ACE 2011-2015 Progress Report and Future Outlook

by

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NB: Section 7 and Appendix B contain internal NASA financial information. These have been redacted from this version of the document.

NASA Earth Science
Decadal Survey Studies

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Executive Summary

Introduction

From its first images of the *Blue Marble* on through to its Mission to Planet Earth (MTPE) and Earth Observing System (EOS), NASA has forever changed human understanding of the interconnectedness and complexity of the Earth's physical and biological systems. With the mandate to advance the intellectual foundation provided by MTPE and EOS, the National Research Council conducted its first Decadal Survey in 2007 to provide a vision regarding the imperatives for earth systems science. With its opening statement of the Executive Summary, "*Understanding the complex, changing planet on which we live, how it supports life, and how human activities affect its ability to do so in the future is one of the greatest intellectual challenges facing humanity,"* the Decadal Survey Panel imparted its vision for NASA, NOAA and the USGS, a vision sharply focused on increasing interdisciplinary science of biogeophysical processes related to the functioning of the coupled human-natural earth system. As the report progressed, a more specific, intellectual challenge for the Earth Sciences emerged: *how do aerosol-cloud-ecosystems and their interactions modify the physical and biogeochemical processes of the earth system?*

Over the last five years, the earth systems science community has converged around the broad area of Aerosol-Cloud Interactions and their impacts on global radiation, hydrological and biogeochemical systems. The opening line of the 2013 IPCC's Chapter 7 Executive Summary states that "clouds and aerosols continue to contribute the largest uncertainty to estimates and interpretations of the Earth's changing energy budget" (p. 573). The authors further assert that "…*until sub-grid scale parameterizations of clouds and aerosol–cloud interactions are able to address these issues, model estimates of aerosol–cloud interactions and their radiative effects will carry large uncertainties*." (p. 574). These unanswered questions from both the decadal survey and the most recent IPCC point to the continued need for a satellite mission to produce the necessary observations to support process studies required to understand how a changing climate affects the role of aerosols and clouds in the transfer and balance of the earth's radiation, and how interactions between aerosols and clouds modify clouds temporally, spatially and physically from their formation through their transition into precipitation systems and beyond.

In response to those questions, the NRC Decadal Survey proposed the Aerosol-Cloud-Ecosystem (ACE) mission as a Tier 2 Decadal Survey mission focusing on Aerosol, Cloud systems, ocean Ecosystems, and the interactions among them so as to reduce the uncertainty in climate forcing due to aerosol-cloud interactions and ocean ecosystem CO_2 uptake (NRC Decadal Survey (2007), pg. 4-4). As one of its fifteen recommended satellite missions put forward by the Decadal Survey, the ACE mission brings together aerosol, cloud, ocean ecosystem and other earth system scientists in a multiple-sensor, multiple-platform, low earth orbit, sun-synchronous satellite mission that combines active and passive sensors to observe the Earth at microwave, infrared, visible and ultraviolet wavelengths.

ACE has built upon experience gained from the current generation of Earth observing satellites e.g. the NASA Terra, Aqua, TRMM, CloudSat, CALIPSO, SeaWIFS and GPM platforms. In doing so, the ACE mission has made significant progress regarding mission requirements and instrument technical readiness during its pre-formulation phase by using the mission resources and leveraging opportunities well. Should ACE become a fully-fledged free-flyer mission, it will extend and complement similar observations produced by the afternoon constellation (A-Train) and the planned ESA EarthCARE (Cloud, Aerosol and Radiation Explorer) mission.

The fundamental science questions that ACE intends to address have not changed over the course of pre-formulation activities, neither has our fundamental approach to addressing those questions. The mission continues to focus on understanding physical processes that require synergistic, vertically-resolved, active and passive remote sensing measurements for those processes to be diagnosed observationally. ACE has and continues to leverage the advances in technical development and readiness of both instrument concepts (with ESTO support) and their related algorithm development (with ACE Decal Survey Study support). Accordingly, ACE has initiated a series of polarimeter and radar field definition experiments over the past 3 years. The Polarimeter Definition Experiment (**PODEX**) took place in January-February 2013, while the first Radar Definition Experiment (**RADEX-14**) was executed in May-June 2014, with the second **RADEX-15** conducted in November-December, 2015. ACE leadership has also initiated monthly teleconferences for the Lidar Working Group.

Perhaps the clearest demonstration of the scientific relevance of ACE lies with the sizeable scientific demand from the community for the participation of ACE science team in a series of high profile field campaigns (see *Table E.1*). ACE science and instrument teams have been entrepreneurial and successful in their leveraging the scientific demand by the larger community for the use of their ACE instrument simulators. Major support for the participation of ACE scientists and instrument teams in a series of high profile field campaigns during the past five years has come from a variety of sources from within NASA, and external partners such as the DoE, the NSF, as well as European sources, e.g. the U.K. Atlantic Meridional Transect (AMT) Program.

Field Campaign Name	Funding Organization
SEAC4RS - Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys	NASA RSP
SABOR - Ship-Aircraft Bio-Optical Research	NASA OBB
DISCOVER-AQ - Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality	NASA EVS
NAAMES - North Atlantic Aerosols and Marine Ecosystems Study	NASA EVS-2
ORACLES - ObseRvations of Aerosols above CLouds and their intEractionS	NASA EVS-2
2012 Azores Campaign	NASA AITT, CALIPSO
OLYMPEX - the GPM Olympic Mountain Experiment	NASA OBB, ACE, CALIPSO
TCAP - Two-Column Aerosol Project	DoE, NASA GPM, ACE, RSP
CHARMS - Combined HSRL and Raman Measurement Study	DoE

Table E.1. List of major field campaigns that have utilized ACE-related instrument concepts and related science questions in their observational framework. Responsible funding organizations are also listed.

Several ACE related concepts, such as the, the Cloud Aerosol Transport Systems (CATS) lidar and the Hyper-Angular Rainbow Polarimeter (HARP) have even drawn the attention and support of ISS and ESTO funding sources enabling their deployment on the ISS (CATS in January 2015; HARP schedule for a 2016 launch).

This report details how the ACE mission has, in its pre-formulation phase, worked towards its goal of extending key measurements made by the aforementioned sensors through its incorporation of several new airborne sensors, both passive and active, specifically, a multi-angle polarimetric imager, a high-spectral-resolution lidar and a multiple frequency Doppler cloud radar. The additional measurements provided by these new sensors will enable determination of properties associated with many cloud, aerosol and ocean-ecosystems interactions that either cannot be determined from current satellites or can only be determined with large uncertainties to advance state of the art earth system models. Examples of these properties include vertical distributions of cloud, precipitation water content and particle size, as well as aerosol number concentration and single scattering albedo. Accurate determination of microphysical properties such as these is critical to conducting process studies to further our understanding of cloud-aerosol interactions that drive much of the uncertainty in our understanding of climate change. Details related to this approach have evolved over the past five years with advances in understanding, modeling capabilities, and technology and are presented in detail in Sections 3, 4 and 5 of this report.

Science Traceability Matrices for the ACE mission are presented in more detail in Section 2 and broadly cover the following thematic areas:

1) Aerosol Sources, Processes, Transports and Sinks (SPTS)
2) Direct Aerosol Radiative Forcing (DARF)
3) Aerosol-Cloud Interactions (ACI);
4) Clouds (Morphology; Microphysics and Aerosols; Energetics); and
5) Oceans (Standing Stocks, Composition and Productivity (SSCP); Biogeochemical Cycle Dynamics; Material Exchange between Atmosphere/Oceans; ACI impacts on Ocean Biogeochemisty; Impacts of Physical Processes on Ocean Biogeochemistry and Ocean Biogeochemistry on Physical Processes; Distribution of Harmful Algal Blooms and Eutrophication Events (HAB and EE, respectively).

Scientific Merit and Continued Relevance of the Mission

Calls for this type of science reach beyond the Decadal Survey and the IPCC and can be found across a range of white papers and synthesis proceedings. The World Climate Research Program has emphasized the necessity of addressing the grand challenges associated with observing and modeling clouds, circulations and climate sensitivity and of working across their numerous time and space scales (http://www.wcrp-climate.org/gc-clouds; Bony et al. (2015)). Examples of the types of outstanding scientific questions produced as part of the 2014 NSF-supported synthesis of the EarthCube End-User Workshop series, the "Engaging the Atmospheric Cloud / Aerosol / Composition Community" workshop[1] include the following:

1) What are the exact roles of the clouds in the cloud systems and in the entire earth system?
2) How do clouds affect the cloud feedback on climate sensitivity?
3) What is the role of clouds on biosphere or ecosystems and vice versa?
4) What is the spatial, temporal, size distribution and composition distribution of aerosol particles in the atmosphere and the aerosol particle emissions globally?
5) What are the exact roles of aerosols in the cloud and climate?
6) What is the impact of aerosol on severe marine storms?
7) What are the changes to Cloud Condensation Nuclei (CCN) with changes in aerosol loading?

From the standpoint of the global earth system modeling community, substantial progress on the aforementioned science questions necessitates at a minimum an observing system capable of providing coincident aerosol, cloud and precipitation

What will ACE do?[2]

In an effort to address a number of the aforementioned grand challenges, ACE will assist in reducing uncertainties related to Effective Radiative Forcing (ERF) by answering fundamental science questions associated with aerosols, clouds, and ocean ecosystems. ACE will accomplish this by making improved and more comprehensive measurements through the use of innovative and advanced remote sensing technologies. Aerosols measured by ACE include those of both man-made

[1] Retrieved from http://earthcube.org/sites/default/files/doc-repository/CombinedSummaries_12Dec2014.pdf, p. 70
[2] Retrieved from http://dsm.gsfc.nasa.gov/ace/mission_details.html

and natural origins, the latter of which is contributed significantly by ocean ecosystems.

For aerosols, ACE seeks to distinguish aerosol types and associated optical properties and size. For cloud systems and processes, the mission as conceived will provide unique information that will allow for diagnosis of microphysical processes that cause clouds, perhaps as modified by anthropogenic aerosol, to produce precipitation within turbulent vertical updrafts. This connection to process will be achieved via multiple independent observational constraints on microphysical properties within the vertical column.

Planktonic ecosystems of the Earth's surface ocean are a crucial link in the global carbon cycle. These ecosystems are hypothesized to impact the cloud, precipitation and climate processes through their productivity and their emission of trace gases that are subsequently converted to aerosols (e.g. Meskhidze and Nenes, 2006; Krüger and Graßl, 2011). Likewise, the wet and dry deposition of biogeochemically important species to the ocean surface are hypothesized to impact the productivity of these globally important ecosystems (e.g. Duce, 1986; Jickells et al., 2005; and Meskhidze et al., 2005). ACE measurements will allow the first-ever depth-resolved characterization of ocean ecosystems, including the standing stocks of phytoplankton and total particulate populations, ecosystem composition, and photosynthetic carbon fixation. ACE measurements will further permit global assessments ecosystem health (through diagnostics of stress), improved separation of optically-active in-water constituents, and the first detailed characterization of plankton annual and interannual changes in high-latitude polar regions, where impacts of climate change have been particularly severe. With these advanced observations, coupled to the atmospheric measurements of ACE, a far improved understanding will be gained on climate impacts on ocean ecology and the goods and services they provide, as well as feedbacks between ocean ecosystems and aerosols, clouds, and climate.

What are the goals of ACE?

1. Providing a data stream of NRT observations of highly resolved temporal and spatial distributions of coincident aerosols, clouds and precipitating systems to the global earth observing modeling community;

2. Improved understanding of Earth system interactions specifically among aerosols, cloud-precipitation systems, and ocean ecosystems;

3. Quantification of the direct radiative effect of aerosols at the surface as well as at the top of the atmosphere;

4. Assessment of the indirect effects of aerosols through modification of hydrometeor profiles in cloud-precipitation systems and cloud radiative properties;

5. Assessment of changes in cloud properties in response to a changing climate;

6. Observation and distinguishability of those ocean ecosystem components that actively take up and/or store carbon dioxide;

7. Measurement and quantification of the linkages between atmospheric aerosols and underlying ocean ecosystems.

Achievement of these goals will result in enhanced capabilities to observe and predict changes to the Earth's hydrological cycle and energy balance in response to climate forcings.

What are the Expected Benefits of ACE?

Scientific

1. Reduced uncertainty in aerosol-cloud-precipitation and radiative interactions and thereby quantification of the net role of aerosols in climate.

2. Improved knowledge of cloud processes, especially advancing knowledge of the partition of liquid and ice-phase.

3. Accurate measurements characterizing the net radiative effects of multi-layer cloud decks, especially low clouds in the tropics and mid-latitudes that will help climate modelers make more precise and accurate predictions of climate.

4. Measurement of the ocean ecosystem changes resulting from aerosol-cloud-precipitation system interactions and a more precise and accurate quantification of ocean carbon uptake.

5. Improved air quality forecasting by determining the height and speciation of aerosols being transported long distances.

6. Leveraged and extended observations from existing space-based assets currently deployed by NASA and our international partners.

Programmatic

1. Establish and incentivize the next generation of earth system sciences through their involvement with the mission from undergraduate/graduate students on through to professionals.

2. Harness and leverage the expertise resident at three major NASA centers - Goddard Space Flight Center, Langley Research Center and the Jet Propulsion Laboratory.

Societal Relevance

1. Improved accuracy of climate prediction, including the prediction of climate change impact on temperature, precipitation and water availability resulting in the possible reduction of human, economic and marine biodiversity loss around the world.

2. Improvement of and extension of air quality monitoring and forecasting on a global scale.

3. Improved understanding of the functioning of the remote regions of the world's oceans.

4. Advancement of earth system science as a means to achieving these goals, while not just being an end in itself.

5. Development of a NRT coupled observation-modeling architecture for earth system science.

Contribution to long-term Earth Observational Record

While contributing to the long-term climate effort is a laudable goal, ACE leadership is mindful that programmatic resource constraints could reduce the ability of the mission to provide an additional observational continuity over and above what is possible from the operational missions of the S-NPP/JPSS and GOES programs. However, ACE will contribute by extending the observational records of unique A-Train assets (CALIPSO, CloudSat, PARASOL), SeaWIFS. PACE, as well as EarthCARE and CATS.

Synergies with Existing and Planned Observational Systems

The ACE mission has potential synergy with the following activities:

Solar reflectance imagery/polarimetry – Mission for Climate and Atmospheric Pollution (MCAP): polarimeter, CSA APOCC (Atmospheric Processes Of

Climate and its Change) as well as the 3MI polarimeter on the Eumetsat 2nd generation polar system (EPS-SG), JPSS missions, and GEOS-R missions.

Precipitation – SnowSat (35/94-GHz Doppler cloud radar): CSA APOCC; AMSR2/GCOM-W2, -W3: JAXA; GPM

Atmospheric Composition – GEO: TEMPO, GEO-CAPE, GEMS, SENTINEL-4; LEO: 3MI (Meteosat)

Ocean Ecosystems - PACE

Other – EarthCare operations precede current ACE launch window: JPSS: as with S-NPP, flies at 825 km orbit. No plans for formation flying.

Regarding PACE

ACE leadership is acutely aware of the recently directed PACE mission and is actively seeking to intersect with PACE planning and implementation. The goal is to best position the two missions to ensure the highest rate of success for each of them individually and to ensure the greatest return on investment scientifically and programmatically. This positioning will be accomplished by leveraging each of the mission's unique scientific contributions to amplify its programmatic and scientific impact. In particular, positioning PACE on a low enough orbit may enable formation flying with active sensors capable of sensing both the atmosphere and upper ocean layers.

Technical Readiness and Key Risks and Risk Reductions

Technical Readiness

Over the past five years, the ACE team has made demonstrable progress in the evolution and deployment of new sensor technology, the acquisition, assimilation and analysis of the resulting data as the concepts embraced by ACE continue to move from technology development, to sub-orbital and even to the ISS on their way to a complete mission. This progress has been the result of ACE leadership investing heavily over the past five fiscal years in two general areas: science and risk reduction. The development of sensors, related algorithms and opportunities to test the larger ACE science mission concept in the field have occurred through involvement of ESTO and its related R&D programs, in a designated ACE-led field campaign, or by leveraging payload deployment opportunities related to funded EVS and R&A field campaigns.

Specifically, the technical readiness level and evolution of sensor technology has been advanced with respect to the development of three polarimeter concepts, two radar concepts and two lidar concepts. Regarding the polarimeters, the AirMSPI instrument TRL is currently 5 with an anticipated increase to 6 by early 2016. The RSP APS instrument TRL currently stands at 8 or 9 whereas the PACS instrument stands at a TRL of 6. Advances in the ACERAD concept have seen its TRL rise to 5 and is anticipated to increase to 6 by the end of 2017. The TRL of the LaRC HSRL, currently stands between 4 and 5 and has flown successfully on ER-2 test flights in May 2015. This airborne HSRL is also scheduled to be deployed on the ER-2 for the ORACLES EV-S mission in August, 2016. Additionally, the recently launched CATS lidar is now operational onboard the ISS.

Technical Risks

Starting in FY13, ACE has increasingly prioritized investments in risk reduction, specifically via algorithm development and the data acquisition and analyses to support that activity. Furthermore, ACE leadership now supports a robust multi-sensor algorithm development activity in the cloud science area. This is regarded as a critical area to reduce technical risk and rapidly advance prior mission formulation, similar to on-going investments in aerosol algorithm development by the polarimeter teams.

ACE Leadership has also convened working groups where participants from a variety of instrument concept teams are brought together regularly (on a monthly to bi-monthly basis) to discuss, in a transparent forum, advances and challenges of their concept as it relates to the larger ACE mission. This has been successful with the Polarimeter and Radar working groups, and most recently, with the creation of a Lidar working group. The open competition of the instrument technology relative to ACE mission objectives ensures the development and enhanced TRL of multiple instrument designs thereby ensuring enhanced optionality for ACE mission leadership regarding instruments and their deployment.

Human Capital Risks

A substantial risk to cost effective realization of the ACE Mission is not being able to take advantage of the considerable human and intellectual capital developed during the era of the NASA Earth Observing System (EOS) and the Earth System Science Pathfinder (ESSP) missions. The Agency finds itself in the rare position of being able to harvest its own intellectual timber while essentially providing a pathway for the next generation of earth system scientists. A delay in the utilization of this human capital runs the risk of having the collective institutional wisdom disperse if not disappear over the next decade as a result of the attrition and retirement of key scientists and agency personnel.

Assessment and Recommendation

First and foremost, the scientific vision still stands and is as much in demand now as it was five years ago. The ACE mission as first conceived puts forth a bold and ambitious vision regarding the observation and study of Aerosol-Cloud-Ecosystem processes, especially its vision for seeking to combine the best of a surveying and a process-oriented mission. Over the past five years, ACE Science Team Leadership has acted upon the recommendations the last Decadal Survey and the directive of NASA ESD leadership and made significant progress during the pre-formulation stage of the mission.

Furthermore, the ACE Study Team is being proactive and actively providing input into the National Academies of Sciences, Engineering and Medicine's Space Studies Board's 2017 Decadal Survey for Earth Science and Applications from Space (DS) process. ACE leadership and Science Team members are part of the larger dialogue that will define NASA Earth Science moving forward and open to advancing in the most parsimonious fashion possible. A number of white papers have been contributed by the ACE Study to recent Request for Information by the 2017-2027 Decadal Survey panel where ACE science questions and measurements concept play a central role.

In light of the aforementioned scientific relevance, continued progress and success in the maturation of instrument technology and algorithm development, ACE leadership has the following recommendations:

1) Continue to evolve/mature the TRLs of polarimeter, radar and lidar concepts
2) Continue to evolve/mature associated algorithms
3) Continue to work closely with PACE Mission leadership to exploit points of intersection and leverage PACE and ACE concepts to enhance scientific return on investment.
4) Develop or extend an existing an airborne campaign to jointly fly ACE-related lidar and polarimeter concepts onboard the NASA ER-2 suborbital platforms to test and refine combined active-passive aerosol and cloud retrieval algorithms.

5) Progress the ACE Mission from pre-formulation to formulation phase in an adaptive fashion in harmony with the recommendations of 2017 DS.

1 Introduction

One of the most pressing contemporary Earth System Science questions is, incontrovertibly, how will life on Earth respond to climate change over the coming century? Global satellite measurements already provide among the greatest insights into this question by observing how today's ocean and terrestrial ecosystems respond to natural, and to some extent anthropogenic forms of climate variation. However, new and innovative measurement approaches are required to advance our understanding of the living Earth System. Current limitations are particularly acute for studies of ocean biology, for direct aerosol climate forcing, for cloud-aerosol interactions, and for precipitation-producing processes. For example, NASA's ocean color missions fail to observe high-latitude ecosystems over much of the annual cycle, yet these climate-critical ecosystems are experiencing the greatest rate of climate-driven change. Furthermore, heritage ocean color sensors only detect the plankton properties in a thin layer of the ocean's surface, leaving major uncertainties in our understanding of ocean productivity, biomass distributions, and interactions between biological stocks and rates, and related physical forcings that will be strongly altered by a changing climate.

Within this grand Earth System Science Challenge of understanding how the biosphere will respond to climate change are two primary sub-questions: (1) How will these responses of the biosphere feed back on atmospheric factors controlling climate? and (2) To what extent and where will changes in climate forcing impact the physical environment in which the biosphere exists? With respect to this latter sub-question, one particular uncertainty supersedes all others: aerosol-cloud interactions and the impact of clouds and aerosols on global radiation, hydrological, and biogeochemical systems. Indeed, the Executive Summary of Chapter 7 in the 2013 IPCC's states that "*clouds and aerosols continue to contribute the largest uncertainty to estimates and interpretations of the Earth's changing energy budget*" (p. 573). The underlying issues are further clarified by noting that "…*until sub-grid scale parameterizations of clouds and aerosol–cloud interactions are able to address these issues, model estimates of aerosol–cloud interactions and their radiative effects will carry large uncertainties*." (p. 574). It is also widely recognized that the treatment of meteorological influences on clouds and aerosols is an equally important subject that needs to be concurrently addressed.

These outstanding issues from the most recent IPCC assessment point to a series of unanswered questions regarding the roles of aerosol, clouds, and precipitation in

Earth's changing climate system. These questions highlight the continued need for global observations allowing process studies addressing how the transfer and balance of energy in a changing climate are influenced by aerosols, clouds, and precipitation, and how the interactions between aerosols and clouds from their formation through their transition into precipitation systems influence the response of the Earth system to a rapidly changing atmosphere and ocean composition. Thus, to fully understand the threat that climate change poses to life on Earth in a quantitative manner, it is essential to relate observed changes in the contemporary biosphere to the magnitude of future change, which in turn requires process-level understanding of biological feedbacks on climate along with the details of aerosol-cloud and other interactions of the physical climate system.

In response to a similar set of questions posed by the Earth Science community, and recognizing the scientific and observational overlaps in ocean ecosystem and atmospheric sciences, the 2007 the NRC Decadal Survey recommended the Aerosol-Cloud-Ecosystem (ACE) mission. At the time, ACE was recommended as a Tier 2, pre-formulation mission focusing on observational requirements to advance understanding of ocean ecosystems, aerosols, and clouds and their interactions and feedbacks. (NRC Decadal Survey, 2007, pg. 4-4). As one of its fifteen recommended satellite missions, ACE represents the primary global mission to advance understanding of the climate-biosphere system. It brings together ecosystem, aerosol, cloud, and other Earth system scientists in a multiple-sensor, multiple-platform, low sun-synchronous satellite mission. The recommendation stresses that to achieve mission objectives active (primarily lidars and radars) and passive sensors need to be combined to observe the Earth at microwave, infrared, visible and ultraviolet wavelengths.

The fundamental science questions that ACE addresses, and the fundamental approach to addressing those questions, have only come into sharper focus over the course of the pre-formulation activities. The mission concept continues to target collecting synergistic active and passive measurements that will aid understanding of ocean biological stocks, rates, and changes from pole-to-pole and from the surface to deep communities, along with the physical processes associated with the Earth's water and energy cycles. ACE activities involve participation from a broad segment of the Earth Science community, in particular from the ocean ecology and biogeochemistry, aerosol, cloud, precipitation, and radiation disciplines.

Since the ACE mission recommendation by the 2007 Decadal Survey Report, pre-formulation activities have made major advances toward refining its observational and science requirements. These developments have resulted in several reports. Most recently, the ocean science community has produced a very detailed description of requirements for the ACE advanced ocean color sensor as part of the Pre-ACE (PACE) Science Definition Team activities; the PACE Science Definition Team Report is available from http://decadal.gsfc.nasa.gov/pace-resources.html . In addition, guidance on numerous ACE-relevant objectives were provided in a recent NASA SMD community meeting (May, 2014, NASA Ames Research Center); recommendations from this workshop were published in a report entitled "*Outstanding Questions in Atmospheric Composition, Chemistry, Dynamics, and Radiation for the Coming Decade*", available from https://espo.nasa.gov/home/content/NASA_SMD_Workshop. The radiation, aerosols, clouds, and convections sections of that report highlight questions and possible observational courses of action that pertain to the roles of aerosols, clouds, precipitation in the climate system. The novel observational approaches attend to significant shortcomings in our present observational systems for tackling the grand challenges in Earth science for the next decade.

In compliance with guidance received from the Associate Director of Flight Programs in the Earth Science Division of the Science Mission Directorate by each 2007 Decadal Survey Mission Team, the ACE Science Team has produced the present document that summarizes the results of the past five years (2011-2015) of pre-formulation work accomplished by the ACE mission team. The paper details the efforts, accomplishments and plans of the ACE mission team for the following aspects: Instrument concept development and assessment; measurement algorithms; field campaigns; mission architecture; and mission funding history. Further, with the white paper the ACE mission team provides an overall assessment as well as its own recommendations regarding the future of the ACE mission.

The white paper is structured in the following main sections:

1. Introduction
2. Mission Science Objectives and Measurement Requirements in the format of Science Traceability Matrices
3. Assessment and Instrument Concept Development for the radar, polarimeter, lidar and ocean color instrument concepts
4. Measurement Algorithms for aerosols, clouds and oceans

5. Field Campaigns for aerosol, cloud and ocean related campaigns
6. Mission Architecture
7. Funding History both in terms of science and technology investments
8. Assessment and Recommendations
9. Program Scientist's assessment and recommendations for improvement of the process of development of Decadal Survey satellite missions.

These sections are in turn followed by sections containing references, list of acronyms and appendices detailing lists of external grants funded by ACE and ACE-related projects funded by ESTO for the periods of 2011-2015.

2 Mission Science Objectives and Measurement Requirements

2.1 Aerosols

Global measurements of the horizontal and vertical distributions of aerosols, and their optical, microphysical, and chemical properties are required to quantify the impacts of aerosols on human health, global and regional climate, clouds and precipitation, and ocean ecosystems. Although spaceborne instruments on the Aqua, Aura and Terra satellites have significantly improved our global understanding of aerosols, critical measurements are either absent or have unacceptably large uncertainties. Therefore, the ACE aerosol Science Traceability Matrix (STM) has been designed to address objectives that are significantly beyond the capabilities of current satellite sensors.

Following the release of the NAS report, work began during 2007 and 2008 on the development of a white paper and STM to capture the specific aerosol-related science questions, aerosol and cloud parameters required, and measurement and mission requirements. A meeting of NASA aerosol scientists was held at GSFC in February 2009 to accelerate development of the aerosol STM, including requirements for two core aerosol-related instruments: polarimeter and lidar. Following this meeting, further discussion and revisions of the STM were facilitated by regular telecons. A revised version of the STM was presented for comment at a meeting held in Santa Fe, NM in August 2009. Based on comments received at this meeting, the STM was revised further. Most notably, increasing the emphasis on the cloud-aerosol interactions (CAI).

The aerosol STM addresses three major science themes: 1) sources, processes, transport and sinks (SPTS); 2) direct radiative aerosol forcing (DARF); and 3) cloud-aerosol interactions (CAI). The first theme addresses the global aerosol budget, long-range transport, and air quality. Comparisons among current global aerosol chemical transport models reveal large diversity in the modeled distribution and attribution of aerosol species, which indicates significant uncertainties in model chemical evolution, microphysics, transport, and deposition, as well as source strength and location. As models become more advanced and simulate aerosol mass, number, and size for multiple aerosol types and modes, aerosol characterization requires additional measurements beyond total column aerosol optical depth (AOD). Consequently, the ACE approach is to provide measurements to permit improved estimates of aerosol source strength and location, vertical distribution, and distributions of aerosol optical properties, mass, number, and composition. The required parameters include vertically resolved microphysical properties to translate retrieved AOD and aerosol type to mass, number concentration, and size distribution and to partition the transported aerosol into different aerosol components.

Table 2.1 ACE Aerosol Science Traceability Matrix

Themes	Focused Science Questions	Geophysical Parameters	Measurement Requirements	Mission Requirements
Sources, Processes, Transport, Sinks (SPTS)	Q1. What are key sources, sinks, and transport paths of airborne sulfate, organic, BC, sea salt, and mineral dust aerosol? Q2. What is the impact of specific significant aerosol events such as volcanic eruptions, wild fires, dust outbreaks, urban/industrial pollution, etc. on local, regional, and global aerosol burden?	Column: Q1 Q2 Q3 Q4 • $\tau_a(\lambda)$ • $\tau_{a,abs}(\lambda)$ • $m_a(\lambda)$ • $r_{eff\ a}(\lambda)$ • $\nu_{eff\ a}(\lambda)$ • Morphology Vertically Resolved: Q1 Q2 Q3 Q4 • $\tau_{a,abs}(\lambda)$ • $m_a(\lambda)$ • $r_{eff\ a}(\lambda)$ • $\nu_{eff\ a}(\lambda)$ • Morphology Cloud Top: Q3 Q4 • τ_c • $\tau_{eff,\ c}$ • $\nu_{eff,\ c}$ • Thermodynamic phase	High Spectral Resolution Lidar (HSRL) • Backscatter (355, 532, 1064 nm) • Extinction (355, 532 nm) • Depolarization (two wavelengths of 355, 532, 1064 nm) Imaging Polarimeter • Minimum 6 to 8 wavelengths spanning either UV or 410 nm to either 1630 nm or 2250 nm • Multiangle TBD, range ±50° • Polarization accuracy 0.5% • Combination polarized and nonpolarized channels • Resolution: 250 m in at least one channel	Integrated satellite, modeling, and data assimilation approach is required to meet science objectives. Expand high-resolution global and regional modeling capabilities to assimilate cloud and aerosol microphysical parameters such as number concentration and optical properties. Required ancillary data: • Land surface albedo map • Ground network $\tau_a(\lambda)$, shortwave and longwave F_d and F_{net} • Ground and airborne: column and vertically resolved $\tau_a(\lambda)$, $\tau_{a,abs}(\lambda)$, $m_a(\lambda)$ (2 modes), morphology, $P_{a,pol}(\theta)$ • Space measurements: Top of atmosphere shortwave and longwave F_u, collocated T(z), q(z), V(z), fire strength, frequency, location
Direct Aerosol Radiative Forcing (DARF)	Q3. What is the direct aerosol radiative forcing (DARF) at the top-of-atmosphere, within atmosphere, and at the surface? Q4. What is the aerosol radiative heating of the atmosphere due to absorbing aerosols, and how will this heating affect cloud development and precipitation processes?			
Cloud-Aerosol Interactions (CAI)	Q5. How do aerosols affect cloud micro and macro physical properties and the subsequent radiative balance at the top, within, and bottom of the atmosphere? Q6. How does the aerosol influence on clouds and precipitation via nucleation depend on cloud updraft velocity and cloud type? Q7. How much does solar absorption by anthropogenic aerosol affect cloud radiative forcing and precipitation? Q8. What are the key mechanisms by which clouds process aerosols and influence the vertical profile of aerosol physical and optical properties?	Vertically Resolved: Q5 Q6 Q7 Q8 P1. N_a P2. $\tau_{a,abs}(\lambda)$ P3. $r_{eff,a}$ P4. N_c P5. LWC P6. Precip Cloud Top: Q5 Q6 Q7 Q8 P7. Cloud top height P8. Cloud albedo P9. LWP P10. τ_c P11. $r_{eff,c}$ P12. Cloud radiative effect Cloud Base: Q5 Q6 Q7 Q8 P13. Cloud base height P14. Updraft velocity	**Threshhold (i.e. minimum)** **HSRL:** P1 P2 P3 P10 **Imaging Polarimeter:** P1 P2 P3 **W band Radar:** P4 P5 P7 P13 P14 **Narrow swath High-Resolution VIS-MWIR Imager:** P9,P11 *Baseline* (additions to threshold): W + Ka Band Doppler radar P6 P14	

The second theme addressed by the STM is the direct radiative aerosol forcing (DARF). Here ACE aims to provide firm, observationally-based estimates of DARF and its uncertainties with the ultimate goal of better constraining future climate predictions of DARF. ACE goes beyond addressing top of atmosphere (TOA) radiative forcing by providing global estimates of surface and within atmosphere, vertically resolved radiative forcing; the latter is especially important for representing how atmospheric heating by absorbing aerosols affects on cloud development and precipitation. In order to derive within-atmosphere DARF, a key ACE objective is for the first time to provide layer-resolved measurements of aerosol absorption from space. Here ACE goes well beyond current satellite measurement capabilities and provide a global, comprehensive dataset of three dimensional aerosol properties to constrain aerosol transport model estimates of globally averaged DARF within the atmosphere and at the top and bottom boundaries.

The third theme is to address the interactions between aerosols and clouds. These interactions include the impacts of aerosols on cloud micro- and macrophysical properties, and the degree to which clouds and precipitation impact aerosol concentrations. The ACE satellite measurements described in the STM are intended to provide strong constraints on the sensitivity of cloud radiative forcing and precipitation to aerosol number density, vertical distribution, and optical properties (e.g., absorption). ACE measurements are intended to constrain model representations of cloud microphysical and optical properties and model simulations of Cloud Condensation Nuclei CCN amount and aerosol absorption near clouds by providing observational targets that are comprehensively characterized. Here again, the detailed, vertically resolved measurements of aerosol optical and microphysical properties from ACE go well beyond the current satellite measurements of total column aerosol measurements. The ultimate goal is to assimilate ACE measurements into advanced earth system models representing aerosol and cloud microphysical processes, extending the information content of the measurements to conditions not directly observed by satellites (*e.g.,* under clouds).

In general, the geophysical parameters required for the three major themes are similar. The parameters listed in the STM are needed to characterize the optical and physical characteristics of the aerosol to specified accuracies, with a combination of satellite and suborbital measurements. The required aerosol characteristics include spectral optical thickness, spectral single scattering albedo, spectral phase function, and composition. These parameters are retrieved from the satellite measurements or derived from other parameters (e.g., size distribution, refractive index, nonsphericity) retrieved from the satellite measurements. In the case of direct radiative forcing and aerosol-cloud interaction themes, layer-resolved aerosol optical (scattering, absorption) and microphysical (e.g., effective radius, nonsphericity) properties are also required. The required spatial coverage for these measurements varies with objective. For example, while resolving global monthly mean trends in AOD and detecting decadal scale trends at continental scales can likely be accomplished using narrow swath measurements, wider swaths will likely be required to reduce the uncertainties at regional and seasonal scales. Further studies regarding sampling should focus on the impact of measurements on aerosol radiative forcing and address aerosol absorption as well as AOD, and consider data assimilation as a tool for extending the usefulness of the data. Aerosol particle number concentration is an additional parameter required to specifically address aerosol-cloud interactions.

The ACE measurement requirements advances the state-of-the art of cloud and aerosol measurements and therefore are technologically ambitious. Even with these ACE measurements, there are important aerosol measurements that cannot be achieved from space. Therefore, suborbital measurements and a strong modeling component are critical to address the ACE aerosol science objectives as well as to validate the ACE satellite measurements. The ACE aerosol STM calls for a combination of satellite and suborbital measurements, combined with a comprehensive data assimilation component, to advance the cloud/aerosol science and enable an advanced climate prediction capability, with reduced uncertainties.

2.2 Clouds

Among other objectives, the ACE measurement suite is being designed to better constrain the characterization of cloud and precipitation microphysical properties. Cloud and precipitation microphysical properties are critical to improving the representation of many physical processes in climate models, which are themselves poorly constrained at present. Uncertainties in the coupling between microphysical processes and atmospheric motions are the underlying cause of the large spread in cloud feedbacks and climate change uncertainty in today's climate models (Knutti et al., 2013; Klein et al. 2013; Stevens and Bony, 2013). To meet this objective, the ACE white paper that was completed in 2010 identified a diversity of measurements and sensors that, when combined synergistically (Posselt et al 2016; Mace et al., 2016, Mace and Benson., 2016), would provide independent, vertically resolved, and vertically integrated constraints on near-cloud-aerosols, cloud/precipitation particle-size-distributions (PSDs), and cloud-scale vertical motion.

The ACE cloud science requirements and the imperative for multi-sensor synergy to meet those requirements have not changed since the original white paper was completed in 2010. The ACE team seeks to develop a coherent and achievable strategy for accomplishing the science goals of ACE using innovative approaches that provide the required measurement synergy in the most efficient and cost effective means possible. Changes in the measurement requirements since the 2010 document have emerged due to advancements in both technology and data processing. These advancements allow us to extract more information from a more focused and streamlined set of measurements.

ACE cloud science objectives are directed at microphysical processes that take place in the vertical column that convert aerosol particles to cloud droplets and to snowflakes and rain droplets within turbulent vertical motions in clouds. Understanding these processes continue to be the limiting factor in simulating the water cycle in the atmosphere (Stephens, 2005; Stevens and Bony, 2013). Put another way, the microphysical/dynamical processes that drive the aerosol indirect effects and cloud-precipitation microphysical processes in general, especially those that involve the ice phase, continue to be the major science motivation of ACE clouds; and all science questions continue to be derived from this motivation.

Clouds and associated precipitation have long been known to be integral components of the planetary energy balance, accounting for almost half of Earth's planetary albedo (*e.g.*, Stephens et al. 2012). Changes in the statistics of global cloud properties in response to warming remain the largest uncertainty in accurately projecting the future climate response to anthropogenic forcing (Soden and Held 2006). The feedbacks due to changes in clouds and precipitation remain the single greatest source of spread in general circulation model (GCM) estimates of global climate sensitivity (Klein et al., 2013; Bony and Dufresne 2005; Zelinka et al. 2012, 2013).

The ACE Clouds Science Traceability Matrix

In this section we discuss the current state of modeling and observation of clouds and pose questions that might be addressed by future observing platforms, including both satellite missions and field experiments. Our focus here is on the thermodynamic-dynamic-microphysical-radiative process coupling that controls the occurrence of clouds and their areal coverage when present and thus determines their feedback under climate change. However, there is always sufficient aerosol to nucleate liquid-phase clouds, and thus indirect effects only become relevant after the dynamics and thermodynamics initiates cloud formation. This differs markedly from the situation for cirrus where nucleation itself is poorly understood because the concentration and properties of nucleating aerosols in the upper troposphere is poorly known. Indeed, the documented compensating forcing and feedback errors that allow many GCMs to correctly simulate the 20^{th} Century temperature record (Kiehl 2007; Forster et al. 2013) can be thought of as two sides of the cloud problem – forcing uncertainty due to aerosol indirect effects and feedback uncertainty due to dynamic and thermodynamic processes and their interaction with radiation.

It has become clear that there is a natural break in measurement strategy between shallow clouds that can be strongly influenced by aerosol and deeper cloud systems where “nearby” aerosols can't be observed and where ice microphysics tend to be important. Accordingly, ACE cloud science questions divide naturally into aerosol-cloud, cloud-radiation and cloud-precipitation themes according to the measurements needed to address those questions.

ACE science objectives are focused on microphysical processes that take place in the vertical column, converting aerosol particles to cloud droplets and to snowflakes, ice crystals, and rain droplets within turbulent vertical motions. Understanding these processes continues to be the limiting factor in simulating the water cycle in the atmosphere. The microphysical and dynamical processes that drive the 1st and 2nd aerosol indirect effects and cloud-precipitation microphysical processes continue to be the major science motivation of ACE clouds. Of special interest and importance are questions that involve ice phase processes.

With a natural break in measurement strategy occurring between shallow clouds that can be strongly influenced by aerosol (1st and 2nd indirect effects), and deeper cloud systems where “nearby” aerosols can not be observed and where ice microphysics tend to be important, ACE science questions have been divided along aerosol-cloud and cloud-precipitation themes according to the measurements needed to address them. In the following paragraphs, we first discuss issues that cut across both classes of questions and broad priorities, then we consider how measurement needs differ between aerosol-cloud, cloud-precipitation and cirrus clouds. A simplified Science Traceability Matrix is presented following this discussion. Throughout the text, we pay special attention to the evolution in our thinking that has influenced the resulting revised STM and overall mission strategy.

The ACE Clouds Science Traceability Matrix (STM) is constructed around the realization that the processes that couple atmospheric motions to cloud and precipitation processes are the fundamental issues that underpin uncertainty in climate prediction (Bony and Dufresne, 2005; Dufresne and Bony, 2008; Stevens and Bony, 2013). While the details of these processes vary across cloud genre (i.e. cumulus, stratocumulus, cirrus, altostratus, etc.), a distinct need for furthering our understanding of these processes is quite independent of cloud type and our revised STM (Table 2.2) , therefore, utilizes a general framework independent of cloud type but focused on the aerosol-cloud-precipitation nexus.

The revised ACE clouds STM is organized around overarching scientific themes (left-most column). These themes range from how the overall three-dimensional distribution of clouds and precipitation may be changing to what the distributions of cloud and precipitation microphysical properties are. As mentioned, we are particularly interested in the processes that cause populations of cloud droplets and ice crystals to evolve into precipitation – in particular how aerosol and atmospheric motions modulate and feed back on these processes (i.e. Mace and Abernathy, 2016; Mace and Avey, 2016). Ultimately, what we learn from ACE measurements and associated modeling studies will help us to understand better the energetics of the earth's atmosphere or just how clouds and precipitation participate in the poleward transport of energy and how that may be changing as the climate system evolves.

Addressing these themes ultimately comes down to science questions for which rigorous answers can be formulated from ACE measurements. We present 4 broad categories of questions that are drawn from a 2014 community whitepaper entitled, *Outstanding Questions in Atmospheric Composition, Chemistry, Dynamics and Radiation for the Coming Decade*, available from

https://espo.nasa.gov/home/content/NASA_SMD_Workshop

These questions are focused on the role of clouds and aerosol in understanding climate sensitivity, changes to shortwave and longwave climate forcing, and the processes that control the water cycle and energetics of the climate system. A careful reading of the clouds, radiation, aerosol, and convection sections of the Ames 2014 whitepaper, where these questions are discussed in detail, suggests that answers to them rest on better observations of cloud and precipitation microphysics, cloud-scale vertical motion, and aerosol microphysics.

What geophysical parameters are needed to address the ACE science questions are listed in the STM and referenced back to the science questions and themes. Broadly, these geophysical parameters include cloud and precipitation microphysics, vertical motion, aerosol, and radiative properties that will allow us to derive heating rate profiles as well as top of atmosphere and surface radiative budgets. Using italicized and bold fonts, we suggest the notional trades that would occur if a threshold set of instruments were used instead of a more aggressive baseline set of instruments. The threshold set of measurements will allow us to retrieve geophysical parameters that address many if not most of the science questions while the baseline mission would allow for more accurate geophysical parameter retrievals over a broader range of conditions.

A centerpiece of the ACE instrument suite is a dual frequency Doppler cloud radar that will operate in the Ka and W bands. The ACE radar combines the CloudSat and GPM capabilities and goes well beyond what either of those instruments could accomplish scientifically. This radar will also include passive radiometer capabilities that allow for passive microwave measurements at least along the nadir track that will enable accurate retrievals of cloud and precipitation properties in optically deep cloud systems such as fronts and shallow convection. Additionally, radar and microwave retrievals of many cloud types benefit greatly by knowing the visible and near infrared reflectances because they constrain cloud droplet properties in the upper portions of many cloud types where the radar and microwave retrievals are challenged by the small droplet sizes. Combined with a High Spectral Resolution Lidar, the visible measurements will provide threshold constraints on the surrounding aerosol. While this set of measurements is here characterized as a threshold or minimum set, we must note that this minimum set goes well beyond the capabilities of the A-Train, GPM, or EarthCare and would allow for significant advances in our understanding of cloud and precipitation processes.

The baseline set of instruments includes various options each of which will incrementally either enhance the accuracy of retrieved geophysical parameters or broaden of the scope of the cloud types we can address. (Table 2 describes what measurements constrain specific aspects of cloud and precipitation microphysics) For instance, adding a third frequency to the ACE radar allows for probing deeper precipitating systems such as heavily raining convection and frontal systems. Adding a polarimeter and an HSRL lidar will enhance some cloud retrievals but will primarily benefit our understanding of the near-cloud aerosol properties that are a critical aspect of many of our science questions. Additional passive constraints provided by higher microwave frequencies or sub-millimeter radiometers would enhance ice-phase precipitation retrievals in deeper convective systems and allow for more accurate characterization of high latitude snowfall.

Table 2.2 ACE Cloud Science Traceability Matrix

Themes	Focused Science Questions	Geophysical Parameters	Measurement Requirements	Mission Requirements
T1. Morphology **Document occurrence, macroscale structure, and decadal scale changes of clouds and precipitation and their interaction with large-scale meteorological and thermodynamic forcing.**	**Q1. Climate Sensitivity** **What is the sensitivity of the climate system to cloud structure and variability? T1 T2 T3 T4** • *What is the role of natural and anthropogenic aerosol in modulating cloud system occurrence and properties?* T1 • **What microphysical processes dictate the lifecycle and coverage of clouds under various atmospheric conditions? T1 T2** • *What dictates the processes that cause and modulate precipitation in cloud systems?* T3	**GP1. Hydrometeor Layer Detection** Q1 Q2 Q3 Q4 GP2. *Simultaneously occurring* **Cloud and Precipitation Thermodynamics Phase profile** Q1 Q2 Q3 Q4 **GP3.** *Simultaneously occurring* **Cloud and precipitation microphysical properties profiles (Water Content, particle sieze, and number concentration)** Q1 Q2 Q3 Q4 GP4. **Precipitation Rate Profile in light** *and heavy (> 5 mm/hr)* **precipitation** Q1 Q2 Q3 Q4 GP5. **Profiles of Cloud Optical Depth,** *single scattering albedo, and asymmetry parameter* Q1 Q2 Q3 Q4 **GP6. Surface, TOA Cloud Radiative Effects** Q1 Q2 Q3 Q4 GP7. **Latent Heating Profile in light** *and heavy (> 5 mm/hr)* **precipitation** Q1 Q3 Q4 GP8. *Radiative Heating Profile* Q1 Q2 Q3 Q4 GP9. **Cloud-Scale Vertical Motion** Q1 Q4 GP10. *Aerosol/CCN number concentration profile* Q1 Q2 Q3	**Threshold Mission** **TM1. 2-Frequency (W- , Ka-bands), Scanning Doppler Radar (with radiometer channels)** GP1 GP2 GP3 GP4 GP5 GP6 GP7 GP8 GP9 TM2. **High Spectral Resolution Lidar** GP1 GP2 GP3 GP5 GP6 GP8 GP10 TM3. **Narrow Swath Vis Imager (0.6 microns, 1.6 microns, 2.1 microns)** GP2 GP3 GP5 GP6 GP8 GP10 *Baseline Mission* *BM1. 3-Frequency (W- , Ka-, Ku-bands), Scanning Doppler Radar (with radiometer channels)* GP1 GP2 GP3 GP4 GP5 GP6 GP7 GP8 GP9 *(replaces TM1)* *BM2. High Spectral Res. Lidar (HSRL)* GP1 GP2 GP3 GP5 GP6 GP8 GP10 *(replaces TM2)* *BM3. High Resolution Narrow Swath VNIR-SWIR Polarimeter* GP6 GP8 GP10 *(Replaces TM3)* *BM4. Narrow Swath High Freq. (183, 389 GHz) Microwave* GP2 GP3 GP4 GP5 GP6 GP7 GP8	We define the **threshold** ACE Clouds Mission as those elements of this matrix that are in **bold font**. We suggest that boldface science objective and questions in columns 1 and 2 could ultimately be addressed by the measurements listed as the Threshold Mission in the Measurement Requirements Column. Elements of this matrix in *italicized font* are defined as a *Baseline Mission* and designate important science questions that require a more aggressive set of coordinated measurements that are listed in italicized font. The set of baseline and threshold ACE clouds retrieval algorithms will be synergistic such that multiple measurements contribute to the retrieval of a geophysical parameter. For instance while microwave brightness temperatures cannot generally be used to retrieve cloud microphysics, when passive microwave is combined with multi frequency Doppler radar, the microwave brightness temperatures provides an important constraint on the retrieval algorithm.
T2. Microphysics **Document the microphysical properties of liquid, ice, and mixed phase clouds and precipitation with a specific focus on high latitude snow and light liquid precipitation (less than 1 mm/hr) at all latitudes that influences cloud morphology and lifecycle and ultimately radiative balance.**	**Q2. Climate Forcing – Solar (T4)** **How will shortwave cloud forcing change as the climate warms? T1 T2 T3 T4** • **Will the coupling between cloud occurrence and morphology with atmospheric motions and thermodynamic structure result in fundamental changes to the planetary albedo? T1 T2** • *What is the specific role of aerosol in modulating the properties of clouds and the planetary albedo under a changing climate? (T2, T3)*			
T3. Microphysical Processes **Identify the occurrence of microphysical processes that cause changes to profiles of aerosol, clouds, and precipitation properties.** *Concurrently quantify the process rates of important microphysical processes such as autoconversion and accretion in liquid and ice-phase stratiform and convective clouds.*	**Q3. Climate Forcing – Infrared (T4)** **How will longwave cloud forcing change as the climate warms? T1 T2 T3 T4** • **What is the coupling between thermodynamic structure convective processes and the properties of convective anvils in modulating the coverage and properties of tropical anvil cirrus T1 T2 T3** • *What is the role of aerosol in changing the microphysical properties of tropical anvils and modulating their coverage, persistence, and feedbacks to the water cycle in the upper troposphere?* T1 T2 T3			
T4. Energetics *Understand the maintenance of and changes to the energetic balance of the atmosphere and earth system due aerosol, clouds, and precipitation.*	**Q4. Water Cycle and Energy Transport (T4)** **What is the role of cloud processes (specifically mixed phase) in snow and rain production in middle and high latitude cloud systems? T1 T2 T3 T4** • **What role does the seasonal cycle of middle latitude cloud radiative forcing play in the poleward transport of heat and how is this radiative forcing partitioned as function of cloud genre? T4** • *To what degree do various microphysical processes when coupled with large-scale dynamics modulate the precipitation production within middle and high latitude frontal systems?* T2 T3 • **What is the role of convection versus large-scale dynamics in producing precipitation in the middle and high latitudes? T1 T3**			

Further Discussion and Justification of the ACE Clouds STM

Rapid improvement in computing power has allowed global models to approach the cloud resolving scale (Myamoto et al., 2013; Satoh et al., 2008) where convective processes can be resolved and the need for convective parameterizations are diminished (Larson et al., 2012). While it will be some years before global Cloud Resolving Models (CRMs) can be used as true climate models, CRMs are still considered the tool by which traditional coarse resolution climate models can be improved and this improvement will come through statistical representations of cloud microphysics on the GCM grid scale. Therefore, understanding microphysical processes globally is relevant now and will be increasingly important as we move through the 2020's. The ACE questions, therefore, focus on small spatial scales (~ 100's of m) and finely resolved vertical scales (~10's of m) that are typical of CRM or Large Eddy Simulations (LES). In short, high-resolution (~100 to 500 m scale) observations of microphysical processes are critical. Likewise, since our target theoretical audience is the CRM/LES communities where high-resolution cloud measurements can be assimilated directly, we seek measurements that cover a swath that is several 10's to 100 km wide along a suborbital track.

In terms of passive microwave measurements, it is conceivable that most of the ACE cloud requirements can be provided by including radiometer channels on the radars so that microwave brightness temperature (Tb) at the radar frequencies are collected only along the swath sampled by the radar. If this were the case, stand-alone microwave imagers would not be required to address ACE-clouds measurement needs. The trade space between the coarse spatial resolution but high accuracy provided by traditional microwave sensors and a footprint that is, by definition, perfectly matched to that of the radar measurements should be carefully examined since not requiring standalone microwave imagers would significantly reduce the complexity and cost of ACE. It is possible that the radiometer channels on the radar would be preferable to the more accurate but larger footprints from traditional radiometer measurements - especially in broken cloud fields. Higher frequency microwave (i.e. beyond the highest frequency of the ACE radar - 94 GHz) and sub-millimeter radiometer measurements would be a major benefit to many of our science questions but we no longer see this as part of the baseline mission. Such high frequency and sub-millimeter measurements could be provided by international partners or otherwise launched independently of ACE and managed as part of a satellite formation or constellation. The A-Train is an excellent example of such a constellation that coalesced opportunistically over time.

As mentioned earlier, our goal is to formulate an ACE mission that addresses the science needs of the aerosol-cloud-precipitation-Ocean Ecosystem communities in the coming decade but that is also achievable in terms of cost and complexity. One approach that could be considered is to seek natural divisions in the science applications that could, for instance, allow for exploitation of natural synergies among measurements. Another approach to an implementation of ACE is to exploit opportunities for collaboration and synergy. The PACE mission, for instance, affords one such opportunity. Using PACE as a foundation, an HSRL and Doppler cloud radar flying in formation with PACE would allow ACE to address most, if not all, of the science questions originally posed in the 2010 white papers in addition to addressing emerging science such as ocean-lidar. Exploiting this synergy would require some compromise among the various disciplines but the end result would be a constellation that is truly an advance over the A-Train that would push NASA Earth observational science into the 2020's and beyond.

Aerosol-Cloud Questions

Consensus has emerged within the broader community (*e.g*., IPCC 2013, Chapter 7) that 1) differences in climate sensitivity among models are due to differences in their simulation of shallow marine boundary layer clouds and 2) the primary mechanisms by which aerosol impacts climate is via the process level perturbations within these shallow convective clouds. The aerosol indirect effects are known by various nomenclature. The first (Twomey, 1974) and second (Albrecht et al, 1989) aerosol indirect effects are conceptually simple but very difficult to document observationally. This is because the processes that result in the indirect effects are microphysical in nature taking place at the scales where aerosol evolves into cloud drops and cloud drops into precipitation. These processes typically occur within optically thick hydrometeor columns in often broken cloud fields, and vary rapidly with height over depth scales of a few hundred meters. As such, these effects are largely beyond the reach of traditional passive remote sensing. All studies claiming observational evidence of these effects have necessarily diagnosed them by how the effects are hypothesized to change the broader cloud field.

The indirect effects of aerosol on clouds are expected to be particularly large in boundary layer clouds such as shallow stratocumulus and cumulus that are ubiquitous across the global oceans from the tropics to the high middle latitudes of both hemispheres (Rosenfeld et al., 2014). Uncertainties in the feedbacks of these clouds as they interact with aerosol and changing circulation under climate change are the primary contributors to uncertainty in predictions of the climate response to doubled CO_2 (Soden and Vechi, 2011). Progress in the last five years in this area has been realized primarily through modeling work and analysis of data from the A-Train. The paper by Stevens and Feingold (2009) and references therein demonstrate, using both modeling and A-Train measurements, the importance of dynamical feedbacks (buffering) that exist between aerosol, shallow clouds, and precipitation that modulate the 1st and 2nd aerosol indirect effects in a cloud field. For example, LES studies have shown that clouds that are perturbed by higher aerosol concentrations, become deeper, precipitate more intensely, and result in stronger downdrafts with higher wind at the surface (Mace and Abernathy, 2016; Koren et al., 2014; Xue et al., 2008).

The lessons to be learned are that a cloud field observed in nature at a particular instant has a history that includes repeated processing of aerosol through cloud elements within large-scale dynamical environments. A field of cumulus or stratocumulus observed by orbiting satellites is a snapshot of a changing system that is responding at the instant of measurement to a perturbed and buffered environment that has been and is undergoing modification by the cloud processes and large-scale motions.

This complexity is a strong argument for global satellite measurements since it will take time to build statistical portraits of cloud fields in various states of evolution especially over remote regions of the global oceans (Mace and Avey, 2016). While field program case studies are useful and necessary, they are not sufficient in terms of either duration or number of cases needed to provide robust statistics. Such limitation is evidenced by the diverse range of contradictory findings that has emerged from recent field experiments seeking to quantify aerosol indirect effects. A satellite-based measurement strategy, therefore, must include data relevant to the changing system that can be assimilated by models that resolve the motions and processes within cloud elements. For shallow convective and stratiform clouds relevant to this class of questions, dual frequency Doppler radar (Ka and W bands) is desirable. However only single frequency W band Doppler radar would likely be considered required (see the aerosol STM) because the dual frequency information in shallow, weakly precipitating clouds is minimal and Ka-band radar will often not provide the required sensitivity to sample these clouds effectively. In addition, high spatial resolution microwave (perhaps provided by the radar), and visible reflectances in a few bands that contain independent information (Nakajima and King, 1990) are critically important for retrieval of cloud properties here, as is information regarding the regional aerosol background that require some combination of lidar (ideally HSRL) and polarimetric visible reflectances as discussed in the aerosol section. Knowledge of the chemical composition and CCN distribution that HSRL and polarimetry could provide (i.e. ultimately composition of the aerosol that act as cloud condensation nuclei) is likely necessary to fully address the 1st and 2nd aerosol indirect effects in shallow cumulus and stratocumulus.

Cloud-Precipitation Questions

The Cloud-Precipitation questions tend to focus on deeper clouds (e.g. frontal layer clouds, moderately deep to deep convection) where ice phase processes that result in precipitation are important to the evolution of the cloud system. Even the most advanced CRMs contain many processes that require observational constraints. For instance, changes in droplet breakup parameterizations, ice crystal collection and riming efficiencies (among others) and their dependence on vertical motion can cause drastic (many hundreds of percent) differences in surface rain/snow accumulations and result in feedbacks on the dynamical environment via latent heat release that totally change the predicted evolution of the cloud field (Van Den Heever et al., 2011). These sensitivities extend across the synoptic spectrum from tropical convective clouds to stratiform rain, to frontal systems and stratiform clouds in the middle and high latitudes (e.g. Adams-Selin et al., 2013; Igel et al., 2013; Saleeby and van den Heever, 2013).

Multi frequency Doppler radar with collocated microwave Tb are fundamental to the measurement strategy needed to address cloud-precipitation centric science questions (Mace and Benson, 2016; Posselt and Mace, 2014). While our earlier thinking focused on dual frequency Ka/W band Doppler radar, the addition of Ku band greatly extends the reach of our science focus into cloud systems that are much deeper and more heavily precipitating. We now include Ku band as an option in the baseline STM. Similarly, higher frequency microwave measurements (> 89 GHz) will provide important constraints on the ice microphysics. However, the quantitative benefit of such measurements when combined with multi- frequency radar has not yet been demonstrated. We therefore, list high frequency microwave and sub-millimeter measurements as part of a threshold mission that could be provided by international partners or other sources. For most of the cloud-precipitation objectives of ACE Clouds, lidar measurements are not as relevant because a lidar attenuates in the first few optical depths of clouds that are very optically thick. Furthermore, these cloud systems tend to be much larger in scale (extending to 1000's of km) making it impossible to constrain the local aerosol environments in which they develop with lidar or polarimeter measurements. Alternative means such as data assimilation will therefore be needed to provide aerosol information in such systems should it be desirable to examine the second-order effects induced by aerosols on these more energetic systems.

Cirrus

We address cirrus as a separate category. Cirrus tend to be optically thin, horizontally extensive, and the role of aerosol is uncertain but likely second order. Cirrus with optical depths less than two drive the radiative heating in the tropics (Berry and Mace, 2014) and it is widely accepted that tropical cirrus impose a positive feedback on a warming climate because tropical cirrus will detrain from deep convection at a constant temperature while the surface warms (Zelinka and Hartmann, 2012). While all models tend to generate this positive feedback, the reason for this agreement is not clear and it is not known if this result is fortuitous or if the global magnitude of this feedback is physically reasonable. Improved understanding of deep convective processes that result in detrainment of ice to the tropical upper troposphere will likely improve our understanding of the role of tropical cirrus in climate change.

Lidar-radar synergy is maximized in thin cirrus near optical depth one (Berry and Mace, 2014) so that both radar and lidar are needed to describe them. However, the specific role of HSRL measurements in addressing cirrus processes remains to be determined. The key science questions here are what controls the amount of ice detrained from deep convection and what processes cause anvils to evolve into self maintaining cirrus layers. Most cirrus questions could be addressed with either the baseline or threshold measurement strategies listed above. For instance, single or dual frequency Doppler radar at W and Ka bands combined with lidar that is considered critical to the aerosol-cloud questions would provide significant and unique information regarding thin cirrus while thicker cirrus beyond optical depth 10 or so would be informed by the clouds-precipitation measurement objectives.

Summary

The set of important questions that underpin the uncertainty in climate change projections due to aerosols, clouds and precipitation, and the fundamental approach of the ACE Cloud Working Group to addressing those questions has matured in the years since the original ACE white paper was completed in 2010. We continue to see microphysical processes as the foundational weak link in present-day climate models. To be diagnosed observationally these processes require synergistic, vertically resolved active remote sensing measurements combined minimally with passive microwave and solar reflectances.

Given the obvious multiplicative value of measurement synergy, it is reasonable to consider whether mission architecture could evolve to exploit emerging opportunities for new constellations that build on the success of the A-Train. For instance, one could envision a constellation built around the directed PACE mission where an HSRL and Doppler radar would allow for nearly the entire ACE science objectives, as well as emerging science such as ocean lidar, to be addressed. In any case, the approach that reduces cost, complexity, and risk should be identified through formal trade studies that account for the science goals and the practicality of actual mission implementation.

*We conclude by noting that aerosol-cloud-precipitation processes have been, are now, and will remain one of the principal underlying causes of climate prediction uncertainty***.** This will remain true until measurements are able to constrain the processes that actually occur in nature so that this knowledge can be included in future generations of climate models. Unfortunately, no single measurement on any satellite can thoroughly address any process-oriented question because of the complex interactive and spatially heterogeneous nature of the processes in question. These processes involve cloud and aerosol microphysical properties and their interaction with the thermodynamic environment across a range of scales. The A-Train satellites have demonstrated that bringing together multiple disparate measurements into a constellation of satellites provides the measurement synergy that can indeed contribute to our understanding well beyond the original scope of the single missions.

As the A-Train begins to disband in 2017, we envision ACE, in some form, as the next step in evolution of measurement strategy to address the fundamental climate problems of the next decade. Thinking strategically, a constellation of synergistic measurements emerging from a suite of instruments on complementary satellites launched by NASA in coordination with international partners can form the nucleus of the set of measurement envisioned for ACE. If history is any indicator, a high-level commitment by NASA to establish the foundation of the next constellation will ensure a growing, dynamic and effective measurement environment as platforms of opportunity join this constellation and enhance this synergy. What is needed at this time is a commitment by NASA to lead this process.

Instrument	Measurement	Cloud Microphysical Constraint	Additional Information and Comments
Backscatter Lidar ***High Spectral Resolution Lidar (HSRL)***	**Extinction,** *Single Scatter Albedo*	• **Attenuated Backscatter profiles in thin clouds** • **Aerosol properties in vertical profiles** • *Aerosol Composition*	• *Produces direct evaluation of optically thin cloud and aerosol extinction and aerosol single scattering properties* • **Provides information on cloud-top-height and more generally insight into vertical structure of thin cloud and aerosol.**
Multi Frequency Doppler Radar **W/Ka Bands** ***With Ku band***	**Radar Reflectivity**	• **Vertically resolved 6^{th} moment of cloud drop size distribution for particles less than 0.1 of the radar wavelength** • **Differential response to large hydrometeors** • *Ku provides additional information on heavy precipitation*	• **Differential frequency radar reflectivity and Doppler velocity for larger particles (> ~0.3 mm) can be used to identify the presence of such particles and help characterize the microphysics of this part of the distribution.** • **Differential attenuation with respect to 94 GHz is likely to prove useful in identification of cloud and precipitation type (phase) and retrieval of precipitation water content.** • **Dual-wavelength ratios at Ka-W and Ku-W bands can further discriminate ice species: snow, graupel, and hail improving ice water content retrieval accuracy**
	Doppler Velocity	• **Vertically resolved $2^{nd}/3^{rd}$ moment of drop size distribution (reflectivity weighted)** • **Differential response in presence of large hydrometeors.**	• **Doppler velocity is a measure of total velocity of the cloud particles. In convective cores, the velocity is dominated by cloud vertical motion. In other conditions, the velocity can be separated into contributions from particle fall velocity and air motion (Dynamics).** • **Cloud liquid water drops generally fall too slowly to be measured via this technique but it is very useful for identification, and characterization of ice clouds, snow, drizzle, and rain.** • *Ku Band desired to characterize heavy precipitation*
	Differential Attenuation, Path Integrated and Vertical Profile	• **Profile of Condensed Water** • **Total column liquid water path.**	• **One can use surface reflectance to estimate total attenuation in the radar in the column, when the radar is not totally attenuated. The attenuation is determined largely by the amount of liquid water (cloud and precipitation) in the column.**

	Radiometer Channels	• **Passive microwave Tb**	• **Constrains integrated liquid water and ice scattering.**
Narrow Swath Vis-IR Imager ***High-Resolution VIS-SWIR Polarimeter***	**UV, Visible and** **shortwave infrared** **radiances** *at multiple view angles.* *Polarized reflectances at some visible wavelengths.*	• **Cloud phase near "cloud top" (in region of cloud where bulk of visible light is reflected)** • *Radiative-effective ice cloud-habit (constrains possible/likely cloud habit mixtures) near "cloud top".* • **2nd moment of drop size distribution near cloud top)** • **Effective radius near cloud top.**	• *Multi-view-angle imagery can be used with stereo-imaging technique to derive cloud top height. This approach is insensitive to calibration and does not rely on any assumptions regarding atmospheric temperature lapse rate. The approach works well except for exceptionally diffuse high clouds, representing a failure rate of only a few percent. 50 m resolution images can be used to determine cloud-top-height with precision of about 50 m assuming view angles at +/- 45 degrees from nadir.* • *Important for defining aerosol type in broken cloud fields* • **Reflectances constrain column optical depth and effective radius.**
Passive Low and High Frequency Microwave Radiometer ***Channels at:*** ***10.65, 18.7, 23.8, 36.5, 89, 166.5, 183±3, 183±9 GHz***	*Brightness temperature*	• *Column liquid water path* • *Column water vapor path* • *Surface precipitation rate in wide swath* • *Ice cloud and ice precipitation* • *Important wide swath* • *Significant constraints for nadir viewing*	• *Column constraint* • *Will provide wide-swath / cloud system context to narrow-swath observations and in particular information on precipitation.* • *With radiometer channels on radar, these instruments are considered to be not required.*
Passive Sub-mm Radiometer ***Channels at high frequency:*** ***325.15, 448.00, 642.90, 874.40 GHz***	*Brightness temperature*	• *Column ice and particle size constraint for ice clouds;* • *Proportional to the 3rd moment of particle size distribution*	• *Column constraint* • *Will provide wide-swath / cloud system context to narrow-swath observations.* • *These measurements are not required. Could be provided by partnership.*

Table 2.3. Potential ACE Instruments and Measurements and their contribution to Level 1 Geophysical Parameters. The instruments that we consider required are denoted in **bold font**. *Italicized* font indicates goals or non-required instruments for ACE Clouds. (Next Page)

2.3 Ocean Biology and Biogeochemistry

The Ocean Ecosystem Science Traceability Matrix (STM) synthesizes the end-to-end requirements associated with addressing 6 groups of overarching *Focused Questions*:

1. What are the standing stocks, composition, & productivity of ocean ecosystems? How and why are they changing? [OBB1]
2. How and why are ocean biogeochemical cycles changing? How do they influence the Earth system? [OBB2]
3. What are the material exchanges between land & ocean? How do they influence coastal ecosystems, biogeochemistry & habitats? How are they changing? [OBB1,2,3]
4. How do aerosols & clouds influence ocean ecosystems & biogeochemical cycles? How do ocean biological & photochemical processes affect the atmosphere and Earth system? [OBB2]
5. How do physical ocean processes affect ocean ecosystems & biogeochemistry? How do ocean biological processes influence ocean physics? [OBB1,2]
6. What is the distribution of algal blooms and their relation to harmful algal and eutrophication events? How are these events changing? [OBB1,4]

Each of these science questions traces directly to one or more of the four broader science objectives of NASA's Ocean Biology and Biogeochemistry (OBB) program, as defined in the document, *Earth's Living Ocean: A Strategic Vision for the NASA Ocean Biological and Biogeochemistry Program*, and indicated above by the bracketed OBBx designations.

To answer the *Focused Questions*, the ACE Ocean Ecosystem team defined a multi-tiered approach involving remote sensing observations, supporting field and laboratory measurements, and ocean biogeochemical-ecosystem modeling, with 9 groups of specific objectives:

1. Quantify phytoplankton biomass, pigments, optical properties, key groups, and productivity using bio-optical models and chlorophyll fluorescence

2. Measure particulate and dissolved carbon pools, their characteristics and optical properties

3. Quantify ocean photobiochemical and photobiological processes

4. Estimate particle abundance, size distributions (PSD), and characteristics

5. Assimilate ACE observations in ocean biogeochemical model fields of key properties (air-sea CO_2 fluxes, export, pH, etc.)

6. Compare ACE observations with ground-based and model data of biological properties, land-ocean exchange in the coastal zone, physical properties (e.g., winds, SST, SSH, etc), and circulation (ML dynamics, horizontal divergence, etc)

7. Combine ACE ocean & atmosphere observations with models to evaluate (1) air-sea exchange of particulates, dissolved materials, and gases and (2) impacts on aerosol & cloud properties

8. Assess ocean radiant heating and feedbacks

9. Conduct field sea-truth measurements and modeling to validate retrievals from the pelagic to near-shore environments

These specific objectives were then traced to the measurement/instrument requirements for the relevant ACE satellite sensors, supporting field and laboratory activities, and modeling. Also identified were specific ACE platform requirements and ancillary supporting global data products from other missions, models, and field studies (see right columns in Ocean STM below).

The three primary instruments on the ACE platform(s) relevant to the mission's ocean ecosystem science objectives are the advanced ocean radiometer, lidar, and polarimeter. In addition to the ACE science team meetings, the ACE Ocean Ecosystem team conducted roughly weekly teleconferences to define the specific measurement and instrument requirements, with outcomes from these deliberations recorded in a series of documents and publications. The team assumed a 'grass roots' approach, beginning with the production of individual Product Assessment Reports for each ocean geophysical property targeted by the ACE instruments. These reports provided detailed descriptions of the derived parameters, their field measurement methodologies, product error analyses, and accuracy assessments.

The ACE Ocean Ecosystem team next constructed a summary table of targeted ocean-relevant properties. These properties include (1) spectral remote sensing reflectance, (2) inherent optical properties (total absorption, phytoplankton absorption, detrital absorption, colored dissolved organic material absorption, backscatter coefficient, beam attenuation), (3) diffuse attenuation coefficient for downwelling plane irradiance at 490 nm, (4) 24-hr flux and instantaneous incident photosynthetically available radiation, (5) surface ocean euphotic layer depth, (6) particulate inorganic carbon concentration, (7) particulate organic carbon concentration, (8) dissolved organic carbon concentration, (9) suspended particulate matter concentration, (10) particle size characteristics, (11) total chlorophyll-a concentration, (12) phytoplankton carbon concentration, (13) normalized fluorescence line-height, (14) fluorescence quantum yield, (15) net primary production, (16) phytoplankton chlorophyll:carbon ratios and growth rate, and (17) phytoplankton funtional/taxonomic groups. For each of these 14 properties, the summary table *defined the baseline and threshold value ranges for ACE retrievals*, along with documenting the basis for these range estimates.

In addition to the above activities, the ACE Ocean Ecosystem team conducted model simulation studies to identify measurement requirements for the ACE ocean radiometer near-infrared (NIR) and short-wave infrared (SWIR) bands and, using a state-of-the-art spectral inversion algorithm, to define spectral signal-to-noise requirements. Results from all of these activities were synthesized in an ACE Ocean Ecosystem white paper and then summarized as the Ocean Ecosystem STM (copied below).

The ACE Ocean Ecosystem white paper and STM provided the needed framework for conducting a very thorough evaluation of instrument requirements for an advanced ocean radiometer, which was published in 2011 (Meister, et al. 2011). The timing of this publication was ideal, as it appeared in parallel with early deliberations of the Pre-Aerosol Cloud Ecosystem (PACE) Science Definition Team (SDT). Multiple members of the ACE Ocean Ecosystem team were also members of the PACE SDT and the Meister et al (2011) document served as a key reference in defining baseline and threshold requirements for the PACE instrument/mission. The final, 274 page PACE SDT recommendation document provides the most thorough recommendation guidelines for an advanced ocean radiometer suitable for the PACE and the ACE missions.

In summary, the ACE Ocean Ecosystem team has conducted an end-to-end evaluation of mission measurement requirements necessary to address the 6 groups of overarching *Focused Science Questions*. This evaluation began with a basic evaluation of state-of-the-art assessment of accuracies and uncertainties in field measurements of targeted key ecosystem properties and then step-wise extended to a very detailed evaluation of satellite instrument requirements and requirements for supporting field, laboratory, and modeling work. Benefitting from the parallel assessments of the PACE SDT, the Ocean Ecosystem team concludes that overall understanding of observational requirements for the Ecosystem aspects of the ACE mission is highly mature. Nevertheless, a variety of additional investigations have been needed, or are still needed, to further refine understanding of specific measurement, validation, analysis, and modeling requirements and reduce mission risk. Many of these issues have been or are being addressed by the ACE funded research studies conducted over the past 5 years and overviewed in Sections 3, 4, and 5 of the current ACE Progress and Future Outlook Report.

2.4 Ocean-aerosol

With support from NASA, NSF, DOE, NOAA and ONR organized an international workshop on sea spray aerosol production mechanisms in Raleigh, NC June 4-6 2012. Over 40 experts attended the workshop to exchange ideas and prioritize future research directions. A workshop was held with the objectives of 1) identifying the most critical open questions regarding sea spray aerosol and developing a list of priorities for conducting novel research, and 2) ranking the most pressing science questions based on their feasibility impact on reducing the current uncertainty ranges for different processes. The recommendations from the working groups were summarized in a science prioritization matrix that is meant to identify areas of investigation by the magnitude of their impact on proposed science questions.

Ocean Ecosystems STM

Goddard Space Flight Center

Category	#	Focused Questions*
Ocean Biology	1	What are the standing stocks, composition, & productivity of ocean ecosystems? How and why are they changing? [OBB1]
	2	How and why are ocean biogeochemical cycles changing? How do they influence the Earth system? [OBB2]
	3	What are the material exchanges between land & ocean? How do they influence coastal ecosystems, biogeochemistry & habitats? How are they changing? [OBB1,2,3]
	4	How do aerosols & clouds influence ocean ecosystems & biogeochemical cycles? How do ocean biological & photochemical processes affect the atmosphere and Earth system? [OBB2]
	5	How do physical ocean processes affect ocean ecosystems & biogeochemistry? How do ocean biological processes influence ocean physics? [OBB1,2]
	6	What is the distribution of algal blooms and their relation to harmful algal and eutrophication events? How are these events changing? [OBB1,4]

Approach	Maps to Science Question
Quantify phytoplankton biomass, pigments, optical properties, key groups (functional/HABS), and productivity using bio-optical models & chlorophyll fluorescence	1, 2, 6
Measure particulate and dissolved carbon pools, their characteristics and optical properties	2, 3
Quantify ocean photobiochemical & photobiological processes	2, 4
Estimate particle abundance, size distribution (PSD), & characteristics	1, 3, 2
Assimilate ACE observations in ocean biogeochemical model fields of key properties (cf., air-sea CO_2 fluxes, export, pH, etc.)	2
Compare ACE observations with ground-based and model data of biological properties, land-ocean exchange in the coastal zone, physical properties (e.g., winds, SST, SSH, etc), and circulation (ML dynamics, horizontal divergence, etc)	3, 4, 5, 6
Combine ACE ocean & atmosphere observations with models to evaluate (1) air-sea exchange of particulates, dissolved materials, and gases and (2) impacts on aerosol & cloud properties	4
Assess ocean radiant heating and feedbacks	5
Conduct field sea-truth measurements and modeling to validate retrievals from the pelagic to near-shore environments	1, 4, 2, 5, 3, 6

Measurement Requirements	Instrument	Instrument Requirements
Water-leaving radiances in near-ultraviolet, visible, & near-infrared for separation of absorbing & scattering constituents and calculation of chlorophyll fluorescence Total radiances in UV, NIR, and SWIR for atmospheric corrections Cloud radiances for assessing instrument stray light	Ocean Radiometer	• 5 nm resolution 350 to 755 nm ▷ 1000 – 1500 SNR for 15 nm aggregate bands UV & visible and 10 nm fluorescence bands (665, 678, 710, 748 nm centers) ▷ 10 to 40 nm width atmospheric correction bands at 748, 765, 820, 865, 1245, 1640, 2135 nm • 0.1% radiometric temporal stability (1 month demonstrated prelaunch) • 58.3° cross track scanning • Sensor tilt (±20°) for glint avoidance • Polarization insensitive (<1.0%) • 1 km spatial resolution @ nadir • No saturation in UV to NIR bands • 5 year minimum design lifetime
High vertical resolution aerosol heights, optical thickness, & composition for atmospheric corrections Subsurface particle scattering & depth profile	Lidar	• 0.5 km aerosol vertical resolution • 2 m sub-surface resolution • < 0.3% polarization misalignment • 0.0001 $km^{-1}sr^{-1}$ aerosol backscatter sensitivity at 532 nm after averaging • < 4 ns e-folding transient response • Brillouin scattering capability; Receiver FOVs: 0-60 m; 0-120 m.
Broad spatial coverage aerosol heights and single scatter albedo for atmospheric correction. Subsurface polarized return for typing oceanic particles	Polarimeter	• Observation angles: 60° to 140° • Angle resolution: 5° • Degree of polarization: 1%

Supporting Field & Laboratory Measurements

- Primary production (NPP) measurement & round-robin algorithm testing
- Inherent optical properties (IOPs) instrument & protocols development, laboratory & field (coastal and open ocean) measurement comparisons
- Measure key phytoplankton groups across ocean biomes (coast/open ocean)
- Expanded global data sets of NPP, CDOM, DOM, pCO2, PSDs, IOPs, fluorescence, vertical organic particle fluxes, bio-available Fe concentrations

Ocean Biogeochemistry-Ecosystem Modeling

- Expand model capabilities to assimilate variables such as NPP, IOPs, and phytoplankton species/functional group concentrations.
- Improve model process parameterizations, e.g., particle fluxes

Platform Requir'ts

Orbit permitting 2-day global coverage of ocean radiometer measurements

Sun-synchronous orbit with crossing time between 10:30 a.m. & 1:30 p.m.

Storage and download of full spectral and spatial data

Monthly lunar calibration at 7° phase angle through Earth observing port

Other Needs

Global data sets from missions, models, or field observations:

Measurement Requirements
(1) Ozone
(2) Total water vapor
(3) Surface wind velocity
(4) Surface barometric pressure
(5) NO_2 concentration
(6) Vicarious calibration & validation **
(7) Full prelaunch characterization (2% accuracy radiometric)

Science Requirements
(1) SST
(2) SSH
(3) PAR
(4) UV
(5) MLD
(6) CO_2
(7) pH
(8) Ocean circulation
(9) Aerosol deposition
(10) run-off loading in coastal zone

* ACE focused questions are traceable to the four overarching science questions of NASA's Ocean Biology and Biogeochemistry Program [OBB1 to OBB4] as defined in the document: *Earth's Living Ocean: A Strategic Vision for the NASA Ocean Biological and Biogeochemistry Program*

** Specific vicarious calibration & validation requirements are defined in the ACE Ocean Ecosystem requirements document developed as part of ACE pre-formulation activities

3 Assessment and Instrument Concept Development

This section describes the technological accomplishments toward the ACE mission, including aircraft instrument development and utilization, origin of support and TRL status. For each type of instrument (radar, polarimeter, lidar, and ocean color sensor) we summarize the roadmap adopted, accomplishments thus far and on-going efforts.

3.1 Radar

The most significant radar advancements in the past 5 years relevant to ACE have been achieved under ESTO's IIP and ACT programs, with important contributions also by JPL and GSFC internal research and development funding, and the SBIR program. The development has followed closely the plan presented in the November 2010 report along three main directions:

1. Completion of the ACERAD concept (PI: S. Durden, JPL) technology maturation through the IIP'08 funding (see Fig. 3.1). This design provides both Ka-band and W-band dual-polarized Doppler observations at nadir, with additional Ka-band measurements over a limited swath (*i.e.*, ~30 km). The key technology developments identified to enable this concept were the Dragonian antenna design (to allow Ka-band scanning; scaled version shown in near-field test chamber), the Dual-Frequency Dual-Polarization Quasi-Optical transmission line, the Ka-/W-band frequency selective surface, and the signal generation and processing strategy. The TRL of each of these was raised through prototype implementation and testing in relevant environment so that the ACERAD overall TRL has been raised to 5 (with many subsystems at higher TRL due to heritage from CloudSat's CPR and airborne cloud and precipitation radars and IIP-funded environmental testing of the frequency selective surface for separating and combining Ka- and W-bands). No further technology maturation is deemed necessary before instrument selection since the remaining steps are only related to scaling and engineering. The level of maturity of ACERAD at this time is higher than the level of maturity of CloudSat CPR at the end of CloudSat's Phase A. This instrument concept meets the minimum requirements set in 2010 by the ACE Science Working Group.

Figure 3.1: Left: ACERAD IIP'08 (PI Durden), subscale Dragonian antenna prototype in test chamber; Right: WiSCR IIP'10 (PI Racette) sub-scale antenna flight demonstration through IPHEX mission in May, 2014 (see also Fig. 3.2)

2. In order to enable instrument performance closer to the scientific needs expressed during the definition of ACE, two additional instrument concepts were defined: WiSCR and 3CPR. Both include use of active electronically scanning linear arrays (AESLA) illuminating a singly-curved parabolic reflector (SCPR) to increase the scanning capabilities of the radar instrument, and both concepts adopt advanced signal generation and processing schemes to achieve the desired radar sensitivities, resolutions and Doppler accuracies. The technological development of WiSCR concept initiated under GSFC internal funding received critical funding through IIP'10 (PI: P. Racette) and IIP'13 (PI: L. Li) and hinges upon AESLA for Ka-band and innovative W-/Ka-band reflectarray main reflector to enable use of CloudSat heritage technology at W-band. Under the IIP'10 the reflectarray antenna achieved a TRL 5 through airborne demonstration of a subscale antenna. The IIP'13 focuses on advancing the TRL of the Ka-band radar electronics and is expected to achieve overall radar TRL 4 by 2017. A plan that calls for modest increase in funding would advance the overall instrument TRL to 6 by October 2017. The technological development of 3CPR concept, initiated under JPL internal funding and SBIR received critical funding through ACT'11 (PI: A. Fung) and IIP'13 (PI: G. Sadowy) and hinges upon existing Ka-band and innovative W-band AESLA technology to enable scanning at all frequencies. This instrument concept is at TRL 3 and is expected to achieve TRL5 by 2017 under existing funding profile. The roadmap beyond that point includes demonstration of integration of Ka-band AESLA with W-band AESLA (demonstrated under IIP) and risk reduction study for 3m x 5m cylindrical parabolic reflector antenna.

3. One concept for a possible partial tech demo of selected subsystems of all of the three instrument concepts discussed above was jointly developed by JPL and GSFC in 2013 in response to a request by NASA HQ. This instrument concept was defined for deployment on the ISS, and adopts COTS parts and Class-D-or-lower standards. It focuses on the demonstration in orbit of some of the Ka- and W-band components, and of a variety of digital processing schemes adopted in the ACE radar concepts.

4. In order to enable the acquisition of observation datasets specifically tailored to advance ACE science definition as well as algorithm development, NASA's airborne cloud and precipitation radar capabilities have been augmented as follows. For the high-altitude platforms (ER-2 and GH) the existing GSFC radars (PI: G. Heymsfield) have been upgraded and re-engineered to enable simultaneous observations at the ACE frequencies (i.e., Ka- and W-band) plus other supporting frequencies (i.e., X- and Ku-band) to provide a complete view of cloud and precipitation systems. Most notably, the CRS (W-band nadir Doppler), HIWRAP (Ku- and Ka-band nadir Doppler) and EXRAD (X-band scanning Doppler) have flown in the RADEX-14/IPHEx experiment to provide the first-ever 4-frequency airborne radar dataset of clouds and precipitation (see one example in Fig. 3.2). For the mid-altitude platforms (DC-8 and P-3) the existing JPL radars APR-2 (Ku- and Ka-band) and ACR (W-band), PI: S. Durden, S. Tanelli and S. Dinardo, are being upgraded and reengineered under the AITT'14 program to radiate through a single antenna to enable collocated scanning acquisition at Ku-, Ka- and W-band for the view below the aircraft, and fixed zenith acquisition at Ka- and W-band. The resulting APR-3 3-frequency Doppler scanning polarimetric cloud and precipitation radar is expected to be completed by April 2016, but current efforts aim at an early delivery to enable 3-frequency acquisitions from DC-8 during the RADEX-15/OLYMPEX field experiment in Nov/Dec 2015 (joint GPM GV and ACE Radar Definition Experiment). A dataset of interest for ACE was acquired during the Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys SEAC4RS field experiment (Aug/Sept 2013) by the APR-2 (see Fig. 3.3).

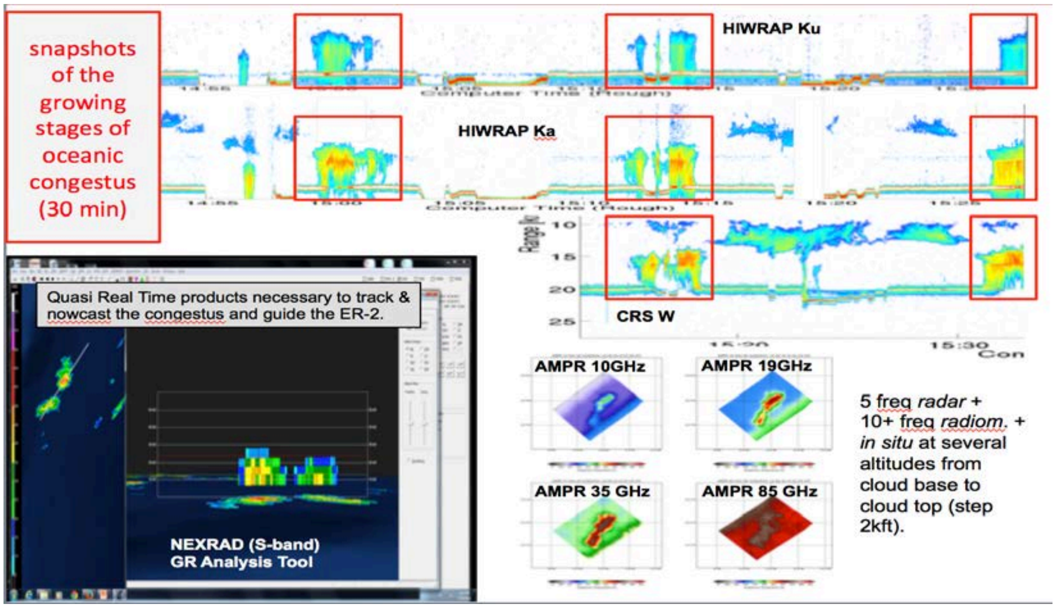


Figure 3.2: Example of data collected in one of the ACE-specific flights during IPHEX/RADEX (NC, May-June 2014): May 28, Oceanic Cumulus Congestus. Top: 3 of the radar channels from the ER-2; lower left: view from NEXRAD coastal weather radar; lower right: 4 of the radiometric channels from ER-2. (N.B. all ER-2 data are preliminary uncalibrated quicklooks). UND citation performed several penetration of the cloud imaged here at various altitudes to capture the evolving microphysics.

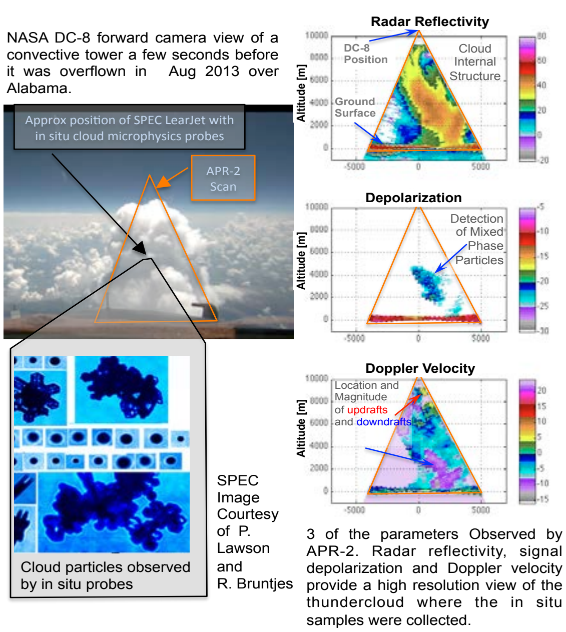


Figure 3.3: Example of data collected in one of the Convection-focused flights during SEAC4RS (TX, Aug-Sept 2013): Aug 23, Cumulus Congestus over Alabama. Top left: DC-8 forward camera view of the cloud of interest, Lower left: example of in situ particle probe imagery for the upper portion of the congestus cloud; right: APR-2 scans of the convective cloud (3 of the 6 calibrated L1 products shown here). Similar datasets are expected from RADEX-15/OLYMPEX with the addition of the W-band channel.

3.2 Polarimeters

AirMSPI/MSPI. The most significant Multiangle SpectroPolarimetric Imager (MSPI)/Airborne MSPI (AirMSPI) advancements in the past 5 years relevant to ACE have been achieved under ESTO's IIP and ACT programs. Specifically, IIP-04, IIP-07, and IIP-10 support from ESTO has been used to advance the technology readiness level (TRL) of the key MSPI subsystems.

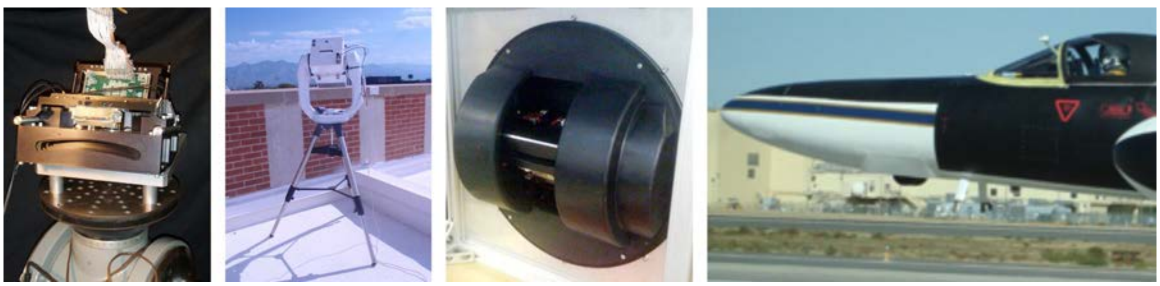
The key to accurate polarimetry in the MSPI measurement approach is rapid rotation of the plane of linear polarization (without the use of moving parts) coupled with synchronous demodulation of the resulting signals. Utilization of polarization modulation as a highly sensitive measurement methodology has been pioneered by the solar and stellar astronomy communities (e.g., Povel *et al*., 1990; Tinbergen, 1996), and the MSPI technology development effort has adapted this approach to meet ACE science requirements. There are two critical technology components to this scheme: (1) a retardance modulator to rapidly rotate the plane of polarization, comprised of a pair of photoelastic modulators (PEMs) and achromatic, athermalized quarter-waveplates (QWPs), and (2) a specialized focal plane consisting of stripe filters with patterned wiregrid polarizers to provide spectral and polarization selection for the detector line arrays, and detector readout integrated circuits that sample the modulated signals with high speed and low noise (Diner et al., 2007, 2010). Because the PEMs are made of fused silica, they efficiently transmit light from the ultraviolet (UV) through the visible/near-infrared (VNIR) and shortwave infrared (SWIR). A reflective telescope design enables optical imaging throughout this spectral range and minimizes instrumental polarization.

Support by the Earth Science Technology Office (ESTO) Instrument Incubator Program (IIP-04) led to the construction of a ground-based camera, GroundMSPI, which demonstrated the basic measurement concept. GroundMSPI has been used to explore the polarimetric and angular reflectance properties of terrestrial surfaces to help constrain the lower boundary condition for aerosol retrievals (Diner et al., 2012). Under the Airborne Instrument Technology Transition (AITT) Program, a second camera was assembled and integrated into the NASA ER-2 high-altitude aircraft, using the housing and electronics rack originally built for AirMISR. The resulting instrument, named AirMSPI (Diner *et al*., 2013a), has been flying on the ER-2 since 2010, and participated in the POlarimeter Definition EXperiment (PODEX), Studies of Emissions and Atmospheric Composition, Clouds and Climate

Coupling by Regional Surveys (SEAC[4]RS), and several pre-HyspIRI field campaigns in 2013 and 2014 (Diner et al., 2013b). AirMSPI data products from PODEX and SEAC[4]RS have been delivered to the NASA Langley Atmospheric Science Data Center for public distribution, along with supporting User Guide, Quality Statement, and Data Product Specification documents, see

https://eosweb.larc.nasa.gov/project/airmspi/airmspi_table.

The second-generation AirMSPI-2 instrument extends the measurements into the SWIR and adds band center and wing channels for the O_2 A-band. The suite of currently operational MSPI instruments is shown in Fig. 3.4. The AirMSPI-2 instrument, currently undergoing integration and test, is shown in Fig. 3.5.



GroundMSPI Camera | GroundMSPI on Tripod | AirMSPI Camera & Housing | AirMSPI mounted in the nose of the NASA ER-2

Figure 3-4: Two MSPI instruments, GroundMSPI and AirMSPI, are currently operational.

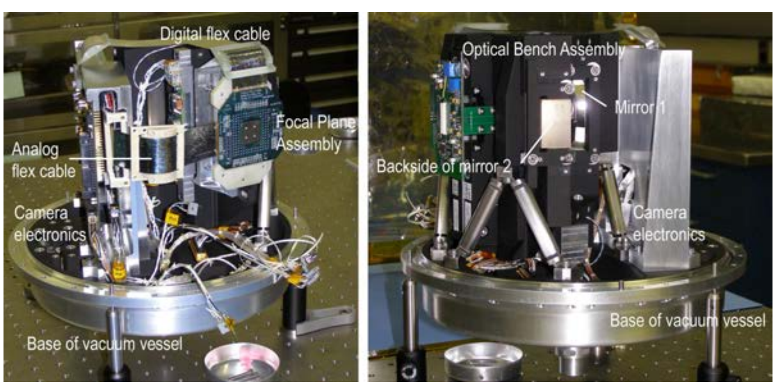


Figure 3-5: Two views of the AirMSPI-2 instrument, currently undergoing integration and at JPL. The camera with integrated optics and focal plane has been focused and the electronic signal chain is undergoing test.

There are three main steps involved in maintaining polarimetric accuracy of the MSPI instruments. The first step is a laboratory calibration to account for optical polarization aberrations within the camera. An example of this is mirror diattenuation (different reflectance for p- and s-polarization). These aberrations lead to crosstalk between the intensity and linear Stokes parameters I, Q, and U. The necessary calibration coefficients are determined by constructing a Polarization State Generator (PSG), a laboratory instrument capable of generating accurately calibrated linear polarization in any orientation. In IIP-10, an earlier version of the PSG (Mahler and Chipman, 2011) was upgraded to achieve an uncertainty in degree of linear polarization (DOLP) < 2 x 10^{-4}, i.e., more an order of magnitude better than the ACE requirement. This high sensitivity is necessary in order to accurately assess the capabilities of the MSPI imaging polarimeter. Fully polarized (DOLP = 1.0) or partially polarized (DOLP = 0.01, 0.05, 0.10, 0.20, 0.40) light generated by the PSG was viewed by AirMSPI to generate a set of polarimetric calibration coefficients that compensate for instrumental polarization aberrations (Diner et al., 2010). As shown in Fig. 3.6, systematic errors in DOLP determined from AirMSPI are < 0.002 (median value < 0.001), implying that random measurement noise (primarily due to photon shot noise) dominates the total DOLP uncertainty. AirMSPI signal-to-noise ratios are sufficiently high to enable meeting the ACE requirement on DOLP error (i.e., within ±0.005).

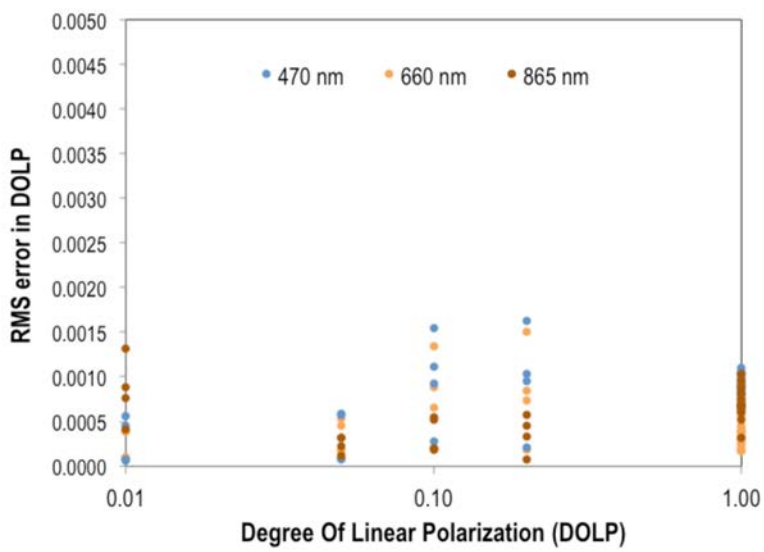


Figure 3-6: Laboratory polarization calibration of AirMSPI using the PSG keeps systematic errors in DOLP well below the ACE requirement.

The second step involves in-flight maintenance of the PEM operating parameters. This is accomplished using an *optical probe* built into the AirMSPI and AirMSPI-2 cameras. A beam of light from an LED is polarized and sent through the dual PEMs at a location not used for imaging, and the modulations are sensed with a high-speed photodiode. Analysis of the signals allows determination of the retardances of the two PEMs and the PEM oscillation phase. These are controlled to the desired values (the same values as used for laboratory calibration) using a feedback control loop. The optical probe is in conjunction with the third step, which is periodic in-flight verification of PEM retardances and phase by viewing an on-board polarization *validator*, consisting of a set of LEDs that illuminate a diffuse panel and polarizers in different orientations. By viewing the validator with the AirMSPI camera during flight, the modulation functions used to analyze polarization data can be determined and verified to be governed by the proper values of the PEM operating parameters. Deviations from the desired values can be corrected in ground data processing.

A custom dual-PEM retardance modulator package was engineered and built to withstand launch loads, and was vibrated in all three axes at 15 g RMS. PEM functionality was retested to verify that there had been no damage to the bond line holding the PEM head to the piezoelectric transducer. PEM retardance stability was tested in the laboratory at a number of fixed set point temperatures from -30°C to +50°C. In space, the PEMs will be thermally stabilized. In addition, a dual PEM has been operating in the lab nearly continuously for more than 5.5 years. The achromatic QWPs are compound retarders comprised of three materials (quartz, sapphire, and MgF_2) that are often used in space applications. IIP-07 work extended the performance of the QWP into the SWIR. A similar compound QWP for OCO-3 demonstrated survivability of the bonds through thermal cycling in vacuum between -20°C and 35°C. Vibration testing of the OCO-3 article showed no vibration-induced structural defects.

The MSPI spectropolarimetric filters are *butcher block* assemblies of patterned wiregrid polarization analyzers and miniaturized stripe filters. Structural replicates of the MSPI filters were run through thermal stress tests in vacuum, consisting of 123 thermal cycles between 220K and 313K and 108 additional cycles between 180K and 313K. The tested filters survived thermal cycling and met bondline integrity requirements with substantial margin. The other element of the focal plane is the sensor chip assembly (SCA), consisting of the readout integrated circuit (ROIC) and hybridized HgCdTe detector for the SWIR. A separate ROIC on the same chip provides UV/VNIR sensing using embedded Si-CMOS photodiodes. The ROICs enable sampling of the PEM modulation patterns at the required readout speeds (~25 Mpix/sec), leading to photon shot-noise limited sensing over a wide dynamic range. Single Event Latchup (SEL) testing using heavy ion bombardment indicates a latchup probability of once per 5000 years. Latchup was also determined to be nondestructive, meaning that in the unlikely event of occurrence, a reset restores normal operation. Total ionizing dose exposure of the ROIC was also completed, using the JPL cobalt-60 source in 5 krad steps up to 25 krad. All tested parts remained fully functional, and dark current remained within specifications at doses corresponding to low Earth orbit. Finally, characterization of the hybridized ROIC/detectors at operating temperature and following thermal cycling was performed. An SCA underwent 100 thermal cycles between room temperature and 235K, and was subjected to an additional 30 cycles between room temperature and 180K. The part remained functional following these environmental stresses.

The above environmental stresses represent “relevant environment” qualification testing of all key MSPI technologies, including the retardance modulator and specialized focal plane. As a consequence, each of these subassemblies is currently at TRL 5. In addition, the MSPI onboard processing algorithm that converts the sampled modulation signals to linear Stokes polarization parameters was tested aboard the CubeSat On-board processing Validation Experiment-2 (COVE-2), providing the first spaceborne application of a new radiation-hardened Virtex-5QV field programmable gate array (FPGA). COVE-2 was launched in December 2013. Telemetry demonstrated successful processing, bringing the maturity of this key component to TRL 7 (Pingree, 2014).

Key technology components of the MSPI system are shown in Fig. 3.7. At upper left is the dual-PEM retardance modulator (including QWPs) in a space-qualified package. The green assembly at top is the optical probe. At upper right is a front- and back-lit photograph of the AirMSPI-2 spectropolarimetric filter showing the stripe spectral filters and patterned polarizers. Lower left shows the UV/VNIR/SWIR detectors and ROICs built for AirMSPI-2. Lower right shows the JPL COVE payload featuring the Xilinx Virtex-5QV FPGA.

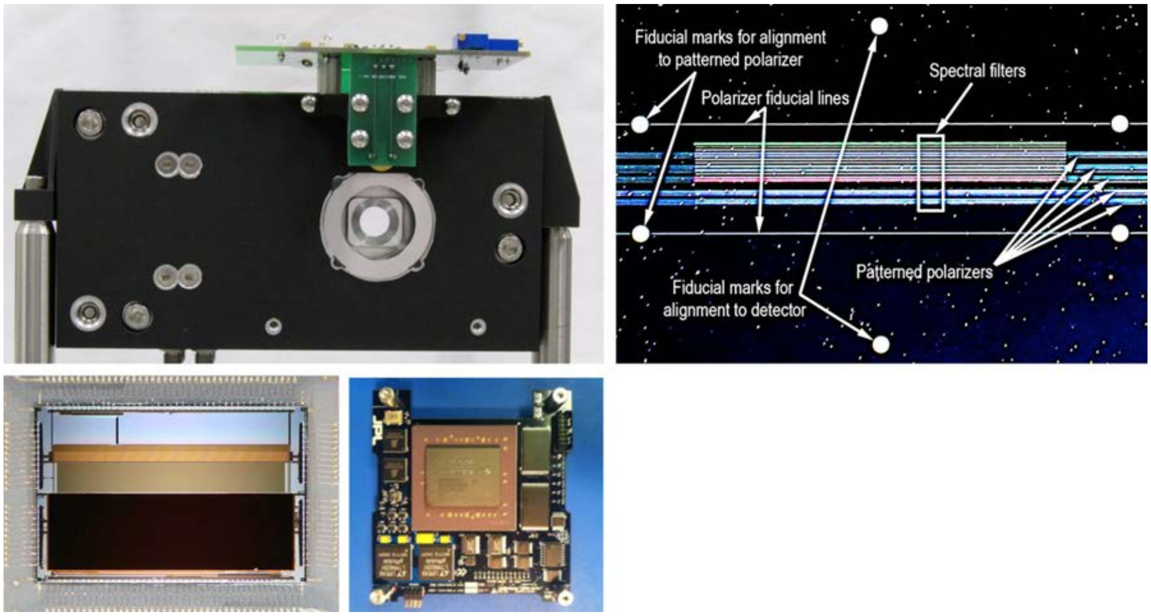


Figure 3.7: Top left: retardance modulator. Top right: filter assembly. Bottom left: ROICs and detectors. Bottom right: COVE payload with Virtex-5QV FPGA.

The AirMSPI-2 instrument has been integrated, performed system radiometric, spectral, and polarimetric calibration and characterization, and the instrument has been flight tested on the NASA ER-2 in October 2015. These flights have demonstrated the functionality of the end-to-end UV/VNIR/SWIR camera system in the aircraft environment, raising the TRL to 6 for the airborne environment. Achieving TRL 6 for the spaceborne environment will require system level vibration and thermal tests.

Regarding the Level 0 to Level 1 processing approach for MSPI, a generalized photogrammetry software library developed for the Terra Multi-angle Imaging SpectroRadiometer (MISR; Jovanovic et al., 1998, 2002) serves as the basis for this. Critical functionality includes collinearity, which makes use of the camera/orbit geometric model to establish the view vectors for each line and pixel in the focal plane. It is expanded to include simultaneous bundle adjustment, which employs ground control points and a digital elevation model to solve for static and/or dynamic changes in certain parameters describing the instrument pointing geometry. This functionality, along with pixel-by-pixel application of radiometric and polarimetric calibration coefficients, is used to convert raw instrument (Level 0) data to calibrated, georectified, and co-registered radiance and polarization imagery at Level 1, and has been prototyped for ACE using AirMSPI. In addition to MISR-like Level 0 to Level 1 processing that generates ellipsoid-projected imagery, georectified imagery map-projected to the surface terrain is used as input to aerosol retrievals (Fig. 3.8). A similar approach is envisioned for MSPI, and has been prototyped using AirMSPI data.

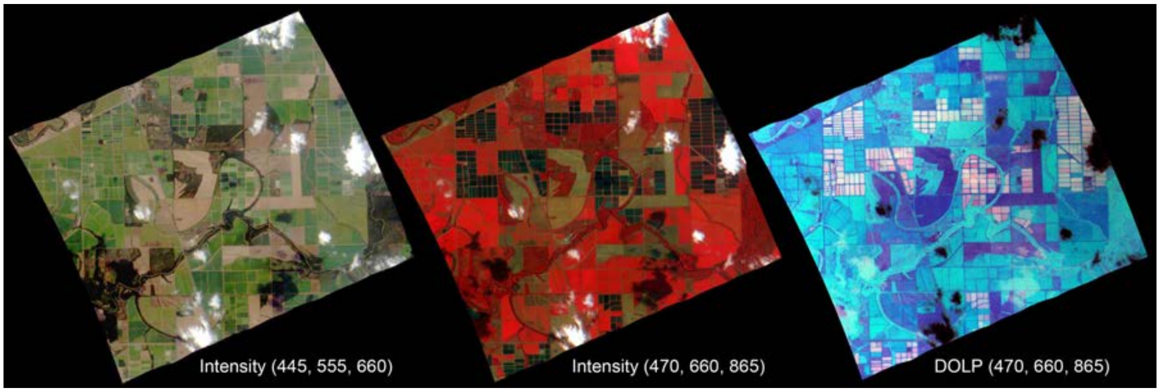


Figure 3.8: Example AirMSPI imagery over Leland, MS, acquired on 9 September 2013 during SEAC^{4}RS. Left: Intensity imagery at 445, 555, and 660 nm. Middle: False color intensity imagery at 470, 660, and 865 nm. Right: DOLP image at 470, 660, and 865 nm. Georectification provides subpixel registration of the different instrument channels as well as registration of images acquired at different angles of view.

RSP. The Research Scanning Polarimeter (RSP) is a functional prototype of the Aerosol Polarimetry Sensor that flew on the NASA Glory mission, which failed to make orbit. The measurement concept used in this sensor has a long heritage starting with the Imaging PhotoPolarimeter on Pioneer 10 and 11 then the Cloud PhotoPolarimeter on Pioneer Venus and more recently the PhotoPolarimeter Radiometer on Galileo. The development of the RSP has been achieved with support from the NASA Radiation Science Program, ESTO's AITT program, the Glory mission and contributions from SpecTIR LLC, the company that built the RSP.

The major difference between RSP and preceding planetary instruments is the implementation of a rotating pair of mirrors in front of the telescopes that provide scene definition and spectral and polarimetric analysis. This allows the field of view of the instrument to be scanned while introducing negligibly small amounts of instrumental polarization into the observed scene. The scanning system also allows well characterized scenes of both low (using a pseudo-depolarizer) and high (using polarizers) polarization to be observed on every scan providing continuous polarimetric calibration and guaranteed polarimetric accuracy over the entire range of possible polarization states, in addition to continuous radiometric calibration/stability monitoring. This ensures that measurements of the degree of linear polarization are made with an absolute uncertainty of less than 0.2% absolute accuracy when the degree of polarization is less than 20% and less than 0.5% when the degree of polarization is greater than 20%.

The polarization compensated scan mirror assembly scans the fields of view of six boresighted, refractive telescopes, with an instantaneous field of view of 14 mrad, to obtain scene data over a range of +/-60° from the normal with respect to the instrument baseplate. The refractive telescopes are paired, with each pair making measurements in three spectral bands. One telescope in each pair makes simultaneous measurements of the linear polarization components of the intensity in orthogonal planes at 0° and 90° to the meridional plane of the instrument, while the other telescope simultaneously measures equivalent intensities in orthogonal planes at 45° and 135°. This approach ensures that the polarization signal is not contaminated by scene intensity variations during the course of the polarization measurements, which could create false polarization. These measurements in each instantaneous field of view in a scan provide the simultaneous determination of the intensity, and the degree and azimuth of linear polarization in all nine spectral bands.

The instrument has nine spectral channels that are divided into two groups based on the type of detector used: visible/near infrared (VNIR) bands at 410 (30), 470 (20), 550 (20), 670 (20), 865 (20) and 960 (20) nm and shortwave infrared (SWIR) bands at 1590 (60), 1880 (90), and 2250 (120) nm. The parenthetic figures are the full width at half maximum (FWHM) bandwidths of the spectral bands. These spectral bands sample the spectrum of reflected solar radiation over most of the radiatively significant range, with measurements under typical clear sky conditions ranging from significant Rayleigh scattering (410nm) to single scattering by aerosol (2250nm) within a single measurement set.

The desired polarization-insensitive scanning function of the RSP is achieved by the use of a two-mirror system with the mirrors oriented such that any polarization introduced at the first reflection is compensated for by the second reflection. Boresighted refractive telescopes define the 14mrad field of view of the RSP. Dichroic beam splitters are used for spectral selection, interference filters define the spectral bandpasses and Wollaston prisms spatially separate the orthogonal polarizations onto the pairs of detectors. The detectors for the VNIR wavelengths are pairs of UV-enhanced silicon photodiodes. The detectors for the SWIR wavelengths are pairs of HgCdTe photodiodes with a 2.5 μm cutoff cooled to 163K to optimize performance. The average data rate of 110kbps provides readout of the 36 signal channels together with instrument status data at a scan rate of 71.3 rpm and is similar to the data rate from APS (160 kbps). A scan rate of ~ 70 rpm is compatible with getting contiguous (nadir view to nadir view) coverage with aircraft ranging from a Cessna 210 to the NASA ER-2. It is also compatible with the velocity and altitude of a typical low earth orbit for the 8 mrad IFOV of an instrument such as APS.

The RSP instrument was designed to meet the scientific requirements for high quality polarimetric data, by having high accuracy, simultaneous collection of all polarization components and spectral bands within an instantaneous field of view, the ability to observe a scene from multiple angles and a broad spectral range. The RSP instrument meets the polarimetric accuracy requirements (less than absolute 0.2% error) and has been used to obtain more than a thousand hours of multi-angle, multi-spectral data since 2000. Instrument performance has been flawless and it has been operated on a wide range of aircraft most recently the NASA Langley Research Center B200 since 2008 and the NASA ER-2 since 2012. All radiance and polarization data are publicly available and is generally calibrated and made public within 2-3 days of acquisition. Funding for flights of the RSP came from the Glory and CALIPSO missions and the Research and Analysis programs, primarily the Radiation Science Program through support of RSP deployment for SEAC4RS and the Ocean Biology and Biogeochemistry program through support of the RSP deployment for SABOR and on HySPIRI airborne preparatory program flights.

The RSP group participated in the Earth Systematic program office's Systems Engineering Working Group (SEWG) assessment of Technology Readiness Level (TRL) for an Aerosol Polarimetry Sensor (APS) rebuild. The assessment was that the sensor had a TRL of 7 and while there are always disagreements about the exact TRL of a complete system and the definition of TRL occasionally changes it is clear that the APS is a mature design with substantial design heritage. In particular the APS successfully completed both sensor level and observatory level EMI/EMC, vibration, thermal/vacuum and shock testing with a total of more than 1200 operational hours in thermal/vacuum testing. The successful performance during sensor level testing is documented in the Raytheon Requirements Verification Matrix and supporting documentation, together with the Consent to Ship Review package. The successful performance during observatory level testing is documented in the observatory Pre-Ship Review package and supporting Orbital Science Corporation requirements verification documentation.

The only likely change to the APS design for the ACE mission would be if a clean view to deep space were not to be available for cooling. In that case two Thermo

Electric Coolers, a cold plate, redundant ethane heat pipes, and a radiator can be used to maintain the SWIR detectors at a temperature of 183K ± 2K. A similar thermal system was flown on Swift and more recently on the Landsat Data Continuity Mission (LDCM) Thermal Infrared Sensor (TIRS), so the design already has heritage. A model of this proven design was assembled and successfully tested under GSFC Internal Research and Development (IRAD) funding to demonstrate feasibility. In addition to providing proof-of-concept for this specific application, the prototype provided realistic mass and power estimates and will allow for the sizing of the SWIR Heat Rejection Radiator early in ACE mission development.

The Level 0 to Level 1 processing of RSP data follows the same flow in terms of required calibration coefficients and their on board calibration sources, as presented in the Glory APS L1B Algorithm Theoretical Basis Document (http://glory.giss.nasa.gov). These coefficients are used to generate the calibrated Stokes parameters I, Q and U and the code developed for the Glory project is used for geolocation and geo-rectification. In addition the L1B data product includes index arrays that can be used to remap the RSP data to any altitude, simplifying the implementation of cloud retrievals.

PACS. The Passive Aerosol and Cloud Suite (PACS) multi angle imaging polarimeter consists of a simple and robust optical design composed of three wide FOV telescopes with no operational moving parts covering the required spectral range (UV, VNIR, SWIR) with 14 polarized wavelengths between 360 and 2250 nm. The PACS VNIR polarimeter concept is currently being prepared for space application on the HARP Cubesat Spacecraft funded under the NASA ESTO InVest program. HARP will carry a full VNIR version of the PACS polarimeter to allow the acquisition and application of hyper-angular polarization data from space for the first time.

In the fall of 2008, prior to the HARP Cubesat, work commenced on the PACS instrument development with seed money from the Earth Science Directorate and a small core team of personnel from both UMBC and NASA GSFC towards the ACE mission requirements. Further PACS development has been achieved with important contributions by GSFC IRADS, UMBC investments, the NASA radiation sciences program and the ESTO InVest program. A first version of the PACS VNIR polarimeter was built and flight-tested on the ER-2 aircraft. By design the PACS polarimeter allows for easy selection (or de-selection) of potentially high angular density (up to 66 viewing angles), which permits detailed characterization of ice and water clouds. Thanks to its wide FOV (up to 110 degrees along and cross track) the

PACS design is also consistent with global measurements in moderate resolution (on the order of 1-2 km).

Each telescope has a telecentric back end that splits the signal into three identical images by a modified Phillips prism over three flight qualified Teledyne detector arrays controlled by a Teledyne Sidecar ASIC system. Wavelengths and angles are defined (and software selectable) by a striped filter mounted on the surface of the detector, though the first version of the PACS VNIR polarimeter on the ER2 used a filter wheel. A first version of the PACS striped filter is being tested in the lab and will fly on HARP by the first time. For each viewing angle and each wavelength the PACS polarimeter telescope will provide 3 intensity images acquired through polarizers aligned at 0, 45 and 90º relative to each other. This approach assures simultaneous polarization measurements and the high accuracy of the measurements. The intensity measurements in each output port of the splitting prism (I_A, I_B, and I_C) performed after polarizers at 0, 45 and 90º respectively are related to the Stokes vector of the incoming light by a 3X3 characteristic matrix that fully represents all the elements of the optical system (Fernandez-Borda et al., 2009). This approach has been demonstrated and validated in the UMBC lab and on ER2 aircraft measurements during the PODEX experiment producing polarization accuracy better than 0.5%. The accuracy measurements have been validated with a polarization generator that can modulate the degree of linear polarization and the polarization angle of the light generated by an unpolarized integrating sphere.

A natural and necessary intermediate step to verify the feasibility of an accurate wide FOV polarimeter in UV, VNIR and SWIR, was to develop and fly an aircraft science instrument. The PACS polarimeter design was intentionally planned to minimize technology development risk and favor space applications. No low TRL technologies were used. The PACS polarimeter design incorporated flight qualified Teledyne HyVisi H1RG and MCT H1RG detectors and Teledyne sidecar ASICS for all telescopes in order to address flight heritage. These detectors and electronics have flown in space on numerous NASA, DOD and ESA missions.

This first prototype for the PACS VNIR polarimeter was built and successfully flown an engineering flight on the ER2 aircraft in the summer of 2012 using the Teledyne detectors and electronics, as well as all the other elements as designed for space flight. All systems worked as planned. The PACS VNIR polarimeter was subsequently flown on the PODEX science fight campaign in January-February 2013. All flights were successful. PACS VNIR was successfully exposed to 10 G shock loads and ER2 take-off and landing structural loads.

In the summer of 2012, a team was assembled to develop a flight proposal for a PACS UV/VNIR/SWIR instrument that had a small foot print. As part of that process a great deal of flight design work was completed. In 2015 the UMBC/GFSC group submitted an EVI proposal with PACS components. All systems were evaluated at being a TRL of 6 or greater. PACS is essentially a room temperature instrument except for the detectors, which are cooled to a nominal 200K for SWIR and 240K for UV and VNIR wavelengths using passive radiators on the S/C implementation. All structural materials are 6061-T6 Aluminum or Titanium (6Al-4V). No exotic lens materials are required. The calibration wheel mechanism consists of simple stepper motors and resolvers; all are at room temperature so lifetime cycle and lubrication requirements have been demonstrated on numerous other GSFC/NASA missions.

The use of the Teledyne flight qualified Sidecar ASIC eliminates any concerns with qualification of ADCs or any other fast readout electronics. Simple ammonia heat pipes and common thermal coatings insure the bulk of the instrument remains within the operating range of 0 to 30C. Calibration procedures for the PACS VNIR aircraft instrument are directly applicable to a spaceflight version. Development and customization of the Teledyne ASIC firmware are also directly applicable. Numerous radiation hardened ICDH computers are available where as much as 80% of the flight software for command control, data handling and housekeeping can be reused from other space qualified programs; this has been confirmed by the Electrical Systems and software Branches at GSFC.

Two options are used for the wavelength and angular selection on each of the PACS telescopes. First is the use of stripe filters that are mounted on the top of the detector arrays. Such filters have been used in numerous space missions in the form of butcher blocks; an alternative photolytic approach that minimizes stray light and reduces optical cross talk between different wavelengths was built and will be demonstrate in space on the HARP CubeSat mission. Although the stripe filter approach has been demonstrated before, a simple filter wheel can possibly be used as a backup to collect the required PACS data. This second approach has been demonstrated in the PACS ER2 instrument simulator.

Work is under way to complete the development and start testing the PACS SWIR prototype. Several of its components are ready and currently under laboratory testing. Plans also include the completion of the HARP CubeSat instrument and spacecraft integration. We also plan to adapt one of the copies of the HARP CubeSat polarimeter to fly on the ER-2 aircraft and replace the previous PACS ER-2 polarimeter. Air-HARP will eventually be composed of two components:

- AirHARP SWIR polarimeter
- AirHARP VNIR polarimeter

As part of AirHARP VNIR we have also developed a new concept for onboard polarization calibration. The first prototype of this system has been demonstrated in the lab and will eventually be implemented as part of Air-HARP on board the ER-2 aircraft. Algorithm development is also planned for both level 1 and level 2 products. In terms of level 1 processing the SCIPP algorithm has been developed to start from PACS level 0 data and slice it in multiple viewing angles and wavelengths. The data are then geo-referenced and calibrated to generate a level 1B product. This product is then packaged into HDF-5 files to serve as input to a geophysically relevant level 2 data processing system that is currently under development in our group based on the GRASP algorithm. The SCIPP package is currently being tested with the PACS data and will be implemented to process the upcoming Air-HARP and HARP CubeSat data.

3.3 Lidar

Early in the program, two lidar instrument concepts were developed for use in ACE mission design studies. One was a multi-beam backscatter lidar that provided some information in the cross-track direction via a pushbroom-like sampling strategy. The other was a single-beam multi-wavelength High Spectral Resolution Lidar (HSRL) that provided only a nadir curtain of lidar measurements but with higher SNR and information content in that curtain. Both concepts were analyzed in the initial GSFC Integrated Mission Design Lab (IMDL) mission studies.

Over the course of the ACE pre-formulation effort, significant advances have been made in technology readiness, retrieval development, scientific demonstration, and validation. Many of these advances are based on the HSRL-2 airborne prototype instrument that implements the full $3\beta + 2\alpha + 2\delta$ ACE lidar concept and which has been flown on four major field missions starting in 2012. Exciting technology and demonstration advances for some of the ACE capabilities have also been with the ACATS and CATS instruments.

HSRL. In February 2009, the Aerosol Working Group met at GSFC to refine lidar requirements. The requirements called for implementation of single-beam multi-wavelength high spectral resolution lidar (HSRL) providing the so-called "$3\beta + 2\alpha + 2\delta$" suite of profiles: 3 aerosol backscatter wavelengths, 2 aerosol extinction wavelengths, and 2 polarization-sensitive wavelengths. It was this concept that was used in subsequent mission design studies (GSFC IMDL and JPL Team-X studies).

The wavelengths required for the $3\beta + 2\alpha + 2\delta$ measurements are UV, mid-visible, and near-IR, which can be achieved with mature laser technology (Nd:YAG, or Nd:YVO4), using the fundamental (~1064 nm), doubled (~532 nm), and tripled (~355 nm) wavelengths of a single pulsed laser transmitter. Unambiguous aerosol extinction measurements required at the 355 and 532 nm wavelengths necessitate use of the HSRL technique. This combination of three backscatter and two extinction wavelengths is the only published method for retrieving the required vertically resolved aerosol optical properties (scattering and absorption) and microphysical properties (size, index of refraction, concentration) using only lidar measurements (Müller et al., 2001; 2002; Veselovskii et al., 2002; Wandinger et al., 2002). The depolarization measurements at two wavelengths provides enhanced skill for aerosol typing (Burton et al., 2012); it remains to be determined which two of the three wavelengths are required for depolarization, but heritage measurements with airborne systems have been made with the 532 and 1064 nm wavelengths. Studies are underway to determine whether a simpler lidar combined with a polarimeter can satisfy the aerosol requirements. Lidar measurements required for the cloud objectives include cloud top height and profiles of cloud phase, backscatter, and extinction in tenuous clouds. These requirements could be met with fewer channels (e.g., a 532 nm HSRL with polarization sensitivity), but drive the dynamic range of the measurements. The ocean objectives call for ocean-profiling HSRL measurements necessary to retrieve particulate backscatter and diffuse attenuation coefficients. Ocean objectives could be satisfied with a single wavelength (either UV or mid-visible) HSRL with depolarization but drive the dynamic range of the measurements and the bandwidth and sampling of the detection electronics to meet the 5-m required vertical resolution (2-m goal).

Airborne prototypes have demonstrated the required ACE lidar technologies and measurements. The LaRC HSRL-2 instrument is a full-up prototype for achieving the ACE $3\beta + 2\alpha + 2\delta$ atmospheric measurements. It implements the HSRL technique at 355 and 532 nm and the standard backscatter technique at 1064 nm and is polarization sensitive at all 3 wavelengths. The development of HSRL-2 originated with ESTO Instrument Incubator Program (IIP) funding in 2004 and continued through an Airborne Instrument Technology Transition (AITT) award in 2007, LaRC internal funding, and current funding to extend the capability to ocean profiling under a 2014 IIP award. The receiver employs and iodine vapor filter to implement the HSRL technique at 532 nm (Piironen and Eloranta, 1994) and a field-widened, off-axis Michelson interferometer at 355 nm (Liu et al., 2012). Funding for advancement of the interferometer implementing the HSRL technique at 355 nm has been provided via an ESTO QRS award, ACE pre-formulation funding, Directed Technology and Research (formerly GOLD) labor support, and LaRC internal funding. HSRL-2 builds on a long history of technology and science demonstration of the two-wavelength HSRL-1 instrument (Hair et al., 2008), the development of which was initiated in 2000 and which has flown on 24 airborne field missions starting in 2006. The ACE-prototype HSRL-2 instrument has been deployed on four major airborne field missions starting in 2012. Operational software code produces full lidar "curtains" of ACE-like aerosol optical and microphysical properties within a few hours after each flight (Müller et al., 2014). Each of the four HSRL-2 field missions involved additional participating aircraft making in situ aerosol measurements coincident with the HSRL-2 measurements. Aerosol measurements made on the participating aircraft and coincident AERONET observations are being used to assess the multi-wavelength lidar aerosol retrievals and development of new algorithm approaches. Most recently, the HSRL-2 has conducted some successful test flights on the NASA ER-2 in May, 2015 and April, 2016. (see Fig. 3.9).

The HSRL-1 instrument was upgraded in 2012 under an AITT award to enable ocean profiling via the HSRL technique as called for in the ACE Ocean Ecosystems STM. It has flown two ocean-focused field missions from which retrievals of ocean particulate backscatter and diffuse attenuation coefficients have been demonstrated (Behrenfeld et al., 2013). These retrievals are currently being assessed against extensive ship-based in situ optical measurements coincident with the lidar measurements under an R&A award from the Ocean Biology and Biogeochemistry Program.

In addition, the LaRC Ultra-Violet Differential Absorption Lidar (UV DIAL) instrument, a flagship instrument flown since the 1980s on over 30 chemistry focused field missions, was recently upgraded under an AITT award to include HSRL capability at 532 nm in both the nadir and zenith directions. It has flown on two field missions in that configuration and aerosol data products are produced from similar code used for the HSRL-1/2 instruments. Cirrus cloud retrievals of backscatter, extinction, and depolarization have been demonstrated with the UV DIAL/HSRL data set.

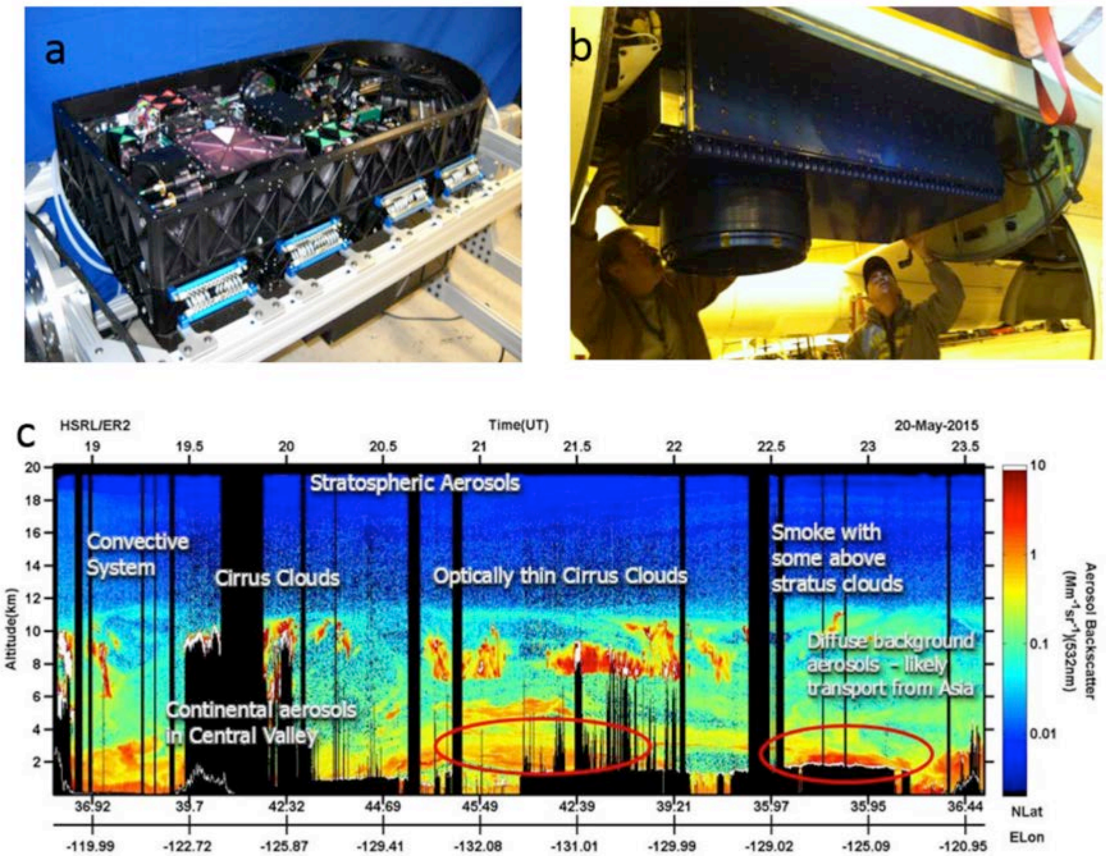


Figure 3.9: (a) HSRL-2 instrument head. (b) HSRL-2 being installed in the Q-bay of the ER-2. (c) HSRL-2 curtain data from a successful test flight onboard the NASA ER-2 on May 20, 2015.

A TRL assessment of the 3β + 2α + 2δ ACE lidar concept was conducted in 2013. This lidar concept was based significantly on CALIPSO heritage. The TRL assessment focused on elements requiring technology development only and excluded elements that could be developed via straightforward engineering (e.g., commonly deployed electronic subsystems, thermal subsystems, structures, etc.). Considering only atmospheric measurements (i.e., considering ocean profiling to be a goal rather than a requirement), the TRL was assessed at TRL-5. The TRL was reviewed again in 2014 and assessed to be closer to TRL 4. The subsystems that were considered to lower the TRL to 4 included the laser transmitter and interferometric receiver that implements the HSRL technique at 355 nm in the LaRC 3β + 2α + 2δ prototype.

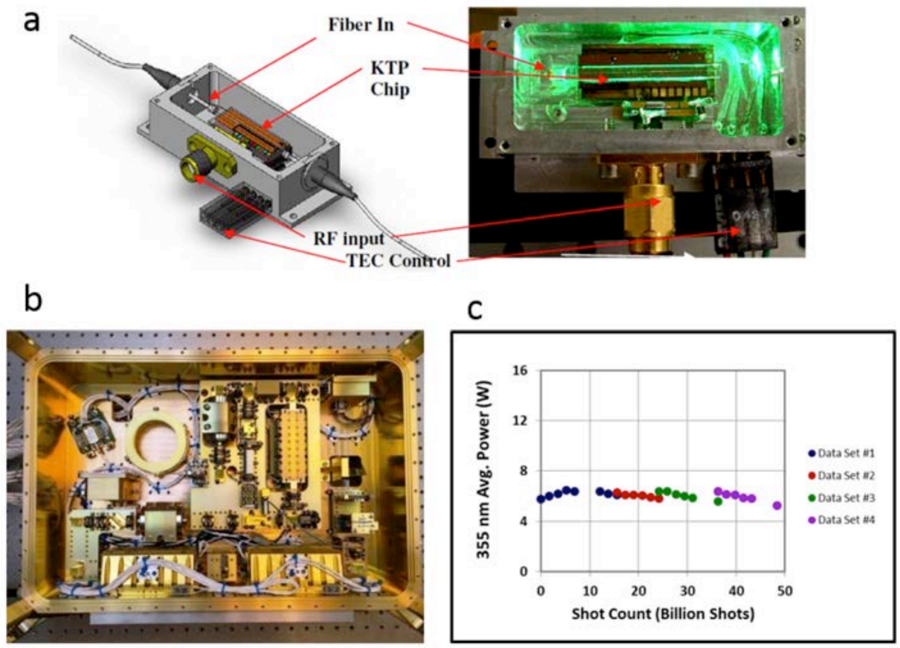


Figure 3.10: (a) Planar lightwave circuit that frequency doubles and phase modulates CW light from the seed laser. (b) HEUVD laser head. (c) 355 nm output power measured in accelerated life tests (50 billion shots would be equivalent to 16 years on orbit for ACE assuming a 100 Hz rep rate.

TRL advances are underway for the laser transmitter, which consists of a seed laser subsystem and a pulsed laser. Advancement of the seed laser subsystem is being fostered under two SBIR awards and the optical elements of that subsystem should reach TRL 6 by FY17 after development and environmental testing of a space-like version under these SBIR awards. This seed laser subsystem consists of a compact diode-based seed laser, a planar lightwave circuit that implements frequency doubling and phase modulation, a compact iodine cell that defines the frequency reference, and compact low-noise current and temperature controllers in a feedback loop that locks the diode seed laser frequency. The pulsed laser is being advanced through the ESTO High Energy UV Demonstration Project (HEUVD), which is building an Engineering Development Unit (EDU) with architecture suitable for both the ACE and 3-D winds missions. This EDU will undergo environmental testing and lifetime testing in FY16. A major concern for the pulsed laser is the lifetime of the laser in the UV wavelengths. This has been assessed by the builder of the EDU for the high risk component, the third harmonic generator crystal, specifically the coating on the exit face of that crystal which is an area of high UV fluence and on which small amounts of contamination can lead to damage. An ACE-funded program conducted over several years led to the development of contamination control procedures and coating choices. Using a 10 kHz laser source, accelerated lifetests in FY15 on crystals with these new coatings and using the new contamination control procedures have demonstrated lifetimes exceeding ACE requirements: results show negligible output power degradation for the equivalent of 16 years of ACE lidar operations assuming a 100 Hz laser repetition rate for ACE. UV laser lifetime issues are also being addressed by ESA for the lidars on ADM-Aeolus and EarthCARE and so will provide additional information on potential impacts on the ACE lidar. The HEUVD project should put the ACE pulsed laser head at TRL 6 by the end of FY16.

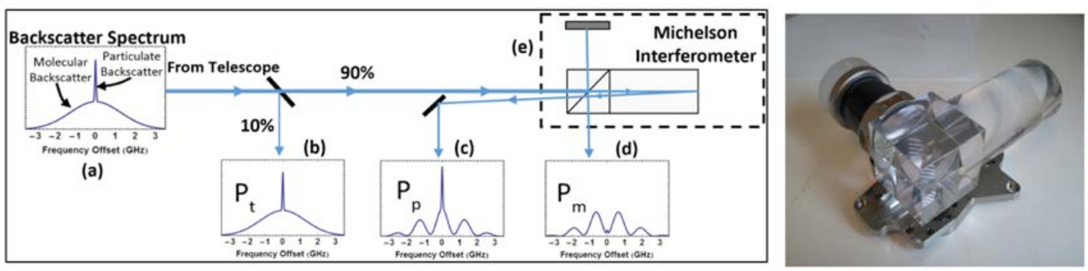


Figure 3.11: Off-axis Michelson interferometric receiver concept and photograph of the space-like quasi-monolithic interferometer tested in the lab and recently installed in HSRL-2 for operational testing.

To elevate the TRL of the HSRL interferometric receiver, advanced interferometer has designed for space application. The advanced interferometer is based on a quasi-monolithic design which is more stable in frequency and more mechanically robust than the piezoelectrically controlled version currently flown in the airborne HSRL-2 instrument. This new device is tuned in temperature, reducing the number of degrees of freedom to 1 as compared to the 3 degrees of tuning freedom for the piezoelectrically controlled unit. This approach simplifies on-board frequency control and provides better overall optical performance. A variation of this design has been tested in the lab with success and installed in the HSRL-2 instrument for testing operationally on upcoming field missions. The TRL of this new interferometer should reach TRL 6 by sometime in 2016 after operational testing of the current model in the HSRL-2 instrument and vibe and thermal testing a space-optimized unit. This interferometric receiver technology can also be used at 532 nm, providing a more photon-efficient approach than the iodine vapor technique currently used at that wavelength in both the HSRL-1 and HSRL-2 airborne prototypes.

For ocean profiling, significant advances have been made in technology, algorithm development, and science demonstration. Ocean profiling has successfully been demonstrated at 532 nm with an airborne prototype instrument (HSRL-1) and the retrievals have been validated via comparison with satellite ocean color products and in situ optical measurements made from a ship (Ship-Aircraft Bio-Optical Research (SABOR) mission conducted in 2014). For these measurements, the lidar was operated in an off-nadir configuration to avoid specular reflections of the laser pulse from the ocean surface, as these reflections can create artifacts in the subsurface ocean profile. Off-nadir pointing may also be option on ACE; however, work is underway on alternative detectors that can either gate out the surface spike or are immune to the effects of "after-pulsing". Recent (summer 2015) tests using micro-channel plate detectors and advanced detection electronics have shown that the ocean profiling measurements can be made at nadir by gating off the detector for a few 10s of ns centered on the surface reflection spike. A full demonstration of HSRL ocean profiling measurements at both 355 and 532 nm will be implemented under an IIP 2014 project, the focus of which is to convert HSRL-2 to a multi-wavelength ocean profiling instrument by FY17. The new HSRL-2 instrument will still retain all the atmospheric capabilities required for ACE. Based on recent advances, the detectors and detection electronics required for ocean profiling are between TRL 4 and 5.

Overall, the TRL of the ACE lidar remains between 4 and 5. Full-up airborne prototypes have been developed and, in the case of CATS, a spaceborne instrument exhibiting some of the ACE capabilities have been deployed. The main limiting factor for comprehensive advance to TRL 5 is that much of the supporting electronics and software in the airborne prototype instrument, HEUVD laser, interferometric receiver, and detection electronics are not designed to space standards and testing has been limited to laboratory environments. However, advancing the electronics is more a matter of straightforward engineering than technology development. Advancing comprehensively to TRL 6 will require hardware development with space grade components and more thorough testing in relevant environments.

The Level-0 through Level-2 algorithms for producing attenuated backscatter, aerosol/cloud backscatter and depolarization profiles would follow those as described by Hair et al. (2008). The background signals are determined from the average of samples over a range in the profile that is beyond the range corresponding to the Earth surface return and, therefore, absent of any lidar signal.

The received backscatter signal is optically separated in the parallel and perpendicular components and the attenuated backscatter profile is constructed using the sum of these components, weighted by the appropriate channel gain ratios. The gain ratio calibration is performed by rotating the transmitted polarization 45° to the receiver analyzer, such that both polarization channels measure equal components of the parallel and perpendicular backscattered return. The volume depolarization ratio is determined from the ratio of the sum of the perpendicular components (aerosol+molecular) channels to the sum of the parallel components (aerosol+molecular). Geolocation employs a simple algorithm using position and attitude information from the platform inertial navigation system.

Retrieval algorithms for producing the ACE lidar Level-2 atmospheric products have been demonstrated operationally using airborne HSRL-2 field data since 2012 as described in section 4. Extensive validation studies have been conducted that show the lidar retrievals of concentrations and effective radii compare well with corresponding values derived from airborne in situ measurements.

CATS. The GSFC Airborne Cloud-Aerosol Transport System (ACATS) lidar implements both the HSRL technique and standard backscatter technique at 532 nm. The ACATS telescope rotates to four different look angles and is set at an off-nadir view angle of 45 degrees. After undergoing modifications to improve performance of the telescope, ACATS was tested on the ER-2 aircraft during August 2015. Performance was satisfactory, and additional future flights are planned.

The GFSC Cloud-Aerosol Transport System (CATS) instrument was developed for deployment on the International Space Station (ISS) as a technology demonstrator. Launched on January 10, 2015 the CATS instrument became operational on the ISS on February 12, 2015. The CATS instrument operates as continuously as possible and provides spaceborne demonstration of a high repetition rate photon-counting approach to atmospheric lidar that may provide a more cost-effective, higher-TRL alternative to the ACE lidar as currently envisioned.

Advances in the implementation of interferometric HSRL measurements have been made with the ACATS and CATS instruments. The CATS space demonstration lidar implements an interferometric receiver at 532 nm using a multi-channel detector technique that can also be engineered to 355 nm for ACE. The hardware for this subsystem is at TRL 8 but data products produced from the ACATS approach require further assessment.

Information on CATS and access to the CATS data can be found at http://cats.gsfc.nasa.gov.

Summary and Recommendations. In summary, technology development for the ACE lidar has focused on the tallest poles rather than the development of a comprehensive hardware implementation. Advancing to TRL 6 appears to be a matter of engineering rather than technology development with the only caveat being concern over the lifetime of the laser for the UV wavelengths. UV liftetime demonstration tasks are currently underway.

We recommend that efforts in the near term focus on two areas: (1) advancing the TRL of key subsystems and (2) advancing and validating retrieval algorithms. Continued focus should be placed on the laser, interferometer, and detection subsystems, with an emphasis on maturing the supporting electronics and more thorough environmental testing. Algorithm development and assessment should focus on the analysis of data sets from airborne prototype instruments and studies with synthetic data to determine the precision and accuracy with which the required products can be retrieved.

3.4 Ocean Color Sensor

The Decadal Survey Report identifying ACE as a tier-2 mission was released in 2007. However, technology assessment and instrument concept development relevant to ACE, in particular regarding the ACE Ocean Color Sensor, has a much longer history that accounts for it relative maturity. This history has been documented in detail in McClain et al. (2012). The following provides a very brief summary of this history leading up to technology and instrument development during the past 5 years of ACE pre-formation studies.

During 2000-2001, a study was conducted to assess satellite, field, and modeling requirements for a NASA carbon program (McClain et al., 2002, Gervin et al., 2002). One of the resultant recommendations was for an advanced ocean biology satellite sensor that expanded upon heritage sensor measurements by including UV bands for more accurate retrieval of colored dissolved organic matter (CDOM). This recommendation was merged with parallel work being conducted on an ocean lidar system for measuring phytoplankton biomass, yielding a new mission concept call the Physiology Lidar Multispectral Mission (PhyLM). The PhyLM mission was focused on improving the characterization of ocean carbon stocks and flows through both a refined separation of optically active in-water constituents and improved atmospheric corrections. At this point, the advanced ocean color sensor was envisioned as having only 3 UV bands, 11 visible bands, and two NIR and two SWIR bands. Importantly, the concept garnered enough interest to be granted funding in 2003 from NASA Goddard to conduct two Instrument Design Laboratory (IDL) studies, largely focused on the ocean radiometer. Thus, technology and instrument development work, ultimately in support of ACE, began more than a decade ago.

Following the IDL studies, an external science team was assembled for PhyLM to define the science objectives and develop an initial Science Traceability Matrix (STM). The ACE Ocean Ecosystem STM (see Section 2 above) bears many similarities to this early draft. Continued developments to the PhyLM concept yielded, by 2005, an expanded mission including a polarimeter and lidar for characterizing aerosols and improving atmospheric corrections and an ocean radiometer with 5 nm resolution retrievals from the near UV into the NIR. At this point, the concept was called the Ocean Carbon, Ecosystem, and Near-Shore (OCEaNS) mission and submitted as a white paper for consideration during the NRC Decadal Survey study.

In 2006, NASA HQ requested formulation studies for several mission concepts in preparation for the Decadal Survey results, one of which was called the Global Ocean Carbon, Ecosystems, and Coastal Processes (GOCECP) mission. This formulation study provided funding for a third IDL assessment, yielding further design changes and refinements for an advanced ocean radiometer. The Decadal Survey results were released in late 2007 and included the interdisciplinary Aerosol, Cloud, and Ecosystems (ACE) mission, equivalent to the OCEaNS mission concept submitted in 2006, but with the addition of a cloud radar.

In June 2008, the ACE science team was formed and began the development of mission STMs for each of the science disciplines (see Section 2 above). Deliberations by the ACE science team resulted in seven additional required specific bands on ocean radiometer (plus 5 nm hyperspectral UV to NIR resolution), bringing the minimum number of 'aggregate' bands to 26 and including three bands in the SWIR. In the spring of 2009, as part of an ACE Mission Design Laboratory study of the baseline ACE mission, a fourth IDL study was conducted.

In 2010, President Obama released the NASA Plan for Earth Observations (NPEO 2010), announcing the PACE mission with an ocean radiometer as the primary instrument and dedicated to making advanced ocean measurements in preparation for the ACE mission. Soon thereafter, the PACE Science Definition Team (SDT) was formed and, as part of the SDT activities, a fifth IDL study was conducted, largely focused on assessing costs for an advanced radiometer.

Ocean Color Validation Sensors

Optical Sensors for Planetary Radiance Energy (OSPREy): ACE ocean color science objectives include geophysical property retrievals in the coastal ocean and contemporaneous observations of the ocean and atmosphere. The OSPREy project has been focused on developing and deploying a new suite of radiometers to support the increasing demands of NASA's ocean color research (Fig. 3.10), with an emphasis on the data quality challenges associated with vicarious calibration and algorithm validation. OSPREy instruments are thermally regulated, ruggedized, and designed to operate autonomously (Hooker et al. 2012). An OSPREy system makes observations of the sea surface plus celestial targets (Sun, sky, and Moon) across the UV–SWIR domain (305–1,670 nm) to derive an unprecedented number of near-simultaneous atmospheric and oceanic parameters. OSPREy can also be used for land, snow, and ice targets, but has not been deployed for those observations. The radiance and irradiance sensors have highly accurate microradiometers (19 and 18, respectively), which can be used to continuously calibrate the temperature-stabilized spectrograph. This type of measurement approach is referred to as hybridspectral, because it uses two types of detector technologies to improve the quality of the collected data. The spectrographs provide high resolution UV-NIR data, and the microradiometers extend the spectral domain to the SWIR. ACE pre-formulation funding for OSPREy development allowed for the addition of a 9-position filter wheel for three-axis polarimetry and improved dark correction for the spectrograph, plus novel performance characterization measurements using diverse celestial targets. The latter included the following during 2012: the Perigee (or Super) Moon on 6 May; the solar eclipse on 20 May; the Venus transit on 5 June; and the Blue (full) Moon on 31 August. Celestial observations provide autonomous above-water systems unique monitoring sources (as is done with the spaceborne sensor) with respect to in-water methods. **TRL = 9.**

Figure 3.10: An OSPREy radiance &irradiance dyad deployed at a lake in 2013.

Compact-Optical Profiling System (C-OPS)**.** To ensure a state-of-the-art in-water validation data set for OSPREy data products of the sea surface, the Compact-Optical Profiling System (C-OPS) instrument (Morrow et al. 2010) was fitted with two digital thrusters as part of the Compact-Propulsion Option for Profiling Systems (C-PrOPS) accessory (Hooker 2014), which also added a conductivity probe. The programmable thrusters allow the C-OPS, which is built with the same microradiometers as OPSREy, to be maneuvered horizontally before a near-simultaneous profile of the water mass is made in close proximity to the OSPREy instrument system. The C-PrOPS prototype (FIG. 3.11) was field commissioned with ACE support and significantly improved the data quality for in-water validation exercises by reducing the amount of time needed to acquire the optical data, because no vessel maneuvering is needed to position the profiler and the thrusters can be used to bring the profiler rapidly to the surface in between optical casts. In addition, the small thrusters orient the profiler vertically and produce negligible turbulence that is directed below the upward pointing irradiance sensor, so water column optical properties (now spanning 312–875 nm) are only minimally influenced by the motion of the profiler. **TRL = 9.**

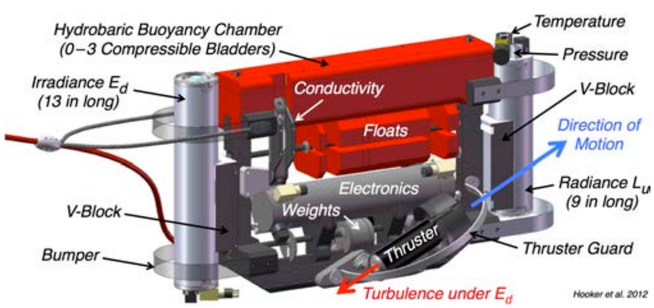


Figure 3.11: C-PrOPS thrusters (one on back) with conductivity probe mounted on a C-OPS instrument. The ydrobaric buoyancy permits descent rates as small as 5 cm/s with stable, ±5°, vertical tilts.

4 Measurement Algorithms

This section presents an overview of the Level 2 (L2) algorithms being developed for the ACE instruments. Level 0 (L0) and Level 1 (L1) algorithms are generally instrument specific and represent the steps needed to transform voltages captured by an instrument to geo-located, calibrated set of geophysically meaningful parameters. They are therefore described in Section 3 under Technology Assessment and Instrument Concept Development separately for each instrument.

While there is an expectation that L1 or L2 ACE measurements will be assimilated into comprehensive earth system models capable of representing cloud and aerosol microphysics, the details of such models and L4 algorithms are not described here.

4.1 Aerosol

The ACE requirements on retrieving the size distribution, complex refractive index and non-sphericity of aerosols mean that a retrieval approach is required that makes full use of the information content of the measurements.

The basis of L2 aerosol retrieval algorithms for both passive polarimetric observations and multi-spectral high spectral resolution lidar is necessarily the inversion of the observations to retrieve a microphysical model (size and complex refractive index) and amount (number concentration, surface area concentration, volume concentration) of aerosol that is consistent with the observations, with some form of regularization to suppress unphysical, or unlikely solutions. The regularization generally has the effect of forcing the retrieved aerosol properties (e.g. size distribution, spectral refractive index) to be smooth (Dubovik *et al.* 2011) or impose constraints on retrieved values (Hasekamp *et al.* 2011). The passive polarimetric observations depend non-linearly on the required aerosol properties and the inversion is therefore iterative in nature and the application of these schemes to the type of global data that is expected from a future ACE mission will be challenging, but currently both standard parallelization techniques (Wu *et al*., 2015) and implementations using Graphics Processing Units (GPUs) and analytical simplifications of radiative transfer (Chaikovskaya *et al.*, 2014) are being applied successfully to processing of global polarimetric data from POLDER.

While different groups will adapt specific implementations of optimal estimation techniques to the measurement set provided by their sensor, there are two aspects of aerosol remote sensing from passive polarimetric observations that are general to any approach. The first is an adequate model of the underlying surface and the second is a fast and accurate radiative transfer model for the atmosphere that ideally provides analytic determination of functional derivatives of the radiation field with respect to the aerosol parameters being retrieved, commonly known as Jacobians.

Surface Characterization

Surface models can be divided between water and land surfaces, with the primary water surface of interest being the ocean. For remote sensing of aerosol over the ocean the specular reflection of light from the surface is well represented by the model of Cox and Munk (1954). We note that while this model always provides a reasonable representation of the sunlight scattered off the ocean surface, if it is estimated from multi-angle observations as part of an aerosol retrieval, the wind speed and direction retrieved will not necessarily correspond to the actual wind speed and direction (Su *et al.* 2002, Chowdhary *et al.* 2005). In addition to surface scattering there is also a contribution from light scattered under water that is not negligible in the visible part of the spectrum. The brightness and spectrum of this light depends on the biomass content of the ocean, such that variations in the color of the ocean can be observed even from space. Rayleigh scattering by pure sea water, and Rayleigh-Gans type scattering by plankton, causes this light to be polarized with a distinctive angular distribution. Chowdhary *et al.* (2012) review a hydrosol model and discuss its sensitivity to variations in colored dissolved organic matter (CDOM) and the scattering function of marine particulates. They show that the impact of variations in CDOM on the polarized reflectance is comparable to or less than the standard error of this reflectance whereas their effects on total reflectance may be substantial (i.e. up to > 30%). This emphasizes the value of multiple polarization measurements through the visible part of the spectrum when performing aerosol remote sensing over the ocean. The model for ocean body scattering developed by the RSP group has recently been incorporated into the Generalized Retrieval of Aerosol and Surface Properties (GRASP) algorithm (Dubovik et al. 2011) in collaboration with the University of Lille. The GRASP algorithm is being used by all the ACE polarimeter groups and the RSP group's collaboration with Dr. Dubovik now allows that algorithm to be applied over ocean to all the ACE polarimeter observations.

Generally land surface models are somewhat ad hoc with the parameters that control the total bidirectional reflectance factor of the surface being unrelated to those controlling the polarized reflectance of the surface (Cairns et al. 2009a). The RSP group has worked with the groups at SRON and the University of Lille to develop a more advanced physically based surface model where the total and polarized reflectance are controlled by the same parameters, which describe the underlying physical scattering processes, that generate the reflection of light at a surface (Litvinov et al. 2012). The observations obtained prior to PODEX during a test flight of the RSP on the NASA ER-2 and some earlier data from the Carbonaceous Aerosols and Radiative Effects Study (CARES) (Zaveri *et al.* 2012) have been used to establish the polarization properties of snow (Ottaviani *et al.* 2012, 2015). The small magnitude of the polarized reflectance of snow and its weak spectral variation over 400 to 2300 nm hold the promise of robust aerosols retrievals over snow from sensors that have a sufficient spectral range of polarized observations.

RSP Aerosol Algorithms

The RSP group is now using the GRASP algorithm to compare against optimal estimation methods developed in house (Waquet *et al.* 2009, Knobelspiesse *et al.* 2011a). While the GRASP algorithm is extremely flexible and is being optimized for global aerosol retrievals from imaging sensors (Dubovik 2014), the use of a successive order of scattering forward radiative transfer model precludes its use in comprehensive aerosol retrievals above clouds (Knobelspiesse *et al.* 2011b, 2014). Aerosol retrievals above clouds are now being performed on global observations (Waquet *et al.* 2013). However, in order to get the maximum information about aerosols above clouds it is desirable to have a linearized vector radiative transfer model that is applicable to optically thick objects such as clouds. Straightforward modifications to standard vector adding/doubling models allow for the calculation of the Jacobians required for the retrieval of aerosol and cloud properties (Cairns *et al.* 2009b). Work planned for the coming year follows up on analyses previously presented at conferences on the retrieval of aerosols in the presence of broken clouds and aerosol retrievals under thin cirrus clouds. In addition the ocean body scattering model is being updated in line with current trends in ocean color remote sensing (Maritorena et al. 2002,2010) and the aerosol retrieval schemes are being speeded up through an improved first guess using a tabular forward radiative transfer model and parallelization of the iterative part of the retrieval algorithm.

MSPI Aerosol Algorithms

Two optimization-based, coupled aerosol and surface retrieval algorithms are being tested for application to AirMSPI observations. The first, developed at JPL, is based on a vector Markov Chain/Adding-Doubling (MCAD) approach. The code incorporates spectral invariance constraints on the angular shape of surface bidirectional reflectance factor (Diner *et al*., 2005, 2012) and polarized surface reflectance (Waquet *et al*., 2009). GroundMSPI surface data have been used to demonstrate the validity of these empirical constraints. Examples are shown in Fig. 4.1-4.3. This algorithm was initially coupled into a Levenberg-Marquardt optimization (*Xu et al*., 2012) for ocean retrieval, and has now has been extended to a generalized algorithm for aerosol retrieval over land by imposing extra constraints on the variations of aerosol properties across neighboring pixels, following Dubovik *et al.* (2011). The other algorithm uses the GRASP code developed at the University of Lille (Dubovik *et al*., 2011). GRASP is based on a Successive Orders of Scattering radiative transfer model. Utilization of both algorithms gives a measure of retrievability and modeling errors when the surface and aerosols are parameterized in different ways. The nonspherical aerosol component is modeled in GRASP as a mixture of randomly oriented spheroids with a fixed shape distribution (Dubovik *et al*., 2006), while MCAD implementation of nonsphericity is currently under development.

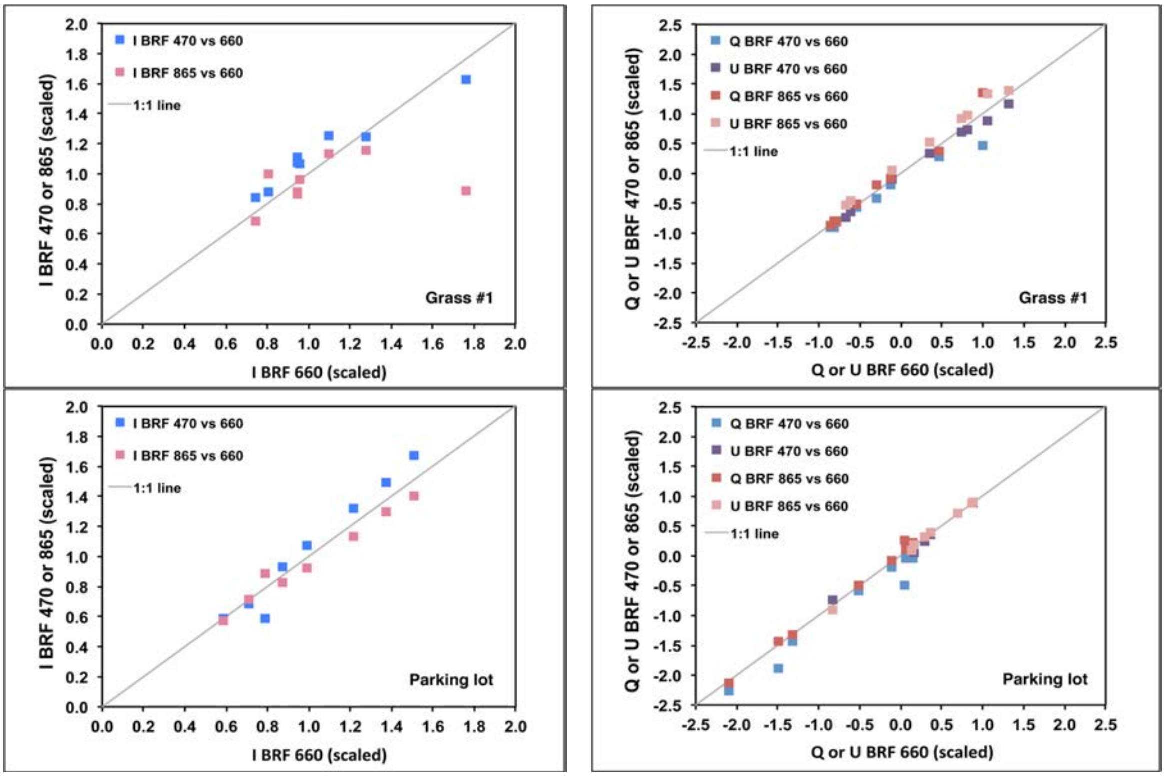


Figure 4.1: Left: GroundMSPI data collected over surface targets as the scattering angle changed due to motion of the Sun across the sky. Scaled bidirectional reflectance factors (BRF) at 470 and 865 relate linearly to the BRF at 865 nm, showing spectral invariance in the angular BRF shape. Right: Relationship between polarized BRF calculated using Q and U at 470 and 865 nm to 660 nm, showing spectral invariance in both the magnitude and angular shape.

Both algorithms have been applied to AirMSPI data acquired during PODEX and SEAC^{4}RS. Initial results show that spectral optical depths and aerosol microphysical properties compare favorably to independent aerosol data derived from AERONET. To address the sensitivity of the coupled aerosol-surface retrieval to initial guesses (a common issue with optimization algorithms), MCAD is currently being used to quantify this source of retrieval uncertainty. In addition, distinguishability of optical depth, refractive index, and size distribution is being investigated to establish uniqueness of the retrieval results; in particular, the sensitivity to aerosol absorption. For image-based remote sensing technologies, data processing efficiency without losing modeling accuracy is another major concern for ACE. Several speed enhancements to the JPL MCAD algorithm are being investigated, including tradeoff of speed and accuracy in the forward radiative transfer module, combination of the optimization algorithm with lookup tables, and use of a Graphical Processing Unit (GPU). These are currently examined in FY15.

Currently, the MCAD algorithm operates over both land and water while the version of GRASP utilized to date operated only over land. Example aerosol retrievals using MCAD are shown in Figs. G and H. Using the MCAD algorithm, comparison of multi-angle aerosol retrievals over ocean using MISR and AirMSPI demonstrated benefits of polarization in distinguishing aerosol particle types (Diner *et al*., 2013a). In addition, inclusion of the sunglint pattern as part of the optimization resulted in reasonable retrievals of surface wind speed and direction. This capability has previously been studied using POLDER data by Bréon and Henriot (2006). Collaboration with the University of Lille has yielded an update to GRASP that also operates over water, and this will be tested on AirMSPI data.

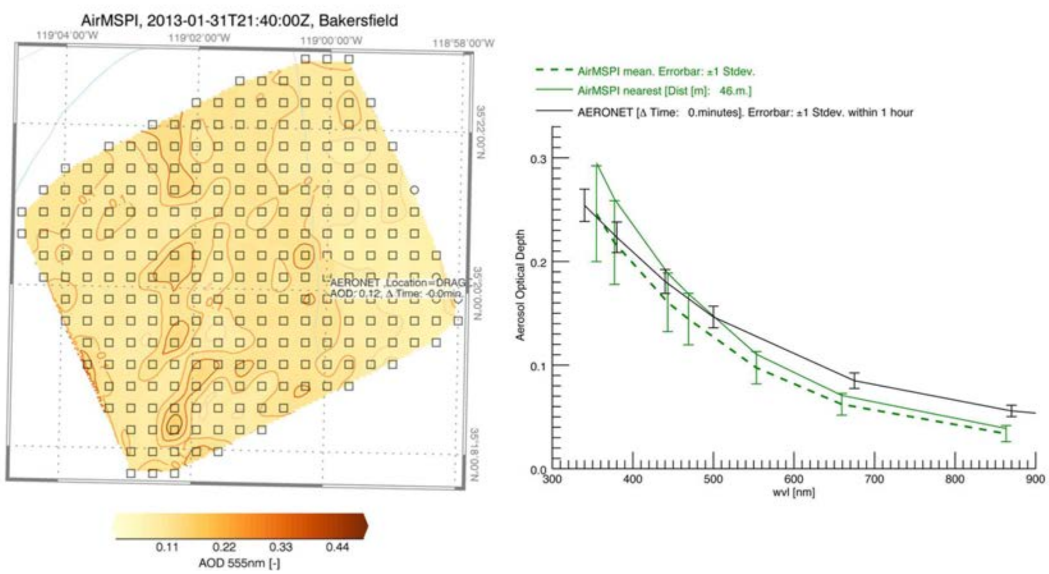


Figure 4.2: Example aerosol AOD retrieval using the land MCAD algorithm applied to AirMSPI data over Bakerfield, CA, 31 January 2013 during PODEX.

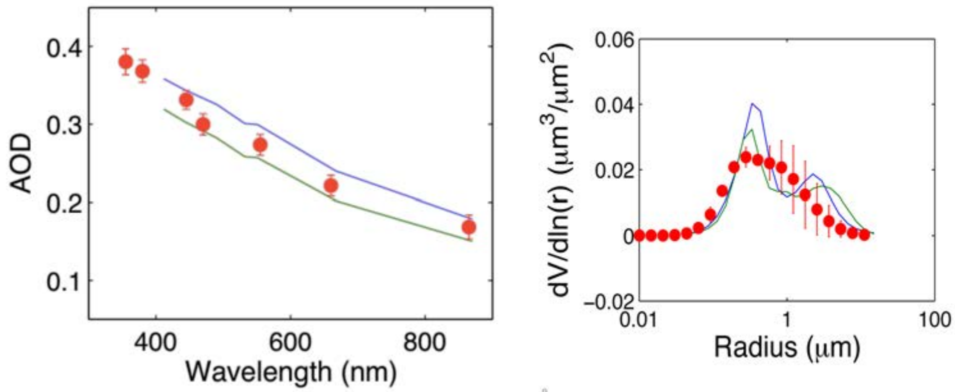


Figure 4.3: Example aerosol AOD and particle size distribution retrieval using the ocean MCAD algorithm applied to AirMSPI data over the USC SeaPRISM AERONET site off the coast of southern CA, 6 February 2013 during PODEX.

PACS Aerosol Algorithms

The PACS group is also working with Dr. Oleg Dubovik on a version of the GRASP algorithm that is optimized for PACS retrievals using its unique angular sampling and wavelength combination. In this case GRASP will be incorporated into UMBC's own algorithm suite (SCIPP), a software stack that integrates Level 1 and Level 2 data production for clouds and aerosols. On the cloud side, we are implementing the CloudPro algorithm that optimizes the usage of the PACS hyperangular measurements for retrieving ice and water microphysical and thermodynamic properties. PACS unique hyperangular imaging capability allows for the first time retrieval of these properties at the pixel resolution level.

In addition to GRASP the PACS group is also investigating the sensitivity of the multi-angle polarization retrievals from the UV to the SWIR wavelengths over ocean by taking advantage of the off-glint dark ocean and the bright sunglint reflectance. These measurements bring additional information content necessary for the retrieval of aerosol scattering and absorption properties over oceanic surfaces. This study is heavily based on our previous work reported in Kaufman *et al.* (2002), Zubko *et al*. (2007) and incorporates new developments based on aerosol and ocean surface property research by Dr. Pengwang Zhai (Zhai et al., 2010a; Zhai et al., 2010b; Zhai et al., 2013). Dr. Zhai has recently joined the PACS team at UMBC and he will be actively engaged in this activity. The remote sensing of aerosols and ocean color needs an accurate radiative transfer model for a coupled system of atmosphere and ocean. The PACS SCIPP package will also incorporate Dr. Zhai's radiative transfer model based on the Successive Order of Scattering (SOS) method

(Zhai, et al., 2009, 2010a). The SOS model can predict the radiance as well as polarization of the light scattered by an atmosphere and ocean system. Sensitivity study shows that the SOS model is very accurate (error smaller than 0.1%) and efficient. It is also physically based, which is particularly important for satellite data interpretation. Dr. Zhai has developed an aerosol retrieval algorithm which performs the least square fitting of the multi-angle, multi-polarization, and multi-wavelength measurements at a specific scene. Using the retrieval algorithm Dr. Zhai has studied the uncertainty and interpretation of the aerosol retrieval for multi-layer aerosol systems in a comprehensive way (Zhai et al., 2013). The main conclusion from that study is that the total optical depth retrieved in a multi-layered aerosol system can still be interpreted as the column averaged optical depth. However, other parameters, for instance, refractive index, size distribution, have to be treated as a weighted average of the different layers.

HSRL Aerosol Algorithms

Operational code for lidar retrievals of ACE aerosol products has been developed and used to produce ACE-like Level-2 data products from the four field missions flown with the LaRC $3\beta + 2\alpha + 2\delta$ ACE prototype HSRL lidar. These products fall into two categories: (a) basic optical products retrieved from the lidar signals (aerosol backscatter, extinction, depolarization) and (b) advanced products produced from those basic optical products via inversion techniques (effective radius, index of refraction, single scatter albedo, absorption, and concentration). Figure 4-4 shows a comparison of aerosol optical thickness from the basic HSRL-2 measurements (at both 355 and 532 nm) with coincident AEROCOM measurements acquired during the NASA DISCOVER-AQ mission over

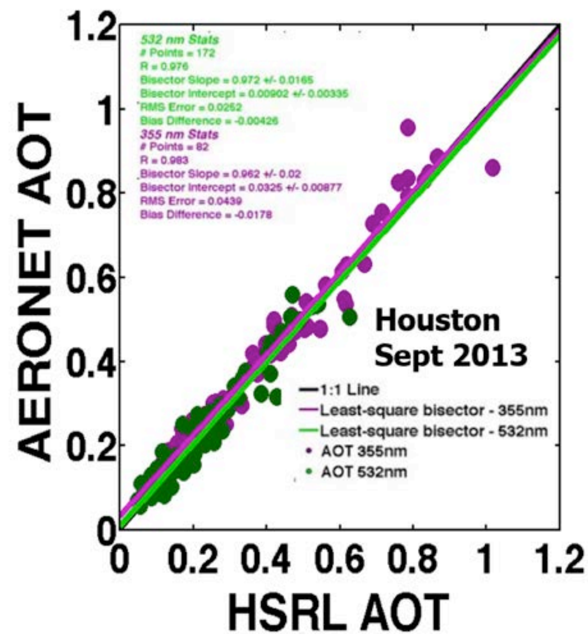


Figure 4-4: Comparison of AOT (355 and 532 nm) from HSRL-2 and DRAGON-AERONET measurements over Houston during the NASA DISCOVER-AQ mission.

Houston. The accuracy of these retrieved aerosol products is being assessed using data acquired on those field missions from other sensors flying on participating aircraft and retrievals from ground-based AERONET instruments placed along the flight tracks (Sawamura *et al*. 2014, Müller *et al*. 2014). Figure 4-5 shows a comparison of aerosol concentration and effective radius profiles derived from the HSRL-2 3 β + 2 α measurements with coincident airborne in situ measurements acquired from the DOE G-1 aircraft during the DOE Two Column Aerosol Project (TCAP). More extensive comparisons with both airborne in situ data and AERONET retrievals collected during the NASA DISCOVER-AQ series of deployments are underway (see Figure 4-6). Studies are underway on combining the lidar and polarimeter products to increase information content and accuracy of the inversion products. With continued funding, some conclusions on the accuracy and information content of both the lidar-only and combined lidar-polarimeter retrievals should be available in FY16. Demonstrating combined lidar-polarimeter retrievals will likely extend into FY17. Coincident lidar and polarimeter datasets exist from several missions flown with the LaRC HSRL instruments and RSP. More data sets may be acquired via future ACE flight demonstrations and possibly the Earth Venture Suborbital program.

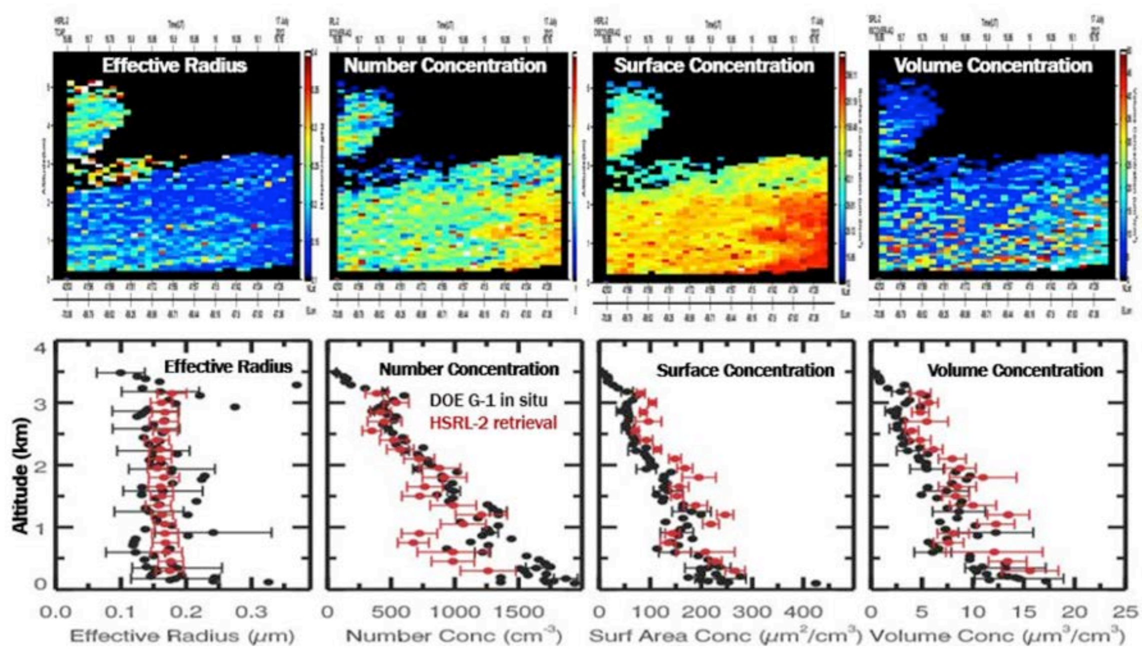


Figure 4-5. (top) Curtains showing HSRL-2 retrievals of microphysical parameters and (bottom) comparisons of microphysical parameters retrieved from the HSRL-2 3b+2a inversion method (red) and from the G-1 in situ measurements (black) on 17 July 2012 (from Müller et al. (2014)).

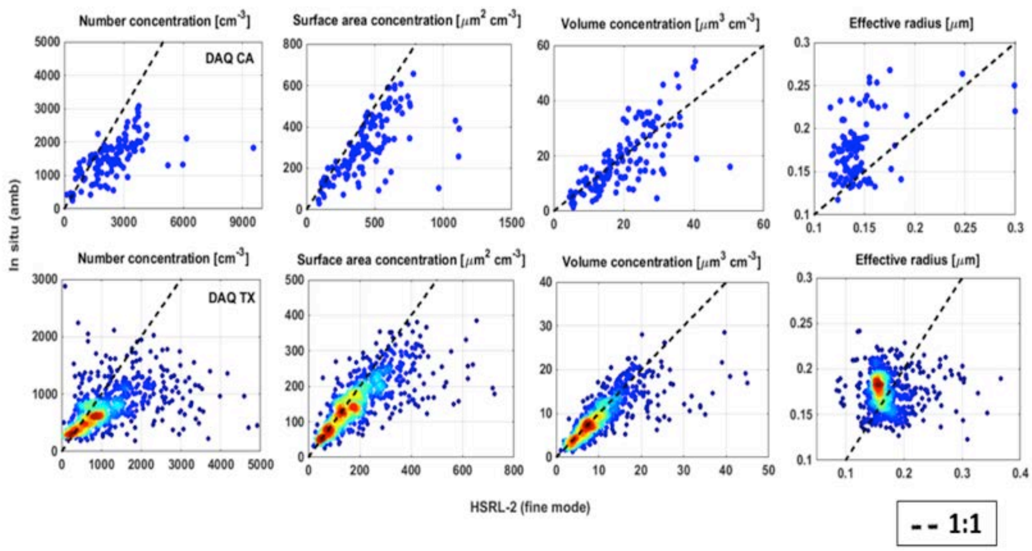


Figure 4-6. Comparison of aerosol microphysical parameters derived from HSRL-2 3b+2a inversion method and coincident airborne in situ measurements acquired during the NASA DISCOVER-AQ missions over the Calfornia central valley (top) and Houston (bottom).

4.2 Clouds

In this subsection we describe the general approach for assessing the impact of the ACE observing system on the retrieval of cloud and precipitation geophysical parameters, and the simplifications necessary for operational implementation of an algorithm suite. This is followed by the description of emerging L2 algorithms being developed for ground based and airborne sensors that will inform the operational ACE clouds processing.

General Approach

In the development of L2 algorithms for ACE Clouds, we have two very specific research objectives that address short and long terms goals. Our most immediate need is to develop tools that allow us to rigorously define the trade space between science objectives and instrument suite complexity, and our more long term goals are to develop L2 algorithms that would be suitable for operational implementation prior to launch of ACE assets.

In our earlier work summarized in the 2010 ACE Report, tools to rigorously define the trade space were not available. While we used a rigorous method to estimate requirements on geophysical parameters, it was impossible to characterize quantitatively how the requirements on geophysical parameters mapped to instrument requirements. This is especially challenging because the L2 algorithms for ACE clouds will rely on synergistic combinations of active and passive measurements that have evolved from the A-Train era (*i.e.,* Mace et al., 2016). While we could theorize what measurements would constrain what aspects of the geophysical quantities of interest appearing in the Science Traceability Matrices of that earlier report (Section 2), we could not say rigorously what the instrument requirements would be when combined in synergistic algorithms. Advanced statistical tools for L2 algorithm development are now becoming available that will allow us to address this issue rigorously as ACE moves forward (Posselt et al., 2016; Posselt and Mace, 2014).

We take the approach that a set of measurements *(y)* have some level of uncertainty and represent an atmospheric state (*x*) and there exists a set of forward models relating x to y that have assumptions with quantifiable uncertainties. We can then utilize methodologies based in Bayesian statistics:

$$p(x|y) = \frac{p(x)\,p(y|x)}{p(y)}$$

Then, the atmospheric state that we seek to characterize is represented as a posterior probability distribution, *p(x|y),* that results from mapping the measurements through a set of forward models that replicate the uncertain measurements as a function of the uncertain atmospheric state. In the short term, we seek to know the optimal set of measurements that produce an atmospheric state probability that satisfies our requirements on geophysical quantities while in the long term, we seek algorithms that efficiently provide *p(x|y)* with reasonable characterizations of uncertainty.

A hierarchy of techniques exist to accomplish both our near and longer term goals. To accomplish our near term goals, we make computational efficiency a secondary objective and seek an approach that is least constrained by assumptions in mapping the relationships between measurements and the posterior probability distribution of the atmospheric state. What is needed is a way to *generate rigorously the posterior p.d.f.* Markov Chain Monte Carlo (MCMC, Tamminen 2004; Tarantola 2005; Posselt et al., 2008; Posselt and Vukicevic 2010) methods provide such a tool.

MCMC algorithms consist of a guided random walk through the probability space. See Posselt and Mace (2014) for an example of MCMC applied to a mixed phase snow cloud using ground-based combinations of radar, microwave radiometer, and surface solar flux and Posselt et al. (2016) for application of this approach to shallow warm cumulus. We envision that such an approach, when combined with actual measurements and model-base observation system simulation experiments (OSSE), will rigorously define the trade space between instrument requirements and geophysical parameter requirements.

Our longer-term goals of developing operational L2 algorithms will utilize more computationally efficient approaches to solving Bayes theorem but at the cost of reduced accuracy in producing the posterior solution probability. Optimal estimation (OE) has emerged as a preferred approach in this regard. To make OE more computationally efficient than MCMC, the PDF's are assumed to be adequately described by Gaussians and the relationships between forward models and measurements are assumed to be described by the first derivative of the measurement with respect to the atmospheric state – i.e. linearity in the relationship is assumed so that a first order Taylor expansion is sufficient to characterize these relationships. OE algorithms that are now under development (Mace *et al*. 2016, among others) will form the basis of the L2 algorithm suite that will ultimately be implemented on ACE flight data. We will use the more rigorous MCMC results, field data, and OSSE studies to develop and validate the OE results.

RSP Algorithms

The property of a cloud that is required first, for a multi-angle sensor, is the cloud top height so that views from all angles can be collocated to cloud top. RSP observations have been used to estimate cloud top height using hyper-stereo intensity observations and cloud top pressure using short wavelength (410 and 470 nm) polarized reflectances and have been verified against lidar derived cloud top heights (Van Diedenhoven *et. al*. 2013). These height estimates are used to remap the multi-view RSP data such that they are coincident at the cloud top altitude and provide contiguous angular sampling over a view angle range of ±60° from nadir for **each** spatial sample of a cloud.

For a sensor in low Earth orbit this view angle range would frequently include a scattering angle range from 135° to 165°, which exhibits a sharply defined cloud bow structure for water clouds. The retrieval of droplet size distributions from cloud bow observations was originally implemented by Bréon and Goloub (1998) using a parametric fit in which the size distribution is represented by the effective radius and variance of a gamma size distribution. The accuracy of this type of approach, its range of applicability and robustness against 3-D effects was evaluated more recently (Alexandrov *et al.* 2012a) using Monte-Carlo simulations of radiative transfer through a modeled (Ackerman *et al.* 2004) cloud field. While parametric fitting provides a simple method for estimating cloud droplet size distributions, it was found that contiguous high (~ 1°) angular resolution observations of the cloud bow can used in a rainbow Fourier transform (RFT) that provides an accurate non-parametric estimate of the shape of the droplet size distribution (Alexandrov *et al.* 2012b). The RFT is valuable in the analysis of cases such as fogs, or multi-layer water clouds where the assumption that the cloud bow is generated by a single gamma distributed droplet size distribution is incorrect. It should be noted that variations in droplet size distribution may be substantial, even within a quite homogeneous cloud deck, but can be retrieved for each pixel from RSP observation.

MSPI Algorithms

Cloud retrievals for MSPI, as with MISR, use imagery map-projected to the WGS84 surface ellipsoid. Algorithms fall into two principal categories: (a) stereophotogrammetric and radiometric retrievals of cloud-top heights and cloud fractions as a function of altitude, making use of feature and area-based pattern image matching and thresholding (both leveraging heritage from MISR), and (b) particle scattering and radiative transfer-based retrievals of cloud microphysical properties, which combine the novel information content of polarimetric data with more conventional approaches based on spectral radiances.

Figure 4.4 shows a retrieval of cloud-top heights using multi-angle stereo pattern matching applied to AirMSPI data from 31 August 2011, using algorithms similar to those employed operationally with MISR. The stereo retrieval makes use of 555 nm images acquired at view angles of nadir and 26.5º forward and backward of nadir. Unlike MISR, however, at aircraft altitudes Earth curvature is insufficient to enable separating stereo parallax from the effects of advection due to wind, hence the heights shown in Fig. 4.4 are not corrected for wind. Application of the MISR stereo algorithms to ACE multiangle imagery will enable simultaneous retrieval of cloud-top heights and cloud motion vector winds.

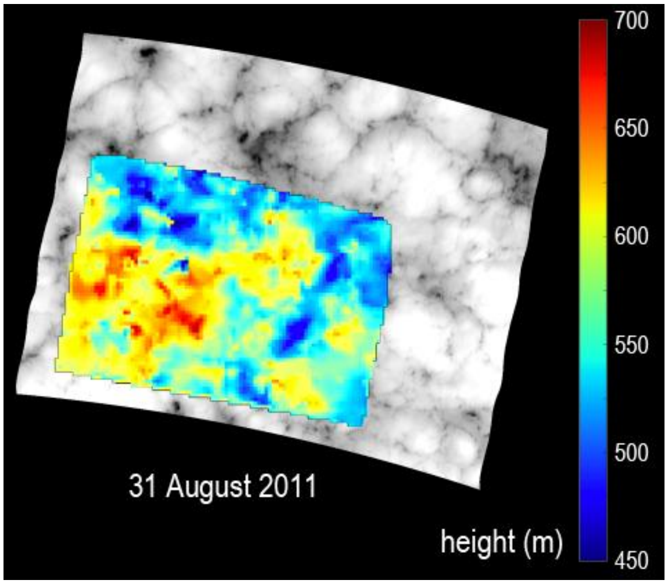


Figure 4.4: Stereoscopic retrieval of cloud-top heights using AirMSPI imagery at 3 view angles. Computational pattern matching is used to identify similar features in the different images and retrieve the cloud-top height field using the spatial disparities, or parallax, between the features in the imagery.

Building upon methodologies described by Bréon and Goloub (1998) and Alexandrov et al. (2012a,b), AirMSPI data have been used to retrieve cloud-top liquid water droplet size distributions for near-homogeneous marine stratocumulus clouds using measurements of the polarization of supernumerary cloud bows (Diner et al., 2013a). Because the polarization signals are dominated by single scattering, they are less susceptible to 3D radiative transfer effects, which are a known source of bias for radiance-based droplet size retrievals (e.g., Liang and Di Girolamo, 2013), hence have the potential for retrieving spatial variability in cloud-top droplet size in broken cloud scenes. Figure 4.5 shows an example of cloud bow and glory imagery from AirMSPI, acquired on 31 August 2011. At left are intensity and DOLP images acquired by sweeping the instrument's gimbal along-track to image an area approximately 110 km in length x 10 km at nadir. At right are fits to the supernumerary bows in the lower portion of the image (south of the glory) using the single-scattering method of Bréon and Goloub (1998) over the scattering angle range 140º-165º. The parametric gamma distribution was employed, and the best-fitting solution yields an effective droplet radius of 9.13 μm and effective variance of 0.006. The region above 165º is used here as a consistency check. The model correctly predicts the location of the interference fringes associated with the higher-order supernumerary bows and glory, though some deviation in magnitude, particularly at the shorter wavelengths, is observed. This may be due to a departure of the droplet sizes from a purely gamma distribution, spatial variability in the droplet sizes, and/or multiple scattering. Multiple AirMSPI images are being used to examine each of these factors in greater detail.

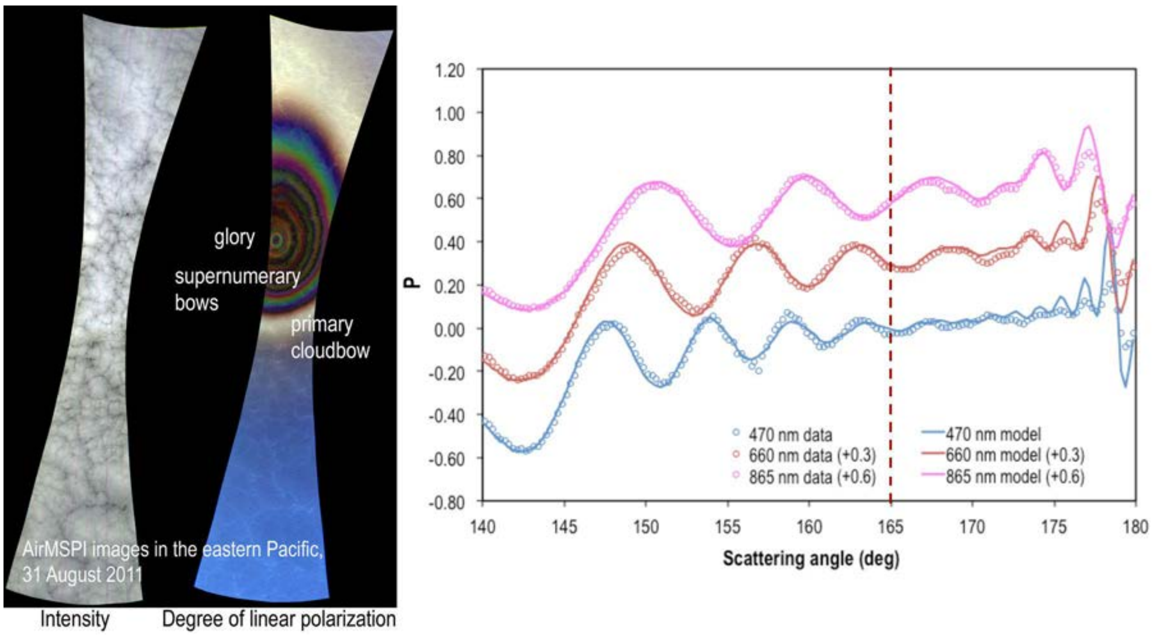


Figure 4.5: Example of cloudbow and glory imagery from AirMSPI. At left are intensity and DOLP images. At right are fits to the supernumerary bows at 3 wavelengths in the lower portion of the image (south of the glory) using the method of Bréon and Goloub (1998). The dashed line indicates scattering angle of 165º.

Armed with knowledge of the droplet size distribution from polarized light, AirMSPI team members are also investigating the use of 1D radiative transfer theory to estimate cloud optical thickness from natural light in the presence of 3D adjacency effects. Specifically, application of a statistical-physics analysis technique (Davis et al., 1997) to AirMSPI cloud imagery enables an objective determination of the radiative smoothing scale, beyond which 3D adjacency effects become negligible. Invoking 1D radiative transfer theory at this and larger scales minimizes 3D adjacency effects. In the near future, the AirMSPI team plans to (1) extend polarimetry-based microphysical retrievals to heterogeneous clouds, and (2) refine new radiance-based retrievals that exploit 3D radiative transfer effects on multiple scales and yield macrophysical cloud properties, namely, optical depth and geometrical thickness (hence a vertically-averaged cloud droplet number density). Although the later type of retrieval depends critically on the fine-scale imaging achievable with AirMSPI from the ER-2 (10–20 m pixels), an anticipated spin-off will be cloud property retrieval algorithms adapted to ACE-type pixel scales (hundreds of meters) that will be robust in 3D cloud structures. Ultimately, the systematic exploitation of passive multi-spectral/multi-angle/multi-pixel data using accelerated 3D radiative transfer forward models will benefit greatly from observational constraints using data from collocated active sensors (namely, ACE's radar and lidar).

For ice clouds a new remote sensing technique to infer the average asymmetry parameter of ice crystals near cloud top from multi-directional polarization measurements has been developed. The method is based on previous findings that (a) complex aggregates of hexagonal crystals generally have scattering phase matrices resembling those of their components and (b) scattering phase matrices systematically vary with aspect ratios of crystals and their degree of microscale surface roughness (Van Diedenhoven *et al.* 2012). Ice cloud asymmetry parameters are inferred from multi-directional polarized reflectance measurements by searching for the closest fit in a look-up table of simulated polarized reflectances computed for cloud layers that contain individual hexagonal columns and plates with varying aspect ratios and roughness values. The asymmetry parameter of the hexagonal particle that leads to the best fit with the measurements is considered the retrieved value. For clouds with optical thickness less than 5, the cloud optical thickness must be retrieved simultaneously with the asymmetry parameter, while for optically thicker clouds the asymmetry parameter retrieval is independent of cloud optical thickness. Evaluation of the technique using simulated measurements based on the optical properties of a number of complex particles and their mixtures shows that the ice crystal asymmetry parameters are generally retrieved to within 5%, or about 0.04 in absolute terms. The retrieval scheme is largely independent of calibration errors, range and sampling density of scattering angles and random noise in the measurements. The approach can be readily applied to measurements of past, current and future airborne and satellite instruments that measure multi-directional polarized reflectances of ice-topped clouds.

Work planned for the current year focuses on developing the method identified by Martin et al. (2014) for efficiently inverting multi-angle, multi-spectral polarimetric observations to estimate a 3D distribution of cloud and aerosol properties. One facet of such retrievals that is of particular interest for determining the types of measurement required of an ACE polarimeter is evaluating the use of polarization observations in absorbing bands. This builds on work by Ferlay *et al.* (2010) and Desmons *et al.* (2013) who used multi-angle radiance only observations in the oxygen A-band to estimate cloud top and cloud middle pressures, but the inclusion of polarization observations reduces uncertainties in the estimated physical thickness of clouds (Cairns et al. 2010) with a consequent improvement in the estimate of droplet number concentration. Such an approach is applicable to satellite missions such as ACE as demonstrated by Ferlay *et al.* (2010).

PACS Cloud Retrievals

The unique hyperangular imaging capability of the PACS sensor will allow for unprecedented coverage of the cloud bow supernumerary arcs with pixel resolution, producing detailed characterization of the effective radius and effective variance of the cloud droplet sizes, allowing for more detailed characterization of the interaction between aerosols and clouds. The PACS design allows for continuous coverage of the cloud bow features covering a wide imaged area. The same PACS hyperangular feature allows for a close monitoring of the microphysical properties of ice crystals linked to the ice surface roughness (Van Diedenhoven et. al. 2012).

4.3 Ocean

As detailed in Section 2, the ACE ocean ecology science objectives require an expansion in the spectral range and resolution of passive ocean color measurements compared to heritage sensors, the development of algorithms for deriving plankton properties from lidar subsurface scattering returns, an evolution in satellite inversion algorithms, and the retrieval of new ocean ecosystem and carbon cycle properties. ACE pre-formulation studies have been focused on key advances in ocean retrievals needed to prepare for mission launch. In particular, algorithm development studies have targeted (1) inversions for inherent optical properties, (2) evaluation of remotes sensing of phytoplankton functional groups, (3) advancement of colored dissolved organic matter and attenuation coefficients for the full range of open ocean to near shore environments, (4) evaluation of physiological signatures in chlorophyll fluorescence retrievals, (5) assessment of Raman scattering impacts on ocean color inversion algorithms, and (6) development of space lidar retrievals of global plankton carbon stocks. The following subsections briefly describe advances made on these topics in preparation for ACE.

Inversion Algorithms for Inherent Optical Properties

Semi-analytical algorithms (SAAs) provide one mechanism for inverting the color of the water observed by the ACE ocean radiometer into inherent optical properties (IOPs). Few SAAs are currently parameterized appropriately for retrieval from all water masses and all seasons. A community-wide discussion of these limitations was therefore initiated and two workshops conducted to accelerate progress toward consensus on a unified SAA framework. These efforts resulted in the development of generalized IOP (GIOP) model software that could be appropriate for implementation during the ACE mission. The GIOP permits isolation and evaluation of specific modeling assumptions, construction of SAAs, development of regionally tuned SAAs, and execution of ensemble inversion modeling. A preliminary default configuration for GIOP (GIOP-DC) was identified during the workshops, with alternative model parameterizations and features defined for subsequent evaluation. An example global image of phytoplankton absorption based on MODIS Aqua data is show in Fig. 4.6 and details on the GIOP algorithm were published in Werdell et al. (2013a).

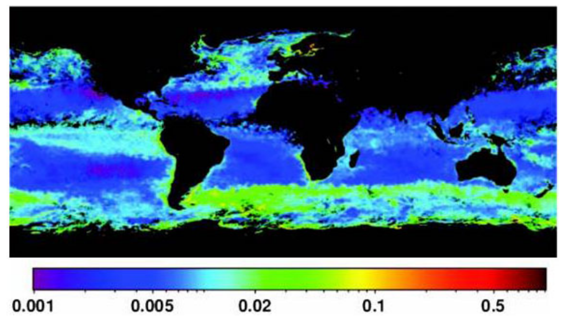


Figure 4.6 Example GIOP global product based on MODIS Aqua data.

Following development of the GIOP algorithm, an additional study was conducted to evaluate the sensitivity of SAAs to the assumed constant spectral values for seawater absorption and backscattering and spectral shape functions for absorption and scattering by phytoplankton, non-algal particles, and colored dissolved organic matter (cDOM). The study revealed that use of temperature- and salinity-dependent seawater spectra significantly elevates SAA-derived particle backscattering coefficients, reduces non-algal particle and cDOM values, and leaves phytoplankton absorption coefficients unchanged. Detailed results from the study were published in Werdell et al. (2013b).

In parallel with the above inversion algorithm developments, work has also been conducted on improving the Garver-Siegel-Maritorena algorithm, which is one of the leading inversion algorithms applied to heritage ocean color data. This work has aimed at improving various components of the model, including phytoplankton absorption, slope of particulate backscattering, absorption by non-algal particles and dissolved matter, the relationship between reflectance and backscattering-to-absorption ratio, reflection and refraction processes at the air-sea interface, and extension of the model into the UV domain measured by ACE. Although still on going, this work has generally improved the spectral accuracy of the model, yielding lower retrieval biases. Issues associated with higher sensitivity to noise in some situations and with in situ data in the UV are still under investigation.

Phytoplankton Functional Groups

Since the launch of the SeaWiFS satellite, it has become increasing apparent that understanding ocean ecosystem dynamics and carbon cycling requires a more refined separation of phytoplankton types in the surface ocean. Accordingly, the ocean ecosystem science objectives for ACE include the retrieval of primary phytoplankton functional groups. Building from earlier proof-of-concept approaches, a study was therefore conducted to investigate the use of inversion models for identifying key phytoplankton groups. The study was focused on distinguishing two particular phytoplankton types known to dominate surface populations in the northern Arabian Sea. The study identified conditions under which the inversion approach was successful in retrieving specific phytoplankton groups and when the current approach is not successful. In addition, the study indicated that the current state-of-the-art approach already shows promise for qualitative group separations, but that quantitative assessments require further algorithm development. Detailed results from the study were published in Werdell *et al.* (2014).

Colored dissolved organic matter and attenuation

In Section 3, a brief summary is provided on progress in instrument development of the C-OPS system. Data from this in situ system has been evaluated in terms of developing improved algorithms for retrievals of in-water spectral diffuse attenuation coefficients (K_d) and cDOM absorption (aCDOM). For example, the left panel in Fig. 4.7 illustrates the use of C-OPS data for evaluating subsurface retrievals of K_d from a lidar. The right panel in Figure 4.7 shows particularly encouraging results from an emerging global algorithm for aCDOM retrievals at 440 nm. This result is particularly noteworthy in its robust capabilities over cDOM values spanning three decades of dynamic range, from clear, deep-ocean conditions to turbid, shallow coastal waters. This approach is being revised for compatibility with ACE and other satellite measurement bands. Detailed results were published in Hooker *et al.* (2013).

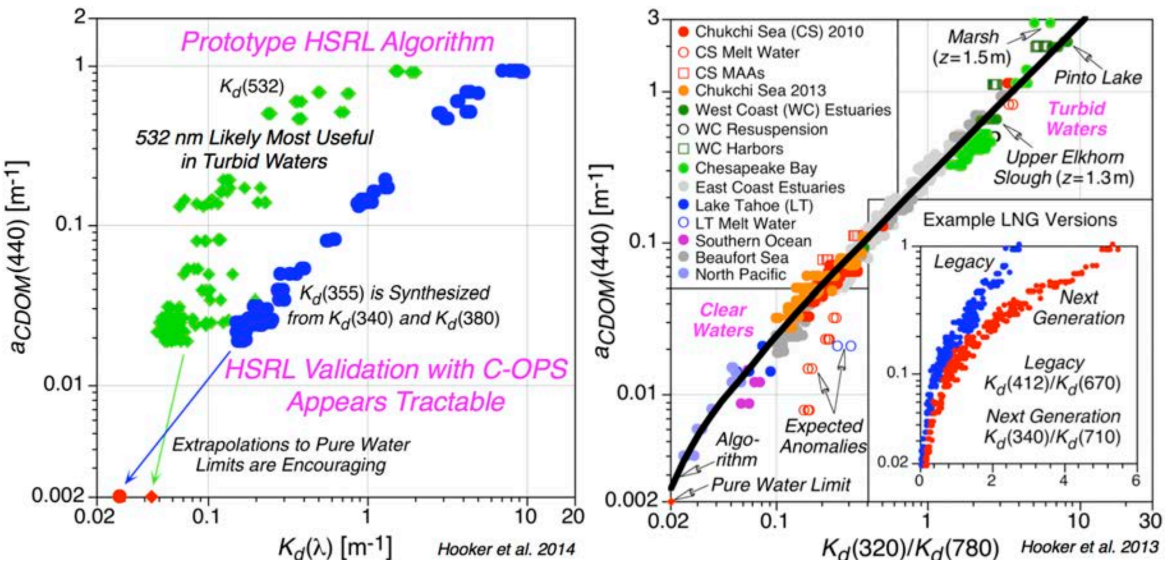


Figure 4.7 A prototype HSRL algorithm and refined aCDOM (440) algorithm based on C-OPS Kd data.

Chlorophyll Fluorescence

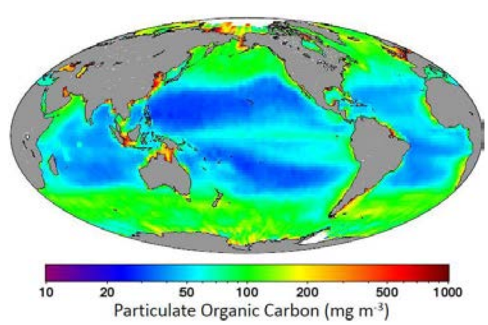


Figure 4.8: CALIOP lidar based global ocean surface particulate carbon *concentration.*

Satellite chlorophyll fluorescence (FLH) retrievals have the potential for providing critical information on phytoplankton standing stocks, physiology, and photosynthesis, but improvements are needed to optimize fluorescence retrieval capabilities for ACE and interpret the underlying physiological signal. Studies were therefore conducted to (1) evaluate sources of error in existing MODIS FLH products based on in situ data and radiative transfer simulations and (2) improve understanding of physiological marks using field data and FLH retrievals from MODIS and the Korean Geostationary Ocean Color Imager (GOCI). To date, significant progress has been made on the physiological interpretation of FLH data that is essential to ACE ocean ecosystem science objectives. These results have been published in: (1) O'Malley et al. (2014); (2) Westberry et al. (2013); and (3) Behrenfeld, M. J., & Milligan, A. J. (2013). Radiative transfer simulations and field FLH validation efforts are still on–going.

Satellite Lidar Retrievals

A unique and powerful aspect of the ACE mission will be its simultaneous measurements of ocean properties with a lidar and ocean radiometer. The ability to retrieve subsurface plankton properties with a space lidar was unproven during initial formulation of the mission concept and was therefore a high-priority target for recent pre-formulation investigations. A lidar specifically designed for ocean retrievals has never been flown in space. However, the atmospheric CALIOP lidar has been producing global data since 2006 and provided an opportunity for a proof-of-concept evaluation and development of algorithms for the ACE lidar. Through a collaboration of researchers from Oregon State University, LaRC, and Plymouth Marine Lab, the first successful satellite lidar retrievals of phytoplankton carbon stocks and total particular organic carbon was achieved (Fig. 4.8), thus demonstrating the feasibility and importance of the advanced lidar capabilities planned for the ACE mission. Detailed results from the study were published in Behrenfeld *et al.* (2013).

Raman Scattering

Raman scattering has the potential to significantly affect ACE retrievals of inherent optical properties (thus, derived geophysical properties) retrieved with semi-analytical inversion algorithms (see above). A study was therefore conducted to evaluate the magnitude of these potential errors and devise an algorithm to correct for Raman. The study demonstrated that errors in particulate backscattering coefficients resulting from Raman contamination can be as large as 50% in clear ocean regions. An analytical method was developed to remove the Raman contribution from remote sensing reflectances and then applied to merged data from OMI and MODIS. The study established an important approach for addressing the Raman scattering issue during analyses of ACE ocean color data. Detailed results from the study were published in Westberry et al. (2013).

Atmospheric Correction

Atmospheric correction refers to removing the atmospheric contribution to the top-of-atmosphere (TOA) radiance from the radiance observed by an ocean color sensor. The atmospheric contribution is 85% to 90% over the open ocean (depth > 1000 km) and ~95% and more over coastal regions (e.g. Chesapeake Bay) and mainly consists of Rayleigh scattered photons by air molecules and Mie scattered photons by aerosols. The former varies as λ^{-4} and the latter as λ^{-n} where, n varies from ~0 to 2. The accuracy of the atmospheric correction depends on microphysical and optical properties of aerosols (e.g., particle size distribution, complex index of refraction), which vary spatially and temporally.

As a part of ACE pre-formulation, radiative transfer (RT) studies were conducted to understand absorbing and non-absorbing aerosol effects on satellite ocean color retrievals. Results showed that the atmospheric correction algorithm proposed by Gordon and Wang (1994) typically works very well for open ocean conditions where aerosols are mostly oceanic in nature and non-absorbing. In the presence of absorbing aerosols (e.g., dust, smoke, industrial pollution), errors in retrieved ocean color become very large, often > 20%. Results also showed that knowledge of single scattering albedo (ω_o) and aerosol layer height (*h*) are extremely important when absorbing aerosols are present. As illustrated in Fig. 4.9, an error of 1 km in aerosol layer height changes the TOA radiance at 412 nm by ~ 0.7%, yielding an ~7% change in water-leaving radiance at the ocean surface. This error increases with increasing aerosol optical thickness (τ_{aer}) in the atmosphere. The RT simulations studies were further extended to include absorbing aerosols in the near UV part of the spectrum. Results showed that absorbing aerosols under low aerosol loading conditions (a major concern in atmospheric correction) could be detected with ACE measurements at 340 and 380 nm.

Due to the importance of accurate atmospheric corrections in the presence of absorbing aerosols, additional ACE supported algorithm development studies were conducting based on the Bayesian approach to inverse problems. In this approach, the solution is expressed as a probability distribution that measures the likelihood of encountering specific values of the input variables (spectral marine reflectance) given the observed output variables (spectral top-of-atmosphere reflectance in the visible and near infrared). This allows for computation of both the conditional expectation of the marine reflectance

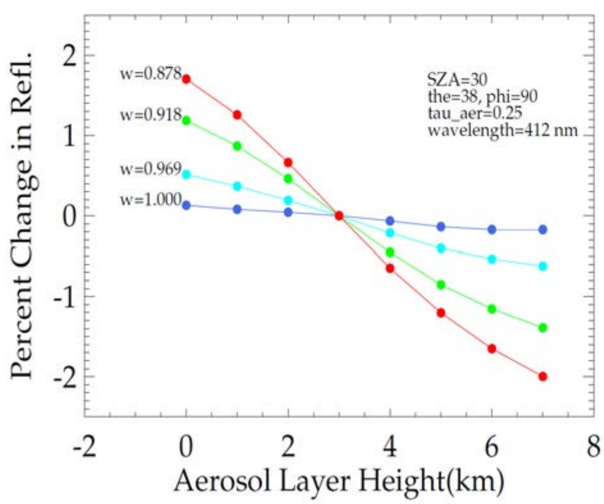


Figure 4.9 Percent change in the top-of-reflectance (TOA) at 412 nm as a function of aerosol layer height. Reflectance values at different heights are normalized with respect to the reflectance values at 3 km *with single scattering albedo (ω_o) of 1.0. The simulations are for solar zenith angle of 30°, view zenith angle of 38° and relative azimuth angle of 90°. The aerosol optical thickness defined at 869 nm is 0.25.*

to be computed and the conditional covariance (a measure of uncertainty), the "p-value" (quantifying the likelihood of an observation with respect to the model), and assessment of situations where observations and model output are incompatible (p-value<0.05). Details of the approach and results are reported in Frouin and Pelletier (2014).

The feasibility of using multi-angular measurements of top-of-atmosphere reflectance to estimate aerosol absorption effects on marine reflectance retrievals was also investigated. The method constrains the spectral extrapolation of scattering properties observed in the near infrared by a value of the aerosol absorption effect obtained in the short-wavelength bands. A separate estimation of the aerosol absorption optical thickness and vertical distribution (variables that govern the aerosol absorption effect) is not necessary. First, the top-of-atmosphere reflectance is corrected for molecular and aerosol scattering using spectral bands in the near infrared and/or shortwave infrared, as in the classic atmospheric correction scheme. Second, the residual signal in all viewing directions, ƛ$_{TOA}$’, composed of the aerosol absorption effect and the marine signal, normalized by the atmospheric transmittance is related to an absorption predictor, i.e., a function representing the directional effect of an absorbing aerosol, namely the product of

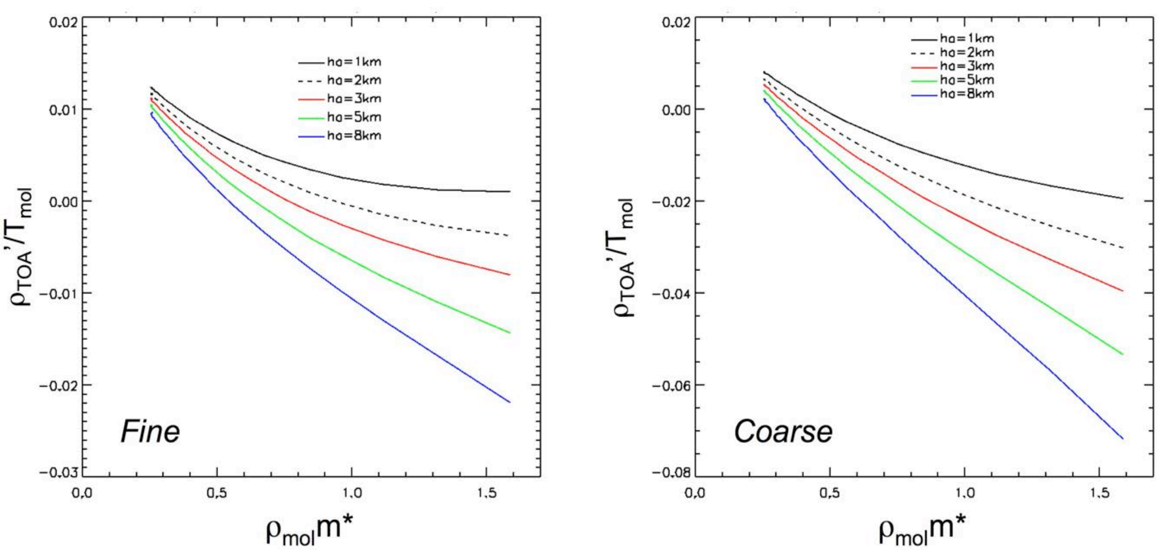


Figure 4.10 Simulated ρ_{TOA}'/T_{mol}, versus ρ_{mol} m* for fine aerosols (left) and coarse aerosols (right). Wavelength is 412 nm and aerosol optical thickness is 0.3. Wind speed is 5 m/s and marine reflectance is 0.02. Solar zenith angle is 30 deg., viewing azimuth angle varies between 0 and 80 deg., and relative azimuth angle is 90 deg. Aerosol scale height varies from 1 to 8 km (8 km correspond to mixed aerosols and molecules). The fine aerosols are defined by r_f = *0.1 µm, σ_f = 0.20, and m_f = 1.40 - 0.010i (single scattering albedo of 0.94), and the coarse aerosols by r_c = 2.0 µm, σ_c = 0.30, and m_c = 1.55 - 0.002i (single scattering albedo of 0.88).*

molecular reflectance, $\tilde{\lambda}_{mol}$, and air mass, m*. Fig. 4.10 illustrates the method for fine and coarse aerosols. Neglecting aerosol transmittance, the marine reflectance (0.02 in this case) is obtained by extrapolating the relation between $\tilde{\lambda}_{TOA}'/T_{mol}$ and $\tilde{\lambda}_{mol}$ m* to zero air mass, where T_{mol} is the molecular transmittance.

Ocean-Aerosols

New wind speed-AOD relationship

We have investigated the wind speed dependence of sea spray aerosol optical depth at 532 nm (AOD532) based on five years of satellite retrievals of aerosol optical properties from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) on board the CALIPSO satellite and the wind speed data from the Advanced Microwave Scanning Radiometer (AMSR-E). The results of our analysis for AOD532 vs. surface wind speed (U10) relationship indicate three distinct regions (Fig. 4.11). At low wind speed (U10 ≤ 4 m s-1) sea spray production is minimal and aerosol properties are expected to be dominated by transport. Under such conditions AOD532 is low, weakly dependent on surface wind speed and representative of background marine aerosols. At an intermediate wind speed values (4 < U10 ≤ 12 m s-1) regression analysis revealed a constant slope of 0.0062 s m-1. At high wind speed values (U10 > 12 m s-1) the AOD532-wind speed relationship levels off. Analysis of CALIPSO-retrieved AOD532 and AMSR-E wind speed suggests that at very high wind speed values aerosol effects on optical turbidity of atmosphere appear to level off, asymptotically approaching value of 0.15. These results have been published in Kiliyanpilakkil, V. P. and N. Meskhidze (2011).

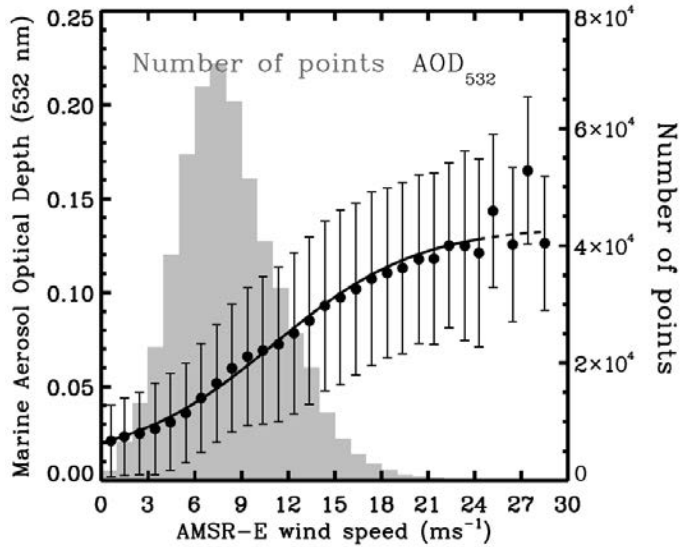


Figure 4.11: The relationship between CALIPSO AOD532 and AMSR-E wind speed. Dotted line indicates that the AOD – wind speed relationship for U10 >24ms−1. Circles and error bars show mean values and standard deviation of AOD for each 1ms−1 wind speed bin, respectively. Logistic regression relationship between AOD532 and wind speed is shown with the solid black line.

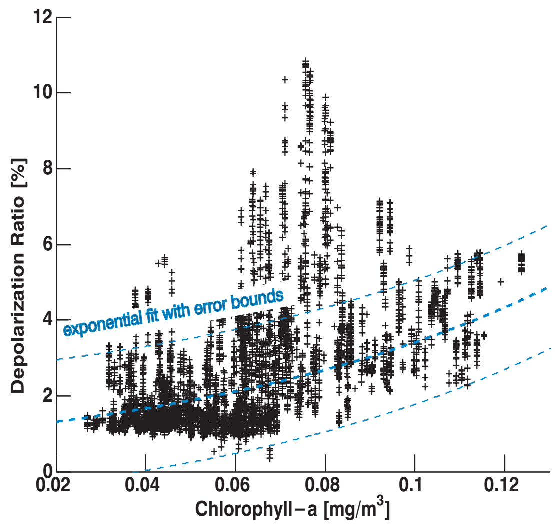


Figure 4.12: Relationship between HSRL boundary layer marine aerosol and [Chl-a] for the HSRL October 18, 2012 flight over the Azores.

Understanding potential sources of organic carbon in nascent sea spray aerosols. Analysis of data from NASA High Spectral Resolution Lidar (HSRL) has shown some interesting anomalies in sea spray aerosol optical properties, most notably the particulate depolarization ratio (a proxy on aerosol shape). However, understanding sea spray aerosol properties is complicated due to its dependence on meteorological conditions and sea state. HSRL flights over the remote marine site at the Azores (Fig. 4.12) have been analyzed to show, among other things, a relationship between the cloud-free marine boundary layer depolarization ratio and chlorophyll-a concentration, [Chl-a]. A suite of even higher resolution data (1.2 m) is being analyzed now in connection with surface [Chl-a] and other variables, such as surface wind speeds to further elucidate air-sea interactions concerning sea spray aerosol. This study will contribute toward our understanding of potential sources of organic carbon in freshly emitted sea spray. Results are described in Dawson *et al.* (2013).

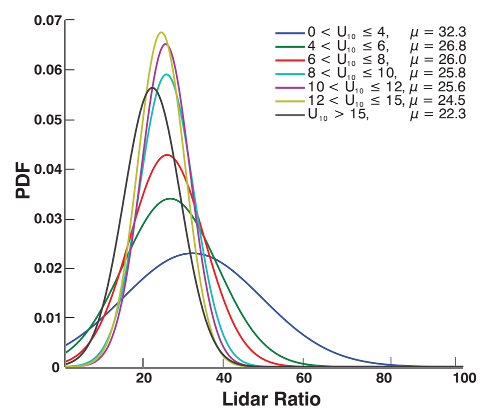


Figure 4.13 Probability density function of clean marine aerosol lidar ratio for selected AMSR-E wind speed regimes. The μ parameter shows the mean of each distribution.

Spaceborne observations of the lidar ratio of marine aerosols. We have developed a new method to calculate the lidar ratio of sea spray aerosol using two independent sources: the AOD from the Synergized Optical Depth of Aerosols (SODA) algorithm and the integrated attenuated backscatter from CALIOP. With this method, the particulate lidar ratio can be derived for individual CALIOP retrievals in single aerosol layer columns over the ocean. The global mean lidar ratio for sea spray aerosols was found to be 26sr, roughly 30% higher than the current value prescribed by

CALIOP standard retrieval algorithm. Data analysis also showed considerable spatiotemporal variability in the calculated lidar ratio over the remote oceans (Fig. 4.13). The calculated aerosol lidar ratios are shown to be inversely related to the mean ocean surface wind speed: increase in ocean surface wind speed (U10) from 0 to $> 15ms^{-1}$ reduces the mean lidar ratios for sea spray particles from 32sr (for $0 < U10 < 4ms^{-1}$) to 22sr (for $U10 > 15ms^{-1}$). Such changes in the lidar ratio are expected to have a corresponding effect on the sea spray AOD. The outcomes of this study are relevant for future improvements of the SODA and CALIOP operational product and could lead to more accurate retrievals of sea spray AOD. These results have been published in Dawson et al. (2014).

5 Field Campaigns

ACE has and continues to leverage the advances in technical development and readiness of both instrument concepts and their related algorithms development made possible with ESTO support. Accordingly, ACE has initiated a series of field experiments over the past 2 years with the purpose of better defining the measurement capabilities of the ACE airborne instrument simulators, as well as advance the corresponding L1 and L2 algorithms. These deployments include the Polarimeter Definition Experiment (**PODEX**) in January-February 2013, the Radar Definition Experiment 2014 (**RADEX-14**) in May-June 2014, and the **RADEX-15** planned for November-December, 2015.

Also during this same period, ACE science and instrument teams have been leveraging the scientific demand by the larger community for the use of their ACE instrument simulators in their campaigns. NASA, DoE, NSF as well as European partners have provided support for ACE scientists and instrument teams to participate in a series of high profile field campaigns. Among these campaigns are 1) Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys (SEAC^{4}RS), 2) Ship-Aircraft Bio-Optical Research (SABOR), 3) Deriving Information on Surface Conditions from Column and Vertically Resolved Observations Relevant to Air Quality (DISCOVER-AQ), 4) North Atlantic Aerosols and Marine Ecosystems Study (NAAMES), 5) ObseRvations of Aerosols above CLouds and their intEractionS (ORACLES), 6) the 2012 Azores Campaign, 7) the GPM Olympic Mountain Experiment (OLYMPEX, coordinated with RADEX-15), 8) DoE 's Two-Column Aerosol Project (TCAP), as well as the European Union Atlantic Meridional Transect (AMT) program.

This section summarizes the scientific gains made by these ACE scientists and instrument teams by participating in these field campaigns.

5.1 Aerosol Related Campaigns

ACE Polarimeter Definition Experiment (PODEX)

The ACE instrument requirements call for a polarimeter to provide retrievals of aerosol optical and microphysical properties. The polarimeter designs currently under development vary widely in their design, spectral and angular coverage, and radiometric calibration/uncertainty requirements. Therefore, the POlarimeter Definition EXperiment (PODEX) mission was conducted in 2013 to help optimize polarimeter design, assess the polarimeter aerosol and cloud retrievals, and intercompare various methods of retrieving aerosol optical properties (e.g., absorption, phase function, refractive index).

Figure 5.1 ER-2 Aircraft during PODEX.

PODEX was conducted from the Armstrong (formerly Dryden) Flight Research Center (AFRC) facility in Palmdale, California during January and February 2013. Three polarimeters were deployed from the NASA ER-2 (809) aircraft: the Airborne Multiangle SpectroPolarimetric Imager (AirMSPI), the Research Scanning Polarimeter (RSP), and the Passive Aerosol and Cloud Suite (PACS). Additional sensors on the ER-2 included the Autonomous Modular Sensor (AMS) which provided multiwavelength calibrated radiances and cloud products generated using MODIS algorithms, the Cloud Physics Lidar (CPL) which provided real-time and post flight aerosol/cloud backscatter profiles to locate and identify aerosol and cloud layers, and the Solar Spectral Flux Radiometer (SSFR) which provided spectrally resolved shortwave irradiance measurements. The ER-2 flights conducted during PODEX were coordinated with airborne and ground-based measurements acquired during the third deployment of the DISCOVER-AQ Earth Venture-Suborbital (EV-S1) project. DISCOVER-AQ used the NASA P-3 and NASA LaRC King Air aircraft to study air quality over the California San Joaquin Valley during this period. The NASA P-3 aircraft was equipped with several in situ sensors that measured trace gas concentrations and aerosol optical (scattering, absorption) and microphysical (size, composition) properties. In particular, the PACS group have also developed the Polarized Imaging Nephelometer (the PI-Neph) for the detailed measurement of the P11 and P12 elements of the scattering matrix of the aerosol particles, which can be directly compared to the polarimetric retrievals of the PACS, AirMSPI and RSP sensors (Dolgos and Martins, 2014). The King Air deployed the LaRC High Spectral Resolution Lidar-2, which is a prototype of the multiwavelength lidar called for by ACE to provide layer-resolved retrievals of aerosol optical and microphysical retrievals. The Distributed Regional Aerosol Gridded Observation Network (DRAGON) of AERONET sun-sky photometers was also deployed in the southern part of the San Joaquin Valley and provided measurements of aerosol optical depth (AOD) and retrievals of column averaged aerosol optical and microphysical properties.

During PODEX, the ER-2 acquired 49 hours of science data during 10 flights between January 14 and February 6, 2013. The flights were designed so that the polarimeters acquired data over bright (desert, snow) and dark (ocean) scenes, during light and moderate aerosol loading conditions in maritime, rural and urban regions, and over fog, stratus, stratocumulus, and cirrus clouds. Data were also acquired over the calibration targets located at Rosamond Dry Lake, Ivanpah, and Railroad Valley. The flights over the San Joaquin Valley contained several legs above the DRAGON AERONET sensors and were coordinated with the DISCOVER-AQ aircraft so that correlative measurements of aerosol optical and microphysical properties were obtained. DISCOVER-AQ also conducted flights over the ocean to support the PODEX flights. The PODEX flights went well, with the exception of the flight on January 28 when RSP lost operation of the SWIR bands due to operator error. This also prevented the operation of these SWIR bands on subsequent PODEX flights. Post mission repairs and calibration showed that the visible channels were not affected.

The PODEX polarimeter datasets are currently in various stages of analysis and archival. AirMSPI and RSP Level 1 (L1) products are currently publicly available at the LaRC Atmospheric Science Data Center (ASDC),

https://eosweb.larc.nasa.gov/project/airmspi/airmspi_table

PACS L1 data are not yet available but will be archived in stages as it becomes processed. Updated radiometric, spectral, and polarimetric calibrations developed for AirMSPI during PODEX will be made available in the form of updated L1 datasets in 2015/2016 timeframe. With the exception of RSP water cloud retrievals (Alexandrov, et al. 2014), as of this writing L2 products from the other polarimeters are in active development but are not yet publicly available. Comparisons of RSP cloud bow and AMS absorbing band droplet size retrievals do not show the type of biases previously reported in comparisons between MODIS and POLDER cloud products (Breon and Doutriaux-Boucher, 2005). In fact the biases are consistent with the quasi-adiabatic vertical variations in liquid water content observed for the stratocumulus clouds in PODEX and our understanding of the weighting functions associated with 1.6, 2.2 and 3.7 μm spectral bands (Platnick 2000). That is, there is a negligible difference between cloud bow and droplet sizes retrieved using the 3.7 μm absorbing band while the 2.2 μm droplet retrievals, with a weighting function deeper into the cloud, are 1-2 μm smaller (Alexandrov et al. 2015). Aerosol retrieval activities using the PODEX datasets are ongoing with several case studies under analysis.

Before comparisons of the PODEX polarimeter radiometric measurements could be performed, the impact of the ER-2 wing flex on the geolocation of the RSP measurements was accounted for using comparisons at known locations (e.g., coastlines) as well as using a parameterization of wing flex developed using data acquired during the subsequent SEAC^{4}RS mission. Following this correction, these comparisons of AirMSPI and RSP data, performed by Kirk Knoblespiesse (NASA Ames) for scenes over dark water, found that the reflectances agree within measurement uncertainties. However, the degree of linear polarization comparisons do not agree within expected uncertainties, indicating that cross-calibration of the polarimeters in the laboratory and/or revision of analytical uncertainty models is warranted. Further discussions regarding polarization calibration techniques and unified methods of describing instrument uncertainties are underway. An online forum for the discussion of these issues has been created at NASA Ames: https://earthscience.arc.nasa.gov/sgg/ACEPWG.

Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys (SEAC^{4}RS). Although PODEX provided a very important initial dataset for evaluating the polarimeter designs and retrieval techniques, it did not provide the full suite of measurement targets that are required to fully evaluate these instruments. Measurements of very high aerosol loadings such as dense forest fire smoke and dust were not obtained because significant forest fires and dust outbreaks did not occur within range of the ER-2 during the PODEX measurement period. There was also no opportunity during PODEX to measure smoke or dense aerosol above clouds, which presents a particularly important and challenging retrieval situation for the polarimeters. There were relatively few measurements of cirrus during PODEX, particularly in cases where there were no underlying clouds.

Fortunately, the SEAC^{4}RS experiment provided another opportunity to obtain these conditions (Toon et al. 2016). Three aircraft were deployed during SEAC^{4}RS: the NASA DC-8 and ER-2 and the SPEC Lear Jet. As in PODEX, AirMSPI and RSP were deployed from the ER-2 and acquired datasets important for evaluating the polarimeter measurements and retrievals. Likewise, CPL and SSFR were also part of the ER-2 payload as in PODEX. However, PACS was not on the ER-2 for SEAC^{4}RS. In place of AMS, the enhanced MODIS Airborne Simulator (eMAS) was deployed on the ER-2 and provided high spatial resolution imagery of aerosol and cloud fields. The DC-8 payload included several in situ instruments for measuring aerosol and optical properties, an airborne HSRL instrument, and the new 4STAR instrument for providing sun and sky measurements from which aerosol optical and microphysical properties are retrieved in a manner similar to AERONET. The SPEC Lear Jet carried in situ sensors for measuring cloud and ice particle size distributions and liquid and ice water content. As in PODEX, a network of AERONET Sun-Sky photometers was deployed over the southeastern US to provide measurements of aerosol optical depth (AOD) as well as retrievals of aerosol absorption.

During SEAC^{4}RS, the DC-8 and ER-2 each flew more than 150 science flight hours; the Lear Jet flew over 50 hours. In the first part of the campaign, the aircraft were based out of the AFRC in Palmdale, CA and flew out of Ellington Field near Houston, TX for the remainder. Although the SEAC^{4}RS flights were concentrated more heavily in the southeastern US and the Gulf of Mexico, there were several flights over the western US to observe targets of interest; in particular, flights targeted smoke from fires in California and Oregon. Of particular interest was the flight on August 6, 2013, when instruments from both aircraft were able to observe and measure smoke properties above stratocumulus clouds. AirMSPI and RSP research teams are currently using these datasets to develop and evaluate aerosol and cloud properties. For example, initial AirMSPI aerosol retrieval results for AOD, single scattering albedo, size distribution for a few cases are consistent with those derived from the AERONET and 4STAR measurements. Initial RSP retrievals of cirrus cloud particle size, optical thickness, and asymmetry parameter compare favorably with those derived from coincident eMAS retrievals. During the same experiment the PACS group has flow the RPI portable imaging polarimeter (analogous to PACS) and the PI-Neph (Dolgos and Martins, 2014) for data validation on board the NASA DC-8 aircraft. Both instruments are being used for the development of ACE aerosol and cloud retrievals as well as potential validation for the ER-2 polarimeters.

Evaluation of aerosol algorithms and aerosol properties retrieved from ACE instruments will rely significantly on AERONET retrievals of column-averaged aerosol properties. Currently, the AERONET retrievals require a set of a minimum aerosol optical depth (at 440nm) of 0.4 and a solar zenith angle greater than 50° to obtain highest quality (L2.0) data products. SEAC^{4}RS measurements provided an opportunity to test the representativeness of the AERONET absorption retrievals for a limited number of these high AOD cases as well as many other cases at lower AOD levels. SEAC^{4}RS data can be used to compare different techniques for measuring and retrieving aerosol absorption.

Additional Field Missions

Both AirMSPI and RSP were deployed on the ER-2 as *piggyback* instruments on flights that were conducted over California as part of the HyspIRI airborne campaign (https://hyspiri.jpl.nasa.gov/airborne). The primary instruments flown in these HyspIRI flights were the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and the MODIS/ASTER Airborne Simulator (MASTER). RSP was deployed on the ER-2 for eleven flights between October 2013 and August 2014, and AirMSPI was deployed for seven of the flights during April and May 2014. RSP and the NASA LaRC airborne HSRL-1 were also deployed on a NASA Langley King Air aircraft during July-August 2014 for the Ship-Aircraft Bio-Optical Research (SABOR) experiment (Hostetler et al. 2014; Sinclair et al. 2014; Powell et al. 2014). Twenty-five research flights were conducted over the western Atlantic Ocean coincident with in-water bio-optical measurements made from the research vessel Endeavor. These data will be used to improve algorithms for lidar and polarimeter retrievals of ocean properties and atmospheric corrections for ocean color retrievals.

The airborne HSRL-2 has acquired such multi-wavelength datasets while flying on the NASA LaRC King Air during four atmospheric field missions conducted since 2012. The first was during the DOE Two-Column Aerosol Project (TCAP) in July 2012 over the Atlantic Ocean east of Cape Cod (Müller *et al*. 2014). The following three deployments were in support of the NASA DISCOVER-AQ campaigns held in 1) the California central valley in January-Febr uary, 2012, (Ferrare *et al*. 2013, Hostetler *et al.* 2013), 2) Houston in September 2013, and 3) Denver in July-August 2014 (Scarino *et al.* 2013, 2014). Approximately 260 science hours of data were acquired by the HSRL-2 during a total of 77 science flights during these four missions.

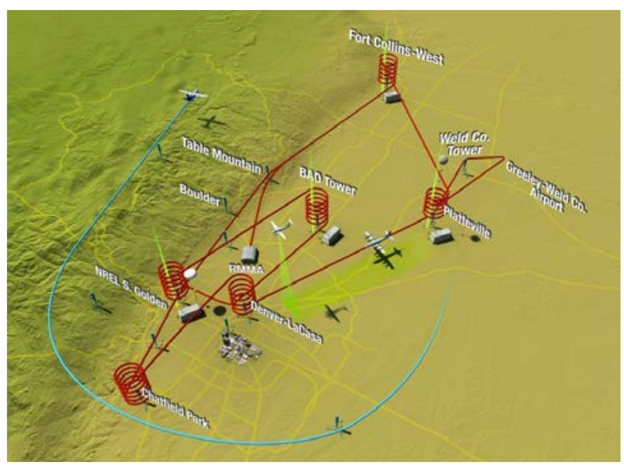


Figure 5.2 Map of the 2014 DISCOVER-AQ campaign near Denver, Colorado.

Beyond supporting the science of these particular missions, HSRL-2 data acquired during these missions are being used to help develop and assess the advanced lidar retrieval algorithms designed to meet the ACE aerosol requirements discussed in Section 2. Operational code has been developed to implement these retrievals. The code has been used to produce ACE-like L2 products including layer-resolved aerosol optical (scattering, extinction) and microphysical (size, concentration) properties in "curtains" below the aircraft. In addition, DISCOVER-AQ overflew the DRAGON AERONET network of Sun-sky photometers that had been specifically deployed during the campaign. These in situ aerosol measurements and AERONET retrievals have proven valuable for assessing the results of the multi-wavelength lidar aerosol retrieval algorithms and for comparing different techniques for measuring and retrieving aerosol properties (Scarino et al. 2013). These comparisons are ongoing as are efforts to improve the accuracy and speed of the retrievals.

Finally, the HSRL-2 team will participate in the upcoming DOE Combined HSRL and Raman Measurement Study (CHARMS) that will test the multi-wavelength 3+2 lidar dataset using ground based Raman lidar and HSRL measurements over the DOE ARM SGP site in Oklahoma. DOE funding will also allow for the processing and analysis of these test data using the LaRC multiwavelength algorithms developed for airborne HSRL data.

5.2 Cloud Related Campaigns

ACE clouds has both short term and long term goals. In the upcoming several years, we will quantitatively explore the trade space between instrument suite complexity and science objectives so that an optimal configuration of instruments that meets the L1 science objectives of ACE clouds can be identified. Beyond this, our objective is to use the algorithms developed to explore this trade space and adapt them to become operational Level 2 algorithms that can be flight ready well before launch. To accomplish our goals, we require data sets that consist of field data collected by aircraft. We also plan to use synthetic data sets produced by models that can be adapted in observation system simulation experiments (OSSE). The forward model simulation suite already exists (Tanelli et al., 2012) and we are beginning the process of creating synthetic data sets suitable for this application.

In the past decade, NASA has invested heavily in generating suborbital data sets that are suitable for addressing the goals of ACE clouds. Ideally, we require measurements from a remote sensing aircraft that effectively simulates a satellite system that is more extensive than what is planned for ACE. The remote sensing measurements must be complimented by coordinated data collected in situ so that algorithms can be objectively validated. In several recent and planned NASA field campaigns, extensive suites of remote sensors were included on the ER-2 and DC-8. Relevant data sets were collected in the 2007 NASA TC^4 campaign where both remote sensing from the ER-2 and DC-8 are available in addition to extensive in situ data by the DC-8 that was collected in close coordination with the ER-2. The radar suite on the ER-2 did not identically mimic what is planned tentatively for ACE although dual frequency Doppler data (W and X bands) were collected along with passive microwave (AMPR) and visible and IR radiance data (MODIS Airborne Simulator). Several flights also included sub mm measurements from the COSSIR instrument. Another data set that will be useful to us was collected during the SEAC^{4}RS campaign in 2013. In SEAC^{4}RS, the NASA DC-8 carried the APR-2 radar that collected scanning Doppler radar data in the Ku and Ka bands. The Stratton Park Engineering Corporation Lear Jet provided insitu validation. The primary target in SEAC^{4}RS was convection both over continental locations and over the Gulf of Mexico. Fig. 3.3 in section 2 shows an example of data collected during SEAC^{4}RS.

Radar Definition Experiments (RADEX)

While neither TC4 nor SEAC^{4}RS campaigns carried the precise remote sensing package anticipated for ACE, the ACE-funded Radar Definition Experiments (RADEX-14, RADEX-15) were designed specifically for this purpose. The initial deployment of RADEX took place in the spring of 2014 and did collect what could be considered a super-ACE data set. RADEX-14 was undertaken in a close and very fruitful collaboration with the Global Precipitation Measurement Mission (GPM) ground validation (GV) team led by Walt Petersen of NASA Wallops. Specifically, ACE funded additional hours of the ER-2 and Citation aircrafts, as well as providing funding for several ACE investigators to participate in the field exercise. During this campaign, the ER-2 was instrumented with 3 Doppler radars built by Gerry Heymsfield's group at NASA Goddard and collected data in the W, Ka, Ku, and X bands. In addition, the ER-2 carried the AMPR and the CoSMIR microwave radiometers (see Fig 3.2 in section 2 for an example case study). The University of North Dakota (UND) Cessna Citation collected coordinated in situ data. ACE funding augmented the instrumentation and flights hours of the Citation. ACE clouds had two specific goals for RADEX-14 that included warm rain in shallow convection and data collected in clouds producing stratiform precipitation that was initiated as snow above the freezing level. See Table 5.1 for a breakdown of the flights that addressed these goals. Several flights collected data in shallow warm cumulus offshore in addition to extensive mixed phase clouds and convection both offshore and over the mountains of North Carolina. Ground-based radar data were also collected by the Aerosol, Cloud, Humidity, Interactions Exploring and Validating Enterprise (ACHIEVE) suite (Tsay et al. 2013). Our preliminary evaluation suggests that RADEX 14 was very successful. The synergy between the goals of ACE RADEX and GPM GV contributed significantly to this success. Analysis of the RADEX-14 data is commencing and we anticipate working with this data over the next several years during the phases of algorithm development.

A second phase of RADEX, RADEX-15, again in collaboration with GPM GV, took place during November/December of 2015, as part of a campaign to examine liquid and mixed phase clouds over and offshore of the Olympic Peninsula in the Olympic Mountain Experiment (OLYMPEX; http://olympex.atmos.washington.edu). Our specific goals in RADEX-15 were to: 1) collect an ACE super-data set in maritime convection in cold air advection behind fronts, 2) examine the warm rain process in stratiform clouds ahead of fronts, and 3) collect mixed and ice-phase cloud and precipitation data in frontal bands. All of these situations represent significant and specific challenges for algorithm development where cloud processes in turbulent vertical motions generate precipitation in the cloud that is eventually realized at the surface as either rain or snow. Demonstrating the degree to which these processes can be diagnosed with actual data is fundamental to the goals of ACE clouds. In RADEX-15, the ACE project invested in supporting the ER-2 with the Heymsfield radar suite and AMPR (supported by GPM GV). In addition, the enhanced MODIS Airborne Simulator (eMAS) was flown on the ER-2 as well as the Cloud Polarization Lidar (CPL), the AMPR microwave radiometer, and Air MSPI on several flights . On the DC-8, the JPL APR3 radar (W, Ka, Ku bands) was flown along with COSMIR. In situ data were collected by the UND Citation. Active analysis of the RADEX 15 data is underway as of this writing.

Table 5.1. Case studies of note for ACE-related science goals generated during RADEX 14. Many of these flight days were partially or fully funded by GPM GV indicating the fruitful collaboration between ACE and GPM GV.

Date (2014)	Notes
May 12: Offshore Convection	Developing convergence line resulted in deepening convection along the Gulf Stream. ER-2 sampled convection in various stages of the lifecycle while the Citation collected data in situ nearby.
May 16: Offshore Frontal Precipitation	Deep frontal clouds and stratiform rain with embedded convection were systematically sampled by the ER-2 while the Citation collected in situ data along sections of the ER-2 track.
May 18: Baroclinic system over the Appalachians	Clouds and precipitation formed by a weak synoptic system in the early morning hours were sampled over the Appalachians by the ER-2 and Citation.

May 19: GPM overpass and warm rain offshore	ER-2 and Citation collected data in a weakening precipitation area offshore. The GPM overpass was closely coordinated by the ER-2 over deeper clouds. Following the overpass, shallower clouds producing warm rain were sampled by both aircraft.
May 28: Warm rain offshore	This flight provided excellent coordinated data in shallow convection and warm rain offshore. ER-2 and Citation were closely coordinated. Likely the best case for warm rain during the campaign.
June 6: Congestus over ground-based	Congestus over Maggie Valley was sampled by ground-based remote sensors in the ACHIEVE instrument suite while the Citation collected data in situ.

5.3 Ocean Related Field Campaigns

For ocean ecosystem science objectives, an important attribute of the ACE mission design is its combination of an advanced ocean radiometer, subsurface- and vertically-resolving lidar, and advanced polarimeter. Each of these instruments provides unique, as well as complementary information on ocean properties. However, field campaigns demonstrating the utility of this instrument suite have been virtually non-existent. To address this issue, two major ocean field campaigns have recently been conducted involving aircraft, ship, and satellite measurements and including lidar, polarimeter, and ocean radiometer measurements. The two studies were referred to as the 2012 Azores Campaign and the 2014 SABOR campaign. While ACE pre-formulation funding contributed to these field efforts, additional major support was provided by NASA's Ocean Biology and Biogeochemistry Program, the CALIPSO mission, the United Kingdom's Atlantic Meridional Transect (AMT) program, and individual PI grants. The outcome of these campaigns has been highly relevant to both ACE and PACE missions. Data analysis from both campaigns is still on-going, but early results have been highly encouraging.

2012 Azores Campaign

The primary objective during the 2012 Azores campaign, was to collect simultaneous ship, aircraft, and satellite ocean optical measurements of particulate scattering coefficients. The study involved collaborators from Oregon State University, Langley Research Center (LaRC), and Plymouth Marine Lab and enjoyed some support by the CALIPSO and ACE projects for supplemental flight hours.

Satellite data included lidar measurements from CALIOP and ocean color measurements from MODIS Aqua. Aircraft instruments included the NASA GISS Research Scanning Polarimeter (RSP) and the LaRC High Spectral Resolution Lidar (HSRL). Ship data focused on in-line, continuous flow-through measurements of surface layer particulate scattering and absorption coefficients.

Figure 5.3a shows the ship track and aircraft flight tracks during the campaign. Aircraft flights were optimized to overfly ship in situ measurements, as well as data collected by CALIOP. Figure 5.3b shows match-up data for ocean particulate backscatter coefficients (b_{bp}) measured in situ (black line), by CALIOP (red line), and as retrieved from MODIS using current ocean color inversion algorithms (green line = Garver-Siegel-Maritorena (GSM) algorithm; blue line = quasi-analytical algorithm (QAA). Fig 5.3c shows match-up results for b_{bp} from the airborne HSRL, CALIOP, and MODIS data using the GSM algorithm and corresponding to the 3 flight tracks shown in Fig 5.3a.

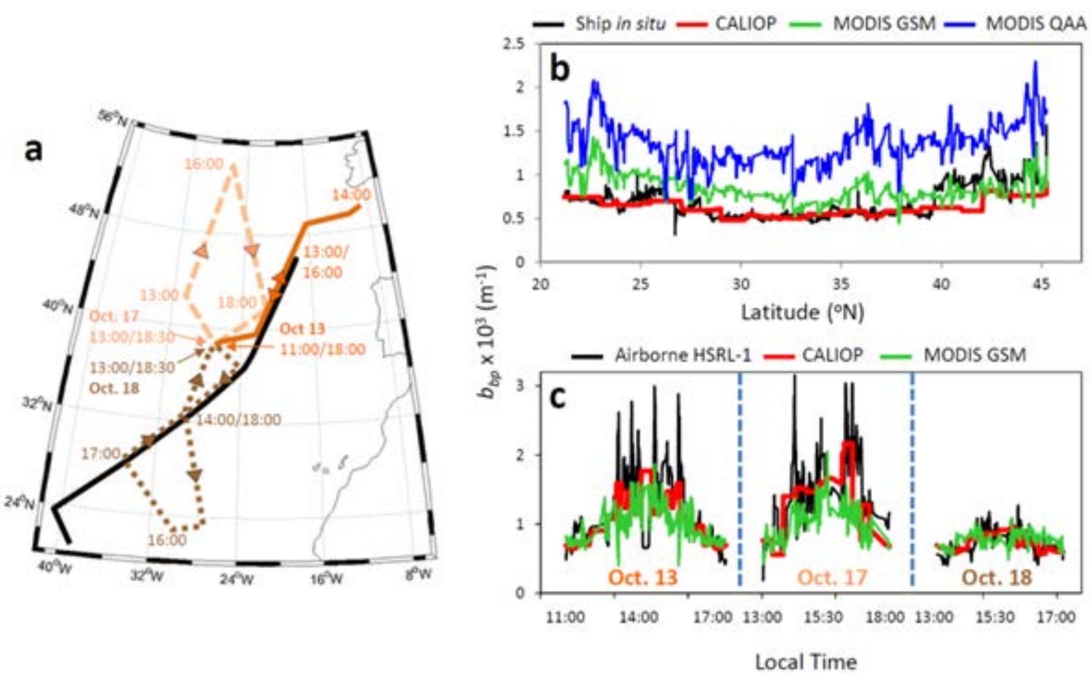


Figure 5.3 Ocean particulate backscattering coefficients (b_{bp}) during the 2012 Azores campaign. (a) black line indicates ship track, solid orange, dashed peach, and dotted brown lines indicate aircraft tracks. (b) b_{bp} values for (black) in situ ship data, (red) CALIOP retrievals, MODIS (green) GSM and (blue) QAA products. (c) b_{bp} values for the airborne campaigns (see panel a). From Behrenfeld et al. (2013)

The 2012 Azores campaign was a highly successful study. The demonstrated correspondence between in situ, aircraft, and CALIOP lidar retrievals provided a key proof-of-concept for the ACE instrument configuration regarding ocean ecosystem retrievals. It was also the first demonstration of effective ocean scattering retrievals from CALIOP and yielded the first space lidar algorithm for assessing phytoplankton carbon and total particulate organic carbon (see Section 4 above). Initial results from the polarimeter measurements are also encouraging, although final data analysis is still on-going. Another outcome of the campaign was that it highlighted some of the technical challenges associated with subsurface particle scattering measurements with a lidar, leading to subsequent revisions in the HSRL instrument design in preparation for the subsequent 2014 SABOR campaign.

The 2012 AMT ship transect was also used to conduct daily radiometric and supporting measurements across 10,000km of the Atlantic Ocean in an ACE funded effort to assemble field matchup data for satellite FLH products. Similar data were collected during the 2014 SABOR campaign. Analysis of FLH matchup data is on-going.

2014 SABOR Campaign

The Ship-Aircraft Bio-Optical Research (SABOR) campaign, was, observationally, a greatly expanded experiment compared to the 2012 Azores study. SABOR was only recently conducted between 17 July to 7 August, 2014, so only preliminary results are currently available. SABOR measurements were focused on the strong ecological gradients persistent over the US northeast continental shelf region (Fig. 5.4). The campaign brought together several PI-lead science projects focused on the biogeochemistry of plankton, radiative transfer, and in situ and remotely sensed ocean optics. The ship measurement contingency included (1) seven flow-through instruments collecting optical data from which are derived a dozen inherent optical properties of seawater, (2) eight instruments for ocean profiling optical measurements for assessing inherent optical properties through the water column, and (3) a wide diversity of discrete surface and subsurface sample collections for assessing biogeochemical properties, including particulate and phytoplankton carbon and plankton species composition. Similar to the 2012 Azores study, the airborne instrument complement during SABOR included and

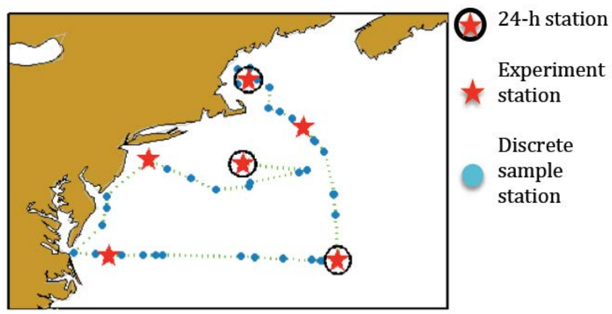


Figure 5.4: Ship track and sampling stations during SABOR.

upgraded LaRC HSRL and the GISS RSP. Flights were conducted out of Massachusetts, Bermuda, and Virginia. Some additional flight hours for the campaign were made possible with additional support from CALIPSO and ACE projects. Supporting satellite data were provided by CALIOP, MODIS Aqua, and NPP VIIRS.

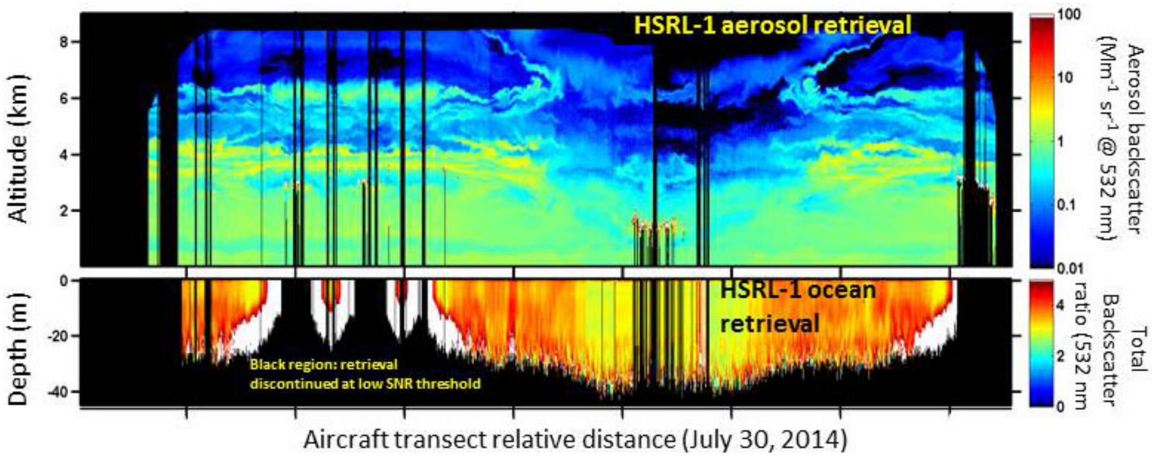


Figure 5.5 Preliminary HSRL results from the SABOR campaign. Top panel = vertical distributions of aerosol backscatter. Bottom panel = subsurface ocean total backscatter ratio. Data from a single aircraft transect conducted on July 30, 2014.

With respect to ACE ocean ecosystem science objectives (as well as atmospheric science objectives), data collected during the 2014 SABOR campaign will be highly beneficial for the development of advanced satellite retrieval algorithms. The upgraded HSRL used during SABOR will allow assessment of design improvements for the ACE lidar (Fig. 5.5). In water and aircraft polarimetric measurements during SABOR is highly relevant to the ACE objective of using a space-based polarimeter to address atmospheric and ocean related science. Furthermore, the extensive ship-based optical and biogeochemical measurements collected during SABOR will provide critical insights on algorithm development for retrieving key geophysical properties from ACE remote sensing data.

Figure 5.6: Inherent optical property instrument package deployed during SABOR.

These measurements included the assemblage and testing of an instrument package for measuring water column Inherent Optical Properties (IOPs) (Fig. 5.6), which are properties fundamental to ACE Ocean Ecosystem objectives. The package employed state-of-the-art sensor technology, including custom MASCOT and Sequoia LISST sensors which, in combination, measured the full angular volume scattering function for light scattering in water. The instruments also measured the dissolved phase and attenuation in an open path (not pumped) configuration. Preliminary analyses indicate that resultant data are if the highest quality possible.

Potential locations for future field studies of marine organic aerosols

Ocean surface waters contain large concentrations of small particulates including phytoplankton, algae, bacteria, viruses, fragments of larger organisms and organic detritus. Organic matter in the oceans contributes to one of the largest active reservoirs of organic carbon on Earth. A growing body of evidence shows that this seawater-derived organic matter can be transferred in the atmosphere where it can also undergo photochemical and bacterial degradation (aging) leading to physicochemical modification of organic compounds. Important effect of seawater-derived organic matter on atmospheric solar radiation transfer and cloud processes has been well documented. Yet, due to the complex mixture of oceanic and continental precursors, very few studies have attempted to characterize aging of marine organics. Through implementation of marine organic aerosol tracers in global chemistry-transport model we are able to identify the regions with large contributions of freshly-emitted or aged aerosol, potential locations for future field studies focused on improved characterization of marine organic aerosols (see Fig 5.7). Additional details were published in Gantt et al. (2014).

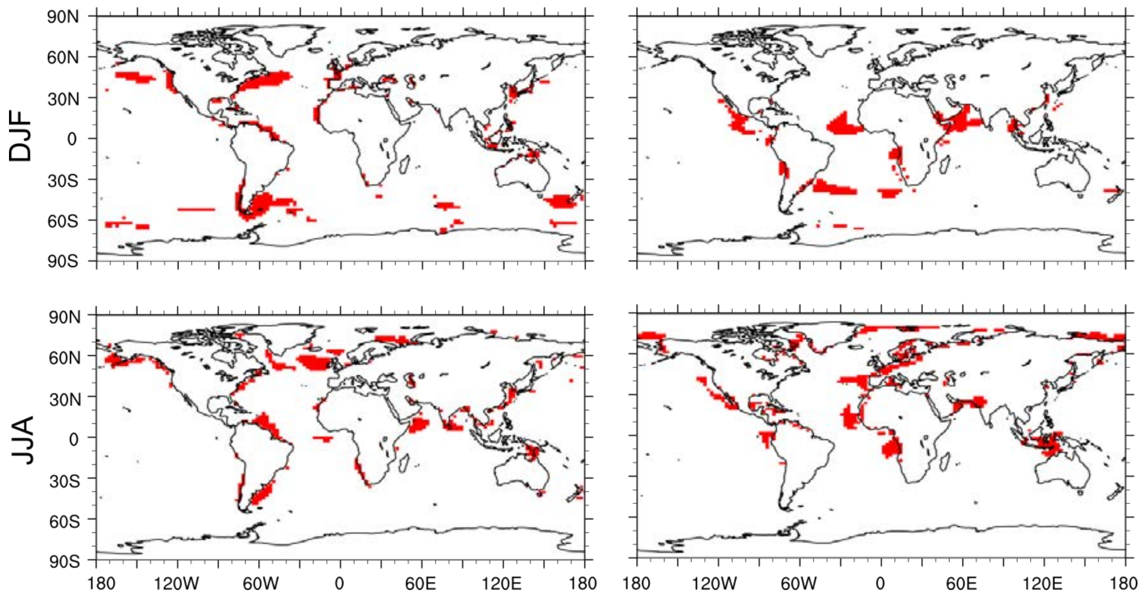


Figure 5.7 Regions (in red) with GEOS-Chem predicted seasonal submicron marine organic aerosol concentrations > 200 ng m-3 for low aged (left column) and highly aged (right column) regimes.

6 Mission Architecture

ACE Leadership and its Mission Architecture Team continue to evaluate a number of mission concepts that meet the ACE science requirements and provide a number of viable options for mission implementation. These include accommodation of the instruments on a single platform, as described in the Decadal Survey, or accommodated on multiple spacecraft to be flown in formation. There has been much discussion over the past five years around the idea of having multiple platforms at different altitudes, most notably, passive sensors flying at a higher altitude and active sensors flying at a lower altitude. Rather than include microwave and infrared imaging radiometers, ACE might be flown in formation with an operational satellite having these capabilities, though at significant impact on the science capabilities of the active ACE sensors (lidar and radar) due to the spacecraft altitude for operational missions, typically more than 800 km. Moreover, while it can be demonstrated theoretically that such multi-sensor retrievals should produce the desired result, this has not been demonstrated with real data. Thus, ACE has embarked on a program to acquire the necessary test data and develop the needed algorithms to demonstrate the potential, and the limitations, of this approach. Accordingly, an orbital study looking into the trades around these different configurations was commissioned by ACE leadership.

Recognizing the unprecedented success of the A-Train, the ACE leadership is also considering a next generation Earth Systems satellite constellation that could be formed around the directed Plankton Aerosol Cloud and ocean Ecosystem (PACE) mission. Such concept is discussed in a recent whitepaper submitted to the 2017 Decadal Survey (Mace et al. 2016).

6.1 ACE Instruments

The following core instruments were identified in the 2007 Decadal Survey:

- HSRL Lidar for aerosol/cloud heights and aerosol properties (L)
- Dual frequency, Doppler cloud radar for profiles of cloud properties and precipitation (R)
- Multi-angle, multi-spectral imaging polarimeter for aerosol and clouds (P)
- Ocean color multi-channel spectrometer for ocean ecosystems (O)

In addition, the ACE Science Definition Team recognizes the high science return from inclusion of the following instruments, with several mission studies included accommodation of the additional instruments:

- IR multi-channel imager for cloud temperatures and heights
- High frequency swath radiometer for cloud ice measurements
- Low frequency swath radiometer for precipitation measurements

6.2 ACE Core Mission: ACE-C

A mission concept to accommodate the ACE Core instrument suite was developed at the GSFC Mission Design Laboratory in May of 2009 and is fully described in the 2010 Aerosol, Cloud and Ecosystems (ACE) Proposed Satellite Mission study report (http://acemission.gsfc.nasa.gov/documents/Draft_ACE_Report2010%20.pdf). It should be noted that significant shortcomings of the 2009-2010 studies were the uncertainty in the assumed technical readiness level and cost of the instruments. A brief synopsis of the architecture explored in that 2010 report is presented below.

A launch in 2020 was assumed and a concept developed including instrument accommodation, mass, power, volume, spacecraft, launch vehicle, mission and science operations. A 450 km, 97^{o} (Sun Synchronous), 1:45 pm ascending node orbit was chosen as baseline. To constrain cost, mission lifetime was set at three years with a goal of five.

Advantages

- Fulfills NRC Decadal Survey requirements for full ACE mission
- Optimizes orbit for atmospheric science and improves atmospheric measurement sensitivity compared to higher altitude orbit
- Minimizes launch vehicle costs and reduces overall operational complexity

Disadvantages

- Requires significant funding in Phase B to fund multiple instrument development
- Limits post-launch flexibility

6.3 Multiple Spacecraft Formulation: ACE-1 and ACE-2

A number of options to separate the ACE Core instruments onto two (or more) platforms were studied by the ACE Integrated Mission Design Team. As a result of these studies, a two-platform approach, ACE-1 and ACE-2, was determined to be the best fit in terms of science accommodation as well as schedule and cost optimization. The following two platform payload accommodation scenarios were studied and costed:

Option 1	ACE-1	O	Option 3	ACE-1	O
	ACE-2	RLP		ACE-2	RLP + IR + sub-mm + microwave
Option 2	ACE-1	OP	Option 4		LOP + IR
	ACE-2	RL			R

Table 6.1: ACE architecture options.

The recommended two-platform approach for ACE, Option 2, separates the payloads onto active and passive platforms. ACE-1 includes the multi-angle polarimeter and ocean color spectrometer. Combing these instruments takes advantage of the fact that polarimeters make measurements that are only weakly sensitive to ocean color and can therefore be used for atmospheric correction which facilitates speciation of phytoplankton. Moreover, there are significant synergies between the polarimeter and the ocean color spectrometer in terms of improving both atmospheric correction of the ocean color observations and reducing uncertainties in aerosols retrievals caused by limitations in polarized bio-optical models of the ocean, as well as improving quantification of fertilization effects by estimating the iron available from dust regionally and measuring aerosol speciation to understand aerosol generations by the oceans and aerosol deposition into the oceans.

An additional consideration of the ACE-1 platform is the possibility to fly as a complement to ESA's EarthCare (EC) mission that will be launched in approximately 2018. ACE-1 would fly in the same orbit and within 1 minute of the EC observatory and would augment the science of EC as the payload has radar and lidar but no swath imager in visible or μ-wave. With the EC payload, the addition of a polarimeter and the ocean color spectrometer would provide early information on critical aerosol-cloud climate processes and continuity with ocean biosphere measurements.

ACE-2 would include the remaining two "core" instruments, the aerosol/cloud lidar and dual frequency cloud radar and launch no later than three years after ACE-1 to ensure overlap with the ocean color spectrometer data measurements. The orbit of ACE-1 could be adjusted to fly ACE-1 in formation with ACE-2 for a combined two platform mission that could provide up to 10 years of measurements given appropriate mission design considerations. The passive instruments operational life is expected to exceed the five year goal mission based on MODIS and Polder experience and the active instruments operational life is expected to exceed the three year minimum goals based on CALIPSO and CloudSat experience. Moreover, the lidar and radar lifetimes can be lengthened by hardware enhancements, such as multiple laser units as done with CALIOP. All told, design accommodations and launching the passive instrument platform in advance of the active platform, could provide long-term data continuity.

Advantages

- Polarimeter provides context for aerosol and cloud measurement
- Potential international collaboration with ACE 1 flying in formation with EarthCARE mission
- Potential for 10+ years of measurements

Note:

The Plankton Aerosol Cloud and ocean Ecosystem (PACE) mission that was included in NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space: 2011, evolved from the ACE-1 study.

6.4 A Constellation built around PACE

Recognizing the unprecedented success of the A-Train, it is clear that advances in Earth System science are maximized most efficiently by coordinating multiple instruments in constellation flight. In a white paper submitted as a response to the Second RFI by the 2017 Decadal Survey Panel (Mace et al. 2016), the ACE leadership and members of the ACE science community at large have recommended a next generation Earth Systems satellite constellation that could be formed around the directed Plankton Aerosol Cloud and ocean Ecosystem (PACE) mission. Four key elements supporting this recommendation are: (1) PACE threshold requirements are for a highly advanced ocean-atmosphere passive sensor and a scanning polarimeter, (2) Preliminary PACE studies show that the mission could accommodate flight altitudes at 425 or 675 km, (3) Radar and lidar sensors are essential to a future Earth observing system and provide critical measurements for interpreting passive sensor data, and (4) these active instruments are most useful when combined in constellation with passive remote sensors and each other. While an advanced satellite constellation could be created at either of the two candidate PACE altitudes, signals measured by active remote sensors decrease with the square of the distance from the target, meaning that the lower PACE altitude has significant advantages. The lower altitude also increases SNRs for the passive PACE sensors and improves spatial resolution, but increases contamination risk, cost, and thermal loads. Mace et al. (2016) argues that the advantages of the lower orbit far outweigh the disadvantages, and advocates the optimization of the PACE orbit for building the next Earth System satellite constellation.

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8 Assessment and Recommendations

First and foremost, the scientific vision still stands and is as much in demand now as it was five years ago. The ACE mission as first conceived put forth a bold and ambitious with its vision regarding the observation and study of Aerosol-Cloud-Ecosystem processes, especially its vision for seeking to combine the best of a surveying and a process-oriented mission. Over the past five years, ACE Science Team Leadership has acted upon the recommendations the last Decadal Survey and the directive of NASA ESD leadership and made significant progress during the pre-formulation stage of the mission.

Through guided and transparent competitions, personnel affiliated with the ACE Science Study Team (ACE SST) have matured a combination of measurement concepts that include radar, polarimeter and lidar technology and associated algorithms. Members of the ACE ST have been entrepreneurial in their pursuit of resources beyond sensor and algorithm development for deployment of both in the field with ACE led field campaigns (PODEX and RADEX 14 RADEX 15) and by supporting flight opportunities on aforementioned field campaigns led by NASA (R&A, OBB, EVS and DS programs) as well as by non-NASA programs.

In addition to field campaigns, ACE leadership has commissioned trade studies focused on the return of investment, both in terms of financial and scientific returns, for further investment in sensor/detector development versus algorithm development. Along these lines, ACE Leadership has established a Lidar Working Group to bring together personnel involved with multiple Lidar instrument concepts under consideration for the ACE mission on a monthly basis, much in the way of the existing ACE Polarimeter Working Group (APWG) and the ACE Cloud Working Group (ACWG). A major charge of the ALWG involves the development of an experiment where the multiple existing lidar concepts will fly concurrently with polarimeters onboard the NASA ER-2 in the next FY.

Furthermore, the ACE ST is being proactive and actively providing input into the National Academies of Sciences, Engineering and Medicine's Space Studies Board's 2017 Decadal Survey for Earth Science and Applications from Space process (DS). ACE leadership and Science Team members are part of the larger dialogue that will define NASA Earth Science moving forward and open to advancing in the most parsimonious fashion possible.

Evidence of Progress includes:

- Establishment of open and transparent instrument working groups
- advancement in the TRL of the Cloud Radar, multiple competing Polarimeter and lidar concepts
- gains in their associated algorithms.
- establishment of trade studies ongoing with results expected late FY 16
- high demand for the science provided by the ACE concept instrument simulators as evidenced by involvement of ACE science team and instrument team members in numerous field campaigns

In light of the aforementioned scientific relevance, continued progress and success in the maturation of instrument technology and algorithm development, ACE leadership has the following recommendations:

- Continue to evolve/mature the TRLs of polarimeter, radar and lidar concepts
- Continue to evolve / mature associated algorithms
- Continue to work closely with PACE Mission leadership to exploit points of intersection and leverage PACE and ACE concepts to enhance scientific return on investment.
- Develop an airborne campaign, or augmented existing airborne campaigns when appropriate, to jointly fly ACE-related lidar and polarimeter concepts onboard the NASA ER-2 suborbital platforms.
- Progress the ACE Mission from pre-formulation to formulation phase in an adaptive fashion as it convergences with recommendations of 2017 DS.

9 Programmatic Assessment and Recommendations

In this section we present the Program Scientist's programmatic assessment and recommendations for improvement of the process of development of Decadal Survey Satellite Missions.

The 2007 Decadal Survey recommended a series of satellite missions with supporting science questions and science traceability matrixes as well as recommendations for sensor payloads and mission architectures. Some of these preliminary mission concepts, ACE included, were assigned to science working groups to develop and refine the Decadal Survey recommendations so the recommended missions could be transitioned from pre-formulation to formulation.

Little guidance was provided as to what was required of the science working groups and when it was due. Into that vacuum, a false sense of urgency pervaded the science working groups, which lead to the perception that the sooner a complete plan was submitted, the sooner that mission would transition from pre-formulation to formulation.

This false sense of urgency lead to a number of undesirable outcomes. First, many aspects of the proposed missions were addressed in a parallel stove-piped fashion. As a result, the refinement of the science questions and development of science traceability matrixes were more separate than they should have been from development of instrument concepts and mission architecture. For example, changes in the science traceability matrixes did not propagate as quickly and completely through the rest of the ACE study as would have been optimal; the process cost more than it should have. Second, worthwhile cross mission fertilization essentially did not take place. Further, neither the augmentation of existing satellite constellations nor the development of next generation satellite constellations were seriously considered. Third, the rush to becoming formulation ready limited working with the Earth Science Technology Office (ESTO) to develop new technologies. This is not to imply ESTO did not work with the Decadal Survey mission science working groups. Quite the opposite is true. However, the interactions were mostly with those who developed sensor concepts. Thus the cross mission, inter-sensor perspective was largely missing.

A remedy for these issues is fairly straightforward. Headquarters should provide guidance as to a task description due date for output from the science working group. Financial guidance would also be helpful. The leadership of the science working groups should be encouraged to carry out the mission studies in a more serial manner. Science questions and science traceability matrixes should be developed first. As the science traceability matrixes become fairly mature, appropriate instrument concept studies should be transitioned from a lower level preliminary state to a larger focused effort. Headquarters should establish a study group whose task is to study cross mission fertilization and augmentation of existing satellite constellations or the development of new satellite constellations. Lastly, plans for mission architecture should be developed based on the recommendations of the science working group and recommendations from the Headquarters instituted cross mission/constellation study group.

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List of Acronyms

ACATS – Airborne Cloud Aerosol Transport System

aCDOM – absorption by Colored/CHROMOPHORIC Dissolved Organic Matter

ACE – Aerosol Cloud Ecosystems mission

ACERAD – Atmospheric Profiling Radar for ACE

ACHIEVE - Aerosol, Cloud, Humidity, Interactions Exploring and Validating Enterprise

ACI – Aerosol-Cloud Interactions

ACR - Airborne Cloud Radar/CloudSat Validation Radar

ACT - Advanced Component Technologies Program

AERONET – Aerosol Robotic Network

AESLA – Active Electronically Scanning Linear Arrays

AFRC – NASA's Armstrong Flight Research Center (formerly Dryden Research Flight Center)

AirMISR – Airborne Multi-angle Imaging SpectroRadiometer

AirMSPI - Airborne Multiangle SpectroPolarimetric Imager

AITT - Airborne Instrument Technology Transition

AMPR – Advanced Microwave Precipitation Radiometer

AMS - Autonomous Modular Sensor

AMSR-E - Advanced Microwave Scanning Radio

AMT – Atlantic Meridional Transect program of the United Kingdo

AOD – Aerosol Optical Depth

APR-2 - Airborne Second Generation Precipitation Radar

APS – Aerosol Polarimetry Sensor

ASIC – Application Specific Integrated Circuit

ASTER - Advanced Spaceborne Thermal Emission and Reflection Radiometer

A-Train – The "Afternoon Constellation" including the OCO-2, GCOM-W1, Aqua, CALIPSO, CloudSat, PARASOL, and Aura satellites.

AVIRIS - Airborne Visible/Infrared Imaging Spectrometer

b_{bp} - ocean particulate backscatter coefficients

BRF – Bidirectional Reflectance Factors

CALIPSO - The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (C

CALIOP - Cloud-Aerosol Lidar with Orthogonal Polarization

CAMP^{2}Ex – Cloud-Aerosol-Monsoon Philippines Experiment

CARES - Carbonaceous Aerosols and Radiative Effects Study

CATS – Cloud Aerosol Transport System

CCN – Cloud Condensation Nuclei

CDOM – Colored Dissolved Organic Matter

[Chl-a] - chlorophyll-a concentration

CloudSat – the NASA satellite-based cloud experiment mission

CO_2 – Carbon Dioxide

C-OPS - Compact-Optical Profiling System

COSSIR - Compact Scanning Sub-millimeter-wave Imaging Radiometer

CoSMIR - Conical Scanning Millimeter-wave Imaging Radiometer

COTS – Commercial Orbital Transportation Services

COVE-2 - CubeSat On-board processing Validation Experiment-2

CPL – Cloud Physics Lidar

CPR – Cloud Profiling Radar

CRM – Common Research Model

C-PrOPS - Compact-Propulsion Option for Profiling Systems

CRS – Cloud Radar System (at 94GHz)

CubeSat - a type of miniaturized satellite for space research that is made up of multiples of 10×10×11.35 cm cubic units

DAOF - Dryden Aircraft Operations Facility

DARF – Direct Aerosol Radiative Forcing

DISCOVER-AQ - Deriving Information on Surface Conditions from COlumn and VERtically. Resolved Observations Relevant to Air Quality

DOLP – Degree of Linear Polarization

DRAGON - Distributed Regional Aerosol Gridded Observation Network

DS – Decadal Survey

EC - EarthCARE - Earth Clouds, Aerosols and Radiation Explorer

eMAS – enhanced MODIS Airborne Simulator

EMC – ElectroMagnetic Compatability

EMI – ElectroMagnetic Interference

ER-2 – NASA/Civilian version of the Air Force's U2-S reconnaisance platform

ERF – Effective Radiative Forcing

ESPO – NASA's Earth Science Project Office

ESTO – NASA's Earth Science Technology Office

EV-I – Earth Venture Instrument

EV-M – Earth Venture Mission

EV-S – Earth Venture Suborbital with EV-S1 being the first round of EV-S funding the EV-S2 being the recently competed and awarded (FY-15) second opportunity of EV-S funding.

EXRAD – ER-2 X-Band Radar

FLH – Satellite Chlorophyll Fluorescence

FPGA – Field Programmable Gate Array

GCM – General Circulation Model

GH – NASA Global Hawk Unmanned Airborne Platform

GIOP – Generalized Inherent Optical Properties

GIOP-DC – GIOP default configuration

GISS – NASA Goddard Institute for Space Studies

GOCECP – Global Ocean Carbon Ecosystems and Coastal Processes mission

GOCI – Geostationary Ocean Color Imager

GEOS-5 – Goddard Earth Observing System Model Version 5

GPM – Global Precipitation Measurement

GPM-GV – Global Precipitation Measurement Ground Validation program

GPU – Graphical Processing Unit

GRASP - Generalized Retrieval of Aerosol and Surface Properties

GroundMSPI – portable, ground-based Multiangle SpectroPolarimetric Imager

GSFC - NASA Goddard Space Flight Center

GSM - Garver-Siegel-Maritorena Algorithm

HARP – HyperAngular Rainbow Polarimeter

HIWRAP – High-Altitude Imaging Wind and Rain Airborne Profiler

HSRL – High Spectral Resolution Lidar

HSRL-1 – First generation

HSRL-2 – Second generation

HyspIRI - Hyperspectral Infrared Imager

ICDH - Instrument Command Data Handling

IDL – Instrument Design Laboratory

IFOV – instantaneous field of view

IIP – ESTO Instrument Incubator Program

IMDL – Integrated Mission Design Laboratory

IOP – Inherent Optical Properties

IPCC – Intergovernmental Panel on Climate Change

IPHEx – Integrated Precipitation & Hydrology Experiment

IRAD – Internal Research and Development

ISS – International Space Station

ITCZ – Inter-Tropical Convergence Zone

JPL – NASA's Jet Propulsion Laboratory

Ka-Band – segment of the microwave region of the electromagnetic spectrum 26.5-40 GHz

Ku-Band - segment of the microwave region of the electromagnetic spectrum 12-18 GHz

LaRC – NASA Langley Research Center

LDCM – Landsat Data Continuity Mission

LED – Light Emitting Diode

LEO – Low Earth Orbit

LES – Large Eddy Simulations

LISST - Submersible Suspended Sediment Sensor/laser particle size analyzer

MAS – MODIS Airborne Simulator

MASTER - MODIS/ASTER Airborne Simulator

MCAD – Markov Chain Adding-Doubling

MCMC – Markov Chain Monte Carlo

MISR – Multi-angle Imaging SpectroRadiometer

ML – Mixed Layer

MODIS – Moderate-Resolution Imaging Spectroradiometer

MPC – Mission Peculiar Cost

mrad - milliradian

MSPI - Multiangle SpectroPolarimetric Imager

NAS – National Academy of Science

NEXRAD - Next-Generation Radar

NIR – Near Infrared portion of electromagnetic spectrum with wavelengths of 0.8-2.5μ

NPEO – NASA Plan for Earth Observations

NPP VIIRS – National Polar-orbiting Partnership Visible Infrared Imaging Radiometer Suite

NRC – National Research Council

OBB – NASA's Ocean Biology and Biochemistry Program

OCEaNS – Ocean Carbon Ecosystem and Near-Shore mission

OE – Optimal Estimation

OLYMPEX - Olympic Mountains Ground Validation Experiment supported by the GPM ground validation (GV) program

OMI – Ozone Monitoring Instrument

ORCA – Ocean Radiometer for Carbon Assessment

OSPREy - Optical Sensors for Planetary Radiance Energy

OSSE – Observational System Simulation Experiment

O_2 A-Band – oxygen absorption band in the electromagnetic spectrum near 0.76μ

PACE – Plankton, Aerosol, Cloud and Ocean ECOSystem mission; formerly Pre – Aerosol Cloud Ecosystem mission

PACS – Passive Aerosol and Cloud Suite multi angle imaging polarimeter

PDF – Probability Distribution Function

PEMs - photoelastic modulators

PhyLM – Physiology Lidar Multispectral Mission

PI-Neph - Polarized Imaging Nephelometer

PODEX – Polarimeter Definition Experiment

POLDER - POLarization and Directionality of the Earth's Reflectances

PSD – Particle Size Distribution

PSG – Polarization State Generator

PWG – Polarimeter Working Group

QAA – Quasi Analytical Algorithm

QRS – Quick Response System

QWPs – Quarter-waveplates

RADEX – Radar Definition Experiment

RFT – Rainbow Fourier Transform

ROIC - ReadOut Integrated Circuit

RPI – Rensselaer Polytechnic Institute

RSP – Research Scanning Polarimeter

RT – Radiation Transfer

SAA – Semi-Analytical Algorithm

SABOR - Ship-Aircraft Bio-Optical Research Field Campaign

SBIR – Small Business Innovation Research program

SCA – Sensor Chip Assembly

SCIPP – Super Composite Image Processing Pipeline

SCPR – Singly Curved Parabolic Reflector

SDT – Science Definition Team

SEAC^{4}RS - Studies of Emissions and Atmospheric Composition, Clouds and Climate Coupling by Regional Surveys

SEL – Single Event Latchup

SEWG – Systems Engineering Working Group

SIDECAR - System for Image Digitization, Enhancement, Control And Retrieval

SNR – Signal to Noise Ratio

SODA - Synergized Optical Depth of Aerosols

SOS – Successive Order of Scattering

SPTS – Sources, Processes, Transports and Sinks

SSH – Seas Surface Height

SST – Sea Surface Temperature

STM – Science Traceability Matrix

STTR – Small Business Technology Transfer program

SWIR – Short-Wavelength Infrared portion of electromagnetic spectrum with wavelengths of 1.4-3μ

Tb – Brightness Temperature

TCAP – Two Column Aerosol Project funded by the DOE

TC^4 – NASA's Tropical Composition, Cloud and Climate Coupling mission

TIRS – Thermal Infrared Sensor

TOA – Top of Atmosphere

TRL – Technical Readiness Level

X-Band - segment of the microwave region of the electromagnetic spectrum 8.0-12.0 GHz

UND – University of North Dakota

UV – Ultra-violet

UV DIAL – Ultra-Violet Differential Absorption Lidar

U10 – Ocean Surface Windspeed

VIS – Visible portion of the electromagnetic spectrum with wavelengths of 0.4-0.7 μ

VNIR – Visible and Near Infrared portion of electromagnetic spectrum with wavelengths of 0.4-1.4μ

W-Band - segment of the microwave region of the electromagnetic spectrum 75 – 110 GHz

WiSCR - Wide-Swath Shared Aperture Cloud Radar

3CPR – Three Band Cloud and Precipitation Radar

$3\beta + 2\alpha + 2\delta$ – Backscatter in 3 Channels (1064, 532 and 355nm), Extinction in 2 Channels (532 and 355nm) and Depolarization in 2 Channels (532 and 355nm)

4STAR - Spectrometers for Sky-Scanning, Sun-Tracking Atmospheric Research