO_2 distributions over the Mexico City, Mexico, metropolitan area (MCMA) during March 2006 from a regional-scale model (left panel) and OMI measurements (de Foy et al. 2009). The satellite measurements were instrumental for

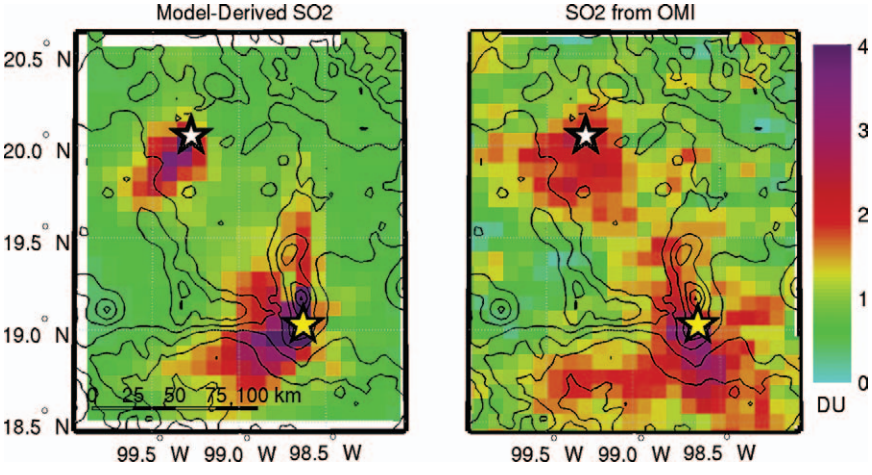

Fig. 2. (left) Model-derived and (right) satellite-observed SO_2 distributions over the MCMA during Mar 2006 (after de Foy et al. 2009). The elevation contour lines every 500 m are shown (thin black lines). Two major sources of SO_2 are the Tula industrial complex, ~ 70 km northwest of the center of the MCMA, and the Popocatepetl Volcano, which lies southeast of the center at an altitude of 5,426 m. Outside of visible eruptions, the volcano emits SO_2 continuously with emission rates that vary by nearly an order of magnitude.

deriving better estimates of sources and for improving the "bottom up" emission inventory that had been derived in previous studies. Hourly measurements of both NO_2 and SO_2 from GEO-CAPE would have provided important insight into the photochemical and meteorological processes that often drive the observed surface concentrations. Both of these processes exhibit fundamental diurnal as well as day-to-day variability that cannot be determined from OMI's once-daily overpass (Fishman et al. 2008).

The GEO-CAPE Atmosphere SWG has focused on providing calculations that quantify the variability of trace gases and aerosols present in the atmosphere. Variability is found at all spatial and temporal scales, and GEO-CAPE must be designed to capture the portion of this variability that is important for describing the emission, chemistry, and transport of gases and aerosols in regional and continental domains. The GEO-CAPE instruments must also be capable of providing information to the air quality community at spatial and temporal scales relevant for analysis of high-emission corridors within urban areas, the photochemical cycles involving nonmethane hydrocarbons, nitrogen oxides (NO_x), and O_3, and the variability induced by mesoscale meteorological phenomena (e.g., land/sea breezes). Variability analyses using state-of-the-art regional-scale chemical transport models have been conducted for regions incorporating substantial urban plumes, plume-to-background transition regions, and rural background areas over geographically diverse domains (Fishman et al. 2011). In-depth analyses of the results from these models using various statistical tools have been compared with trace-gas measurements from a number of field missions (e.g., Fehsenfeld et al. 2006; Singh et al. 2006, 2009, and references therein). Results from these studies are being used in developing and supporting the measurement requirements for the integrated tropospheric trace-gas columns as specified in Table 1.

Improvement to measurement capabilities by GEO-CAPE. In the planned configuration, atmospheric observations will be made from a geostationary orbit positioned near 100°W to regularly view the domain extending from 10° to 60°N and from the Pacific to the Atlantic Oceans (Fig. 3). Land and near-coastline regions will be sampled hourly; open ocean regions will be sampled daily. The horizontal product resolution will be approximately 4 km × 4 km in the center of the domain, nominally at 35°N, 100°W. A higher spatial resolution cloud camera will be included to avoid cloud contamination in the retrieved products.

In addition to the ultraviolet (UV), ozone also has absorption features in the visible (VIS) and thermal infrared (TIR) ranges that can provide information on its vertical distribution within the troposphere. Because of its importance in so many aspects of atmospheric chemistry, an accurate measurement of O_3 with as much vertical resolution as possible in the troposphere is desirable. The ability to retrieve concentrations in the lowermost troposphere (LMT) is important for the characterization of pollution sources, and when combined with a free troposphere profile, also allows local production to be discriminated from transported pollution.

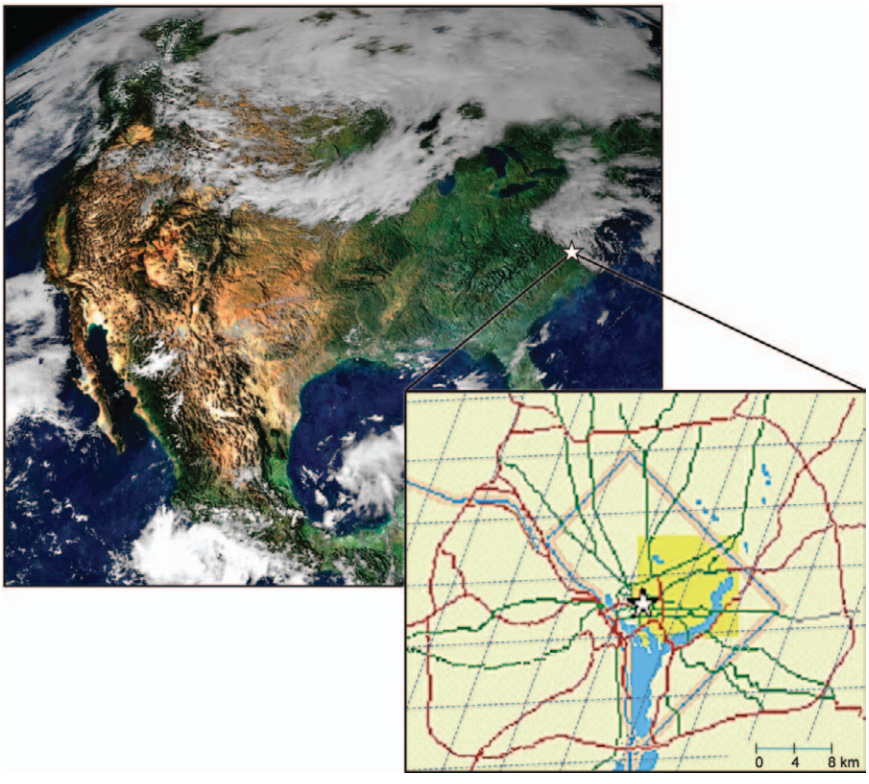

Fig. 3. Approximate field of view from a geostationary orbit positioned above 100°W.

Measurements in different parts of the electromagnetic spectrum have different sensitivities to the gas vertical distribution. In the TIR, measurement sensitivity in the lower atmosphere requires significant thermal contrast between Earth's surface and the near-surface atmosphere. Measurements that rely on reflected solar radiation in the near-infrared (NIR) are often used to obtain total column information from weak spectral features. In addition to total column information, measurement in the visible might be used to provide enhanced retrieval sensitivity to LMT ozone (Natraj et al. 2011) as a result of wavelength-dependent multiple scattering. At the shorter wavelengths of the UV, measurement sensitivity to the LMT is low because of Rayleigh backscatter of the incoming solar radiation as the air density increases in the lower troposphere. These measurements are illustrated schematically in Fig. 4.

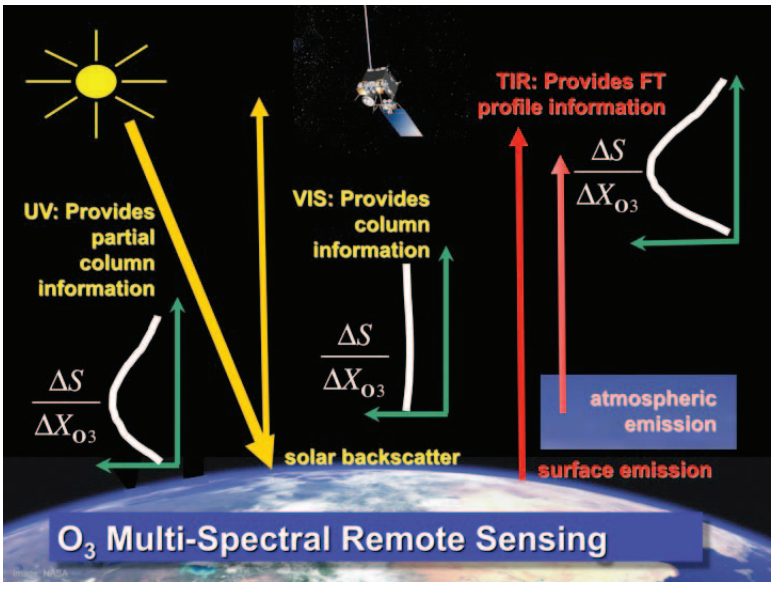

Fig. 4. Illustration of the GEO-CAPE approach to the multispectral measurement of ozone. The three measurements being considered are shown along with representative profiles of the signal *S* sensitivity to the change in ozone mixing ratio at different altitudes.

In general, measurements in the UV have broad sensitivity everywhere except the LMT, while those in the TIR are most sensitive to the free troposphere and above; measurements in the NIR provide total column information that also includes the LMT, while those in the visible portion of the spectrum provide very good sensitivity to the LMT. Together, the UV, visible, and TIR spectral regions have the potential to provide excellent vertical trace-gas information. Although the NIR and VIS measurements are sensitive to the gas concentration in the LMT, the retrieval cannot use these measurements alone to isolate this quantity. The attainment of a trace-gas quantity in the LMT is achieved through a multispectral approach that will be used by GEO-CAPE to provide daytime information on CO and potentially O_3.

Natraj et al. (2011) examined the capability of different spectral combinations to retrieve ozone from a geostationary platform and found that a UV + VIS + TIR combination can provide up to three independent pieces of information on the vertical ozone profile with sensitivity below 800 hPa. Their synthetic retrievals have been used by Zoogman et al. (2011) in an observing system simulation experiment (OSSE) to quantify the usefulness of such a geostationary instrument to constrain surface ozone. They show that UV + VIS + TIR observations greatly improve the constraints on surface ozone relative to measurements in the UV, VIS, or TIR alone, and that UV + VIS or UV + TIR also provides substantial improvement compared to the UV-only scenario. Observation in the TIR is necessary to quantify ozone in the upper troposphere where it is a powerful greenhouse gas.

Ocean measurements. Current measurement capabilities. The coastal ocean is where the land and ocean exchange materials and where atmospheric deposition of dust, nutrients, and pollutants occurs (e.g., Poor 2002; McKee 2003; Salisbury et al. 2004). Although continental margins (<2000-m water depth) occupy only 14% of the ocean surface area, they contribute to >40% of the carbon sequestration in the ocean (Muller-Karger et al. 2005). Predicting how coastal productivity and carbon sequestration will be perturbed by future climate variability remains a great challenge to the scientific community.

The GEO-CAPE mission will provide a time series of observations at sufficient spatial and temporal resolutions to document long-term trends and short-term variability, study anthropogenic and climatic influences, and understand processes taking place in coastal ecosystems. Indeed, tremendous success has been achieved using existing polar-orbiting satellite instruments for managing fisheries, assessing coral reef environment, establishing nutrient criteria for coastal and estuarine waters, and mitigating impacts of harmful algal blooms (HABs; e.g., Platt et al. 2003, 2008). The enhanced capacity of GEO-CAPE to

observe short-term variability at a higher spatial resolution will provide unprecedented data to address various science and management questions (e.g., see Fig. 5)

The coastal ocean ecosystem data products that will be generated from GEO-CAPE observations are described in Table 3 and classified as either mission critical or highly desirable and also in terms of the maturity of the products based on current ocean color retrievals: climate data record (CDR), candidate CDR, research products, and exploratory products. Many of these products have been derived using instruments from LEO, such as Sea-viewing Wide Field-of-View Sensor (SeaWiFS) and MODIS, and the goal of GEO-CAPE is to improve upon these proven retrieval capabilities and to expand our current product suite.

The societal benefits of ocean color measurements have been extensively detailed in reports 7 and 8 of the International Ocean Color Coordinating Group (IOCCG; Platt et al. 2008; Forget et al. 2009). As addressed in those reports and numerous other documents cited therein and elsewhere, ocean color observations can be utilized to support a number of important research and applied or operational efforts, such as assessments of climate variability and change through improved understanding of biogeochemical cycles and food web impacts, integrated ecosystem assessments and living marine resource management, coastal and inland water quality monitoring, natural and anthropogenic hazards assessment, improved understanding of ocean and coastal dynamics, development of robust indicators of the state of the ocean ecosystem, and ecological modeling and forecasting activities.

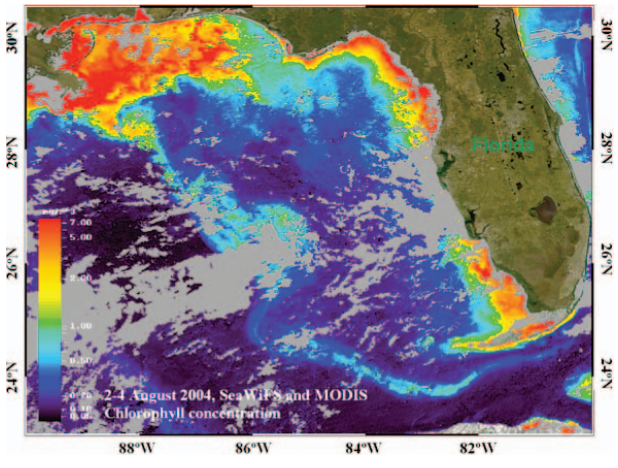

Fig. 5. Composite image of surface ocean chlorophyll-a concentration from SeaWiFS and MODIS between 2 and 4 Aug 2004 showing the Mississippi River plume meandering through the eastern Gulf of Mexico and Florida Straits to the Atlantic Ocean. How riverine materials transform, exchange with the ocean waters, and affect the ocean's biogeochemistry remains largely unknown. The prevailing cloud cover prevents any study of the short-term variability; such difficulty may be circumvented by the GEO-CAPE mission.

In support of IOCCG efforts, ocean color observations from a geostationary platform such as GEO-CAPE will provide significantly improved temporal coverage of nearshore coastal, adjacent offshore, and inland waters, and likely improved spatial and spectral coverage relative to current LEO sensors, which are generally more focused on global observations of open ocean waters. The higher-frequency observations from GEO-CAPE will help mitigate the effects of cloud cover, as well as better resolve the dynamic, episodic, and/or ephemeral processes, phenomena, and conditions commonly observed in coastal regions. A denser and more comprehensive ocean color dataset will result, allowing for further development, use, and operational implementation of more timely and accurate products, for example, harmful algal bloom forecasts. This, in turn, will provide better information to users in support of management and decision/policy-making needs.

Each year, huge quantities of oil and petroleum products enter the sea, land, and groundwater (NAS 2003). Monitoring of oil spills at sea is critical in assessing the spill's characteristics, fate, and environmental impacts. Satellite instruments applied for spill monitoring include optical, microwave, and radar [e.g., synthetic aperture radar (SAR)] sensors, each having its own advantages and disadvantages (Fingas and Brown 1997, 2000; Brekke and Solberg 2005). Although SAR is perhaps the most often used, it suffers from high cost, a lack of coverage, and difficulty in differentiating oil from other suspicious features (Alpers and Espedal 2004). Most importantly, the only SAR signal is the dampened surface backscattering resulting from modulation of the oil slick/film to surface waves, which is difficult to use for thickness estimates. Optical instruments provide alternative means that can potentially overcome these difficulties. The use of optical remote sensing to detect oil spills has a substantial heritage (e.g., Macdonald et al. 1993). Hu et al. (2003) first demonstrated the advantage of using MODIS for spill monitoring in a turbid lake.

The Deepwater Horizon event in the Gulf of Mexico in spring and summer 2010 (Fig. 6) presents an example of why a geostationary, well-designed ocean color sensor is required. GEO-CAPE will provide continuous observations during the day, which can improve spatial and temporal coverage. More importantly, multiple

Table 3. Classification of satellite data products for GEO-CAPE coastal ocean ecosystem dynamics. Mission critical: products that drive measurement and instrument requirements. Highly desirable: products relevant to addressing mission science questions but not critical because the retrieval algorithm and/or field/laboratory measurement is not mature. The maturity level of the satellite product is also included.

Ocean products	Product maturity[a]
Mission critical	
Spectral remote sensing reflectances[b]	CDR[c]
Chlorophyll-a	CDR
Diffuse attenuation coefficient (490 nm)	CDR
Inherent optical properties and products: colored dissolved organic matter (CDOM) absorption; particle absorption and scattering; phytoplankton and detritus absorption and scattering	CDR candidates
Euphotic depth	CDR candidate
Photosynthetically available radiation (PAR)	CDR candidate
Fluorescence line height (FLH)	CDR candidate
Primary production	CDR candidate
Suspended particulate matter (SPM)	CDR candidate
Particulate inorganic carbon (PIC)	CDR candidate
Particulate organic carbon (POC)	CDR candidate
Dissolved organic carbon (DOC; coastal)	Research
Phytoplankton carbon	Research
HAB detection and magnitude	Research
Functional/taxonomic group distributions	Research
Highly desirable	
Particle size distributions and composition	Research
Phytoplankton physiological properties (fluorescence quantum yields, etc.)	Research
Trichodesmium concentration	Research
Other plant pigments (carotenoids, photoprotective pigments, photosynthetic pigments, phycobilins, etc.)	Research
Beam-c	Research
Net community production of POC	Exploratory
Net community production of DOC	Exploratory
Export production	Exploratory
Petroleum detection, type, and thickness	Exploratory
Terrigenous DOC	Exploratory
Photooxidation	Exploratory
Detection of vertically migrating species	Exploratory
pCO_2(seawater)	Exploratory
Air–Sea CO_2 fluxes	Exploratory
Respiration	Exploratory

[a] CDR algorithms are the most mature followed by CDR candidate, research, and exploratory algorithms. Research products are those with validated algorithms discussed in the scientific literature. Exploratory products represent products for which algorithms are under development or have not been studied thus far.

[b] All other ocean products listed are derived from the remote sensing reflectances.

[c] "The NASA Earth Science Division has focused on data sets creation for particular Earth science research measurement needs, and has defined a term for data sets to be used these needs: Earth System Data Records (ESDRs), including Climate Data Records (CDRs). An ESDR is defined as a unified and coherent set of observations of a given parameter of Earth system, which is optimized to meet specific requirements in addressing science questions. These data records are critical to understanding Earth System processes, are critical to assessing variability, long-term trends and change in Earth System, and provide input and validation means to modeling efforts" (see http://science.nasa.gov/earth-science/earth-science-data/Earth-Science-Data-Records-Programs/).

observations from the same instrument with better wavelength resolution will provide potential capabilities to derive information on oil thickness and type as well as the capability to differentiate oil from other features. Combined with the cloud-free and higher-resolution ancillary observations, such as from SAR, as well as targeted ground-truthing measurements, GEO-CAPE should provide completely novel information on oil slicks and, therefore, significantly enhance our capability in spill monitoring.

Improvement to measurement capabilities by GEO-CAPE. Ocean color instruments on geostationary platforms will provide unprecedented opportunities to monitor oil spill and other oil pollution events. Among the challenges posed by satellite observations of water-leaving radiances from coastal waters is their small contribution to the total radiant energy flux at the top of the atmosphere (TOA). Signals from oceans generally contribute <10% to the total flux, but the presence of colored dissolved organic material and absorbing particles in coastal waters can reduce this reflectance to <1% of the total signal (Wang 2010). As a result, it is imperative to correct the total signal adequately for various atmospheric and ocean contributions. Indeed, this was the motivation of the NRC (2007) for combining the AQ and OC objectives from geostationary orbit into one mission: to enable optimal aerosol corrections to the OC retrievals. In highly urbanized coastal zones, correcting for near-real-time aerosol distributions and concentrations of trace gases, such as O_3 and NO_2 as well as water vapor, is critical, especially to avoid an atmospheric signature imposing a false impression of temporal and spatial variability within coastal waters.

A primary challenge of atmospheric correction (also the main source of uncertainty) is accurately removing the aerosol effect from the sensor-measured TOA radiance spectra data (Wang 2010). The aerosol effect on the derived ocean color products has been studied extensively (e.g., Gordon and Wang 1994; Gordon 1997; Antoine and Morel 1999; Wang 2007, 2010). Results show that for open oceans both SeaWiFS and MODIS have been producing high-quality ocean color products (McClain 2009). However, there are issues for accurate retrieval of water properties in coastal regions, where waters are often optically complex/highly turbid (resulting from river inputs, sediment suspension and resuspension, plankton blooms, etc.), and aerosols from adjacent urban sources are sometimes strongly absorbing. With spectral bands in the UV and shortwave infrared (SWIR) wavelengths, as well as high temporal measurements, GEO-CAPE will significantly improve ocean color data quality in the coastal ocean region.

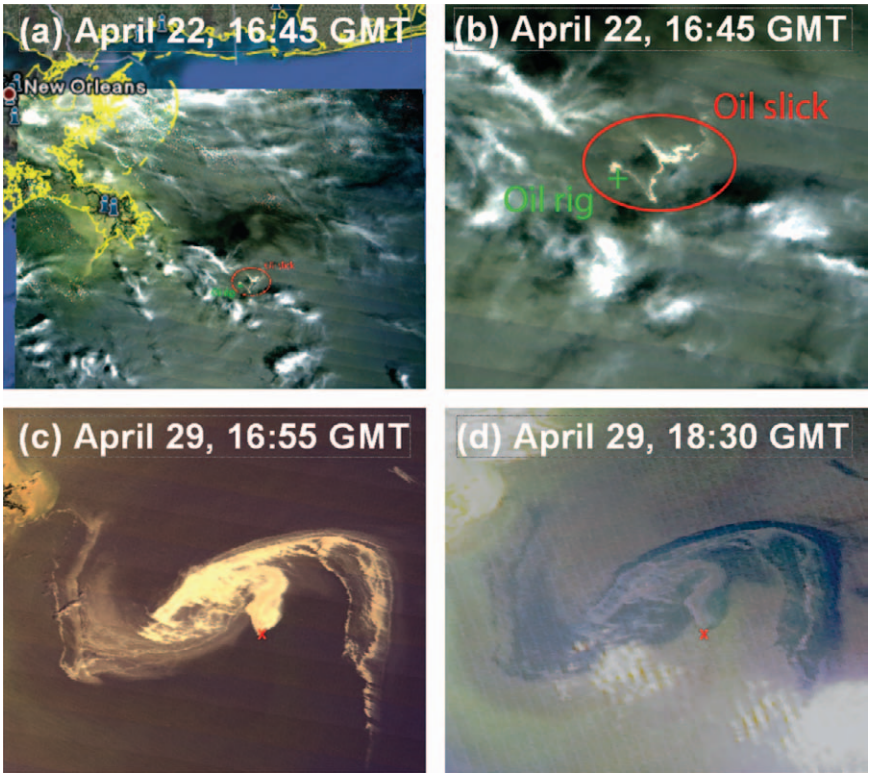

Fig. 6. MODIS 250-m images showing oil slicks in the northern Gulf of Mexico resulting from oil spills from the Deepwater Horizon sunken oil rig (marked as a cross). (a),(b) MODIS image on 22 Apr 2010 overlaid on a Google Earth map shows that the oil rig is approximately 40 km southwest of the Mississippi River mouth. The image shows the oil slick and the surrounding clouds. (c) MODIS image on 29 Apr 2010 (1655 UTC) shows the oil slicks in positive contrast. (d) MODIS image on the same day but at 1830 UTC shows the same oil slicks in negative contrast and no contrast. The horizontal scale of (b)–(d) is about 120 km. GEO-CAPE will provide unprecedented opportunities to monitor oil spill and other oil pollution events with high temporal resolution.

In addition, the quality of other atmospheric data required for satellite ocean color data processing (i.e., total column O_3, H_2O, and NO_2 amounts; sea surface wind speed; and atmospheric pressure) significantly impacts the quality of satellite-derived ocean color products (Ahmad et al. 2007; Ramachandran and Wang 2011). The diurnal and spatial variability of aerosols, O_3, NO_2, and water vapor within the coastal domain may require nearly coincident satellite retrievals of these constituents with GEO-CAPE OC observations for application of appropriate atmospheric corrections to derive the fundamental OC product and water-leaving radiances (or remote sensing reflectances) from which all other OC products are derived.

The Ocean SWG has recommended an ocean sensor that can observe the land–ocean interface, adjacent coastal oceans, and other key regions of interest (see Fig. 7). A geostationary coastal sensor located near 95°W on the equator would image coastal waters off eastern South America and most of Hawaii. Because of the high sensor view angle at the outer regions of the ocean color field of regard (67° sensor view angle), the shape and size of the pixels will be distorted and much larger than at nadir. GEO-CAPE will observe coastal regions at sufficient temporal and spatial scales to resolve nearshore processes, tides, coastal fronts, and eddies, and track carbon pools and pollutants. The following two complementary operational modes will be employed: i) a survey mode for evaluation of diurnal to interannual variability of constituents, rate measurements, and hazards for estuarine and continental shelf and slope regions with linkages to open ocean processes at appropriate spatial scales; and ii) targeted, high-frequency sampling for observing episodic events, including evaluating the effects of diurnal variability on upper-ocean constituents and assessing the rates of biological processes and coastal hazards. GEO-CAPE observations will be integrated with field measurements, models, and other satellite data as follows: i) to derive coastal carbon budgets and determine whether coastal ecosystems are sources or sinks of carbon to the atmosphere; ii) to quantify the responses of coastal ecosystems and biogeochemical cycles to river discharge, land use change, airborne-derived fluxes, hazards, and climate change; and iii) to enhance management decisions with improved information on the coastal ocean, such as required for Integrated Ecosystem Assessment (IEA), protection of water quality, and mitigation of harmful algal blooms, oxygen minimum zones, and ocean acidification.

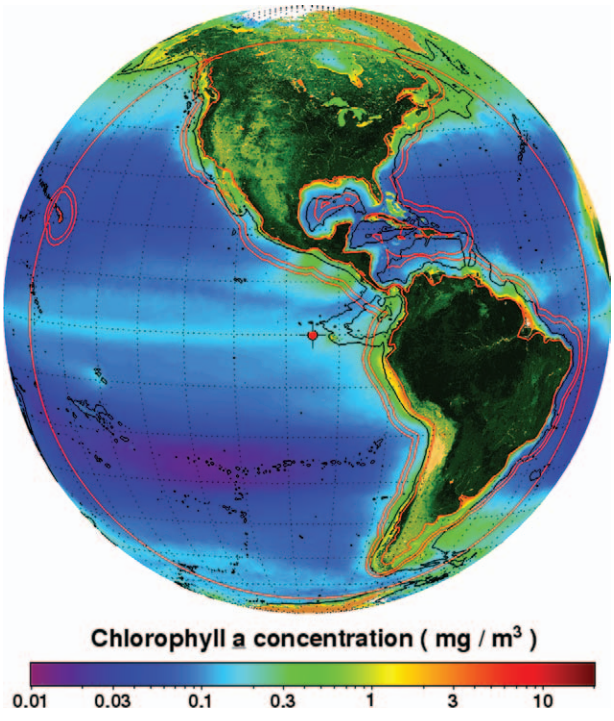

Fig. 7. Geostationary view from 95° W for the GEO-CAPE coastal ecosystem sensor overlain on the SeaWiFS chlorophyll-a mission composite. Much of North and South America region that is encompassed within the 67° sensor view angle is the approximate limit to ocean color retrievals from 95°W (red outer circle). The continental landmasses at 375- and 500-km distances from the inland boundary to the oceans are represented (two red lines). Both lines generally extend beyond the 2,500-m bathymetry of the continental margin (black line). [Image courtesy of Dirk Aurin. SeaWiFS chlorophyll-a data courtesy of the NASA GSFC Ocean Biology Processing Group.]

PROGRESS TOWARD IMPLEMENTATION OF THE GEO-CAPE MISSION. The DS defined GEO-CAPE as a "tier 2" mission that could be implemented with mature instrumentation that had significant space heritage in LEO. The implied mission implementation would be similar to current Earth science missions such as *Terra*, *Aqua*, and *Aura* with multiple instruments on one large spacecraft. Although this implementation approach for GEO-CAPE was studied and found to be technically feasible, the total mission cost would be ~$2 billion. Current funding availability and budget run-outs for the next 5 yr make it unlikely that such an expensive mission could be launched before the next decade (i.e., beyond 2020). Consequently, alternative mission implementation concepts are being studied with the goal of reducing cost and launching sooner while still accomplishing all of the scientific objectives of

GEO-CAPE. The most promising option is to fly instrumentation as secondary payloads on COMSATs. The commercial satellite community is interested in hosting secondary payloads as a way of using excess satellite capacities to generate additional revenues. Implementing the GEO-CAPE mission using this hosted payload approach would significantly reduce risks and cost for accomplishing all of the GEO-CAPE science objectives. Hosted payloads provide the opportunity to leverage a planned or existing satellite bus, launch vehicle, and satellite operations, which would permit GEO-CAPE to be planned and implemented on shorter cycles than typical NASA missions. A hosted payload on a commercial satellite costs a fraction of the amount required to build, launch, and operate an entire satellite. The commercial partner only charges for the integration of the payload with the spacecraft and the marginal use of resources such as power, launch services, and operations. The cost to the hosted payload provider is far below that of deploying an independent, government-owned satellite for the payload. The total cost of implementing the GEO-CAPE mission can be spread out by phasing the development and launches of each instrument. Phased implementation also reduces the overall mission risk. If one instrument fails and the others are not affected, then the recovery cost is only that of building a replacement instrument. If GEO-CAPE is implemented with all instrumentation on a single platform, and there is a mission launch failure like *Glory*, then NASA would have to pay the entire mission cost again to recover.

The phased implementation concept being studied has instrumentation launched on separate satellites. The first launch would be a risk-reduction pathfinder mission in the 2017 time frame to demonstrate that a GEO-CAPE-hosted payload implementation approach is viable programmatically, technically, and scientifically. A significant goal of this mission is to demonstrate that GEO-CAPE science measurements are attainable using a COMSAT-hosted payload. Therefore, the risk-reduction payload must be capable of making GEO-CAPE science measurements, in addition to being low cost and low risk. One concept for this pathfinder payload is an instrument for measuring atmospheric CO. This first segment of a phased mission implementation could be accomplished for a total cost of ~$150 million and would allow NASA to assess the feasibility of using the hosted-payload approach for the remainder of the GEO-CAPE mission implementation.

The hosted payload–phased implementation approach does nothing that precludes switching to a traditional single dedicated mission implementation, so while the risk-reduction mission is in development, the atmospheric science and ocean science instrumentation can also be developed as NASA's budget permits. Follow-on phases of the mission could launch soon after the risk-reduction payload, ideally within 1 yr of each other in order to address synergistic atmospheric–ocean science objectives. The notional instruments envisioned for the later phases would be one or more spectrometers covering the UV + VIS + IR spectral region for continental atmospheric chemistry and a UV + VIS + NIR + SWIR ocean color spectrometer scanning coastal waters of North, Central, and South America.

Global constellations of geostationary atmospheric chemistry and coastal ocean color sensors are a possibility by 2020. ESA and KARI are planning to launch atmospheric UV + VIS capabilities similar to GEO-CAPE's in the 2018 time frame (CEOS Atmospheric Composition Constellation 2011). At present all three missions use the UV–VIS wavelength range from 300 to 500 nm for the products that can be retrieved over that range. GEO-CAPE and ESA's *Sentinel-4*/Meteorological Satellite (Meteosat) Third Generation (MTG) also have the TIR region in common. As requirements mature there may also be other wavelength ranges in common (VIS and SWIR). The combination of geostationary platforms measuring atmospheric composition over the Americas, Europe, and Asia would be a virtual constellation, as recommended by the Atmospheric Composition Constellation of the Committee on Earth Observation Satellites, and fulfill the Integrated Global Observing System vision of a comprehensive measurement strategy for atmospheric composition (IGACO 2004).

GEO-CAPE could contribute to an international effort to achieve global coastal coverage accompanied by high temporal revisits for dynamic regions (IGOS 2006) that will include other regional efforts by the Korea Ocean Research and Development Institute (KORDI) and KARI, such as the recently launched GOCI sensor with follow-on plans for a GOCI-II launch in 2018, as well as interests by European and Indian space agencies to launch geostationary ocean color sensors by 2020. The IOCCG is working to facilitate international coordination and cooperation in this context and established a working group on "Ocean Color Observations from the Geostationary Orbit" that will articulate needs and requirements and evaluate present and planned capabilities with regard to geostationary ocean color observations in support of both research and applications (Antoine 2012).

NASA, through its Earth Science Technology Office, is presently investing in advanced instrument concepts, including a more compact geostationary ocean color instrument and a more capable but still compact spectrometer for atmospheric composition. Successful development of concepts such as these would lower the cost, improve the science capabilities, and potentially influence the sequencing of a GEO-CAPE-phased mission implementation. However, a phased implementation that accomplishes the global constellation capabilities discussed earlier is only possible using the fast cycle time and low cost of commercially hosted payloads.

The GEO-CAPE team continues to refine science requirements; assess instrumentation capability, cost, and risk; and update mission implementation plans. These efforts will support a mission implementation recommendation by the end of 2012 and readiness to conduct a NASA mission concept review (MCR) in 2013. If mission plans and costs are acceptable, and NASA's budget permits, then the GEO-CAPE mission could begin development in 2014. This would enable launches to begin around 2017, with full implementation by 2022. The complete GEO-CAPE mission will provide valuable science information that identifies human versus natural sources of aerosols and ozone precursors, tracks air pollution transport, and studies the dynamics of coastal ecosystems, river plumes, and tidal fronts.

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