GEO-CAPE

GEOSTATIONARY COASTAL AND AIR POLLUTION EVENTS

Advancing the science of both coastal ocean biophysics and atmospheric pollution chemistry: A White Paper report to the NASA Earth Science Division by the GEO-CAPE Team.

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1. EXECUTIVE SUMMARY AND RECOMMENDATIONS

The 2007 Decadal Survey (DS) included the recommendation for the Geostationary Coastal and Air Pollution Events (GEO-CAPE) mission to launch in 2013–2016 to advance the science of both coastal ocean biophysics and atmospheric-pollution chemistry. In 2009 the NASA Earth Science Division (ESD) initiated study activities for GEO-CAPE and 8 other near- to medium-term missions to help determine the readiness of these conceptual missions to begin the formulation phase. For FY15 the GEO-CAPE mission study team was directed to complete this white paper summarizing the results of the pre-formulation work accomplished to date.

GEO-CAPE has fully matured during the 2010–2016 pre-formulation study activities. Early studies confirmed that the mission as recommended in the 2007 DS was at a high level of technology readiness, with launch feasible by 2015, but also found that the 2007 DS cost estimate of $550 million for a dedicated geostationary mission was low by a factor of 2 to 3. Therefore the study team developed a novel mission implementation strategy featuring operation of GEO-CAPE instruments on one or more host geostationary satellites (commercial or government). This strategy reduces mission risk and potentially total mission cost, but most importantly provides programmatic flexibility by allowing smaller components of the mission to be individually initiated as NASA funding profiles allow. The team has completed all other pre-formulation objectives (including developing science traceability matrices to express measurement requirements, conducting field campaigns and other science studies to affirm and refine these requirements, and maturing enhancing technologies) and is now continuing synergistic activities with ESD research, applications, technology, and flight programs.

The selection of the Tropospheric Emissions: Monitoring of Pollution (TEMPO) mission through the Earth Venture Instrument 1 solicitation may be viewed as a first step for the GEO-CAPE distributed implementation strategy. TEMPO has the potential to meet many of the GEO-CAPE atmospheric science objectives and is also a pathfinder for the hosted payload mission strategy. The principal remaining atmospheric measurement objectives can be met by an instrument of comparable cost to TEMPO that makes measurements in infrared wavelengths, as defined in the GEO-CAPE atmospheric science traceability matrix, and use of data from the Advanced Baseline Imagers on the GOES-R/S series satellites. The coastal waters science objectives can be met by a variety of instrument concepts within an instrument cost range of $100–200 million. While full mission cost estimates for the distributed implementation strategy ultimately depend on the commercial market for hosting this class of instruments at the time of selection, the available estimates at this time continue to support a hosted payload implementation rather than a dedicated satellite.

Given this progress, the opportunity now exists to fulfill all GEO-CAPE mission elements in a very cost effective manner by leveraging TEMPO and beginning formulation of two remaining

GEO-CAPE instruments, ideally in time to operate concurrently with TEMPO. In addition, nascent NASA and partner activities to fully enable readiness to use the observations at launch must continue to be fostered. It has also become evident that the value of GEO-CAPE observations will be amplified by being embedded within an integrated observing strategy featuring similar geostationary observations from missions over other parts of the globe combined with low Earth orbit observations to provide full global context. GEO-CAPE study team members have been key participants in international activities to define this potential under the auspices of the Committee on Earth Observation Satellites (CEOS), and as members of mission science teams in Europe and Korea. Data harmonization activities featuring common validation strategies will be essential for providing truly interoperable data products from these satellite constellations. GEO-CAPE study activities have helped define and begin to build the modeling capabilities necessary for realizing these visions.

Specific recommendations follow.

1. Prepare to fully exploit the TEMPO data for air quality over North America by sustaining ongoing activities to improve retrieval algorithms, chemical data assimilation capabilities, diurnal validation strategies, and integrated observing system frameworks (such as observation system simulation experiments).
2. Begin formulation of a GEO-CAPE Infra-Red Instrument (GCIRI) mission, operating concurrently with TEMPO during as much of its mission as possible, to enable fulfillment of the GEO-CAPE atmospheric science objectives, providing in particular the observations of methane and the modeling framework to estimate emissions in support of rapidly emerging U.S. policies.
3. Begin formulation of a coastal ecosystems mission to conduct GEO-CAPE coastal waters science, enabling interdisciplinary GEO-CAPE atmosphere/ocean science objectives when concurrent with the TEMPO and GCIRI missions.
4. Continue to develop mechanisms for engaging air- and water-quality managers and other end-users to aid early adoption of TEMPO and other GEO-CAPE observations and jointly define and implement integrated observing systems including surface validation networks and data assimilation systems.
5. Create formal Constellation Science Teams for Air Quality and Ocean Color, supported by stable funding for U.S. members, to collaborate with international partners in order to mature harmonized, consistent, well-validated interoperable data products from the constellations of geostationary and low-Earth orbit satellites now coming into existence.
6. Given that highly time-resolved observations are the next frontier of Earth science from space, build on the lessons learned from GEO-CAPE study activities by continuing to work with all stakeholders to jointly identify priorities and develop advocacy for sustainable future geostationary observations.

2. INTRODUCTION TO GEO-CAPE

The Geostationary Coastal and Air Pollution Events (GEO-CAPE) mission was recommended by the 2007 National Research Council's (NRC's) Earth Science Decadal Survey (DS) to measure tropospheric trace gases and aerosols, coastal ocean phytoplankton, water quality and biogeochemistry from geostationary orbit, providing continuous observations within the field of view. In 2009 the NASA Earth Science Division (ESD) initiated study activities for GEO-CAPE and 8 other near- to medium-term missions to help determine the readiness of these conceptual missions to begin the formulation phase. The motivation for this document is FY15 guidance received from the ESD Associate Director for Flight Programs "to complete a white paper summarizing the results of the six years of pre-formulation work accomplished by the mission study team." Sections of this document address the specific topics requested, including science objectives and requirements, technology assessment, mission concepts, field campaigns, measurement algorithms, and coordination with other ESD elements.

The 2007 DS defined GEO-CAPE as a Tier 2 mission that could be implemented with mature instrumentation that had significant space heritage in low-Earth orbit (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. The 2007 DS identified two GEO-CAPE instruments for the atmospheric composition, or air quality, objectives: a "UV-Visible-near-IR wide-area imaging spectrometer" and "an IR correlation radiometer for CO mapping over a field consistent with the wide-area spectrometer." At a high level, these instruments would be geostationary versions of the GOME series of instruments on ESA/EUMETSAT MetOp, and MOPITT on NASA's Terra, respectively, with improved spatial resolution over the LEO counterparts. A third instrument in the original 2007 DS definition of GEO-CAPE was "a steerable high-spatial-resolution (250 m) event-imaging spectrometer with a 300-km field of view" for coastal ecosystem science, or coastal ocean color. Ocean color instrument heritage in LEO began with the Coastal Zone Color Scanner on Nimbus-7 and continued with other NASA scanning sensors, SeaWIFS, and MODIS, and an alternate approach with ESA's MERIS, which was a push-broom imaging spectrometer. The full description of GEO-CAPE given by the 2007 DS can be found in Appendix A.

The GEO-CAPE Study Team formed two Science Working Groups (SWGs) to represent its air quality and coastal ocean color disciplines and a Mission Design Coordination Team (MDCT) to coordinate instrument, mission implementation, and technology assessment activities. These groups were designed to engage all GEO-CAPE stakeholders, including multiple NASA centers and organizations, other government agencies, universities, and industry. The Study Team maintains a public website to communicate team accomplishments: *http://geo-cape.larc.nasa.gov*

The SWGs have developed realistic science objectives using input drawn from several community workshops (Table 2-1) and have performed extensive studies to refine requirements and reduce uncertainties, as described in Section 3. The coastal ocean color SWG has recommended a sensor that can observe the land-ocean interface, adjacent coastal oceans that extend to the continental shelf and the open ocean, large inland water bodies, estuaries, and other key regions of interest. The atmospheric composition SWG objectives require routine hourly observations by instruments capable of moderate spatial resolution and high sensitivity to trace gas and aerosol signatures across the UV-Vis-IR. The selection of the Tropospheric Emissions: Monitoring of Pollution (TEMPO) mission in the 2012 Earth Venture Instrument solicitation has had a tremendous positive impact on GEO-CAPE. TEMPO will meet the GEO-CAPE atmospheric science UV-Vis measurement requirements, and it is feasible that an IR instrument operating concurrently with TEMPO can fulfill the GEO-CAPE atmospheric science mission.

Table 2-1. Dates and Locations of GEO-CAPE Workshops Conducted to Date.

Date	Type of Event	Location
August 2008	Open Community Workshop	University of North Carolina, Chapel Hill, NC
September 2009	Open Community Workshop	Columbia, MD
March 2010	Closed Team Meeting	University of South Florida, St. Petersburg, FL
May 2011	Open Community Workshop	National Center for Atmospheric Research, Boulder, CO
May 2013	Closed Team Meeting	NASA Ames Research Center, Moffett Field, CA
August 2015	Open Community Workshop	U.S. EPA, Research Triangle Park, NC

Section 4 discusses mission and instrument implementation considerations, including a variety of efforts led by the MDCT. The notional 2007 DS implementation approach of GEO-CAPE as a single dedicated satellite was studied and confirmed to be technically feasible but more expensive than the 2007 DS estimate. This assessment prompted the Atmospheric Composition and Ocean Color SWGs to work with the MDCT to develop a creative alternative mission concept, using smaller cost-effective instrument designs and a hosted payload implementation, while still meeting the 2007 DS science requirements. The hosted payload approach is expected to significantly reduce risks and cost for accomplishing the GEO-CAPE science objectives. TEMPO is a pathfinder for validating this approach. Several modest-cost instrument concepts are capable of meeting the ocean color measurement requirements and remaining atmospheric science measurement requirements.

Technology Assessment and Development efforts are described in Section 5. These efforts were coordinated with the NASA Earth Science Technology Office (ESTO). During the evolution of the GEO-CAPE mission design, it was confirmed that no new technology development was required to enable the mission architecture. This finding was corroborated by a parallel study by the NASA Systems Engineering Working Group (SEWG).

Section 6 summarizes GEO-CAPE mission development achieved through several field measurement campaigns. These campaigns were able to leverage other ESD Flight and technology development activities (described in Sections 5 and 8). The GEO-CAPE mission has supported two coastal field campaigns collecting an intensive suite of optical, in-water constituent, and biological rate data to provide relevant information for refinement of the measurement and instrument requirements developed by the Ocean SWG. GEO-CAPE has also funded two deployments of the ESTO-funded airborne Geostationary Trace Gas and Aerosol Sensor Optimization (GEO-TASO) instrument, leading to the creation of GEO-CAPE test-bed data sets.

Section 7 presents efforts that have advanced algorithms for retrieval and analysis of both ocean color and atmospheric data. Current coastal ocean color efforts are focusing on applying hyperspectral UV observations and addressing atmospheric correction and sun-sensor geometry issues relevant to discerning diurnal variability from geostationary orbit. While atmospheric trace gas and aerosol algorithms are mature, having been developed and applied to observations from a series of satellites in LEO since 1995, current efforts are focused on accurately discerning variability through the day at the finer spatial resolution that GEO-CAPE will provide.

Section 8 summarizes how GEO-CAPE development activities have been very well aligned and integrated with funded activities from all four NASA ESD program areas: Flight, Research and Analysis, Applied Sciences, and ESTO. The two most significant external activities are the Earth Venture Instrument 1 TEMPO mission and Earth Venture Suborbital 1 DISCOVER-AQ mission. These activities have been of tremendous benefit to GEO-CAPE. ESTO-managed investments are discussed further in Section 5.

Brief closing thoughts and lessons learned are offered in Section 9. The opportunity now exists to complete the three elements of the GEO-CAPE mission defined by the 2007 DS in a timely and cost-effective manner by beginning the formulation of the remaining GEO-CAPE instruments in time to operate in orbit during the lifetime of TEMPO.

3. MISSION SCIENCE REQUIREMENTS AND OBJECTIVES

3.1 Introduction

Most remotely sensed coastal ocean color and atmospheric composition data available today are collected from low Earth orbit (LEO) at most once per day at any given location (twice per day in the special case of the two MODIS instruments flying on the Terra and Aqua satellites). More frequent observations, such as from geostationary orbit (GEO), are necessary to resolve processes with diurnal evolution on appropriate time scales. More frequent observations also improve the detectability of day-to-day variations in processes, and make possible reliable daily retrievals for some products that otherwise require days, weeks or even months of averaging observations from LEO. Observation from GEO further increases the probability of at least some daily cloud free scenes, and improves confidence in cloud detection and clearing approaches. These GEO-CAPE data will have unprecedented temporal and spatial resolution to more accurately guide atmospheric composition and coastal ocean science and policy, including partnerships with environmental managers and operational practices.

U.S. EPA staff in air and water quality assessment and policy, and NOAA operational and research offices in water and air quality participated from the start of GEO-CAPE definition including participation in the first (2008) GEO-CAPE community meeting. Surface-based observations and airborne field campaigns contributed substantially to the definition of GEO-CAPE's requirements. The science and applications communities for both coastal ocean color and atmospheric composition all support the development of data sets with multiple observations each day. The 2007 Decadal Survey (DS) combined Coastal Ocean Color and Atmospheric Composition objectives that could be met from GEO, despite different observing locations and strategies. The science communities responded to the challenge to prioritize the many objectives of the 2007 DS-defined GEO-CAPE mission to be responsive to cost, schedule, and NASA Earth Science Division (ESD) program realities. Ultimately, both the Atmospheric Composition and Coastal Ocean Color Science Working Groups (SWGs) concluded that the instruments for air quality and coastal ocean color are not required to be on the same satellite.

3.2 Coastal Ocean Color

3.2.1 Coastal Ocean Color Initial State in 2009

The scientific community has made significant progress in applying ocean color observations from CZCS, SeaWiFS, MODIS, and MERIS (MEdium-spectral Resolution Imaging Spectrometer; ESA) to understand phytoplankton and carbon cycling at global and regional scales. Ocean color satellite records from SeaWiFS and MODIS-Aqua have provided climate quality monthly records of clear blue water chlorophyll-a and remote sensing reflectances since 1997. These observations have permitted the derivation of long-term trends in chlorophyll-a (proxy for phytoplankton biomass) and estimates of phytoplankton productivity for the global ocean. The radiometric uncertainties (sensor capabilities and atmospheric correction challenges), small set of multi-spectral bands (8 to 10 Vis-NIR bands), moderate spatial resolution (~1 km nadir to >4 km at edge-of-scan), and LEO circumstances (single imaging opportunity per location each day and cloud cover impacts, see Figure 3-1) have impeded the potential scientific advances of ocean color satellite observations.

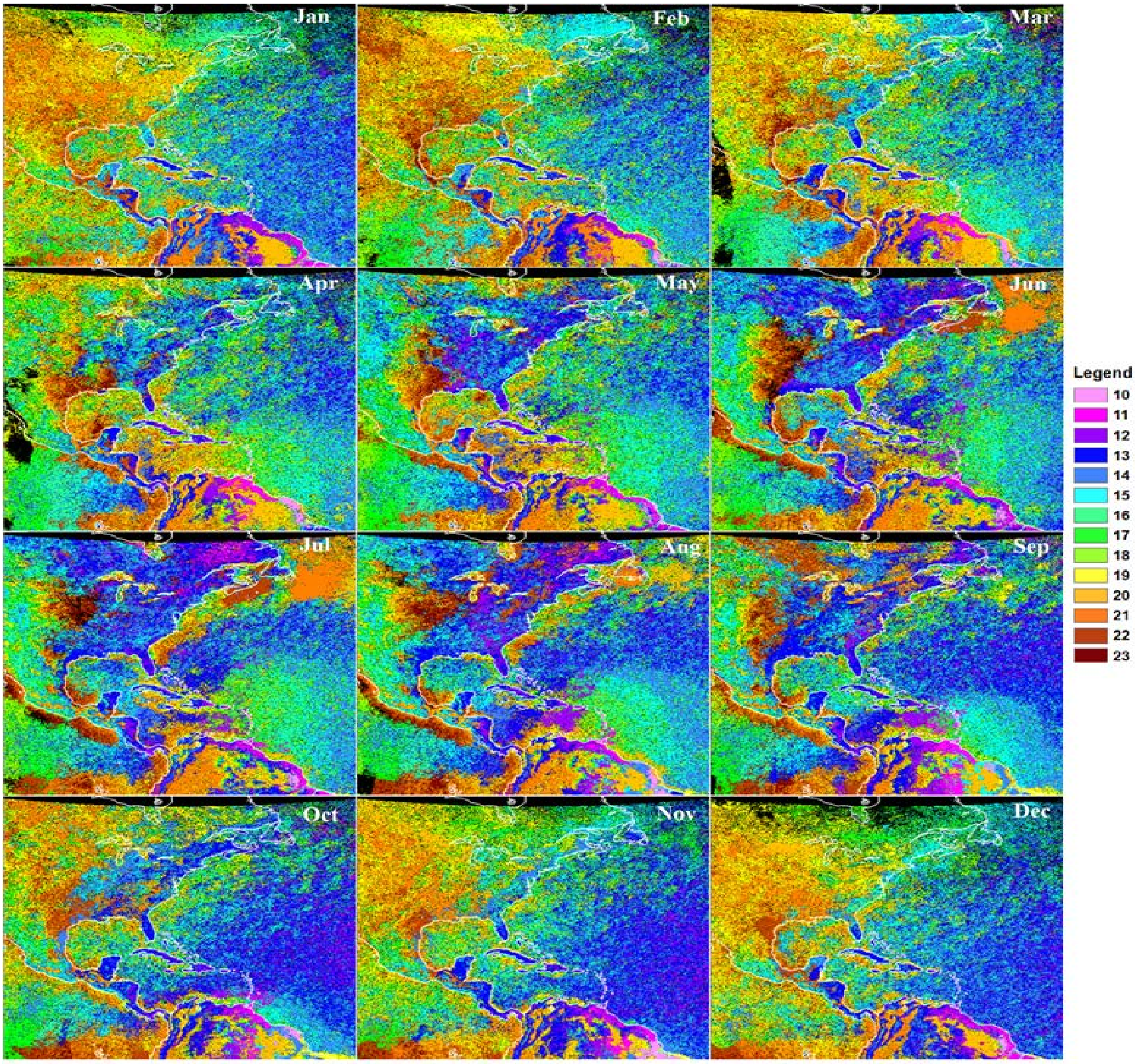


Figure 3-1. Impact of cloud cover. GMT hour corresponding to maximal cloud-free and glint-free probability during a day for each climatological month (2006–2010) for solar angle $\theta_0 < 80^o$. Glint-free is defined as $L_{gn} < 0.005\ sr^{-1}$. GOES-E cloud analysis shows that the time-of-day for maximum cloud-free condition varies considerably from location to location, supporting the need for geostationary sensor capabilities to image any area at any time of the day to maximize spatial coverage of cloud-free pixels (analysis by Feng, Hu, and Barnes).

Despite accomplishing remarkable science, heritage LEO sensor capabilities are inadequate to address the key scientific questions of the ocean biology and biogeochemistry community (NASA OBB 2007) because coastal and open ocean waters are dynamic in both time (diurnal) and space (sub-km).

The 2007 DS called for a steerable high spatial resolution (250 m) event-imaging spectrometer with a 300-km field of view: "A primary objective for observing coastal ocean regions is to determine the impact of climate change and anthropogenic activity on primary productivity and ecosystem variability (NRC 2007)."

A GEO-CAPE coastal waters sensor would observe time and length scales not covered by past and current sensors or planned missions such as PACE (see Figure 3-2, below). GOCI I and GOCI II are present and planned Korean geostationary coastal sensors that image the area surrounding the Korean peninsula with full disk capability on the GOCI II sensor. The Korean sensors will not observe coastal waters in North or South America.

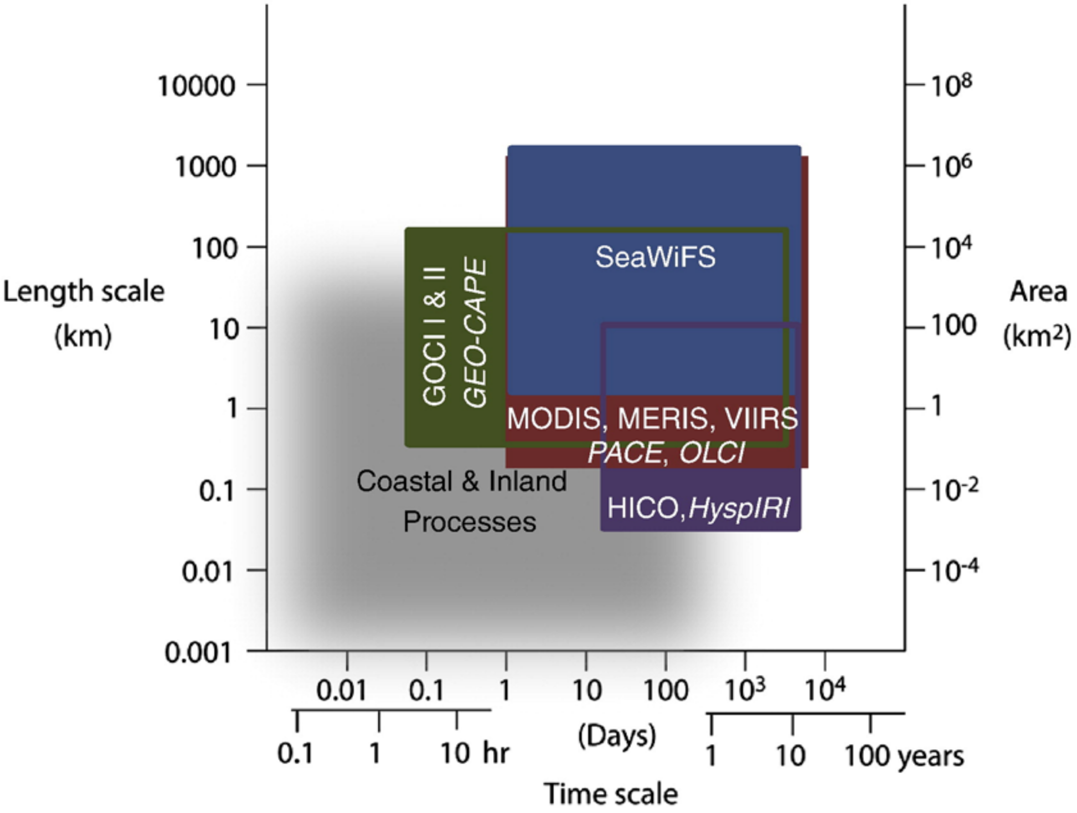


Figure 3-2. Comparison of GEO to other ocean color sensors on the spatial length and time scales of coastal and inland processes in relation to heritage, as well as to current and planned aquatic color sensors (SeaWiFS, MODIS, MERIS, VIIRS, HICO, GOCI, OLCI) and missions (PACE/ACE, GEO-CAPE, HyspIRI). Planned sensors and missions are italicized (Mouw et al. 2015).

3.2.2 Coastal Ocean Color Accomplishments 2009–2015

In addition to GEO-CAPE's multi-center Mission Design Coordination Team (Section 4), both coastal ocean color and atmospheric composition established SWGs of roughly 40 experts to lead GEO-CAPE pre-formulation efforts in their respective fields. The OSWG largely operated as a "committee of the whole" in which all members participated in all activities (Table 3-1).

Table 3-1. Ocean Science Working Group Activities and Accomplishments (2008–2015).

Activity	Objective	Accomplishment
Science Traceability Matrix (STM)	Define the high priority coastal ocean biology and biogeochemistry science questions, approach, measurement and instrument requirements.	3.2.2.1; Appendix B; STM white paper (in revision)
Applications Traceability Matrix	Identify the applications requirements of other government stakeholders. Match compatibility	3.2.2.1
Interdisciplinary Science	Identify and describe topics of coastal ocean-atmosphere interactions.	3.2.2.5; interdisciplinary white paper
Field Campaigns	Reduce mission risk by collection & analysis of *in situ* measurements to refine STM measurement and instrument requirements.	§6.2; §7.2
Science Value Matrix	Quantify value of science objective.	3.2.2.4
International collaboration	Korean Institute of Science and Technology; European science teams developing geostationary ocean color missions	Access to GOCI L1 data; Awaiting Korean ministry approval to distribute GOCI data to NASA investigators. Working towards a quasi-global constellation of geostationary ocean color sensors.
Recommendation and Prioritization of Science and Engineering Studies	Identify gaps in knowledge and address through scientific and engineering studies; Improve TRL	§3.2.3; §6.2; §7.2 More than 70 GEO-CAPE ocean color-relevant publications by OSWG members. §4; Table 4.1

3.2.2.1 Evolution of Coastal Ocean Color Science Requirements

While the original combination of atmospheric and ocean color measurements onto a single platform was suggested to be beneficial for atmospheric correction needed for the ocean color data production, it quickly became apparent that the viewing locations and strategies of the two science communities were not sufficiently matched. While the atmospheric composition observations require a systematic observing strategy with frequent and regular observations of cities and other land-based targets, viewing very little ocean area, the coastal ocean observations require both a systematic and a targetable episodic observing capability with a primary focus over water. In addition, the Atmospheric Composition Working Group (ASWG) conducted a trade that found air quality observations of North American Pacific coast population centers would be significantly degraded if the field-of-regard encompassed both North and South

America and adjacent coastal waters, eventually deciding to require North American observations only. However, the Coastal Ocean Color Science Working Group (OSWG) identified several regions of special interest along the coast of South America with ecological and biogeochemical significance (Amazon and Orinoco River coastal plumes, Peruvian upwelling, Patagonian shelf). Given those constraints, the OSWG determined that the coastal ecosystems instrument may be designed with native capability for atmospheric correction due to NO_2 and aerosol, reducing dependence on other GEO-CAPE instruments. Thus, the use of separable, distributed payloads with an overall strategy for accomplishing all GEO-CAPE objectives was accepted as a possible path forward.

By improving upon the temporal resolution planned in 2009 (from 3 hours threshold to <2 hours), GEO-CAPE will enable studies of harmful and non-harmful algal blooms, evaluation of the impacts of short-term physical processes (tides and eddies) on the biology and biogeochemistry of coastal waters, estimates of riverine and coastal fluxes of carbon, nutrients and sediments, estimates of phytoplankton primary production with lower uncertainties, estimates of surface oil films, tracking of the origin and evolution of hazardous events more effectively, and more precise assessments of impacts.

While the GEO-CAPE Coastal Ecosystem Imager continues to require high spatial resolution to resolve near-shore processes, fronts, eddies, and track carbon pools and pollutants, the OSWG has relaxed the spatial resolution recommended by the 2007 DS to optimize the science return versus cost (including the cost of achieving precision pointing). The OSWG has also invested significant effort in refining the spectral coverage and spectral resolution requirements to achieve ocean data products, including atmospheric NO_2 retrieval for atmospheric correction.

The observing strategy is envisioned as a combination of a Survey Mode (systematic observations) for evaluation of diurnal, seasonal and interannual variability in U.S. coastal waters and Regions of Special Interest and Targeted Observations of high-frequency and episodic events including evaluation of tidal and diurnal variability.

The OSWG updated the STM on a routine basis as new scientific and engineering findings became available. Significant changes to the STM occurred in late 2011 to incorporate results of the CEDI (Coastal Ecosystem Dynamics Imager) study performed in the Instrument Design Lab at GSFC, as well as the results of a line-of-sight pointing study, informal instrument Request for Information (RFI), and GEO-CAPE science studies. By the end of 2012, completed and on-going science studies defined a threshold temporal resolution requirement of ≤ 3 hours with ≤ 1 hour desirable. A spatial resolution of ≤ 375 x 375 m was identified, with a baseline (goal) resolution of ≤ 250 x 250 m. It was articulated that uncorrected atmospheric variability due to aerosols and NO_2 will lead to false estimates of time-dependent underwater processes. Typical, at-sensor radiances and SNR recommendations were published (Hu et al. 2012). An optimal number of spectral bands (if not hyperspectral continuous bands) in the visible-IR domain were specified (Lee et al. 2014). Additional studies allowed for specification of spectral resolution of 0.8 nm (sampling of 0.4 nm), at least in the 400-450 nm range, for NO_2 correction. Furthermore, a correction for absorbing aerosols to retrieve normalized water leaving radiance in regions impacted by absorbing aerosols was deemed desirable but would require the retrieval of additional aerosol properties (single scattering albedo (SSA) and aerosol layer height).

Based on the results of instrument design efforts, science studies, and two field campaigns (see Section 6.2), the STM was most recently revised in July 2015. The temporal resolution requirement has been tightened for the US Coastal survey objective, to a threshold value of ≤2 hours, with the baseline requirement remaining at ≤1 hour. In addition, the desired orbit position has been adjusted from 95° W to 94°±2° W (threshold) and 94°±1° W (baseline) longitude. The Measurement, Instrument, and Platform Requirements determined by the SWG are captured in the Coastal Ocean Color STM shown in Appendix B.

A coastal ocean color Applications Traceability Matrix (ATM) has also been created by the OSWG, with considerable input from a variety of stakeholder agencies. The OSWG prepared a White Paper describing and justifying STM and ATM and requirements, which will be published as a NASA Technical Memorandum. This document also includes application agency requirements based on inputs from NOAA, EPA, the U.S. Navy, Bureau of Ocean Energy Management, and the U.S. Army Corps of Engineers.

3.2.2.2 Oceanographic Campaigns

In July 2011, the Chesapeake Bay Oceanographic campaign with the Earth Venture Suborbital Mission DISCOVER-AQ (CBODAQ) was performed with the primary goal of obtaining detailed atmospheric and oceanographic observations for characterizing short-term dynamics and spatio-temporal variability in atmospheric and coastal ecosystem processes in order to better constrain GEO-CAPE requirements (Additional information can be found at: http://neptune.gsfc.nasa.gov/osb/index.php?section=250, and at http://www.nasa.gov/topics/earth/features/chesapeake-quality.html).

A second field experiment was designed to enable a more thorough understanding of temporal and spatial coastal ocean color mission requirements and to collect data sets that could be analyzed to address exchanges across the land/ocean interface. This experiment, named NASA GOMEX, was conducted in the northern Gulf of Mexico from September 9–22, 2013. GOMEX addressed a wider dynamic range of river plumes and coastal ocean conditions (turbid river water to clear Gulf waters) compared to CBODAQ.

Data analysis and data synthesis from these experiments continue, and the measurements collected have been submitted to NASA SeaBASS (http://seabass.gsfc.nasa.gov/) for archiving. Section 6.2.2 contains additional detail on these GEO-CAPE field campaigns.

3.2.2.3 Coastal Ocean Color Science Leads Successive Instrument Design Studies

In 2010, GEO-CAPE sponsored an instrument design study to improve upon an existing concept and evaluate the feasibility of scanning U.S. coastal waters three times per day with a spatial resolution of 375 m x 375 m. The resulting CEDI design met the requirements of the STM and identified several areas where additional studies could improve the performance and reduce the mass/volume of the instrument.

Three IDL studies were commissioned by the GEO-CAPE ocean color SWG in FY14: design studies for a Wide-Angle Spectrometer (WAS) and Filter Radiometer (FR) implementations for an ocean color instrument, and a cost scaling exercise to compare the costs of the various implementations studied to date (and variations on them) for implementing different science performance requirements. Details of these studies are provided in Section 4.3.

The intent of these studies was to provide a consistent assessment of instrument capability versus cost for a range of feasible instrument architectures, to aid the SWG in further refinement of instrument requirements in a cost-constrained mission environment. The studies evaluated the cost sensitivities for fundamental science requirements, including spatial and spectral resolution, spectral range, scanning rate and signal-to-noise ratio.

The outcome of these studies is that multiple instrument concepts are capable of achieving GEO-CAPE ocean science requirements within an affordable cost range ($100–200M). All three primary geostationary ocean color instrument types (FR, WAS, and a multi-slit spectrometer, MSS) are viable technologically and from a cost perspective.

3.2.2.4 Initial Assessments of Coastal Ocean Color Measurement Science Value Developed

The Coastal Ocean Color SWG established scientific and measurement priorities to complete development of the Science Value Matrix (SVM). This activity provided insight leading to revisions of the STM. Development of the SVM is ongoing.

3.2.2.5 Assessment of Interdisciplinary Science Potential

Coastal processes are inherently interdisciplinary. The combination of high temporal resolution atmospheric and oceanic observations from GEO-CAPE has the potential to provide datasets that will permit investigation of tightly coupled processes between the atmosphere, land, and coastal waters that influence both coastal aquatic ecosystems and the overlying marine boundary layer air. A draft white paper examining the potential for the future GEO-CAPE data set to advance interdisciplinary science activities across ocean/atmosphere/terrestrial boundaries has been prepared with four goals: (1) to aid the OSWG in evaluating trade-offs involving instrument spectral requirements; (2) to present the scope of interdisciplinary activities to which GEO-CAPE ocean color retrievals are expected to contribute; (3) to stimulate planning for integration of GEO-CAPE ocean color with other remote sensing and in situ data sets and models; and (4) to engage coastal scientists across many disciplines to ensure the GEO-CAPE coastal ocean color sensor is designed to maximize scientific benefit within an acceptable cost framework.

3.2.3 Ongoing and Future Work

Coastal ocean ecology and biogeochemistry requirements for GEO-CAPE have evolved to fit the cost and schedule requirements of NASA's programs. Ocean color instrument design studies at a greater level of technical fidelity would provide clearer trades for requirements versus cost. The 2014 instrument studies were based on a limited optical design effort. Alternative telescope and focal plane designs are possible that would further constrain the size and cost of these three instrument types. Scientific studies addressing the temporal, spatial, spectral, and SNR requirements as well as atmospheric correction, algorithm development for novel products, bidirectional reflectance distribution function (BRDF), and sun-sensor geometry are continuing in the present and future. These engineering and scientific studies are currently providing the basis for further revisions to the STM.

To further constrain the measurement and instrument requirements from GEO, on-going and future studies that address high priority issues defined by the OSWG are needed. These high priority studies include short-term dynamics of physical, biogeochemical and bio-optical processes to inform observations on required temporal frequency; definition of spatial scales of features of interest in the GEO-CAPE time-space domain; and definition of the BRDF of coastal particles with varying solar angles. Such studies will employ existing and new observations of high temporal resolution, high spatial resolution or high spectral resolution field data sets that have an abundant set of associated observations, as well as geostationary observations from GOCI or weather satellites, and observations from high latitude polar orbiters.

The Korean-U.S. Ocean Color (KORUS-OC) field campaign in Korean coastal waters was proposed because the region is directly under the field-of-view (FOV) of GOCI, the first ever and as yet, only, geostationary-based ocean color satellite in operation (launched in June 2009). The KORUS-OC team will collect unique datasets that include both in situ measurements, airborne, and geostationary ocean-color satellite data. KORUS-OC data will be evaluated to determine the limitations of the GOCI sensor on the retrieval of biogeochemical properties and to provide key information on satellite specific issues, e.g., impact of atmospheric corrections, view angle, and diurnal solar radiance variability on the quality of satellite retrievals, which can be applied to further refine the GEO-CAPE coastal ocean color requirements. A key advance provided by geostationary ocean color sensors, which will be evaluated through KORUS-OC, will be the capability to directly quantify diurnal and daily measurements of biological productivity from hourly GOCI observations.

3.3 Atmospheric Composition

3.3.1 Atmospheric Composition Initial State in 2009

The 2007 DS directed atmospheric composition observations from two instruments, one similar to ESA GOME and one to the Canadian MOPITT on NASA's Terra, as described in Section 2. From geostationary Earth orbit, GEO-CAPE will provide observations with the spatial and temporal resolution necessary for studying regional scale air quality and its relation to global atmospheric composition. GEO-CAPE observations of ozone, aerosol, methane, carbon monoxide, and related trace gases are key to co-management of air quality and climate change.

The atmospheric composition science objectives of GEO-CAPE arose from an open community meeting held at NCAR prior to the release of the original 2007 DS (Edwards et al. 2006). This community meeting sought to inform the 2007 DS, and showcased community expertise in surface, airborne and satellite measurements of air pollutants; global and regional chemical modeling; and applications of modeling and measurement tools to public policy. The 2007 DS GEO-CAPE atmospheric composition objectives strongly reflect the community meeting report.

The concept of an integrated observing strategy (based on surface, airborne and space observations of atmospheric composition) had been established in 2004 through international coordination by the intergovernmental group Integrated Global Observing Strategy (IGOS) in their Integrated Global Atmospheric Chemistry Observations (IGACO) report (Barrie et al. 2004). IGOS now operates under the United Nations Educational, Scientific, and Cultural Organization (UNESCO), in close collaboration with the Global Earth Observation System of Systems (GEOSS), the structure that proactively links together existing and planned observing systems around the world and supports the development of new systems where gaps currently exist. GEOSS promotes common technical standards so that data from the thousands of different instruments can be combined into coherent data sets.

The 2006 community meeting at NCAR reviewed and affirmed the goals set forth by IGACO in 2004. While the observation and modeling capabilities of 2004 could not achieve the IGACO goals, the GEO-CAPE community adopted these internationally established goals to guide the 2007 Decadal Survey's GEO-CAPE atmospheric mission definition.

3.3.2 Atmospheric Composition Accomplishments 2009–2015

In addition to GEO-CAPE's ASWG and multi-center Mission Design Coordination Team (see Section 4), ASWG members with relevant expertise further established smaller groups to address specific tasks. The initial ASWG small group structure is defined in Table 3-2.

Table 3-2. Initial Atmospheric Composition Science Small Group Structure (2008–2012).

Group	Objective	Accomplishment
Science Traceability Matrix (STM)	Create and maintain the STM to ensure that the science objectives map appropriately to measurements. This group relies on inputs from groups below.	3.3.2.1
Geophysical Variability	Develop tools and examine horizontal, vertical and temporal gradients in atmospheric composition data at fine measurement scales.	3.3.2.3
Retrieval Sensitivity	Determine capabilities of GEO-CAPE spectral observations and associated algorithms to provide independent information on near-surface composition (vertical resolution).	3.3.2.1
Aerosol Group	Address unique requirements for aerosol observations and retrievals and their impact on atmospheric composition and coastal ocean color science goals.	3.3.2.3

After the community approved and published the atmospheric composition STM (2012), most of the small groups disbanded, with their leaders remaining responsible for the published products. With finite but continued funding, ASWG then formed new small groups to begin to develop capabilities to estimate emissions, as required by the highest priority atmospheric composition Science Question and stated in the STM: **What are temporal and spatial variations of emissions of gases and aerosols important for air quality and climate?**

GEO-CAPE observations will provide snapshots of the abundance of selected key pollutants in the atmosphere. The emissions required for environmental policy are produced by an inversion of an atmospheric model which has assimilated the pollutant observations. Thus, both advanced observations and advanced modeling capabilities are necessary to address the GEO-CAPE Science Questions. The ASWG's new small group structure (see Table 3-3) has begun to develop the necessary analysis capabilities to produce air pollutant emissions and to build preparedness for applications of GEO-CAPE (TEMPO) data.

3.3.2.1 Defined Prioritized Science Questions and Approved Atmospheric Composition Science Traceability Matrix (STM)

In 2010, GEO-CAPE's ASWG developed key Science Questions for the mission, and set their priority order. The GEO-CAPE Atmospheric Composition Science Questions are provided in Appendix C as the first column of the STM. GEO-CAPE's atmospheric composition Science Questions address significant atmospheric composition data gaps, demonstrate synergies with the international constellation of GEO atmospheric composition missions, and establish fundamental progress in understanding emissions, tropospheric chemistry and transport at a time when human activity is quantitatively changing the atmosphere.

The STM atmospheric composition Science Questions drove the definition of measurement objectives and subsequent measurement requirements. Atmospheric composition measurement

Table 3-3. Present Atmospheric Composition Science Small Group Structure (2012–present).

Group	Objective	Selected Achievements
Aerosol	Evaluate aerosol retrieval algorithms, information content with available GEO and LEO satellites, air-borne remote sensing measurements, and synthetic TOA radiance Assess the aerosol product availability and quality from multi-instrument/multi-platform (TEMPO+GOES-R) synergy	Generated retrieval products using MODIS MAIAC (multiangle implementation of atmospheric correction) algorithm over the U.S. for algorithm and product evaluation Published observation-based assessment of TEMPO and GOES-R synergy for aerosol retrievals and value to constellation observations (Wang et al. 2014) Tested sensitivity of retrieving aerosol absorption and type from UV and blue spectral measurements Developed algorithm for retrieving aerosols with hyperspectral remote sensing measurements (GEO-TASO) Evaluated value of daytime-resolving observation in estimating the aerosol direct radiative forcing
Global OSSE	With international partners, develop capabilities to provide Atmospheric Composition Constellation products	Developed a Nature Run from combined Numerical Weather Prediction/aerosol global models to assess constellation aerosol product capability (da Silva et al. 2014) Described capability of satellite and EPA surface ozone observations to identify local and distant sources of ozone and precursors (Bowman 2013; Huang et al. 2013b) Conducted first OSSE for GEO observations of CO over USA, Europe and Asia using computationally economic scene-dependent Observation Simulator with accurate representation of vertical sensitivity. Captured near-surface pollution emissions in each region and the importance of long-range transport between the regions (Barré et al. 2015).
Regional-Urban OSSE	Develop multiple species data assimilation for GEO-CAPE atmospheric composition multi-instrument configurations (TEMPO + GCIRI)	Demonstrated methodology and evaluation of the current data assimilation system with coupled meteorology and multi-platform chemistry data assimilation (Barré et al., in press) Multi-spectral O_3 OSSE progress: Baseline Regional (12km) and Urban (1, 4km) WRF-CHEM runs generated background error covariances. Completed full forward model for subset of CONUS profiles, full diurnal cycle for UV, VIS, IR spectra at all sites for 10 days in July 2011. Limited by computational resources Completed multi-spectral retrievals for ozone OSSE study; generated averaging kernel regression to extend training set to entire North America
Emissions and Processes	Assess the improvement in understanding emissions and processes for the full suite of GEO-CAPE observables.	Assessed anthropogenic VOC emissions using satellite retrievals of HCHO (see Section 7). Evaluated and optimized regional chemical-transport model with field campaign and LEO observations (Follette-Cook et al. 2015) Reviewed current emissions estimation capability; identified special value GEO-CAPE observations; recommended techniques that enhance the usefulness of current retrieval capability (Streets et al. 2013)
Methane Emissions	Determine the ability of GEO-CAPE (GCIRI) to quantify methane emissions at a county scale.	Quantified the error reduction in CH_4 emissions estimates following assimilation of synthetic observations from multiple geostationary instruments (Bousserez et al. 2015)

requirements were not flowed to instrument requirements because the GEO-CAPE community actively developed several different instrument implementations, each of which could achieve GEO-CAPE atmospheric measurement requirements in the relevant spectral regions. The atmospheric instrument concepts are briefly described in Section 4, and their high technical readiness was confirmed by activities discussed in Section 5.

GEO-CAPE's Science Questions can be addressed with realistic measurement objectives that are based on measurement techniques demonstrated by more than a decade of LEO observations. Current and planned LEO observations complement GEO-CAPE's time-of-day resolved observations. Together, GEO and LEO satellite, surface, and suborbital observations form the necessary integrated observing system. ASWG endorsed the baseline requirements of the STM (Fishman et al. 2012) and clarified aerosol/cloud requirements. GEO-CAPE's atmospheric composition Science Questions and STM have been stable since 2011.

3.3.2.2 Established U.S. Role in International Atmospheric Composition Constellation

With the strong participation of Korean (GEO-KOMPSAT-2B), European (Sentinel-4), Canadian, Argentine, and Japanese teams with similar scientific needs and similar observation strategies, GEO-CAPE assisted the evolution of planned atmospheric composition observations into a global constellation of geostationary air quality observations, now identified as the Committee on Earth Observation Satellites (CEOS) Atmospheric Composition Constellation (ACC).

The GEO-CAPE ASWG recognized the value of continued international partnerships for creating virtual constellations to achieve global coverage and to leverage international scientific investments. With other international scientific teams, the GEO-CAPE ASWG developed a position paper describing such a virtual air quality constellation (CEOS 2011) and submitted this paper to the CEOS Strategic Implementation Team-26. CEOS, the primary forum for international coordination of space-based Earth observations, endorsed the Atmospheric Composition Constellation concept and the recommendations for harmonizing a GEO-CAPE air quality mission with European and Asian geostationary air quality missions to enable global air quality science and applications. NASA support for U.S. participation in these missions sustains atmospheric science, algorithm, and calibration/validation capability.

3.3.2.3 Demonstrated Realistic Requirements Based on Existing Surface Network Capability, Airborne Data, and Satellite Performance

GEO-CAPE used existing and planned measurements to demonstrate that the atmospheric composition STM requirements are appropriate and can be met.

GEO-CAPE's required near-surface atmospheric measurement sensitivity can be achieved with multi-spectral measurements and multi-spectral retrieval techniques. GEO-CAPE's requirements for multi-spectral carbon monoxide (CO) measurements are built upon MOPITT capability to determine air pollution emissions and trace vertical transport up and away from sources on Earth's surface (Worden et al. 2010). Natraj et al. (2011) showed that near surface sensitivity for ozone would be achieved for the first time in GEO-CAPE through traditional UV and/or IR measurements combined with observation in the weak Chappuis (visible) bands. Further studies using existing LEO data showed that multi-spectral, multi-instrument O_3 retrieval from TES (thermal infrared) and OMI (UV-Vis) can quantify near surface ozone variations (Fu et al. 2013), and that joint CO and ozone retrievals improve surface ozone information (Zoogman et al. 2013b). Analysis of aerosol data from EPA's surface AERONET, NASA MODIS, NOAA GOES, and JAXA GLI shows that hourly GEO-CAPE aerosol extinction and absorption observations will increase the accuracy of aerosol radiative forcing estimates compared to current capability.

Analytical studies demonstrated that GEO-CAPE methane (CH_4) observations, designed to identify North American methane emission hotspots and features approaching the 10 km spatial scale, improve upon methane emissions estimates presently achievable from LEO (Bousserez et al. 2015). GEO-CAPE's dense coverage would enable first-ever observations to constrain the emissions and photochemistry of point and regional sources of NOx (including lightning), ammonia associated with agricultural activities, and SO_2 associated with industrial activities. GEO-CAPE expanded the use of the ground based PANDORA spectrometer at permanent surface sites (e.g., CAPABLE, Knepp et al. 2013) and during field campaigns.

Analysis of observations from the NASA Earth Venture Suborbital Project DISCOVER-AQ demonstrated that spatial variability in the real atmosphere supports the GEO-CAPE requirement for 4 km horizontal (center of domain), and that satellite observations require vertical sensitivity in the 0-3 km layer for air quality management applications.

GEO-CAPE supported data analysis for GEO-TASO, an airborne evolution of a NASA Instrument Incubator Project with measurement characteristics similar to TEMPO, during the summer 2014 DISCOVER-AQ campaign (see Section 6). The combined DISCOVER-AQ and GEO-TASO archive provides a rich data set for use in confirming GEO-CAPE instrument requirements, visualizing future GEO-CAPE data, and testing algorithms (see Section 7).

3.3.2.4 Developed a Distributed Mission Implementation Responsive to NASA Program Constraints

While the 2007 DS envisioned GEO-CAPE's instruments together on a single dedicated spacecraft, the overall cost and the operations complexity of multiple scanning instruments and high platform stability requirements drove an assessment of separating high spatial resolution ocean instruments and high spectral resolution atmospheric instruments. The SWGs determined that GEO-CAPE ocean and atmospheric science objectives could be met separately, although opportunities for ocean-atmosphere synergistic science may be reduced. GEO-CAPE's

Mission Design Coordination Team (Section 4) then initiated the definition and evaluation of other mission architectures with potential for lower cost and risk. After thorough review, the GEO-CAPE team fully endorses a distributed mission implementation that can be achieved by flying GEO-CAPE instruments separately as secondary hosted payloads on commercial or government-owned geostationary satellites to accomplish GEO-CAPE science objectives.

3.3.2.5 Assessed TEMPO as an Element of GEO-CAPE's Atmospheric Composition Mission

As part of the distributed implementation strategy, and in keeping with the innovative science goals of NASA's Earth Venture (EV) Program, members of the GEO-CAPE community have independently proposed several investigations for competitive peer review by the EV Program.

In 2012, NASA's EV Program funded the TEMPO proposal from the Smithsonian Astrophysical Observatory. In 2013, NASA HQ tasked the GEO-CAPE ASWG with conducting an assessment of the GEO-CAPE atmospheric composition suite in light of the TEMPO selection. The ASWG concluded that TEMPO achieves most of the science objectives planned for the GEO-CAPE UV-Vis instrument (Appendix C, STM). However, GEO-CAPE requires additional infrared measurement capability to address specific emissions with both air quality and climate impact, such as methane, and carbon monoxide to address air quality transport science objectives.

Thus, the ASWG determined that TEMPO plus a GEO-CAPE InfraRed Instrument (GCIRI) flown in a similar timeframe, and collaboration with NOAA GOES-R/S, will meet GEO-CAPE minimum atmospheric composition science objectives. A minimum GCIRI capability measures the remaining high value GEO-CAPE gas species (column CH_4 and multi-spectral CO) which cannot be measured by the UV-Vis instrument TEMPO. Such a minimum GCIRI can be accomplished as EV-size mission. Peer-reviewed proposals have been submitted and highly rated in the NASA process but not yet funded. A complete GCIRI capability that meets all GEO-CAPE requirements not met by TEMPO (Appendix C) is feasible, but at this time is more costly than an EV-size mission. The ASWG determined that retrievals combining GOES R/S and TEMPO observations could advance aerosol science even beyond GEO-CAPE goals.

With GEO-CAPE endorsement, the international community now views EV TEMPO as the U.S. component of the baseline CEOS Atmospheric Chemistry Constellation (ACC), along with the Korean GEO-KOMPSAT-2B and ESA Sentinel-4. As the U.S. contribution to an integrated global observing system for air quality, TEMPO helps to maintain U.S. leadership and to multiply scientific knowledge for a relatively small financial investment. GEO-CAPE ASWG and TEMPO Science Team members were competitively selected to participate in the 2013 ESA Sentinel-4, 5 Mission Advisory Group. These formal appointments provide ongoing coordination for TEMPO as part of the CEOS ACC and GEO-CAPE.

3.3.2.6 Confirmed that GEO-CAPE Infrared Instrument (GCIRI) Observations of Methane Would Significantly Improve Methane Emissions Estimates Over North America.

Over a 20-year policy-relevant time frame, methane has a global warming potential of 86 compared to CO_2 (IPCC 2013). Reductions in methane emissions provides both climate and air quality benefits. Lack of confidence in the available CH_4 emissions inventories (e.g., Miller et al. 2013) remains a problematic limitation to the design of efficient environmental policies and to accomplishing the objectives set forth in the U.S. Strategy to Reduce Methane Emissions (2014). GEO-CAPE GCIRI could provide methane emissions estimates that are consistently measured, transparent, complete (over greater North America), accurate, and spatially attributed.

Short wave infrared (SWIR) observations are essential for constraining methane emissions from space because they are sensitive to atmospheric methane down to Earth’s surface. Thermal infrared (TIR) observations by themselves are only sensitive to the free tropospheric methane background. The combination of both SWIR and TIR observations could provide additional information to separate boundary layer enhancements from the methane background over source regions (J. Worden et al., 2015).

Alexe et al. (2015) demonstrated the value of existing SWIR observations from SCIAMACHY and GOSAT to constrain methane emissions on a spatial scale of hundreds of km and an annual temporal scale. However, these spatial and temporal scales are inadequate to understand the relevant processes. There is considerable spatial overlap at hundreds of kilometers between different methane source types (such as oil and gas, livestock, landfills); finer spatial resolution is needed to separate individual sources. Methane emissions can also have very large temporal variability, including “super-emitters” from oil/gas production and distribution systems that are thought to contribute a large share of total emissions. LEO observations are incapable of resolving the temporal variability of methane sources.

GEO-CAPE analysis of in situ methane measurements from DISCOVER-AQ demonstrated that real-world methane variability is captured at GCIRI spatial resolution. In addition, analysis using the NCAR community WRF-CHEM modeling framework shows that discrimination between clean and polluted profiles (3-5% enhancement in total column methane) can be determined from GCIRI observations with 1% precision for total column methane (Figure 3-3).

GEO-CAPE OSSE studies (Section 3.3.2.7) have demonstrated the value of GEO observations for addressing this current large gap in our ability to constrain methane emissions over continental domains (North America). Wecht et al. (2014) presented an inversion of the CalNex aircraft campaign (May–June 2010) data to constrain emissions over California (Figure 3-4) showing significant value for densely sampled column methane measurements to estimate emissions.

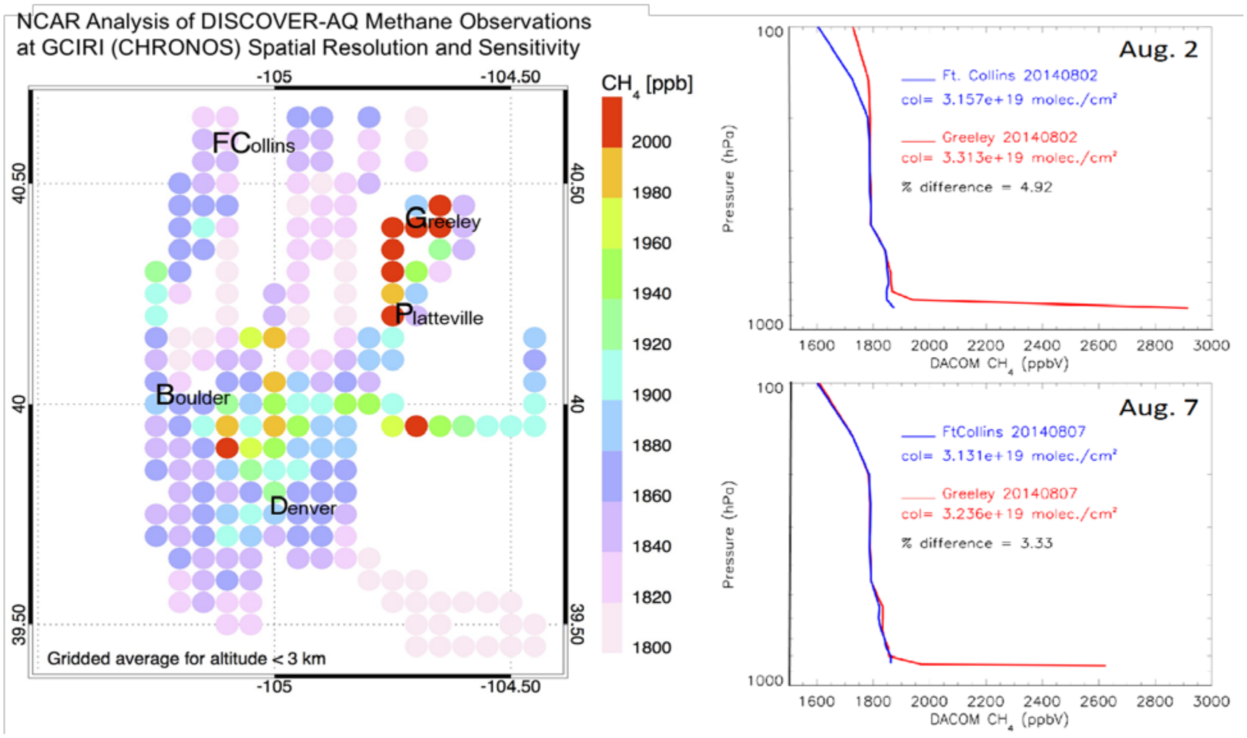


Figure 3-3. GEO-CAPE's GCIRI SWIR observations can capture the methane spatial variability and boundary layer enhancements observed in FRAPPE/DISCOVER–AQ in Colorado in 2014.

Bousserez et al. (2015) compared the information contents of different satellite observing strategies for constraining methane emissions over the U.S. spatial domain and found that a GEO SWIR instrument would substantially increase our ability to constrain methane sources relative to the current LEO SWIR observations; a GEO SWIR+TIR instrument could provide

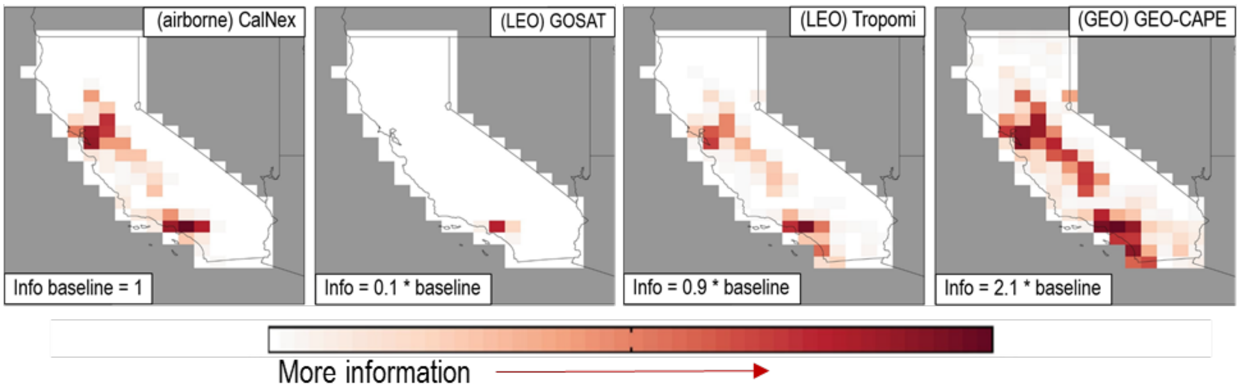


Figure 3-4. High value of methane observations from GEO. Adapted from Wecht et al. (2104), the model inversion of assimilated CalNex aircraft campaign methane data establishes current observational capability to constrain methane emissions over California ("Info baseline"). Information content from LEO depends on sampling and revisit times. A GEO-CAPE SWIR instrument would constrain methane emissions better than even a dedicated aircraft campaign.

some additional information. The GEO-CAPE Methane Working Group is exploring GCIRI potential to observe methane sources at ~ 5–10 km resolution including temporal variability.

Thus, analysis of GEO-CAPE's advanced methane measurement requirements and advanced modeling capability both confirm that GCIRI observations of methane would significantly improve methane emissions estimates over North America.

3.3.2.7 Initiated Coordinated Effort to Build Modeling Framework for Data Simulation and Exploitation

In 2012, the GEO-CAPE ASWG began to build a modeling framework supporting Observing System Simulation Experiment (OSSE) capability to comprehensively assess the value that observations required by the Atmospheric STM will contribute to the observing system for atmospheric composition in the context of addressing specific scientific and applications questions. Creating this OSSE capability (Figure 3-5) is a major objective for GEO-CAPE.

The comprehensive modeling system is essential to integrate surface, airborne, and space observations; to assess combinations of candidate measurement systems (instruments); to perform accurate retrievals from measurements at shorter time resolution and smaller spatial resolution than current practice; to inform instrument designs with simulated data while providing estimates of the data's value in addressing the GEO-CAPE Science Questions using accurate representation of instrument information content and uncertainty; to enable Atmospheric Composition Constellation products; and to provide emissions estimates as required in the atmospheric composition STM.

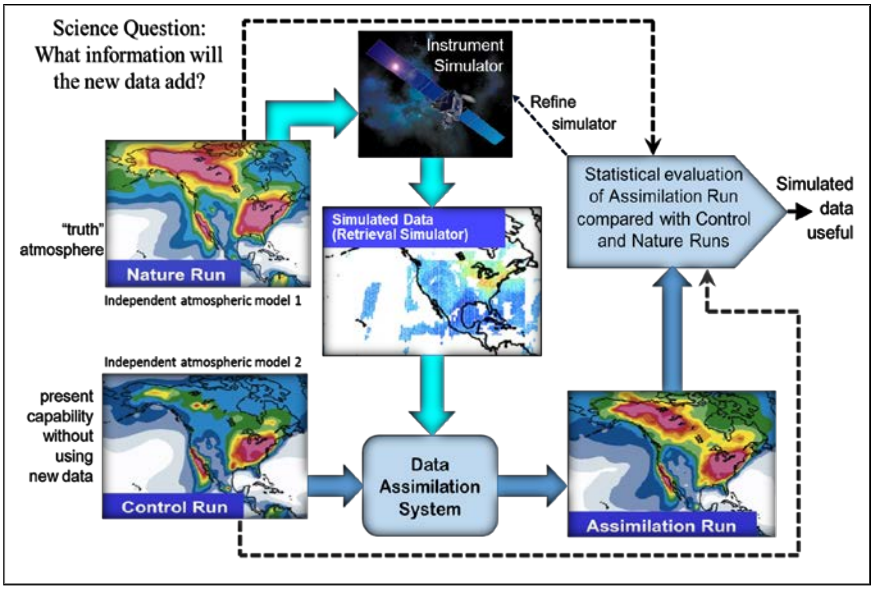


Figure 3-5. GEO-CAPE OSSE framework. Both advanced observations and advanced modeling capabilities are necessary to address the GEO-CAPE science questions. The Nature Run is a model representation of 'truth' that is sampled by the Instrument Simulator to produce simulated data, which are assimilated into the Control Run (which uses an independent model) to produce the Assimilation Run. The impact of the candidate observations is assessed by statistically evaluating if the Assimilation Run tends to the Nature Run compared to the Control Run.

Such a comprehensive modeling framework requires:

1. Independent estimates of the chemical as well as meteorological state of the atmosphere on time and space scales relevant to GEO-CAPE (atmospheric models);
2. The ability to propagate the atmosphere radiance produced by those model atmospheres to the top of the atmosphere with full spectral resolution (forward model);
3. An accurate representation of potential instrument acquisition of the atmospheric radiance including instrument artifacts, noise, and accounting for viewing geometries and other errors, which then produces simulated instrument data (instrument model);
4. Capability to perform retrievals on simulated instrument data, typically using optimal estimation techniques and creating synthetic observations (e.g., ozone abundance);
5. A data assimilation capability so that model atmospheres may be adjusted based on observations and compared to "true" atmospheres to assess the benefit of observations.

During a 3-year effort to build the modeling framework needed to assess GEO-CAPE's responsiveness to the STM's Science Questions at both regional and global scales, GEO-CAPE has demonstrated parts of this framework in case studies (Figure 3-5; also Section 7).

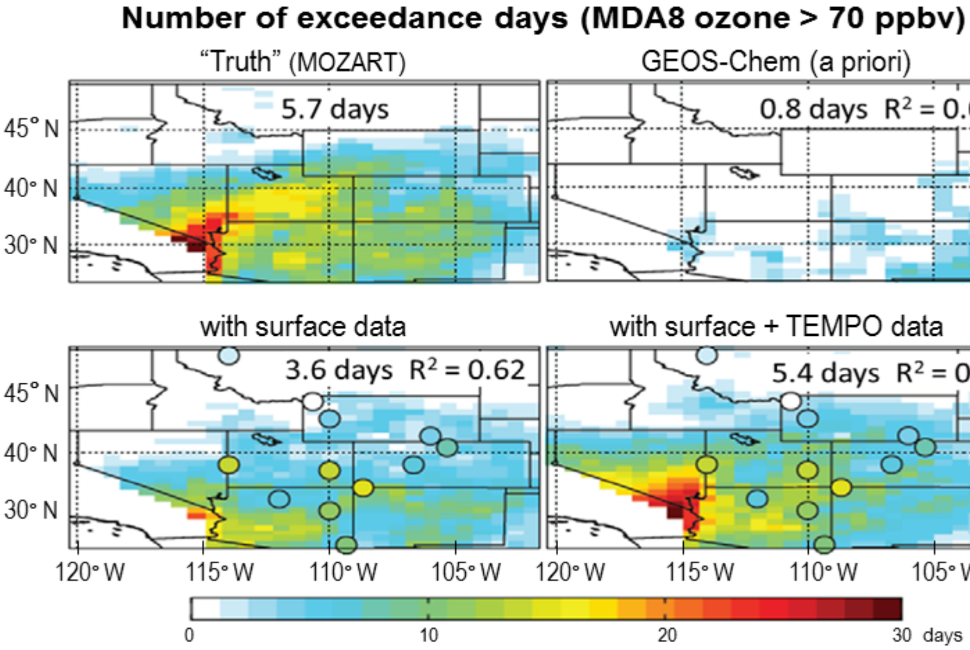


Figure 3-5. OSSE results from testing the value of TEMPO data for detecting exceedances of the O_3 air quality standard in the Intermountain West. MOZART and GEOS-Chem models simulate Apr-Jun 2010 with different meteorological fields. MOZART is taken as the "true" atmosphere (Nature Run) and GEOS-Chem assimilates pseudo-data from surface sites (circles), and from TEMPO. Inset are the average number of exceedance days and R^2 relative to "truth". The analysis run (with surface + TEMPO) performs better than the control run (a priori) in estimating exceedance days. From Zoogman et al. (2014).

Publications documented key OSSE development accomplishments. Initial OSSE capability enabled assessment of the effectiveness of GEO-CAPE observations for CO (Edwards et al. 2009) and O_3 (Zoogman et al., 2011). Analyses showed that GEO-CAPE's dense sampling will allow first-ever observations of the seasonally and diurnally varying background ozone concentrations, particularly when O_3 and multi-spectral CO measurements (such as would be provided by a GCIRI) are both available (Zoogman et al. 2013). The team created an essential tool for the OSSEs, a computationally efficient method to define the scene-dependent vertical sensitivity of measurements as expressed by retrieval averaging kernels (Worden et al. 2013).

Multiple models run at high resolution across the entire Earth make global OSSE activity resource-intensive. GEO-CAPE initiated and co-sponsored a CEOS atmospheric composition OSSE workshop with European and Asian collaborators at ECMWF (Reading, England) in 2012 to begin quantifying the impact of GEO-CAPE observations in a global observing system.

The ASWG began an assessment of all input data to the model framework in light of the markedly shorter time resolution and smaller spatial resolution than current practice. Input data include fine scale meteorological information, surface spectral reflectance and terrain height at high spatial resolution, fine spatial structures in the stratosphere-troposphere boundary, and other ancillary data at all times of day and all viewing angles, and their representative errors. OSSEs are used extensively in Numerical Weather Prediction to develop and optimize contemporary meteorological instruments. Instrument and observation simulation models have been evaluated for several candidate GEO-CAPE instruments.

3.3.2.8 Developed Community Assessments of Science and Applications Value

ASWG developed a draft Science Value Matrix in 2012 with baselined, expert-estimated values of the contributions of individual atmospheric chemical observables (e.g., O_3, NO_2) toward realizing the GEO-CAPE science goals. The expert assessment provided an initial Value Matrix while the longer term development of the OSSE capability will provide objective science values for each observable and potential combinations of observables, including the specific information content and uncertainty characterization of the measurement technique selected. The initial Science Value Matrix (provided in Appendix C) was used effectively in assessing the contribution of TEMPO observations toward achieving GEO-CAPE science goals.

ASWG also began the definition of an Applications Value Matrix (AVM, Appendix C), creating a structure that includes heritage-based product confidence as estimated by a small pool of potential applications users (for example, regional air quality managers). As expected, the draft AVM identified somewhat different values for the GEO-CAPE observables than the STM.

The value of GEO-CAPE observations for both science and applications evolves as human activity changes the atmosphere and drives new priorities in air quality management and climate change. For example, the importance of methane observations has increased since GEO-CAPE's initial definition and value assessments; methane mitigation is now understood to benefit both air quality and climate (Shindell et al. 2012).

3.3.3. Ongoing and Future Work

GEO-CAPE planned observations on time and space scales relevant to the Science Questions served as a catalyst to create new analysis capabilities to address both air quality and climate needs for actionable information. The modeling framework of analytical tools for advanced chemical data simulation and assimilation, analysis, and assessment is the basis for integrating future GEO-CAPE observations with existing surface and airborne observations that are trusted by decision makers.

Investments in an Atmospheric Composition Constellation (ACC) Science Team to support U.S. investigator participation in GEO observation missions of other (international) space agencies will enable coordination, data sharing, and leadership in global and regional data assimilation activities. Formal Science Team support will further maximize use of TEMPO (and potentially GCIRI) data and carry these GEO-CAPE analysis advances forward to the international ACC.

Additionally, funding an expert user group to assist U.S. agencies in use and interpretation of the advanced GEO-CAPE products will support public decision making on air quality and climate change. An expert user group might be modeled on the highly successful NASA Air Quality Applied Sciences Team (AQAST).

To reiterate, near term implementation of a GEO-CAPE InfraRed Instrument for methane emissions and tropospheric pollution transport (using multispectral carbon monoxide as an atmospheric tracer) significantly strengthens urgent national and international policy objectives on intercontinental transport of air pollution and climate change associated with AQ emissions.

3.4 Summary

The GEO-CAPE community reshaped the visionary but currently unaffordable notional DS mission by prioritizing the science set forth in the 2007 DS, by identifying separable instruments that could be fielded in a distributed implementation, and by actively responding to NASA Earth Venture opportunities to demonstrate that distributed implementation. NASA's 2012 selection of TEMPO for flight development represented a first step in delivering GEO-CAPE's compelling time-resolved ocean and atmospheric science.

Coastal ocean color and atmospheric composition scientific communities responded to the challenge to prioritize the science that could be done for the resources available, and continue to invest their talents in strong support of GEO-CAPE science.

4. MISSION AND INSTRUMENT CONCEPT STUDIES

4.1 Mission and Instrument Concept Studies Initial State in 2009

In 2006, NASA Headquarters initiated a series of conceptual instrument and mission design studies to inform planning associated with the release of the 2007 Decadal Survey (DS). Two instrument studies conducted in the GSFC Instrument Synthesis and Analysis Laboratory (ISAL, currently designated as the Instrument Design Laboratory, or IDL) were directly relevant to the initial GEO-CAPE mission concept. The Geostationary Multispectral Atmospheric Composition (GeoMAC) ISAL study in September 2006 focused on a two-instrument payload, essentially identical to the atmospheric science component of the GEO-CAPE mission ultimately recommended by the DS: a UV/Vis spectrometer (the GeoMAC instrument itself) and an IR gas-correlation radiometer (the Compact Imaging Spectro-Radiometer, or CISR). These two instrument concepts had evolved from highly rated NASA mission proposals in the 1990s, with CISR having been developed in the LaRC Integrated Design Center. The Geostationary Earth Observing Multi-Discipline Imager (GEO-MDI) ISAL study in October 2006 focused on a third instrument, a UV/Vis/NIR/SWIR spectrometer for ecosystem and carbon assessment of coastal waters and terrestrial biosphere and atmospheric trace gases and aerosols. This multi-discipline instrument was much larger than the two atmospheric instruments due primarily to its requirements for much finer spatial resolution, broad spectral coverage and multiple focal planes. These instrument studies were followed by two mission studies in the GSFC Integrated Mission Design Center (IMDC), including a Geostationary Multi-discipline Observatory (GMO) that incorporated the GeoMAC, CISR, and GEO-MDI sensors to serve a range of atmospheric, coastal waters, and terrestrial biosphere science objectives. The mission studies affirmed that a dedicated geostationary Earth science mission faced no major implementation obstacles and that heritage instrument concepts at very high TRL existed. Major conclusions in the final study reports included: (1) significant additional optimization of the instrument designs that were considered was possible; (2) alternative instrument concepts existed albeit at lower initial TRL; (3) additional mission trade studies would be needed to optimize cost versus science benefit; (4) selective mission-enhancing technology investments existed, such as fine pointing control; and (5) commercial ride sharing opportunities should be explored as an option for lowering mission cost. The GEO-CAPE mission recommended in the 2007 DS was essentially a targeted subset of the GMO mission study, focusing on the atmospheric and coastal waters science objectives and instrument concepts with high TRL.

4.2 Mission Concept Studies

As noted in Section 4.1, the initial GEO-CAPE mission concept was an Observatory-class mission consisting of multiple instruments on a single dedicated NASA platform to accomplish 2007 DS science and applications needs. In 2009–2010, GEO-CAPE study team members held fact-finding discussions with U.S. geostationary satellite stakeholders including the NOAA GOES Program, NASA TDRSS Program, satellite builders, and launch service providers. A consistent message was that the actual cost of a dedicated geostationary mission with the notional GEO-CAPE payload defined in the 2007 DS was likely to cost 2-3 times more than the 2007 DS estimate of $550M. The study team judged that a mission costing in excess of $1.0B would be cost prohibitive for a new mission start during the decadal scope of the first DS. Subsequent studies therefore emphasized concepts to reduce mission cost and risk while still meeting most of the 2007 DS science requirements. The formal mission and instrument concept studies conducted by the GEO-CAPE team are summarized in Table 4-1. The design studies reported here were conducted by the multi-Center GEO-CAPE Mission Design Coordination Team, integrating perspectives from JPL, GSFC, and LaRC space mission implementation cultures into a team approach. The GEO-CAPE Ocean and Atmosphere Science Working Groups (SWG) provided up-to-date measurement requirements for each study.

In light of the escalating dedicated mission cost estimates, in August 2010 the team conceived and conducted a novel hosted payload concept mission design study with the GSFC Mission Design Lab (MDL) staff to assess feasibility and costs of implementing the GEO-CAPE mission as hosted payloads (HPL) on commercial spacecraft. The study leveraged the experience of several NASA teams that since the 1990s had been exploring the potential for flying Earth science instruments as secondary payloads on commercial or governmental geostationary host satellites (Little et al. 1997; Caffrey and Baniszewski 2004; Futron Corp. 2010). The study focused on individually hosting a notional "planning payload" of three GEO-CAPE instruments that together would meet all mission requirements. The planning payload construct was efficient and practical because it used existing IDL instrument concepts and the different sizes of the 3 instrument concepts (45 kg, 140 kg, 620 kg) allowed generalization of the study results according to small, medium, and large instruments. Four domestic spacecraft manufacturing companies (Loral, Lockheed, Boeing, and Orbital) participated in the study. The study determined that there were no technical showstoppers to the HPL implementation; even the largest instrument could be accommodated on the standard satellite buses considered, although the largest instrument in the study was on the verge of being a primary rather than secondary payload. During the cost-estimating phase of this study, the cost estimate for a dedicated mission was also updated. The study determined that an HPL implementation strategy could realize cost savings compared to a dedicated mission: the full mission life cycle cost estimates were $147M, $298M, and $720M respectively for the hosted small/medium/large instruments, for a total of $1.1B, versus $1.5B for the dedicated mission (all estimates in FY11 dollars). Another key finding was that significant mission implementation risk reduction could be achieved by hosting instruments separately on multiple platforms; the impact of a launch failure would be the cost of building a copy of the affected instrument rather than the cost of replicating the entire mission.

Table 4-1. Formal Mission and Instrument Design Center Studies.

Dates	Title	Summary
July 29-30, 2009	GEOCAPE 2007-09 FTS Study Final Report	JPL Team X FTS instrument concept study. An upgrade to the more-capable wide and narrow field FTS resulted in the inability of the Falcon 9 to support the launch mass. An Atlas 401 is required. In addition to a mass increase, inclusion of a wide and narrow field FTS results in a 38% cost increase. Data compression is required to allow transmission of the FTS with reasonable antenna sizes and data processing.
January 25-29, 2010	GEO-CAPE Coastal Ecosystem Dynamics Imager (CEDI) Instrument Design Study	GSFC IDL study to design an instrument meeting specific science requirements established by the GEO-CAPE Ocean SWG Reduce size and mass from the 2006 GEO-MDI study (which also included terrestrial biosphere and atmosphere requirements) Instrument volume reduced by 50% and mass reduced by 33%
August 30-September 3, 2010	GEO-CAPE Hosted Payload Concept Mission study	GSFC MDL study to examine hosted payload mission options for reducing cost and/or risk Evaluate hosting three GEO-CAPE conceptual instruments (GeoMAC UV-VIS; CISR SWIR; CEDI UV-VIS-SWIR) on individual geostationary commercial spacecraft Loral, Lockheed, Boeing and Orbital offered spacecraft options and capabilities in order to understand accommodation requirements Confirmed HPL strategy has no technical showstoppers, lower mission risk, and estimated 27% total mission cost reduction
September 14-20, 2011	GEO-CAPE Geostationary Multispectral Atmospheric Composition (GeoMAC) Instrument Study	GSFC IDL refresh of 2006 GeoMAC instrument study Use GEO-CAPE Atmosphere SWG requirements and ensure capability for hosting as a commercial satellite hosted payload No technology development required Pointing requirements can be met on a commercial spacecraft GeoMAC plus CISR could accomplish 2007 DS GEO-CAPE atmosphere measurements
October 31-November 4, 2011	GEO-CAPE Hosted Payload Pathfinder Feasibility/Risk Reduction Analysis	GSFC IDL study in partnership with ESSP CII to characterize interface environment of commercial communication platforms for future science opportunities Designed instrument suite capable of measuring relevant on-orbit performance characteristics, e.g. mechanical disturbance spectrum Designed optional science risk reduction payload with $10M cost cap to be co-manifested with the sensor suite Informed development of CII geostationary guidelines
November 15-17, 2011	GEO-CAPE PanFTS Study	JPL Team X instrument study considered four configurations of PanFTS atmospheric composition instrument as a hosted payload The configurations covered differing spectral ranges to selectively or fully meet GEO-CAPE atmosphere requirements All four options met their requirements with margin.
September 2014	GEO-CAPE Ocean Color Sensor Capability vs. Cost Instrument Studies	Sequence of 3 GSFC IDL studies to inform Ocean SWG of the cost sensitivity of key science requirements Included instrument design studies for two very different technical approaches (spectrometer, radiometer) and a cost scaling exercise Multiple instrument concepts are capable of achieving the science requirements within an instrument cost range of $100M to $200M

These study findings provided the technical basis for the phased HPL mission implementation approach endorsed by the GEO-CAPE study team during the May 2011 Open Community Workshop and broadly communicated by Fishman et al. [2012]. The cost estimates also made it clear that instrument size and simplicity were drivers of HPL costs, reinforcing the team focus on continued instrument studies to reduce instrument size and complexity summarized in Section 4.3.

4.3 Instrument Concept Studies

4.3.1 Coastal Waters

4.3.1.1 2010 Coastal Ecosystem Dynamics Imager (CEDI) Study

The CEDI instrument study conducted in January 2010 in the GSFC Instrument Design Lab (IDL) was a follow-on to the 2006 GEO-MDI study which included coastal ecosystem and terrestrial biosphere requirements. The intent of the CEDI study was to design an instrument capable of meeting specific baseline science requirements established by the GEO-CAPE Ocean SWG, with smaller size and mass than GEO-MDI. CEDI is a single-slit spectrometer (SSS) covering the UV-Vis-NIR spectral range. The study was successful in that GEO-CAPE instrument requirements were met with volume reduced by 50% and mass reduced by 33% compared with GEO-MDI. The two primary factors that resulted in the reduction in volume and mass between the two studies were coarsening of the nadir spatial resolution from 250×250m to 375×375m and removal of a secondary UV-Vis focal plane designed for atmospheric retrievals of trace gases. Because CEDI was still considered to be a large instrument in the context of commercial hosted payloads, follow-on studies continued to explore approaches for further reducing instrument size.

4.3.1.2 2014 Coastal Ocean Science Instrument Cost-versus-Capability Studies

Three companion IDL studies were commissioned in the GSFC IDL in FY14: design studies for Wide-Angle Spectrometer (WAS) and Filter Radiometer (FR) implementations of an ocean color instrument, and an instrument architecture cost scaling exercise to compare the costs of the various instrument implementations studied to date (and variations on them) for meeting ranges of key science performance requirements. Combined, these capability versus cost studies were intended to allow the assessment of the impact of various science requirements, including spatial and spectral resolution, spectral range, scanning rate and signal-to-noise ratio (SNR), on the instrument cost.

The Wide-Angle Spectrometer (WAS) instrument design study, which concluded on July 29, 2014, provides a baseline design implementation for a UV-Vis-NIR (340-1100 nm) hyperspectral instrument and an optional design that includes three additional SWIR bands (1235 nm, 1640 nm and 2135 nm), all with a 375×375 m ground sample distance (GSD) at nadir. The bands are sampled at 0.4–0.5 nm. The WAS operates in a step and stare mode and possesses a large instantaneous field-of-view (iFOV) in one spatial axis (>1500 km at nadir). Three WAS concepts were examined and costed: the baseline instrument without the SWIR bands, and two designs incorporating a single UV-Vis-NIR spectrometer (instead of two as in the baseline), one with and one without the SWIR bands. No significant technical issues were identified. The WAS study assumed any instrument would fly as a hosted payload on a commercial geosynchronous satellite, and noted that roll knowledge or active compensation would be recommended. A vibration suppression system at the spacecraft interface would be required to limit jitter. The design met all performance goals, with the possible exception of polarization, where additional study was needed.

The Filter Radiometer (FR) instrument design study, which was concluded on August 6, 2014, provides a design implementation for a multispectral instrument, including two SWIR bands (1245 nm and 1640 nm for the HgCdTe detector configuration), all with a 250 x 250 m GSD at nadir. Spectral bandwidth was at 5 nm in most bands, with 10 to 40 nm bandwidths at longer wavelength bands used for atmospheric corrections. The Filter Radiometer operates as a multispectral 2D imager with 50 spectral filters. A disadvantage of this design is that it does not provide the capability to retrieve atmospheric NO_2 (potentially important for atmospheric correction near cities) due to the broader bandwidths. The image quality requirement was flagged as challenging, but no major technical development issues were identified. The FR study also assumed the instrument would fly as a hosted payload on a commercial geosynchronous satellite, and noted that roll knowledge or active compensation would be recommended. A vibration suppression system at the spacecraft interface would be required to limit jitter. The design met all performance goals. It is noteworthy that the Korean Geostationary Ocean Color Imager (GOCI; launched in 2010 and built by EADS Astrium), a filter wheel radiometer instrument similar to FR, does not possess either a vibration suppression system or an active roll compensation system. To minimize disturbances to instrument pointing stability, the solar panels on the spacecraft are maintained stationary during GOCI data acquisition. GOCI has met all the pointing stability and image navigation registration requirements.

The GEO-CAPE Ocean Instrument Architecture Performance Study, completed on September 10, 2014, was intended to allow assessment of the sensitivity of instrument cost to changes in key science requirements. Multiple instrument concepts were examined to capture a broad range of possible costs. Four primary sensor concepts were costed in detail including the WAS and FR designs described above, an SSS concept, represented by the 2010 GEO-CAPE CEDI study (similar to WAS except for significantly smaller iFOV), and a GSFC-developed step-and-stare dual-slit spectrometer concept identified as COEDI, representative of a multi-slit spectrometer (MSS). The performance parameters studied for cost impact were: spatial resolution, spectral resolution, spectral range, ground coverage (scanning rate), and SNR. Costs were compared using both NICM and parametric (Price H) estimation tools. In some cases, the data were outside the NICM ranges due primarily to high data telemetry rates, so only parametric estimates are discussed in this summary. It is noteworthy that the NICM sub-system tool yielded cost estimates equivalent to the parametric costing. Comparable instruments were also considered in generating the estimates. Only NICM system costing was available for sensors not studied in the IDL.

For the WAS, the impact of increasing spatial resolution from 500 m to 375 m was estimated at 34-42%. The impact of increasing spatial resolution from 500 m to 250 m was much greater, with an increased cost of 125-160%. The cost impact for increasing spectral resolution from 2.0 nm to 0.4 nm was less than 3%. The estimated cost using Price H ranged from $156.3M to $196.2M for the various WAS instrument configurations studies.

For the SSS, the data indicated that cost was significantly greater for the 250 m GSD compared to the 375 m or 500 m resolutions, with the 250 m cost being approximately 110% greater than the 500 m cost. The cost increase for going from 500 m to 375 m was much smaller, about a 28% increase. The cost impact of going from a 2.0 nm spectral resolution to a 0.4 nm spectral resolution was small, less than a 5% increase. An SSS implementation based on GeoMAC (1333 m spatial resolution, 0.6/1.2 nm spectral resolution, same spectral range) was also included to provide a data point for a much coarser GSD. The estimated cost was $162.5M.

For the FR, only the effects of spatial resolution and SWIR capabilities were considered. The spectral resolution was fixed at 5 nm. Unlike in the other three cases, the cost was not significantly greater for 250 m spatial resolution compared to 375 m resolution. The estimated impact of increasing spatial resolution from 500 m to 375 m was a 14-34% increase, while the estimated impact of increasing spatial resolution from 500 m to 250 m was 30-49%. The baseline design (250 m GSD) with SWIR capabilities (HgCdTe detector) resulted in a 9% higher cost than the sensor version costed without SWIR capability (CCD detector). The estimated cost for a FR instrument (250 m GSD) using Price H for this design ranged from $137.8M (CCD detector) to $151.2M (HgCdTe detector).

For the MSS, the cost for increasing spatial resolution from 500 m to 375 m was estimated at approximately a 20% increase. The cost for increasing spatial resolution from 500 m to 250 m was estimated at a 68–76% increase based on parametric models. The estimates for increasing the spectral resolution from 2.0 nm to 0.4 nm were generally predicted to be 4–11%, based on parametric models. NICM produced higher estimated impacts, particularly for spectral resolution impacts. However, some of the input values for the 250 m cases were outside the NICM input ranges, which could have affected the results.

4.3.2 Atmospheric Composition

4.3.2.1 2009 GEO-CAPE Pan-Chromatic Fourier Transform Spectrometer (PanFTS) Study

A 2009 study in JPL's Team X Design Center evolved Fourier Transform Spectrometer (FTS) instrument design options to fly on a dedicated geosynchronous spacecraft. Two configuration options were studied with potential to meet some or all GEO-CAPE atmosphere requirements: (1) an FTS with a wide-field FOV only, and (2) a design featuring an FTS with wide- and narrow-field capability. Not surprisingly, the multi-FOV option-2 design resulted in an instrument with significantly higher mass, data rate, and cost. The mass increase from the first to the second option also drove the launch vehicle selection since the less-expensive Falcon 9 option (in 2009) could not accommodate the mass increase. Team X concluded that the dedicated S/C with the option 2 PanFTS design required launch on an Atlas V 401.

4.3.2.2 2011 Geostationary Multispectral Atmospheric Composition (GeoMAC) Study

A 2011 GSFC IDL study was conducted for the GeoMAC atmosphere UV-VIS instrument. This study was a refresh of the 2006 GeoMAC pre-DS concept study, using requirements developed by the GEO-CAPE Atmosphere SWG. A goal of the study was to ensure capability of the instrument to be hosted as a commercial satellite payload. The concept study resulted in a significant increase in capability (Vis-NIR channel and cloud camera added) and compatibility as a hosted payload (design adjusted to accommodate mounting on a satellite nadir deck). The study determined that GeoMAC together with the previously studied CISR instrument measuring in the shortwave infrared (SWIR) could meet GEO-CAPE atmosphere science requirements expressed in the DS. No technology development was required and pointing requirements could be met on a commercial spacecraft.

4.3.2.3 2011 Hosted Payload Pathfinder Studies

A 2011 GSFC IDL study for the GEO-CAPE Hosted Payload Pathfinder Feasibility/Risk Reduction Analysis was conducted. In collaboration with the NASA Common Instrument Interface (CII) group, the team evaluated the characteristics and costs for a GEO-CAPE Pathfinder risk reduction hosted payload with a self-imposed payload cost cap of less than \$10M. The goal of the pathfinder study was to fully understand the programmatic and technical requirements for such a mission. A secondary goal was to design an optional demonstration payload that could produce relevant science data as a precursor to a hosted payload implementation of the GEO-CAPE mission. The design consisted of a Priority Characterization Suite (PCS) as the environmental instrument and an Optional Instrument Suite (OIS) as the "science" instrument. The information from this study was used by the CII to develop guidelines for NASA GEO hosted payload missions in preparation for Earth Venture Instrument solicitations.

4.3.2.4 2011 PanFTS Configuration and Hostability Studies

By 2011 the GEO-CAPE team had determined that the more cost-effective GEO-CAPE system design included launching instrumentation as hosted payloads on geostationary communications satellites. A 2011 JPL Team X PanFTS study was framed to consider design options of the PanFTS instrument concept as a hosted payload. Four scalable PanFTS configurations were studied (Table 4-2), covering combinations of spectral ranges that would selectively meet some or all GEO-CAPE atmosphere requirements. These configurations were selected to provide cost versus capability information to inform the Atmosphere SWG regarding options for possible combinations of instruments to fully meet measurement requirements, thereby providing additional mission design flexibility. Configuration 1 could be a companion to GeoMAC and CISR to meet all then-current GEO-CAPE requirements; configuration 2 could be an alternative concept to CISR; configuration 3 could be an alternative concept to GeoMAC; configuration 4 could meet all then-current GEO-CAPE atmosphere requirements. The study resulted in a preliminary design of all four configurations that met their requirements with margin and that could be integrated on a hosted spacecraft mission to conduct the science investigation for the required 3-year lifetime. Given the normal 15-year plus commercial communications satellite life, the support of the science was not an issue.

Table 4-2: GEO-CAPE 2011 Team X PanFTS Instrument Configuration Options

No	Spectral Bands$^+$	Spectral Range (μm)	Measurements
1	LWIR, MWIR	11.1-4.55	O_3, NH_3, CH_3, SO_2, CO, (Temp., H_2O, N_2O, CO_2)
2	LWIR, MWIR, SWIR	11.1-2.27	O_3, NH_3, CH_3, SO_2, CO*, CH_4 (Temp., H_2O, N_2O, CO_2)
3	UV, Vis/O_2, A-Band	0.78-0.30	O_2, NO_2, CHOCHO,O_3, HCHO, SO_2
4	LWIR, MWIR, SWIR, UV, Vis/O_2 A-band	11.1-0.30	O_3*, NH_3, CH_3, SO_2*, CO*, CH_4 NO_2, CHOCHO, HCHO (Temp., H_2O, N_2O, CO_2)

$^+$ IR = infrared; LW = long wave; MW = mid wave; SW=short wave

* Vertical profile

4.4 Additional Studies

4.4.1 Analysis of Alternatives for Completing GEO-CAPE Given TEMPO

As described in Section 3.3.2.5, in 2013 the GEO-CAPE Study Team was directed by ESD to assess the implications of the 2012 Earth Venture Instrument selection of Tropospheric Emissions: Monitoring of Pollution (TEMPO) on GEO-CAPE's atmospheric composition instrument suite. TEMPO has much in common with the well-studied GeoMAC concept described in this section, therefore the study team determined that a formal design lab study was not needed to address this question. The team instead evaluated GEO-CAPE Atmosphere SWG requirements to determine which of them were likely to be met by TEMPO and to identify feasible options for meeting GEO-CAPE requirements that were beyond the scope of the cost-capped TEMPO mission. It was confirmed that TEMPO observations together with those from the Advanced Baseline Imagers on the NOAA GOES R/S platforms would meet GEO-CAPE atmospheric science requirements for species observable in UV-Vis wavelengths. It was further determined that an additional concurrent companion instrument measuring at high spectral resolution in IR wavelengths would allow all GEO-CAPE atmospheric science requirements to be met. The team coined the name GEO-CAPE Infrared Instrument (GCIRI) to be fully inclusive of the various conceptual instrument designs that could meet the remaining GEO-CAPE requirements. The Analysis further confirmed that TEMPO and GCIRI could be on different satellites as long as both satellites were in positions to view the coterminous United States.

4.4.2 Pointing Studies

An early question faced by the study team was whether commercial geostationary host satellites could provide sufficient pointing stability, control, and knowledge for GEO-CAPE requirements. Therefore, the GEO-CAPE activity included a 3-year development of analytical pointing tools to evaluate pointing requirements and performance under varying host spacecraft and sensor disturbance inputs. As described in Appendix C, the pointing study activity defined assumptions for the GEO-CAPE instrumentation environment to generate separate frequency and time domain analytical pointing tools. The pointing study also developed a 3D pointing visualization add-on for graphical representation of the end-to-end effects on instrument performance. Appendix C concludes with a case study that provides examples of the pointing tools output under defined operational environments. The tools developed were used in many of the integrated design studies described in Sections 4.2 and 4.3 and helped identify feasible approaches to meeting pointing requirements for all studies.

4.4.3 2015 Intelligent Coastal Waters Observing Strategy Studies

Observations in areas where clouds are obscuring the ocean surface may be an inefficient use of scanning time, depending on the instrument characteristics. For example, a study investigating sub-km cloud cover over the Gulf of Mexico (Figure 4-1) shows that more clear-sky pixels can be retrieved in the presence of clouds from a higher spatial resolution sensor. Observing strategy studies were initiated in 2015 to explore options to maximize the GEO-CAPE Coastal Ocean Color science return in cloudy scenes. These strategies range from a ground-based scheduler informed by cloud forecasts to a smart onboard scheduler with onboard cloud detection and image processing. A team of NASA Ames and Goddard members examined scheduling strategies and concepts of operations to compare the time constraints and quality of observations for several instrument concepts including the Filter Radiometer, Multi-Slit Spectrometer (e.g., the Coastal Ocean Ecosystem Dynamic Imager) and Wide Angle Spectrometer. Instrument scene geometries and scan times were used to determine scheduling strategies to meet the science requirements. Sources of cloud forecasts were identified to

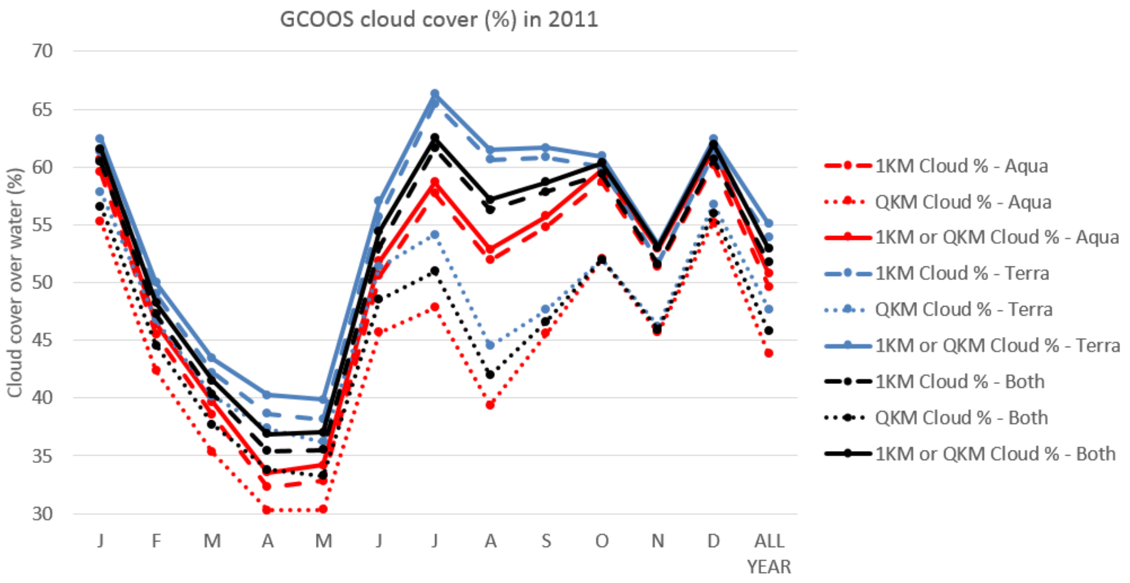


Figure 4-1. Preliminary results of cloud cover statistics using MODIS Terra and MODIS Terra 1-km and 250-m (QKM) data covering the Gulf of Mexico (18°N–31°N, 102°W–79°W). Cloud cover was obtained from the standard MOD35 cloud mask product. Clear seasonality is observed for all products, and QKM cloud cover is always lower than 1-km cloud cover. For this particular year, MODIS/Aqua QKM cloud cover between June and November (~39–52%) is significantly lower than 1-km cloud cover (~50–60%). (Provided by Chuanmin Hu.)

support cloud avoidance strategies to minimize measurement time and data downlink resources lost to low visibility/low science value scenes. Cloud data examples were generated to estimate how many scenes would be expected to pass cloud thresholds per geographic region in each season. Candidate cloud detection algorithms were identified, including the value of a SWIR band at 1375 nm for high altitude cirrus cloud detection. A GEO-CAPE Operations simulator tool was developed to visualize scene acquisition based on cloud forecasts. The preliminary scheduling efforts completed to date clearly demonstrate that analyzing scene geometry, clouds, instrument performance and operational considerations *together* is needed to optimize accomplishment of mission objectives. Ongoing work will evaluate feasibility of using intelligent cloud avoidance strategies with candidate instrument concepts and allow science users to explore "what if" scenarios incorporating actual cloud forecast data for specific targets.

4.4.4 Studies in Support of Proposal Activities

In addition to studies funded as part of GEO-CAPE pre-formulation, the larger GEO-CAPE community invested in several high quality peer-reviewed instrument concept studies, submitted to NASA as proposals to the Earth Venture Program. Most notable is the EVI-1 selection of the TEMPO investigation. Several GCIRI-related concepts have been proposed to

Earth Venture solicitations; those that were evaluated as Category 2 (selectable) include 2011 EVI-1 Commercially Hosted spectRO-radiometer and New Opportunities for Science (CHRONOS), 2012 Earth Venture Instrument-1 Geostationary Carbon Process Investigation (GCPI), and 2013 EVI-2 CHRONOS. Additional GCIRI concepts presented to the community at professional (American Geophysical Union) meetings include geoCARB, using the Tropospheric Infrared Mapping Spectrometer (TIMS) and the Geostationary Remote Infrared Pollution Sounder (GRIPS).

4.5 Summary

The conclusion from these studies is that GEO-CAPE is ready for implementation. The phased HPL mission implementation strategy provides flexibility to initiate new mission starts for components of the mission as funds are available. Multiple instrument concepts are capable of achieving GEO-CAPE requirements with no new technology development required. TEMPO has very similar capability to GeoMAC; if TEMPO proves to be an initial component of GEO-CAPE, there are several mature instrument concepts that could provide the IR measurements needed to complete GEO-CAPE atmospheric science (i.e., GCIRI) within a modest cost range ($90M to $150M). There remain concepts that could complete GEO-CAPE atmospheric science without reliance on TEMPO, albeit at approximately double the cost of GCIRI. Multiple instrument concepts are now capable of achieving the GEO-CAPE coastal waters science requirements within an affordable instrument cost range ($100M to $200M). While full mission cost estimates for the distributed implementation strategy ultimately depend on the commercial market at the time of selection for each instrument, the available estimates have not changed significantly during this study period and continue to support a hosted payload implementation rather than a dedicated satellite.

5. Technology Assessment and Development

5.1 Introduction

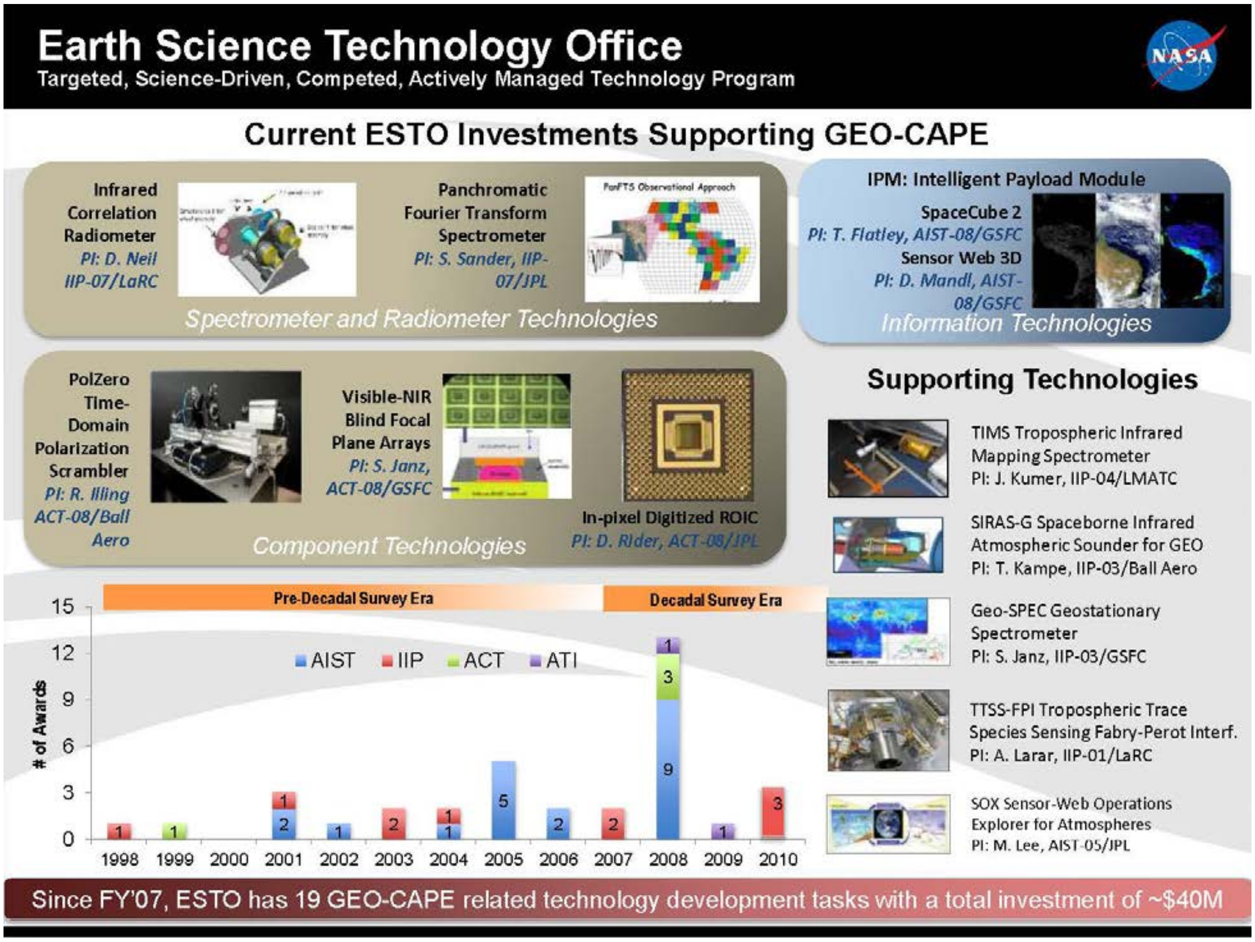
The original technology readiness assessment for GEO-CAPE was provided in the 2007 DS:

"All the [GEO-CAPE] instruments have a low-Earth-orbit space heritage and are at a high level of technology readiness, and so launch would be feasible by 2015."

Instrument capabilities that meet the subsequent evolution of GEO-CAPE science and mission objectives continue to be assessed at high technology readiness.

5.2 Initial State in 2009

In the 2007 DS definition of GEO-CAPE, instruments were notionally based on existing low Earth orbiting instruments in NASA's EOS fleet, which are therefore mature. Specifically, this meant that the measurement concepts for atmospheric composition and coastal ocean are fully



Earth Science Technology Office
Targeted, Science-Driven, Competed, Actively Managed Technology Program

Current ESTO Investments Supporting GEO-CAPE

Spectrometer and Radiometer Technologies

Infrared Correlation Radiometer
PI: D. Neil IIP-07/LaRC

Panchromatic Fourier Transform Spectrometer
PI: S. Sander, IIP-07/JPL

Information Technologies

IPM: Intelligent Payload Module

SpaceCube 2
PI: T. Flatley, AIST-08/GSFC

Sensor Web 3D
PI: D. Mandl, AIST-08/GSFC

Component Technologies

PolZero Time-Domain Polarization Scrambler
PI: R. Illing ACT-08/Ball Aero

Visible-NIR Blind Focal Plane Arrays
PI: S. Janz, ACT-08/GSFC

In-pixel Digitized ROIC
PI: D. Rider, ACT-08/JPL

Supporting Technologies

TIMS Tropospheric Infrared Mapping Spectrometer
PI: J. Kumer, IIP-04/LMATC

SIRAS-G Spaceborne Infrared Atmospheric Sounder for GEO
PI: T. Kampe, IIP-03/Ball Aero

Geo-SPEC Geostationary Spectrometer
PI: S. Janz, IIP-03/GSFC

TTSS-FPI Tropospheric Trace Species Sensing Fabry-Perot Interf.
PI: A. Larar, IIP-01/LaRC

SOX Sensor-Web Operations Explorer for Atmospheres
PI: M. Lee, AIST-05/JPL

Since FY'07, ESTO has 19 GEO-CAPE related technology development tasks with a total investment of ~$40M

Figure 5-1. ESTO investments before 2007 DS through 2010.

demonstrated, and the capability to retrieve the desired observables from such measurement concepts had been documented (Algorithm Theoretical Basis Documents, ATBDs). The principal adaptation of these measurement concepts to GEO-CAPE was to move the observing capability from ~700-km precessing orbits to geostationary orbit, 35,786 km from Earth, and to adapt observation strategies like push-broom and side-scanning techniques to the stationary orbit. GEO-CAPE instrument concepts include simple staring spectroradiometers as well as spectrometers that scan a single spatial line or 2-D patch. In addition, GEO-CAPE instruments would operate with lower incoming radiance due to the increased distance from the source (Earth). These adaptations are fully within standard engineering practice. With the 2007 DS release, NASA Earth Science Technology Office (ESTO) investments were aligned with the recommended mission concepts through solicitation awards. Figure 5-1 depicts highlights of key ESTO investments associated with the GEO-CAPE mission concept as of 2010 that also contributed to the technology maturation.

5.3 Accomplishments 2009–2015

Since the 2007 DS release, ESTO continued to support the GEO-CAPE mission concepts with added awards. Funding for the Instrument Incubator Program (IIP) development is the major ESTO investment in GEO-CAPE, totaling $28M through 2014; those eight projects are listed in Table 5-1. This table highlights additional ESTO investments of interest to GEO-CAPE outside of the IIP. These include efforts to develop and test/validate component technologies totaling $10M, on-board processing capabilities, and especially relevant software processing techniques and design tools totaling $12M. Both IIP and component technology investments are cited in GEO-CAPE relevant instruments that have been proposed to NASA’s Earth Venture program and have been peer -reviewed. Some of the pre-2006 IIP projects (Geo-SPEC and GEO-TASO, not listed) were evolved into airborne remote sensing instruments used in field campaigns in support of measurement requirements definition.

The ESTO investment review for GEO-CAPE addressed technology developments to support mission design feasibility leading to launch. In addition to instruments and components technology, mission design tools are included. Thus, technology supporting mission operations and science data processing functions were also identified and listed. ESTO GEO-CAPE investments are summarized in Tables 5-1 and 5-2.

Table 5-1. ESTO Instrument Incubator Program Highlights 2006–2015.

PI Name	PI Org	Project Title	Total Funding	End Date
Stanley Sander	JPL	Panchromatic Fourier Transform Spectrometer Engineering Model (PanFTS EM) Instrument for the Geostationary Coastal and Air Pollution Events (GEO-CAPE) Mission	$4,500,000	05/31/2014
James Leitch	Ball Aerospace & Tech. Corp.	Prototype Sensor Development for Geostationary Trace gas and Aerosol Sensor Optimization (GEO-TASO) for the GEO-CAPE Mission	$4,482,129	04/30/2014

PI Name	PI Org	Project Title	Total Funding	End Date
Timothy Valle	Ball Aerospace & Tech. Corp.	Multi-Slit Optimized Spectrometer (MOS)	$4,304,164	04/30/2014
Doreen Neil	LaRC	Infrared Correlation Radiometer Fabrication and Characterization as Applied to the GEO-CAPE Decadal Survey Mission	$2,198,897	10/31/2011
Components				
Stanley Sander	JPL	Panchromatic Fourier Transform Spectrometer (PanFTS) Instrument for the Geostationary Coastal and Air Pollution Events (GEO-CAPE) Mission	$3,600,100	11/15/2011
John Kumer	Lockheed Martin Advanced Tech. Center	Tropospheric Infrared Mapping Spectrometers (TIMS) for CO Measurements With Much Improved Vertical, Temporal and Spatial Resolution, Especially in the Lower Troposphere by Utilizing Both the NIR and MWIR Regions	$2,933,019	12/13/2008
Scott Janz	GSFC	Geostationary Spectrograph (GeoSpec) for Earth and Atmospheric Science Applications	$3,300,000	12/31/2006
Thomas Kampe	Ball Aerospace & Tech. Corp.	The Spaceborne Infrared Atmospheric Sounder for Geosynchronous Earth Orbit (SIRAS-G)	$2,976,229	01/26/2007

Table 5-2. ESTO Components and Information Systems Program Highlights 2006–2016

PI Name	PI Org.	Project Title	Total Funding	End Date
Chris Hostetler	LaRC	Modification of HSRL and RSP for ACE, GEO-CAPE, and Glory Applications from the NASA P-3	$1,126,142	01/03/2013
Pantazis Mouroulis	JPL	Enhancing the Utility of PRISM to Coastal Ocean Science	$1,258,000	09/01/2016
Components				
Antonio Mannino	GSFC	Coastal Ocean Ecosystem Dynamics Imager (COEDI) Dual Slit Implementation	$181,000	12/31/2014
David Rider	JPL	GRIFEX: GEO-CAPE Read Out Integrated Circuit (ROIC) In-Flight Performance Experiment	$1,875,000	06/30/2015
Pantazis Mouroulis	JPL	Portable Remote Imaging Spectrometer (PRISM)	$2,500,000	10/31/2012
David Rider	JPL	In-Pixel Digitization Read Out Integrated Circuit for the Geostationary Coastal and Air Pollution Events (GEO-CAPE) Mission	$1,080,000	01/29/2012
Scott Janz	GSFC	Hybridized Visible-NIR Blind (Al, In) GaN Focal Plane Arrays	$1,065,105	10/01/2012
Rainer Illing	Ball ATC	PolZero: Time-domain polarization scrambler for wavelength-diverse sensors	$712,612	02/14/2011
On-Board Processing				
Paula Pingree	JPL	On-Board Processing (OBP) to Advance the PanFTS Imaging System for GEO-CAPE	$1,468,790	05/31/2015
Jacqueline Le Moigne	GSFC	A Reconfigurable Computing Environment for On-Board Data Reduction and Cloud Detection	$1,015,500	12/31/2006

PI Name	PI Org.	Project Title	Total Funding	End Date
Daniel Mandl	GSFC	A High Performance, Onboard Multicore Intelligent Payload Module for Orbital and Suborbital Remote Sensing Missions	$919,080	04/30/2015
Thomas Flatley	GSFC	Advanced Hybrid On-Board Data Processor, SpaceCube 2.0	$1,125,894	09/30/2012
Matthew French	USC / ISI	SpaceCubeX: A Hybrid Multi-core CPU/FPGA/DSP Flight Architecture for Next Generation Earth Science Missions	$923,000	07/01/2016
Design and Processing Tools				
Simone Tanelli	JPL	Instrument Simulator Suite for Atmospheric Remote Sensing	$1,489,600	08/01/2012
Jacqueline Le Moigne	GSFC	Tradespace Analysis Tool for Designing Earth Science Distributed Missions	$528,000	07/01/2016
Meemong Lee	JPL	Sensor-Web Operations Explorer (SOX)	$1,607,940	09/24/2009
Christopher Lynnes	GSFC	Multi-Sensor Data Synergy Advisor (MDSA)	$811,497	04/20/2012
Amy Braverman	JPL	Geostatistical Data Fusion for Remote Sensing Applications	$1,257,850	04/30/2012
Amy Braverman	JPL	Multivariate Data Fusion and Uncertainty Quantification for Remote Sensing	$1,496,000	08/01/2015

5.3.1 Technology Assessments

During the course of these studies, no technology development was identified as required to enable the mission architecture. This finding was corroborated in part by a parallel study by the cross-Center Systems Engineering Working Group (SEWG) chartered by NASA's Earth Science Division. Therefore, investments in GEO-CAPE technology are mission-enhancing, not enabling.

The SEWG conducted a technology readiness assessment for several GEO-CAPE instrument concepts and concluded that technology readiness levels (TRL) were equal to or greater than TRL 6. The TRL assessments are performed to aid in the determination of the maturity of the instrument technology either being proposed or under development at each milestone phase of either the project or development lifecycle. The assessment is performed from the lowest intact component level (not EEE parts), such as detector array, lens or filter coating, detector read out electronics (if never used or flown before), etc. The assessment also looks at vendor components such as star trackers, mechanism, gyros, diffuser/filter wheels, etc., all of which are an integral part of the instrument system.

5.3.1 1 Coastal Ocean Color Technology Readiness Assessments Completed

Three different ocean instruments were assessed for TRL readiness: COEDI, GeoSpec, and MOS, with results of:

- Multi-Slit Optimized Spectrometer (MOS)—This ESTO IIP funded spectrometer was developed by Ball Aerospace & Technologies Corp. After a successful demonstration at the completion of the IIP MOS was supplemented by a telescope and data acquisition system and subsequently flown on a Twin Otter in conjunction with the NASA Interdisciplinary

Science project "Impacts of Population Growth on the San Francisco Bay and Delta Ecosystem." Coincident airborne and in-water data collections validated MOS's ability to deliver science grade data as evidenced by retrieval of chlorophyll and turbidity with an instrument uncertainty of <2%, comparable to the best spaceborne instruments. MOS exited the IIP at TRL 4 for space and TRL 9 for airborne.

- A GSFC Instrument Design Laboratory (IDL) study was performed at GSFC in August 2012 for the Coastal Ocean Ecosystem Dynamics Imager (COEDI). At the time of assessment, it was determined to be at TRL 5 and remains under development by Goddard Space Flight Center (GSFC). The instrument concept presented only had one low TRL item—the Zero Pitch Flexures, at TRL <6. The Diffuser Select Assembly is a scaled-up version of flight heritage from the Geostationary Ocean Color Instrument (GOCI). The scaled-up version's size has no previous flight heritage and, as a result, was determined to be TRL 5 until environmental testing is be performed and the results assessed.
- Geostationary Spectrograph (GeoSpec)—The primary mirror stabilization system of the instrument was assessed to be TRL 3 for a spatial resolution of 300 m. Studies have been performed to support feasibility and no hardware has been built and tested at the time of the assessment. Mirror stabilization systems for larger spatial resolution have been proven in flight and continue to fly.

5.3.1.2 Atmospheric Composition Technology Readiness Assessment Confirms Concept Maturities

The SEWG reviewed draft TRL assessments for four instruments covering the full range of atmospheric composition instrument requirements (GEO-MAC, PanFTS, CHRONOS, and IRCRg). The results were:

- Geostationary Multi-spectral Atmospheric Composition (GEO-MAC) is a UV-Vis instrument concept for GEO-CAPE assessed in the GSFC IDL. At the time of assessment, it was determined to be TRL 6 due to an immature mirror mount, which is Landsat Data Continuity Mission (LDCM) heritage. All other components were assessed at TRL ≥8. Since the assessment, the LDCM has launched and been operational since February 2013.
- Panchromatic Fourier Transform Spectrometer (PanFTS) presented options for several spectral regions relevant to GEO-CAPE – in November 2011, JPL Team X performed an instrument conceptual design for four different instrument configurations using as much heritage as possible. PanFTS was determined to be at TRL 6 by Team X due to several common components within all four configurations. The SEWG assessment concurred with this finding.
- CHRONOS addresses GEO-CAPE's infrared instrument requirements—In June 2013, the Langley Research Center (LaRC) team presented an instrument design concept study, which had been peer reviewed in an Earth Venture proposal, including a TRL assessment. The CHRONOS study was performed using as much heritage as possible and it was determined to be at TRL 6 due to several components, some of which have launched and are currently operational on orbit. . The SEWG assessment concurred with this finding.
- Infrared Correlation Radiometer for GEO-CAPE (IRCRg) is an Instrument Incubator Project prototype for a GEO-CAPE infrared instrument—in June 2013, the LaRC team presented the

instrument performance results, which included a TRL assessment. The IRCRg demonstration instrument had been designed, fabricated, and operated within a thermal-vacuum environment, and it was determined to be at TRL 6. The SEWG assessment concurred with this finding.

5.3.2 ESTO Investments

Geostationary Spectrograph for Earth and Atmospheric Science Applications, or GeoSpec, is an early ESTO IIP project lead by GSFC that concluded in 2007, and demonstrated the feasibility of UV/VIS/NIR hyperspectral imaging from geostationary orbit. The project successfully designed and fabricated the optical bench structure and the system optics, which were also tested for polarization sensitivity, spectral sampling, image quality and detector packaging, and thermal control.

GeoSpec instrument team members went on to develop the Geostationary Trace Gas and Aerosol Sensor Optimization, or GEO-TASO (Figure 5-2), another IIP project headed by Ball Aerospace that concluded in 2014. The GEO-TASO team successfully built a wide-angle push broom UV/VIS spectrometer and the associated retrieval algorithms. The airborne spectrometer was flown in the Earth Venture (EV) DISCOVER-AQ field campaign (see Section 6). The EV-Suborbital project DISCOVER-AQ field campaigns generated test data for algorithm development. This capability is important because engineering models are not typically part of cost-constrained missions. For GEO-CAPE, the prototype data (from airborne remote sensors) is crucial to support development and testing of the analysis models at GEO-CAPE's high spatial resolution (much smaller than 1 degree x 1 degree in the models) and high temporal resolution (much better than daily or 6 hourly updates in the models).

Figure 5-2. Tom Delker (left) and Jeremy Craner (right) from Ball Aerospace, with NASA Langley's Les Kagey (center), installing the GEO-TASO instrument on the NASA Falcon in 2013. GEO-TASO is a test bed for the TEMPO instrument. (Image Credit: NASA/David C. Bowman)

In 2007 and again in 2010, ESTO awarded IIPs to design and develop an engineering model for the PanFTS, an imaging Fourier Transform Spectrometer (FTS) designed to operate in geostationary orbit, to increase the PanFTS TRL. In 2011, ESTO's Advanced Information Systems Technology (AIST) program awarded the development of on-board processing to advance the PanFTS imaging system for GEO-CAPE. In January 2015, a companion technology validation experiment, the GEO-CAPE ROIC In-Flight Experiment (GRIFEX, Fig. 5-3) CubeSat was launched from Vandenberg AFB, as an auxiliary payload to the SMAP mission. GRIFEX was intended to verify the spaceborne performance of a readout integrated circuit (ROIC) / Focal Plane Array (FPA) with in-pixel digitization and frame rate of 16 kHz for imaging interferometry instruments and missions. The detector technology maturation supports the imaging system for a PanFTS instrument, and its ROIC is based on a 2008 ESTO Advanced Component Technology (ACT) investment.

Figure 5-3. A 3-unit CubeSat launched in 2015 to validate theROIC technology (Image Credit: NASA JPL and U. Michigan).

5.4 Ongoing and Future Work

ESTO has continued to invest in the 2010 IIP awards with a mirror enhancement to the GEO-TASO instrument to increase its SNR performance prior to the KORUS campaign, and a recently concluded task with the Multi-slit Optimized Spectrometer (MOS) to perform an aircraft demonstration of the key multi-slit performance with real world scenes. The GEO-CAPE community continues to propose mission-enhancing technologies for peer-review and funding through ESTO processes.

5.5 Summary

GEO-CAPE's high TRLs, , science obtained through separate missions with co-incident observations adding value, and reduced cost of access to geostationary orbit through commercial hosted payloads position GEO-CAPE to be prepared to launch in this decade. The Earth Science Division (ESD) and ESTO investments continue to buy down risk for GEO-CAPE, along with continued liaison with ongoing ESD hosted payload efforts (Earth Venture TEMPO, U.S. Air Force Hosted Payload Solutions (HoPS) Program, NASA's Common Instrument Interface (CII)) to refine the mission architecture and cost. ESTO assessments confirmed the maturity of instruments and technologies presented for the GEO-CAPE mission.

Ongoing instrument study activities are targeted to inform requirements definition and leverage substantial Earth Venture, ESTO, Research and Analysis, and Airborne Science Program investments. The GEO-CAPE team is confident that a range of technologically mature instrument solutions exist that can meet GEO-CAPE requirements, and after leveraging ESTO instrument studies will be better able to successfully propose within well-understood cost caps.

6. FIELD CAMPAIGNS

6.1 Introduction

The GEO-CAPE study team accomplished a range of field campaign activities that often simultaneously served the needs of both its ocean color and atmospheric science communities. The team was extremely fortunate to be able to leverage major activities funded by other Earth Science Division program elements, for example by adding ship-based campaigns to air quality campaigns being conducted in coastal regions under Earth Venture Suborbital funding and by using sensors developed under NASA Earth Science Technology Office (ESTO) funding.

6.2 Coastal Ocean Color Studies

6.2.1 Coastal Ocean Color Studies Initial State in 2009

Prior to 2009, datasets containing information relevant to GEO-CAPE spatial resolution, temporal frequency and spectral resolution requirements were either inadequate or did not exist. Furthermore, datasets containing a comprehensive suite of coincident measurements necessary to address GEO-CAPE science objectives and requirement specifications did not exist. Such a comprehensive suite of measurements included ocean optical properties (water-leaving radiances, absorption, scattering coefficients), process rate measurements (primary production, net community production), phytoplankton taxonomy, biogeochemical constituents (carbon and nutrient stocks, phytoplankton pigments, etc.), physical properties (temperature, salinity), and atmospheric chemical properties necessary for ocean color atmospheric correction including aerosol properties (aerosol optical thickness, single scattering albedo), and absorbing trace gas measurements (column ozone and NO_2). The NOAA GOES-R Coastal Ocean Applications and Science Team (COAST) conducted an experiment in Monterey Bay, California, in September 2006 that examined temporal and spatial requirements for the GOES-R Coastal Waters Imager (Davis et al. 2007). Based on that experiment, COAST recommended a measurement frequency of at least 3 hours and spatial resolution of 300 m, though a ground sample distance (GSD) of <100 m for turbid waters (Davis et al. 2007). An airborne coastal ocean color campaign during the summer of 2001 that was associated with the Office of Naval Research-sponsored HyCODE LEO-15 study (central New Jersey coastal ocean) recommended GSD of <50 m within 1 km of the coast, and 50–200 m GSD within 1–10 km of the coast (Bissett et al. 2004). For areas beyond 10 km from the shore, Bissett et al. (2004) suggested that the required GSD would be dictated by the spectral information and that hyperspectral data would be better suited to resolving coastal optical properties and thus constituents. Such studies provided a basis for GEO-CAPE requirements, but it was apparent that further work was needed among diverse coastal systems to develop and justify measurement and instrument requirements for the GEO-CAPE coastal ocean color sensor.

6.2.2 Coastal Ocean Color Studies Accomplishments 2009–2015

To provide datasets that can be evaluated to refine the measurement and instrument requirements developed by the Science Working Group (SWG), the GEO-CAPE mission has supported two coastal field campaigns collecting an intensive suite of optical, in-water constituent, and biological rate data.

In July 2011, the Chesapeake Bay Oceanographic campaign with DISCOVER-AQ (CBODAQ) was performed with the primary goal of obtaining detailed atmospheric and oceanographic observations for characterizing short-term dynamics and spatio-temporal variability in atmospheric composition and coastal ecosystem processes. These results have been used to confirm the spatial and temporal resolution requirements in the Science Traceability matrix (STM). This campaign was designed to coincide with the NASA DISCOVER-AQ (Deriving Information on Surface Conditions from COlumn and VERtically Resolved Observations Relevant to Air Quality) Earth Venture (EV-1) airborne project.

The CBODAQ activity consisted of 10 daily cruises (~12 hours each) from July 11 to 20, 2011 aboard the NOAA SRVx vessel. Several sampling modes were conducted during the field campaign to address GEO-CAPE science objectives, including (1) transects—sampling a series of stations along a gradient (north to south, river tributary to open waters of the bay, marsh creek to open bay); (2) sampling a water mass throughout a day by following a surface drifter; and (3) sampling the same location throughout a day.

During the 10 days of operation in the Bay, the cruise participants sampled 71 discrete stations. Two in-water profiling radiometers, C-OPS (Biospherical Instruments, Inc.) and HyperPro (Satlantic), were deployed to estimate the water-leaving radiances in the UV-Vis-NIR spectral range. An above-water custom radiometer was also employed to measure water-leaving radiances in the UV-Vis-NIR. An inherent optical properties (IOP) package with a suite of optical sensors was deployed to compute in-water profiles of spectral particle and dissolved absorbance, particle volume scattering function, fluorescence by chlorophyll and dissolved organic matter as well as salinity and temperature. An underway seawater instrument package measured surface concentrations of pCO_2, dissolved oxygen, sea-surface temperature, salinity, turbidity and fluorescence by chlorophyll and colored dissolved organic matter (CDOM). Seawater samples were collected at multiple depths by deploying Go-Flo bottles. Primary production experiments were conducted on the ship daily with collected seawater samples. Laboratory analyses of the seawater samples included phytoplankton pigments, fluorometric chlorophyll-a, pCO_2, dissolved inorganic carbon, alkalinity, dissolved organic carbon and nitrogen, particulate organic carbon and nitrogen, nutrients, CDOM and particle absorption, fluorescence of CDOM, and suspended particulate matter. Data were submitted to NASA's ocean biology and biogeochemistry data archive (SeaBASS; http://seabass.gsfc.nasa.gov/).

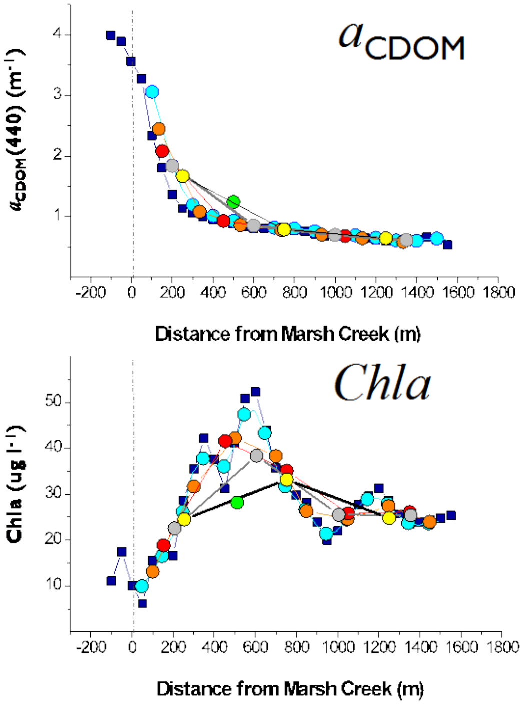
Several atmospheric sensors were employed on the ship to collect measurements of aerosols and trace gases. A new modified Pandora sensor (using feedback from a digital camera to the sun-tracker) was used for continuous measurements of atmospheric trace gases (total column NO_2, O_3, SO_2) from the ship. A set of analytical instruments continuously collected and monitored ozone, NO, and NOy levels within the marine boundary layer (http://www.atmos.umd.edu/~RAMMPP/Instruments.html). A micropulse lidar was installed on the evening of July 15th to conduct measurements of aerosols and clouds including aerosol and cloud layer heights (http://www-air.larc.nasa.gov/missions/discover-aq/reports/). Air samples were collected throughout each day for laboratory analysis of aerosols including water-soluble organics and inorganic ions as well as measurements of methane, CO_2, and N_2O. One Microtops Ozonometer and two Microtops sunphotometers were used for measurements of total column ozone and aerosol optical thickness (AOT) in the spectral range 340–936 nm (data available through the AERONET/Marine Aerosol Network; http://aeronet.gsfc.nasa.gov/new_web/cruises_new/Discover_AQ.html)

During four flight days of the DISCOVER-AQ activity, the NOAA SRVx was positioned to sample in the upper bay (between Baltimore and south of Annapolis) to provide ground-truth data for DISCOVER-AQ. These airplanes (UC-12 and P3-B) conducted several passes over the ship location each day, including some spiral flight tracks by the P3-B directly over the ship. Observations collected by the ACAM sensor (UV-Vis radiometer) and the HSRL (lidar) in the DISCOVER-AQ payload will also be applied for ocean color analyses.

The field data were used to improve chlorophyll-a (chl-a) retrieval algorithm to establish long-term patterns. Its findings justify the use of more spectral bands such as those required for GEO-CAPE so one can choose the optimal bands for algorithm development (Le et al. 2013). Results demonstrate significant diurnal variability in chl-a on time scales of 1 to 2 hours. Such findings have changed the temporal resolution threshold requirement for the survey mode from <3 hours to <2 hours. Ocean color satellite data analysis of MODIS 250 m data showed that a spatial resolution of <500 m is necessary to capture the spatial variability in turbidity across river and estuarine plumes and adjacent ocean waters (Aurin et al. 2013). Overly coarse spatial resolution can introduce significant error in data products as observed near the land-water interface of Chesapeake Bay (Tzortziou et al. in prep; Fig. 6.-1). A spatial resolution of better than 250-300 m is recommended to resolve gradients in biogeochemical and optical properties between wetlands and estuarine waters and to study processes at the land-ocean interface where strong photochemical and microbial transformations result in non-conservative mixing with salinity.

Based on risk reduction recommendations from the GEO-CAPE Mission Design Coordination (MDC) group, a second field experiment was designed to enable a more thorough understanding of temporal and spatial mission requirements and to collect data sets that could be analyzed to address exchanges across the land/ocean interface. In order to effectively address the STM science questions, we chose a region exhibiting intense spatial and temporal variability in biogeochemistry and optically active constituents. This experiment, named NASA GOMEX, was conducted in the northern Gulf of Mexico from September 9–22, 2013 and was coordinated to coincide with the 2013 NASA DISCOVER-AQ field campaign, due in part to the availability of airborne sensor capabilities.

The cruise originated in Cocodrie, Louisiana, aboard the UNOLS Vessel Pelican and proceeded westward to Galveston, Texas, before returning. One hundred-and-nine (109) stations were sampled, and measurements made during transects along gradients allow questions of spatial variability to be addressed. The sampling strategy included cross shelf stations, a (24-hr) occupation of the WAVECIS AERONET ocean color site, a transect up the Mississippi to Pilottown, Louisiana, where (<1 psu was encountered), tracking of five Lagrangian drifter deployments to investigate diurnal evolution of biology and biogeochemistry, and small boat activities in shallow marsh-dominated waters and urban river outflows in Galveston Bay. A drifter deployment southwest of the Mississippi River delta showed a significant increase in dissolved oxygen (Fig. 6-2a), chlorophyll-a (Fig. 6-2b) and particulate organic carbon between



	a_{CDOM}	chl-a
100m	± 7%	-10% to 25%
200m	up to 13%	-20% to 40%
300m	up to 25%	-20% to 40%
400m	up to 36%	-25% to
500m	> 40%	-25% to 40%
1 km	> 40%	-40% to 55%

Figure 6-1. Field data of CDOM absorption coefficient (a_{CDOM}) and Chl-a collected at various locations along transect from the surface of the Kirkpatrick Marsh to open waters of Chesapeake Bay (Tzortziou et al. in prep.).

approximately 8 a.m. to 6 p.m. local time, which are consistent with increasing phytoplankton production and biomass from morning to late afternoon.

To address sensor requirements and algorithm development a comprehensive suite of IOP, AOP, physical, and biogeochemical measurements were taken with the measurement suite similar to that taken on the Chesapeake cruise described above. Continuous underway IOPs were collected, and small boat operations allowed the team to access more optically complex waters. Furthermore, phytoplankton taxonomy data through both flow-cytometry and microscopic taxonomy have also been collected.

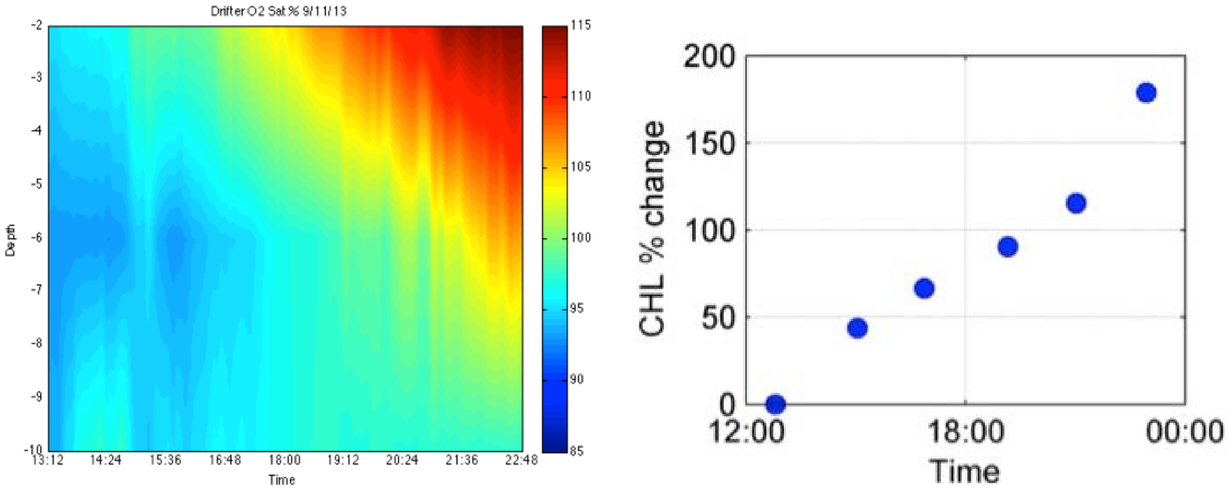


Figure 6-2. Diurnal change in a Gulf of Mexico water mass (a, left) dissolved oxygen saturation and (b, right) chlorophyll-a percent change in near surface waters (Mannino et al., in prep.) between approximately 8am to 6pm local time during a drifter experiment on September 11, 2013, conducted southwest of the Mississippi River delta. Time shown in UTC (local + 5 hours).

6.2.3 Ongoing and Future Work

A workshop to discuss field campaign results, manuscript preparations, and explore synergistic collaborations among co-I's took place in conjunction with the 2015 GEO-CAPE Community Workshop.

These past experiments did not include measurements from a geostationary platform such as from the Korean Geostationary Ocean Color Imager (GOCI), thus they were unable to address some specific questions related to using data from a sensor in a geo orbit to address the dynamics of coastal waters. Resolving these questions is critical for defining key GEO-CAPE ocean color requirements and reducing mission risk regarding atmospheric correction, BRDF and other elements involved in ocean color data processing. Thus, the GEO-CAPE OSWG has planned to undertake a 2-week joint field campaign in the East and Yellow Seas with scientists from the Korea Institute of Science and Technology (KIOST). This field campaign called KORUS-OC will occur in May 2016 to coincide with the joint U.S.-Korean air quality campaign supported by NASA (KORUS-AQ). Defining appropriate requirements and advancing our understanding of the challenges posed by geo ocean color will require continued support for field activities such as KORUS-OC and PI-led measurement collection and data analysis, development of simulated GEO-CAPE ocean color datasets, satellite data analysis, and studies to resolve challenges in atmospheric correction and BRDF.

6.3 Atmospheric Composition Studies

6.3.1 Atmospheric Composition Studies Initial State in 2009

There is a rich history of NASA tropospheric chemistry R&A airborne field campaigns prior to the GEO-CAPE era. From 1983 to 2001 a series of 16 campaigns was conducted within the Global Tropospheric Experiment (GTE) project. GTE exploratory studies helped establish fundamental understanding of tropospheric ozone and aerosol distributions including the influences of emissions, chemistry, and redistribution through long-range transport [http://www-gte.larc.nasa.gov/GTE_Bibliography/gte_bib2.pdf]. Following the launches of the EOS satellites in 1999 – 2004, subsequent tropospheric chemistry campaigns (TRACE-P 2001; INTEX 2004 and 2006; ARCTAS 2008; SEAC4RS 2013) conducted increasingly comprehensive targeted surveys while also validating and using the available satellite remote sensing observations. Validation activities associated with the EOS-Terra MOPITT and MODIS, EOS-Aqua MODIS and AIRS, and EOS-Aura OMI and TES instruments are particularly relevant to GEO-CAPE, since GEO-CAPE products are similar to those currently available from these sensors. GEO-CAPE relevant validation capabilities developed and/or demonstrated in the field campaigns funded under EOS and R&A programs include: systematic ozone vertical profile measurements via ozone sondes; airborne in-situ and remote-sensing tropospheric vertical profile measurements of aerosol, O_3, NO_2, HCHO, CO, CH_4, and NH_3; and the development of ground-based (Pandora) and airborne (Airborne Compact Atmospheric Mapper (ACAM)) instruments for remote sensing of O_3, NO_2, and HCHO.

6.3.2 Atmospheric Composition Studies Accomplishments 2009–2015

GEO-CAPE has benefited tremendously from other ESD investments since 2010 and has been able to effectively leverage them in field campaigns through targeted augmentation with mission study funding. A major highlight has been the use of the Geostationary Trace gas and Aerosol Sensor Optimization (GEO-TASO) airborne TEMPO simulator during the final two DISCOVER-AQ deployments.

The EVS-1 DISCOVER-AQ project (see Section 8.1) was a pathfinding 2011–2015 effort to improve the usefulness of satellite data for air quality science and applications. In particular, DISCOVER-AQ simultaneous observations of remotely sensed columns and in-situ concentrations of pollutants multiple times per day will be crucial for preparing for geostationary observations. Development of the airborne GEO-TASO instrument (see Section 5.3) was funded by ESTO following proposal selection via the 2010 Instrument Incubator Program solicitation. GEO-TASO is a nadir-viewing UV/VIS spectrometer that covers the same spectral range as TEMPO, providing column measurements of O_3, NO_2, HCHO, and aerosols. Initial flight demonstration of GEO-TASO occurred in July 2013 on a NASA HU-25C Falcon aircraft. In partnership with ESTO and DISCOVER-AQ, GEO-CAPE funded the first deployment of GEO-TASO to Houston, Texas, in September 2013 in concert with 10 days of the DISCOVER-AQ Houston campaign. In FY14, GEO-CAPE funded deployment of GEO-TASO on the Falcon in concert with the full month-long DISCOVER-AQ Denver campaign. A particular success was the creation of TEMPO/GEO-CAPE test-bed data sets. As a TEMPO airborne simulator, GEO-TASO was flown in a raster pattern over most of the DISCOVER-AQ Denver domain to provide hourly maps of the species that TEMPO will observe. As an example, Figures 6-3 and 6-4 show how NO_2 changes from late-morning to mid-afternoon on the same day. These deployments were highly synergistic; the data from DISCOVER-AQ airborne and ground assets provided extensive correlative data for the GEO-TASO observations, while the GEO-TASO mapped data products augmented the DISCOVER-AQ dataset by providing contiguous horizontal information (i.e., maps). These TEMPO-simulator measurements are providing a very effective means of illustrating the potential of GEO-CAPE observation to the U.S. air quality applications community (including US EPA and state/local air quality agencies).

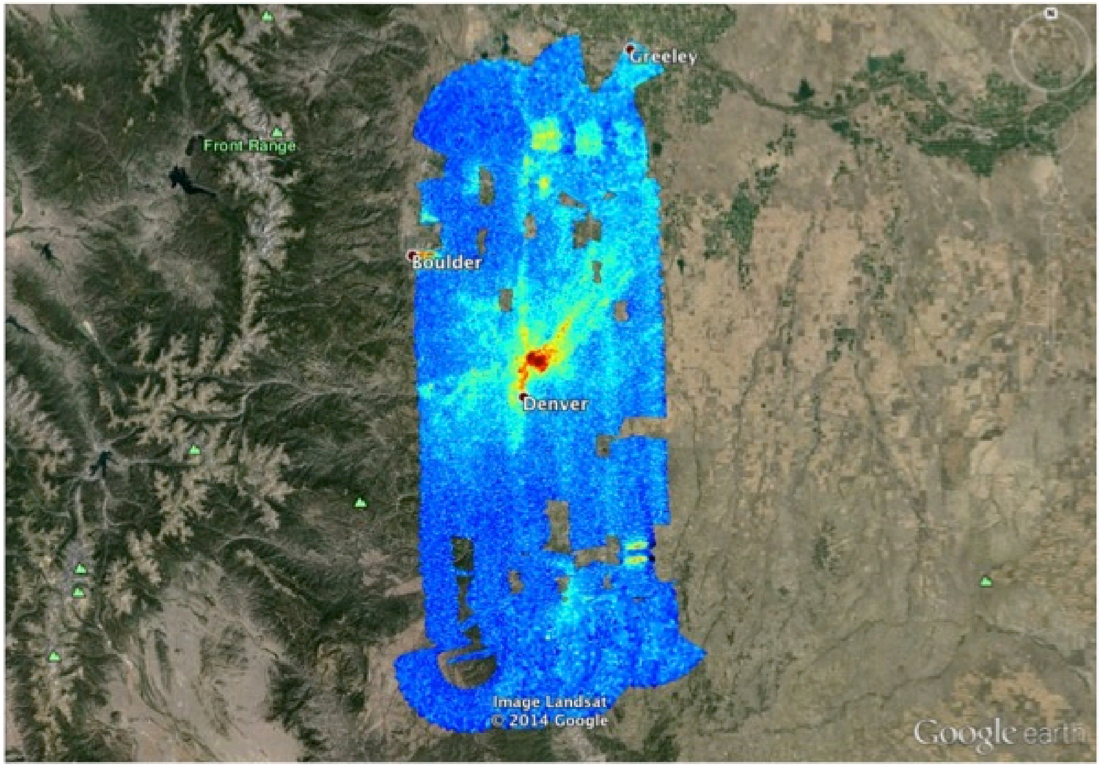


Figure 6-3. Map of preliminary column NO2 retrievals from a 45-minute segment of GEO-TASO flight in late morning of August 2, 2014.

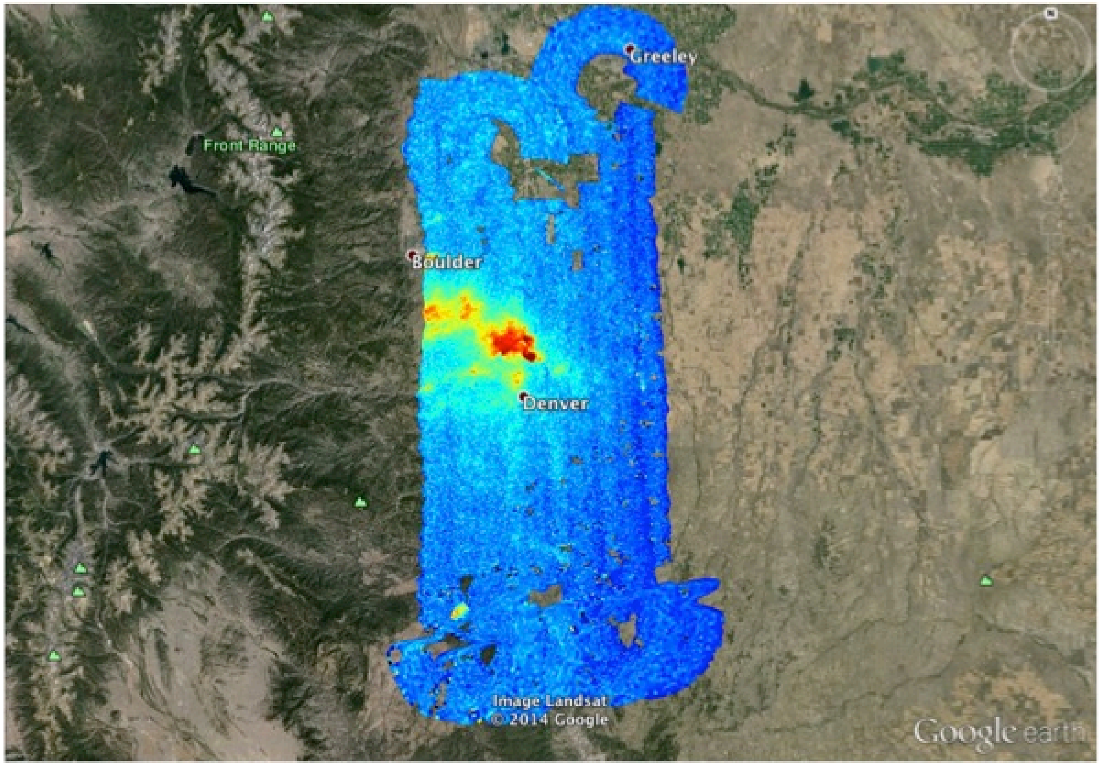


Figure 6-4. As in Figure 6-3 but for early afternoon.

In FY15 a large emphasis is being placed on producing and analyzing mature data products from the GEO-TASO measurements acquired to date. Activities include improved instrument calibration and improved retrieval algorithms. One core piece of DISCOVER-AQ was airborne remote-sensing measurements of the GEO-CAPE species O_3, NO_2, and HCHO from the ACAM instrument (or, in the latter deployments, from an upgraded instrument called GEO-CAPE Airborne Simulator (GCAS)) on a NASA King Air aircraft. ACAM/GCAS and GEO-TASO make similar measurements but the instruments have different characteristics (including spectral range, native spatial resolution, and signal to noise performance). ACAM/GCAS and GEO-TASO retrievals are being evaluated through comparison with aircraft in-situ, ground-based Pandora remote sensing, and OMI satellite data. Data from coincident flights of ACAM/GCAS on the King Air and GEO-TASO on the Falcon during flights in the Houston and Denver areas offer the chance to evaluate and compare retrievals from each of those instruments. Also of interest is a comparison of retrievals, using the best information available from DISCOVER-AQ observations, with those that do not incorporate any information from DISCOVER-AQ. Such comparisons will help assess what information is most valuable and guide optimization of future ground networks to best serve an observing strategy that includes GEO observations. These activities will significantly advance mission readiness of the TEMPO/GEO-CAPE retrieval algorithms.

The initial GEO-TASO measurements were so promising that the study team began identifying priorities for future data sets to be obtained with the instrument. Although the NASA Falcon is an excellent platform for GEO-TASO, it is also a relatively expensive aircraft to operate, limiting future flight opportunities. Therefore in FY15 the GEO-TASO mounting fixture was adapted so that the instrument could also be accommodated on other aircraft, such as a NASA King Air. The new capability was demonstrated in summer 2015 by installing GEO-TASO and GCAS together on a NASA King Air and conducting 3 local flights from Langley Research Center. These flights included several overflights of a NOAA research ship conducting ocean color measurements and also a mapping flight (similar to Figs. 6-3, 6-4) of the Hopewell, Virginia, area, which is believed to experience high industrial emissions of HCHO. Analysis of these data will occur in FY16.

Another highlight of GEO-CAPE funded field campaign activity concerns atmospheric methane measurements. A key GEO-CAPE measurement objective is to map the distribution of atmospheric CH_4 with high precision and high spatial resolution. CH_4 is one of the key precursor hydrocarbons driving tropospheric ozone formation and is a major radiative forcing component for global climate. In FY14, GEO-CAPE leveraged the investments of several NASA and non-NASA programs by supporting data acquisition and analysis of CH_4 data using the ground-based CLARS-FTS instrument which overlooks the Los Angeles basin from an altitude of 5700 ft. on Mt. Wilson, California. CLARS-FTS is a near-infrared interferometer, and a precursor to the flight-like Panchromatic Fourier Transform Spectrometer (PanFTS) instrument discussed below (and in Section 5). CLARS-FTS maps the spatial and temporal distributions of CH_4, CO_2, CO, and O_2 across the LA basin using a scan pattern that focuses on selected reflection points to build up hourly maps, similar to the data products that would be produced by GEO-CAPE. CLARS-FTS has been acquiring data every day, weather permitting, since mid-2011 with the data publically available in the near future (https://megacities.jpl.nasa.gov/portal/data). Fu et al. (2014) have described the CLARS-FTS instrument, retrieval algorithms, sample data and precision in detail.

Figure 6-5 shows sample diurnal XCH_4 and XCO_2 data from two LA basin reflection points over a week's period in May, 2012. The "X" designation indicates that the slant column abundance of the gas has been divided by the measured O_2 slant column abundance to obtain the dry-air column mixing ratio. The figure shows that both XCH_4 and XCO_2 exhibit large diurnal variability as would be expected in a megacity with large emissions of both species from transportation, fossil fuel combustion and many other sources. The CLARS-FTS averaging kernels favor the PBL because of the long optical slant path in the boundary layer. Measurements from GEO-CAPE or from an aircraft platform would not show such large diurnal variations because of the much smaller viewing angles.

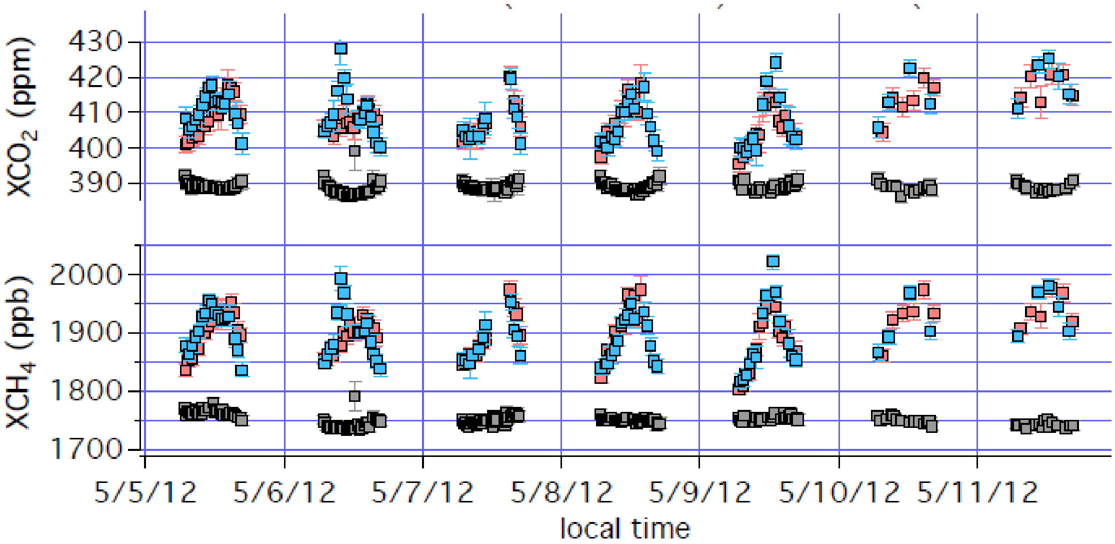


Figure 6-5. Diurnal variations of XCH_4 and XCO_2 from two CLARS-FTS reflection points centered in west Pasadena (red) and Santa Anita Park (blue) on seven consecutive days in May 2012. The black points are from observations in the free troposphere using a Spectralon target near the instrument (from Wong et al. 2015).

Wong et al. (2015) have used the CLARS-FTS data to determine the Los Angeles basin-averaged CH4 emissions from maps of relative CH_4:CO_2 emission ratios. One such map is shown in Fig. 6-6, which shows that XCH_4:XCO_2 exhibits large spatial variability across the LA basin. Since the uncertainty in CO_2 emissions inventories is much smaller than those for CH_4, analysis of the emission ratios provides an excellent top-down constraint on seasonal CH_4 emissions over multiple temporal and spatial scales. The derived CH_4 emissions of 0.39 ± 0.06 Tg/year are 18–61% larger than the state government's bottom-up estimates for the Los Angeles basin (Wong et al. 2015).

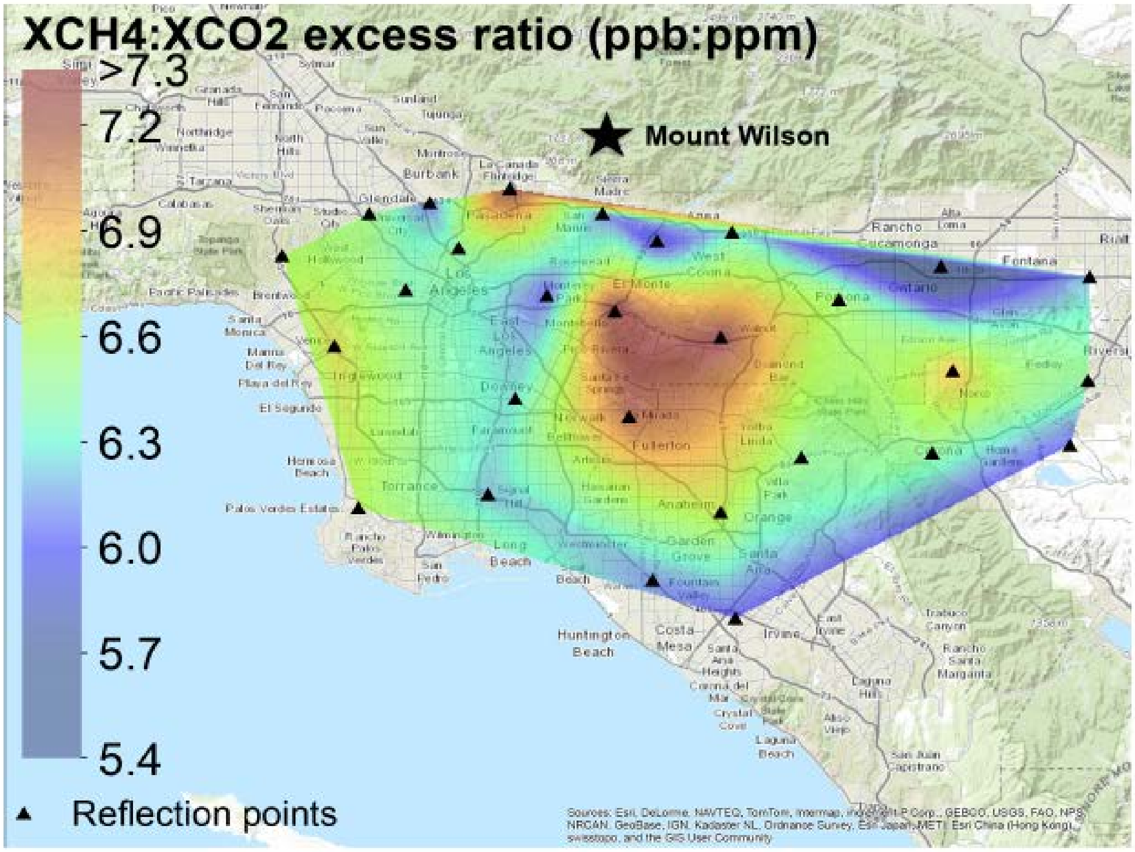


Figure 6-6. Map of the correlation slope of XCH_4 (XS):XCO_2 (XS) ratio in the Los Angeles megacity observed by CLARS-FTS during the period Sept., 2011–October, 2013. From Wong et al. (2015).

6.3.3 Ongoing and Future Work

While the GEO-TASO data products are still preliminary, the previous deployments have been considered such a success that the GEO-CAPE team received ESD Flight direction to proceed with additional targeted GEO-TASO data acquisition in FY15-16. The GEO-CAPE study team is now planning to fund deployment of a small aircraft able to accommodate GEO-TASO or a similar instrument during the 2016 Korea-U.S. Air Quality (KORUS-AQ) study, leveraging planned R&A investments (ROSES 2015 Element A.19). Deployment of an instrument like GEO-TASO during the 2016 KORUS-AQ campaign is already a TCP programmatic priority; the KORUS-AQ white paper lists remote sensing measurements of trace gas columns (O_3, NO_2, C_2HO) and multi-spectral optical depth as Priority-1 (required) measurements. Korea is an excellent location for conducting additional geostationary air quality simulator measurements, given the linked development of the TEMPO and Korean GEMS instruments. These measurements will foster additional U.S./Korea algorithm collaboration and harmonization, also supporting CEOS-ACC Air Quality constellation objectives. As demonstrated during DISCOVER-AQ Denver, an optimal flight strategy for simulating geostationary observations is to conduct regular raster flights at constant altitude. However, the primary NASA aircraft in KORUS-AQ (NASA DC-8) is anticipated to spend substantial flight time conducting vertical profiling with an in-situ payload. Thus, the GEO-CAPE funding of an independent remote-sensing platform will maximize data collection from all instruments. Deployment in concert with an ongoing campaign will once again provide extensive correlative ground-based and airborne observations.

The CLARS-FTS results on CH_4 emissions in the Los Angeles basin showed that persistent, wide-area measurements of trace gases from a “geo-like” vantage point hold great utility for quantifying sources with high spatial and temporal resolution. Over the past several years, the next-generation spectrometer, PanFTS, specifically designed to demonstrate key technologies required for GEO-CAPE measurements, has been developed under several ESTO programs including IIP-07, IIP-10, ACT-08, AIST-12 and others (Key et al. 2012). While CLARS-FTS has a single “pixel” which is pointed to a set of discrete reflection points to build up spatial and temporal maps, PanFTS is a true imaging interferometer using 128x128 pixel2 detector arrays. A version of PanFTS covering the 0.7–2.5 µm spectral range has been deployed on Mt. Wilson, and will begin measuring the same complement of trace gases as CLARS-FTS. As part of the FY15 GEO-CAPE study, PanFTS will acquire data every day, weather permitting, and produce Level-2 maps several times per day. Fine spatial structure will be correlated with known CH_4 “hot spots” identified by CLARS-FTS in the Wong et al. (2015) study.

6.4 Summary

Field campaigns conducted with GEO-CAPE study funding are providing extremely useful sample data for beginning to engage ultimate users of GEO-CAPE data products. The campaigns have been able to effectively leverage activities within other ESD program elements, including the EVS-1 DISCOVER-AQ mission and ESTO-funded instrument developments. These activities are providing data for affirming and adjusting GEO-CAPE science measurement requirements (Section 3) and for refining and testing GEO-CAPE measurement algorithms (Section 7).

7. Measurement Algorithms

7.1 Introduction

At the beginning of GEO-CAPE studies, algorithms to derive data products from passive remote sensing radiances had mature heritage from low-Earth-orbit missions for both the ocean color and atmospheric composition disciplines. Mission study activities therefore generally focused on improvements to existing algorithms to adapt them to GEO-CAPE requirements. Examples include enabling accurate water data products in complex near-shore scenes and atmospheric data products at higher spatial resolution and at times of day other than the 2 satellite overpass times previously available from low-Earth orbit (LEO) missions.

7.2 Coastal Ocean Color Studies

7.2.1 Coastal Ocean Color Studies Initial State in 2009

Algorithms for the derivation of in water constituents from the measurement of water (ocean) color, represented by the remote sensing reflectance (Rrs), play a critical role in the observation and monitoring of global oceanic properties from satellite ocean color remote sensing. Among the various parameters, the ocean color research community focused on the following: chlorophyll a concentration (Chl), diffuse attenuation coefficient at 490 nm (Kd_490), euphotic zone depth (Zeu, m), concentration of total suspended particulate matter (SPM), dissolved organic carbon concentration (DOC), Inherent Optical Properties (IOPs) such as absorption and scattering coefficients of water constituents, as well as phytoplankton functional types (PFTs). Most of the algorithms are empirical where a parameter is derived through regression against Rrs in two or more bands. Alternatively, semi-analytical algorithms based on in-water IOPs are also developed and used by the community (Carder et al. 1999; Lee et al. 2002, 2005; Maritorena et al. 2002).

The following is a list of major ocean color data products with their associated algorithms applied to heritage sensors including SeaWiFS, MODIS, MERIS and now VIIRS: (1) For global ocean retrieval of Chl, the "operational" algorithm is the blue/green band ratio algorithm (OCx, O'Reilly et al. 2000). For coastal waters, some regional tuning of the algorithm coefficients or new algorithm forms using the red and near-IR bands to avoid perturbations of colored dissolved organic matter (CDOM) are proposed (e.g., Ruddick et al. 2001; Tzortiou et al. 2006; Gitelson et al. 2008; Dall' Olmo et al. 2005). Other approaches include neural-network (Keiner and Brown 1999; Doerffer and Schiller 1998) and semi-analytical algorithms (Maritorena et al. 2002); (2) The Kd_490 standard algorithm for global ocean retrievals is based on a blue/green band ratio (Mueller et al. 1997; Mueller 2000). Alternatively, semi-analytical algorithms based on IOPs have been proposed for the global ocean (Kd_lee; Lee et al. 2005a&b) and for some estuaries (e.g., Wang et al. 2009); (3) Euphotic zone depth (Zeu) is a measure of the clarity (or quality) of an aquatic system, and used in models for water-column primary production.

Historically Zeu is empirically estimated based on Chl (Morel 1988, Morel and Maritorena 2001). More recently an algorithm based on IOPs was developed (Lee et al. 2007) and validated (Shang et al. 2009) for Zeu; (4) There is no standard algorithm for SPM because it is not only a function of color (spectral reflectance) but also a function of particle size distribution and refraction index. SPM algorithms are region specific and thus can only be improved through regional field work and algorithm tuning (Gordon and Morel 1983; Miller et al. 2004; Hu et al. 2004; Doxaran et al. 2005); (5) The IOP algorithms include scattering properties and spectral absorption of phytoplankton, non-algal particle (NAP) and CDOM as well as Chl. For the global ocean, four algorithms have been implemented by NASA for routine data processing (Lee et al. 2002; Maritorena et al. 2002; Werdell et al. 2013). For coastal oceans, various empirical algorithms have been proposed using look-up-tables (LUTs) (Carder et al. 1999; Liu and Miller 2008) or band-ratio algorithms (Lee et al. 1998; D'Sa and Miller 2003; Doxaran et al. 2005; Mannino et al. 2008; Tzortziou et al. 2007; 2009), among others; (6) Determining various Phytoplankton functional types (PFTs) from space is experimental and often empirical in nature, and there is no standard algorithm (example algorithms include: Dekker 1993; Brown and Podesta 1997; Subramaniam et al. 2002; Sathyendranath et al. 2004; Alvain et al. 2005; Westberry et al. 2005; Ciotti and Bricaud 2006; Simis et al. 2007; Cannizzaro et al. 2008; Nair et al. 2008; Raitos et al. 2008; Ruiz et al. 2008; Tomlinson et al. 2009); (7) Nair et al. (2008) provides a review of size distribution for PFTs; and (8) A number of algorithms have been developed for the estimation of primary production, yet there is no general consensus on "standard" primary production products for NASA (see reviews of Campbell et al. 2002, Carr et al. 2006, and Friedrichs et al. 2009). Commonly used algorithms by the community include VGPM (Behrenfeld and Falkowski 1997) and CbPM (Westberry et al. 2008), with global products. Hyperspectral UV-Vis-NIR water-leaving radiances and narrower bands (≤5 nm) planned for GEO-CAPE will yield improved algorithms for product retrievals in coastal waters, which are particularly challenging due to their optical complexity from high concentrations of multiple constituents (sediments, phytoplankton, detritus, DOM). The diurnal measurement capability of GEO-CAPE enables quantification of processes such as primary production through changes in phytoplankton carbon and chlorophyll-a (Fig. 6-2b).

7.2.2 Coastal Ocean Color Studies Accomplishments 2009-2015

The Geo-Cape SWG members and other researchers have been working on these algorithms to overcome the various limitations with the following accomplishments. For the global ocean, Hu et al (2012) developed a band-difference algorithm (OCI algorithm), which significantly improved the data accuracy, image quality, and cross-sensor consistency over the NASA default OCx algorithms for most (~80%) of the global ocean where Chl is below 0.25 mg m^{-3}. For coastal/inland waters, Tzortziou et al. (2007, 2009) used red-green band ratios to retrieve Chl in the optically complex Chesapeake Bay estuarine waters. Le et al. (2013b&c) developed the Red-Green-Chlorophyll-Index (RGCI) to relate red/green band ratio to Chl for Tampa Bay and

Chesapeake Bay, and then applied to long-term MODIS and SeaWiFS data. The semi-analytical algorithm for Kd_490 has been further refined by Lee et al. (2013), where the spectral Kd can be derived. The algorithm also estimates the light penetration depth in the global ocean. For UV light attenuation, an EOF empirical approach, originally developed by Craig et al. (2012), was modified for MODIS over the Florida Keys for waters as shallow as 5 m (Barnes et al. 2014). The impact of Raman scattering on the semi-analytical retrieval of particle backscattering coefficient has been demonstrated by Westberry et al. 2013, and algorithms (Westberry et al. 2013; Lee et al. 2013) have been developed to reduce such an impact and to improve the retrievals for open-ocean waters. A generalized inversion algorithm for IOPs (GIOP) has been developed (Werdell et al. 2013). For coastal waters, to avoid the problems in the blue bands (mainly due to atmospheric correction artifacts), a hybrid approach to take advantage of semi-analytical and empirical retrievals has been developed to retrieve CDOM for Tampa Bay (Le and Hu 2013). For mineral-dominated estuarine waters (e.g., Chesapeake Bay estuary), an empirical approach was published for deriving non-algal particles (detrital material) using Rrs in red wavelengths (based on NAP backscattering signal), allowing for a better discrimination between CDOM and NAP absorption (Tzortziou et al. 2009). For continental margins and estuarine waters, Mannino et al. (2014) combined the advantages of several empirical and semi-analytical algorithms to estimate CDOM along the northeastern U.S. coast using SeaWiFS and MODIS data. The study also demonstrated that the addition of UV bands improved CDOM algorithm performance. A review of techniques for remote sensing of major phytoplankton groups has been provided by IOCCG (2014). Phytoplankton size classes have been classified using model-based spectral analysis (Mouw and Yoder 2010). PFTs have been classified from phytoplankton pigment absorption (Moisan et al. 2013). An algorithm based on the spectral curvature in the blue-green wavelengths was developed to differentiate diatoms from dianoflagellates, and applied to satellite data (Shang et al. 2014). A new algorithm has been developed by Hu et al. (2010a) to combine the MODIS ocean and land bands to overcome the difficulty in differentiating Trichodesmium blooms from other blooms in coastal waters. The FAI algorithm has been applied to Taihu Lake to document spatial/temporal patterns of cyanobacterial blooms (Hu et al. 2010b). This is possible because of the a priori knowledge of the Taihu environment. A 3-band subtraction algorithm has been developed to examine the spectral shape around 620 nm, which is further related to phycocyanin (PC) pigment concentration of cyanobacteria blooms in Taihu Lake (Qi et al. 2014). This simple algorithm is tolerant to many problems typically encountered in coastal/inland waters such as thick aerosols, sun glint, high turbidity, etc. A review chapter has been published in the recent IOCCG monograph to summarize the current algorithms to detect and quantify dominant algal blooms (Hu et al. 2014). The approach of using remotely sensed phytoplankton absorption coefficient to estimate primary production was further reinforced from a Southern Ocean experiment (Lee et al. 2011).

In addition to these algorithm-related accomplishments, the SDT members also worked on the priority issues identified for the GEO-CAPE mission, with the following accomplishments: Signal-to-noise ratios (SNRs) and typical/maximum radiance of heritage sensors have been quantified (Hu et al. 2012b), which provides the basis to specify typical/maximum radiance and SNR at various solar angles for GEO-CAPE. Uncertainty limits have been quantified through analysis of SeaWiFS and MODIS data over the ocean gyres (Hu et al. 2013). These limits serve as the lower bounds for the retrieved Rrs data. Impact of spatial resolution on retrieval accuracies has been demonstrated by Lee et al. (2012a). Requirement on spatial resolution to study turbidity (and TSM) in large river plumes has been studied and specified by Aurin et al. (2013). Requirements on spatial and temporal resolution to study DOC, CDOM, POC, Chl and DIC dynamics related to tidal marsh outwelling and carbon exchanges in wetland-estuarine systems have been studied and specified by Tzortziou et al. (2011a&b). Tzortziou et al. concluded that 3-hour temporal resolution and 250–500 m spatial resolution are needed to resolve biogeochemical gradients associated with wetland-estuarine exchanges. The advantage of multiple measurements per day has been demonstrated by a series of studies using GOCI and GOES-Imager (Taihu Lake primary production, Lee et al. 2012b; Red tide in East China Sea, Lou and Hu 2014; Trichodesmium bloom on the west Florida shelf, Hu and Feng 2014). Tidal effect on optical properties of Chesapeake Bay has been quantified through analyzing MODIS data (Shi et al. 2013). The impact of NO_2 on ocean color retrievals has been demonstrated by Tzortziou et al. (2014). High-spatial and -temporal resolution retrievals of atmospheric NO_2 are critical for geostationary ocean color measurements in highly polluted coastal areas, to avoid aliasing atmospheric variability for diurnal changes or spatial gradients in ocean composition (Tzortziou et al. 2013, 2014; He et al. 2014; Loughner et al. 2014; Goldberg et al. 2014). Even if wavebands in the spectral range affected by NO_2 absorption (i.e., 330–490 nm) are not used for Chla retrievals, this spectral range is crucial for space-based retrievals of CDOM and DOC dynamics (Tzortziou et al. 2014). Nick Tufillaro in collaboration with Erik Bollt, and colleagues at Clarkson University developed a framework for estimating fluid flow from digital imagery as demonstrated with GOCI imagery (Luttman, et al. 2013).

7.2.3 Ongoing and Future Work

A range of activities are needed to make further progress on algorithms for GEO-CAPE coastal waters. These activities include continuing analysis of prior field measurement collections, ongoing and planned science activities such as the KORUS-OC campaign, and other future studies that will advance algorithms within optically complex coastal waters that incorporate hyperspectral, ultra-violet (UV), and narrow-band sensor capabilities of GEO-CAPE. The oceans SWG has defined the following high priority issues: apply existing and new observations of high temporal, high spatial or high spectral resolution data sets that have a rich set of associated observations to address: (1) algorithm development for coastal ocean products including non-heritage products that are mission critical, highly desirable or relevant to interdisciplinary atmosphere-ocean studies. (2) Retrieval and viewing enhancements for GEO-CAPE ocean color science involving (a) development of atmospheric correction methodology and code, look-up tables, etc. for geostationary application to account for a combination of geo sensor viewing angles and variability in diurnal and seasonal solar geometry (solar zenith angle and earth's orbit) and for retrieval of ocean Rrs in the UV as well as VIS-NIR including appropriate corrections for absorbing aerosols and trace gases and non-absorbing aerosols; (b) development of bidirectional reflectance distribution function (BRDF) correction of Rrs at relevant solar angles; (c) refinement of sea-state and surface reflectance models for use at varying solar zenith angles and geostationary view angles.

7.3 Atmospheric Composition Studies

7.3.1 Atmospheric Composition Studies Initial State in 2009

Atmospheric trace gas and aerosol remote sensing from passive nadir-viewing instruments relies on radiance measurements in UV, visible (VIS), infrared (IR), and/or thermal infrared (TIR) wavelengths. Retrievals based on radiative transfer calculations are then used to determine the atmospheric composition that best represents the observed radiances.

Retrievals of all the GEO-CAPE target atmospheric trace gases using an optimal estimation approach are mature, having been developed and applied to observations from a series of instruments in LEO beginning with GOME in 1995 and progressing through MOPITT, AIRS, SCIAMACHY, OMI, TES, GOME-2, IASI, OMPS, and CrIS (e.g., Martin 2008; Fishman et al. 2008). Specific examples include retrievals of O_3 (Bowman et al. 2002; Boynard et al. 2009; Liu et al. 2005, 2006, 2010a, 2010b; Nassar et al. 2008; Worden et al. 2007), NO_2 (Boersma et al. 2007, 2011; Lauer et al. 2002; Richter et al. 2002, 2011), HCHO (Chance et al. 2000; de Smedt et al. 2008, 2012), SO_2 (Krotkov et al. 2006; Lee et al. 2008, 2009), CO (Clerbaux et al. 2002; Deeter et al. 2003; George et al. 2009; Luo et al. 2013; Worden et al. 2013), CH_4 (Crevoisier et al. 2009; Frankenberg et al. 2006; Worden et al. 2012) and NH_3 (Beer et al. 2008; Shephard et al. 2011). A particular innovation in recent years has been the utilization of multispectral observations of CO and O_3 to take advantage of the fact that atmospheric radiative transfer in different spectral regions can provide differences in sensitivity to the vertical distribution of the gas, leading to retrieval sensitivity in the boundary layer that is critical for air quality applications.

Retrievals of all the GEO-CAPE target aerosol products are also mature from LEO but could use very different algorithms depending on the ultimate spectral coverage of GEO-CAPE. The most mature options at the beginning of GEO-CAPE studies included the MODIS Dark-Target (DT) algorithm (Levy et al. 2007) and OMI UV aerosol algorithm (Torres et al. 2007).

A major challenge for retrievals from geostationary sensors is that ancillary information and relations will need to be established for all hours of the day (in contrast to the 1 or 2 times per day that have been available from LEO sensors). For trace gases, GEO retrievals will also be at much finer spatial resolution than has previously been achieved. Accurate retrieval of tropospheric trace gas and aerosol amounts from passive remote sensing observations depends on several assumptions, including vertical distribution of the species in the atmosphere and spectral reflectance of the underlying surface. Trace gas retrievals are also influenced by scattering from aerosol. Sources of error in the retrieval of tropospheric partial columns include knowledge of the stratosphere/troposphere separation and errors associated with the Air Mass Factors (AMF) used to convert measured total slant column density to the inferred tropospheric vertical column density (e.g., Streets et al. 2013). Over continental pollutant emission regions, error in AMF dominates the total error, and the largest contributors to AMF error include incorrect assumptions about the vertical profile shape, surface reflectivity, cloud parameters, and aerosols (Streets et al. 2013). These influences are accounted for using relationships, or climatologies, that have been derived from available observations and/or global model predictions. All of the key parameters in the AMF are sensitive to spatial resolution and time of day. The vertical profile shape and the vertical distribution of aerosols can change rapidly due to diurnal growth and collapse of the planetary boundary layer. Surface reflectivity depends on viewing geometry and sun angles, and the high heterogeneity in urban areas will need to be represented to retain retrieval accuracy at finer spatial resolution. Accurate aerosol retrievals are particularly dependent on accurate characterization of surface reflectivity.

7.3.2 Atmospheric Composition Studies Accomplishments 2009–2015

Because air quality fundamentally depends on near-surface pollutant concentrations, GEO-CAPE studies from the beginning have considered the potential for multi-spectral retrievals to improve knowledge of pollutant concentrations in the lowermost troposphere. A multi-spectral retrieval approach was first explored by Worden et al. (2007) and Worden et al. (2010), with subsequent work by several groups, including Deeter et al. (2013) and Fu et al. (2013). From 2009–2012, the retrieval sensitivity team worked to develop a tool to assess the ability of GEO-CAPE-like measurements to meet the trace gas and aerosol requirements established in the Science Traceability Matrix (STM). This tool comprises a radiative transfer (RT) model (also referred to as the forward model) and a retrieval model (also referred to as the inverse model). The RT model used in the tool is VLIDORT (Spurr 2006), which has been extensively validated in the solar scattering, thermal emission and crossover spectral regimes relevant to GEO-CAPE. The inverse model uses optimal estimation (Rodgers 2000) to compute averaging kernels (AKs) and Bayesian error statistics.

Natraj et al. (2011) applied this retrieval tool to examine the capability of different spectral combinations to retrieve ozone from a GEO platform and found that UV+VIS, UV+TIR, and UV+VIS+TIR combinations provide more information in the lowermost troposphere than retrievals in any of the individual spectral regions. For example, a UV + VIS + TIR combination can provide up to three independent pieces of information on the vertical ozone profile including sensitivity below 800 hPa (see Figure 7-1). Zoogman et al. (2011) subsequently used these retrievals in an observing system simulation experiment (OSSE) to quantify the usefulness of such a GEO instrument to constrain surface ozone. They showed 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.

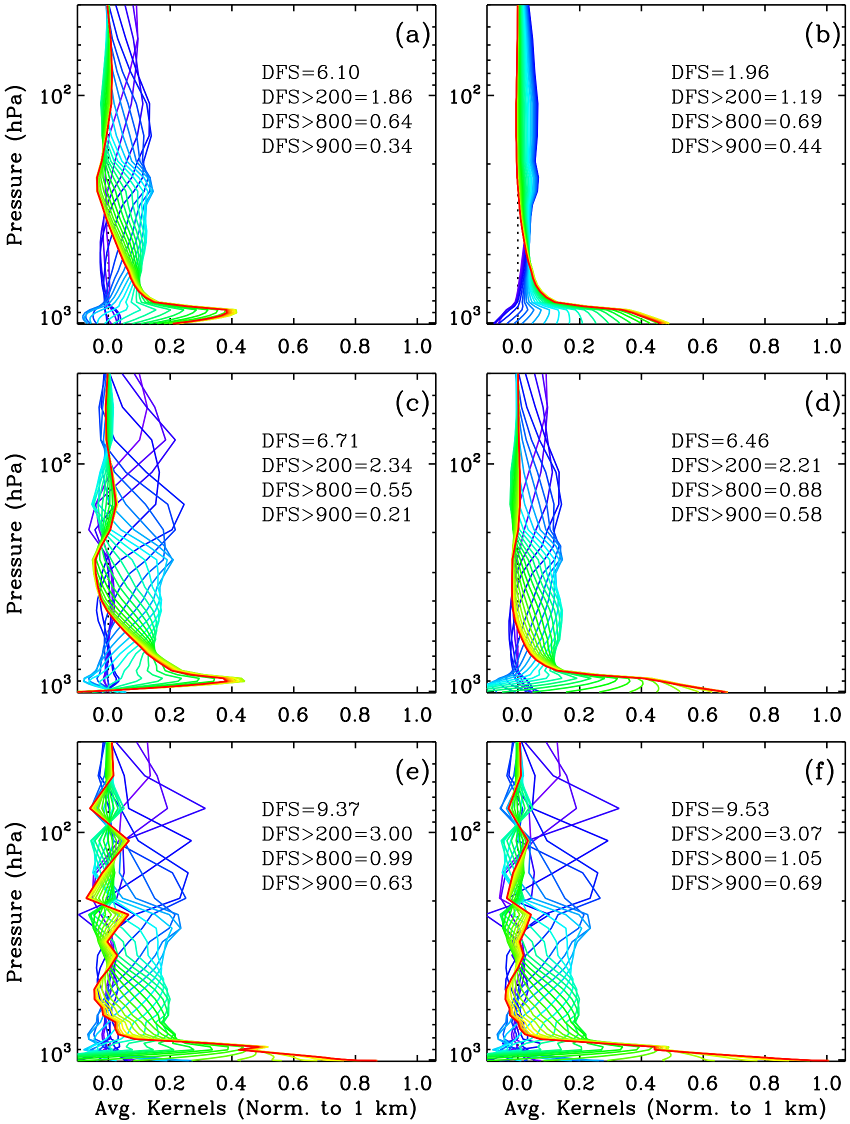


Figure 7-1. Sample averaging kernels for selected individual and combined spectral regions. (a) UV, (b) VIS, (c) TIR, (d) UV+VIS, (e) UV+TIR, (f) UV+VIS+TIR. The averaging kernels have been normalized to 1 km layers to account for the variable altitude grid and also been normalized by a priori error. The different colors refer to different wavelengths within the spectral region or combination.

While observation in the weak Chappuis band takes advantage of the relative transparency of the atmosphere in the VIS to achieve sensitivity to near-surface ozone, this measurement is more sensitive to errors in the surface reflectance, which is highly variable. Zoogman et al. (personal communication) have utilized reflectance measurements of individual plant, man-made, and other surface types to calculate the primary modes of variability of visible surface reflectance at a spectral resolution comparable to that of TEMPO (0.6 nm). Using the MODIS (Moderate-resolution Imaging Spectroradiometer) BRDF/albedo product and the derived primary modes, a high spatial resolution climatology of wavelength-dependent surface reflectance is being constructed over all viewing scenes and geometries. In the ozone profile retrieval from VIS measurements, the surface reflectance can be modeled by either fitting a combination of primary modes or by using the derived high spatial resolution spectral reflectance. The improvement using this new reflectance data is currently being evaluated in multispectral UV + VIS ozone retrievals from the GOME-2 (Global Ozone Monitoring Experiment–2) instrument.

The Emissions and Processes Working Group has undertaken several studies to address challenges associated with processing and interpretation of high-resolution GEO-CAPE retrievals of NO_2, NH_3, HCHO, CH_4, and aerosols. Current retrieval algorithms for HCHO from LEO observations (e.g., OMI) use a limited set of prior information for characterizing *a priori* profile shapes and terrain height. Building from model simulations and measurements from the CalNex field campaign, the impact of realistic treatment of these factors in retrievals at the spatial and temporal scales of TEMPO measurements has been shown (Kim et al., in preparation) to afford increasingly vivid detection of urban HCHO plumes (Figure 7-2). High-resolution NO_2 retrievals over point sources have been shown to allow for disentanglement of

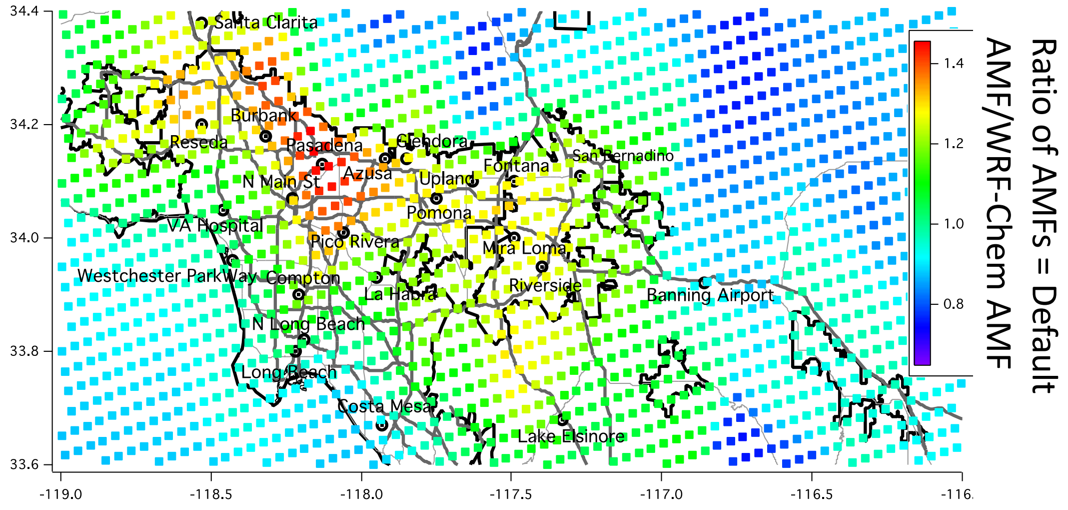


Figure 7-2. Ratio of the AMFs for retrievals using spatially variable a priori HCHO information compared to current default algorithms.

photochemistry from emissions magnitudes (Valin et al. 2011; 2013), fundamental to addressing GEO-CAPE science questions. Retrieval sensitivity studies have shown that geostationary observations provide constraints on diurnal variability of NH_3 sources, which influences $PM_{2.5}$ formation and is not presently well represented in air quality models (Zhu et al. 2015). Multiple retrieval approaches for CH_4 have been evaluated in OSSEs to estimate constraints on North American CH_4 emissions using profile, column or multispectral geostationary measurements (see Figure 7-3), the benefit of the latter being more than twice the number of resolvable emissions components than current observations from the LEO GOSAT mission (Bousserez et al. 2015). OSSEs have also been performed to compare the benefit of AOD measurements at multiple wavelengths versus multiple times per day for constraining emissions of dust.

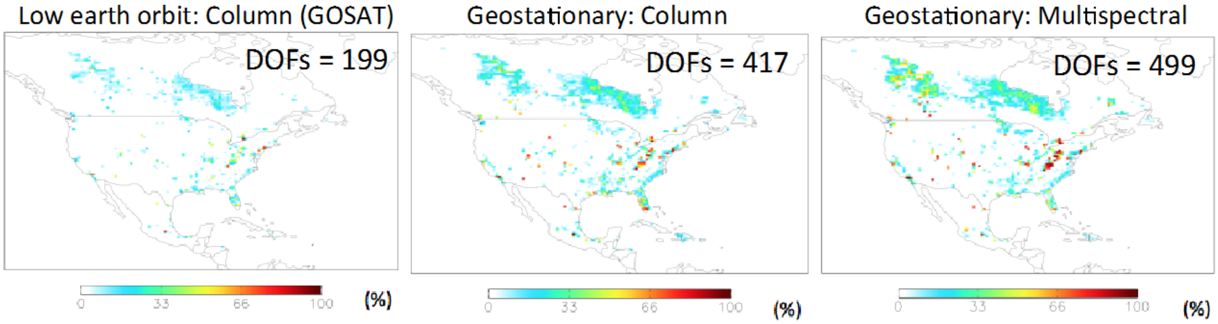


Figure 7-3. Error reductions in CH_4 emissions from inversions using different types of remote sensing observations, where a priori emissions are presumed to have a 40% uncertainty. For details, see Bousserez et al. (2015).

As introduced above and in Section 3.3, OSSE frameworks provide a formal comprehensive approach for evaluating the impact of new measurements in an integrated system. Retrieval algorithms convert observed or simulated atmospheric radiances to physical data products, thus they are also fundamental to OSSE. Since 2013, the Regional and Urban OSSE (RU-OSSE) and Global OSSE working groups have focused on introducing increasingly realistic components to GEO-CAPE OSSE studies. With respect to retrieval algorithms, two significant team accomplishments have been (1) the inclusion of realistic variability in the synthetic atmospheric radiances by incorporating higher fidelity surface UV and VIS reflectivities and TIR emissivities, and (2) creation of higher fidelity instrument retrieval sensitivities by generating individual averaging kernels for each retrieval for use in assimilation studies. One example includes the generation and evaluation of UV, VIS, TIR, UV/VIS, UV/TIR, and UV/VIS/TIR ozone retrievals using state-of-the-art high resolution regional modeling systems and ozone observations during the 2011 NASA DISCOVER-AQ campaign.

The Aerosol Working Group has been working for several years to evaluate existing and develop new retrieval algorithms to fulfill the GEO-CAPE STM for aerosols. Three algorithms have been evaluated, including MODIS DT algorithm (Levy et al. 2007), MODIS MAIAC algorithm (Lyapustin et al. 2011), and OMI UV aerosol algorithm (Torres et al. 2007). The MODIS DT algorithm is now mature, especially after recent Collection-6 refinement on cloud mask (for detecting heavy smoke layers), treatment of gas absorption, and retrieval at large solar zenith angles up to 84° (Levy et al. 2013). Important refinements were also recently made for the OMI UV aerosol algorithm, including the adjustment of refractive indices of absorbing aerosols at UV wavelengths, and the adoption of climatology of aerosol vertical profile complied from CALIOP and AIRS data (Ahn et al. 2014; Torres et al. 2013). The OMI UV aerosol algorithm is considered to be the baseline algorithm for retrieval of AOD from TEMPO, although the OMI spatial resolution (20 km) is much coarser than TEMPO. In contrast, MODIS DT algorithm relies on the use of wavelength at near infrared (2.1 um) that is not available on TEMPO, but its inclusion of visible wavelengths can guide TEMPO research algorithm development for aerosols because TEMPO's spectral coverage reaches close to 740 nm. The MAIAC algorithm has the potential to exploit hourly series of TEMPO data to improve retrievals of aerosol and surface reflectance. Preliminary results show that MAIAC has the potential to increase the number of successful retrievals with accuracy in AOD comparable to MODIS and VIIRS. However, it is still a research retrieval.

Following TEMPO's selection and with the consideration to leverage TEMPO to fully accomplish GEO-CAPE aerosol objectives, the focus of the Aerosol Working Group evolved to develop an algorithm that can combine TEMPO with GOES-R, and possibly VIIRS and other polar-orbiting sensors. Simultaneous retrieval of aerosol properties from sensors in different platforms is a new field in satellite remote sensing. The challenges include: (1) the effect of surface BRDF that makes the surface reflectance different for GOES-R and TEMPO when they view the same location at the Earth surface from different angles at the same time; (2) the difference of sensor's spatial resolution (TEMPO approximately 4 km vs. GOES-R 0.5 km) that can have complications for pixel co-registration and cloud screening; and (3) the difference of sensor's spectral coverage (TEMPO 290–740 nm, GOES-R visible, NIR) that requires good understanding of hyperspectral characteristics of aerosols and surfaces for the development of retrieval algorithm. The Aerosol Working Group has developed a retrieval testbed framework to help evaluate the conditions under which joint TEMPO and GOES-R aerosol retrievals will be possible. Wang et al. (2014) showed that combination of GOES-R and TEMPO can lead to better retrieval of aerosols than either of the sensors alone, and has potential to meet GEO-CAPE aerosol requirements. This improvement is in part due to (1) the complementary of spectral coverage in TEMPO and GOES-R that allows better characterization of surface reflectance and aerosol properties, and (2) the viewing of different angles at hourly basis from TEMPO and GEOS-R that enables a multi-angle approach to aerosol retrieval (Wang et al. 2014). Figure 7-4 illustrates the degree-of-freedom-for-signals (DFS) for AOD retrievals as function of viewing geometries in three cases respectively with GOES-R only, TEMPO only, and the combination of GOES-R and TEMPO.

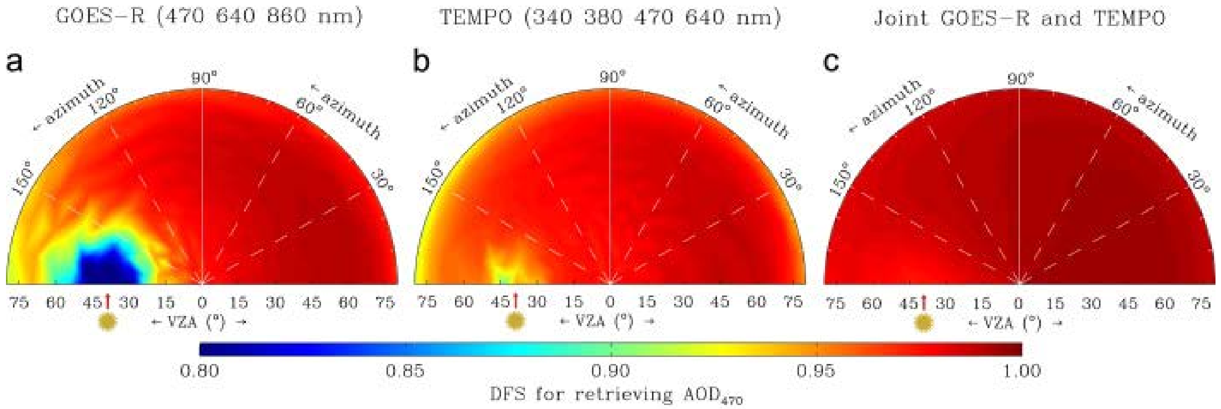


Figure 7-4. Polar plots of Degree of Freedom for Signal (DFS) for the retrieval of the total aerosol optical depth at 470 nm (AOD470) from: (a) GOES-R, (b) TEMPO, and (c) joint measurements of GOES-R and TEMPO. In each polar plot, the viewing zenith angle (VZA) is shown as the radius, while the polar angle represents the relative azimuth. The solar zenith angle is fixed at 40°. For details, see Wang et al. (2014).

In addition to these model based studies, the ACAM/GCAS and GEO-TASO airborne instruments offer satellite-analog measurements for GEO-CAPE gas and aerosol products (see also Section 5.3 for technology relevance and 6.3.2 for field campaign relevance). In particular, GEO-TASO matches the spectral range of TEMPO. The DISCOVER-AQ campaigns have acquired data over four different regions of the US that are helping to refine the trace gas (including AMF) and aerosol retrieval algorithms in preparation for geostationary observations. The ACAM/GCAS and GEO-TASO retrievals are being evaluated through comparison with aircraft, Pandora, and OMI data. GEO-CAPE has provided specific funding for GEO-TASO trace gas and aerosol retrieval products to be produced and archived as part of the DISCOVER-AQ data set. Retrievals using the best information available from DISCOVER-AQ observations are being compared with retrievals that do not incorporate any information from DISCOVER-AQ to help assess what ancillary information is most valuable to further improve GEO-CAPE TEMPO retrievals. Hyperspectral measurements such as from GEO-CAPE offer new capabilities for aerosol retrievals (Wang et al. 2014). Existing algorithms for aerosol retrievals from radiometers (such as MODIS) have been limited by the usage of several atmospheric window channels. GEO-CAPE study funding has supported progress in maturing such algorithms, including characterization of the surface reflectance in hyperspectral resolution through principal component analysis, use of measurements from GEO-TASO to retrieve aerosol optical properties and surface reflectance in hyperspectral resolution, quantification of the errors in surface BRDF model using in situ observations, and refinement of the surface BRDF model with data from MODIS/VIIRS (as a proxy for GOES-R) and GLI/CAI (as a proxy to represent TEMPO's UV channels).

7.3.3 Ongoing and Future Work

The development of the regional and urban OSSE frameworks is by necessity a multi-year activity that will continue. In particular, approaches for speeding up the radiative transfer calculations and/or accurately parameterizing the dependence of averaging kernels on all relevant atmospheric and surface parameters at GEO-CAPE's spatial and temporal scales (e.g., Worden et al. 2015) is now being pursued to ultimately enable accurate inclusion of these dependencies in operational processing.

Trace gas and aerosol retrieval studies using the existing data collected during the DISCOVER-AQ campaigns will continue. Exploitation of the GEO-TASO data will be particularly useful given that its spectral characteristics are so similar to TEMPO. Ongoing activities include further improvement of approaches to account for diurnal variation in vertical profile shapes and surface reflectance, evaluation of joint retrievals (multi-species, multi-platform, and combined gas-aerosol), and evaluation of improved aerosol and surface reflectance retrieval techniques, including MAIAC.

The airborne and ground data to be obtained from the 2016 KORUS-AQ campaign in Korea will greatly extend the range of data (stronger signals of pollutants, strong gradients, wide range of surface types including land/water boundaries) for developing GEO-CAPE/TEMPO algorithms and relationships with ancillary data. The hourly multispectral GOCI satellite data available over the Korean region will provide very useful constraints on the diurnal variation of aerosol and surface reflectance.

7.4 Summary

The refinements that the GEO-CAPE study team continues to make to measurement algorithms will enable launch-readiness of high quality GEO-CAPE data products. Data being acquired in field campaigns (Section 6) are allowing the algorithms to be tested and improved, while the modeling frameworks being developed (Section 3) will lead to broad use and application of the data products. Much of the progress is also directly applicable to data products from the EVI-1 TEMPO mission.

8. SUPPORT AND INVESTMENTS FROM OTHER ESD ELEMENTS

GEO-CAPE development activities have been very well aligned and integrated with funded activities from all 4 ESD program areas, as summarized in Table 8-1. Several of these activities are described in detail in other sections of this report and others are described in this section. ESTO managed investments are discussed further in Section 5.

Table 8-1: Summary of Support and Investments from Other ESD Elements

Program Element	Activity	Dates	Approx. Investment
Flight	EVS-1 DISCOVER-AQ	2011-2015	$30M + $10M partner
Flight	EVI-1 TEMPO	2013-2021	$94M
Flight	ESSP CII	2012-2013	$3M
Flight	HoPS development and TEMPO hosting	2013-current	$70M (est.)
R&A	JCSDA, ACMAP, MAP OSSE Framework Development	pre2010-current	$1M/yr (est.)
R&A	TOLNet	2011-current	$1.5M/yr
R&A	2 USPI GEO Selections	2013-2017	$1.5M
ASP	AQAST	2011-2015	$18M
ESTO	8 IIP Selections	2006-2015	$28M
ESTO	8 ACT, AITT, ATI	2010-2016	$10M
ESTO	11 AIST	2006-2016	$12M

8.1 Flight

Two of the first Earth Venture solicitations selected projects of key relevance to GEO-CAPE. These selections attest to the strong scientific and applications value of GEO-CAPE, the highly motivated and well-organized expert science community capable of conducting the projects, and the high maturity of the measurement systems needed to implement GEO-CAPE.

The EVS-1 Deriving Information on Surface conditions from Column and Vertically Resolved Observations Relevant to Air Quality (DISCOVER-AQ) project has a fundamental focus on improving the usefulness of satellite data for air quality science and applications. In a series of 4 field campaigns (Baltimore/Washington, June-July 2011; San Joaquin Valley, CA, January-February 2013; Houston, TX, September 2013; Denver, CO, July-August 2014), the project has acquired first-ever data to link remote sensing observations multiple times per day, as will be provided by geostationary observations, to surface concentrations of the major air-quality pollutants. By engaging national (EPA, NOAA) and state/local partners as members of the science team, DISCOVER-AQ is significantly advancing the ability and desire of applied users to routinely use the data that GEO-CAPE will provide (Crawford et al. 2014). Notably, partners have been investing their own resources (approximately $10M current total) throughout the campaigns, for example by deploying additional instruments to make extensive companion measurements collocated with DISCOVER-AQ.

The EVI-1 Tropospheric Emissions: Monitoring of Pollution (TEMPO) project is anticipated to accomplish a large fraction of GEO-CAPE atmospheric science. TEMPO will measure the key gases of tropospheric air pollution chemistry over greater North America, hourly and at high spatial resolution. TEMPO evolved from the GEO-CAPE STM as a concept to achieve as much of the recommended GEO-CAPE atmosphere UV-Visible measurement capability as possible within EV cost constraints. Current estimates are that TEMPO may meet 50-70% of GEO-CAPE requirements, depending on the metric used and on pending TEMPO design/performance details. Critically, TEMPO will also be a pathfinder for demonstrating the feasibility of a distributed implementation architecture using commercially hosted payloads, as recommended by the GEO-CAPE SWG (Fishman et al. 2012).

The GEO-CAPE MDWG worked with the ESSP Common Instrument Interface (CII) Study Activity to develop the initial geostationary interface guidelines for hosted payloads. During 2011, CII funded a GSFC IDL geostationary pathfinder (GeoPath; see Section 4.3) study to develop a simple optical instrument concept as a notional HPL pathfinder payload. GEO-CAPE team members were key participants in this study, bringing design knowledge gained in previous GEO-CAPE instrument design studies (GeoMAC, CEDI, COEDI, PanFTS). This Geo-Pathfinder instrument concept informed the RFI put forward by the CII to help initially populate the GEO interface guidelines, ultimately helping lead to NASA's involvement in the Hosted Payload Solutions (HoPS) contract. HoPS is a single acquisition framework administered by the U.S. Air Force that is intended lead to simpler, faster, and lower-risk satellite mission hosting procurements across the U.S. Government. Motivated in part by the GEO-CAPE study team recommendation to pursue hosted mission accommodations, the 2012 Hosted Payload Alliance Workshop was held at NASA HQ, and NASA and the U.S. Air Force agreed to coordinate commercial hosting acquisitions to simplify Government-Industry procurement interfaces. ESD Flight funded NASA participation in the development of the HoPS contract, awarded July 2014. Particularly relevant to GEO-CAPE, ESD has subsequently used the HoPS contract to fund two TEMPO mission activities: TEMPO early-mission studies to help refine specific instrument interface requirements, and a draft request for proposals for TEMPO mission hosting. These activities specifically aid completion of the portion of GEO-CAPE science that will be accomplished by TEMPO and are also pathfinders that will inform future decisions about whether to use an HPL model for the remaining GEO-CAPE instruments.

8.2 Research and Analysis

Observation system simulation experiments (OSSEs) have been increasingly used in weather prediction to quantify the potential performance of future remote sensing systems, but the use of OSSEs for atmospheric chemistry and aerosol systems is significantly more complex. Recognizing this growing importance of OSSEs for development of future remote sensing systems, NASA R&A has been investing in the development of OSSE frameworks for atmospheric composition for almost 10 years. Funding avenues have included direct support of the NASA/NOAA Joint Center for Data Assimilation (JCSDA) and also five individual R&A grants selected via the ACMAP and MAP programs (some of which started prior to GEO-CAPE activity but were later leveraged for GEO-CAPE application). A conservative estimate of the overall R&A funding for these activities is approximately $1M/yr. The strong recent publication record evidences the steady progress being made (Zoogman et al. 2011, 2014a, 2014b; Worden et al. 2013b; Barré et al. 2015).

In 2011 the R&A program began making a sustained investment in prototype continuous ground-based tropospheric ozone profile measurements using lidar systems. The Tropospheric Ozone Lidar Network (TOLNet) includes systems at 5 institutions across the U.S.: NASA JPL Table Mountain Facility, NOAA Earth System Research Laboratory, University of Alabama at Huntsville, NASA LaRC, and NASA GSFC. Two of these systems include key components developed in the SBIR program approximately 10 years ago. Three of the systems are deployable to locations away from their home institutions. TOLNet data are providing first-ever information about temporal variation of near-surface ozone at better than hourly time resolution. Because observations many times per day are fundamental to GEO-CAPE science, the TOLNet measurements are providing sample data sets that are useful for GEO-CAPE retrieval algorithm development.

NASA R&A solicits proposals under the Earth Science U.S. Participating Investigator Program (USPI) approximately every 2 years. Selections from the 2012 solicitation, covering a funding cycle beginning in 2013, included two proposals of very high relevance to GEO-CAPE. These activities are developing data products from international geostationary missions for air quality (Kelly Chance/Smithsonian Astrophysical Observatory, "SAO Participation in the Korean Geostationary Environment Monitoring Spectrometer (GEMS): Instrument Design and Algorithm Development") and ocean color (Antonio Mannino/Goddard Space Flight Center, "Development, Production and Distribution of GOCI Data Products in Preparation for the GEO-CAPE Ocean Color Mission").

8.3 Applied Sciences Program

The NASA Air Quality Applied Sciences Team (AQAST) was created in 2011 by the NASA Applied Sciences Program to serve the needs of US air quality management through the use of Earth Science satellite data, suborbital data, and models. AQAST members have expertise in the wide array of Earth Science tools and data sets available from NASA and other agencies. They have the resources to carry out quick-turnaround projects responding to urgent and evolving needs of air quality management. They form Tiger Teams to pool their expertise in addressing multi-faceted problems. All AQAST projects are conducted in close partnership with air quality management partners. AQAST has significantly advanced both the ability and desire of applied users to routinely use the data that GEO-CAPE will provide.

[http://acmg.seas.harvard.edu/aqast/index.html]

8.4 Earth Science Technology Office

ESTO has funded multiple competitive selections directly relevant to GEO-CAPE, spanning all of its program areas. Further details of these activities are presented in Section 5.

9. CLOSING THOUGHTS

The 2007 Decadal Survey (DS) “Earth Science and Applications from Space” was a first for the NASA Earth Science Division (ESD). While the needs expressed in the survey met with broad endorsement in the Earth science and applications communities, it quickly became apparent that assumptions made in the 2007 DS regarding future ESD budgets had been overly optimistic. Faced with this situation, ESD initiated an unprecedented strategy of funding all 9 of the so-called Tier-1 and Tier-2 missions to conduct in-depth mission definition studies to help guide planning for future budgets and preparation for potential new mission formulation. This approach has proven exceptionally fruitful in the case of GEO-CAPE.

GEO-CAPE was a challenging fit in the ESD program, especially in a constrained budgetary environment, because of its geostationary orbit and notional payload of multiple instruments serving two very different sets of observing requirements. The GEO-CAPE study team leaders developed a strategy to engage the broadest possible range of GEO-CAPE stakeholders, including multiple NASA centers and universities. In addition to the expected funding of concurrent-engineering design studies and technology assessment, study team funding provided an effective seed for building and maintaining broad stakeholder involvement. Team members either donated their efforts at no cost to the program or were able to leverage other ongoing activities to support focused GEO-CAPE needs at low cost to the program. After 2–3 years of study and vigorous debate, the team came to consensus that the best strategy for GEO-CAPE was to avoid scope creep, constrain costs, and remain as small and flexible as possible to enable most of the science of GEO-CAPE to be accomplished sooner rather than waiting until later to accomplish “all” the science. The EV-I TEMPO mission and multiple other well-rated proposals to the EV solicitations are fruitions of this spirit.

While the GEO-CAPE study team approach of funding many small competed activities has succeeded in fostering broad community engagement, one lesson learned is that managing this approach has been very labor intensive. The planning of activities on an annual basis, with only one year of funding direction received each year, has made it unnecessarily challenging to undertake development activities that require multiple years (for example the development of frameworks for observing system simulation experiments). The administrative burden associated with implementing many small 1-year grants is high. One future solution would be to provide the study teams with at least a core part of their budgetary guidance on 3-year cycles, possibly complemented by annual 1-year augmentations. This approach should improve the efficiency of these study team activities while still retaining annual programmatic flexibility for ESD. The study team expresses its thanks to ESD leadership for its vision in constructing these study teams and sustainably funding them over a period of years. It is the team’s belief that ESD has obtained excellent value from its investment in the team.

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11. ACRONYMS AND ABBREVIATIONS

ACAM	Airborne Compact Atmospheric Mapper
ACC	Atmospheric Composition Constellation
ACT	Advanced Component Technology
AIST	Advanced Information Systems Technology
AMF	Air Mass Factors
AOT	Aerosol Optical Thickness
AQAST	Air Quality Applied Sciences Team
ASP	Airborne Science Programs
ASWG	Atmosphere Science Working Group
ATBD	Algorithm Theoretical Basis Document
BRDF	Bidirectional Reflectance Distribution Function
CBODAQ	Chesapeake Bay Oceanographic campaign with DISCOVER-AQ
CDOM	Colored Dissolved Organic Matter
CEDI	Coastal Ecosystem Dynamics Imager
COEDI	Coastal Ocean Ecosystem Dynamics Imager
CEOS	Committee on Earth Observation Satellites
CH_4	methane
Chl-a	Chlorophyll-a
CII	Common Instrument Interface
CO	carbon monoxide
COAST	Coastal Ocean Applications and Science Team
DFS	Degree-of-Freedom-for-Signals
DISCOVER-AQ	Deriving Information on Surface Conditions from COlumn and VERtically Resolved Observations Relevant to Air Quality
DOC	Dissolved Organic Carbon Concentration
DOFS	Degrees of Freedom for Signal
DS	Decadal Survey
DT	Dark Target
EPA	Environmental Protection Agency
ESD	Earth Science Division
ESTO	Earth Science Technology Office
ESTO-QRS	Earth Science Technology Office-Quick Response System
EV	Earth Venture
FPA	Focal Plane Array
FR	Filter Radiometer

FTS	Fourier Transform Spectrometer
GCAS	GEO-CAPE Airborne Simulator
GCIRI	GEO-CAPE InfraRed Instrument
GEMS	Geostationary Environment Monitoring Spectrometer
GEO-CAPE	Geostationary Coastal and Air Pollution Events
GEO-MAC	Geostationary Multi-spectral Atmospheric Composition
GeoSpec	Geostationary Spectrograph
GEO-TASO	Geostationary Trace gas and Aerosol Sensor Optimization
GEOSS	Global Earth Observation System of Systems
GOCI	Geostationary Ocean Color Imager
GRIFEX	GEO-CAPE Readout Integrated Circuit Experiment
GSD	Ground Sample Distance
GSFC	Goddard Space Flight Center
GSI	Grid-point Statistical Interpolator
GTE	Global Tropospheric Experiment
HICO	Hyperspectral Imager for the Coastal Ocean
HoPS	Hosted Payload Solutions
IDL	Instrument Design Laboratory
iFOV	instantaneous Field-of-View
IGACO	Integrated Global Atmospheric Chemistry Observations
IGOS	Integrated Global Observing Strategy
IIP	Instrument Incubator Program
IOP	Inherent Optical Properties
IR	Infrared
IRCRg	Infrared Correlation Radiometer
ISAL	Instrument Synthesis and Analysis Laboratory
JCSDA	Joint Center for Data Assimilation
KIOST	Korea Institute of Science and Technology
KORUS-AQ	Korea-U.S. Air Quality
LaRC	Langley Research Center
LDCM	Landsat Data Continuity Mission
LEO	Low-Earth Orbit
LMT	Lowermost Troposphere
LUT	Look-Up Table
LWIR	Long Wave Infrared
MDC	Mission Design Coordination

MDCT	Mission Design Coordination Team
MDSA	Multi-Sensor Data Synergy Advisor
MERIS	Medium-spectral Resolution Imaging Spectrometer
MODIS	Moderate-resolution Imaging Spectroradiometer
MOS	Multi-Slit Optimized Spectrometer
MSS	Multi-Slit Spectrometer
MWIR	Midwave Infrared
NAP	Non-Algal Particle
NOAA	National Oceanic and Atmospheric Administration
OBP	On-Board Processing
OSSE	Observing System Simulation Experiment
PanFTS	Panchromatic Fourier Transform Spectrometer
PanFTS-EM	Panchromatic Fourier Transform Spectrometer-Engineering Model
PC	phycocyanin
PFT	Phytoplankton Functional Types
PRISM	Portable Remote Imaging Spectrometer
RFI	Request for Information
RGCI	Red-Green-Chlorophyll-Index
ROIC	Read Out Integrated Circuit
Rrs	Remote Sensing Reflectance
RT	Radiative Transfer
RU-OSSE	Regional and Urban Observing System Simulation Experiment
SEWG	Systems Engineering Working Group
SIRAS-G	Spaceborne Infrared Atmospheric Sounder for Geosynchronous Earth Orbit
SOX	Sensor-Web Operations Explorer
SNR	Signal to Noise Ratio
SPM	Suspended Particulate Matter
SSA	Single Scattering Albedo
SSS	Single-Slit Spectrometer
STM	Science Traceability Matrix
SWG	Science Working Group
SWIR	Short Wave Infrared
TEMPO	Tropospheric Emissions: Monitoring of Pollution
TIMS	Tropospheric Infrared Mapping Spectrometers
TIR	Thermal Infrared
TOLNet	Tropospheric Ozone Lidar Network

TRL	Technology Readiness Level
UNESCO	United Nations Educational, Scientific, and Cultural Organization
USPI	U.S. Participating Investigator Program
UV	Ultraviolet
VIS	Visible
WAS	Wide Angle Spectrometer

12. GEO-CAPE PUBLICATIONS

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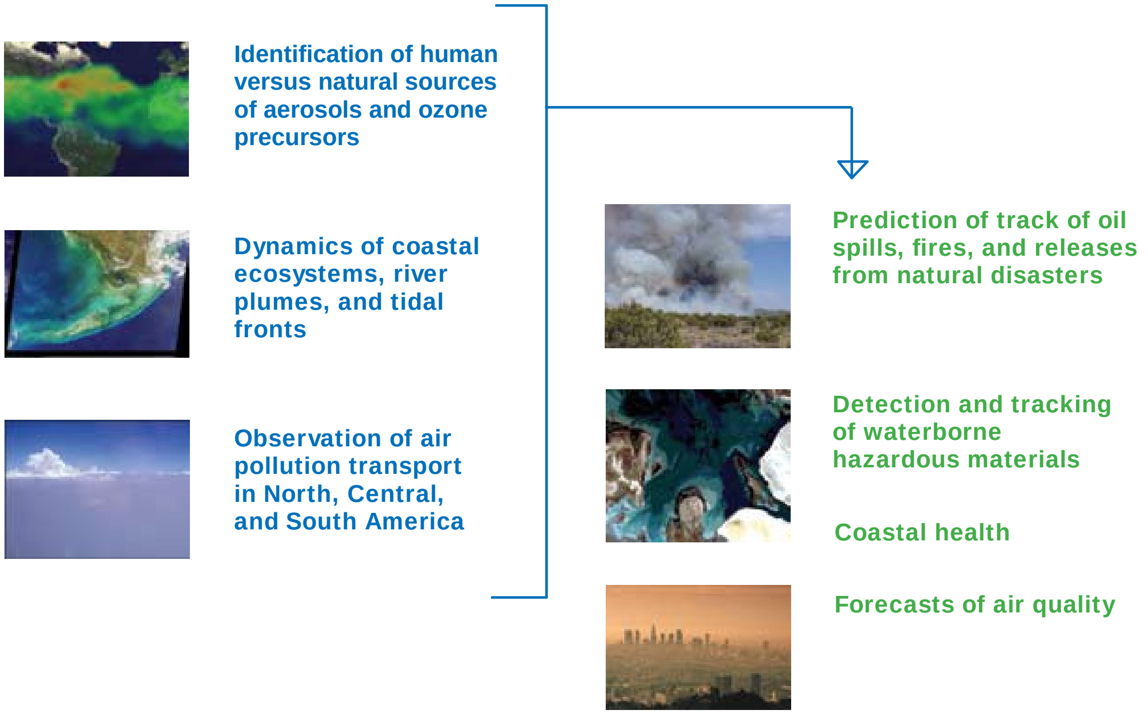
A. GEO-CAPE MISSION SUMMARY: NATIONAL ACADEMY OF SCIENCES

The concentration of people living near coasts is causing enormous pressure on coastal ecosystems. The effects are visible in declining fisheries, harmful algal blooms, and eutrophication such as the "dead zone" in the Mississippi delta and more than 20 other persistent dead zones around the world. Climate change combined with the continuing growth of populations in coastal areas creates an imperative to monitor changes in coastal oceans. Key needs include the ability to forecast combined effects of harvesting, coastal land management, climate change, and extreme weather events on economically important seafood species. The GEO-CAPE mission would provide observations of aerosols, organic matter, phytoplankton, and other constituents of the upper coastal ocean at multiple times in the day to develop capabilities for modeling ecological and biogeochemical processes in coastal ecosystems.

GEOSTATIONARY COASTAL AND AIR POLLUTION EVENTS (GEO-CAPE)

Launch: 2013–2016 Mission Size: Medium



Identification of human versus natural sources of aerosols and ozone precursors

Dynamics of coastal ecosystems, river plumes, and tidal fronts

Observation of air pollution transport in North, Central, and South America

Prediction of track of oil spills, fires, and releases from natural disasters

Detection and tracking of waterborne hazardous materials

Coastal health

Forecasts of air quality

The mission would be of considerable value in improving the ability to observe and understand air quality on continental scales and thus in guiding the design of air-quality policy. Air pollutants (O_3 and aerosols) are increasingly recognized as major causes of cardiovascular and respiratory diseases. Based on networks of surface sites, the current system for observation of air quality is patently inadequate to monitor population exposure and to relate pollutant concentrations to their sources or transport. Continuous observation from a geostationary platform will provide the necessary data for improving air-quality forecasts through assimilation of chemical data, monitoring pollutant emissions and accidental releases, and understanding pollution transport on regional to intercontinental scales.

A.1 Background

The GEO-CAPE mission advances science in relation to coastal ecosystems and air quality. If both types of measurements are made from the same platform, aerosol information derived from the air- quality measurements can be used to improve the ocean ecosystem measurements.

Coastal ocean ecosystems are under enormous pressure from human activities, both from harvesting and from materials entering the coastal ocean from the land and the atmosphere. Compared with the open ocean, these regions contain greatly enhanced amounts of chlorophyll and dissolved organic matter, but the coastal ocean is not simply a region of enhanced primary productivity; it also plays an important role in mediating the land-ocean interface and global biogeochemistry. The high productivity of the coastal ocean supports a complex food web and leads to a disproportionate harvesting of the world's seafood from the coastal ocean regions. Persistent hypoxic events or regions associated with riverine discharge of nutrients in the Gulf of Mexico, the increasing frequency of harmful algal blooms in the coastal waters of the United States, and extensive closures of coastal fisheries are just a few of the issues confronting the coastal areas. Both short-term and long-term forecasts of the coastal ocean require better understanding of critical processes and sustained observing systems. Characterizing and understanding the short-term dynamics of coastal ecosystems are essential for the development of robust, predictive models of the effects of climate change and human activity on coastal ocean ecosystem structure and function. The scales of variability in the coastal region require measurements at high temporal and spatial resolution that can be obtained only from continuous observation, such as is possible from geosynchronous Earth orbit.

Air-quality measurements are urgently needed to understand the complex consequences of increasing anthropogenic pollutant emissions both regionally and globally. The current observation system for air quality is inadequate to monitor population exposure and develop effective emission-control strategies. O_3 and aerosol formation depends in complex and nonlinear ways on the concentrations of precursors, for which few data are available. Management decisions for air quality require emission inventories for precursors, which are often uncertain by a factor of two or more. The emissions and chemical transformations interact strongly with weather and sunlight, including the rapidly varying planetary boundary layer and continental-scale transport of pollution. Again, the scales of variability of these processes require continuous, high-spatial-resolution and high-temporal-resolution measurements possible only from geo-synchronous Earth orbit.

A.2 Science Objectives

The GEO-CAPE mission satisfies science objectives for studies of both coastal ocean biophysics and atmospheric-pollution chemistry. It also has important direct societal applications in each domain. Compatibility with objectives of the terrestrial biophysical sciences should also be explored.

The ocean objectives are to quantify the response of marine ecosystems to short-term physical events, such as the passage of storms and tidal mixing; to assess the importance of high temporal variability in coupled biological-physical coastal-ecosystem models; to monitor biotic and abiotic material in transient surface features, such as river plumes and tidal fronts; to detect, track, and predict the location of sources of hazardous materials, such as oil spills, waste disposal, and harmful algal blooms; and to detect floods from various sources, including river overflows.

The air-quality objective is to satisfy basic research and operational needs related to air-quality assessment and forecasting to support air-program management and public health; emission of O_3 and aerosol precursors, including human and natural sources; pollutant transport into, across, and out of North, Central, and South America; and large puff releases from environmental disasters. Measurements of aerosols from the air-quality instrument can be used to correct aerosol contamination of the high-resolution coastal-ocean imager.

Mission and Payload: GEO-CAPE consists of three instruments in geosynchronous Earth orbit near 80°W longitude: a UV-visible-near-IR wide-area imaging spectrometer (7-km nadir pixel) capable of mapping North and South America from 45°S to 50°N at about hourly intervals, a steerable high-spatial-resolution (250 m) event-imaging spectrometer with a 300-km field of view, and an IR correlation radiometer for CO mapping over a field consistent with the wide-area spectrometer. The solar backscatter data from the UV to the near-IR will provide aerosol optical depth information for assimilation into aerosol models and downscaling to surface concentrations. The same data will provide high-quality information on NO_2 and formaldehyde tropospheric columns from which emissions of NOx and volatile organic compounds, pre-cursors of both O_3 and aerosols, can be characterized. Combination of the near-IR and thermal-IR data will describe vertical CO, an excellent tracer of long-range transport of pollution. The high-resolution event imager would serve as a multidisciplinary programmable scientific observatory and an immediate-response sensor for possible disaster mitigation. The data from the high-resolution event-imaging spectrometer would be coupled to the data generated by the wide-area spectrometer through on-board processing to target specific events (such as forest fires, releases of pollutants, and industrial accidents) where high-spatial- resolution analysis would provide benefits. A substantial fraction of its time would be made available for direct support of selected aircraft and ground-based campaigns or special observing opportunities.

Mission Cost: About $550 million.

Schedule: All the instruments have a low-Earth-orbit space heritage and are at a high level of technology readiness, and so launch would be feasible by 2015.

Further Discussion: See in Chapter 10 of the Decadal Study the section "A Cross-disciplinary Aerosol-Cloud Discovery Mission," and in Chapter 7 the section "Coastal Ecosystem Dynamics Mission."

Related Responses to Committee's RFI: 21, 30, 52, 60, and 105

GEO-CAPE Oceans STM

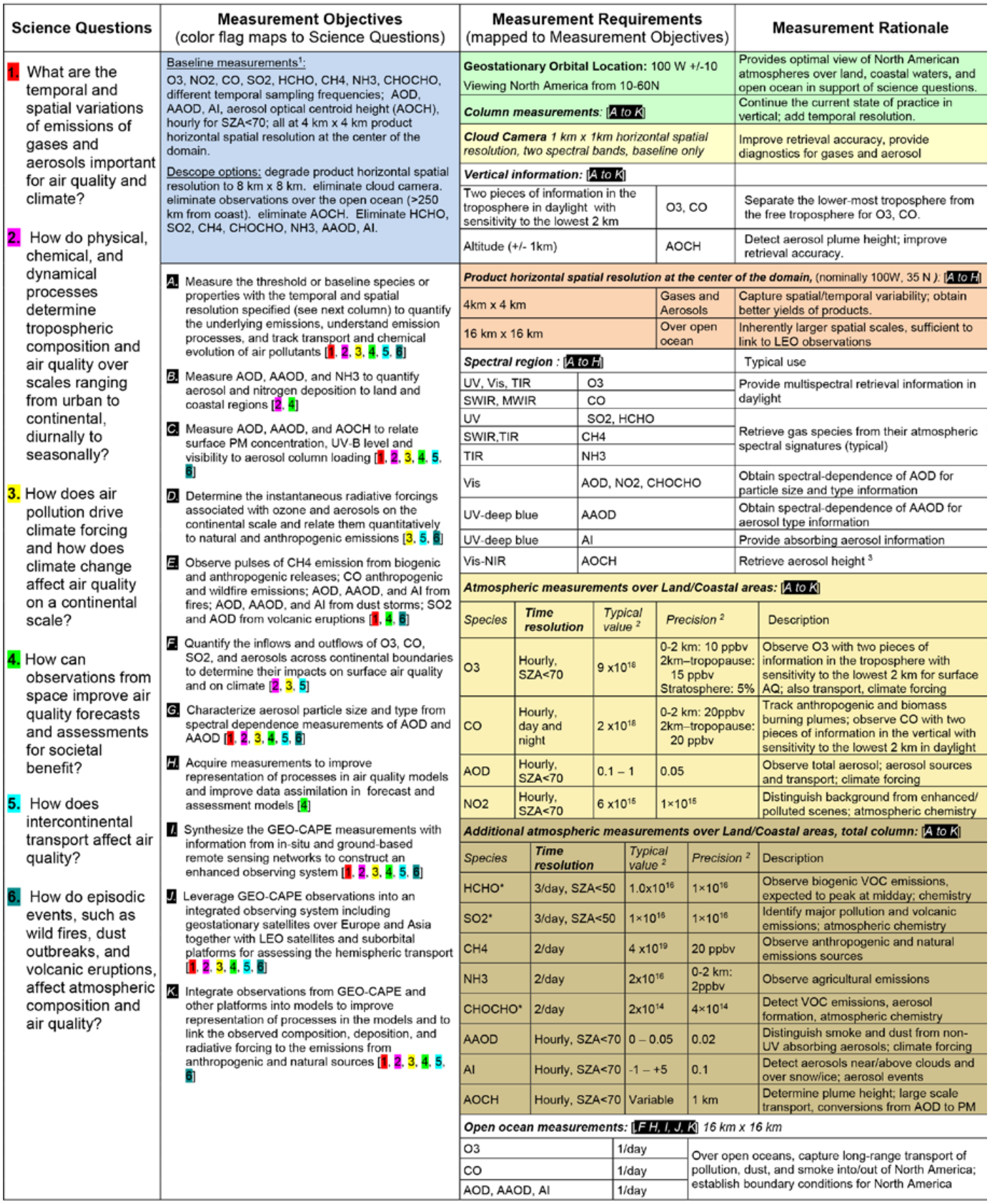
Draft v.4.7 - 30 July, 2015

Science Focus	Science Questions	Approach	Maps to Science Question	Measurement Requirements	Instrument Requirements	Platform Requirem.	Ancillary Data Requirem
Short-Term Processes	1 **How do short-term coastal and open ocean processes interact with and influence larger scale physical, biogeochemical and ecosystem dynamics?** (OBB 1)	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 (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. *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. (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. (c) Measure the inherent optical properties of coastal ecosystems: absorption and scattering of particles, phytoplankton and detritus, CDOM absorption. (d) Estimate upper ocean particle characteristics including particle abundance and particle size distribution. (e) Detect, quantify and track hazards including HABs and petroleum-derived hydrocarbons. 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) to quantify the responses of coastal ecosystems and biogeochemical cycles to river discharge, land use change, airborne-derived fluxes, hazards and climate change, and (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.	1 2 3 4 1 2 4 5 1 2 3 1 2 3 4 5 1 2 3 4 5 1 2 3 5 2 3 1 2 3 4 5 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: ≤2 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:* • 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 **Scanning Priority:** •Threshold: 1. Survey of U.S. Coastal Waters 2. Other coastal and large inland bodies of water 3. Open ocean waters within FOR	**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; Baseline: No aggregation. **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** — <50% — <10% **Pointing Accuracy LOS** — <100% — <25% **Pointing Stability LOS** — <25% — <10% **Geolocation Reconstr.** — <50% — <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** Baseline only: Near Real-Time satellite data download from other sensors (GOES, etc.) for on-board autonomous decision making. **Pre-launch characterization:** Adequate to achieve the required on-orbit radiometric precision	Geostationary orbit Threshold: 94°±2° W longitude; Baseline: 94°±1° W to permit sub-hourly observations of coastal waters adjacent to the continental U.S., North, Central and South America Storage (up to 1 day) 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.
Land-Ocean Exchange	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; CCSP 1 & 3)						
Impacts of Climate Change & Human Activity	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; CCSP 1 & 3)						
Impacts of Airborne-Derived Fluxes	4 **How do airborne-derived fluxes from precipitation, fog and episodic events such as fires, dust storms & volcanoes affect the ecology and biogeochemistry of coastal and open ocean ecosystems?** (OBB 1 & 2; CCSP 1)						
Episodic Events & Hazards	5 **How do episodic hazards, contaminant loadings, and alterations of habitats impact the biology and ecology of the coastal zone?** (OBB 4)						

GEO-CAPE Science Questions are traceable to NASA's OBB Advanced Planning Document (OBB) and the U.S. Carbon Cycle Science Plan (CCSP).

* Coastal coverage within field-of-view (FOV) includes major estuaries and rivers such as Chesapeake Bay, Lake Pontchartrain/Mississippi River delta and the Laurentian Great Lakes, 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).

C.1 GEO-CAPE Atmospheric Composition Science Traceability Matrix (Fishman et al. 2012)



Science Questions	Measurement Objectives (color flag maps to Science Questions)
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. 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]

Measurement Requirements (mapped to Measurement Objectives)		Measurement Rationale
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.
Product horizontal spatial resolution at the center of the domain, (nominally 100W, 35 N): [A to H]		
4km 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 x10^{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 x10^{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 x10^{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	1.0x10^{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 x10^{19}	20 ppbv	Observe anthropogenic and natural emissions sources
NH3	2/day	2x10^{16}	0-2 km: 2ppbv	Observe agricultural emissions
CHOCHO*	2/day	2x10^{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.

C.2 GEO-CAPE Science Value Matrix

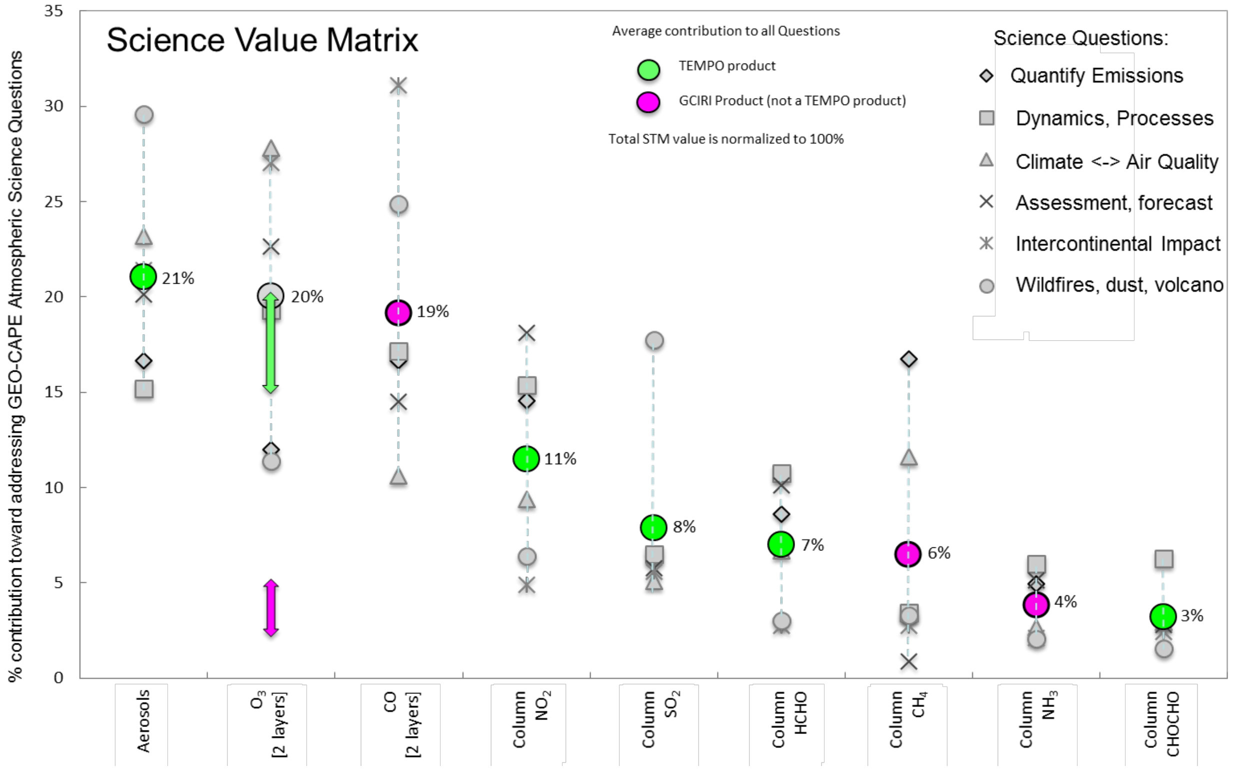


Figure C-2. Atmospheric Composition Science Value Matrix. The value of a GEO-CAPE science measurement is defined as its contribution toward answering the GEO-CAPE Science Questions presented in the Science Traceability Matrix (Figure C-1). Minimum success criterion for the GEO-CAPE Atmospheric Composition Science mission is defined as realizing the top 80% of the full science. By this criterion, TEMPO must be complemented by at least the multi-spectral CO measurement.

All GEO-CAPE atmospheric science products have been demonstrated from space in low-Earth orbit, except for multi-spectral (i.e., 2-layer) ozone using UV-Vis wavelengths. The green arrow indicates a range of expected contributions if the UV-Vis multi-spectral approach is successful. The pink arrow indicates a potential contribution toward meeting the ozone requirements in the infrared by some GCIRI concepts.

C.2.1 GEO-CAPE Atmospheric Composition Science Value Matrix

The Atmosphere Science Working Group (ASWG) found that even in the science community, the information content of instrument data was poorly understood. The goal of establishing a modeling framework, with analytic representations of instrument information, was ASWG's response to more objectively valuing different instrument capabilities.

ASWG also investigated other science value metrics, including Science Impact (S, the potential to meet STM requirements) combined with programmatic value (P, value >1 for synergies with other missions), risk (R, the greatest technical likelihood for mission success), and cost (C). Then new metrics could be defined as follows:

- Science Impact, completeness of accomplishing science measurements as defined in the STM.
- Science Expectation = S * P * R
- Science Value = Science Expectation/ C

These metrics offer possibilities for better implementation trades. However, they were found to require more rigor than a pre-formulation study could provide.

C.3 Draft GEO-CAPE Atmospheric Composition Applications Value Matrix

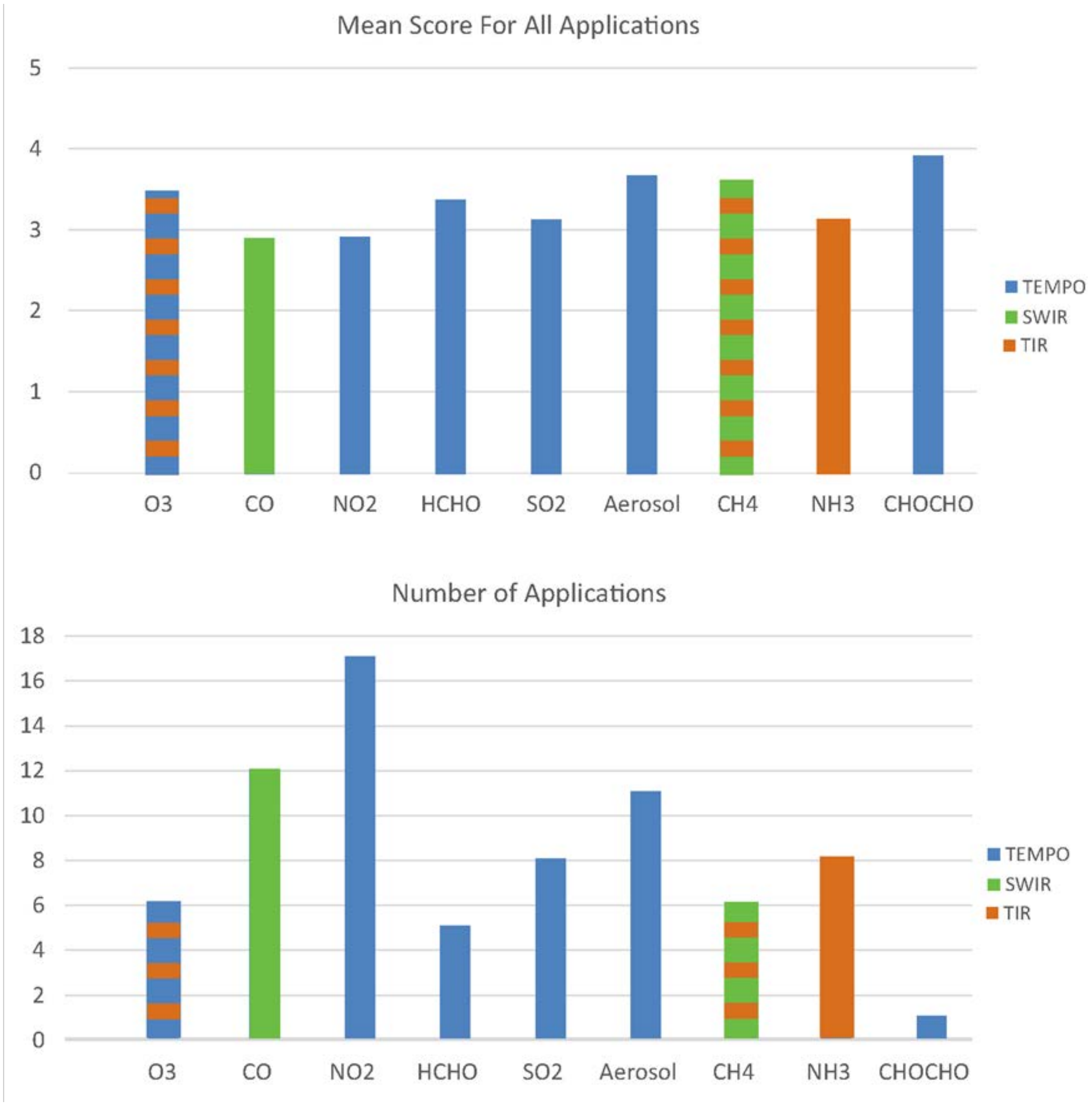


Figure C-3. Draft Atmospheric Composition Applications Value Matrix. Applications value of a GEO-CAPE science measurement was assessed by air quality planning experts at EPA in 2015. Both SWIR and TIR represent observations that may be made by different concepts for a GEO-CAPE infrared instrument (GCIRI). Striped bars indicate potential contributions from combined TEMPO and GCIRI configurations.

C.3.1 GEO-CAPE Atmospheric Composition Applications Value Matrix

The ASWG sponsored the definition of an Applications Value Matrix, creating a unique structure that includes heritage-based product confidence. The initial Value Matrix was sent to a cross-section of air quality scientists and managers at state and federal institutions, who were asked to rank the value of the GEO-CAPE measurements for a variety of applications needs in several broad categories. The ranking criteria measured both the usefulness and the uniqueness of the products. Input is ongoing, but preliminary results can be seen in Figure C-3.

Preliminary findings include (1) TEMPO will likely provide much needed measurements to the applications community (NO_2 in particular has very high value), (2) CH_4 and NH_3 (both are infrared products) have higher relative importance than they do in the Science Value Matrix because of regulatory priorities and the lack of measurements from other sources, and (3) there are significant synergies between measurements for ozone and aerosol applications that can be addressed by a combination of TEMPO and GCIRI.

NH_3 and O_3 measured in the thermal infrared (TIR) may have higher relative value to applications users than science users.

The full GCIRI capability is defined as multi-spectral CO, column CH4, and TIR O_3 and NH_3. GEO-CAPE funded studies of a PanFTS (Section 4) instrument to examine its performance as a single instrument solution for GEO-CAPE, and also as a TIR addition to a UV-vis instrument (like TEMPO) and a combined short wave infrared (SWIR) and mid wave infrared (MWIR) instrument.

Only the full baseline GEO-CAPE mission, either accomplished through a combination of TEMPO and a full capability GCIRI, or as a TEMPO follow-on can meet all of the critical needs identified in the draft Applications Value matrix.

D. POINTING STUDIES

D.1.1 Pointing Architecture

A generic instrument pointing architecture has been proposed, as illustrated in Figure D-1. This architecture provides a common framework to study the pointing of different GEO-CAPE instrument concepts.

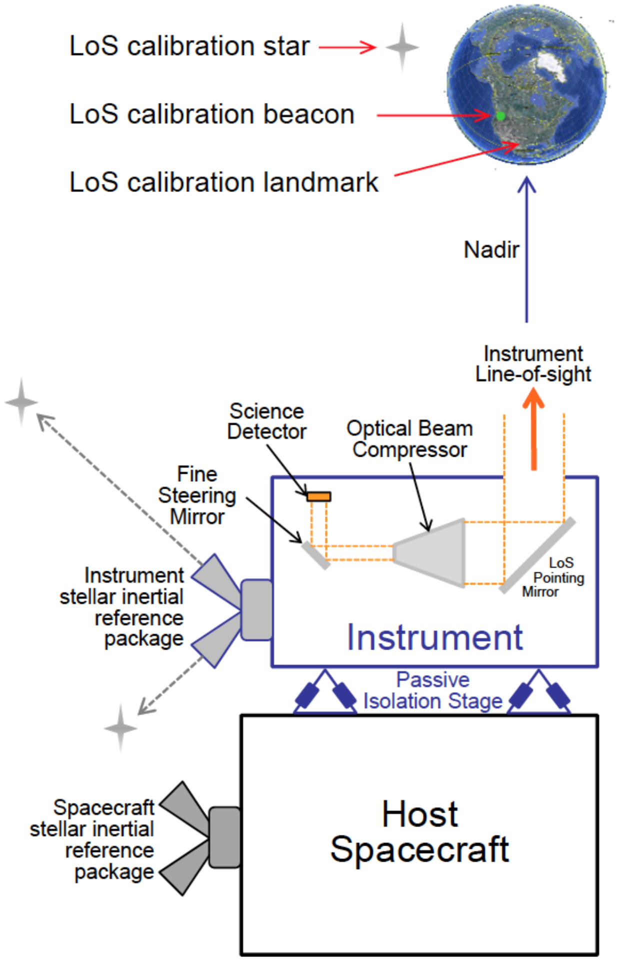


Figure D-1. Pointing architecture

This architecture includes the following, assumed key features:

- Passive isolation stage at the mechanical interface between the host spacecraft and the instrument to minimize host spacecraft jitter imparted to instrument;
- Instrument stellar inertial reference package (star tracker, gyro, attitude estimator) to achieve its line-of-sight (LoS) pointing knowledge requirements;
- Satellite ephemeris (position) measurements via GPS;

- Instrument entrance aperture pointing mirror with a 2 degree-of-freedom mount to locate the instrument field of view on the desired target. Capable of pointing large mirrors over a large range of motion;
- Fine steering mirror (FSM) to stabilize line of sight during science observations. With reduced size and reduced range of motion (few degrees), but fast and precise (Note: Roll around the LoS is uncontrollable. Spacecraft pointing errors that map into the instrument line of sight cannot be corrected with pointing mirrors);
- Pointing calibrations strategies:
    - Post observation landmark identification for geo location pointing reconstruction
    - Image the star background through the instrument to estimate instrument internal bias errors
    - Cal beacon on the ground to eliminate bias error; and Internal artificial star calibration source (i.e. an LED)

D.1.2 The Pointing Error Analysis and Simulation Tool

A software tool was developed in support of the pointing study for NASA's GEO-CAPE program. This tool enables fast, reliable, and accurate calculation of the LoS pointing errors for remote sensing scientific instruments. Although the motivation for this development originated from the analysis needs for instruments operating as hosted payloads on geostationary satellites, the tool is reconfigurable for a wide range of pointed scientific instrument applications.

The tool consists of two parts: (1) the three-axis frequency domain Instrument Pointing Error Analysis Tool (IPEAT) and (2) the three-axis time domain Instrument Pointing Simulation Tool (IPST).

The IPEAT is coded in MATLAB and offers numerous features. The main functions are:

1. Construct the pointing system configuration including coordinate transformations, estimators, controllers, vibration isolators, etc. An embedded database is available for the selection of state-of-the-art IMU, star trackers, and GPS receivers;
2. Develop end-to-end models of the pointing process and associated critical error sources (host spacecraft disturbance, ephemeris knowledge errors, celestial and inertial sensor errors, component alignment errors and errors related to the measurement, and actuation of the pointing mechanism);
3. To conduct 3-axis, end-to-end covariance analysis in the frequency domain via power spectral densities (PSD) of the processes involved and compute the pointing error metrics (accuracy and stability) for specified observation intervals.

The tool also provides the pointing calibration strategies as described earlier.

Figure D-2 depicts a typical error tree associated with spaceborne pointed instruments. The shaded blocks indicate the error sources modeled in to-date in this.

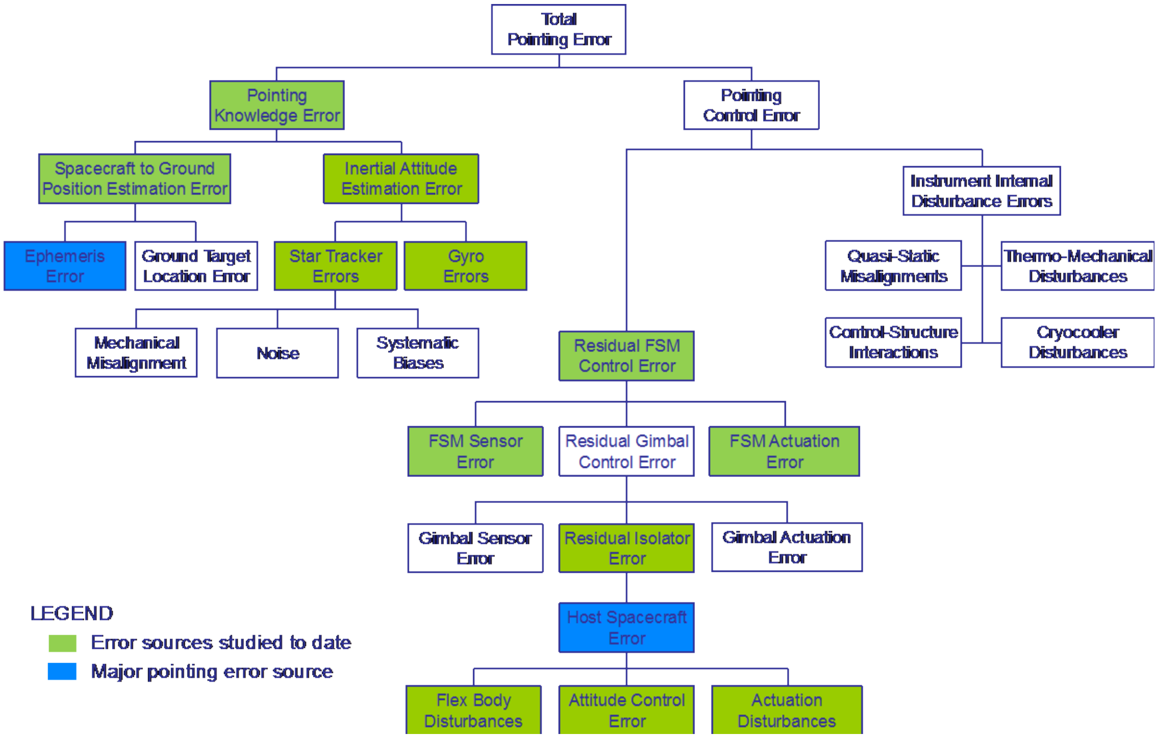


Figure D-2. Pointing error budget

The IPST is a three-axis time-domain simulation of the instrument pointing process implemented in MATLAB/Simulink. The main utility of this environment is to demonstrate the error analysis results from IPEAT, as well as to evaluate the performance of various instrument pointing control system designs. The simulation includes:

1. The system configuration defined in IPEAT;
2. Environmental disturbance signals generated using coloring filters consistent with the PSDs obtained in IPEAT;
3. Host spacecraft—instrument interface via passive or active isolator;
4. Error models of the star tracker, gyro and gimbal encoders.

The pointing control system may be configured for one or two-stage (coarse and fine) architectures and consists of a fast observer performing attitude determination using star tracker and gyro measurements, and the two-axis (tip/tilt) high bandwidth FSM gimbal control loop. The control system is designed to perform disturbance rejection and meet stringent accuracy and stability pointing requirements. The block diagram in Figure D-3 represents one configuration of IPST.

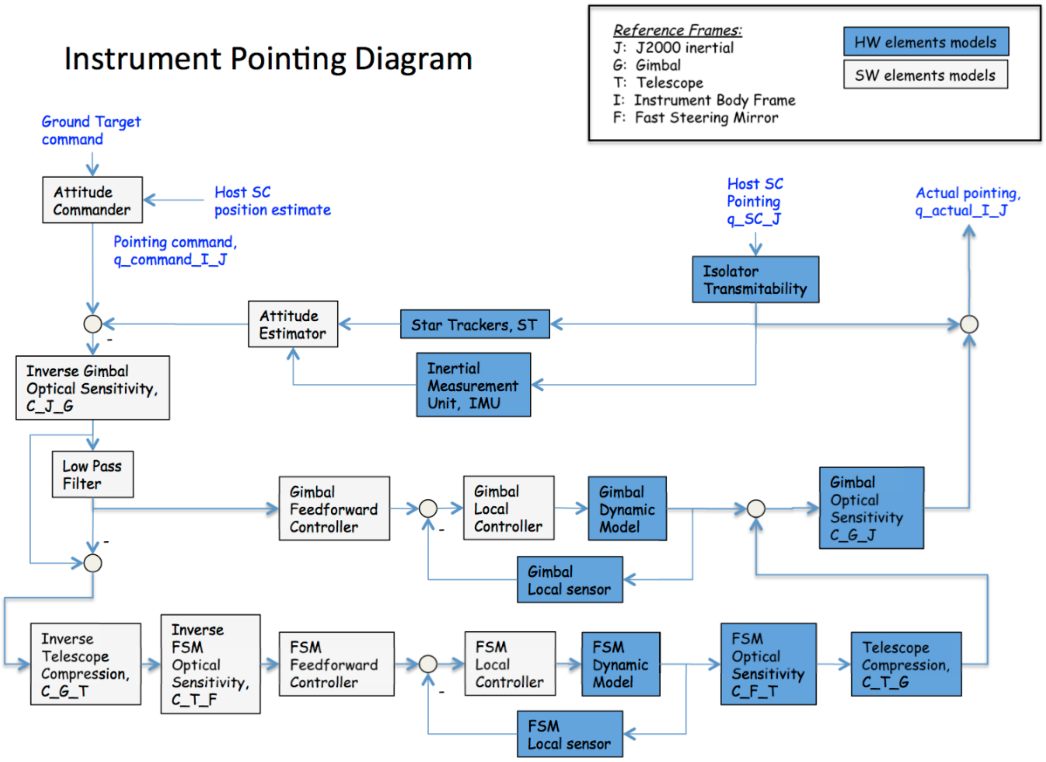


Figure D-3. IPEST block diagram

D.1.3 3D Pointing Visualization

A 3D pointing visualization add-on to the instrument line-of-sight time domain pointing simulation tool has been developed. This tool enables visualization of pointing error effects on instrument footprint on the ground. The tool is parameterized by: science-array-size NxM, science observation duration, refresh rate, and satellite pointing error sources (GPS, Star Tracker, Gyros, FSM, etc.). Figure D-4 shows a screen shot from a GEO-CAPE simulation.

D.1.4 Case Study

Based on the IPEAT described above, a simplified pointing analysis tool was developed in Matlab and Mathcad in 2013. The pointing tool accepts a host spacecraft disturbance spectrum along with spacecraft position uncertainties, applies various filters, and predicts the resulting pointing accuracy and stability. The various filters represent models of passive isolation systems, star tracker-IMU attitude observers, a fast steering loop, and a windowing function to represent the instrument integration time. By breaking these elements down into simple components, the pointing tool facilitates evaluation of performance over a range of input spectra, estimator and controller parameters, and architectures, all of which support instrument concept trade studies.

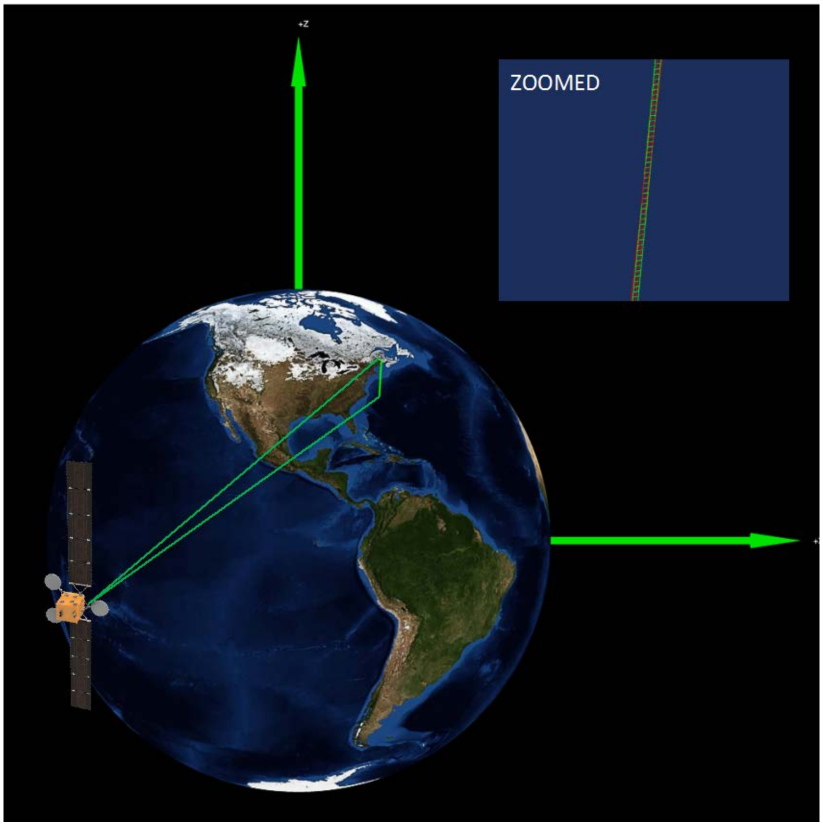


Figure D-4. Screen shot of 3D visualization

Several host spacecraft disturbance input spectra (PSDs) are shown in Figure D-5. The 160-arcsec curve represents a typical generic communications satellite. The OSC/EADS and SSL curves were provided by CII RFI respondents. The GOES curve is a conservative envelope of GOES-13 on-orbit data. Comparing the GOES curve to the 160-arcsec curve, GOES has lower inputs at lower frequencies, reflecting better attitude control. GOES also has more disturbances at higher frequencies, including some narrow peaks. The finer attitude control may be considered as representative of scientific geo-synchronous satellites, as opposed to communications satellites. The high-frequency disturbances are caused by scanning mechanisms. Spacecraft position uncertainty has a small contribution to pointing accuracy, concentrated at low harmonics of orbit rate.

The pointing tool features simple pole-zero models of several transfer functions that affect the impact of input errors on the pointing accuracy and stability. The passive isolator is essentially a low-pass filter, either adapted from existing hardware or representing a custom design. The attitude observer is a complementary filter, blending star tracker and IMU inputs to predict attitude estimation performance based solely on the star tracker noise-equivalent angle and the IMU angle random walk. Reducing the model to this simple level facilitates component selection trades, since the impact of star tracker and IMU performance may be easily and rapidly evaluated. A fast steering loop transfer function compensates for the disturbances that are poorly rejected by the passive isolator. It should be designed to overlap with the isolator, to provide good disturbance rejection over the entire spectrum. Finally, the windowing transfer function is a sine function that partitions the pointing performance into the low-frequency portion (accuracy) and the high-frequency portion (stability), based on the instrument integration period.

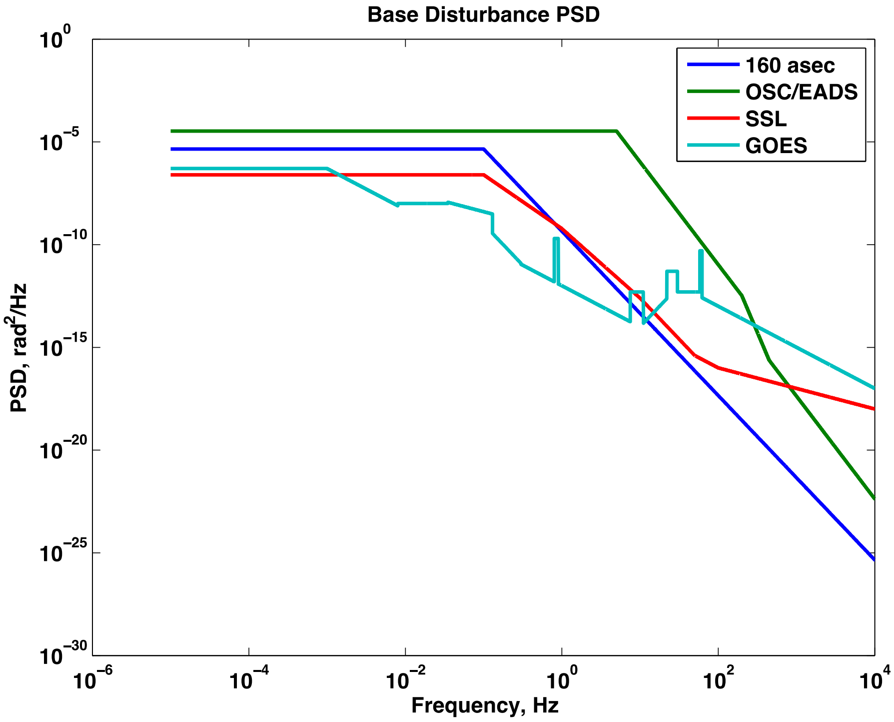


Figure D-5. Host spacecraft base disturbance PSDs

The pointing tool was applied in Goddard's Instrument Design Lab (IDL) to study two instrument concepts: the Wide Angle Spectrometer (WAS) and the Filter Radiometer (FR). A custom passive isolation system was designed with a fast steering loop. Performance predictions are presented in Table D-1 and graphically in Figures D-6 and D-7 for the 160-arcsec and GOES input disturbance spectra and a range of instrument integration times. The FR field-of-view requirement is 250 m, with the WAS requirement at 375 m, so pointing performance is compared to the more stringent FR requirement:

- Baseline
  - RMS Accuracy: 0.360 arcsec
  - RMS Stability: 0.144 arcsec
- Threshold
  - RMS Accuracy: 1.441 arcsec
  - RMS Stability: 0.720 arcsec

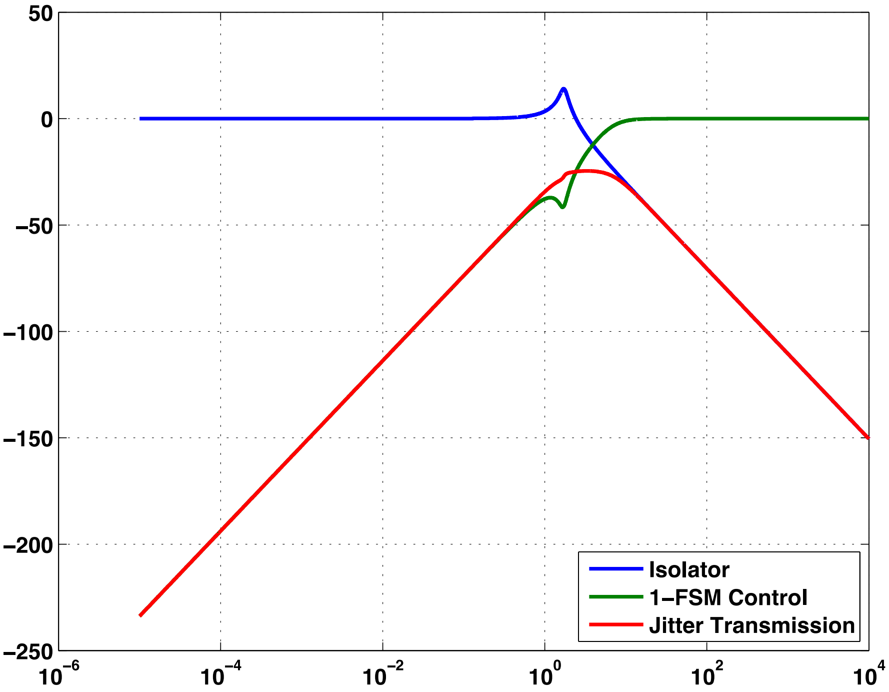


Figure D-6. Pointing tool disturbance rejection transfer functions

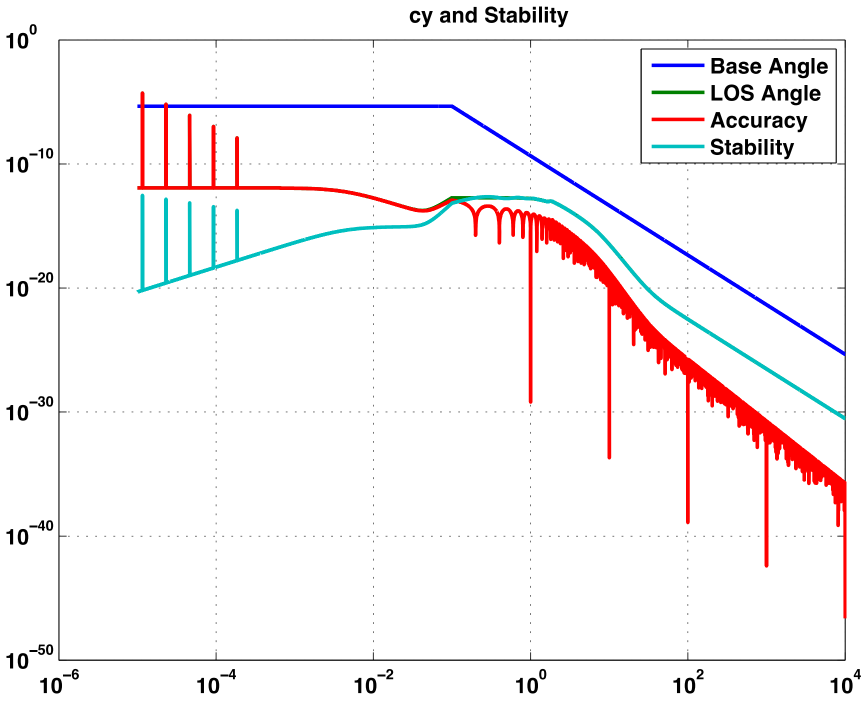


Figure D-7. Pointing tool output PSDs

Table D-1: Pointing Tool Results for Filter Radiometer (FR) Instrument Study.

RMS Pointing Accuracy (arcsec)		
Window (sec)	160-arcsec Input	GOES Input
0.5	0.284	0.270
1.0	0.278	0.269
2.0	0.274	0.269
5.0	0.271	0.269

RMS Pointing Stability (arcsec)		
Window (sec)	160-arcsec Input	GOES Input
0.5	0.084	0.016
1.0	0.105	0.019
2.0	0.115	0.020
5.0	0.120	0.019

D.1.4.1 Roll Error Compensation

GEO-CAPE pointing accuracy requirements are more stringent than their host spacecraft attitude control requirements. The GEO-CAPE instrument concept uses two star trackers and an IMU to estimate the instrument orientation. The fast steering loop can steer the instrument LoS to compensate for spacecraft attitude errors transverse to the instrument boresight, but it cannot compensate for spacecraft errors about the boresight (roll) axis. Roll errors cause smear in the instrument measurements. For two-dimensional detectors, this smear can be compensated through post-processing on the ground, but for linear detectors, this smear is uncorrectable. A roll compensation system concept was developed to address this issue.

The roll compensation system consists of a roll camera and a roll actuator. The roll camera images a long linear feature on the Earth, such as a coastline. Measurements of this feature are compared to an onboard model, generating a roll error measurement. The roll camera must have a width in pixels at least commensurate with the detector’s linear dimension in pixels, to provide the same sensitivity to roll as the science measurement. Active roll control actuation is applied by voice coil actuators at the spacecraft-instrument interface. This actuator system may also provide some active vibration isolation in addition to the passive isolator, should that be desired.

D.1.4.2 Pointing Study Accomplishments

The pointing task of the GEOCAPE effort spanned several years (FY11–FY14). A summary of the accomplishments for each year:

- FY11: The team developed the generic pointing architecture and pointing analysis tools. Requirement for five instrument concepts were developed. The GEO-CAPE Science Instrument Line-of-Sight Pointing Study was conducted to “Develop a fine pointing control system design for a generic GEO-CAPE science instrument that illustrates how GEO-CAPE pointing requirements can be met.” Pointing architectures and analyses were completed for four instruments. Three of these (CEDI, GEOMAC, and GEOPATH) were conducted in GSFC’s concurrent-engineering Instrument Design Lab (IDL). The fourth (GeoFTS) was completed by JPL’s Team X;
- FY13: The team developed an independent pointing error analysis tool and a 3-D visualization-add-on to the pointing simulator, as described above;
- FY14: The team updated the spacecraft disturbance model, adding the GOES on-orbit-derived spectrum to our list of representative host inputs. The team also supported two more IDL studies (WAS and FR), and a Team X re-evaluation of the PanFTS pointing approach.

E. GEO-CAPE STUDY TEAM MEMBERSHIP

The GEO-CAPE mission concept matured greatly between 2007 and 2015 because outstanding people engaged in the planning, discussion, and work of the mission study. The list of participants evolved over the years, and a sincere effort has been made to identify all contributors in order to recognize the value of their time. The authors extend apologies to anyone who may have inadvertently left out, although their talent is certainly reflected in GEO-CAPE accomplishments. NASA ARC, GSFC, JPL, and LaRC collaborated on the pre-formulation of the GEO-CAPE mission. Inter-Agency partners EPA and NOAA engaged with NASA, and made significant contributions to the definition of GEO-CAPE. Study team members from the National Center for Atmospheric Research, the Monterey Bay Aquarium Research Institute, and the Woods Hole Oceanographic Institution advanced the science of GEO-CAPE along with Study Team members from over 20 universities.

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