Risk reduction measurements for GEO-CAPE:
A US-Korea joint field campaign (US-Korea JFC) in the East Sea and Yellow Sea

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1. Introduction

Biological and biogeochemical processes play critical roles in forming and modulating the ecosystems of both open ocean and coastal environments. Observing and monitoring the spatial and temporal changes of these environments are important for maintaining the quality of life for everyone on Earth. Decades of operation of CZCS, SeaWiFS, MODIS etc. have demonstrated that Sun-synchronous ocean color missions can provide excellent observations on longer-term (weeks to years) biogeochemical processes, but are unable to detect/monitor short-term (diurnal to a few weeks) processes, such as the dynamics of algae blooms, tidal dynamics, diurnal changes in photosynthesis, etc. Building on the success of SeaWiFS and MODIS and following the recommendations of the National Research Council, NASA is planning a geostationary ocean color satellite system to fill the temporal gap, with a focus on the coastal regions of the North and South American continents.

Due to the unique sampling strategy and sensor-target geometry, as well as the demand to address a wide range of challenging scientific questions, the radiometric sensor for GEO-CAPE cannot simply be a duplicate of the historical sensors such as SeaWiFS or MODIS. In addition to frequent sampling (every hour or better), the GEO-CAPE sensor is required to be able to provide high-spatial and high-spectral resolution measurements with high signal-to-noise ratios (SNR). To facilitate the design of such a sensor, a series of field campaigns for risk-reduction purposes were carried out in the Chesapeake Bay region (2011) and the northern Gulf of Mexico (2013). These experiments, however, 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 geostationary orbit to address the dynamics of coastal waters (see Science Questions 1-3 in Appendix I). These include:

a) Can the diurnal changes in sediment resuspension and settling be resolved with hourly satellite normalized-water leaving radiance (nLw) data?
b) Can the diurnal dynamics in organic carbon (dissolved and particulate) due to tidal exchanges at land-ocean interfaces be resolved in hourly nLw data?
c) How do particle size, shape and composition impact the ocean bi-directional reflectace distribution function (BRDF) and in turn the nLw signature at different view angles during a diurnal period?
d) Can diurnal changes in CDOM from production and photooxidation be detected with hourly data from a geostationary satellite?
e) How accurately do the atmospheric properties need to be estimated in order to obtain reliable diurnal nLw from a geostationary satellite?

f) How does BRDF variation in water-leaving radiance (Lw, $w/m^2/nm/sr$) affect the GOCI hourly nLw retrievals?

g) Given the spatial and spectral specifications of GOCI how well can we address the diurnal variation of biogeochemical properties in the coastal oceans? What improvements are needed in future sensors to address coastal dynamics?

h) How do geostationary ocean color products compare with both polar-orbiting ocean color satellite products and with *in situ* measurements?

i) To what extent can hourly geostationary data improve the estimation of primary productivity?

To address these questions that are important for characterizing a geostationary coastal ocean-color sensor, and to obtain important data for risk reduction of the GEO-CAPE mission, we propose to undertake a 2-week field campaign with Korean scientists in the East and Yellow Seas. There are multiple reasons for conducting this study in coastal waters adjacent to Korea. First and foremost, these waters are directly under the field-of-view (FOV) of GOCI, the first ever and as yet, only geostationary-based ocean color satellite (launched in June 2009) in operation. Thus we will be able to obtain unique datasets that include both *in situ* measurements and geostationary ocean-color satellite data to address various technique questions such as those listed above. Second, the lessons learned will be directly applicable to future GEO-CAPE studies in American coastal waters as similar features are present in both regions. Third, observations and analyses related to the above questions are especially critical for mission planning and risk reduction as the trade space is probed to optimize scientific achievement at an affordable cost for GEO-CAPE. Data from this field campaign will be able to define the limitations of the present GOCI sensors on the retrieval of biogeochemical properties and 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. Fourth, an international constellation of geostationary sensors are envisioned from Asia to the Americas to Europe. Developing international partnerships and collaborations is essential to the success of a truly international global observing system. A joint field campaign with our Korean partners is an important step in developing such collaborations.

2. Scientific rationale

2a. Primary (required) objectives

The GEO-CAPE ocean color (OC) science working group (SWG) was tasked with developing a science traceability matrix (STM) that not only sketches out the key science objectives of the OC mission (see Appendix I), but also provides measurement and instrument requirements to achieve those objectives. The overarching challenge of OC retrievals from space derives from the fact that <10% of the total radiant fluxes at the top of the atmosphere (TOA) are contributed by water-leaving radiances (Lw) and in coastal waters this may be reduced to <1% in the blue-green wavelengths where chemical and biological information reside [*Fishman et al.* 2012; *IOCCG* 2010]. Also along highly urbanized coasts, it is crucial to accurately correct for atmospheric contributions from aerosols, NO_2, O_3, and water vapor for the retrieval of Lw from TOA measurements. Experience and lessons from past ocean color missions (CZCS, SeaWiFS, MODIS, MERIS, VIIRS, etc.) indicated that it is critical to have exceptional sensor capabilities in order to achieve the desired science goals and these requirements have been summarized for a GEO-CAPE ocean color sensor in the current STM (Appendix 1).

The fundamental characteristics of an ocean color satellite sensor are spatial resolution, temporal resolution, signal-to-noise ratio, spectral range and spectral resolution. Each of these drives mission cost to some extent. Several instrument design studies for potential GEO-CAPE OC sensors have been performed over the years [CEDI 2010; FR 2014; WAS 2014; OC architecture scaling study 2014], including most recently this summer, to provide guidance on how best to define the instrument requirements in the STM to achieve the scientific goals within an acceptable budgetary framework. For example, one set of the options involves choices among hyperspectral versus multiband approaches; another involves spatial resolutions at nadir [OC architecture scaling study 2014]. Such laboratory studies, however, are insufficient to address the instrumental needs to meet the challenges of measuring widely varying coastal environments from space. This void in knowledge can be filled to a good extent with a risk reduction field campaign in Korean waters where a geostationary OC instrument (GOCI) is in operation. GOCI has a multiband design with 8 bands (412, 443, 490, 555, 660, 680, 745, and 865 nm; with a typical 20 nm bandwidth). Its ground sampling distance is 360 m at nadir (~500 m local), which is comparable to GEO-CAPE threshold requirements. By comparing intensive and comprehensive *in situ* measurements with GOCI retrievals, we can test the band set used on orbit, study the level of detail offered by a 360 m nadir pixel size, examine retrievals throughout the day as a function of evolving conditions both in water and in the atmosphere, and collaborate with our Korean colleagues on optimizing retrievals from geostationary orbit with its novel solar zenith angle, viewing angle, BRDF, etc. All of these efforts will provide desired information to the OC SWG as they continue to refine measurement and instrument requirement recommendations to NASA for the future GEO-CAPE sensor.

A joint cruise in collaboration with our Korean colleagues within the field of view of GOCI is sufficient to meet the primary research objectives of this field campaign. The data obtained will permit an assessment of the questions outlined in the preceding paragraph, as well as the questions listed in the introduction.

2b. Secondary (highly desirable) objectives

A secondary argument in favor of a risk reduction field campaign in the Korea region is a potential collaborative opportunity with the air quality (AQ) community. In addition to OC, GOCI is also retrieving hourly aerosol optical depth (AOD). This combined with the fact that there are three funded geostationary atmospheric chemistry instruments scheduled for launch in the 2018-2019 time frame (GEMS, Republic of Korea; TEMPO, U.S.A.; and Sentinel-4, Europe) has motivated the tropospheric composition community to propose an airborne field campaign in Korea for April-June 2016. Their goals are multi-fold [*Al-Saadi and al.* 2014]: 1) GOCI presents a "unique opportunity for end-to-end demonstration and refinement of the cal/val campaign techniques that will be required for full use of the data from the forthcoming GEO atmospheric chemistry missions"; 2) "Korea also offers the potential for strong gradients in both AOD and O_3 precursors (esp., NO_2) for which remote sensing algorithms can be tested and improved in advance of the launches of GEMS, TEMPO, and Sentinel-4"; 3) "Only an airborne campaign that can evaluate the over-ocean aerosol retrievals and the aerosol evolution across the land-sea boundary can contribute meaningfully to the evaluation of aerosol retrievals relevant to air quality assessments in Seoul"; and 4) to build international collaborations among Korean and U.S. scientists that involves cooperation on all aspects of research in the expectation that such partnerships will be essential to successfully exploiting the potential of the forthcoming international constellation.

Although it is not essential to forge a joint OC-AQ campaign for the risk reduction of the OC mission within the GEO-CAPE concept, the opportunity to leverage the activities of the AQ community is one not to be missed if the proposed joint AQ campaign in Korea (called KORUS-AQ) goes forward. The proposed flight tracks (see figure in Appendix II) include passes over the same regions of interest in the East and Yellow Seas that are proposed here (see Figure 1 in Section 3) for investigation during the cruise. Among the proposed KORUS-AQ measurements that are required for mission success (see table in Appendix II) are remote sensing of trace gas columns of O_3 and NO_2, multi-spectral optical depth, nadir/zenith O_3 lidar profiles, and nadir lidar profiles of the extinction, backscatter, and depolarization of aerosols. All of these proposed measurements would be advantageous for comparison with proposed column measurements here of atmospheric constituents from the deck of the ship. Further, the spatial resolution, temporal resolution, signal-to-noise ratio, spectral range and spectral resolution of these airborne and ship-based remotely sensed parameters will be of great value in comparison with GOCI retrievals. In addition, KORUS-AQ proposed *in situ* measurements include O_3, NO_2, water vapor, and various aerosol properties made aboard the DC-8. Ground-based stations would provide a crucial data point underneath vertical profiles when evaluating the retrieved column properties, as well as improved understanding of the relationship between surface values and aloft measurements. *Only a ship can provide such surface data above water.*

The acquisition of these additional complementary data sets to the primary measurements proposed herein would be extremely valuable to the OC SWG in furthering the refinement of the GEO-CAPE OC sensor and measurement requirements. *For this reason alone, if both campaigns are approved for funding, the US-Korea Joint Field Campaign (JFC) team would make every effort to coordinate with the airborne campaign to maximize the scientific potentials from such opportunities.* Another benefit of such a joint endeavor between the AQ and OC communities in the US and Korea is the potential to foster greater interdisciplinary science exploration, as well as improved retrievals across the land/sea interface. Just as urbanized coastlines (where there are intense local atmospheric emissions with large gradients) can pose challenges for retrievals in coastal waters for the OC community, the optical complexity of coastal waters pose challenges for retrieving atmospheric constituents of interest to the AQ community.

A collaborative effort between the US-Korea-JFC cruise and the KORUS-AQ mission would produce a dataset that would combine retrievals from GOCI with airborne, ground-based, and in-water measurements to assess retrieval algorithms, advance atmospheric/oceanic corrections for both communities, offer an opportunity to evaluate the GOCI configuration in the context of refining requirements for the GEO-CAPE OC sensor, and further algorithm development/refinement for geostationary retrievals. *The Korean peninsula, its surrounding wide-range of water types, and upwind/upstream inputs to the region provide a rigorous testing ground under potentially challenging episodic conditions that will be ideal for developing our capabilities to maximize the anticipated gain in scientific knowledge from geostationary sensors.* These lessons promise to yield tangible benefits when applied to American coastal regions when GEO-CAPE takes flight.

3. Targeted regions for field campaign

Tentatively the time window is planned for April-June 2016 to accommodate collaboration with the US-Korea AQ effort, but the ocean-color segment of this field campaign is not tied to the AQ effort.

Generally the sampling will take place in waters that are viewed by GOCI as shown by Figure 1. Two regions (one in the Yellow Sea and the other in the East Sea, the two red boxes) have been identified that represent different combinations of biogeochemical properties and processes. These areas are influenced by the passage of cold air outbreaks and exhibit distinct seasonality in their biogeochemistry. Both regions also lie under the proposed flight tracks of the US-Korea AQ campaign (see Appendix II).

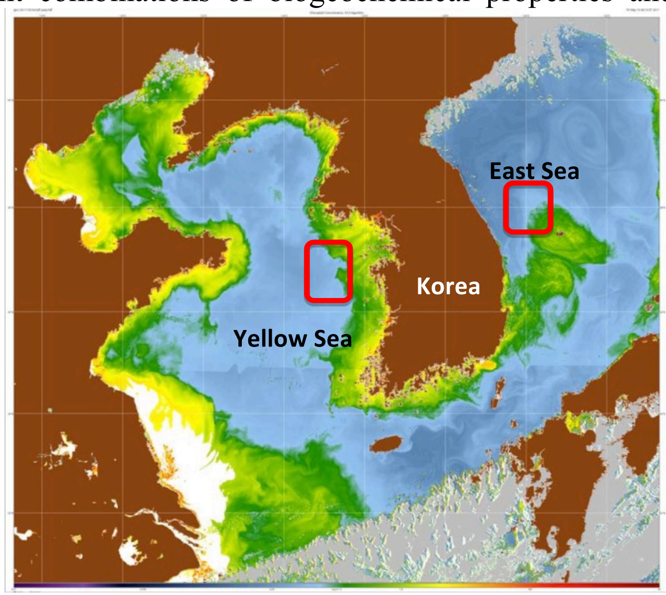

Figure 1. Typical chlorophyll distribution of the region derived from GOCI data. The red boxes indicate proposed sampling areas. Specific sampling sites and strategy will be planned jointly by the Korean and US cruise participants based on the latest data and conditions.

The shallow area in the Yellow Sea is selected to represent an area influenced by strong coastal tidal mixing with elevated sediment suspension. These coastal waters show strong variability in particle size, particle settling and aggregation, CDOM and phytoplankton pigments, all of which have diurnal signatures. In addition, the Anmyon AERONET site is located in this area, which provides atmospheric measurements for GOCI calibration and validation. Sampling strategies include diurnal stations at one location or following a drogue marked water mass to evaluate diurnal changes and underway mapping at night to assess spatial variability and nighttime changes not seen with GOCI data.

The area in the East Sea is selected to represent open ocean waters influenced by the subpolar front. This area includes dynamic offshore eddy fields resulting from the interaction of the eastward Korean current with offshore waters, which mimic the eddy fields associated with the Gulf Stream. Various biogeochemical processes, such as bloom dynamics, CDOM production and oxidation, are associated with these highly dynamic eddies. Similar sampling strategies will be employed including diurnal stations at one location or following a drogue marked eddy and underway mapping at night to assess spatial variability. The specific sampling strategy will be developed jointly by the US and Korean cruise participants once they have been selected for the project.

4. Parameters to be measured and measurement methods

To address the geostationary related science and observation questions listed in the introduction, comprehensive measurements will be made for a suite of physical, optical and biogeochemical parameters of both the ocean and atmosphere. These measurements will include both underway (continuous) observations, hourly visit of drogue marked water mass, and more detailed measurements of processes and properties determined from discrete in-water profiles and water samples. Parameters to be measured include water-leaving radiance, inherent optical properties (IOPs), carbon, nutrients, pigment concentrations, as well as atmospheric properties. This section provides a list of measurement parameters as summarized in Table 1. These are all well-established methods and a more detailed description of the current methods for these measurements is provided in Appendix III. The actual methods used will be proposed by the cruise participants who are experts at making these measurements. All methods will meet or exceed NASA protocols and all data will be posted to NASA SeaBASS archive after the cruise and processing is complete.

Table 1: Physical, optical and biogeochemical properties to be measured during the joint GOCI – GEO-CAPE OC campaign.

	Measurement	**Potential instruments used for data collection**
Physical properties	Temperature and salinity	CTD sensor (Seabird)
Apparent Optical Properties	Water-leaving radiance; remote-sensing reflectance	HyperPro (Satlantic); Handheld spectrometer (ASD); C-OPS (Biospherical); HyperSAS (Satlantic)
	Diffuse attenuation	HyperPro, C-OPS
	Photosynthetic available radiation	HyperPro, PAR sensors, HyperSAS
Inherent Optical Properties	Total and dissolved beam attenuation and absorption	ac-s spectrophotometer (WETLabs)
	Backscattering	Eco BB3, Eco VSF3 or BB9 (WetLabs) HydroScat-6 (HOBILabs)
	CDOM absorption	ac-s – Filtered for CDOM Ultrapath (WPI)/Spectrophotometer WETStar fluorometers (WETLabs)
	Absorption of particulate and phytoplankton pigments	Spectrophotometer
Biogeochemical Properties	Concentration of phytoplankton pigments	HPLC, underway fluorometric measurements
	TSM, particle size distribution	Gravitational; LISST
	Particulate (POC) and Dissolved Organic Carbon (DOC)	CEC 440HA Elemental Analyzer; MQ1001 carbon analyzer
	Nutrients (NO_3, NO_2, PO_4)	Spectrophotometer (Colorimetric analyses) , AutoAnalyzer
	pCO2, Dissolved Inorganic Carbon, pH and Total Alkalinity	Sunburst SAMI-CO_2, Turner C-sense
	Phytoplankton Taxonomy	Imaging flowcytometer (McLane,

		Inc.); FlowCAM (Fluid Imaging)
	Productivity	^{14}C or ^{13}C incubations; FRRF
Atmospheric	Aerosol optical depth	Sunphotometer
Properties	NO_2, O_3, trace gases	Pandora

Underway sampling will be conducted whenever the ship is underway and during most stations to provide a high frequency time series of measurements for comparison with the GOCI data. Underway sampling typically includes temperature, salinity, limited AOPs (HyperSAS and PAR sensors during daylight hours), IOPs, chlorophyll fluorescence, CDOM fluorescence, backscattering at 440 nm. Additional measurements including a-c9 absorption and beam attenuation, filtered a-c9 for CDOM absorption, particle size measurements, pCO_2 and nutrients may also be considered. The exact methodologies and instruments for measurements will depend on the participants funded to be on the cruise.

In addition to those underway measurements, station sampling includes detailed surface measurements of Rrs, vertical profiles of AOPs, IOPs, temperature, salinity, chlorophyll fluorescence and water sample collection for further analysis. Water samples are processed for detailed analysis of CDOM, phytoplankton (HPLC pigments, species analysis, and productivity), nutrients, partial pressure of carbon dioxide (pCO_2), POC and DOC. Short duration field measurements of biological production including gross primary production (GPP), net primary production (NPP), and net community production (NCP) will be made using water samples incubated in shipboard incubators. Methods for all of these measurements are described in Appendix III. The specific measurements will be chosen by the cruise participants to meet the proposal requirements.

5. Budget

The estimated budget for the NASA contribution to this field campaign (ocean color measurements) described herein is $990K. A breakdown of the anticipated costs is shown in Table 2. The Korean vessel (R/V Onnuri) can accommodate 20 scientists. The berths will be shared between U.S. and Korean scientists.

Table 2. Estimated cost to NASA for this US-Korean joint field campaign.

	Total Cost	Korean Contribution	NASA Contribution
Ship time 14 days ($15K/day)	$210K	$105K	$105K
Support for ~8 US PIs on 2 yr grants	$885K	0	$885K
Support for Korean PIs	TBD	TBD	0
TOTAL	TBD	TBD	$990K

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APPENDIX I: GEO-CAPE OCEAN COLOR STM

GEO-CAPE Oceans STM

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Science Focus / Science Questions

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)

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)

Approach (Maps to Science Question)

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, — 1 2 3 4
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. — 1 2 4 5

Measurement objectives for both modes include:
(a) Quantify dissolved and particulate carbon pools and related rate measurements such as export production, air-sea CO2 exchange, net community production, respiration, and photochemical oxidation of dissolved organic matter. — 1 2 3
(b) Quantify phytoplankton properties: biomass, pigments, functional groups (size/taxonomy/Harmful Algal Blooms (HABs)), daily primary productivity using bio-optical models, vertical migration, and chlorophyll fluorescence. — 1 2 3 4 5
(c) Measure the inherent optical properties of coastal ecosystems: absorption and scattering of particles phytoplankton and detritus, CDOM absorption. — 1 2 3 4
(d) Estimate upper ocean particle characteristics including particle abundance and particle size distribution. — 5 / 1 2 3
(e) Detect, quantify and track hazards including HABs and petroleum-derived hydrocarbons. — 5

GEO-CAPE observations will be integrated with field measurements, models and other satellite data:
(1) to derive coastal carbon budgets and determine whether coastal ecosystems are sources or sinks of carbon to the atmosphere, — 2 3
(2) to quantify the responses of coastal ecosystems and biogeochemical cycles to river discharge, land use change, airborne-derived fluxes, hazards and climate change, and — 1 2 3 4 5
(3) to enhance management decisions with improved information on the coastal ocean, such as required for Integrated Ecosystem Assessment (IEA), protection of water quality, and mitigation of harmful algal blooms, oxygen minimum zones, and ocean acidification. — 3 5

Measurement Requirements

Water-leaving radiances in the near-UV, visible & NIR for separating absorbing & scattering constituents & chlorophyll fluorescence

Product uncertainty TBD

Temporal Resolution:
Targeted Events:
- Threshold: ≤1 hour
- Baseline: ≤0.5 hour

Survey Coastal U.S.:
- Threshold: ≤3 hours
- Baseline: ≤1 hour

Regions of Special Interest (RSI): Threshold: ≥1 RSI 3 scans/day
- Baseline: multiple RSI 3 scans/day

Other coastal and large inland bodies of water within ocean color FOR:
- 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. U.S. Coastal Waters* 3 to 8 times per day
2. Other coastal and large inland bodies of water
3. Open ocean waters within FOR

Instrument Requirements

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 km^2/min; Baseline: ≥50,000 km^2/min

Field of Regard:
- Full disk: 20.8° E-W and 19° N-S imaging capability from nadir for Lunar & Solar Calibrations

Error (as % of nadir pixel)	**Threshol**	**Baselin**
Pointing Knowledge LOS	**<50%**	**<10%**
Pointing Accuracy LOS	**<100%**	**<25%**
Pointing Stability LOS	**<50%**	**<10%**
Geolocation Reconstr.	**<100%**	**<10%**

Non-saturating detector array(s) at Lmax
On-board Calibration:
- Lunar: Threshold: minimum monthly; Baseline: same as threshold
- Solar: Threshold: none; Baseline: daily

Polarization Sensitivity: <1.0%
Relative Radiometric Precision:
- Threshold: ≤1% through mission lifetime
- Baseline: ≤0.5% through mission lifetime

Mission lifetime: Threshold: 3 years; Goal: 5 years

Intelligent Payload Module 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

Platform Requirem.

Geostationary orbit at 95W longitude to permit sub-hourly observations of coastal waters adjacent to the continental U.S., North, Central and South America

Storage (up to 1 day) and download of full spatial data and spectral data.

Ancillary Data Requirem

Western hemisphere data sets from models, missions, or field observations

Measurement Requirements
(1) Ozone
(2) Total water vapor
(3) Surface wind velocity
(4) Surface barometric pressure
(5) Vicarious calibration & validation - coastal
(6) Full prelaunch characterization
(7) Cloud cover

Science Requirements
(1) SST
(2) SSH
(3) PAR
(4) UV solar irradiance
(5) MLD
(6) Air/Sea pCO2
(7) pH
(8) Ocean circulation
(9) Tidal & other coastal currents
(10) Aerosol deposition
(11) run-off loading in coastal zone
(12) Wet deposition in coastal zone
(13) Wave height & surface wind speed

Validation Requirements
Conduct high frequency field measurements and modeling to validate GEO-CAPE retrievals from river mouths to beyond the edge of the continental margin.

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

<u>APPENDIX II: KORUS-AQ PROPOSED FLIGHT TRACKS & MEASUREMENT SUITE</u>

Figure reproduced with permission from Al-Saadi et al. [2014]

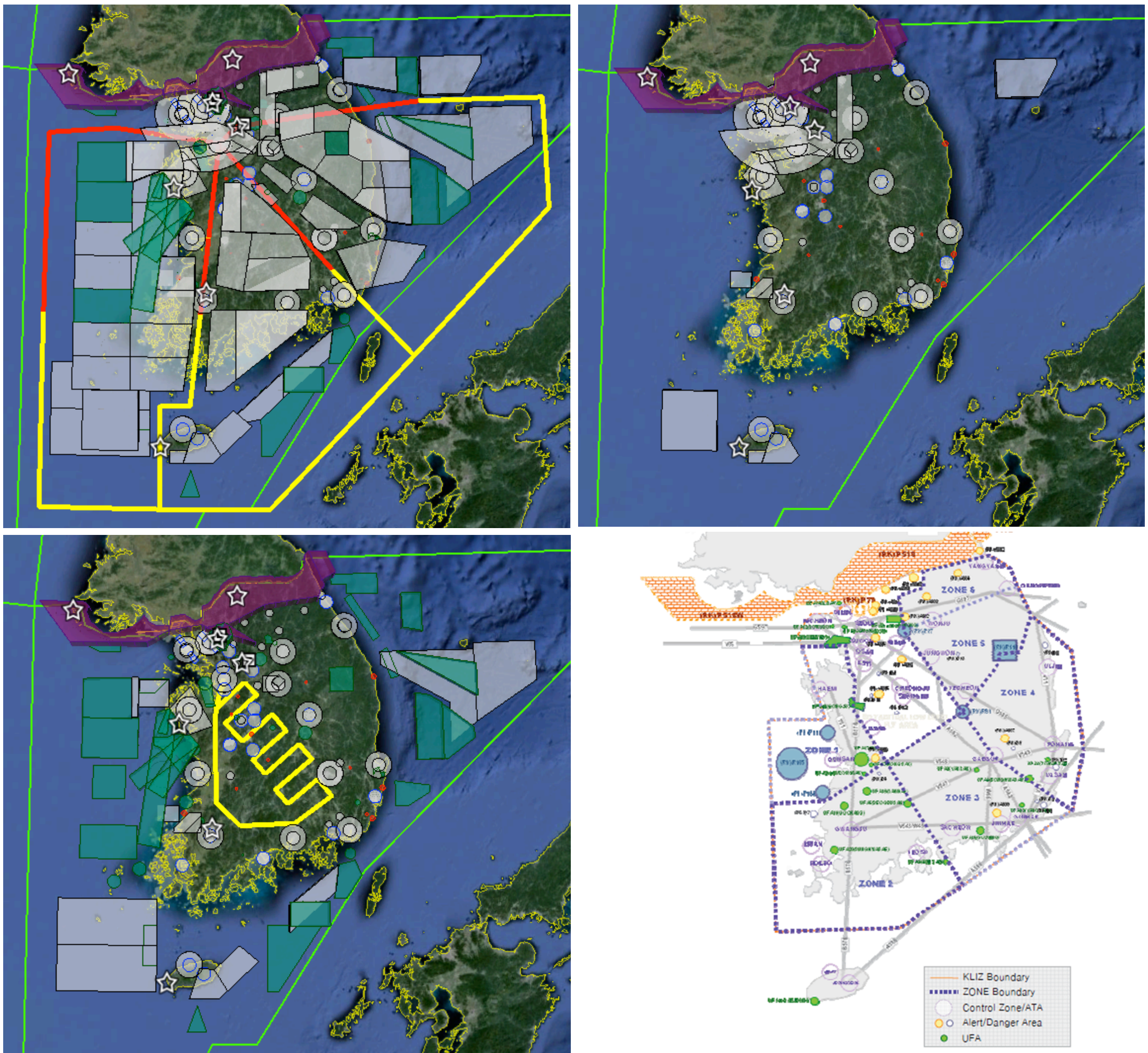

Figure 13. Special use airspace within the South Korean FIR (green border) for weekdays (top left) and weekends (top right). Flight areas to support military operations and training are not active on weekends, offering greater flexibility for sampling. Flight lines (shown in red and yellow) indicate potential lanes for survey sampling that should be feasible on any day (see discussion in text). Low altitude flight (below 3000 ft) to sample near-surface pollution is more broadly feasible as only a subset of special use airspace extends to the surface (bottom left). Instead, low altitude flight is regulated by the ROK Air Force across six zones (bottom right).

Table. Proposed measurements for KORUS-AQ that are required for mission success (priority level 1). See Al-Saadi et al. [2014] for full list of proposed measurements that include priority levels 2 (desired) and 3 (useful).

Gas Phase In Situ	Priority	Detection Limit	Resolution
O3	1	1 ppbv	1 s
H2O	1	10 ppmv	1 s
CO	1	5 ppbv	1 s
CH4	1	10 ppbv	1 s
CO2	1	0.1 ppm	1 s
NMHCs	1	<10%	1 min
NO	1	10 pptv	1 s
NO2	1	20 pptv	1 s
HCHO	1	50 pptv	1 s
Aerosol In Situ	Priority	Detection Limit	Resolution
Size Distribution/Number	1	NA	10 s
Volatility	1	NA	1 s
Scattering	1	1 Mm-1	1 s
Absorption	1	0.2 Mm-1	10 s
Hygroscopicity	1	NA	10 s
Ionic composition	1	50 ng m^{-3}	5 min
Organic composition	1	100 ng m^{-3}	1 min
Black carbon	1	50 ng m^{-3}	1 s
Remote Sensing and Radiation	Priority	Detection Limit	Resolution
UV spectral actinic flux (4π sr)	1	80° SZA equivalent	5 s
Ozone lidar (nadir/zenith)	1	5 ppbv or 10%	300 m
Trace Gas Columns (O_3, NO_2, C_2HO)	1	variable	variable
Multi-spectral optical depth	1	0.01	1 s
Aerosol profiles of extinction	1	10 Mm^{-1} or 10%	300 m
Aerosol profiles of backscatter	1	3%	30 m
Aerosol profiles of depolarization	1	3%	30 m

Appendix III. Properties and measurement procedures

1. Water-leaving radiance (Lw) or remote sensing reflectance (Rrs)

Remote-sensing reflectance, Rrs, sr^{-1}, is defined as the ratio of water-leaving radiance (Lw) to downwelling irradiance just above the surface ($E_d(0^+)$). Rrs is a fundamental property in ocean-color remote sensing. It is the sole input for the derivation of sub-surface properties, and it is the property generally used to validate the performance of a satellite remote sensing system. A few schemes to measure Rrs in the field have been developed and commonly adopted in the past decades. The following approaches will be implemented during this field campaign:

Approach 1 (A1) or the commonly termed above-surface method: This method measures upwelling radiance ($L_u(0+)$) from an above-surface platform (usually at the bow of a boat). Because ($L_u(0+)$) includes surface-reflected skylight, it is then necessary to remove this noise (or interference) for the calculation of L_w. This is achieved by measuring downwelling skylight (L_{sky}) that is reciprocal to the direction of $L_u(0+)$, and the Lw could be derived from the measured ($L_u(0+)$) and L_{sky} [*Lee et al.* 2010; *Mobley* 1999]. For the calculation of Rrs, $E_d(0^+)$ will be measured with a well-calibrated sensor or using a calibrated reference panel [*Mueller et al.* 2003].

Approach 2 (A2) or the commonly termed in-water method: Vertical profiles of upwelling radiance ($L_u(z)$) and downwelling irradiance ($E_d(z)$) within the water column will be measured with calibrated hyperspectral sensors (e.g., the Hyperpro sensors developed by the Satlantic, Inc.). Regression analysis will be carried out between depth (z) and $\ln(L_u(z))$ or $\ln(E_d(z))$, respectively, and the intercept of these regressions will result in $L_u(0\text{-})$ and $E_d(0\text{-})$. Propagating these values upward across the sea surface will produce L_w and $E_d(0^+)$, allowing for calculation of R_{rs} [*Smith et al.* 1984]. Spectral $E_d(0^+)$ could also be obtained by placing a sensor above the surface.

Approach 3 (A3) or the Skylight-Blocked Approach (SBA): Lee et al. [2013] recently highlighted that Lw can be measured directly in the field with very high precision. Different from the in-water or above surface methods, this method combines the advantages of both. Basically, the whole system floats on the surface, and a small black cone is placed in front of the radiance sensor to measure upwelling radiance. The cone is inserted just below the surface while the sensor itself maintains a position in the air, thus the measurement coming out of the sensor is L_w. In the meantime, another spectrometer is placed just above the surface to get $E_d(0^+)$, and then Rrs can be quickly calculated from the two measured radiometric quantities.

A1 can be operated from appropriate positions on the boat, as long as no objects interfere with the measurements of the three associated quantities. A2 and A3 will have instruments released in the water column, and both could be carried out at the same time.

2. Inherent optical properties (IOPs)

Both underway (continuous) and at-station (upper-water column) measurements will be carried out for the measurement of IOPs.

2.1. Underway measurements

Water from the clean seawater underway feed will be continuously passed through a system used for deriving temperature and salinity, chlorophyll and CDOM fluorescence, multispectral backscattering, and hyperspectral total and dissolved attenuation and absorption. All data from the instruments will be simultaneously recorded via a data handler, and will be time-stamped with the ship's navigation information (time, latitude, longitude). Pre-processed data will be analyzed real time and areas of particular interest or events including fronts and spectrally different water masses will be targeted for parallel collection of discrete water samples for bio-optical analyses. These samples will be collected from the outtake of the system to warrant that all the analyses are from the same water parcel. Water will be immediately filtered and the resulting samples properly stored (-80° C or -20° C accordingly) for later analyses in the lab for chlorophyll-a concentration (Chl-a), HPLC pigment analysis, filter pad absorption (particulate absorption spectra (a_p), phytoplankton pigment absorption (a_{ph}), detrital absorption spectra (a_d), and CDOM absorption (a_g). Data processing and analyses will be conducted using protocols established in the literature and in NASA technical reports [*Mueller et al.* 2003].

Separately, CDOM absorption with samples filtered through pre-cleaned 0.2 μm, 47 mm diameter polycarbonate filters will be measured using the Ultrapath system [*Miller et al.* 2002] and a double beam spectrophotometer (e.g., Mannino et al. [2008]).

4.2.2. Water column profiles

Surface and subsurface observations will be done at pre-defined hydrocast stations planned for this expedition. These water column profiles, in combination with the underway measurements will provide the horizontal and vertical structure of bio-optical properties and will help develop a three-dimensional process understanding. Water column profiles will be obtained with a package equipped with optical and hydrographic instruments similar to the set used for underway measurements. These measurements include temperature and salinity, chlorophyll and CDOM fluorescence, multispectral backscattering, and hyperspectral total and beam attenuation, and CDOM absorption coefficients. Discrete water samples for later bio-optical analyses will also be collected from the casts at depths of interest and treated/stored as described for the underway water samples. Discrete samples of biogeochemical properties and process measurements will be collected and analyzed (see Table 1).

4.3. Nutrients and pCO_2

4.3.1. Partial pressure of carbon dioxide (pCO_2)

The spatiotemporal variability of carbon dioxide in ocean waters provides information about the interacting physical and biogeochemical processes. The state of carbon dioxide (CO_2) solution in seawater can be characterized by four measureable parameters: the total alkalinity (TAlk), the total dissolved inorganic carbon (DIC), pH, and either the fugacity of CO_2 (fCO_2) or the partial pressure of CO_2 (pCO_2). The knowledge of any two of these parameters allows for the determination of the other two components in equilibrium. pCO_2 can be determined using a direct approach based on the equilibrator technique, where water is placed in a closed chamber and the pressure is equilibrated to that of the water sample [*DOE* 1994; *Frankignoulle et al.* 2001; *Pierrot and others* 2009; *Takahashi et al.* 2014]. The indirect method involves the determination of pCO_2 from discrete measurements of pH, TAlk and DIC. Seawater samples for DIC, TAlk, and pH analysis will be collected at various depths using the CTD-Rosette system Niskin bottles [*Dickson et al.* 2007; *DOE* 1994; *Gran* 1952; *Hanson and Jagner* 1972; *Johnson and others* 1998]. The samples will be collected hourly to study the diurnal variation of the parameters and pCO_2, which will be analyzed later in the laboratory. The pCO_2 of the samples will then be calculated from temperature, salinity, DIC, TAlk, and pH using carbonate equilibrium constants from [*Dickson et al.* 2007; *Lueker et al.* 2000]. During underway and on-station the pCO_2 of surface waters from the ship's flow-through system will be determined as described by Pierrot et al. [2009]. The water column pCO_2 will be measured using a pCO_2 sensor (e.g. Sunburst SAMI-CO_2 or Turner C-sence) deployed with the CTD Rosette system during profiling casts.

4.3.2. Nutrient measurements

During the campaign nutrient information for nitrate+nitrite (NO_3 and NO_2), phosphate (PO_4), silicate (SiO_2), and ammonia (NH_3) will be collected, with methods and procedures commonly adopted by the community [*Parsons et al.* 1984; *Strickland and Parsons* 1972].

4.4. Concentration of phytoplankton pigments, POC and DOC

Water samples will be collected, filtered, and phytoplankton pigment concentrations will be measured using High Performance Liquid Chromatography (HPLC). Chlorophyll-a concentration will also be analyzed through fluorometric analysis. In general, the methods to be used will follow the recommended protocols described in the NASA Technical Memorandum *Ocean Optics Protocols For Satellite Ocean Color Sensor Validation, Revision 5, Volume V: Biogeochemical and Bio-Optical Measurements and Data Analysis Protocols* by Mueller et al. [2003] with modifications. Particles for optical and POC analyses will be collected in duplicate onto precombusted (450^{o}C for 4 hours) Whatman GF/F glass fiber filters, and subsequently measured with a vario MICRO cube CHN elemental analyzer (Hedges & Stern 1984). DOC will be measured in triplicate by high temperature combustion oxidation using a Shimadzu TOC-V or TOC-L instrument [*Mannino et al.* 2008].

4.5. Total suspended particulate matter (TSM) and particle size distribution

Total suspended particulate material (TSM, SPM, TSS) and particle size distribution (PSD) are important indicators of environmental status and biogeochemical processes. TSM dry weight concentration in mg/l or g/m^3 will be determined gravimetrically, where TSM includes both organic and inorganic particles. The procedure for TSM determination is mature and summarized in many articles (e.g., Strickland and Parsons [1972], Stavn et al. [2008] and Neukermans et al. [2012]). During this field campaign, TSM will be measured with samples from the outtake and for water samples in the upper water column.

There is no single technique to cover the whole size range of suspended particles in seawater, submicron to millimeters [*Reynolds et al.* 2010], thus three different techniques will be employed

a) a laser diffractometer (LISST-100X): widely used in field measurements,
b) an electrical impedance particle sizer (Coulter Counter) : most accurate but labor-intensive
c) a particle imaging system (FlowCAM): size limitation to large particles (D >~ 5 micron)

4.6. Solar radiation and PAR

The ocean's biogeochemical processes and their temporal response are highly dependent on the availability of solar radiation, commonly represented by the photosynthetic available radiation (PAR). Examples of such processes impacted by the surface solar radiation include: 1) primary productivity; 2) CDOM concentration; 3) response of chlorophyll concentration to internal chloroplast cell self-shading; 4) vertical movement of subsurface phytoplankton layers in response to subsurface light levels. For the determination of surface PAR, spectral downwelling irradiance (350 – 700 nm range) will be measured. During the field campaign, hyperspectral (10 nm or better resolution) radiometric sensors (e.g., OCR from the Satlantic, Inc.) will be deployed on board the ship to take continuous measurements, from which PAR could be easily calculated. Separately, PAR sensors will be attached to the CTD package to measure the vertical change of solar radiation.

4.7. GPP, NPP and NCP

A key advance provided by geostationary ocean color sensors will be the capability to directly quantify diurnal and daily measurements of biological productivity from space based on high frequency (hourly) satellite observations. Short duration field measurements of biological production including gross primary production (GPP), net primary production (NPP), and net community production (NCP) are necessary to develop and evaluate geostationary ocean color products for diurnal or daily GPP, NPP and NCP. Currently, low-earth-orbit satellite-based estimates of NPP rely on satellite chlorophyll and other products observed only during the mid-day period at a frequency of approximately few days per week. Hourly observations from GOCI and field observations from early morning to late afternoon can be applied to understand the instrument (and algorithm) requirements for the retrieval of diurnal or daily biological productivity. There are multiple techniques that can be applied to quantify GPP, NPP, and NCP [*Cullen* 2001]. Most require shipboard or *in situ* incubations. GPP and NPP can be quantified through measurement of oxygen evolved or carbon fixed in light and dark incubations. Carbon fixation rate methods include the use of radioactive (^{14}C) [*Steemann Neilsen* 1952] or stable carbon isotope addition [*Hama et al.* 1983]. Approaches for NCP include monitoring the change in dissolved oxygen concentrations (via incubations or underway oxygen/argon ratios) [*Kaiser et al.* 2005] or underway measurements of the stable carbon isotopic composition of the inorganic carbon pool. Fast Repetition Rate Fluorometry (FRRF) measurements may also be applied to estimate instantaneous rates of primary productivity *in situ* (e.g., Smyth et al. [2004]), but this method may underestimate NPP [*Robinson et al.* 2014].

4.8. Phytoplankton taxonomy

It is always important and necessary to understand the diurnal dynamics of phytoplankton. Traditionally such measurements were made with a microscope, which is significantly lab intensive and low efficiency. During this joint campaign, phytoplankton taxonomy of the research area will be sorted out with the latest Imaging Flow Cytobot (IFCB) developed jointly by WHOI and the McLane Research Laboratories. IFCB is an automatic system for the detection, identification and quantification of phytoplankton species/classes. We will install an IFCB on board the boat to continuously run water samples from the outtake and water samples taken at a station from different depths.

4.9 Atmospheric properties (aerosol and trace gases)

Variability in aerosols and atmospheric trace gases such as NO_2 and O_3 remains one of the largest sources of uncertainty for accurate atmospheric correction of satellite ocean color, especially in coastal waters that are close to heavily polluted urban areas [*Ahmad et al.* 2007]. At the same time, evaluating atmospheric variability over coastal waters is extremely challenging, as ground-based stations that monitor air quality come to an abrupt end at the coastlines. We recommend that field measurements during the GEO-CAPE campaign in the Korean coastal waters include a range of measurements of atmospheric properties. To achieve the primary goals of the ocean color campaign the following total column atmospheric measurements are considered critical:

a). Deployment of a shipboard Pandora spectrometer on the main oceanographic research vessel for continuous measurements of total column amounts of atmospheric NO_2 and O_3 [*Tzortziou et al.* 2014]. Measurements will be used to assess (i) diurnal variability, (ii) day-to-day changes, and (iv) spatial gradients in atmospheric NO_2 and O_3.

b). High-frequency and high spatial resolution measurements of AOD, including spectral AOD in the spectral region 340-936 nm (Smirnov et al., [2011]), the Angstrom parameter, and AOD at 500 nm partitioned into fine and coarse components according to the Spectral De-convolution Algorithm by O'Neill et al. [2001; 2003]. These measurements could be achieved with the Pandora instruments and handheld Microtops sun-photometers.

In the event of an opportunity to coordinate with the AQ campaign, additional shipboard measurements to obtain *in situ* trace gas and aerosol data would be particularly valuable to serve as surface data points underneath aircraft spirals over water used to examine the vertical distribution of *in situ* atmospheric constituents. Such measurements should be coordinated with those aboard the aircraft and are likely to include measurements of NO_2, and O_3, along with aerosol composition, size distributions, and optical properties.

These data, along with retrievals from GOCI and polar orbiting satellites can be used to assess the spatial and temporal variability of these atmospheric constituents in the context of the underlying optically complex waters to better understand future retrieval algorithm development needs. Analyses of the atmospheric data collected will aid decision-making regarding the trade-offs to be considered among the fundamental aspects of the GEO-CAPE OC sensor design. Finally, in conjunction with the extensive OC measurements described above, and collaborations with colleagues across disciplines, we anticipate furthering our understanding of interdisciplinary science and technical challenges to be overcome.

4.10 GOCI data processing

GOCI data will be collected and processed products sent to the ship on a routine basis to help guide the collection of the above listed field measurements. In addition, the processing of GOCI data will also be evaluated with the measured products, and this will also be achieved jointly among US and Korean scientists. In particular, the BRDF correction and the atmospheric correction procedures will be tested and characterized, and validated against the ship measurements. This will provide us a needed understanding of processing of geostationary ocean color measurements, a key aspect for the risk reduction of the GEO-CAPE mission.