NASA Studies of the Earth's Carbon Cycle: From Observations to Products

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*** This talk is prepared with input and assistance from numerous colleagues at NASA HQ, NASA centers, and the broader research community!**

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Summary of Talk

- Introduction
- Satellite Observations
- Airborne Observations and Related Field Work
- Models
- Putting the Pieces Together: Providing Data Products
- Future Carbon-Relevant Satellite Missions
- Conclusion

Leveraging NASA's Satellite Observations

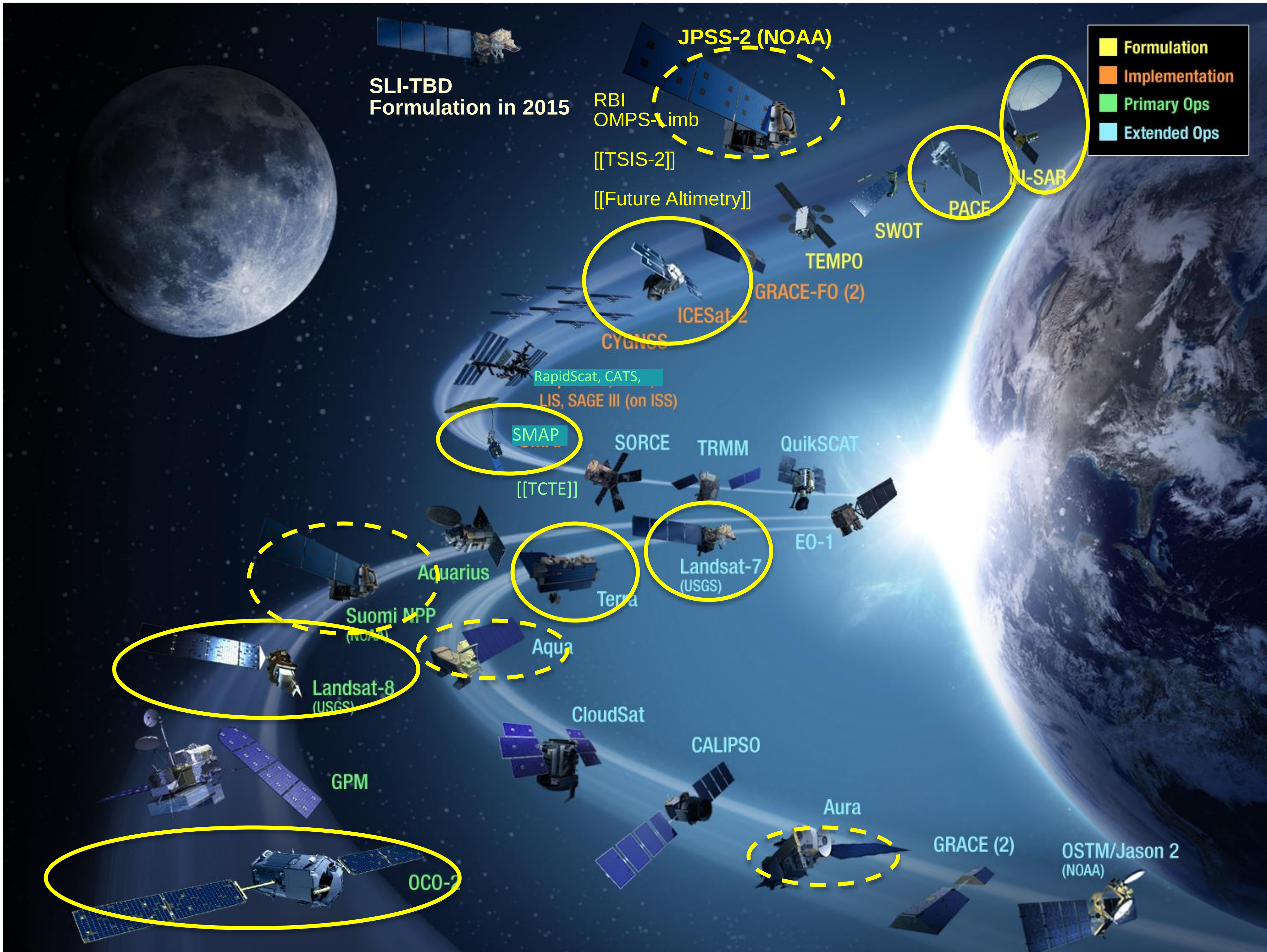
The ongoing approach lays the groundwork for Carbon-related applications of current and future NASA satellite sensors now in development. This includes:

- Orbiting Carbon Observatory-2 (OCO-2, 2014);
- Ice, Cloud, Land Elevation Satellite-2 (ICESat-2 – 2018);
- NASA/ISRO Synthetic Aperture Radar (NISAR – 2021);
- OCO-3 (2019), and Global Ecosystem Dynamics Investigation (GEDI - 2020);
- Pre-Aerosol, Clouds, and ocean Ecosystem (PACE – 2022/3);

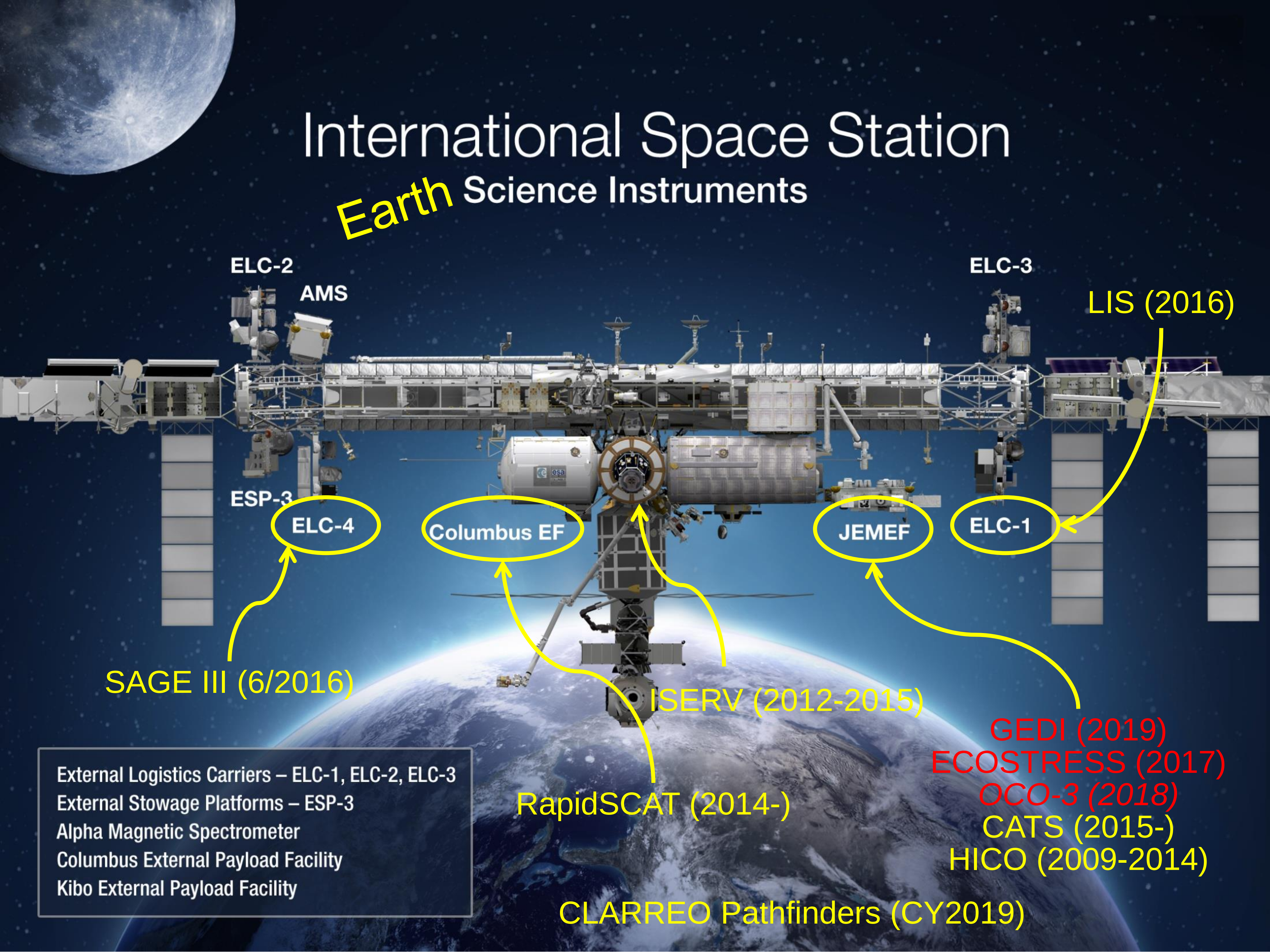
in pre-formulation:

- Active Sensing of CO_2 Emissions Over Nights, Days, and Seasons (ASCENDS);
- Hyperspectral Infrared Imager (HyspIRI).

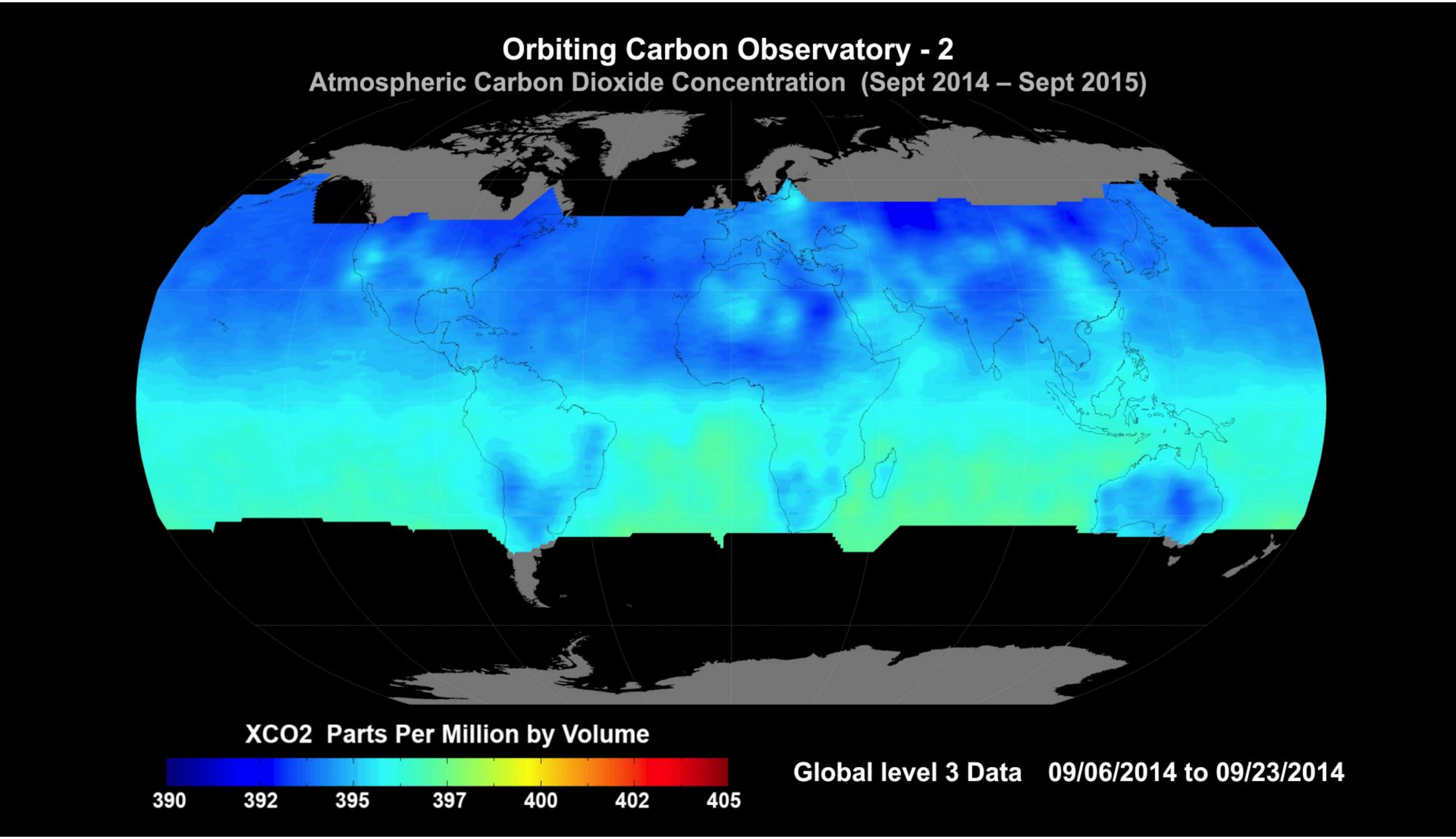
Past/existing sensors/satellites include ICESAT, LandSAT (NASA/USGS), MODIS, VIIRS (NASA/NOAA/DOD), GOSAT (Japan), ALOS (Japan), EnviSAT (ESA)



Formulation
Implementation
Primary Ops
Extended Ops
JPSS-2 (NOAA)
SLI-TBD
Formulation in 2015
RBI
OMPS-Limb
[[TSIS-2]]
[[Future Altimetry]]
NI-SAR
PACE
SWOT
TEMPO
GRACE-FO (2)
ICESat-2
CYGNSS
RapidScat, CATS,
LIS, SAGE III (on ISS)
SMAP
[[TCTE]]
SORCE
TRMM
QuikSCAT
EO-1
Landsat-7
(USGS)
Aquarius
Terra
Suomi NPP
(NOAA)
Aqua
Landsat-8
(USGS)
CloudSat
CALIPSO
GPM
Aura
GRACE (2)
OSTM/Jason 2
(NOAA)
OCO-2


International Space Station
Earth Science Instruments
ELC-2
AMS
ELC-3
LIS (2016)
ESP-3
ELC-4
Columbus EF
JEMEF
ELC-1
SAGE III (6/2016)
ISERV (2012-2015)
RapidSCAT (2014-)
GEDI (2019)
ECOSTRESS (2017)
OCO-3 (2018)
CATS (2015-)
HICO (2009-2014)
CLARREO Pathfinders (CY2019)
External Logistics Carriers – ELC-1, ELC-2, ELC-3
External Stowage Platforms – ESP-3
Alpha Magnetic Spectrometer
Columbus External Payload Facility
Kibo External Payload Facility

OCO-2's First Year of Measurements



Field Observations

- Major Airborne Campaigns (examples)
  - CARVE (2010-2015)
  - ACT-AMERICA (2015-2019)
  - AToM (2015-2019)
  - NAAMES (2015-2019)
  - CORAL (2015-2019)
- Smaller Airborne Campaigns
  - AfriSAR/G-TEC (joint with ESA, DLR, AGEOS)
  - Methane
- Integrated (Surface-Airborne-Satellite) Field Campaigns
  - ABoVE

CARVE: A NASA Earth Ventures (EV-1) Airborne Sciences Investigation

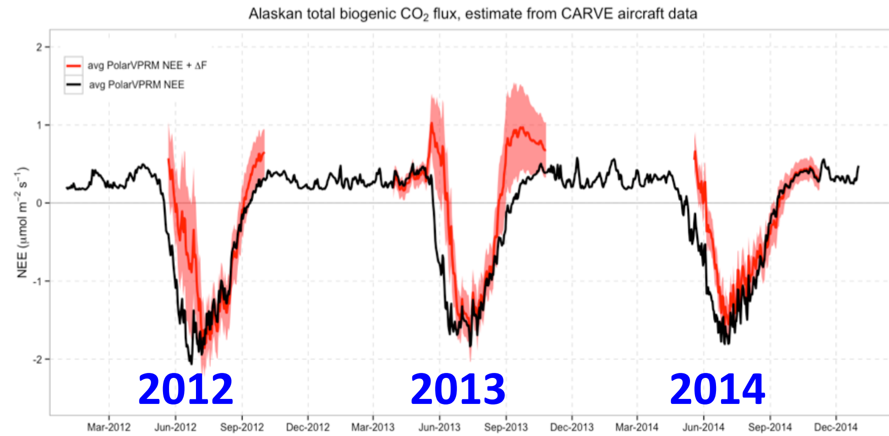
CARVE

- ~1000 hours of science flights across Arctic and boreal Alaska from 2012-2015
- Quantify CO2 & CH4 surface-atmosphere fluxes

CARVE bridges critical gaps in our understanding of

- Arctic ecosystem vulnerability
- Linkages between the Arctic hydrologic and terrestrial carbon cycles
- Feedbacks from fires and thawing permafrost
- Changing seasonal dynamics

2012 -2014 CO2 Fluxes



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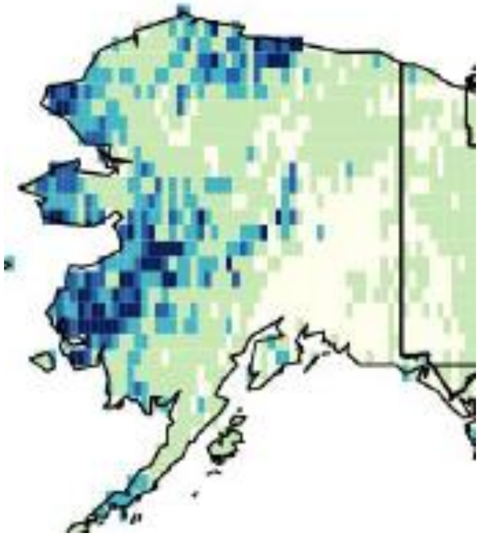
2012 -2014 Mean CH4 Fluxes



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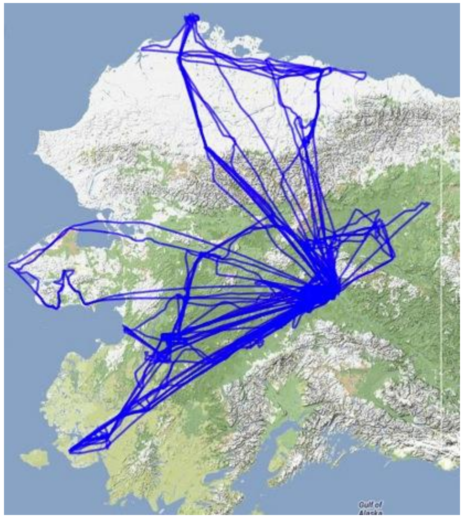
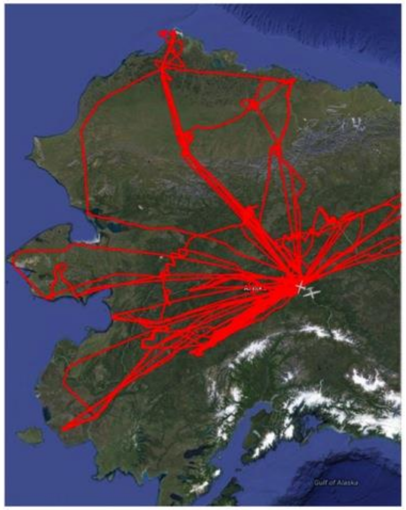
Thanks to Chip Miller./JPL and Ken Jucks/NASA HQ

CARVE Observation Summary

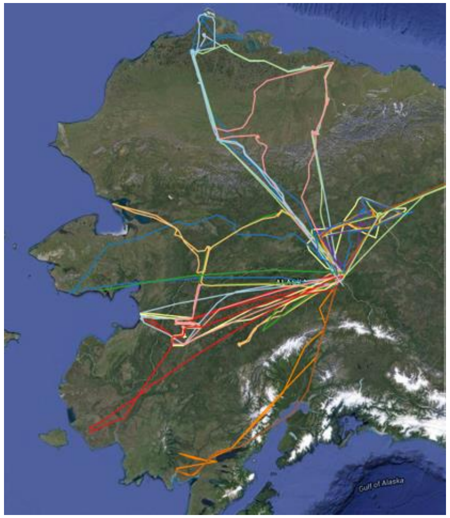
May-Sep 2012



Apr-Oct 2013

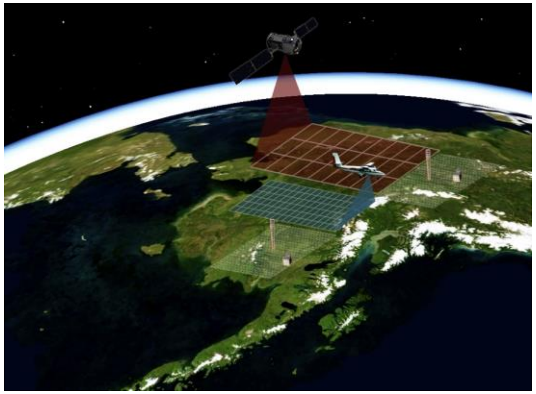


May-Nov 2014



Apr-Sep 2015

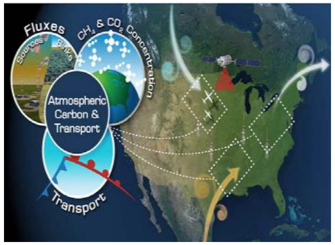
CARVE Laboratory– C-23 Sherpa



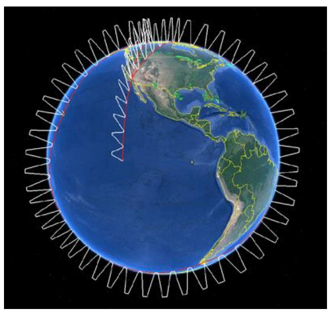
CARVE Observation Strategy

Thanks to Chip Miller./JPL and Ken Jucks/NASA HQ

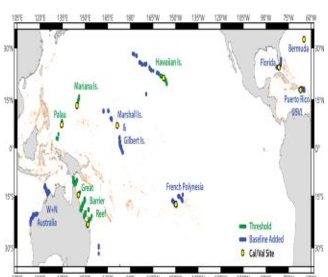
Earth Venture Suborbital – 2: Investigations



ACT-America (*Atmospheric Carbon and Transport – America*): Quantify the sources of regional carbon dioxide, methane, and other gases, and document how weather systems transport these gases; Ken Davis, Penn State Univ

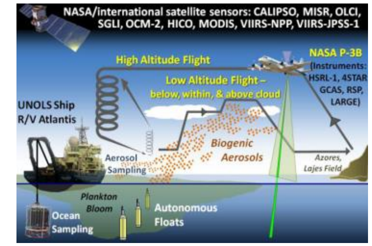


ATom (*Atmospheric Tomography Experiment*): Study the impact of human-produced air pollution on certain greenhouse gases; Steven Wofsy, Harvard Univ

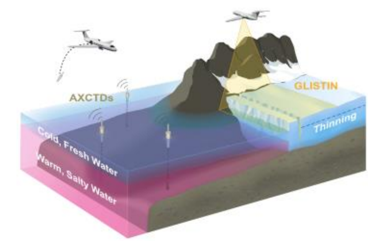


CORAL (*Coral Reef Airborne Laboratory*): Develop critical data and new models needed to analyze the status of coaral reefs and predict their future; Eric Hochberg, Bermuda Institute of Ocean Science

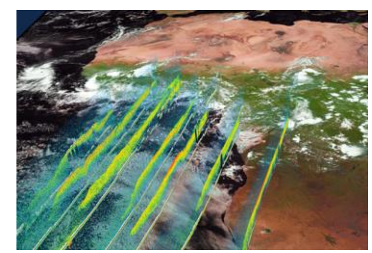
NAAMES (*North Atlantic Aerosols and Marine Ecosystems Study*): Improve predictions of how ocean ecosystems would change with ocean warming; Michael Behrenfeld, Oregon State Univ



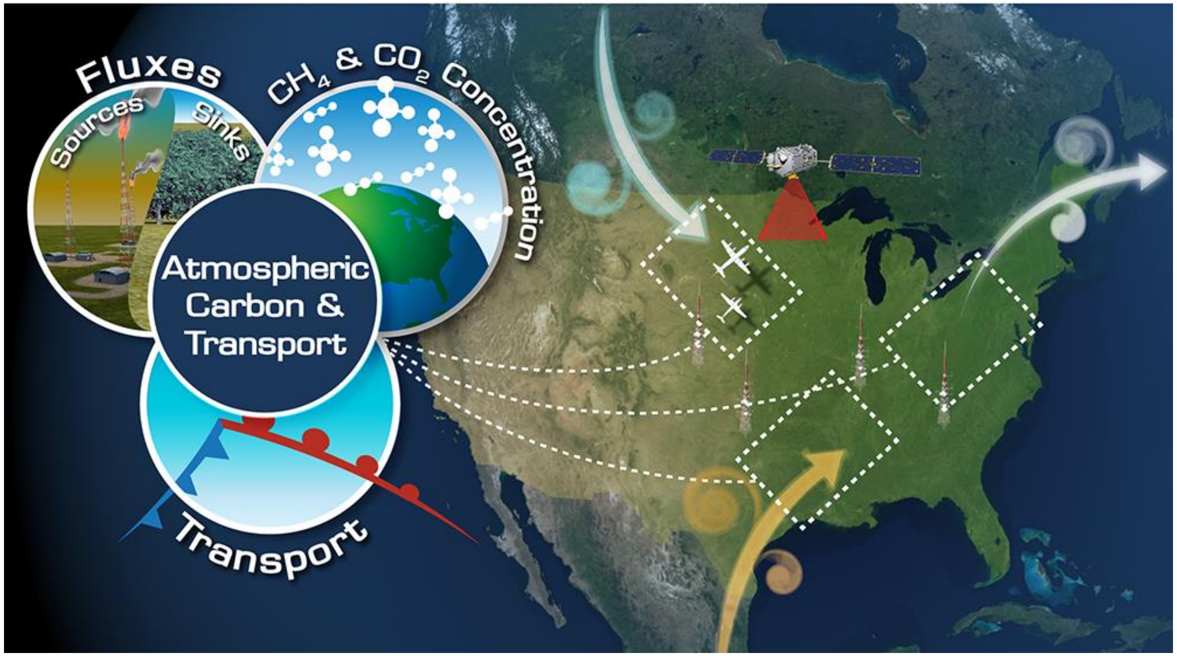
OMG (*Oceans Melting Greenland*): Investigate the role of warmer, saltier Atlantic subsurface waters in Greenland glacier melting; Josh Willis, JPL



ORACLES (*ObseRvations of Aerosols Above CLouds and Their IntEractionS*): Probe how smoke particles from massive biomass burning in Africa influences cloud cover over the Atlantic; Jens Redemann, ARC



ACT-America



PI: Ken Davis, PSU
Aircraft: C-130 @ WFF, UC-12 @ LaRC
Instruments: active CO2 remote sensor, active aerosol lidar, in situ CO2 and CH4, other key in situ gases.
5 deployments in 3 regions during all 4 seasons.
Coordination with OCO-2

Overarching Goals:

- The overarching goal of the Atmospheric Carbon and Transport-America (ACT-America) mission is to improve regional to continental scale diagnoses of carbon dioxide (CO_2) and methane (CH_4) sources and sinks.
- The mission will enable and demonstrate a new generation of atmospheric inversion systems for quantifying atmospheric CO_2 and CH_4 fluxes.
- These inverse flux estimates will be able to:
  - Evaluate and improve terrestrial carbon cycle models, and
  - Monitor carbon fluxes to support climate-change mitigation efforts.

NAAMES is an interdisciplinary investigation of the annual plankton cycle and its associated atmospheric aerosols

Overarching Science Goals:

1. *Define environmental and ecological controls on plankton communities to improve predictions of their structure and function in a warmer future ocean*

2. *Define linkages between ocean ecosystem properties and biogenic aerosols to improve predictions of marine aerosol-cloud-climate interactions with a warmer future ocean*

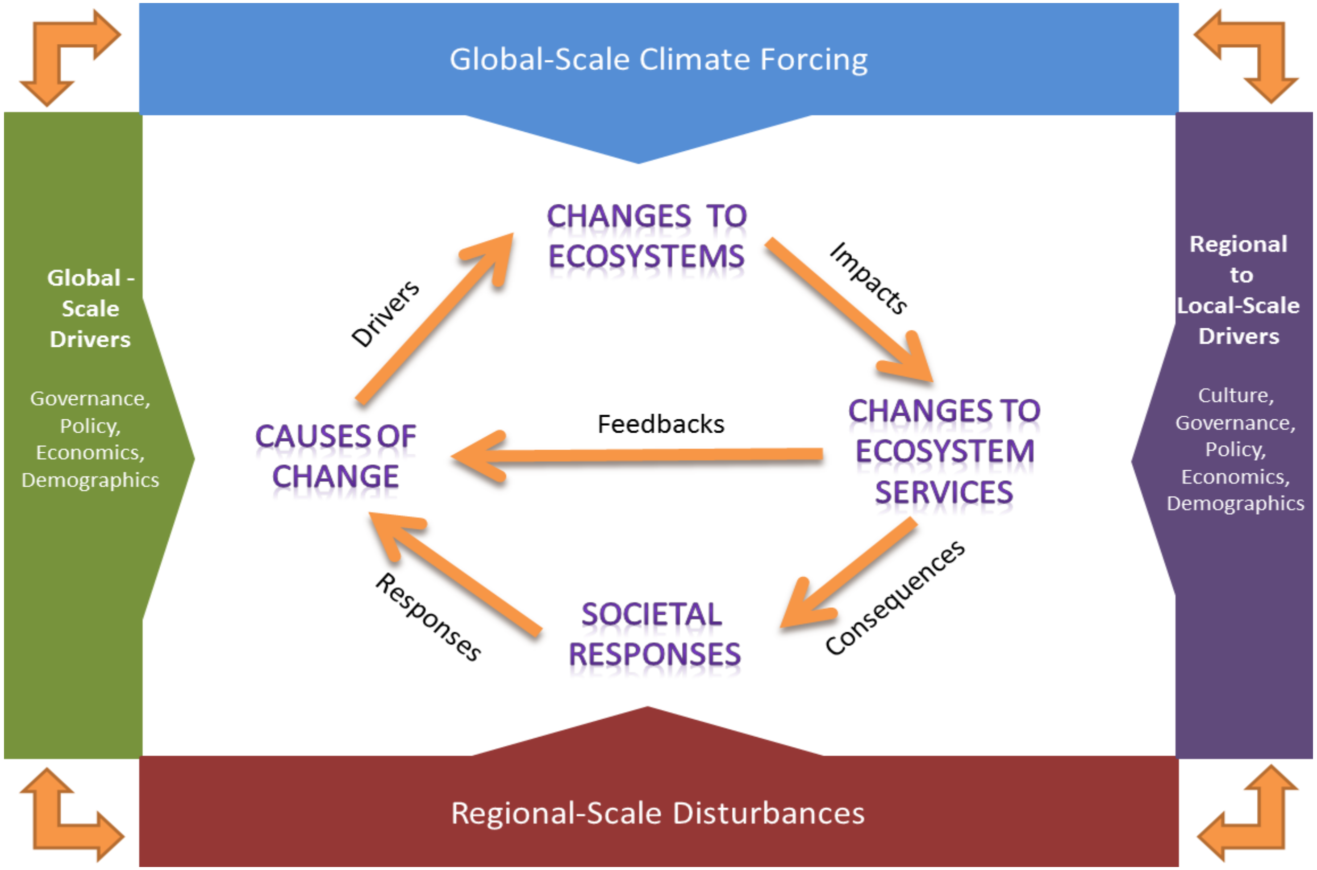
Baseline Science Objectives:

1. *Characterize plankton ecosystem properties during primary phases of the annual cycle in the North Atlantic and their dependence on environmental forcings*

2. *Determine how primary phases of the North Atlantic annual plankton cycle interact to recreate each year the conditions for an annual bloom*

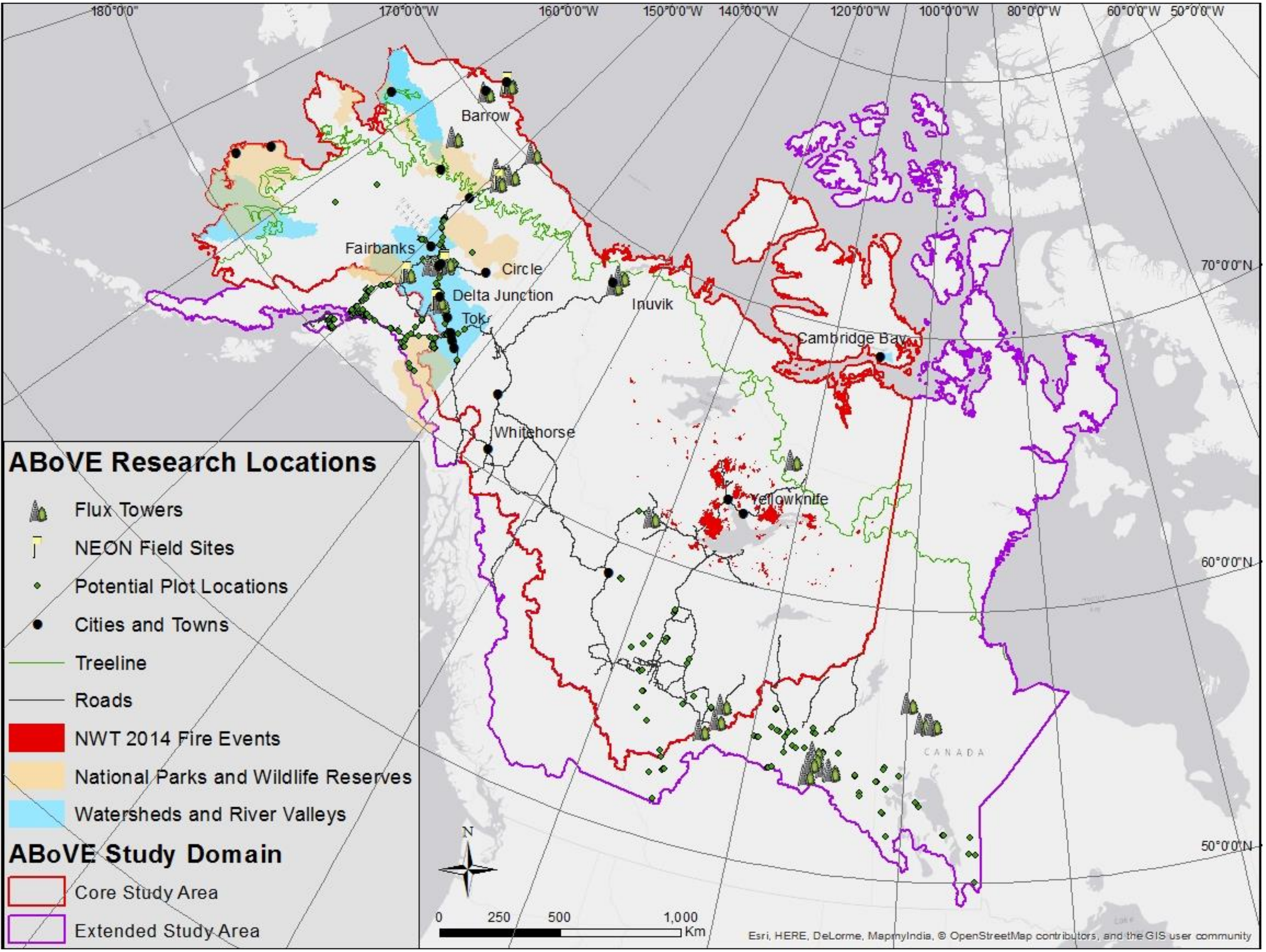
3. *Resolve how remote marine aerosols and boundary layer clouds are influenced by plankton ecosystems in the North Atlantic*

Conceptual Diagram of the Vulnerability/Resilience Framework Used for Organizing the ABoVE Science Questions and Objectives



ABoVE's Overarching Science Question:

How vulnerable or resilient are ecosystems and society to environmental change in the Arctic and boreal region of western North America?


180°0'0"
170°0'0"W
160°0'0"W
150°0'0"W
140°0'0"W
120°0'0"W
100°0'0"W
80°0'0"W
60°0'0"W
50°0'0"W
70°0'0"N
60°0'0"N
50°0'0"N
Barrow
Fairbanks
Circle
Delta Junction
Tok
Inuvik
Cambridge Bay
Whitehorse
Yellowknife
CANADA
ABoVE Research Locations
Flux Towers
NEON Field Sites
Potential Plot Locations
Cities and Towns
Treeline
Roads
NWT 2014 Fire Events
National Parks and Wildlife Reserves
Watersheds and River Valleys
ABoVE Study Domain
Core Study Area
Extended Study Area
N
0
250
500
1,000
Km
Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community

AfriSAR Science Objectives

Overall Objective:

Internationally coordinated campaign (**ESA**, **DLR**, **NASA and AGEOS**) to acquire well calibrated SAR, Lidar, and *in situ* datasets in dense tropical forests using aircraft and field measurements in support of the **ESA BIOMASS**, **NASA NISAR** and **NASA GEDI** mission requirements to develop biomass and forest structure inversion algorithms.

This effort will leverage **the high quality forest inventory data collected** in **one of the least studied** and **unique forest ecosystems** in the world; thereby providing excellent data for **scientific research**, **technology demonstrations** and **Calibration/Validation activities**.

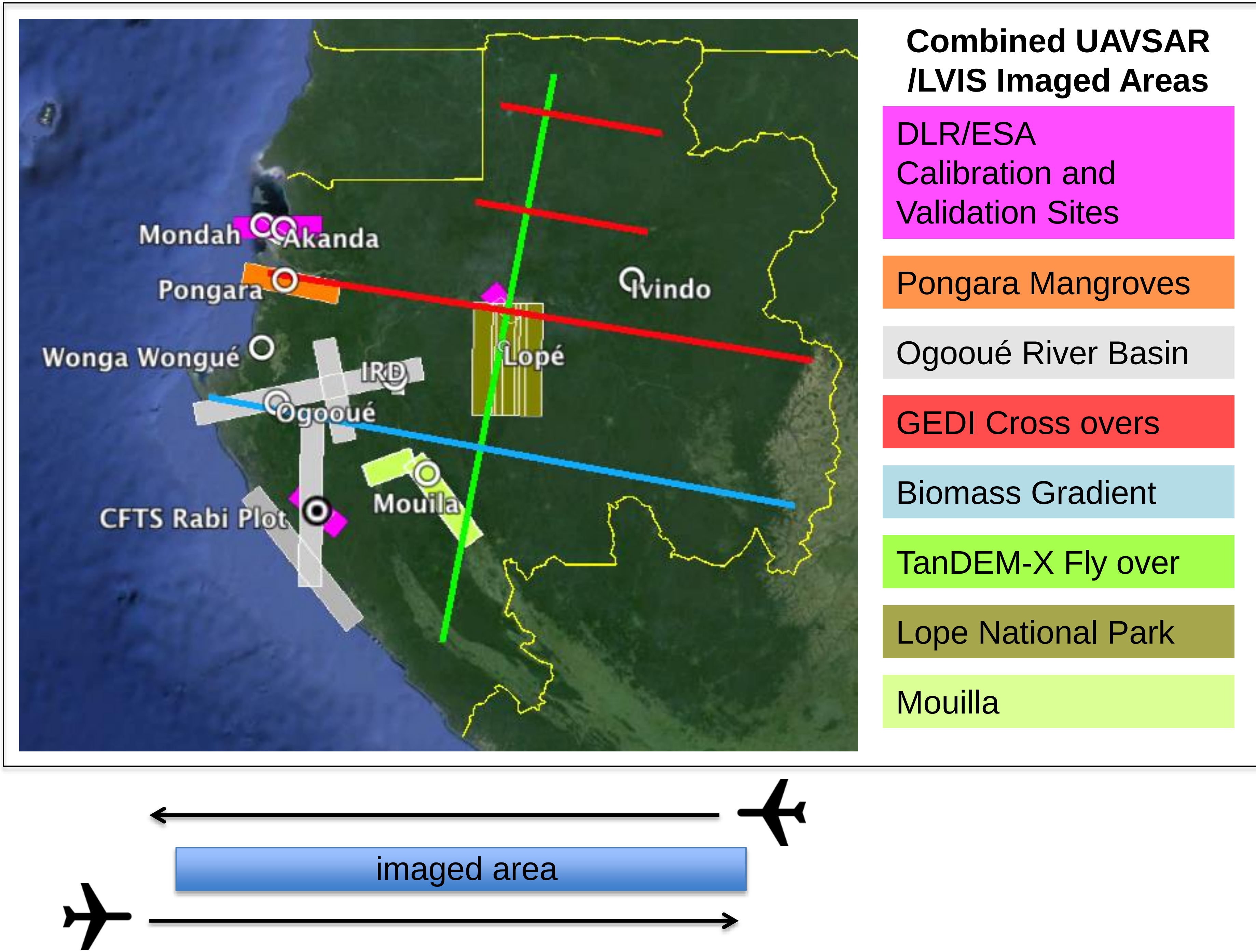
Specific Objectives:

1. Using NASA's **LVIS** and **UAVSAR** instruments to **measure forest canopy height, canopy profiles and biomass density**, under a variety of **Forest conditions** (including tropical rainforests, mangrove forests, forested freshwater wetlands and savannah) and **topographic and surface conditions** (including flat, mountainous).

2. Acquire detailed measurements of **airborne SAR data (at L and P band)** and **Lidar** data for **cross calibration** of NASA and ESA/DLR instruments and for **CAL/VAL support** of the **BIOMASS**, **NISAR, GEDI** and **TanDEM-X** missions

3. Generate a time-series **of L- and P-band SAR data** covering varying soil moisture and atmospheric conditions (including dry and rainy seasons).

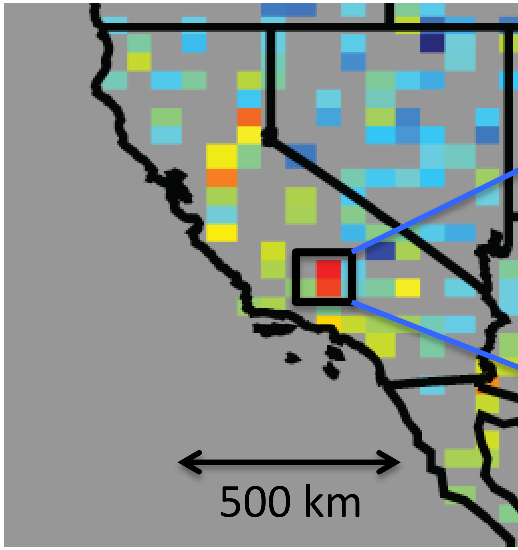
4. Conduct **Technology demonstrations** such as **Lidar-Radar Fusion**

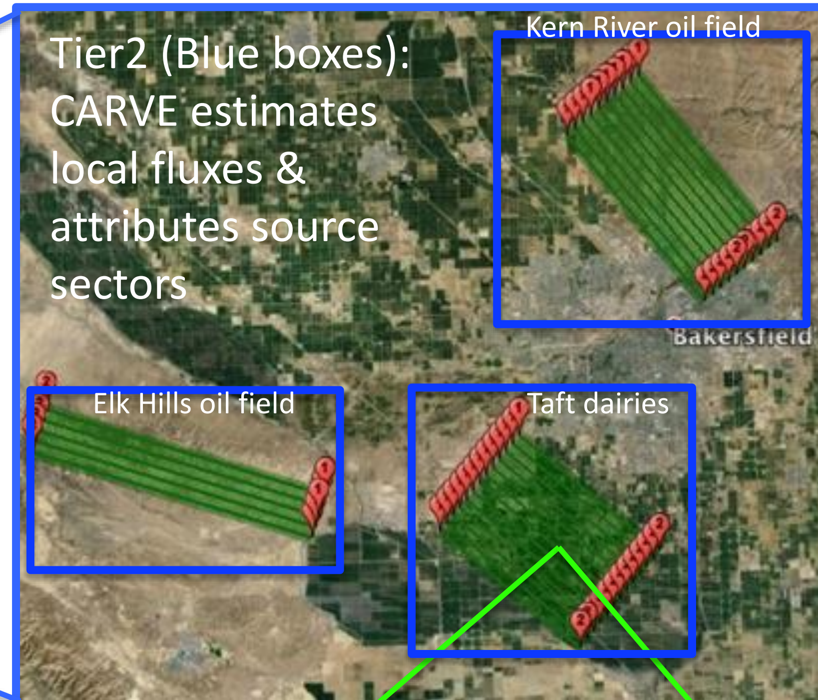

Combined UAVSAR /LVIS Imaged Areas
DLR/ESA Calibration and Validation Sites
Pongara Mangroves
Ogooué River Basin
GEDI Cross overs
Biomass Gradient
TanDEM-X Fly over
Lope National Park
Mouilla
Mondah
Akanda
Pongara
Ivindo
Wonga Wongué
IRD
Lopé
Ogooué
Mouila
CFTS Rabi Plot
imaged area

Methane Tiered Observing Strategy

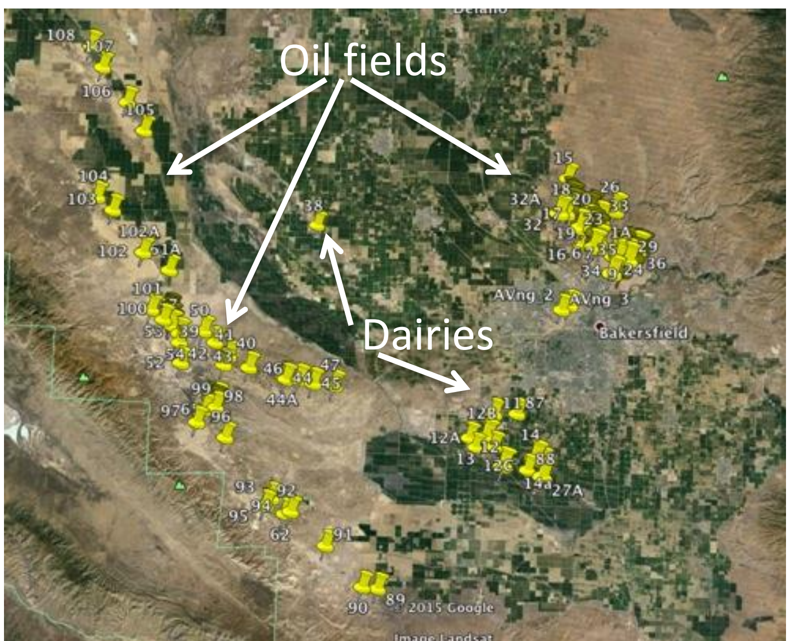
Tier 1: GOSAT detects hotspot
In Bakersfield region

Turner et al 2015





50 km



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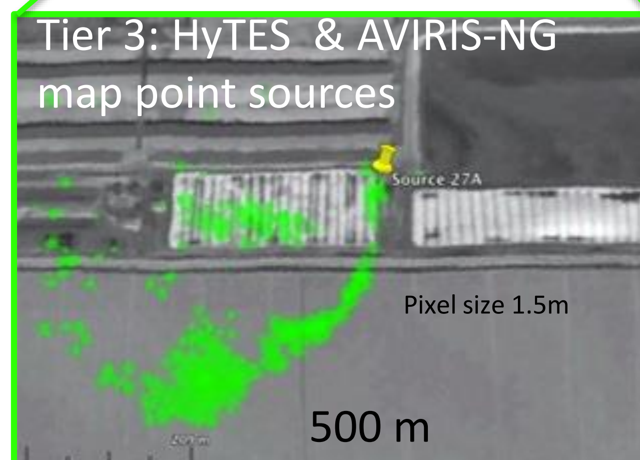
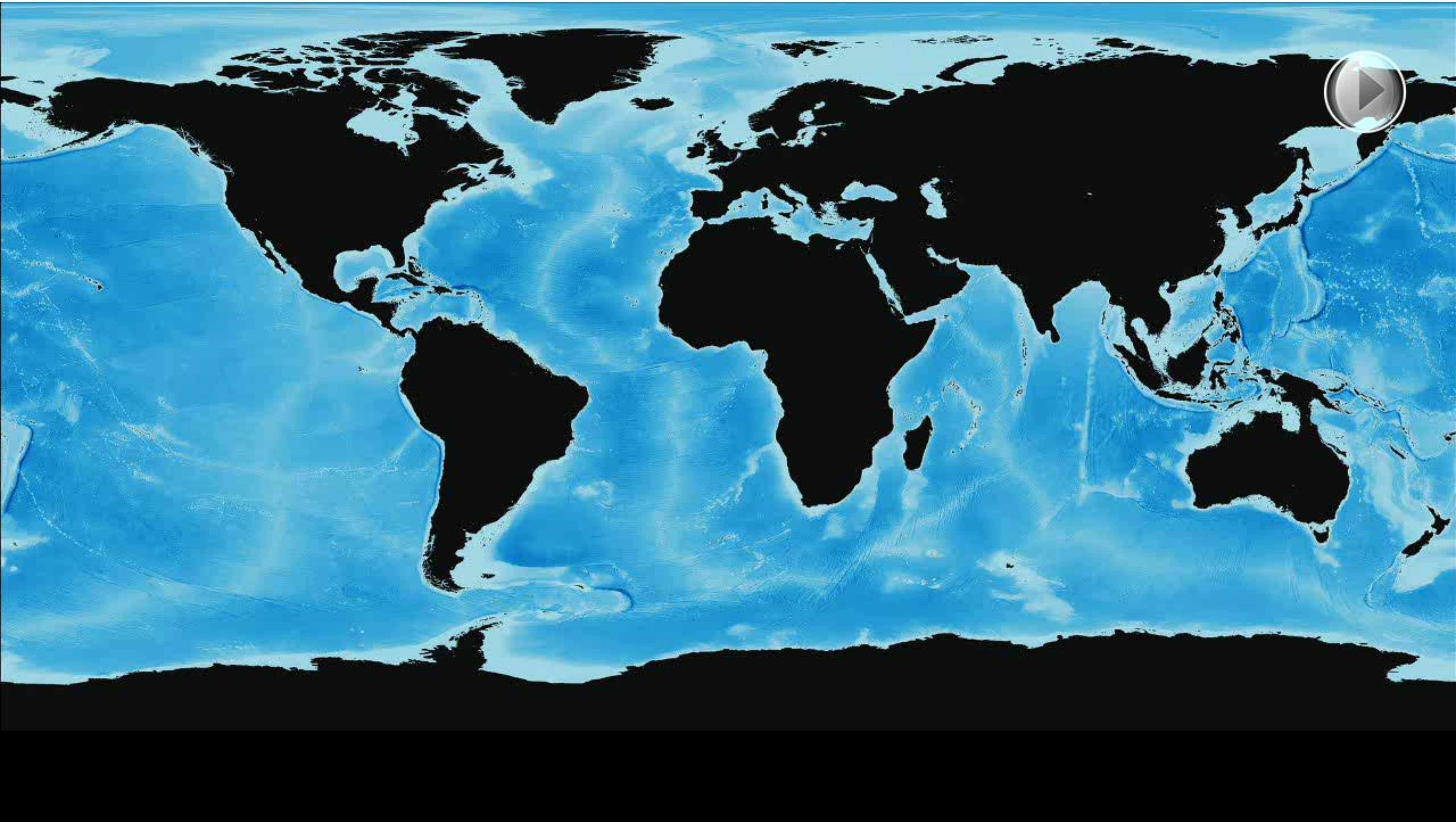
Riley
Duren/JPL



High Resolution Model Simulation



Thanks to NASA/GSFC Global Modeling and Assimilation Office

NASA's High-Level Carbon Monitoring System (CMS) Objectives

- Make significant contributions in characterizing, quantifying, understanding, and predicting the evolution of global carbon sources and sinks as well as biomass
- Use the full range of NASA satellite observations and modeling/analysis capabilities to support national and international policy and policymakers
  - Use space-based and in-situ data to maintain global emphasis while also providing finer scale regional information
  - Develop an evolutionary approach which accommodates planned increasing capabilities in space-based measurements, modeling, and data assimilation
  - Leverage capabilities of NASA centers and incorporate NASA-funded researchers through the competitive process
  - Continue to engage with and contribute to related U.S. and international systems
  - Create products to evaluate and inform near-term policy development and planning
- Ensure high quality community involvement through open solicitations and peer review.

CMS Core Elements

Biomass Pilot: Use satellite and in-situ data to produce quantitative estimates of aboveground terrestrial vegetation biomass on a national and local scale; and assess whether these results meet our monitoring needs (24 investigations, 15 ongoing)

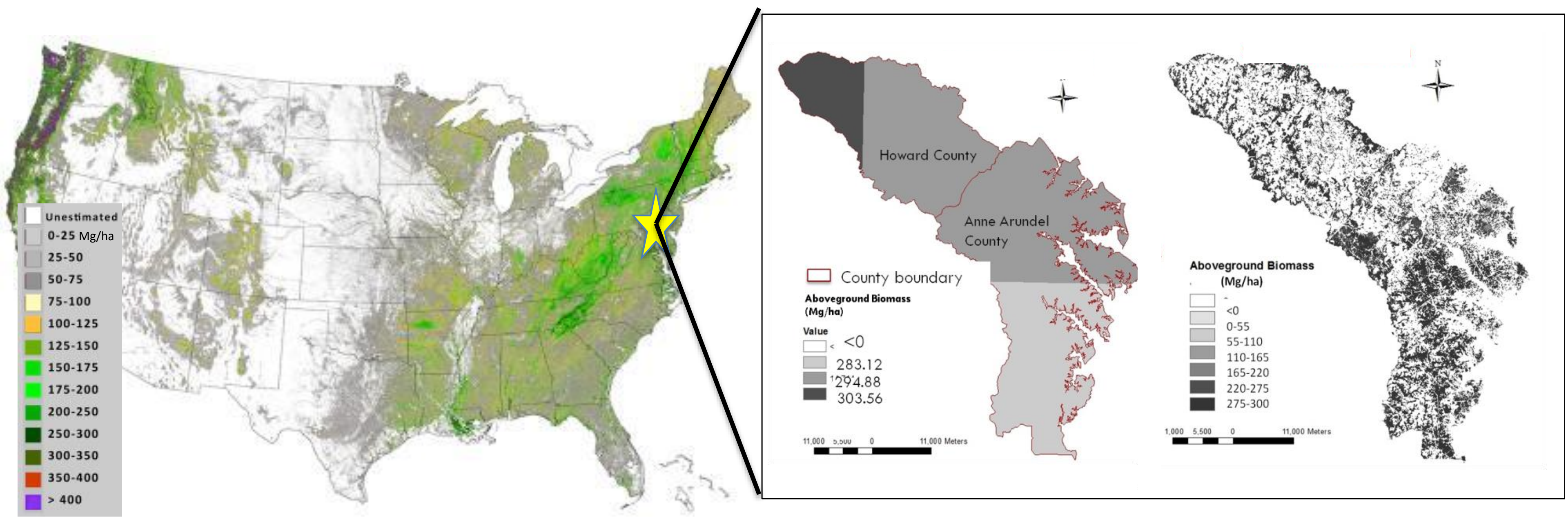
Flux Pilot**: Use satellite data and models tied to** Combine satellite and model (terrestrial and oceanic) data to tie the atmospheric observations to surface exchange processes; and estimate the atmosphere-biosphere CO_2 exchange. (28 investigations, 18 ongoing)

Scoping/End User Engagement Efforts: Identify research, products, and analysis system evolutions required to support carbon policy and management as global observing capability increases. (3 investigations, 2 ongoing)

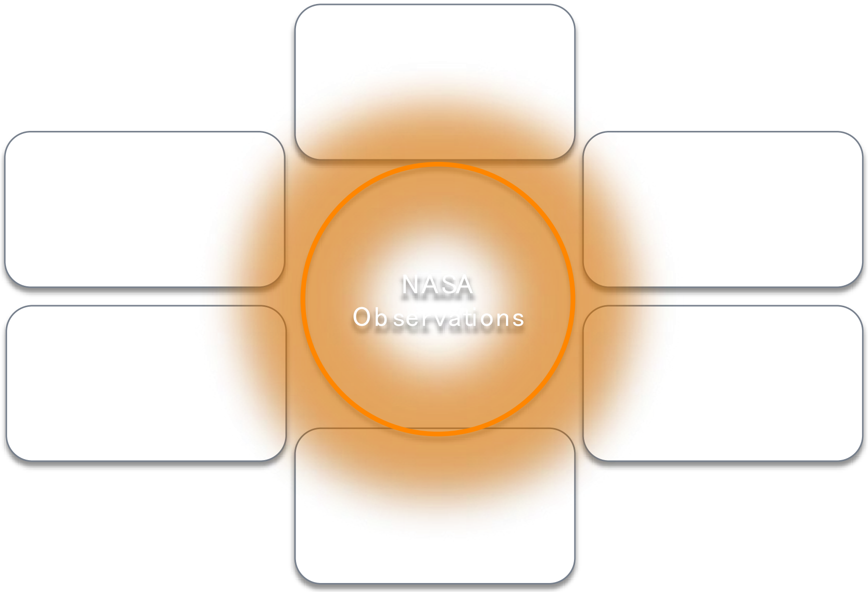
National Aeronautics and Space Administration

CMS pilots: Biomass

The Biomass pilots combines Continental US estimates from imaging satellites with local airborne lidar observations of vegetation canopy biomass qualities. This allows one to scale up the local, more precise, observations more globally.

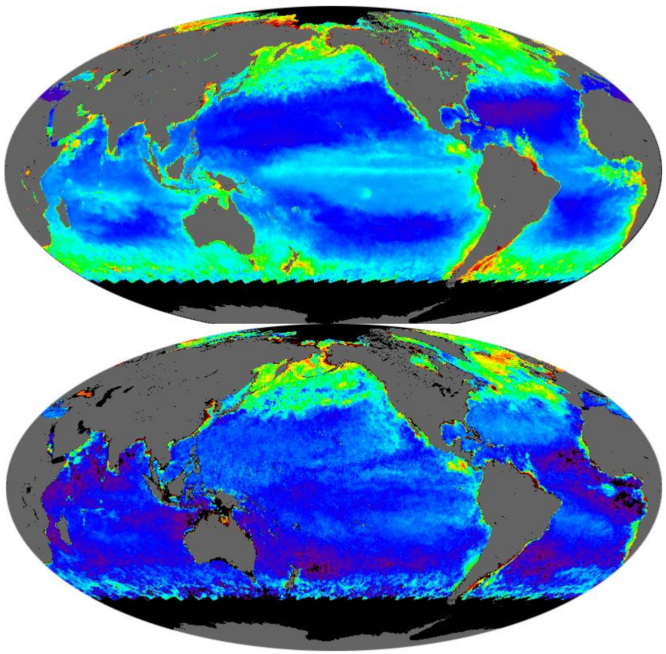


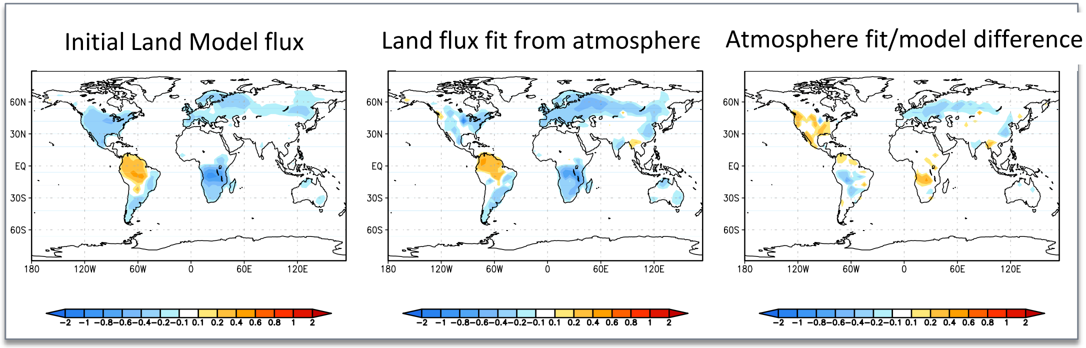
CMS Pilots - Flux



Flux products are determined by observationally constrained models of land and ocean exchange with the atmosphere, atmospheric transport models, and atmospheric observations of CO_2/CH_4 from space (like OCO-2).

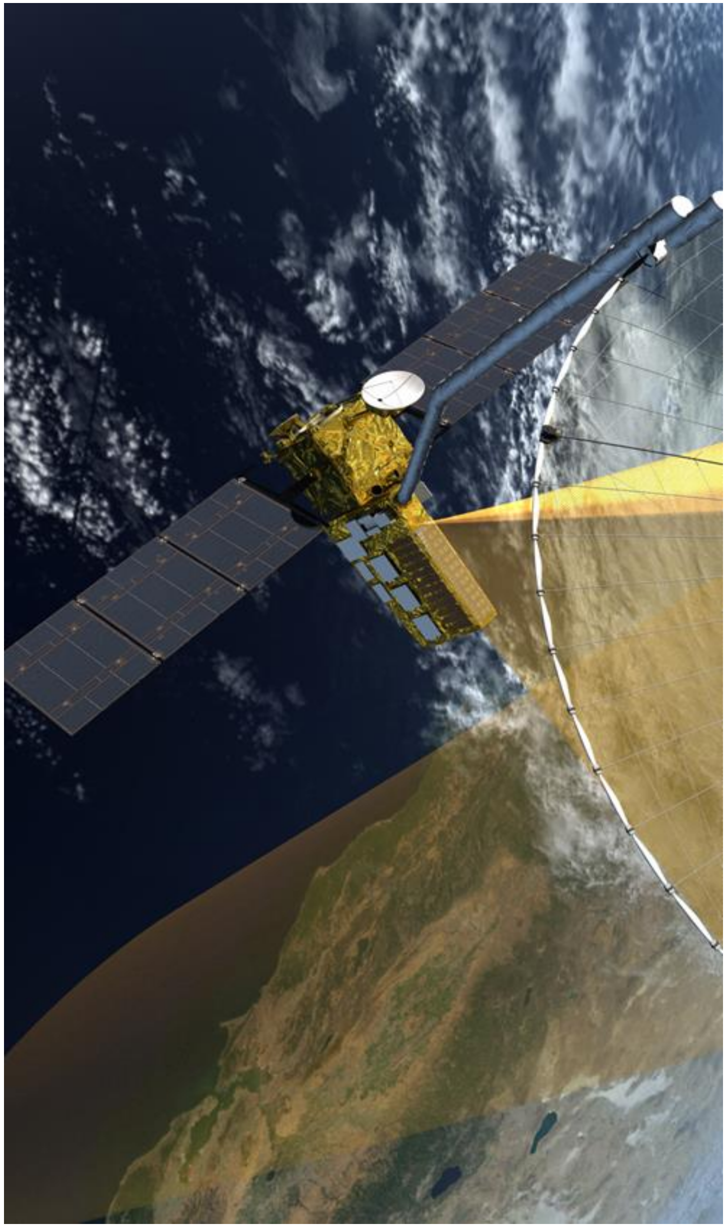
Initial model Ocean constraints



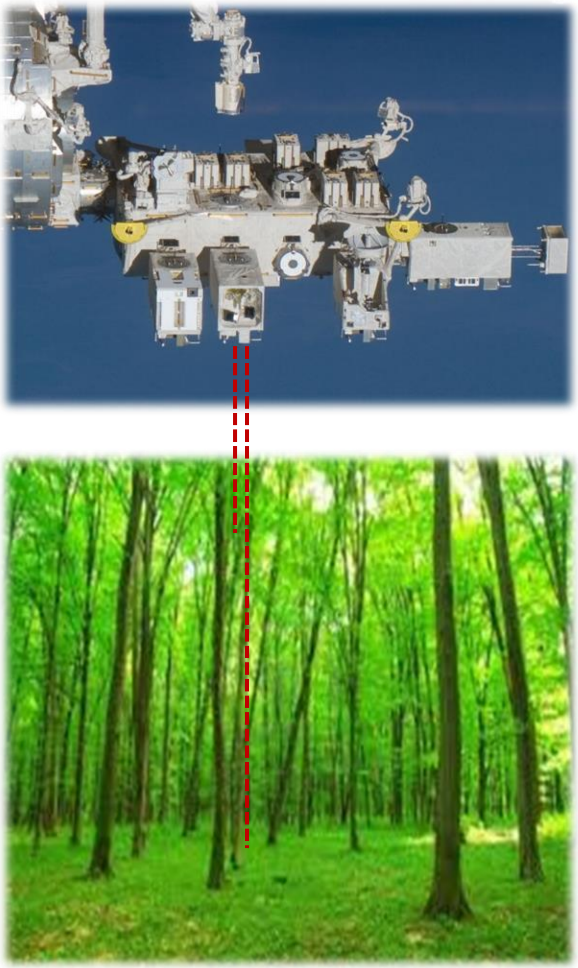


NISAR Mission Overview

- NISAR is a dual frequency (L+S band) Synthetic Aperture Radar Mission to be launched in late 2020/ 2021.
- Orbit: 747km altitude circular, 98º inclination, sun-synchronous, dawn-dusk (6 AM – 6 PM); 12-day repeat cycle.
- Primary mission operation is planned for 3 years with consumable up to 5 years.
- NISAR is a Directed mission for implementation by the Jet Propulsion Laboratory in partnership with Indian Space research Organisation (ISRO).
- All data will be made available freely and openly, consistent with the long-standing NASA Earth Science open data policy.

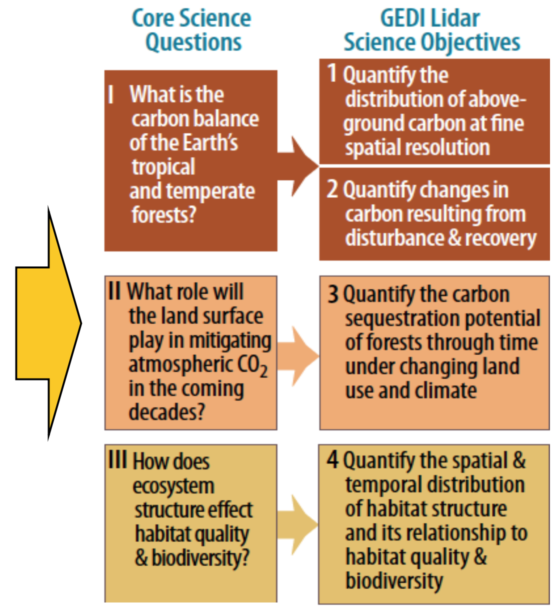


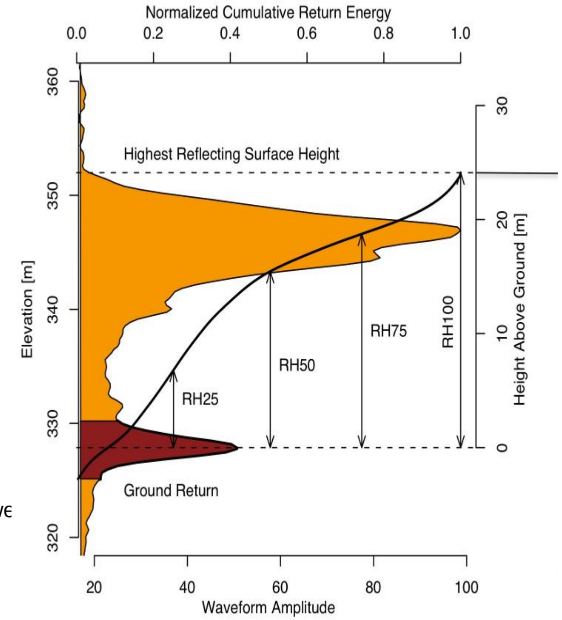
GLOBAL ECOSYSTEM DYNAMICS INVESTIGATION (GEDI)

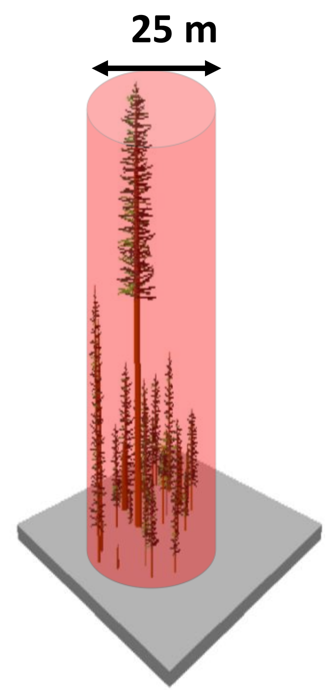


Science Goal

Characterize the effects of changing climate and land use on ecosystem structure and dynamics to enable modeling of the Earth's carbon cycle and biodiversity







<u>GEDI Instrument</u>

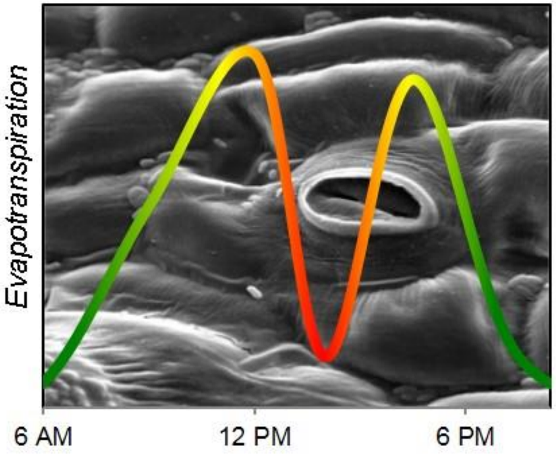
- Self-contained laser altimeter
- Multi-beam waveform LIDAR
- 14 ground tracks, 60m track x 450m width (may be reduced to 10 tracks to conserve powe
- Single axis, active track pointing, 1064 nm lasers

NASA to provide access to ISS

Location on ISS is Japanese Experiment Module – External Facility Unit (JEM-EFU) Site #6

ECOSTRESS Science Overview

ECOSTRESS will provide critical insight into ***plant-water dynamics*** *and how* ***ecosystems change with climate*** *via* ***high spatiotemporal*** *resolution thermal infrared radiometer measurements of evapotranspiration (ET) from the International Space Station (ISS).*



Science Objectives

- Identify **critical thresholds of water use and water stress** in key climate-sensitive biomes
- Detect the timing, location, and predictive factors leading to plant **water uptake decline** and/or cessation over the **diurnal cycle**
- Measure **agricultural water consumptive use** over the contiguous United States (CONUS) at spatiotemporal scales applicable to improve drought estimation accuracy

Pre-Aerosol, Cloud, and ocean Ecosystem (PACE) Mission

Pre-Aerosol, Cloud, and ocean Ecosystem (PACE) is an ocean color, aerosol, and cloud mission identified in the 2010 report "Responding to the Challenge of Climate and Environmental Change: NASA's Plan for a Climate-Centric Architecture for Earth Observations and Applications from Space Science".

Science Objectives

- *Primary:* Understand and quantify global biogeochemical cycling and ecosystem function in response to anthropogenic and natural environmental variability and change: ocean color sensor
- *Secondary:* Understand and resolve/quantify the role of aerosols and clouds in physical climate (the largest uncertainty): polarimeter
- Extend key Earth system data records on global ocean ecology, biogeochemistry, clouds, and aerosols (expanded ocean color sensor similar to MODIS)

Risk	• 8705.4 Payload Risk Class C
Launch	• 2022/2023, budget and profile driven
Orbit	• 97° inclination; ~650 km altitude; sun synchronous
Duration	• 3 years
Payload	• Ocean color instrument; potential for a polarimeter
LCC	• **$805M Cost Cap**

Conclusion

- NASA satellites, both individually and in conjunction with those of our partners, are making important contributions towards documenting many aspects of the global carbon cycle
- Integrated surface-airborne field campaigns are providing new insight into processes that affect carbon distributions, as well as improving calibration/validation for satellite products, and allowing for testing of new measurement approaches
- Advances in modeling are allowing for integration of different types of environmental observations that allow for study of the global carbon cycle, including hypothesis testing and production of data sets for community use
- Products of distributions of carbon, including fluxes and reservoirs covering both terrestrial and oceanic components are being produced and made available to research and applications communities and multi-lateral forums such as the Committee on Earth Observation Satellites (CEOS)