NASA Science Mission Directorate
Research Opportunities in Space and Earth Sciences –2021
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A.45 Decadal Survey Incubation Program: Science and Technology

The National Aeronautics and Space Administration (NASA) solicited Decadal Survey Incubation proposals to accelerate readiness of high priority observables in Planetary Boundary Layer (PBL) and Surface Topography and Vegetation (STV) Targeted Observables (TO) as outlined in the 2018 Decadal Survey, which are not yet feasible for cost-effective flight implementation. PBL and STV science goals call for exploring next-generation measurement approaches that could be ready for spaceborne implementation perhaps in the next decade. This program element supported the development of Earth observing instrument sensor systems, advanced information systems, and enabling science studies to further advance PBL and STV. The ultimate intent of DSI is to enable the next generation of possible measurement approaches, system architectures, and mission concepts to address PBL and STV needs. NASA received a total of 76 proposals in response to this NRA and selected 35 for funding. The total funding to be provided for these investigations for the first year of work is approximately $9.5 million. The investigations selected are listed below. The Principal Investigator, institution, and investigation title are provided.

Chi Ao/Jet Propulsion Laboratory
High Resolution PBL Profiling with LEO-LEO Occultation (HiPPO)
21-DSI-21-0018

The planetary boundary layer (PBL) has been recognized in the 2017-2027 Decadal Survey for Earth Science and Applications from Space [ESAS 2017] as a key Earth science targeted observable essential across multiple discipline areas. ESAS 2017 specifically called out high-resolution vertical profiles of temperature and water vapor as well as PBL height as the most important physical parameters to measure from space. While existing remote sensing technology such as GNSS radio occultation (RO) can provide high vertical resolution refractivity (which is a combination of temperature and water vapor), it cannot disentangle temperature and water vapor within the PBL without a priori information. Emerging technologies such as DIAL (Differential Absorption Lidar) and DAR (Differential Absorption Radar) can potentially yield high resolution water vapor profiles, but they are still at low TRLs and are limited to clear and cloudy sky conditions, respectively. The technological challenges and the motivation for placing PBL observations in the incubation program are recognized by ESAS 2017 and detailed in the NASA Incubation Study Team Report for the PBL.

We propose to study a new instrument concept that offers the potential to simultaneously profile water vapor, temperature, and possibly liquid water content with high vertical resolution within the PBL. The concept is based on an emerging remote sensing technique known as LEO-LEO occultation where amplitude changes in microwave signals in multiple bands (e.g., Ka/Ku/X) are transmitted and received between two low Earth orbiters (LEO) to yield absorption due to water vapor and other atmospheric constituents. The objective of this study is to mature this concept by quantitatively assessing the expected accuracy, sampling and resolution of temperature and water vapor profiles retrievable from LEO-LEO occultation for various PBL regimes covering subtropical ocean, mid-latitude land, and the Arctic. As a result of this study, we will determine the optimal frequencies, component hardware maturity, feasibility of smallsat/cubesat implementation, and orbital configurations to achieve the desired spatial and temporal coverages.

The study will consist of three key parts. First, we will perform a theoretical study to quantify the retrieval accuracy, resolution, and depth penetration for different instrument (e.g., choice of frequencies, SNR) and PBL scenarios. Second, we will characterize the spatial and temporal sampling of these measurements with different orbital configurations, including constellations of smallsats comprised of a few to tens of satellites in varying altitudes and inclinations. It is expected that different orbital configurations will be optimal for the study of different PBL regimes and associated science objectives. Third, we will document instrument performance requirements and assess the current hardware sub-component maturity level, with a goal to enable a smallsat/cubesat class instrument concept. Successful completion of the proposed research will bring this instrument concept, which we refer to as High Resolution PBL Profiling with LEO-LEO Occultation (HiPPO), from an entry TRL of 2 to an exit TRL of 3. Furthermore, we will identify the paths required to mature the technology beyond TRL 3.

The HiPPO instrument concept is a compelling extension of RO signals of opportunity. While similar concepts have been previously proposed to both NASA and ESA, the significant and unique application of such a technique to PBL profiling has never been rigorously explored. The proposal team consists of instrument and retrieval experts in RO and microwave technologies that will ensure that the study objectives are met and to support the technology developments in the PBL Incubation Program.

Avelino Arellano/University of Arizona
Advancing Capabilities for Systems Analysis of PBL and Its Interactions with the Earth System
21-DSI-21-0051

As new concepts to observe the planetary boundary layer (PBL) from space are being planned and current observing systems are subsequently advanced, the ability to integrate these observational constraints into numerical models of weather and climate correspondingly needs to be developed.In response to the NASA ROSES 2021 A.45 Decadal Survey Incubation (DSI) program (2.1.1 PBL Science), we propose to: a) develop and advance ensemble-based approaches to assimilate current and potential future observations of PBL properties within a coupled numerical prediction system (Program Element 2.1.1.2); b) conduct observing system experiments (OSEs) for program of record (POR) datasets to assess how these sensors can be better exploited including their synergies; (Program element 2.1.1.1); and c) conduct sensitivity studies to identify potential gaps and investigate how best to augment the POR infrastructure with new observation concepts. We focus our analysis on systems over the United States using a high-resolution configuration of the NASA Unified Weather and Research Forecasting (NU-WRF) model and an ensemble-based data assimilation software (Data Assimilation Research Testbed, DART). We explore new advances and introduce refinements to contemporary multi-scale data assimilation strategies that would be more practical yet most effective for PBL observations. For example, ensemble-based systems, such as DART, can represent flow-dependent covariances and add new (complex) observation operators without the need of building their adjoints. This is especially relevant for PBL height (PBLH) observations since PBLH is a diagnostic variable in WRF and other NWP systems that needs to be related to the atmospheric state vector through an observation operator and its adjoint. In this work, we take advantage of ensemble covariances between atmospheric states and PBLH variable to construct the necessary observation operator. We conduct a suite of observing system experiments (OSEs) using NU-WRF/DART to demonstrate the impact of PBL height (PBLH) retrievals on short-to-medium range weather forecast. In particular, we assimilate into WRF: 1) lidar backscatter PBLH retrievals from the Automated Weather Service (AWS) network of lidar-based ceilometers, 2) thermodynamic profile retrievals from Atmospheric Emitted Radiance Interferometer (AERIoe), along with 3) GNSS-RO, and 4) conventional meteorological observations (e.g., radiosondes). This observing system (while upward looking) mimics the combination of space-based lidar and hyperspectral IR components for the targeted observables (T,Q profiles+PBLH) identified in the NASA PBL Incubation Study Team Report. First, we analyze their corresponding impacts and synergies using high-quality measurements from 2015 PECAN field campaign. We will then evaluate and assess their constraints on land surface states, especially in updating estimates of surface fluxes, and soil moisture and temperature. Lastly, we assess the robustness of these impacts by conducting short DA experiments on sensitivity to model physics schemes, sampling resolution of PBLH and AERIoe, and regional DA using PBLH across the Unified Ceilometer Network along I-95 corridor. Our emphasis will be on building this capability and creating a robust methodology in exploiting observational synergies across the land atmosphere interface, while addressing inherent (and unique) challenges in assimilating PBL datasets, which exhibit characteristics of nonlinearity, non-Gaussianity, and greater degree of inhomogeneity.

Rory Barton-Grimley/Langley Research Center
Combining Lidar Profiles of Aerosol and Water Vapor to Determine PBL Height
21-DSI-21-0076

The 2017 Decadal Survey for Earth Science Applications from Space (ESAS) as well as the PBL Incubation team report identified the planetary boundary layer height (PBLH) as a Most Important" observable. High resolution observations are required, 5-to-10-fold improvement over the Program of Record (PoR), to improve model representation of key exchange and feedback processes that contribute uncertainty in our understanding of weather and climate systems. Lidar was identified as an optimal measurement candidate in both reports to overcome observational gaps and provide high spatial resolution distributions of PBLHs compared to the PoR. Water vapor (WV) differential absorption lidar (DIAL) was specifically identified for its additional cross-cutting capabilities beyond 'standard' backscatter lidar, providing high resolution WV profiles. Techniques and airborne instrumentation for WV DIAL and for High Spectral Resolution Lidar (HSRL) profiling of aerosol properties have been developed and deployed at NASA Langley Research Center (LaRC) for decades. This airborne PoR forms the foundation of our proposal to combine cross-cutting and synergistic observables of aerosol optical properties and atmospheric state parameters to improve the spatial resolution, coverage, and retrieval accuracy of PBLHs compared to traditional aerosol gradient methods.

The HSRL and DIAL data sets form a rich PoR for advancing PBLH algorithms and determining priorities for future space-based PBL lidar. The LaRC airborne lidar PoR will be leveraged to optimize the accuracy and spatial coverage of a heritage Wavelet Covariance Transform (WCT) PBLH algorithm, remove the need for manual optimization when measurements span diverse atmospheric and geographic conditions, and provide uncertainty estimation. Performance of this heritage algorithm is fundamentally limited in certain environments as current methods employ only lidar backscatter profiles as input. To further constrain the traditional PBLH algorithm to improve accuracy and coverage, additional lidar observables from the airborne PoR will be incorporated, namely depolarization and color ratio as these are advantageous for PBLH determination and are tractable elements for most lidar architectures (i.e., not exclusively HSRL or DIAL).

We propose a threefold approach to optimizing lidar PBLH retrievals and informing the design of a future space-based PBL observing system. First, we will incorporate additional aerosol intensive variables (depolarization and color ratio) into the PBLH algorithm. We will evaluate the extent to which variables independent of aerosol loading intensity can help improve retrievals of PBLH in cases where aerosol gradients confound traditional methods. Second, we will incorporate WV DIAL profiles to further constrain the PBLH retrieval. It is anticipated that high vertical resolution profiles of atmospheric state variables like WV will significantly improve the coverage and accuracy PBLH retrieval over clean open oceans or heterogeneously loaded PBLs where lofted aerosol gradients are adjacent to the surface-connected layer. A sensitivity study will also be performed utilizing the DIAL retrieval's precision-vs-resolution trade space to determine the upper limit on PBLH retrieval resolution; the first work of its kind. To bookend the advances in the PBLH retrieval and inform the formulation of a future space-based PBL optimized lidar, we propose to employ the optimized algorithm to simulated space-based lidar scenes using both airborne and reanalysis data to generate the scene. We will employ a flexible instrument forward model, novel signal processing techniques, and a combination of lidar observables to evaluate the improvement to the coverage and accuracy of PBLHs retrieved from space-based lidar compared to the PoR. These improvements will be documented and help the formulation of a future PBL optimized space-based DIAL. The period of performance for this project is 36 months.

Ruben Delgado/University of Maryland Baltimore County
Quantifying the Accuracy of Combined Artificial Intelligence Microwave/Optimal Estimation Infrared Single Footprint All-Sky Retrievals in the Planetary Boundary Layer
21-DSI-21-0033

We propose to assess the accuracy of thermodynamic retrievals in the Planetary Boundary Layer (PBL) using the current generation of satellite-based microwave (MW) and infrared (IR) instruments. When compared to measurements from aircraft and continental US ground based lidar/ceilometers (L/C)networks and global sonde database, will allow us to carry out the assessment over all seasons and under a variety of climate conditions. An important parameter, namely the PBL height (PBLH), will be computed from satellite instrument retrievals using the derivative of the relative humidity with respect to pressure.

The combined MW and hyperspectral IR sounder thermodynamic retrieval will work at the single field of view IR horizontal resolution (currently 15 km) under heterogeneous cloud conditions. The microwave sounder will provide thermodynamic profiles even if the conditions are cloudy; the infrared sounder will improve the vertical resolution of the retrieved products. The core of the retrieval will be a combination of MIIDAPS-AI, an Artificial Intelligence (AI) based algorithm for the microwave (MW/IR) retrievals, fed into a physically based Optimal Estimation Method (OEM) algorithm coupled to a fast scattering radiative transfer algorithm (RTA) for the infrared retrievals. The novelty of the single footprint infrared (SFPIR) retrieval is the cloud initialization (cloud loading, cloud top/bottom, cloud fraction), using a combination of best initial fit" clouds from a Numerical Weather Prediction (NWP) model and cloud profiles obtained from the AI/MW retrieval. Two (randomly overlapping) clouds can be handled in each retrieved column, either or both of which can consist of ice particles or water droplets.

The flexibility of the AI retrieval will allow us to switch between generating AI MW only, AI MW+IR or AI IR only profiles as initialization for the physically based SFPIR retrieval. The modular design of the AI(MW/IR)/SFPIR code will allow us to easily switch between sensor pairs such as NOAA's Cross Track Infrared Sounder (CrIS) and the Advanced Technology Microwave Sounder (ATMS) on the Suomi and JPSS satellites, or the Atmospheric Infrared Sounder (AIRS) and the Advanced Microwave Sounding Unit (AMSU) on board NASA's Aqua satellite. We anticipate that our methodology will immediately achieve the following improvements over existing IR sounder products (AIRS L2, AIRS and CriS NUCAPS): (a) retrievals at the native resolution of the sounders (15 km) instead of the 3x3 45 km footprint currently achieved using cloud clearing (b) improved yield of retrievals (currently 60% globally) and easier quantification of quality assurance (using the degrees of freedom).

Validation and quantification of PBL parameters will use a combination of radiosondes, aircraft and ground based (L/C) data. Thermodynamic profile validation will include radiosonde data (from Global Climate Observing System (GCOS) Reference Upper-Air Network (GRUAN)), DOE Atmospheric Radiation Measurements, profiles from ground-based (L/C) and MW radiometer data, lidar profiles from airborne instruments and AIRS and CriS L2 products.

Importantly, in line with the requirements of this call, we will also have access to water vapor and aerosol extinction profiles from the NASA Langley's aircraft-borne High Altitude Lidar Observatory (HALO). We have combined experience in using AI based algorithms to detect boundary layer thickness from lidars and will apply this knowledge to studying the thermodynamic retrievals from the combined AI(MW/IR)/SFPIR retrieval.

The proposal is highly relevant to the A.45 Decadal Survey Incubation" solicitation, as it will generate a new data set that quantifies how well a novel all-sky thermodynamic retrieval using data fusion from the current generation MW/IR instruments, can capture properties of the planetary boundary layer, in particular the PBLH.

Timothy Dixon/University of South Florida, Tampa
DEMs from Satellite and Ultra-High Resolution UAV platforms: Mitigating Trade-Offs for Arctic Permafrost and Sub-Tropical Coastal Wetland Applications
21-DSI-21-0062

Improving Digital Elevation Models (DEMs) in terms of spatial resolution, vertical accuracy, and frequency of coverage, would help to address a host of scientific and practical applications. A satellite-based global model would be especially useful, but of course would be unable to meet some of the more demanding requirements, presumably the domain of more detailed local surveys. NASA's recent Surface Topography and Vegetation Study Team report (Donnellan et al, 2021) examined many of the trade-offs, but gaps remain in assessing requirements for certain environments.

Here we propose detailed studies in two such environments, Arctic permafrost and a sub-tropical coastal wetland. In both cases a two meter DEM already exists, but more detailed information is required to maximize the science. In both areas the ability to separate bare earth elevation from vegetation height is crucial. The Arctic environment in particular would benefit from improved vertical accuracy to measure elevation change as the volume difference between ice and water means that areas undergoing permafrost thaw generally experience significant elevation loss. Both environments are also evolving rapidly due to climate change, and the Arctic environment has the potential to accelerate this change via feedbacks in the carbon system. Preliminary work suggests that simply improving the vertical accuracy of existing DEMs would enhance utility in both environments. Such improvements in DEMs would facilitate change detection, improve vegetation change measurements, and allow merging with more precise local data. Our preliminary work also suggests that some LiDAR products considered to be bare earth do not reliably return bare earth elevation in regions of dense vegetation.

We propose to generate a series of ultra-high resolution and accuracy DEMs (~ 5 cm 3-D RMS) using UAV-based Structure from Motion photogrammetry, airborne or UAV-based LIDAR, and high precision GPS-GNSS tracking. Our short-term goal is to measure and understand elevation change in the two test areas. Our long-term goal is to provide guidance on cost-effective high resolution elevation measurement techniques in these two contrasting environments.

Andrea Donnellan/Jet Propulsion Laboratory
High-Resolution Stereophotogrammetry and Analysis for Achieving STV DSI Goals: 3D and 4D topography
21-DSI-21-0003

We will mature the airborne Quantifying Uncertainty and Kinematics of Earth Systems Imager (QUAKES-I) into an end-to-end operational system. This includes maturing data processing, understanding optimal experiment design, quantification of uncertainties, and developing information tools for analysis of QUAKES I data products. This project will analyze and create information system tools, primarily from airborne QUAKES-I data collected with an 8-camera array that flew in June 2021 over the Grand Canyon and along numerous fault and wildfire-modified features in California totaling over 7500 km of 12 km wide swaths. The two flights produced over 9.6 TB and 480,000 images. Challenges exist in processing and managing the large volumes of data. Tools are needed to extract scientific information from the data products, manipulate and preprocess the raw imagery, and extend existing stereophotogrammetry techniques to incorporate the multiple stereo views provided by QUAKES-I in the computation of the data products. Entry and exit TRLs are 5 and 7.

The key technological need fulfilled by this project is a robust processing and analysis workflow for diverse and large-scale optical photogrammetry data. It will enable the production of high-resolution topographic data and its application to three-dimensional and four-dimensional multitemporal analyses. Deployment of overhead optical imaging sensors has increased dramatically in recent years and stands as the most rapidly collected form of high-resolution data available following seismic, volcanic, and environmental hazard events. Algorithmic and technological development is required to process and manage these rapidly acquired data sets, along with recent and legacy collections to baseline pre-event characteristics, to generate rapid analysis of landscape change, and to develop topographic metrics required to understand solid earth, earth-surface, and ecological changes across landscape scales.

The objectives of this work are threefold. 1) Improve processing speed and algorithms for stereophotogrammetric products, in particular those derived from QUAKES-I and follow-on systems, 2) Quantify uncertainty and improve accuracy of the data products, and 3) develop tools to compute geomorphic metrics, detect change, and carry out science analyses using stereophotogrammetric products. We expect to improve significantly the production, accuracy, and availability of stereophotogrammetric data products of Earth's land surface for science studies. This work addresses gaps in information systems and stereophotogrammetry identified in the STV Study Report (Donnellan et al, 2021). Information Systems and Stereophotogrammetry are both essential technologies identified in the STV Study Report necessary to collect the data and to produce useful data and knowledge products. We will develop tools to extract science information from single baseline measurements and to measure change and quantify uncertainty from repeat measurements from the same or different platforms. These tools and prototype data products will be developed with practical application and usability in mind given the broad experience of the proponent team.

This project addresses NASA's Earth Surface and Interior Program goals and will improve understanding of land surface processes including earthquakes, landslides, and post-wildfire effects. The project supplies complementary observations to UAVSAR. Information Systems and Stereophotogrammetry are technologies identified in the STV Study Report. Sub-meter baseline measurements and ability to measure change over time are key needs identified. We will develop tools to extract science information from single baseline measurements and to measure change and quantify uncertainty from repeat measurements from the same or different platforms. These tools and data products will be developed with practical application and usability in mind given the broad experience of the proponent team.

Antonia Gambacorta/Goddard Space Flight Center
A Combined Passive-Active, Multi-Sensor Approach to Earth's Planetary Boundary Layer (PBL) Sounding
21-DSI-21-0040

The overarching goal of this proposal is to develop and demonstrate a novel passive-active multi-sensor data fusion retrieval algorithm of thermodynamic (temperature and water vapor) profiles with improved structure in the PBL. The proposed work builds upon state-of-the-art expertise in active (BSL) and passive (infrared; IR, microwave; MW) operational sounding algorithms to address three fundamental objectives: 1) harness information content in the PBL vertical structure and depth from active measurements where passive measurements are lacking; 2) verify and quantify the enhanced 3D thermodynamic structure achieved by this data-fusion approach in the PBL; 3) perform signal/noise trade studies and simulation sensitivity experiments intended to inform future pathways (e.g., enhanced passive and active sensors) to filling technology and uncertainty gaps. To this end, the proposed algorithm is a modular design intended to be expandable to future sensors to build the algorithm infrastructure needed for future integrated observing systems architectures and will have long-term viability for PBL Incubation regardless of specific instrument development paths.

This work integrates Artificial Intelligence/Machine Learning (AI/ML) tools to harness PBL information content in existing Program of Record (POR) left underutilized by the complex nature of the data-fusion processing. Conceived with a user's application focus, a significant part of the proposed research is the verification that the scientific requirements expressed in the NASA PBL Study Team Report Science and Applications Traceability Matrix are met by this algorithm.

The proposed work is relevant to the program element because it aims to develop algorithms, approaches to sensor fusion using POR data" and harnesses content in existing POR data sets for PBL information content via data mining, machine learning techniques". It proposes feasibility investigations to leverage the POR to harmonize different PBL observations towards a merged product (e.g., active and passive measurements).

This work should be funded now because it proposes to exploit POR datasets for making advancements to prepare for measurements from the space environment and provide information for future space-based architectures". It proposes key activities that are important to accomplish early in the incubation period" such as: determining gaps, exploiting the POR, simulations, and trade studies" (A.45 proposal announcement, Section 2-1, page 4).

Craig Glennie/University of Houston
Characterizing Expected Uncertainty in Spaceborne High-Resolution Terrain Models for Examining Surface Processes
21-DSI-21-0030

The Decadal survey and the surface topography and vegetation study report both highlighted the uncertainty in the requirements for horizontal resolution and accuracy of a future high-resolution topography mission. A primary cause of this uncertainty is the unknown linkage between the scale and magnitude of surface processes proposed to be studied and the raw satellite observations required to sufficiently observe these processes. The linkage is difficult to define because the nature of the surface being observed will have a direct effect on the requirements for accuracy and resolution rough terrain and/or the presence of vegetation cover will require higher resolution and lower uncertainty to model at the same magnitude and scale as for a smooth and non-vegetated surface. This proposal seeks to fill these fundamental knowledge gaps by: (1) examining the relationships that link surface parameters such as slope, roughness and vegetation cover to uncertainty in the modeling of that surface, (2) developing a rigorous model to estimate the uncertainty in surface locations due to space-based lidar observing system errors, and (3) determining the capacity of a high-resolution STV mission to estimate surface change from temporally spaced high-resolution surface models. This characterization of expected targeted observable errors will elucidate the connections between the achievable accuracy for observing surface processes and the uncertainty in the raw satellite observables, enabling a better understanding of the observing platform specifications required to meet the STV mission science and applications goals, objectives and product needs.

Richard Hodges/Jet Propulsion Laboratory
Deployable MetaLens for G-Band Earth Science Applications
21-DSI-21-0073

This proposal addresses the Decadal Survey Incubator (DSI) call for disruptive technologies that enable innovative SmallSat-based measurement techniques to meet Planetary Boundary Layer (PBL) science objectives. The key objective is to develop a deployable G-band high gain antenna that reduces instrument size, weight and power (SWaP) to enable a new measurement capability that is not currently feasible. Specifically, the 2019 NASA decadal survey incubation program focused on priority PBL science and technology components that require advancement and development prior to implementation. The PBL Study Team Report, Toward A Global Planetary Boundary Layer Observing System" identified G-band Lightweight Deployable Antennas" as one of the five key technologies needed to enable a PBL mission.

The proposed antenna technology is a unique new artificial dielectric lens. Lenses have long been favored as a simple and effective method to focus light because they are less sensitive to tolerances than a reflector antenna and have no aperture blockage. Despite these advantages, lenses are rarely used at microwave or mm-wave frequencies due to size, mass, and fabrication challenges. This proposal brings lens advantages to the mm-wave band by using an artificially engineered metal particle dielectric lens, or MetaLens, that overcomes these limitations. We will develop a deployable multi-layer MetaLens antenna design that enables future PBL missions. This breakthrough in antenna technology is needed because solid composite reflectors are currently the only large (~2 m) G-band antennas available. These composite reflectors are very expensive and do not stow compactly, which limits their applicability for PBL missions. MetaLens is an innovative new technology that will provide a lightweight and comparatively low-cost and antenna that can meet SmallSat stowage requirements.

The MetaLens fabrication concept uses multiple layers of polyimide sheets, each with a pattern of photoetched copper disks. This three-dimensional array of disks creates an artificial dielectric that can produce a wide range of permittivity values, and supports inhomogeneous and/or zoned lens designs. The mechanical concept is to stack closely spaced (< lambda/5) sheets on a frame, which permits the lens to be folded for deployment. A related antenna concept, the tensioned membrane reflectarray, was successfully demonstrated at 32 GHz by John Huang at JPL, but the practical utility of his innovative antenna was limited by reflectarray tolerances. A tensioned membrane MetaLens effectively eliminates this problem because surface positioning tolerances are relaxed by an order of magnitude, so that membrane displacement errors do not significantly degrade or modulate RF performance. Moreover, unlike a reflectarray, the artificial dielectric is not a resonant electromagnetic structure   the permittivity is determined by volume density of the disks etched on each sheet, which means that transmission phase is not highly sensitive to Kapton sheet separation distance. Periodic laser cut polyimide sheets can be bonded to the layers to insure proper nominal separation. The entire assembly can be folded for stowage using a mechanism. A similar deployment mechanism was recently demonstrated on the JPL LADeR deployable reflectarray.

Radar instruments are currently in development that address the key PBL science objectives. However, a breakthrough in antenna technology is essential to realize the potential of these new radars. This proposal will leverage recent investments in lens technology in order to provide an innovative new technical approach to G-band radar antennas.

Entry TRL=2. Exit TRL=4

Fredrick Irion/Jet Propulsion Laboratory
Boundary Layer Measurement with Combined Near and Thermal-Infrared Observation
21-DSI-21-0005

Hyperspectral thermal-infrared instruments have good sensitivity to temperature and water vapor through the free troposphere, but can often lack sensitivity in the planetary boundary layer. Near-infrared instruments have good sensitivity to water vapor and temperature in the boundary layer over land and ocean glint, in clear and near-clear conditions using reflected daylight, but can lack sensitivity through the free troposphere.

We propose a study of boundary layer to free troposphere measurement of temperature and water vapor profiles by combining near-infrared spectra from the Orbiting Carbon Observatory-2 (OCO-2) with single-footprint, thermal-infrared spectra from the Atmospheric Infrared Sounder (AIRS) in a joint retrieval system. Combining these programs-of-record measurements can provide a consistent information content analysis and error estimation. Results will help guide decision-making and resource allocation in the development of remote sensing for the planetary boundary layer and its interactions with the free troposphere above.

Robert Knuteson/University of Wisconsin, Madison
Refining Planetary Boundary Layer Remote Sensing Requirements Using Merged Orbital And Sub-Orbital And Merged Active And Passive Observations From The Program Of Record
21-DSI-21-0031

The overarching goals of the DSI program are to promote (1) innovation in the research, development, and demonstration of new measurement technologies in preparation for future integrated observing system architectures, and (2) science activities that support maturation of measurement concepts, retrieval algorithms, models, data assimilation, and/or integrated observing system approaches. We propose to exploit datasets from the Program of Record (POR) sensors to create new merged passive and active, orbital and sub-orbital products along with validation truth data that can be used to refine remote sensing requirements of the Planetary Boundary Layer (PBL) thermodynamic state and PBL height. The ultimate goal is to help define the next generation of sensors that can probe the PBL over all climate regimes to augment future Earth observations from operational weather satellites.

Five tasks are proposed to address the four PBL science goals:
G1. PBL, Convection and Extreme Weather.
G2. Cloudy PBL.
G3. PBL and Surface Interaction.
G4. PBL Modeling, Mixing and Air Quality.
The global daily coverage of hyperspectral infrared and microwave sounders will be merged with 1) ground-based hyperspectral infrared data, and 2) active sensor profiles from radio occultation. These data will be used to quantify the spatial, vertical, and temporal uncertainties in the Program of Record and inform the future of space-based observations to monitor the PBL.

The expected significance of this project is that the PBL science team will have early access to quality merged datasets that can be used to test and refine PBL retrieval algorithms and OSSE data assimilation techniques. In addition these merged datasets will provide the basis for simulation studies of hyperspectral infrared channel selection and information content for refinement of future measurement requirements from space.

Keith Krause/Battelle Memorial Institute
Globally-Derived Measures of Structure Informed by Ecological Theory and Observation
21-DSI-21-0027

Lidar is an invaluable remote sensing tool for 3d measurement. However, instruments have platform constraints and are typically driven by what technology is currently available rather than by science requirements or data quality/utility. Informed by ecological knowledge gaps and model limitations, and focusing on the next generation of lidar-based products, the project objectives are to:
1. Identify the suite of next generation" lidar derived data products, akin to LAI, that are broadly useful to advancing and improving modeling application and fundamental ecological knowledge across scales;
2. Assess the capabilities and limitations of current lidar systems to produce ecologically meaningful next generation data products;
3. Determine the instrument parameters of future systems needed to derive next generation lidar products;

4. Evaluate the accuracy and uncertainty of next generation data products across several spatial scales including change with time.

The high-level work plan is broken into three categories: ecological relevance, existing data sets, and simulation. All categories will begin with an evaluation of common lidar derived data products, such as those listed in the STV Study Report. The ecological relevance aspect of the project will aid in the identification and development of next generation structural indices of broad interest to ecologists, modelers, and remote sensing scientists. Candidate structural indices will be selected based on ecological criteria, with prioritization given to indices that correlate with ecological processes at multiple spatial scales and across ecoregions. The indices will be produced from existing data sets (if possible) and/or will be developed from simulated lidar data sets. Existing data sets include but are not limited to: GEDI, ICESat2, LVIS, MABEL, Sigma Space MPL, G-LiHT, NEON AOP, UAS, and TLS field data. Coincident data collections of most of these sources exist for a few instances and those sites will be prioritized, however, comparisons for a subset of data sources will be necessary from other sites/times in order to span the variety of measurement techniques, sampling strategies, and instrument parameters. Simulations will be performed using Rochester Institute of Technology's DIRSIG software where inputs of scene geometry, optical properties, and instrument/collection parameters can be controlled and modified. DIRISG has a long heritage of simulating linear mode discrete and full-waveform lidar and is capable of simulating Geiger-mode lidar. In addition to evaluating existing instruments and next generation systems/platforms, DIRSIG provides significant flexibility for trade studies of instrument and collection parameters plus contains truth information about the physical vegetation structure in the scene. For all three work plan categories, tasks will include evaluation of data quality/utility, assessment of accuracy/uncertainty, and analysis at different spatial scales.

The proposed research contains Science activities to support the objectives of the targeted observable Surface Topography and Vegetation as described within the NASA ROSES2021 A.45 Decadal Survey Incubation Program Element, with a core focus on vegetation structure (including underlying surface topography) and will address knowledge, methodology, algorithm, and measurement gaps. The work plan has applicability to all 6 vegetation structure knowledge gaps identified in the STV Study Report, although the focus will be on current plus needed quality/accuracy of 3D vegetation structure, understory, and structural diversity products evaluated across a variety of different ecoregions (including sparse and low vegetation). A technology gap related to sampling density and footprint size is also relevant. This study will assess the quality, accuracy, and uncertainty of lidar instruments, collection methods, and resulting data products necessary to address several questions from the Decadal Study.

Rachael Kroodsma/University of Maryland, College Park
Hyperspectral Capability for CoSMIR: Enhancing Capability for Future PBL Suborbital Campaigns and Enabling PBL Science from Space

21-DSI-21-0041

The NASA Planetary Boundary Layer (PBL) Incubation Study Team found that hyperspectral microwave sounders are an Essential Component" of a future global PBL observing system due to their perceived ability to capture the three-dimensional structure of temperature and water vapor in the free troposphere. As such, significant resources have been directed at building this capability as part of a comprehensive technology portfolio targeting PBL science. In this proposed effort, we will upgrade the Conical Scanning Millimeter-wave Imaging Radiometer (CoSMIR) with new hyperspectral receivers including wideband application specific integrated circuit (ASIC) spectrometers developed under SBIR (80NSSC18C0102). Subsequent test and engineering flights with the new CoSMIR Hyperspectral (CoSMIR-H) will provide airborne validation of the hyperspectral architecture and demonstrate advancement in high-resolution measurement of the thermodynamic structure of the boundary layer by using hyperspectral microwave radiometry.

Recent modeling studies performed internally at Goddard and elsewhere have supported the assertion that hyperspectral microwave radiometry can provide temperature and humidity profiles with vertical resolution superior to traditional microwave sounding architectures. The fine spectral resolution over wider bandwidth translates to this improved vertical resolution while also reducing uncertainty. Additionally, when compared with infrared sounding, microwave sounding is less sensitive to trace gasses with better penetration through clouds. These benefits of hyperspectral microwave sounding are what led the PBL Incubation Study Team to emphasize the value of these observations.

To address the needs of the PBL science community, our team aims to deliver a highly capable airborne hyperspectral microwave sensor that will demonstrate high spectral resolution profiling and support future suborbital campaigns probing the PBL. Moreover, CoSMIR-H will validate the critical 4-GHz spectrometer ASIC technology. The effort will modify the V-band (temperature) and G-band (water vapor) receivers of the well-regarded CoSMIR with hyperspectral capability using the ASIC spectrometers as an enabling component. Importantly, our team will implement a new data system that can capture and process the finely resolved spectra. Laboratory and airborne demonstration will raise the Technical Readiness Level (TRL) of the hyperspectral profiling technique from 2 to 6.

Marco Lavalle/Jet Propulsion Laboratory
An OSSE Framework for STV Multi-Mission Design and Performance Evaluation
21-DSI-21-0001

Multiple and simultaneous synthetic aperture radar observations taken from different look angles (i.e., operating in multi-baseline interferometric or tomographic mode) have the potential to provide high-resolution, gap-free maps of vegetation structure and underlying topography with characteristics reported in the 2021 Surface Topography and Vegetation (STV) Study Report. We propose to develop a scalable community-based Observing System Simulation Experiment (OSSE) Framework to evaluate the multi-mission STV observational needs, and implement a multi-static Radar OSSE Component to quantify the end-to-end TomoSAR/PolInSAR performance of distributed smallsat radar formations for STV. The specific goals of our proposal are to: (1) Architect and implement a modular and scalable OSSE framework for STV with the required flexibility to support multiple OSSE components associated with different observational technologies and measurement approaches; (2) Design and implement a specific OSSE component for end-to-end simulations of multi-static/tomographic and polarimetric-interferometric radar measurements; and (3) Conduct a rigorous and comprehensive trade study using the radar OSSE component to design a multi-static radar mission concept for multiple STV needs.

Stephen Leroy/Atmospheric & Environmental Research, Inc.
Profiling Water Vapor in the Planetary Boundary Layer using GNSS RO in Data Assimilation
21-DSI-21-0049

The planetary boundary layer (PBL) has been designated a high priority for theoretical investigation and remote sensing by the NASA Earth Science Decadal Survey of 2018 because the uncertainties in the workings of the PBL and the inadequacies of its parameterization are driving large, unresolved and under-addressed uncertainties in a wide range of fields in the atmospheric and climate sciences. For the Decadal Survey Incubation (DSI) program, we will initiate a project that will advance the science of the retrieval of water vapor in the PBL, will test and validate two candidate retrieval schemes with program-of-record (POR) data, will finalize the development and implement an accurate and extremely efficient tool to find collocations of RO data and scanner data types, and will implement the retrieval schemes and collocation algorithm in a data preprocessor for infusion of high vertical resolution profiles of water in the PBL into the GEOS-5 data assimilation system.

First, two PBL water vapor retrieval schemes will be tested and validated, one that fuses GNSS radio occultation (RO) data with passive nadir microwave soundings (MW), and another that fuses GNSS RO with the forecasts of a numerical weather prediction system (NWP). The schemes will be tested with POR GNSS RO data (Metop and COSMIC-2) and POR MW data (Suomi-NPP, NOAA-20, Metop) and validated against high vertical resolution radiosonde profiles of water vapor. The PI recently completed a project that showed that both schemes can theoretically retrieve water vapor with 2% precision, near perfect accuracy, and with 100-meter vertical resolution. Second, we will finalize a fast and accurate algorithm to find RO+MW collocations and will implement it for operational retrieval and data assimilation. Mature development already shows the algorithm to be 98% accurate and 1,000 times faster than a standard, brute force approach. Finally, we will implement the retrieval schemes and the collocation tool into a data preprocessor for the GEOS-5 data assimilation system. The data to be assimilated will be retrievals of water vapor in the PBL, making the assimilation of RO data much more likely to positively impact PBL water vapor than previous attempts at assimilating RO data. This project is a continuation of two other projects, one funded by the U.S. Air Force, and the other funded by the National Science Foundation. Theoretical demonstrations of the retrieval algorithms shows that both greatly exceed the performance of other proposed retrieval algorithms according to their theoretical performance because of the robustness of the MW and NWP soundings and the amount of information mined from these data. This work responds directly to the DSI call by advancing GNSS RO retrieval by fusing it with other data and by developing tools that will enable these retrieval schemes to improve the analysis of PBL water vapor in data assimilation.

The work to be done is to be considered PBL Science", addressing the advancement of retrieval algorithms, testing on POR data, and developing tools needed for mission architecture studies. We have assembled the team necessary to the successful completion of this work, mentoring a graduate student in the process. Dr. Stephen Leroy (PI; AER) and Dr. Rob Kursinski (Collaborator; PlanetiQ) are well-known experts in GNSS RO and its application to atmospheric and climate research, possessing over 50 years of experience in the field. Prof. Kerri Cahoy (Co-I; MIT) is a leader in the design and development of RO and MW nano-satellites and the science of fusing GNSS-RO data with MW data. Dr. Mohar Chattopadhyay (Co-I; SSAI/GMAO) is an expert in data assimilation and is responsible for the assimilation of new data types into the GEOS-5 system. Dr. Kursinski (PlanetiQ) is the progenitor of RO retrieval algorithms that correct for super-refraction thus enabling the unbiased, precise, and high vertical resolution retrieval of water vapor in the PBL.

Zhen Liu/Jet Propulsion Laboratory
Assessing the Sensitivity and Measurement Needs of Surface Topography Towards the Study of Earthquake and Fault Creep Processes
21-DSI-21-0006

This proposal aims to understand the effects of high-resolution topography and change on earthquake and fault displacement science by exploiting existing digital elevation models (DEMs), optical imagery, lidar and interferometric synthetic aperture radar (InSAR) data. We will test the resolution and accuracy needs on deformation measurement and geophysical studies of earthquakes and fault creep through global earthquake simulation and selected target studies.

We have three objectives:
1) Quantify the resolution and accuracy needed for capturing earthquake related topography change. We will do so through a global analysis along with selected focused studies (objective 2). For global analysis, we will use SRCMOD, a global compilation of finite-fault earthquake rupture models of past earthquakes (http://equake-

rc.info/srcmod/), which occurred over a diverse range of tectonic settings, vegetation coverage, magnitudes of ~4.5-9.1 and variable focal mechanisms (strike-slip, thrust, normal, mixture), to simulate topography changes from these earthquakes, perform trade-studies between desired topography resolution/accuracy, and instrument measurements needed from a future STV mission.
2) Assess the impact of high-resolution topography measurements on details of earthquake rupture and postseismic deformation mapping using the 2019/07 Ridgecrest earthquake sequence and the 2013/09/24 Mw7.7 Baluchistan earthquake as target events. Our preliminary results from the topography difference of optical-derived digital surface models (DSMs) reveal complex fault geomorphology and near fault deformation including non-negligible vertical displacements for both events (see 1.1.1.2 for details). We will use the two events as case studies to assess the sensitivities of lidar and photogrammetric techniques and existing data to 3-D differential topography displacements associated with earthquakes, and examine the impact of detailed topography change on earthquake models. We will use the Ridgecrest earthquake as a selected example, thanks to the availability of a hybrid set of post-earthquake airborne lidar and high-resolution satellite optical images, to develop the integrated analysis of multi-sensor data for mapping the topography change and 3-D deformation following the earthquake. We will assess the capability improvement by leveraging the strengths of complimentary measurements (lidar and stereo photogrammetry).
3) Assess the sensitivities of fault slip studies to the resolution and vertical accuracy of global baseline topography and repeat measurements. The bare earth DEM is essential in InSAR processing (e.g, topography phase correction, image co-registration, geocoding) to obtain reliable deformation measurement from InSAR. How different DEMs, as a function of resolution and accuracy, affect InSAR mapping of near fault creep processes is not well understood. We will use the central San Andreas fault as a target area, where NASA UAVSAR measurement with high spatial resolution of ~5x7m at 3x12 range x azimuth looks, a suite of bare earth DEMs with various spatial resolution/accuracy are available to test the sensitivities of fault creep and off-fault deformation to different DEM products. In addition to baseline DEM effects, we will also exploit the joint use of lidar and high-resolution stereo photogrammetry data for 3-D differential topography displacement rate estimates, uncertainty characterization and reduction in rate of change for fault creep study. We expect the insights from this study will help inform the architecture design and observing strategy of a future STV mission towards global mapping of fault zone landscape change and creep processes.

Paul Lundgren/Jet Propulsion Laboratory
STV Volcano Science and Applications Observation
21-DSI-21-0002

Volcanoes experience some of the largest and most dynamic topographic changes of any Earth surface process, spanning a wide range of spatial and temporal scales. Processes include creating topography through extrusion of new lava flows or domes, or removing topography by explosive eruptions, caldera and sector collapse. During eruptions, volcanoes also change topography by depositing ash or pyroclastic flows or even between eruptions through remobilization of deposits from lahars and landslides. The highly variable nature of these processes in space and time places stringent constraints on the spatiotemporal requirements for topography data products.

We will focus on three mutually linked topics relating topography and its change to hazard assessment and mitigation: 1) Dynamical models of volcanic eruptions; 2) The effects of topography quality on lava flow dynamics, slope instability and pyroclastic flows; 3) Assess candidate observing methods and architectures based on data analysis and simulations in topics (1) and (2).) the 2018 K+lauea, eruption, Hawaii, featuring caldera collapse and large basaltic lava flows; 2) silicic lava flows and dome eruptions: Cordón Caulle and Nevados de Chillán, Chile; Ibu, Indonesia; La Soufrière, St. Vincent, West Indies; and Great Sitkin, Alaska; 3) slope stability at Sinabung, Indonesia, and pyroclastic flows at Fuego, Guatemala. Datasets will include: TanDEM-X (TDX), GLISTIN-A, EarthDEM, Planet, Pleiades, and locally acquired Lidar and photogrammetry.

Dynamic volcano source modeling will build off of existing models for caldera collapse-effusion (Roman and Lundgren, 2021) and lava dome extrusion (Delgado et al., 2019). Flow simulations will use existing software for lava and pyroclastic flows (e.g. VolcFlow, Kelfoun and Vallejo-Vargas, 2016; DOWNFLOW, Favalli et al., 2005), dome and slope instability potential (Scoops3D; Reid et al., 2015) as well as advanced physics-based dynamic models. We will use flow thickness to constrain lava flow forecasts, where both the spatial quality and temporal sampling affect model predictions.

Our proposal responds to the A.45 2.2.1 STV Science component by combining exemplary topography observations from recent radar, lidar, and stereo-photogrammetry observations with physical forecasting models to quantify the product needs for volcano science and applications. Through it we will create the analysis tools during the current decade to support the development of Surface Topography Vegetation (STV) observing capabilities through the next decade.

Our proposal responds to A.45 2.2.1 STV Science component of the NRA. Through the combination of exemplary topography observations from recent radar, lidar, and stereo-photogrammetry observations combined with physical forecasting models we will quantify the product needs and develop the analysis tools during the current decade that will support the development of STV observing capabilities in the next decade.

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Lori Magruder/University of Texas, Austin
Exploring the Quality of Space-Based Laser Altimetry and Imagery Data Fusion for Benthic Studies and Coastal Processes
21-DSI-21-0036

Addressing the Surface Topography and Vegetation (STV) science priorities for filling knowledge, methodology and algorithm gaps using program of record (POR) is a goal of this project. This effort will focus on exploitation of existing resources for uncertainty quantification, and sensitivity analyses with a goal of advancing the current understanding of measurement quality and system performance relative to geophysical and operational information (Decadal Survey Incubation (DSI) topic 2.2.1). More specifically this proposal will look to determining the capability and quality of bathymetry elevation retrievals with respect to environmental and system acquisition influences on space-based laser altimetry for morphological change and benthic habitat characterization.
As stated in the 2017 Decadal Survey (DS), Earth Observation from Space: A transformative capability, satellite based observations allow us to see the extent to which Earth's ever-changing processes influence our lives". This is a true sentiment but definitely realized when the Ice, Cloud and land Elevation Satellite-2 (ICESat-2) launched in 2018 and opened eyes with respect to high-resolution along-track surface elevations at the global scale with a new type of active remote sensing technology. Possibly even more transformative with this mission was the realization of shallow water bathymetry from an altitude of ~500 km above the surface. This capability of ICESat-2 allows for the generation of underwater topography with highly accurate vertical certainty and the opportunity to merge the data with other resources/products to enhance our understanding further, either spatially or temporally.
In response to the 2017 DS, NASA formed an incubation study around the STV targeted observable to identify knowledge gaps, sensor needs, and required measurements deemed critical for understanding impacts associated with climate change on our ecosystems. The STV incubation team's final report highlighted methods and activities to improve science, applications, as well defining the measurement technologies necessary to achieve the science goals. Along with solid earth, cryosphere, vegetation structure, and hydrology, coastal processes are a recognized focus topic in need of better understanding regarding how they react to climate variability and how those changes will subsequently affect societal resources. As such, the motivation behind this proposal is to improve our understanding of critical observations to support coastal process discoveries such as sediment transport (erosion and deposition), and benthic habitat variability all of which requires knowledge of shallow water bathymetry. In fact, one of the STV observables

deemed paramount to understanding coastal processes is maximum water depth. As part of evaluating space-based observations for determination of maximum water depth and benthic characterization is the need for a comprehensive look at how the environment (turbidity, wave structure, sea floor type) and operational aspects (incident angle, time of day, energy level) influence the retrieval quality and fidelity. Further, is the importance of understanding how these data can be effectively combined with other resources to create a more relevant product for bathymetry applications and discoveries.
This proposed effort is focused on answering the specific set of questions associated with coastal dynamics and benthic characterization as an indicator to the Earth's changing climate. The work will support development of a scalable shallow water bathymetry product using combined satellite imagery and altimetry to quantify the changes of coastal environments, monitor coastal resources and create a traceable error budget for the technology's potential to satisfy the STV objectives and plans for future mission concepts, systems and implementation strategies.

Brooke Medley/Goddard Space Flight Center
Addressing the Knowledge Gaps in Ice-Sheet Surface Processes to Inform and Advance the Next Generation STV Mission Concepts
21-DSI-21-0057

When investigating ice-sheet height change at shorter time scales, the signal due to processes such as snow accumulation and its compaction become much more relevant. Thus, the next generation STV mission has the potential to reveal surface mass balance over ice sheets as never before, improving our ability to determine their role in sea-level change. Here, we analyze output from surface process model, forced by atmospheric reanalysis models, to demonstrate the needed measurement thresholds to observe, characterize, and understand ice-sheet height change and the role of surface processes. We will specifically address the following STV Cryosphere gap-filling activities:
- Comprehensive assessment of measurement technologies and algorithms for retrieving snow accumulation and firn compaction over glaciers and ice sheets from airborne and satellite platforms"
- Systematic experiments with existing altimetric datasets (airborne and spaceborne), surface-mass balance, and firn models"
- Identification of potential improvements to surface mass balance and firn models, based on calibrated/ validation experiments with in-situ data"

Pietro Milillo/University of Houston
New Observing Strategies for Beach and Dune Topography and Implications for Coastal Flood Risk

21-DSI-21-0022

The largest cities in the United States, and around the world, lie adjacent to low-lying coastal terrain. It is predicted that in 30 years, flood disaster risk will increase tenfold in these regions, and the recent 2021 IPCC Assessment Report further solidifies the influence of irreversible anthropogenic climate change, thus furthering uncertainty in future conditions. A significant source of uncertainty in coastal flood risk derives from uncertainty in coastal topography and nearshore bathymetry. The overarching goal of this project is to develop new observing strategies (NOS) for measuring the topographic heights and widths of sandy beaches and dunes and reducing uncertainties in coastal flood hazard assessment. To achieve this goal, the project will address two complementary research questions:

(1) What level of horizontal resolution, temporal coverage, and vertical accuracy in beach/dune measurement (horizontal and vertical) can be achieved by combining InSAR, optical and LIDAR methods?
(2) What improvements in coastal flood hazard prediction and sea level rise risk assessment become possible based on the coverage, resolution (spatial and temporal) and accuracy of InSAR/optical/LIDAR derived beach/dune topographic measurements?

To address these questions, we have designed a project with four complementary tasks: (Task 1) We will deploy an acquisition campaign involving TanDEM-X (TDX) InSAR high resolution data, IceSAT-2, sUAS photogrammetry surface elevation models, airborne LIDAR DEMs, and GNSS contemporary surveys of 4 beach/dune test sites in Southern California on a monthly to sub-monthly basis, over a period of three years, to document surface elevation changes and intercompare observational methods; (Task 2) We will test innovative DEM processing algorithms and characterize their accuracy; (Task 3) We will evaluate the accuracy of TDX DEMs relative to the prediction of wave-driven beach overtopping and compound flood hazards from combinations of waves, total water level, precipitation and streamflow, and (Task 4) We will develop a data/model fusion approach to ingest time-dependent, beach/dune DEMs and shoreline positions to estimate the sediment deficits driving coastal erosion and shoreline retreat critical information for adaptation planning. This project responds to STV science and technology goals in the areas of solid Earth, coastal processes and applications. Specifically, we will answer How can large-scale geological hazards be accurately forecast in a socially relevant timeframe? (DS: S-1), How will local sea level change along coastlines around the world in the next decade to century? (DS: S-3) and What processes and interactions determine the rates of landscape change? (DS: S-4). Moreover, we will support achievement of the STV expected outcomes to: Improve understanding of measurement needs, identify which measurements needs can be obtained through suborbital means and which require a space-based component and considerate appropriate split between global observations from space and potentially less expensive and higher resolution airborne measurements.

Adam Milstein/Massachusetts Institute of Technology
AI-Enhanced Infrared Sounding of the Planetary Boundary Layer
21-DSI-21-0034

Improved understanding of thermodynamics within the Planetary Boundary Layer (PBL), including its structure and PBL height (PBLH) over land and water as a function of time of day, is a very high priority for NASA, as recommended by the National Academy of Sciences in the 2017 Decadal Survey for Earth Science and Applications from Space (ESAS 2017"). During the ESAS 2017 process, improved PBL monitoring from space was identified as a high priority across multiple interdisciplinary panels and science and application questions, leading to the current NASA PBL Incubation effort that will invest in future spaceborne PBL mission development. In recent decades, microwave and hyperspectral infrared (HIR) sounding instruments on Aqua, Suomi NPP, and JPSS have significantly improved weather forecasting. However, existing retrievals of lower troposphere temperature (T) and water vapor (q) profiles have limitations in vertical resolution, and often cannot accurately represent key features such as the mixed layer thermodynamic structure and the inversion at the PBL top. Because of the existing limitations in PBL remote sensing from space, there is an urgent need to improve routine, global observations of the PBL and enable advances in scientific understanding and weather and climate prediction. We summarize the key questions to be addressed in this investigation as follows:

- What is the upper limit of HIR vertical sounding capability in the PBL?
- How can both AI and physics be used to constrain retrieval estimates in an explainable way, and improve upon current state of the art retrieval approaches?

We will use a new modular framework to fuse physics constraints (from one or more sensors) with a powerful AI prior model in a way that generalizes traditional optimal estimation techniques familiar to the remote sensing community. A key difference versus previous work is the use of a deep neural network as a generative prior model that exploits temperature and moisture structure over a 3D volume to improve vertical resolution. Such neural network priors, trained on ensembles of real scenes from reanalysis fields, are expected to be more powerful than existing regularizing prior models, representing the joint statistics of the whole 3D scene being reconstructed with high fidelity. In addition, the prior information is incorporated in a way that is explainable to the user, with the physical radiative transfer model-based data fit clearly demarcated from the prior model information as separate modules. This framework, called consensus equilibrium", has been recently introduced in the computational imaging research community, but is new to HIR sounding. We will develop this approach for multiple HIR and microwave sounders (including those of Aqua, NPP, and JPSS). We will produce improved T and q profiles in the lower troposphere, that have the physical (realistic) structure of the PBL mixed-layer and PBL-top inversion. These profiles will then be used to derive PBLH. We will then evaluate the performance versus PBL-focused radiosonde profile data over land and ocean conditions, establishing the performance limit of HIR sounding when prior information is maximized. We will also compare to other PBL data sources, such as GNSS-RO. While the ESAS 2017 outlines numerous high priority scientific questions that will be addressed with improved observations of the PBL, the proposed project will evaluate the scientific utility of the improved retrievals in the context of land-atmosphere (L-A) interactions. This project, by providing improved vertical representation of PBL temperature T, moisture q, and PBLH from satellite remote sensing, will immediately impact and improve the applicability of L-A coupling metrics to the scientific and operational communities, and thus allow for model development to be based on observations of the full 'process-chain' of observations that couple the land surface with the atmosphere, through the PBL.

Myoung-Jong Noh/Ohio State University
High Resolution, Repeat Surface Elevation Models from SmallSats Using Multi-Pair Matching and Data Fusion Approaches to Improve Quality, Efficiency and Error Constraint
21-DSI-21-0021

We propose the development and application of approaches to increase the quality and utility of stereo photogrammetrically-derived Digital Surface Models (DSMs) obtained from constellations of SmallSats. NASA's SVT Incubation Study Team recognized the high potential of commercial SmallSat imagery for surface elevation measurements but identified several critical gaps related to spatiotemporal coverage and DSM quality, including poor stereoscopic geometry, a lack of algorithms able to obtain quality results over varying terrains and surface types and lack of reliable, quantitative metrics of DSM relative accuracy and quality without ground control. We will address these issues by utilizing the frequent, repeat image acquisitions of SmallSat constellations and fusion of SmallSat and high-resolution imagery from conventional satellites.

Utilizing a large archive of PlanetScope SmallSat imagery, acquired by Planet Inc. and distributed through NASA's Commercial SmallSat Data Acquisition Program, we will develop (1) an approach for obtaining optimized DSMs from sets of multiple, overlapping stereo-pairs; (2) a data fusion system for obtaining DSMs from pairs of images collected from satellites with substantially different resolutions and radiometric characteristics; and (3) a methodology for constraining DSM quality based on stereo-geometry. Our work will build upon the open-source, fully automated, HPC-optimized Surface Extraction from TIN-Based Searchspace Minimization (SETSM) software package. SETSM is used to generate continental-scale, high-resolution DSM datasets from commercial satellite imagery as part of the ArcticDEM, REMA and EarthDEM projects.

Our project directly addresses the objectives of this NRA by advancing innovation in the research, development, and demonstration of new measurement technologies in preparation for future integrated observing system architectures" and performing science activities that support maturation of measurement concepts and retrieval algorithms." We will develop new approaches and algorithms that will further mature existing capabilities provided by SETSM. We will use a new, and currently underutilized, dataset

(PlanetScope imagery) to fill key STV knowledge, methodology, and algorithm gaps. Consistent with the stated STV science focus, we will use these and other existing topography datasets to advance understanding of the dependence and limitations of geophysical information quality," specifically that of SmallSat DSMs, on current measurement performance and algorithm maturity." This activity will also exploit existing STV datasets in order to learn the advantages and limitations of relevant existing datasets to better inform technology advancements needed to meet STV science goals." Notably, our objectives to improve DSM coverage and quality, as well as reduce errors and constrain uncertainty, are relevant to all STV science disciplines.

Alek Petty/University of Maryland, College Park
New Sea Ice and Ice Sheet OSSE Frameworks for Determining Ice Topography Science Requirements from a Future STV Mission
21-DSI-21-0063

The polar regions are witnessing some of the fastest climatic changes on Earth. The Greenland and West Antarctic ice sheets are losing mass and this rate of mass loss has been accelerating in recent years. Ice sheet mass loss is expected to be the dominant contributor to global sea level rise in the coming century. Arctic sea ice has been in decline for the last several decades, while Antarctic sea ice has only more recently experienced a sharp decline. Sea ice loss is significantly altering the biogeochemical balance of the polar oceans and is a key factor in the polar amplification of surface warming.

Motivated by these rapid changes, the National Academies 2017-2027 Earth Science Decadal Survey identified 'ice sheet change and its consequences for sea level change' and 'identifying the role of sea ice change in contributing to Arctic amplification' as Most Important and Very Important objectives, while also recommending the incubation of Surface Topography and Vegetation (STV) as a new Targeted Observable, including the measurement of 'ice topography'.

To objectively inform future STV ice topography requirements, our project team will develop new sea ice and ice sheet Observing System Simulation Experiment (OSSE) frameworks. OSSEs have been successfully applied in various flavors within the weather/atmosphere domains for several years, but these approaches are still very much in their infancy within the sea ice and ice sheet domains. Our project will seek to identify the benefits of current (e.g. NASA's ICESat-2) and future ice topography observations most beneficial for constraining ice sheet surface elevation and change and sea ice thickness distribution and change, with a secondary focus of snow depth on sea ice and snow/firn over ice sheets.

Advances in our ability to simulate key processes at the surface and margins of sea ice and land ice, where processes are more complex and change is most rapid, increase confidence that we can achieve the necessary realism in both OSSE frameworks. Satellite altimeters now reliably and routinely generate ice elevation observations that can resolve centimeter-scale ice topographic variability with footprints of meters across entire ocean basins/ice sheets, meaning we can now also plan on the capability to routinely profile, from space, the key features that control the evolution of our sea ice and ice sheets

To establish these two distinct but related OSSE frameworks our project will seek to accomplish the following objectives:
- Integrate model components into the NCAR Data Assimilation Research Testbed.
- Develop necessary OSSE components (nature runs, forward operators, instrument/performance models) across both domains .
- Run, calibrate and validate our OSSE output and generate STV recommendations.

Developing new OSSE frameworks and creating a more objective decision-making process for determining future STV ice topography mission requirements, including a simultaneous impact analysis across both sea ice and ice sheet domains, will be a significant advance. We hope to optimize our work effort through an integrated project team and the coordination of our OSSEs to provide a synthesized cost-benefit assessment of two related but distinct elements of our cryosphere.

All data and tools developed throughout our project will be produced in accordance with established Open Science protocols. Our tools will be well documented and make publicly available to expedite the construction of community-based tools to enable future data assimilation and OSSE activities across cryospheric sciences.

Derek Posselt/Jet Propulsion Laboratory
An OSSE Framework for the NASA PBL Decadal Survey Incubation Activity
21-DSI-21-0017

The trade space of measurements for a future planetary boundary layer mission is large and rapidly expanding. As such, an observing system simulation experiment (OSSE) framework for the PBL must be capable of accurately and efficiently determining which measurement combinations are needed to meet PBL science and applications goals and objectives. In developing a PBL OSSE system, there are a number of challenges that must be addressed.

1. Modern data assimilation systems are not currently capable of assimilating boundary layer measurements at sufficient resolution.
2. Global nature runs do not have sufficient resolution to realistically capture PBL spatial or temporal heterogeneity. Regional (large eddy resolving) simulations can capture PBL processes, but are not global in scale.
3. Exploring trades among the diverse set of PBL measurements requires a collection of instrument simulators of many different types.
4. Effective use of multiple measurement types requires techniques to combine information from observations with very different spatial and temporal resolution.

We will design a system that meets these challenges and thoroughly and efficiently explores the instrument trade space for PBL science and applications. Because assimilation of PBL measurements will necessarily continue to be a research topic for the next decade, and because of the diverse set of measurements that are available, our PBL OSSE system will focus on quantifying the relative information in various measurement and orbit combinations. This will result in 1) immediate actionable instrument-level trades for the PBL formulation effort, and 2) a longer-term and comprehensive assessment of measurement combinations and constellation configurations to inform PBL mission design.

We will leverage capability that has been developed at the Jet Propulsion Laboratory (JPL), NASA Langley Research Center (LaRC), and at the NASA Goddard Global Modeling and Assimilation Office (GMAO). We will use the Global Earth Observing System (GEOS) nature run (G5NR) as context, as the two-year integration is expected to contain a large range of large scale and relatively coarse resolution dynamic and thermodynamic states. To obtain the spatial and temporal resolution needed for detailed instrument simulations, we will employ a library of large eddy simulations produced at JPL for a range of different PBL environments (marine, continental, stratocumulus topped, convective, etc). Simulation of measurements will be accomplished using state of the art forward models developed at NASA LaRC for the differential absorption lidar, and at JPL for differential absorption radar, thermodynamic sounding, and GPS radio occultation. The NASA ESTO AIST-funded parallel OSSE (ParOSSE) toolkit will be used to rapidly assess the measurement trade space for combinations of various instruments and to track and tag experiments. An orbit simulator also developed under ESTO AIST funding (the Tradespace Analysis Toolkit for Constellations; TAT-C) will be used to assess the effectiveness of various orbit and swath configurations for PBL science and applications objectives.

The result will be an OSSE system that will be capable of rapidly and thoroughly evaluating various measurement and orbit combinations for PBL science and applications. It utilizes tools that have already been developed and brings them together under a unified umbrella. It leverages both comprehensive global and fine scale regional information, and is easily extensible to new nature runs, new LES experiments, and new measurement types. This system can be used to provide guidance to NASA in determining an optimal mission concept and architecture to address PBL science in the next decade.

Patrick Rennich/Aloft Sensing, Inc.
Embedded PNT Module for Distributed Radar Sensing
21-DSI-21-0079

Techniques for collecting interferometric synthetic aperture radar (SAR) data over multiple simulta-neous baselines, such as polarimetric interferometric and tomographic

SAR (PolInSAR and TomoSAR), are emerging as key enablers for new insights into Surface Topography and Vegetation (STV) science. To fully realize the accuracy and resolution benefits of these distributed interferomet-ric techniques, however, the precise relative positioning and timing of the distributed sensing plat-forms must be known to a small fraction of a wavelength and the equivalent distance in time. Patent-pending algorithms developed by Aloft Sensing, Inc. (Aloft) have demonstrated the necessary lev-els of precision and accuracy both theoretically and with representative field data to achieve the full potential of multi-baseline distributed interferometric collections.

The Aloft team proposes to develop, implement, and validate a hardware module that efficiently deploys these algorithms for real-time position, navigation, and timing (PNT) onboard radar sensing platforms. Suitable for both satellite constellations and suborbital platforms, this self-contained mod-ule can retrofit existing radars or be tightly integrated into new designs and observing systems.
Objectives and Benefits: Aloft will develop, implement, and demonstrate a hardware module that captures and digitally processes radar pulses to establish the precise relative positioning and timing of a sensor within a distributed sensing architecture such that coherent image alignment for interferometrics can readily occur and high-quality products can be achieved. Embedded software provides the PNT updates in real-time, supporting onboard data processing needs and minimizing the amount of data to be shared between nodes.

Outfitting each platform with this PNT module facilitates the accurate and timely construction of mul-ti-baseline interferometric products. This module is best suited for sensors with multiple receive channels and systems with inter-platform communication links, but it is also applicable to single channel sensors operated as a distributed system without inter-platform communications. The end results are distributed interferometric products with accuracy and resolutions that are improved by 10 to 100× beyond the current state of the art and facilitates near real-time product generation. This level of advancement enables new science in multiple STV areas.
Outline and Methodology: The first year conducts a mission requirements and concept of op-erations study, establishes the module hardware architecture, orders long-lead components, maps the existing floating-point algorithms to the hardware architecture, and implements the embedded software. The second year establishes a detailed layout and design of the hardware board, fabri-cates units for testing, and ends with a lab-based test vector demonstration of the full embedded module. The third year validates the real-time PNT module performance and capabilities within an existing radar testbed, first in the laboratory and then with outdoor tests and demonstrations.

Period of Performance: A 33-month effort: 1 April 2022 to 31 December 2024.

Entry and Exit TRL: (Entry: TRL2/3, Exit: TRL5/5) With internal funding, the concept for the PNT system module has been established and key pieces of the Matlab-based algorithms have been demonstrated with field data (System: TRL2, Algorithms: TRL3). The first year establishes the mod-ule's detailed hardware design and validates the algorithms as mapped onto that hardware (Sys-tem: TRL3, Algorithms: TRL 4). The second year fabricates and tests the hardware and conducts an end-to-end benchtop test of the full hardware module with embedded firmware/software (System: TRL4). The third and final year demonstrates real-time operation of the PNT module within a representative radar system, in both a laboratory setting as well as in an outdoor environment (System: TRL5, Algorithms: TRL5).

Sassan Saatchi/Jet Propulsion Laboratory
Multi-Sensor Multi-Platform Surface Topography and Vegetation Structure Data Fusion Information System (STV-FIS)
21-DSI-21-0066

We propose to develop a multi-sensor, multi-platform surface topography and vegetation structure (STV) data fusion information system (STV-FIS) to characterize future STV performance. Our STV-FIS will address all four major gaps and gap-filling activities identified in the STV incubation study white paper (STVWP, p. vii): 1) Knowledge Gaps by providing a large number of simulated data products, 2) Methodology Gaps by developing and implementing a multi-sensor data fusion information system, and 3) Algorithm Gaps by integrating physically based models with AI for STV change detection, and 4) Measurement Gaps by developing trade study for simulating multi-sensor and multi-platform architecture and smart-tasking. Our goal is to leverage existing models and data in active sensing of STV geophysical parameters to build a multi-sensor, multi-platform STV Data Fusion Information System (STV-FIS) to address the STV identified gaps by focusing on the following objectives:
Obj-1. Develop a multi-sensor (Radar and Lidar) fusion formulation and testing platform based on a dedicated EM model of vegetation 3D structure and surface condition (topography, dry, wet, snow, etc.).
Obj-2. Develop Artificial Intelligence (AI) model-data analytics for sensitivity analysis, STV parameter retrieval, change detection, and uncertainty assessment.
Obj-3. Simulate a dedicated data fusion observing system for multi-sensor and multi-platform trade study, and on-board processing and smart-tasking.
Obj-4. Integrate model and data fusion within a visualization system and on-line analytical toolbox for enabling simulations of STV observations, AI algorithms, and implementation future OSSEs.
The proposed STV-FIS include a user-friendly platform along with visualization and algorithmic tool boxes to meet the needs of all STV disciplines for data analysis, trade studies and OSSEs. STV-FIS components will start at average TRL of 2 and exit at the average TRL of 5.

David Shean/University of Washington, Seattle
Advanced Information Systems to Fill STV Gaps: Next-Generation Stereo+Lidar Fusion and Sensor Technology

21-DSI-21-0008

Instrument fusion is the prerequisite to data fusion for the high-resolution global Surface Topography and Vegetation (STV) targeted observable   data collected by a combination of single- or multi-platform radar, lidar, and stereo instruments must be precisely aligned with known uncertainty to enable essential downstream fusion and scientific analysis. This is one of many critical measurement gaps identified by the Decadal Survey Incubator (DSI) program for the STV TO that will require new, innovative technology. Other priority gaps include 1) insufficient multi-sensor data fusion methods and algorithms, 2) insufficient measurement geolocation and vertical accuracy, 3) stereo processing uncertainty and shortcomings for vegetation, and 4) poorly defined requirements for key stereo acquisition parameters.

This crossover proposal focuses on two priority technologies identified by the DSI to reduce these STV measurement gaps: Information systems (including improved multi-sensor data fusion methods and algorithms)," and Subsystems/components to significantly improve spaceborne high-resolution stereo photogrammetry over the current state-of-the-art." We assembled an experienced team from academia, government, and industry to address these priority gaps. Specifically, we will:

1) Develop novel information systems and on-board algorithms that can deliver the precise pointing knowledge needed for next-generation lidar and TDI linescan image sensors. These subsystems will solve the notorious jitter" problem responsible for large residual geolocation uncertainty in commercial stereo images. We will co-develop these information systems through a long-standing partnership with Planet.
2) Develop information systems that use cutting-edge, multi-sensor deep learning fusion techniques to improve the horizontal resolution, vertical accuracy/precision, and quality of stereo+lidar datasets for priority STV targets (vegetation, ice/snow).
3) Develop stereo photogrammetry information systems with robust joint optimization routines, rigorous uncertainty metrics, and stereo+lidar fusion alignment to support next-generation stereo imaging rigs and constellations
4) Leverage state-of-the-art radiative transfer model simulations (DART) and existing/new on-orbit and airborne datasets to support development activities and evaluate key stereo acquisition parameters, which will complement STV OSSE efforts to define STV instrument requirements.

We will primarily focus on fusion of lidar and stereo photogrammetry to improve lower-level elevation data products (e.g., point clouds, gridded raster DSM/DTM), as these topographic data products are fundamental for many downstream applications and science fusion" approaches involving high-level products from other measurement approaches (e.g., SAR). These innovative algorithms will guide development of a next-generation, cloud-based processing framework that will efficiently generate enhanced, high-quality data products for STV and commercial satellite imaging constellations in the coming decades.

Matthew Siegfried/Colorado School of Mines
Quantifying Bias and Uncertainty Sources between Laser and Radar Retrievals of Surface Topography Over Cryospheric Targets
21-DSI-21-0056

Motivation: Accurate quantification of the primary observables identified by the Surface Topography and Vegetation (STV) working group bare surface land topography, ice topography, vegetation structure, shallow water bathymetry, and snow depth requires geodetic measurements with sub-meter vertical resolution and sub-weekly temporal repeat-sampling. A multi-sensor fusion approach combining lidar, radar, and stereophotogrammetry from both orbital and suborbital platforms will likely be necessary to achieve these resolution requirements. However, a thorough investigation of the biases and uncertainties inherent to each of these geodetic measurements, as well as how these biases and uncertainties might compound in a multi-sensor fusion approach, is needed before any such multi-sensor framework can be developed and optimized.

Proposed Work: We propose to investigate the sources of measurement bias and uncertainty in orbital laser altimetry, radar altimetry, and interferometric synthetic aperture radar (InSAR) measurements over ice sheet surfaces and periglacial land surfaces. These two surface types are subject to the time- and space-varying surface dielectric properties of snow, ice, and surface water, and subjected to seasonal and interannual geomorphic processes that can reshape surface topography (such as sub- or supra-glacial lake drainage at ice sheet boundaries and permafrost thaw and thermokarst initiation in periglacial regions), all of which complicate the error inherent in and interpretation of surface height measurements. Our proposed work will consist of three cross-cutting objectives:

1. Characterize and reduce sources of uncertainty and biases in laser altimetry, radar altimetry, and InSAR measurements over ice sheet surfaces and periglacial land surfaces.
2. Quantify the effect of these uncertainties on vertical and rate of change accuracies for both cryospheric and solid-earth/hydrologic targets.
3. Develop and test novel multi-sensor data fusion methods and algorithms that leverage complementary geodetic measurements for improved topographic products and temporal-repeat measurements.

We will achieve our objectives by using existing STV datasets collected by NASA and ESA missions, such as ICESat-2, UAVSAR, Operation IceBridge, ABoVE, Sentinel-1, -3, and -6, and CryoSat-2.

Relevance: Our proposed investigation of measurement biases and uncertainties in single and multi-sensor geodetic measurements directly responds to Section 2.2.1.1 of the STV Solicitation. We will 'exploit existing STV datasets [to] conduct uncertainty quantification, sensitivity analyses, and other assessments to advance understanding of the dependence and limitations of geophysical information quality on current measurement performance and algorithm maturity', with the further goals of 'help[ing]

[to] fill key STV knowledge, methodology, and algorithm gaps using POR and other existing data', and 'inform[ing] an architecture of platforms and sensors that will support the breadth of geophysical, ecological, cryospheric, and hydrological science objectives outlined in the STV STR.' Finally, we are an 'interdisciplinary team [seeking to] address two or more of the STV science disciplines in an integrated fashion.'

Marc Simard/Jet Propulsion Laboratory
STV for Coastal Wetlands
21-DSI-21-0067

JPL, NASA GSFC and the US Fish and Wildlife Service propose science activities designed to advance and accelerate the readiness of the Surface Topography and Vegetation (STV) Targeted Observable (TO).
We propose to address the knowledge and data gaps identified in the STV Incubation Study Report focusing on a particularly challenging but vital environment: coastal wetlands. Coastal wetlands are spatially and temporally complex systems that embody multiple disciplines of the Report: vegetation structure, hydrology, solid Earth (topography) and coastal processes (shallow water bathymetry). Coastal wetlands, along with the socioeconomic services they provide, are threatened by the impacts of climate change (e.g. storm surge and sea level rise) and human activity (e.g. water diversion projects, sediment starvation, pollution). STV mission data in these regions will support multidisciplinary scientific breakthroughs with direct societal benefits.
Coastal wetlands are shallow water environments characterized by herbaceous (marsh) and/or woody (swamp) wetland vegetation that are often intersected with estuaries, tidal channels and channel networks, lagoons and lakes. Micro-topography (including shallow bathymetry) is a major control that determines the hydrology and spatial patterns of vegetation. Flood extent, nutrient loads, hydroperiod and salinity gradients vary with elevational gradients, and with changes in river discharge and tides. In these environments, the STV-TO should resolve 3 categories of vertical layers: micro-topography (bathymetry and terrain elevation), water surface elevation and vegetation vertical profile (including height).
Our approach begins with surveying the research and applications communities about data gaps and needs to confirm and refine wetland-related requirements of the STV Incubation Study Report. Then we will evaluate existing airborne and spaceborne data as well as simulated spaceborne data with respect to refined community requirements. The existing spaceborne data (GEDI, ICESAT-2, TanDEM-X, NASADEM, ALOS/PALSAR-2, Sentinel-1a/b, TerraSAR-X) will be used to evaluate current data capabilities and identify data gaps. We will exploit existing airborne datasets collected during the AFRISAR and Delta-X campaigns. This data set (UAVSAR, LVIS, discrete green and NIR Lidar, AirSWOT), which we deem to be near-ideal, will be used to simulate upcoming NISAR and SWOT data. They will be subsampled and degraded to simulate a range of potential spaceborne observation configurations (e.g. spatial and temporal resolutions, noise level, technology) and data fusion approaches.

Within these campaign sites, we will also compare the airborne with spaceborne data to assess current spaceborne measurement capabilities. The proposed airborne data sets cover a wide range of wetland conditions (e.g. phenological stage, swamps vs marshes, etc.), geophysical (e.g. lakes, riverine, lagoons, estuaries and deltas, width of channels and islands, etc.) and environmental settings (e.g. discharge, tidal range, precipitation patterns, temperature). However, time permitting, we will explore the potential of current spaceborne data in other sites to increase the representativeness of our two sites.
Our deliverables include refinement of STV Study Report's science questions and geophysical measurement requirements specific to coastal wetlands, recognizing the wetland theme may impact requirements of multiple STV disciplines. In addition, we will deliver quantitative evaluations of the capabilities of a wide range of current and future sensors to provide needed measurements of ground micro-topography and shallow bathymetry, water surface elevation, water surface slope and vegetation vertical structure, as well as corresponding elevation changes.

Benjamin Smith/University of Washington, Seattle
Data Fusion for Mass-Change Measurements Over Complex Ice Surfaces
21-DSI-21-0013

This proposal is aimed at measuring ice-sheet surface topography and mass change in critical areas of the Antarctic and Greenland ice sheets, with the goal of developing records of change that are relevant for estimating the rate ice-sheet mass loss, for understanding changes in glacier dynamics, and developing estimates of short-wavelength ice-sheet features that we will use to understanding the role of crevasses and surface channels in ice-sheet hydrology, to understand material properties of the near-surface ice, and to predict how potential STV mission scenarios will perform in recovering ice-sheet mass change in different parts of the ice sheets. We choose six focus areas for this study, in part because common techniques for ice-sheet change measurement have difficulty achieving consistent results in these areas due to the fast ice motion and large surface roughness caused by crevasses, rifts, and surface melt features, and in part because of their importance as sites of fast ice-dynamic change. Because surface features move between measurements, even sensors with high intrinsic precision can produce badly scattered height-change measurements in these areas. As part of this analysis, we will develop techniques to account for the motion of surface features to create mass-change time series, to understand the evolution of surface features, and to estimate the contribution of small-scale surface features evolution to mass change and to glacier dynamics. These techniques take into account the distinction between surface-height changes due to thinning of the entire ice column and surface-changes due to surface feature advection, and should produce separate records of the ice-column thickness change, the advecting fields, and rates of change in the advecting fields. We will develop metrics for surface topography that describe the features whose motion produces the largest scatter in altimetry time series, and will apply these metrics to data from around Greenland and Antarctica to help evaluate potential measurement strategies for the Decadal Survey Surface Topography and Vegetation mission. As part of this work we will update existing sets of stereophotogrammetric data for our study areas, and will develop records of surface metrics that describe small-scale features of the ice sheets. These records will be shared through the National Snow and Ice Data center, as well as smaller datasets that will be shared through a set of publications in the third year of the project.

Kay Suselj/Jet Propulsion Laboratory
A Novel Data Assimilation Tool for Optimizing PBL Observing System Design in Support of Parameterization Development
21-DSI-21-0016

In the light of the latest Earth Science Decadal Survey (DS) recommendations to improve observations, understanding and parameterization of the atmospheric planetary boundary layer (PBL) processes, we will design a novel data assimilation system that will help refine DS science requirements for the design of a future PBL-targeted observing system, and prepare science community to jumpstart utilizing the new observations for PBL parameterization improvements.

To refine observational requirements in an objective and scientifically sound manner, we will first evaluate the skill of the current program of record observations to constrain PBL parameterizations via assimilation of simulated observations. Evaluating the added value of observations from different scenarios of possible future PBL-targeted observing system will help us infer an optimal observing system design for parameterization development. For the robustness of observing system requirements, the data assimilation system will be applied to two parameterizations, one from the operational PBL parameterization in the NASA GEOS model, and the other one representing a future unified parameterization.

To jumpstart utilizing future PBL observations, the new data assimilation system will assimilate actual PBL-relevant observations in the operational NASA GEOS model to provide a global observational constraint for PBL parameterization and to help with a process-based parameterization improvement. We will demonstrate the utility of the new system by assimilating current PBL observations, but the key goal is to design a data assimilation system that will revolutionize parameterization development by utilizing new PBL-targeted observations.

Joao Teixeira/Jet Propulsion Laboratory
Observing the Interactions between PBL Thermodynamic Vertical Structure and Horizontal Variability with an Optimal Combination of Instruments: The Merged Infrared + Radio Occultation (IR+RO) Approach

21-DSI-21-0059

Some of the key planetary boundary layer (PBL) science questions discussed in the NASA PBL Study Team Report are related to critical interactions between the PBL thermodynamic vertical structure and horizontal variability. To properly address these questions, a new PBL satellite mission would require both high vertical and high horizontal resolutions for temperature and water vapor profiles. Unfortunately, there is no single instrument that from a space-based perspective will be able to provide the required high vertical and horizontal resolutions.

A strategy to overcome this issue is to take advantage of the optimal combination of instruments with different characteristics. In this proposal, we address the issue of merging information provided by: (i) instruments with (current and/or potential) high vertical resolution (approximately 100-200 m) but poor horizontal resolution and horizontal sampling (e.g., radio occultation RO, differential absorption lidar DIAL, and differential absorption radar DAR), with (ii) instruments with potential high horizontal resolution (approximately 1 km2) and good horizontal sampling but poor vertical resolution such as hyperspectral infrared (IR) instruments.

In particular, we will take advantage of the positive characteristics of these different types of measurement technologies (i.e., high vertical and horizontal resolution, and high horizontal sampling) by introducing a fairly straightforward methodology in which we utilize the high vertical resolution profiles of water vapor (and/or temperature) (e.g., from GNSS-RO) as a priori for an IR retrieval.

We will evaluate this approach using: (i) synthetic data obtained from a basic PBL observing system simulation experiment (OSSE) framework that includes large-eddy simulation (LES) models, forward radiative transfer models and retrievals, for a variety of key PBL physical regimes; and (ii) data from the current program of record (POR), namely global navigation satellite system (GNSS)-RO retrievals and single footprint IR retrievals from the Atmospheric Infrared Sounder (AIRS).

We will use these combined datasets, that take advantage of both high horizontal and vertical resolution, to address key PBL science questions regarding the interactions between the PBL thermodynamic vertical structure and horizontal variability.

Qing Yue/Jet Propulsion Laboratory
Regime-Based Assessment on the Capability, Limits, and Gaps of the Space-Borne Hyperspectral Infrared Sounders for Resolving PBL Thermodynamic Structures
21-DSI-21-0004

We propose to use high-quality in-situ global radiosonde observations to quantitatively assess the capability, limits, and gaps of the current space-borne hyperspectral infrared (IR) sounders to resolve planetary boundary layer (PBL) thermodynamic vertical structures and PBL height in a variety of PBL regimes. This study is motivated by the importance of exploiting and utilizing the content in the key components of Program of Record (POR) Observations for PBL. It directly responds to the research themes of 2.1.1.1 in the NOFO. As pointed out by the NASA PBL Incubation Study Team Report (Teixeira et al. 2021, hereafter PBL2021): the ability to leverage research and operational satellite observations to extend the POR until a new and improved PBL observing system is realized is critical.

The space-borne hyperspectral IR sounders provide global vertical profiling of atmospheric temperature (T) and water vapor (Q), with enhanced capability by accompanying microwave sounders for profiles below the cloud. The global coverage, long-term continuity, and potential in the retrieval algorithm developments make the IR sounders an important POR element for PBL science. Over the years, the operational IR sounder retrieval algorithms have been developed without necessarily prioritizing the vertical resolution and accuracy in PBL, although studies have hinted at underutilized information existed in regimes with clear or partially cloudy conditions, subtropical marine boundary layer, and the characterization of lower troposphere large-scale environment in deep convective events. Quantitative evaluations on how current operational retrieval algorithms utilize spectral information and a priori constraint and their dependence on PBL regimes are critical to assess the instrument capability in the sounding of PBL thermodynamic structure, which is key for the PBL-targeted optimization of sounder retrieval algorithms.

Motivated by these considerations, we propose three primary goals in this effort:
"   Goal-1: Classify global PBL into regimes by distinguishing various PBL thermodynamic structures obtained from high quality global in-situ observations and large-scale circulation conditions from reanalysis, by applying deep learning models.
"   Goal-2: Quantify the instrument information content and sensitivity of the major modern hyperspectral IR sounders in PBL T and Q profiles and PBL height to resolve critical structures and separate various PBL regimes, and evaluate the performance of NASA operational IR sounder retrieval algorithms in various PBL regimes.
"   Goal-3: Investigate the improvements that can be made to the current IR sounder retrieval algorithms for better sounding of PBL thermodynamic vertical structure and PBL height.
By reaching these goals, our study will quantitatively answer the following questions:
"   How well do the current space-borne hyperspectral IR sounders resolve global PBL thermodynamic structures and PBL height in the varying PBL regimes?
"   What improvements could be made to the operational NASA IR sounder retrieval algorithms to provide better PBL T and Q profiles?

We will focus on multiple major modern operational IR sounders, including AIRS, CrIS, and IASI instruments. The proposed regime-based instrument information content analysis, and PBL-centered evaluation and improvement on operational IR sounder retrieval algorithms will provide new tools to obtain better observations of PBL T and Q profiles and of PBL height from the existing IR sounder POR.

Our analyses and the framework established here will help to quantify how much valuable information can be further obtained from operational sounder measurements to extend POR for PBL science. Our work will also provide a thorough characterization for gaps that could not be addressed by the existing observation system and need to be the focus of future PBL technique developments on sounding of PBL thermodynamic vertical structures.

Yanqiu Zhu/Goddard Space Flight Center
Exploring Strategies and Developing PBL Data Assimilation Including PBL Height from Multiple Observing Systems in the Global GEOS System
21-DSI-21-0042

Objectives: We propose to develop Planetary Boundary Layer (PBL) data assimilation capabilities, focusing on PBL height (PBLH), from multiple observing systems in the global Goddard Earth Observing System (GEOS) data assimilation system to improve the representation of PBL thermodynamic structure. We will explore optimal global data synergy strategies for PBLH data, pinpoint scenarios and regions where PBLH data of different observing systems are most suitable and identify data gaps in the existing Program of Record (POR). We will also aim to improve the characterization of the PBL by exploring strategies of assimilating surface-sensitive radiances and Global Navigation Satellite System Radio Occultation (GNSS-RO) data together with the PBLH data in the GEOS system, and by developing methods to assess and improve retention of information from PBL observations.

Motivation: The accuracy of PBLH simulation is a key issue in many applications including forecasting near-surface meteorology and air quality, however, it is a very challenging problem due to the lack of not only comprehensive, global PBL observations but also a strategy and infrastructure to utilize PBLH data from a variety of sensors. To prepare for integrated PBL observing systems in the coming decade, we propose to explore and develop novel ways to utilize PBL observations focusing on PBLH data from multiple observing systems into the GEOS system.

Technical Approach: In this proposal, estimates of PBLH suitable for assimilation will be derived from GNSS-RO refractivity, space-based lidars, radiosonde, radar wind profilers and Micro Pulse Lidar Network (MPLNET) backscatter, and corresponding model-based PBLH definitions will be derived based on a deep understanding of the retrieval algorithm for each observing system in order to make consistent comparisons between the observed and simulated PBLH.

We propose to explore optimal global data synergy strategies for the assimilation of PBLH data from multiple observing systems. The control variable vector will be augmented with the PBLH variables, thereby allowing the assimilated PBLH data to impact not only the PBLH analysis but also temperature and moisture analyses through ensemble background error covariance. We will also explore the possibility of an innovative approach to assimilating GNSS-RO refractivity gradient in the lower troposphere, and investigate interactions and joint impacts of using radiances, GNSS-RO and PBLH data on temperature, moisture and PBLH in the GEOS system. The impact of these interactions will be assessed using sondes, reanalyses and land-atmosphere coupling metrics.

We propose to develop methods to assess and improve the retention of PBL observation information, assessing model forecast response to assimilation tendencies, and developing methods to reduce compensation by model parameterizations and to improve consistency of PBL structure.

Relevance: This PBL Science proposal will develop PBL data assimilation techniques and exploit POR datasets, as specifically requested in the A.45 Decadal Survey Incubation (DSI) solicitation. This proposal also addresses methods to determine how information content of PBL observations will be retained in data assimilation systems" as requested by the call. The infrastructure developed in this proposal will remain relevant in the coming decade, and indeed is a critical capability to evaluate the impact and ultimately make use of future PBL observing systems including the array of PBLH information that will be available going into the next decade.