The Aerosol, Clouds, Convection, and Precipitation Mission Study: Observing System Simulation Experiments for Multi-angle Polarimeters

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Outline

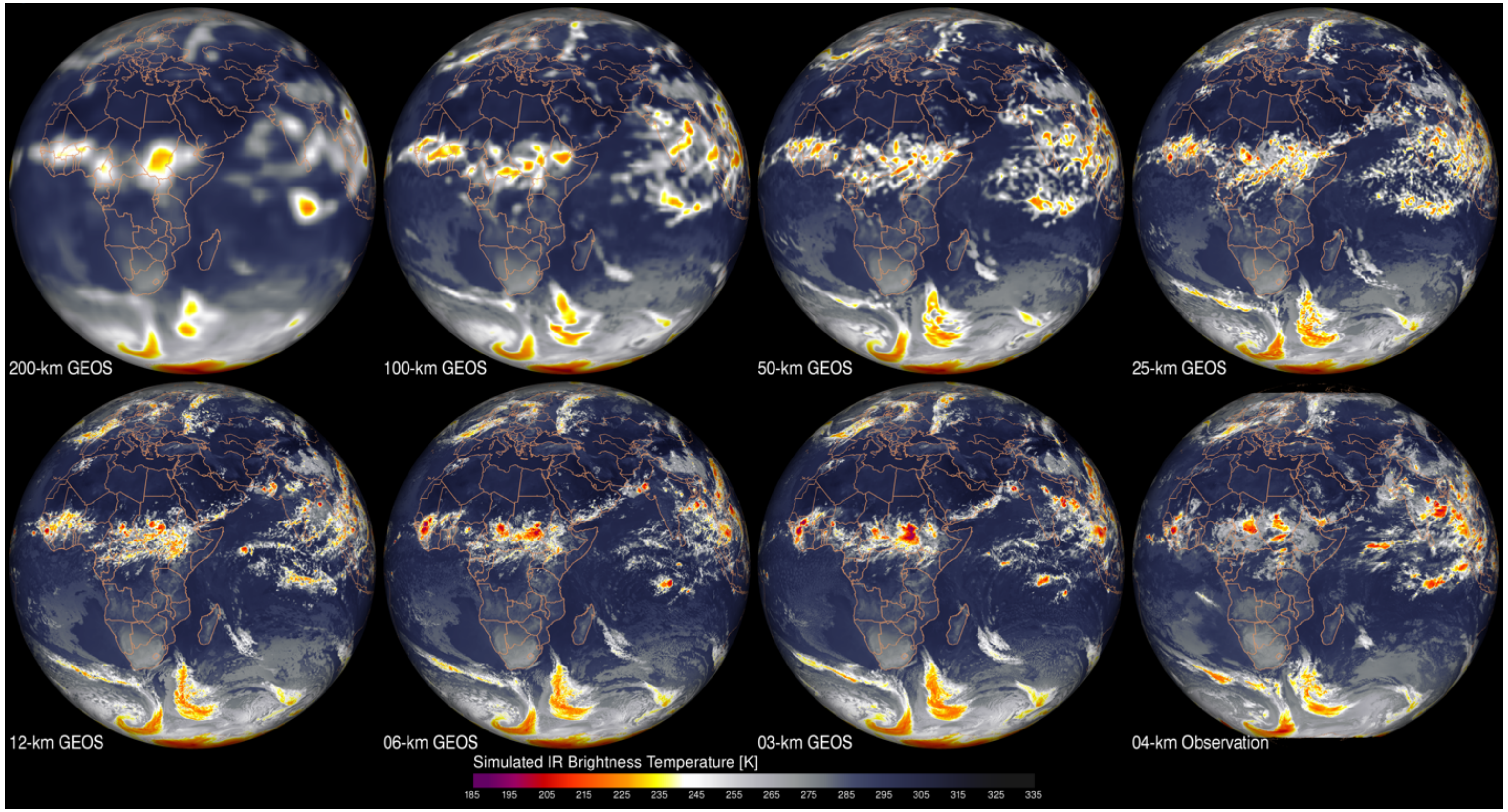
- Global Modeling and Assimilation Office (Who am I?)
- Observing System Simulation Experiments (OSSEs)
- The Aerosol Clouds, Convection, and Precipitation (ACCP) Mission Study

Global Modeling and Assimilation Office (GMAO)

- GMAO IS NASA's Earth System Modeling and Analysis group
- Responsible for development of the GEOS (Goddard Earth Observing) Model

GEOS APPLICATIONS

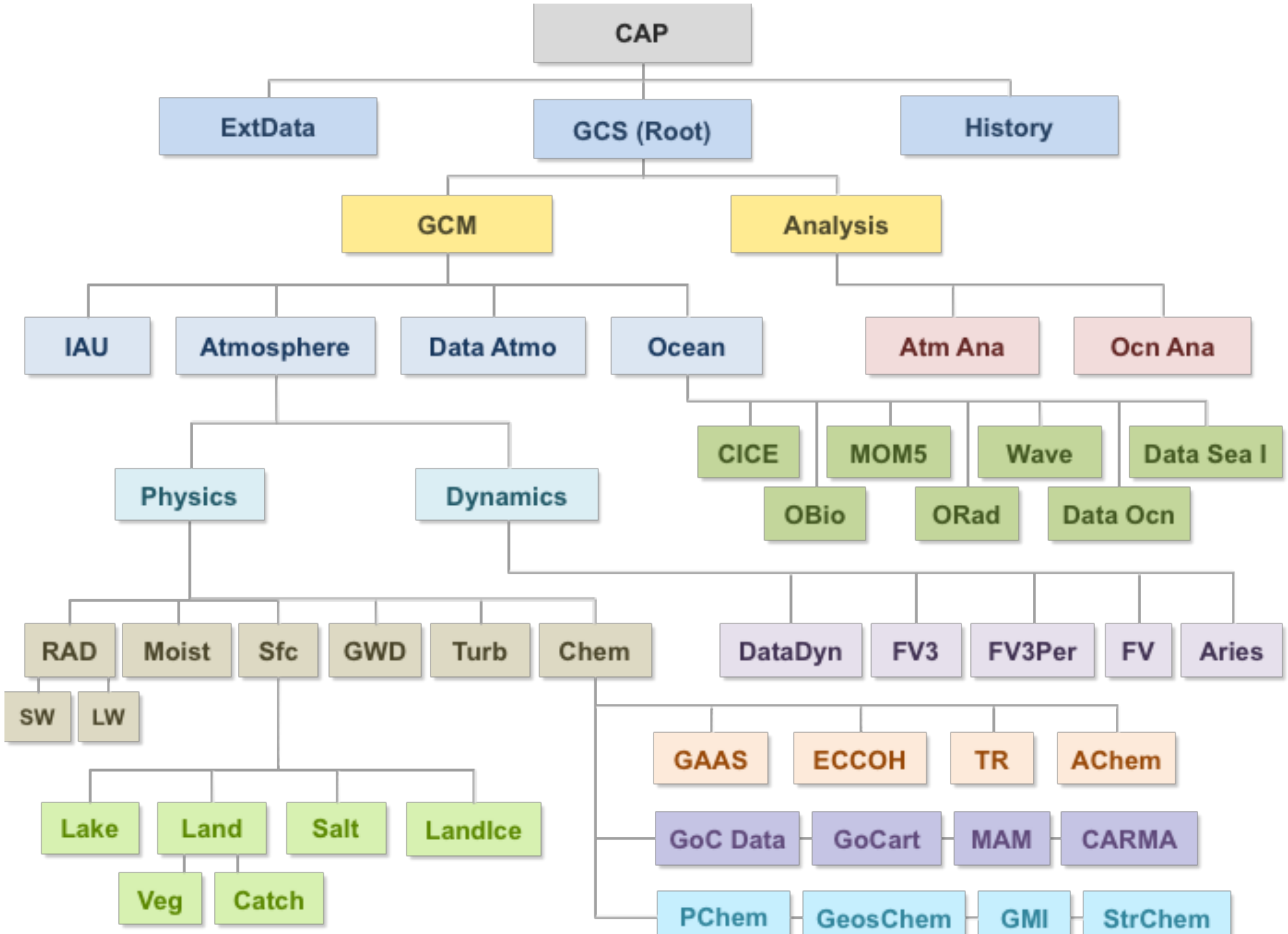
- Weather Analysis and Prediction
- Subseasonal-to-Seasonal (S2S) and Decadal Prediction
- Multi-decadal Reanalysis (MERRA-2)
- National Climate Assessment
- Observing System Simulation Experiments (OSSEs)



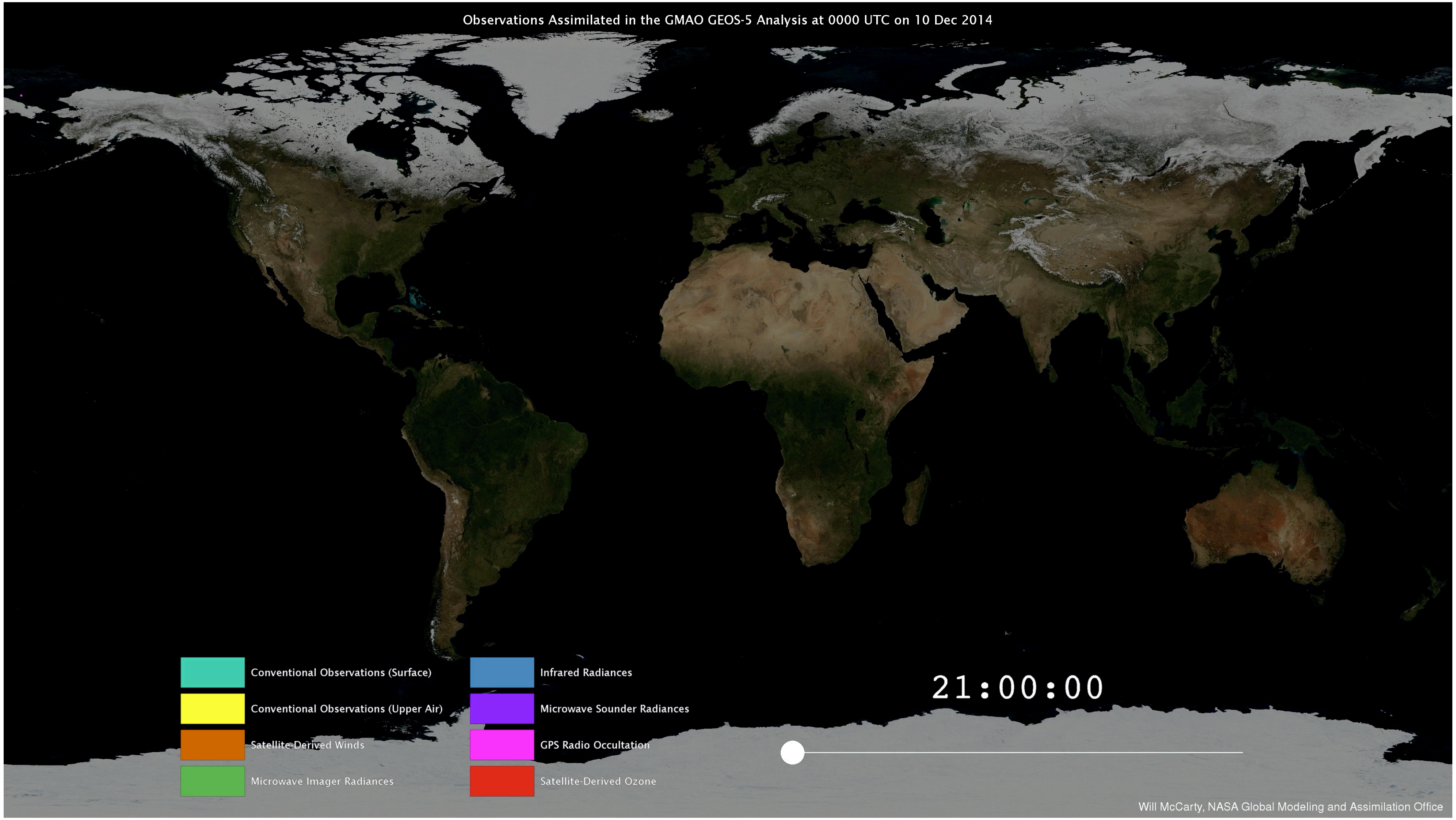
GEOS Model Architecture

- GEOS is a hierarchy of ESMF components
  - An infrastructure for building GEOS applications
- The MAPL layer interface to ESMF provides an abstraction of software issues including:
  - Generic Initialize/Finalize/Run
  - Simplified hierarchy (creation of child components)
  - IO Layers (Asynchronous file server output)
  - Regridding transforms (grids and tiles)
  - Profiling (Performance and Memory)
  - Input (ExtData) / Output (History)
- Architecture permits flexibility
  - NWP configuration
  - S2S configuration (seasonal, w/coupled ocean)
  - CCM configuration (advanced chemistry)
  - CF configuration (full chemistry NRT forecasting)
  - NR configuration (high resolution for OSSEs)
  - CTM configuration (offline met fields)

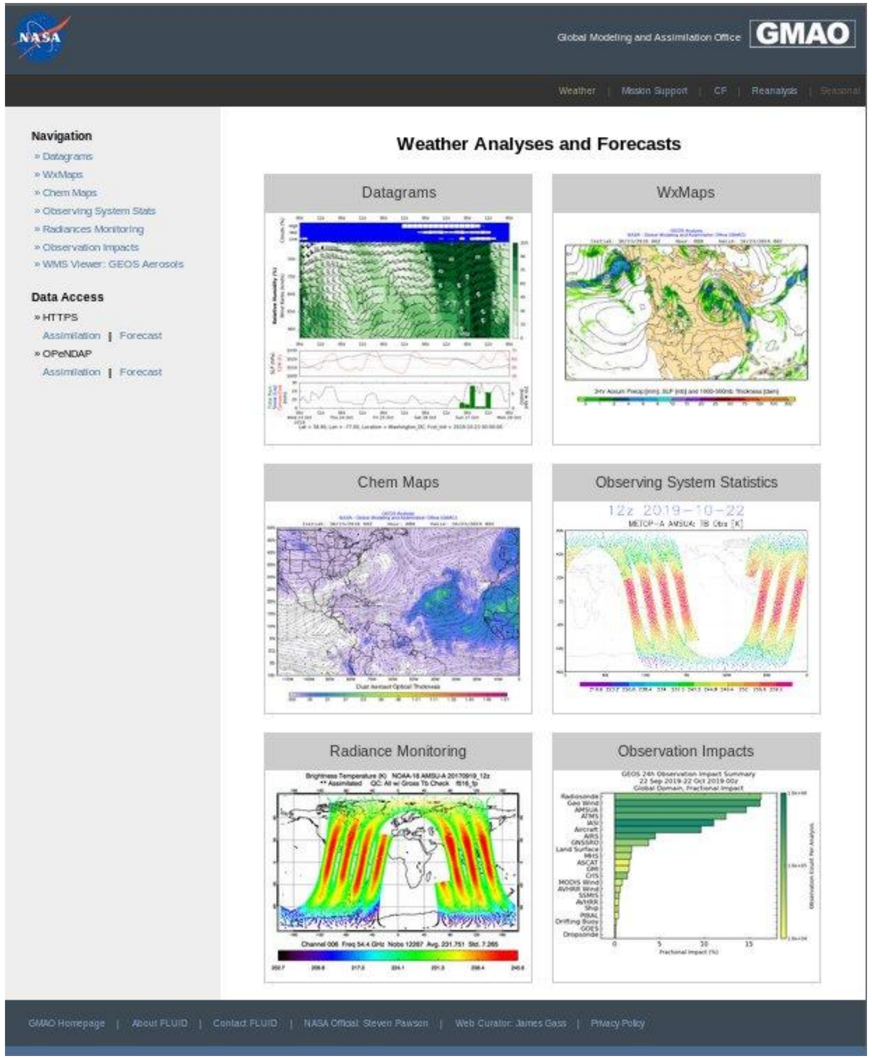
All these configurations use the same core model components



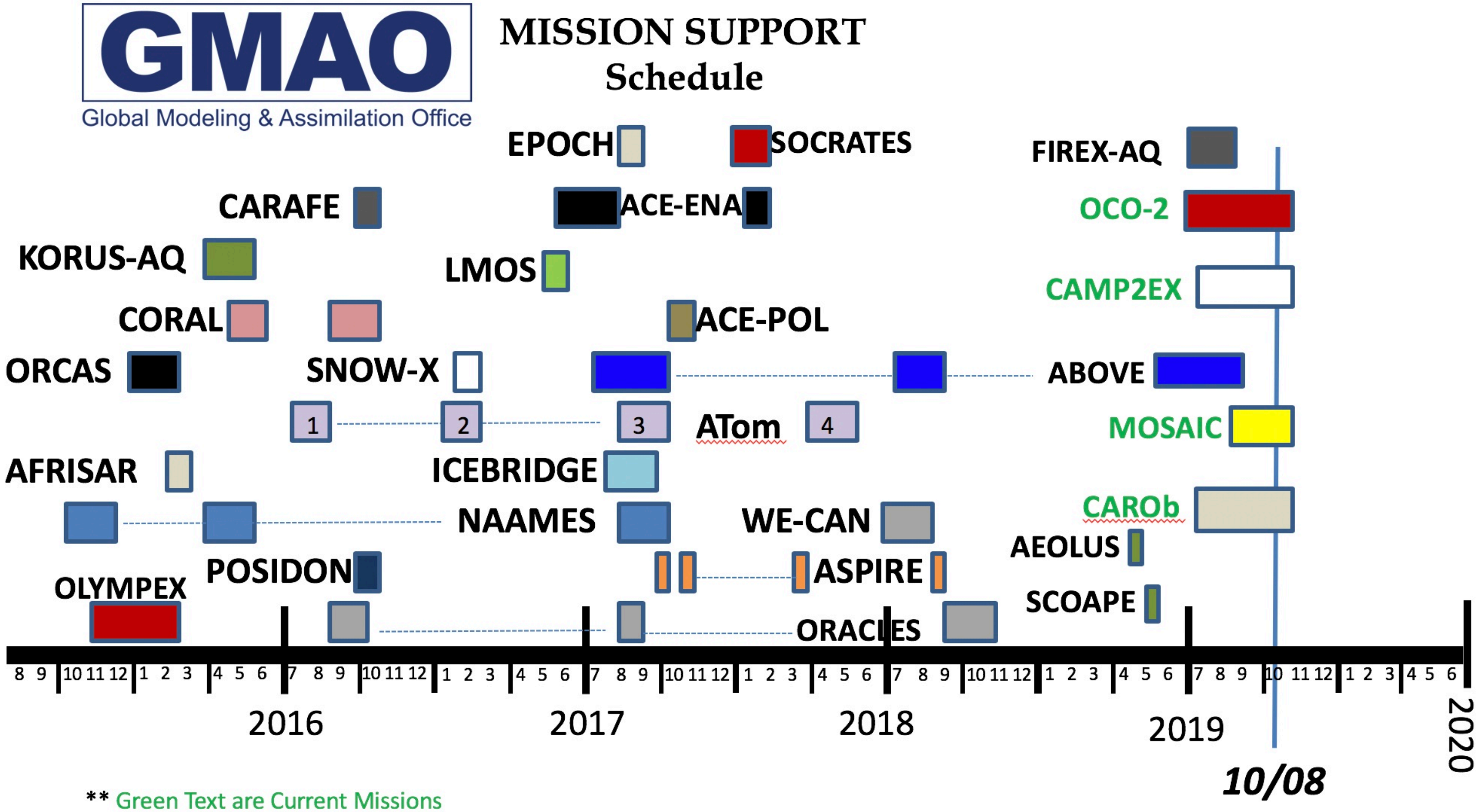
GEOS Analysis System Brings Together the Earth Observing System



Field Mission Support



https://fluid.nccs.nasa.gov/weather



** Green Text are Current Missions

CAROb (Cloud Aerosol Rain Observatory) – Thru Sept 30
OCO-2 (Orbiting Carbon Observatory)
MOSAIC (Arctic Climate Study)
CAMP2EX (Cloud – Aerosol – Monsoon - Web support only) to Oct. 31

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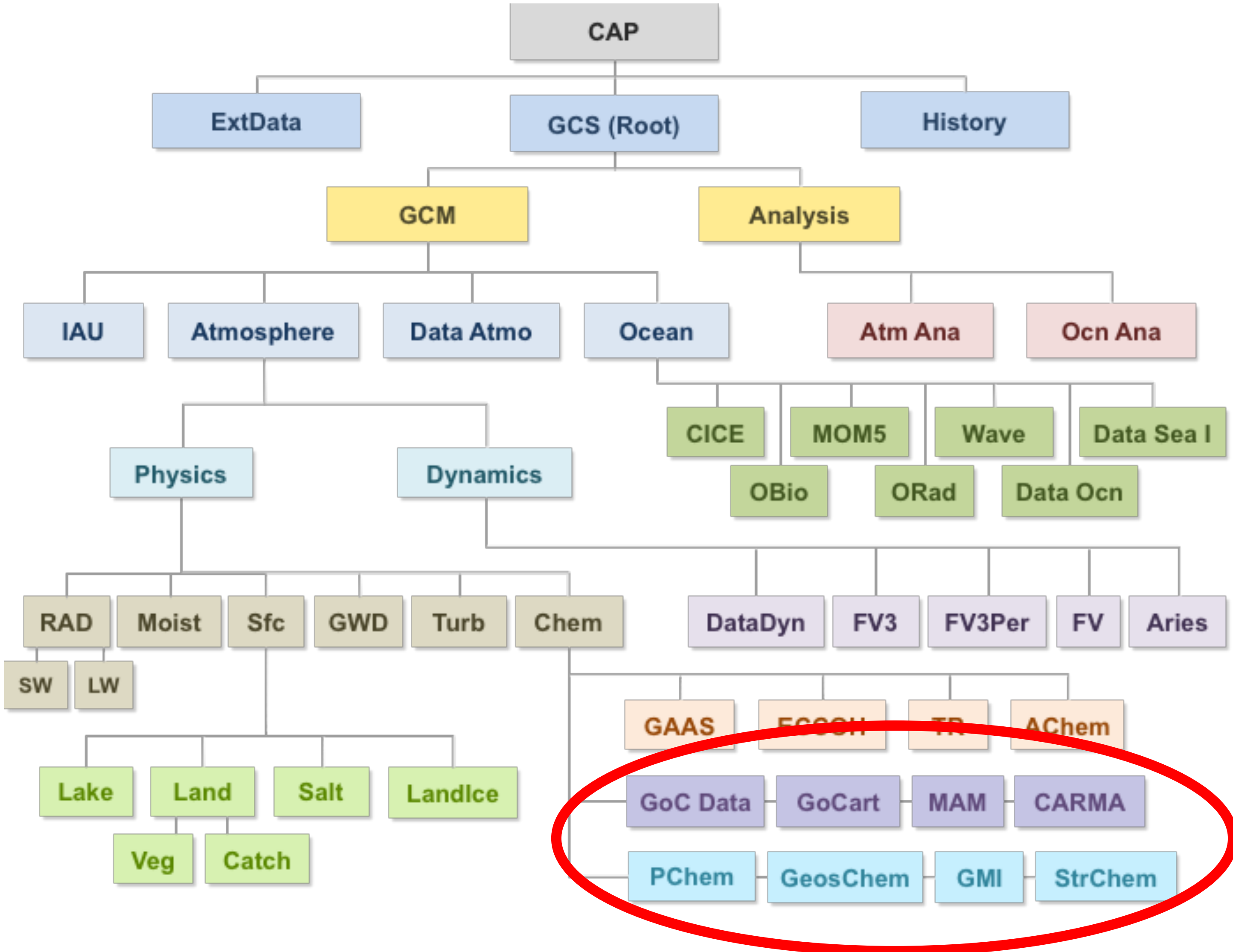
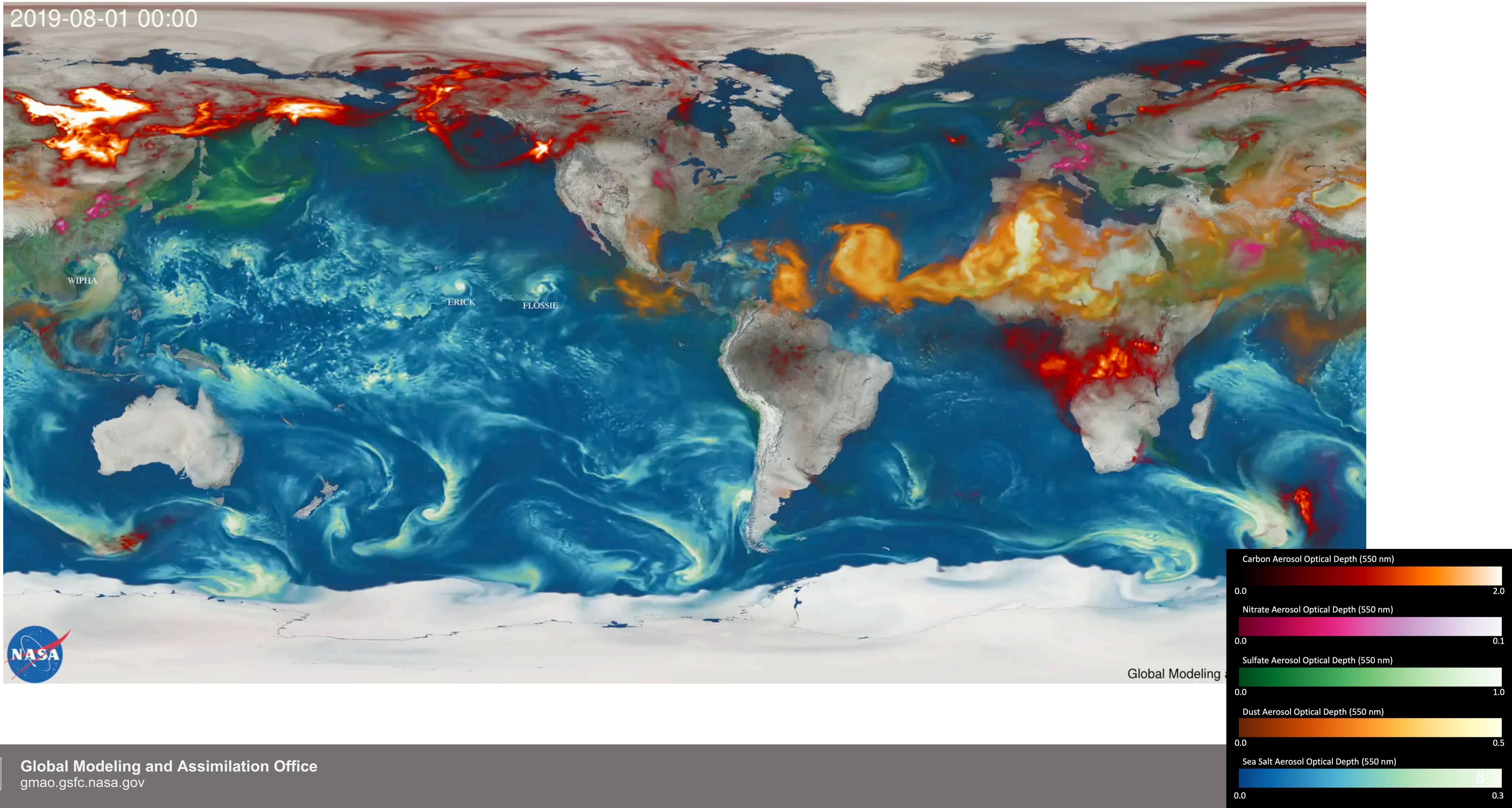
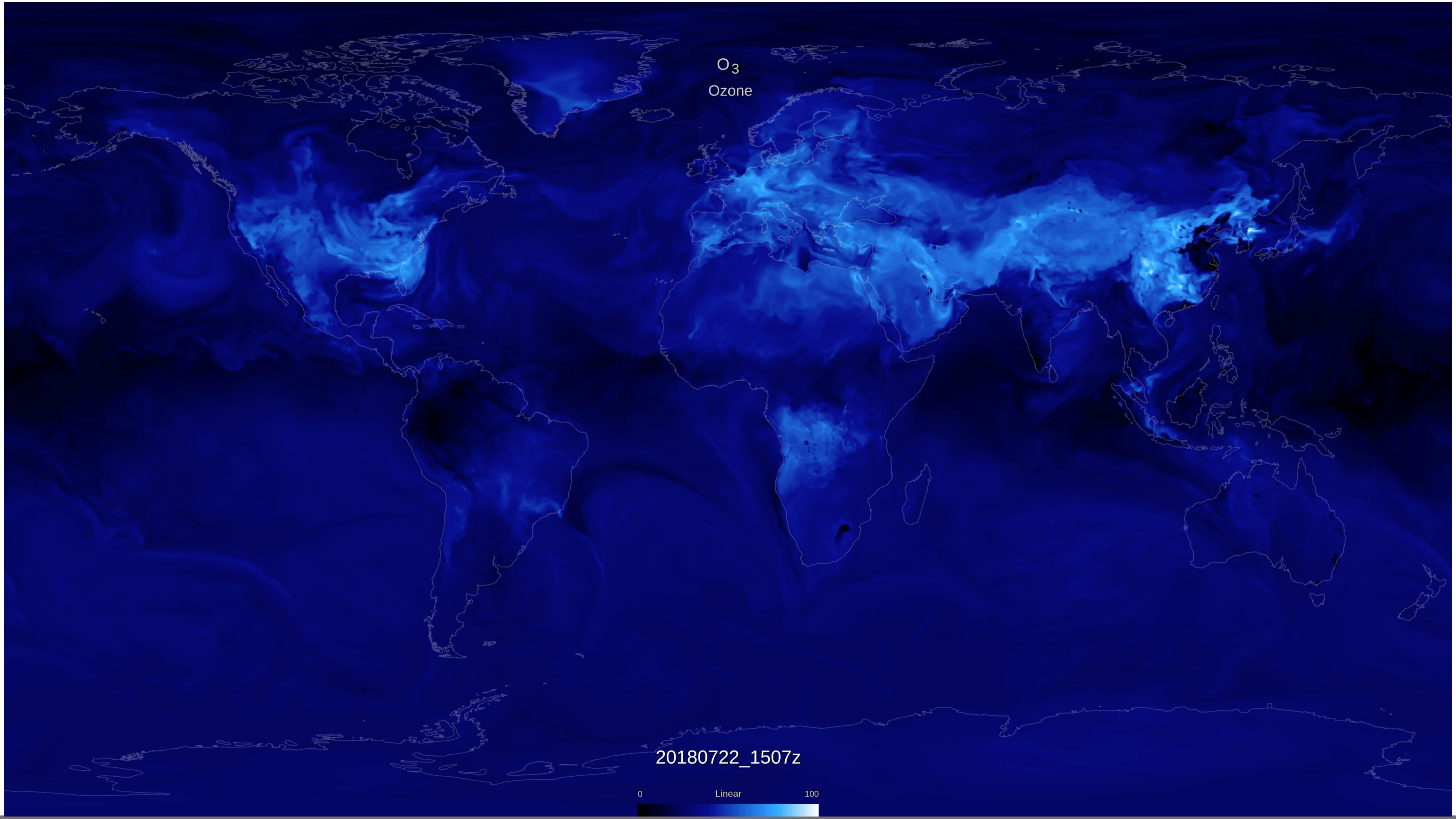


GEOS Aerosol Assimilation and Forecast



GEOS-CF: Full Chemistry NRT Forecast



O.S.S.E

- **O**bserving **S**ystem
- **S**imulation
- **E**xperiment

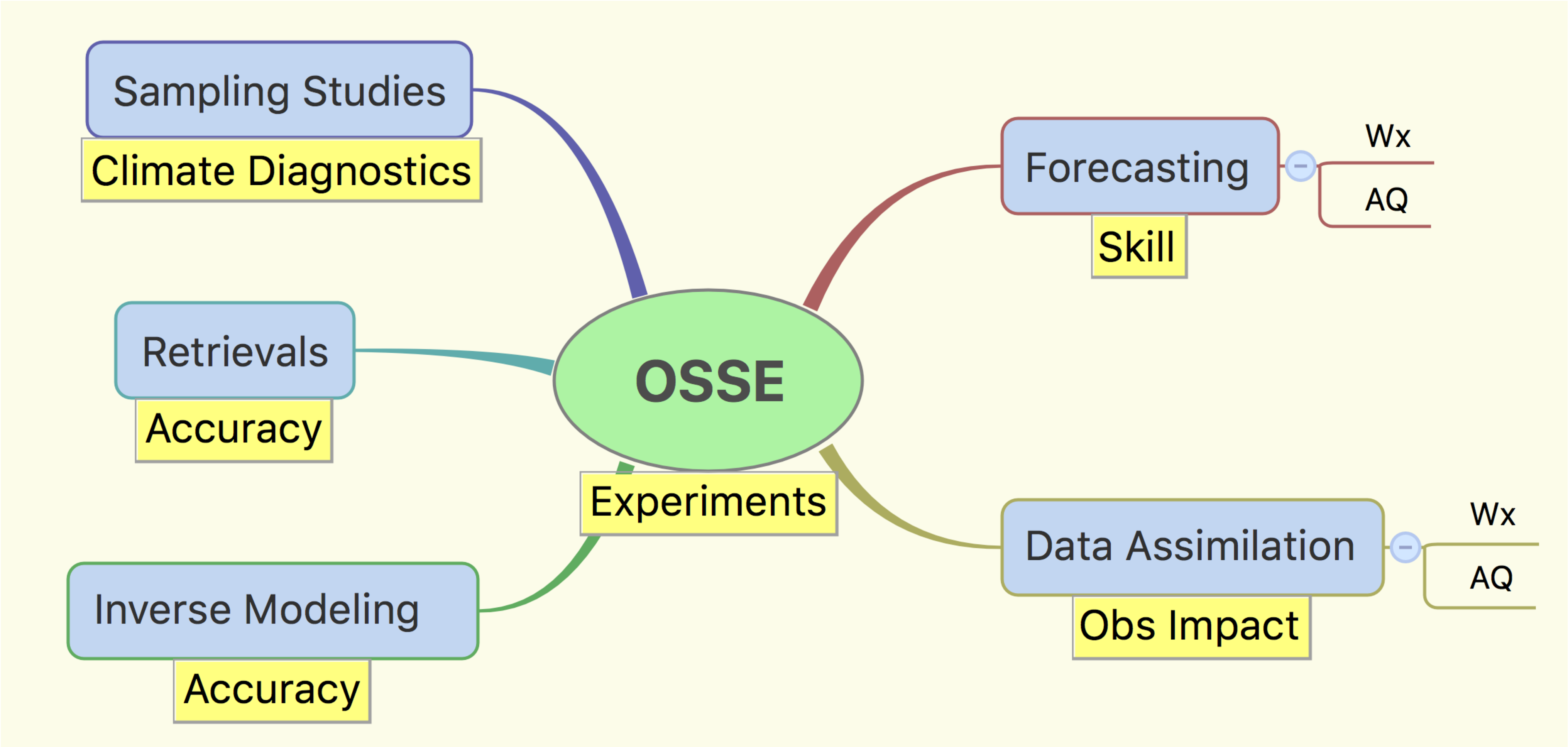
- **Traditionally:** OSSEs evaluate potential impact of new observations on a weather forecast (Hoffman and Atlas, 2016; BAMS)
- **Fundamentally:** OSSEs quantify information in a future observing system

Model-based OSSE

A framework for numerical experimentation in which *observables* are simulated from fields generated by an earth system model, including a *parameterized* description of the *observational error* characteristics.

Simulations are performed in support of an experimental goal.

The “E” in OSSE

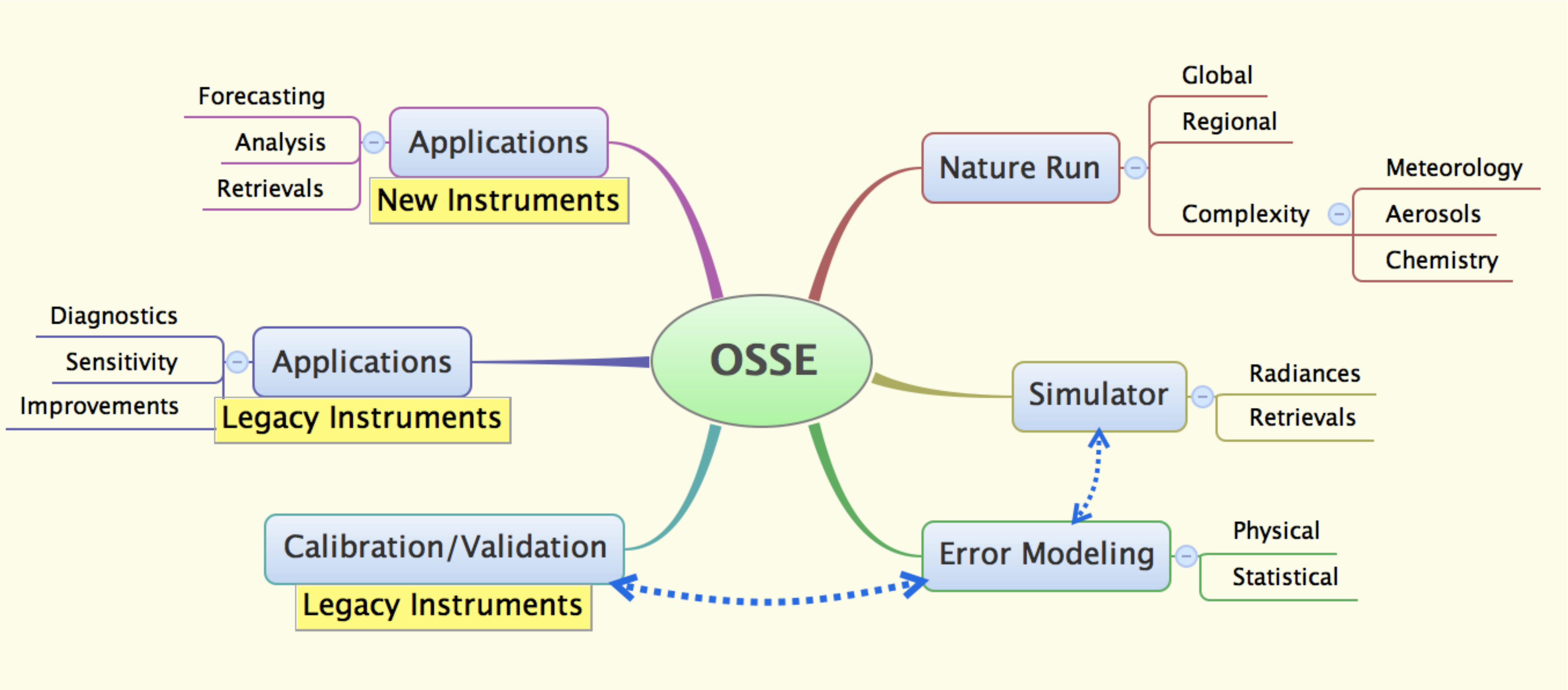

Sampling Studies
Climate Diagnostics
Retrievals
Accuracy
Inverse Modeling
Accuracy
OSSE
Experiments
Forecasting
Skill
Wx
AQ
Data Assimilation
Obs Impact
Wx
AQ

The Validation Imperitive

- As with any simulation, OSSE results apply to new instruments only to the degree they have been validated with existing legacy instruments.
- OSSE credibility is first determined by carefully comparing a variety of statistics that can be computed in both the real and OSSE simulated contexts.

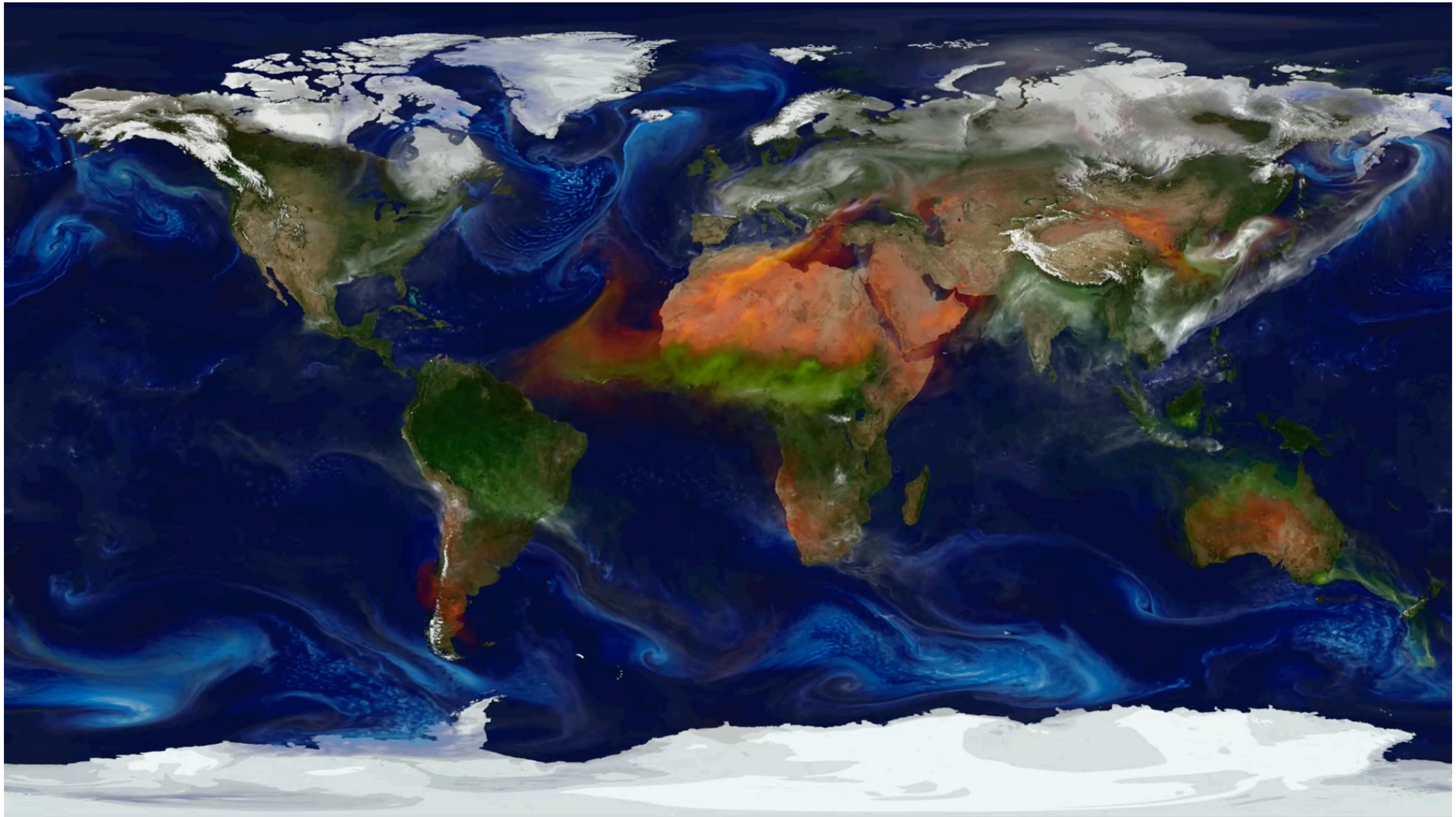
OSSEs need to be validated as a *System*

Elements of an OSSE System

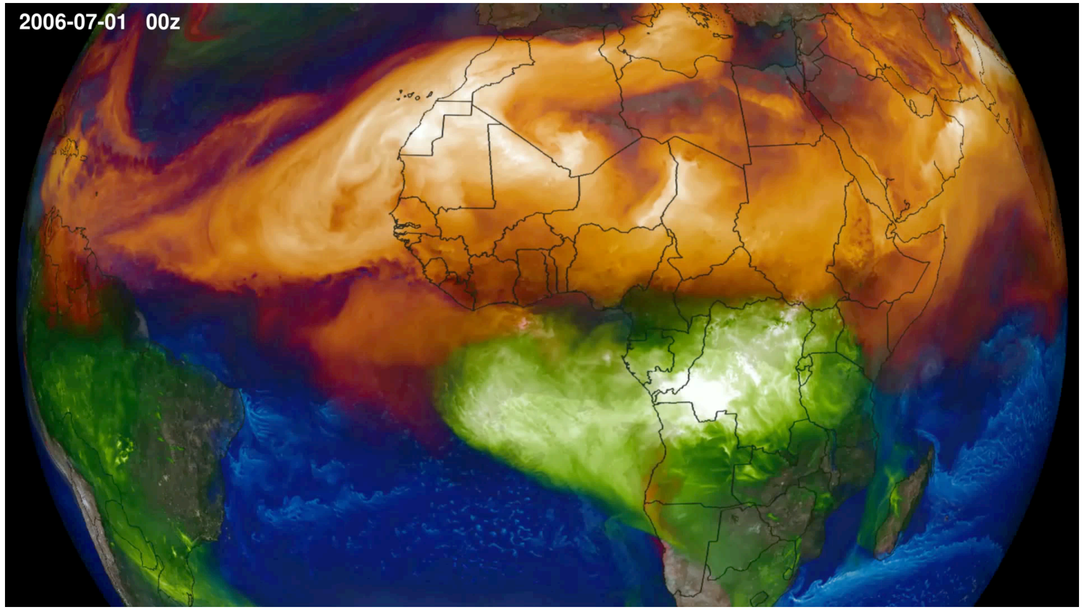


GEOS Global 7 km Nature Run (G5NR)

- G5NR is a non-hydrostatic free-rrunning simulation
- 7 km resolution
- 72 layers
- 30 min timestep
- 1.5 years
- Includes GOCART aerosols, O_3, CO, and CO_2

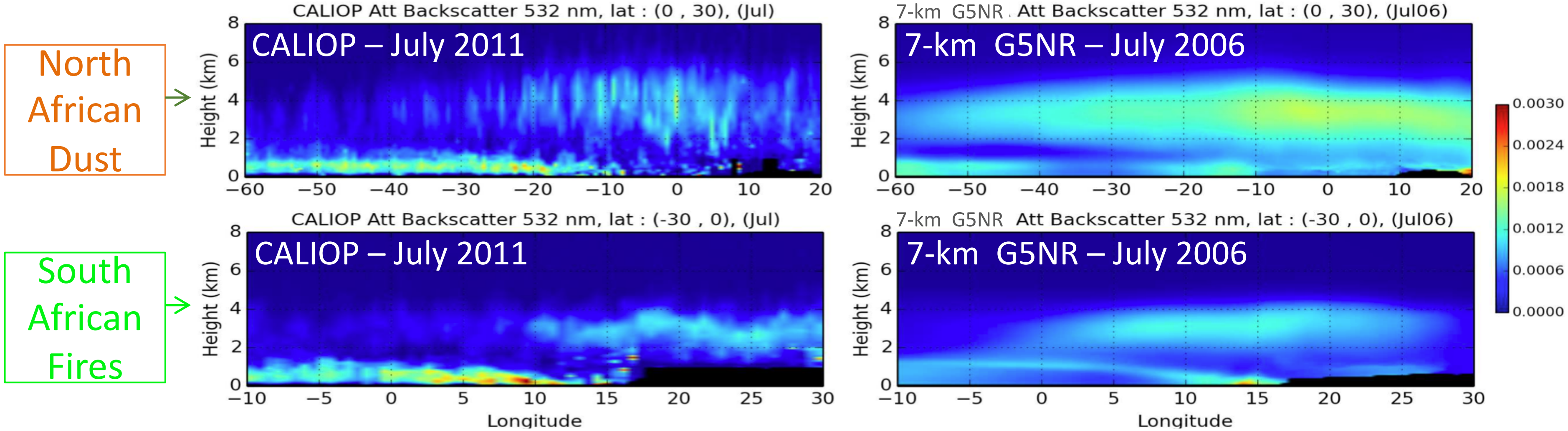


G5NR Validation

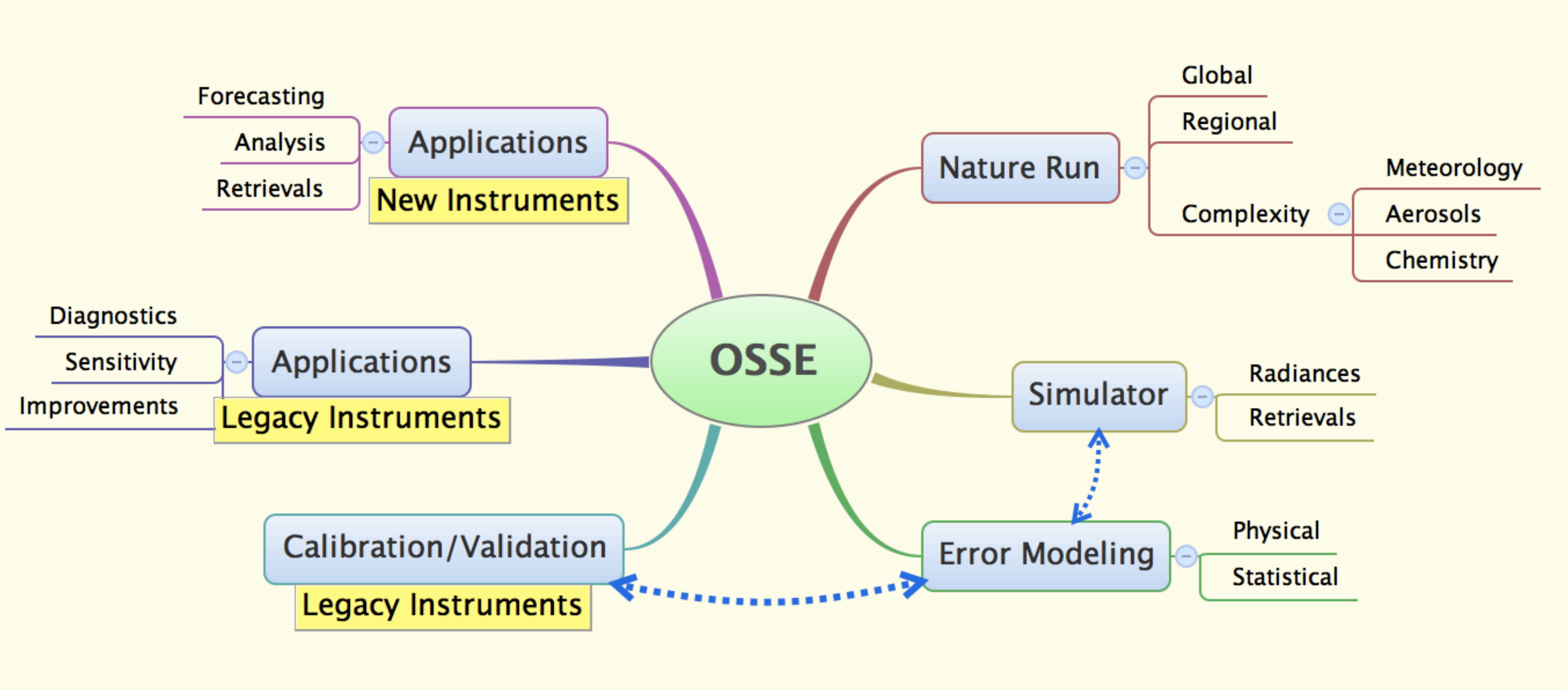


Compared to long-term datasets

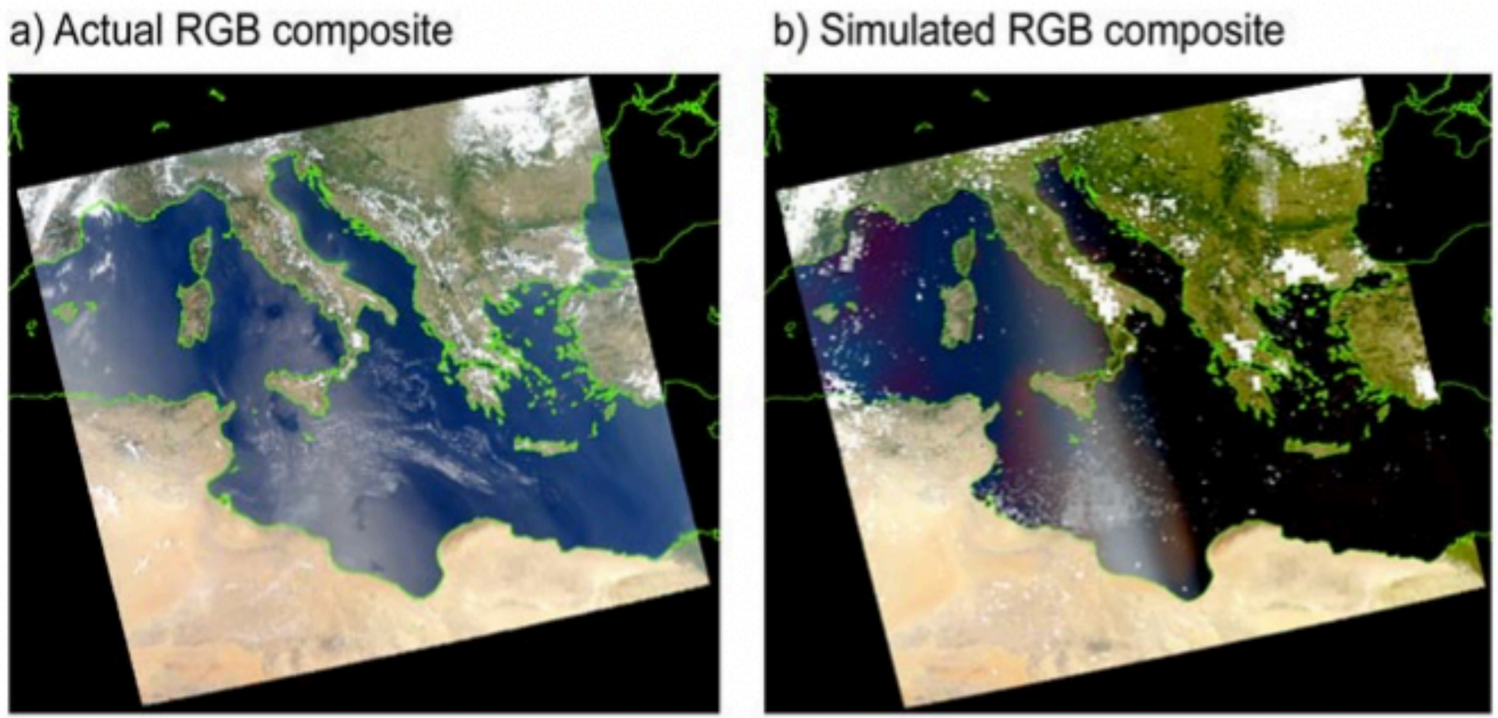
- Monthly mean observations
- Reanalysis: MERRA & MERRAero
- Multi-model Statistics: e.g. AeroCom



Elements of an OSSE System



GEOS Instrument Simulator

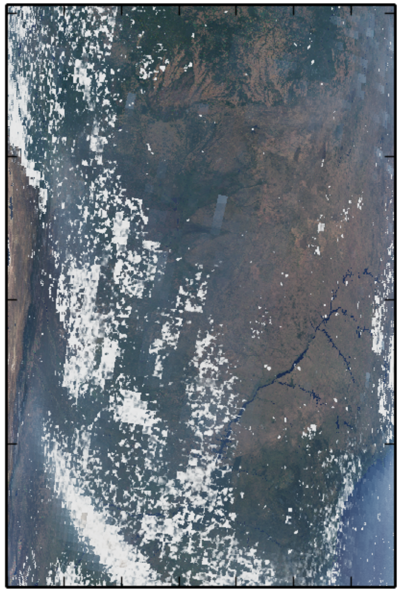


- Detailed radiative transfer calculation in the presence of clouds, aerosols, ice, etc.
- Apply instrument characteristics
- Create Simulated Observables:
  - top of the atmosphere polarized radiances
  - backscatter
  - etc.

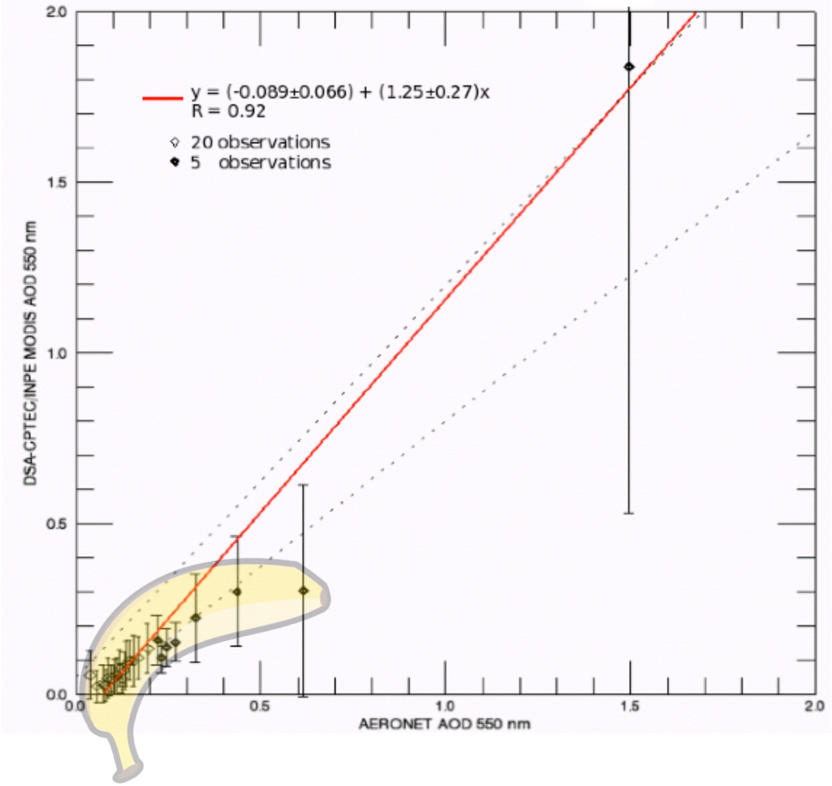
Wind et al., 2013 and 2016

AOD OSSE For Smoke over Brazil

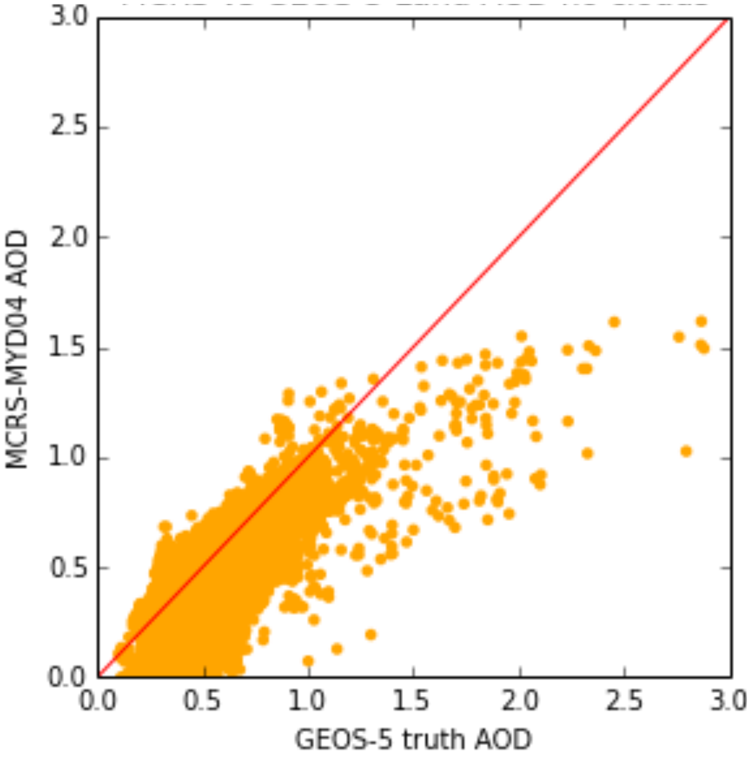
Simulated MODIS Granule



Real Comparison of Retrieved AOD and Observed Ground Truth

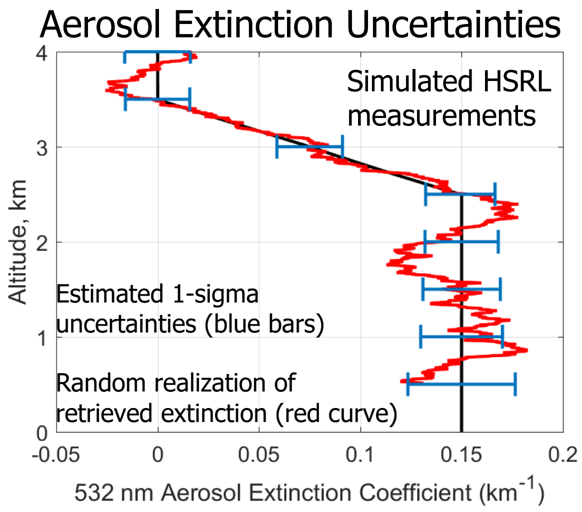


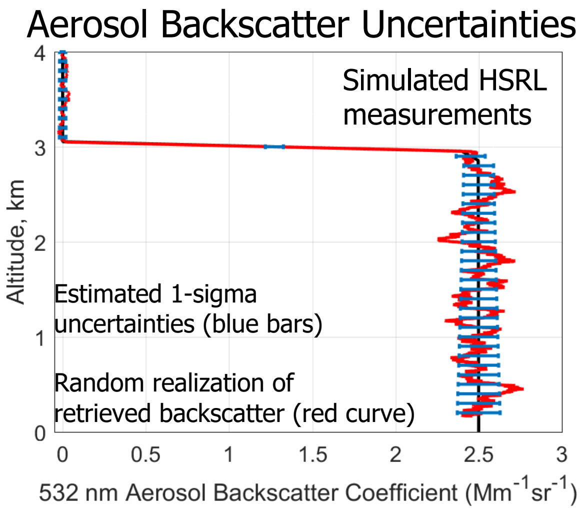
Simulated Comparison of Retrieved AOD and Model Ground Truth

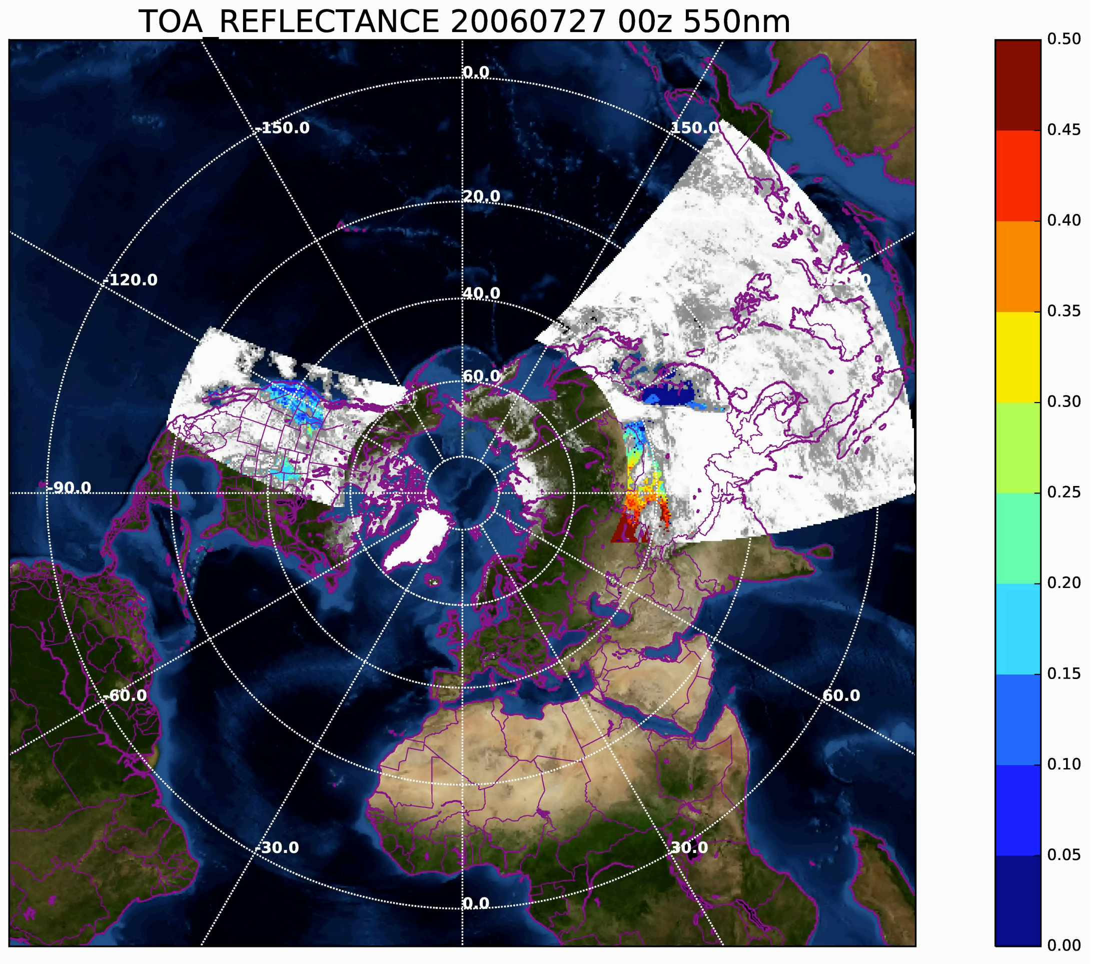


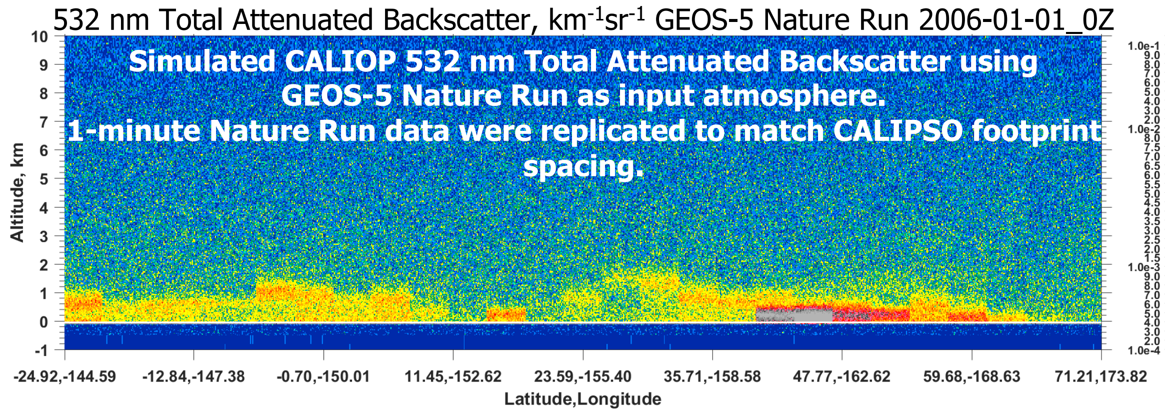
Wind et al., 2013 and 2016

GEOS Instrument Simulator









Decadal Survey for Earth science and applications from space

US science community (National Research Council - NRC) **provides** long-term **guidance for NASA**'s Science Mission Directorate (SMD)

NRC identifies and prioritizes

- **leading-edge scientific questions** and
- **observations** and
- **funds** required to answer them
- in the **Decadal Survey** (DS) for Earth science and applications from space.

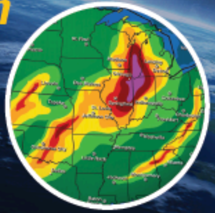
https://science.nasa.gov/earth-science/decadal-surveys

THE IMPORTANCE OF EARTH INFORMATION

Earth-observing satellites provide critical information about our planet. This information supports a broad range of societal needs and enables the scientific discovery required to meet those needs, making us all healthier, safer, and more efficient.

Helping Plan Our Day

300 billion *weather forecasts used by Americans every year*



100+ million *American adults use internet-based mapping services*

Americans rely on sophisticated Earth information throughout their everyday lives, from weather forecasts to navigation applications in their cars. Satellites are the original sources of much of the data.

Protecting Our Health

6.5 million *premature deaths from air pollution around the world every year*

Earth-observing satellites track the concentration of harmful pollutants across the country, providing air quality data for rural areas without ground-based monitoring systems and measuring the effects of air quality regulations.

50% *of the world's population is at risk from malaria.*

Satellite observations of temperature, vegetation, and rainfall help predict the spread of mosquito-borne illnesses like malaria, Zika, and West Nile Virus.

Keeping Us Secure

The estimated value of NASA and NOAA information services to the U.S. Navy's operational effectiveness is ***$2 billion*** *per year.*

The U.S. Navy and other U.S. defense agencies partner with NASA and NOAA to use satellite data, to access operational services, and to leverage their scientific progress.

Mitigating Natural Disasters

Extreme weather and fires have cost the federal government more than ***$350 billion*** *over the past decade.*

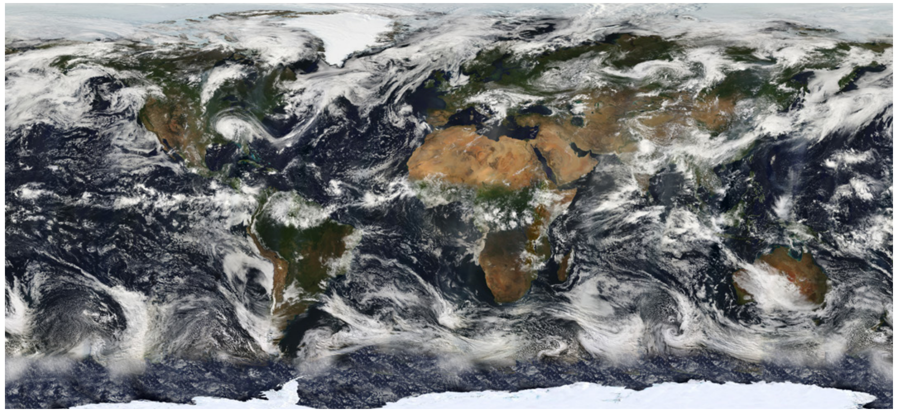
Satellite measurements play a critical role in tracking the paths of hurricanes and wildfires so that we can warn populations at risk, assess the damages, and avoid future costs.

Ensuring Resource Availability

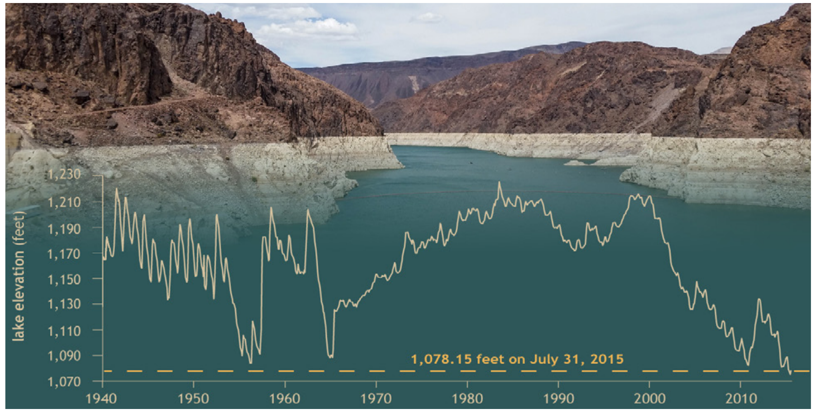
Advanced technology, including many types of Earth information, will unlock up to ***$1.6 trillion*** *in economic savings for energy generation and use by 2035.*

Satellite observations can also help ensure water availability, which is particularly important to the 20% of the world now living in areas of water scarcity.

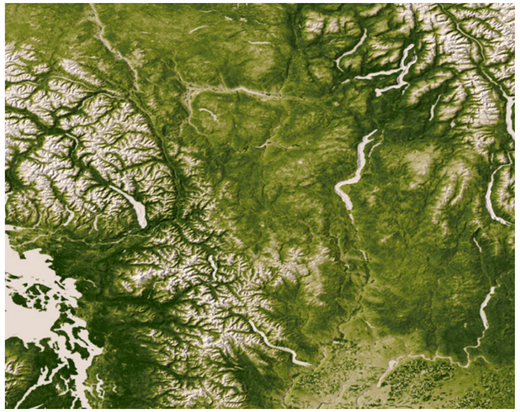
Designated Program Elements



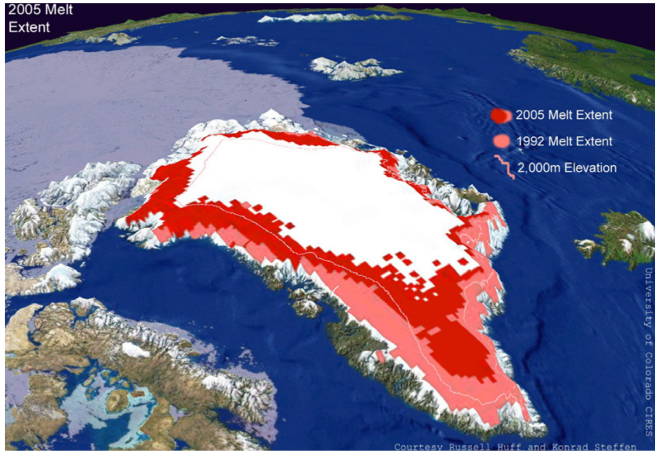
Make-up and distribution of aerosols and clouds



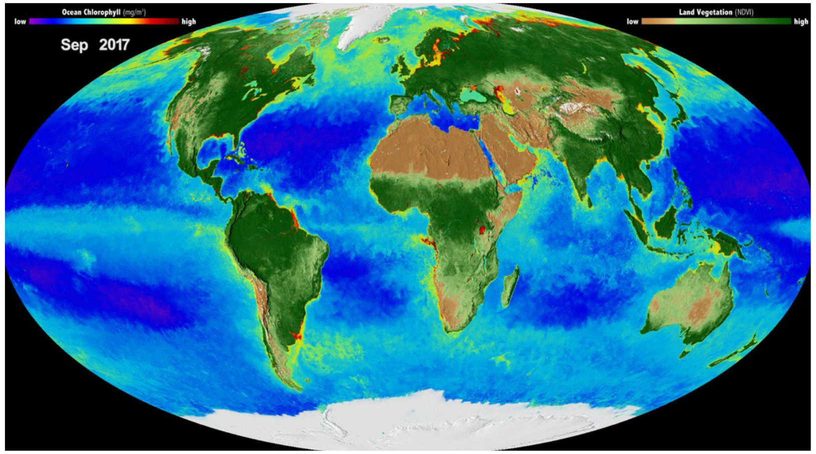
Trends in water stored on land



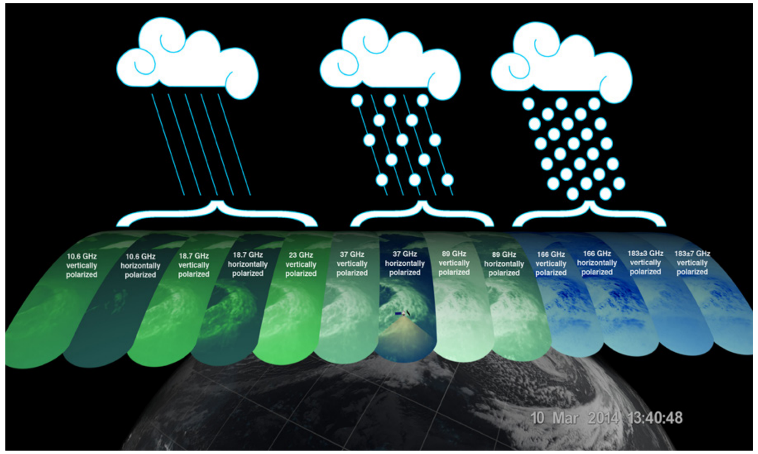
Evolving characteristics of terrestrial vegetation and aquatic ecosystems



Changes in glaciers and ice sheets

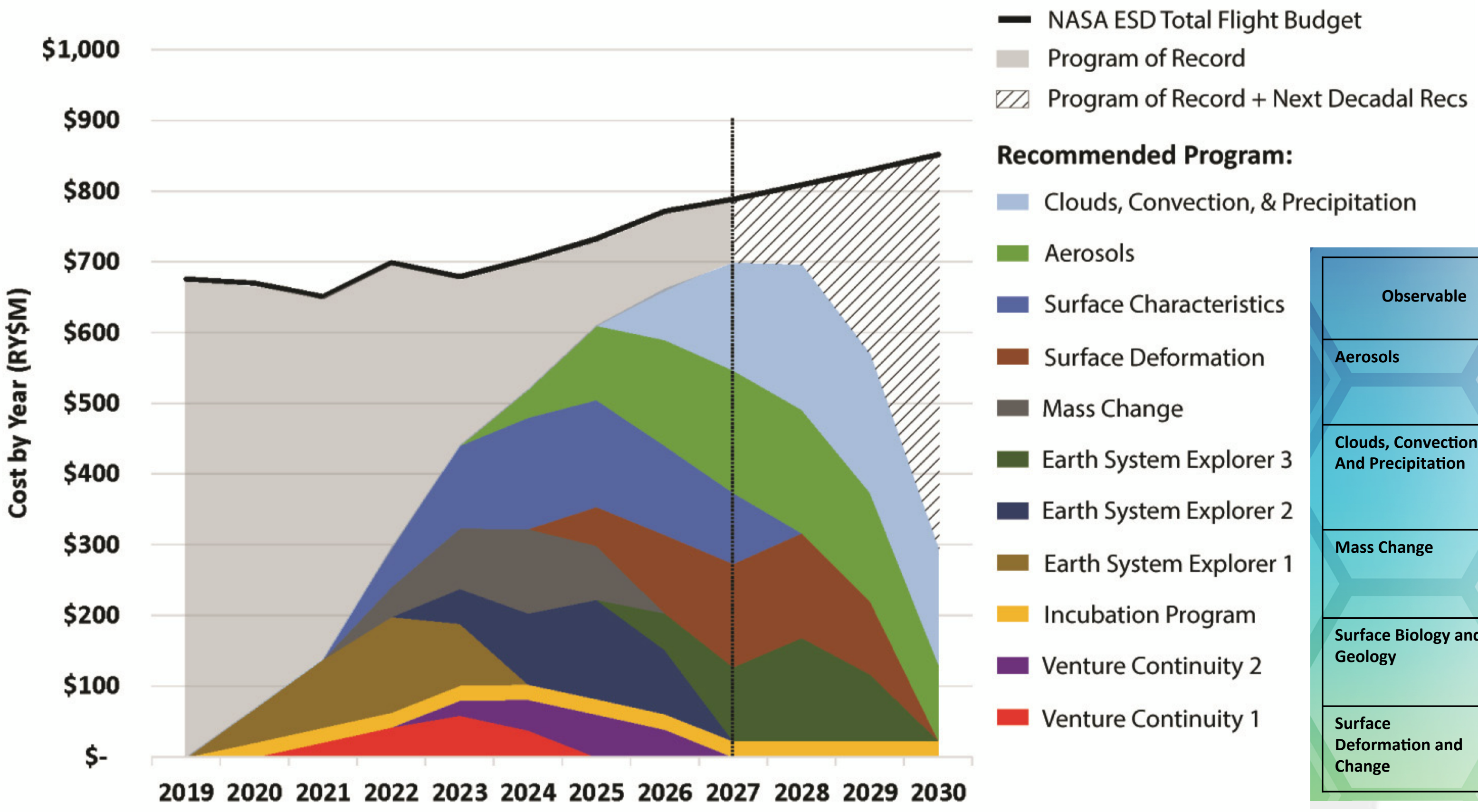


Alterations to surface characteristics and landscapes



Impacts of changing cloud cover and precipitation

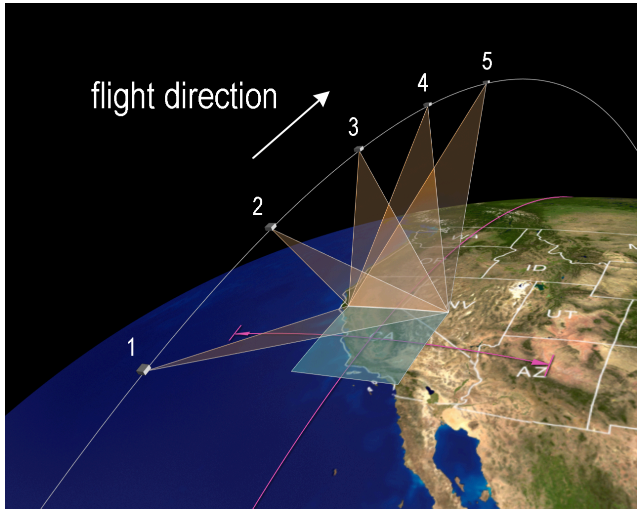
Designated Observables Proposed Budgets

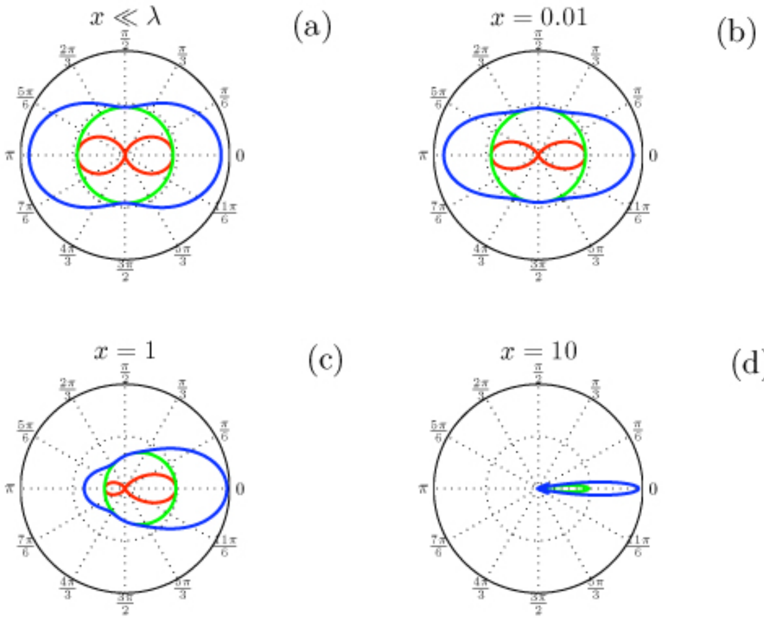


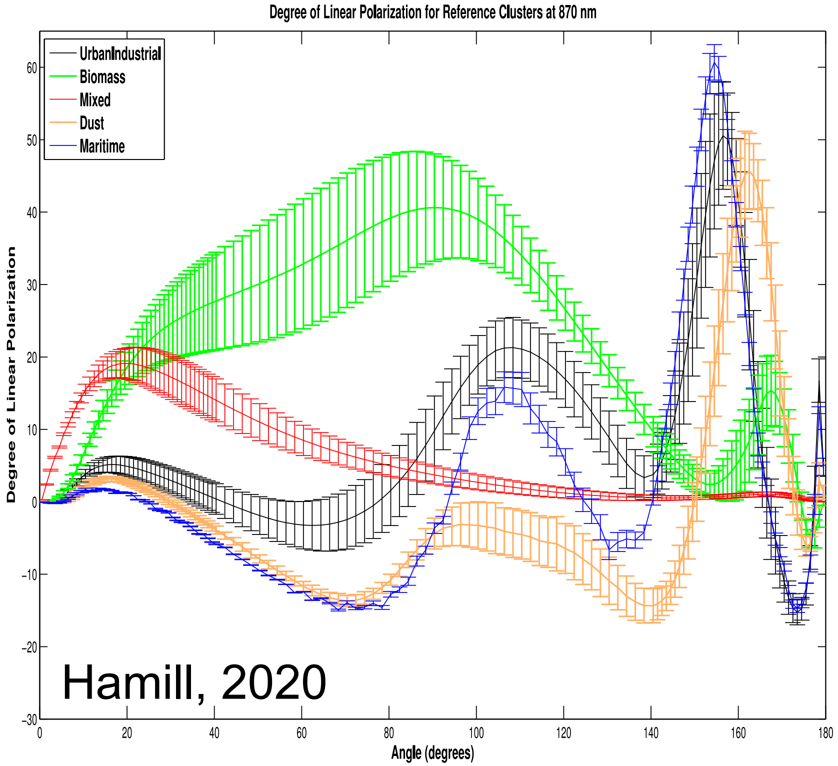
Observable	Science/Applications Summary	Candidate Measurement Approach	ESAS maximum cost
Aerosols	**Aerosol properties, aerosol vertical profiles, and cloud properties** to understand their effects on climate and air quality	Backscatter lidar and multichannel/multi-angle/polarization imaging radiometer flown together on the same platform	CATE Cap $800M
Clouds, Convection, And Precipitation	**Coupled cloud-precipitation state and dynamics** for monitoring global hydrological cycle and understanding contributing processes including cloud feedback	Radar(s), with multi-frequency passive microwave and sub-mm radiometer	CATE Cap $800M
Mass Change	**Large-scale Earth dynamics** measured by the changing mass distribution within and between the Earth's atmosphere, oceans, ground water, and ice sheets	Spacecraft ranging measurement of gravity anomaly	Est Cap $300M
Surface Biology and Geology	**Earth surface geology and biology**, ground/water temperature, snow reflectivity, active geologic processes, vegetation traits and algal biomass	Hyperspectral imagery in the visible and shortwave infrared, multi- or hyperspectral imagery in the thermal IR	CATE Cap $650M
Surface Deformation and Change	**Earth surface dynamics** from earthquakes and landslides to ice sheets and permafrost	Interferometric Synthetic Aperture Radar (InSAR) with ionospheric correction	Est Cap $500M

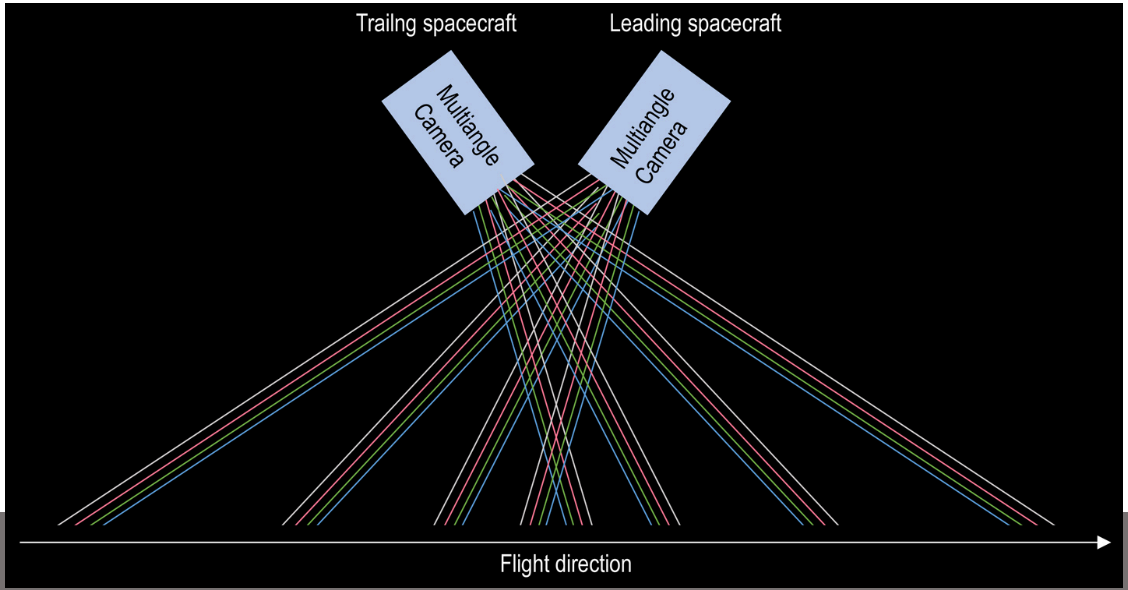
National Academies of Sciences, Engineering, and Medicine. 2018. *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space.* Washington, DC: The National Academies Press. https://doi.org.10.17226/24938.

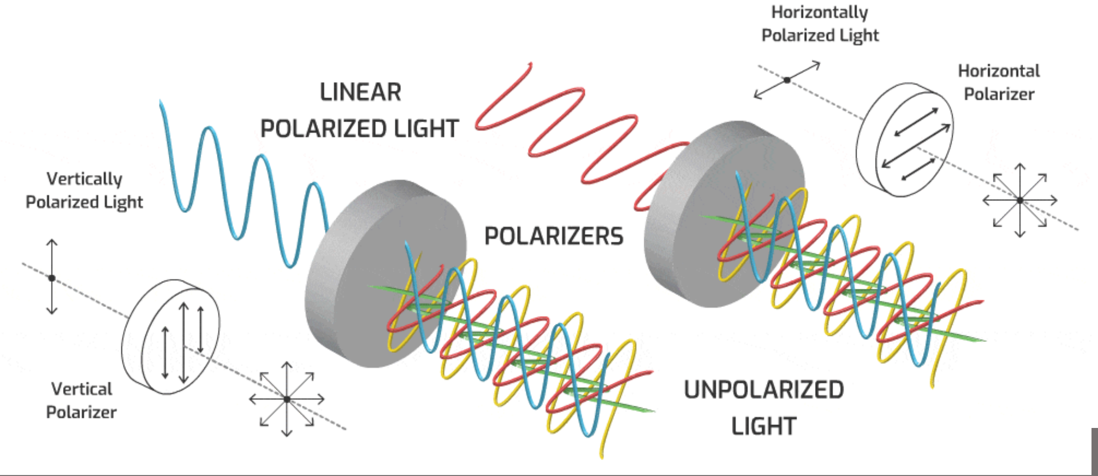
Multi-Angle Polarimeters



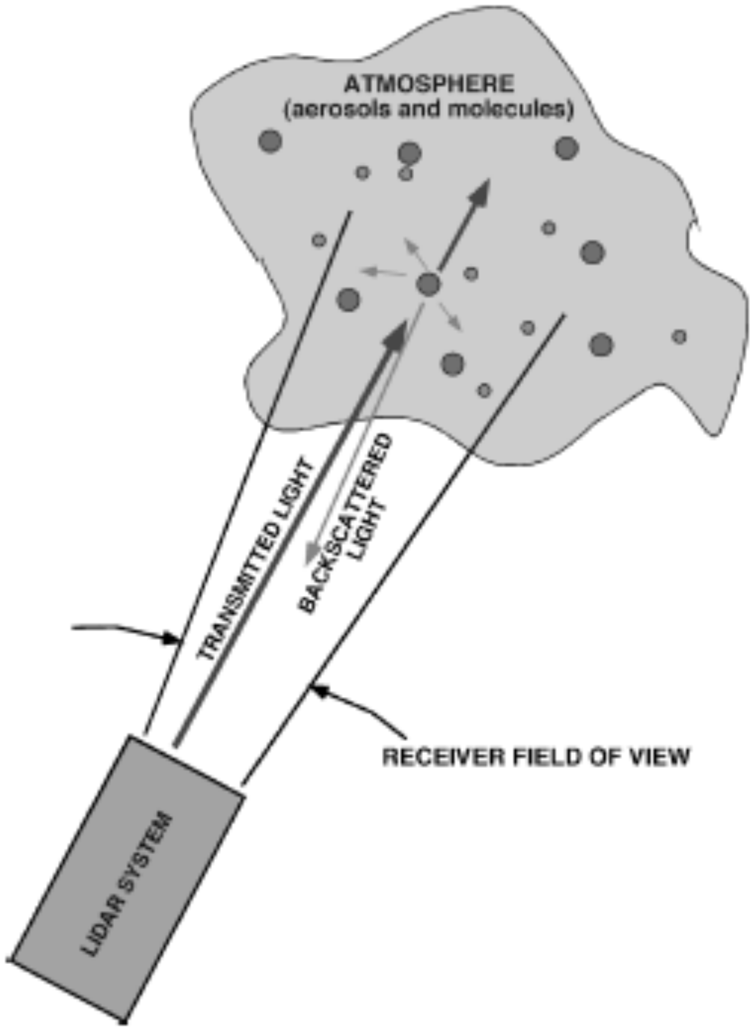


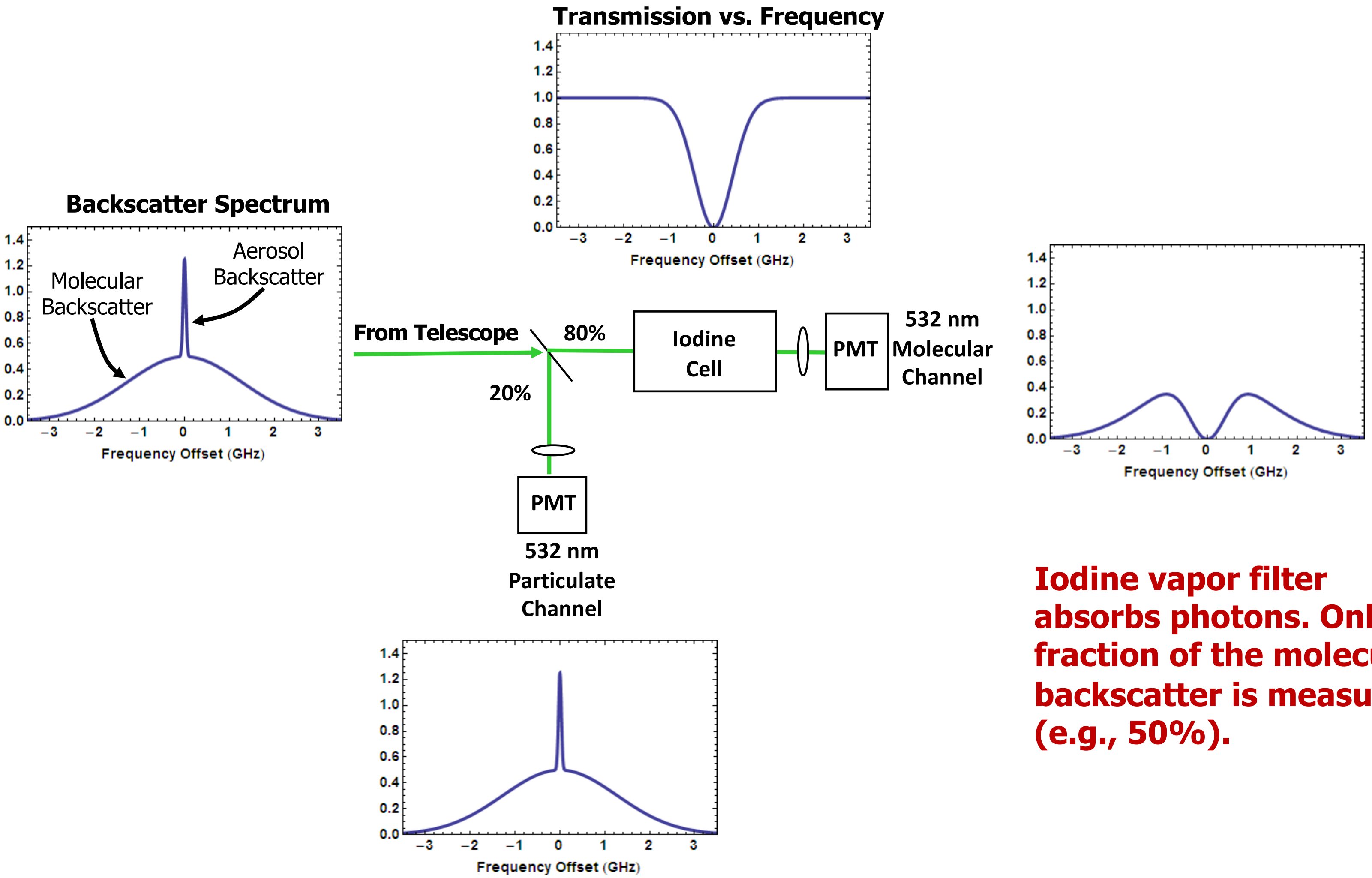






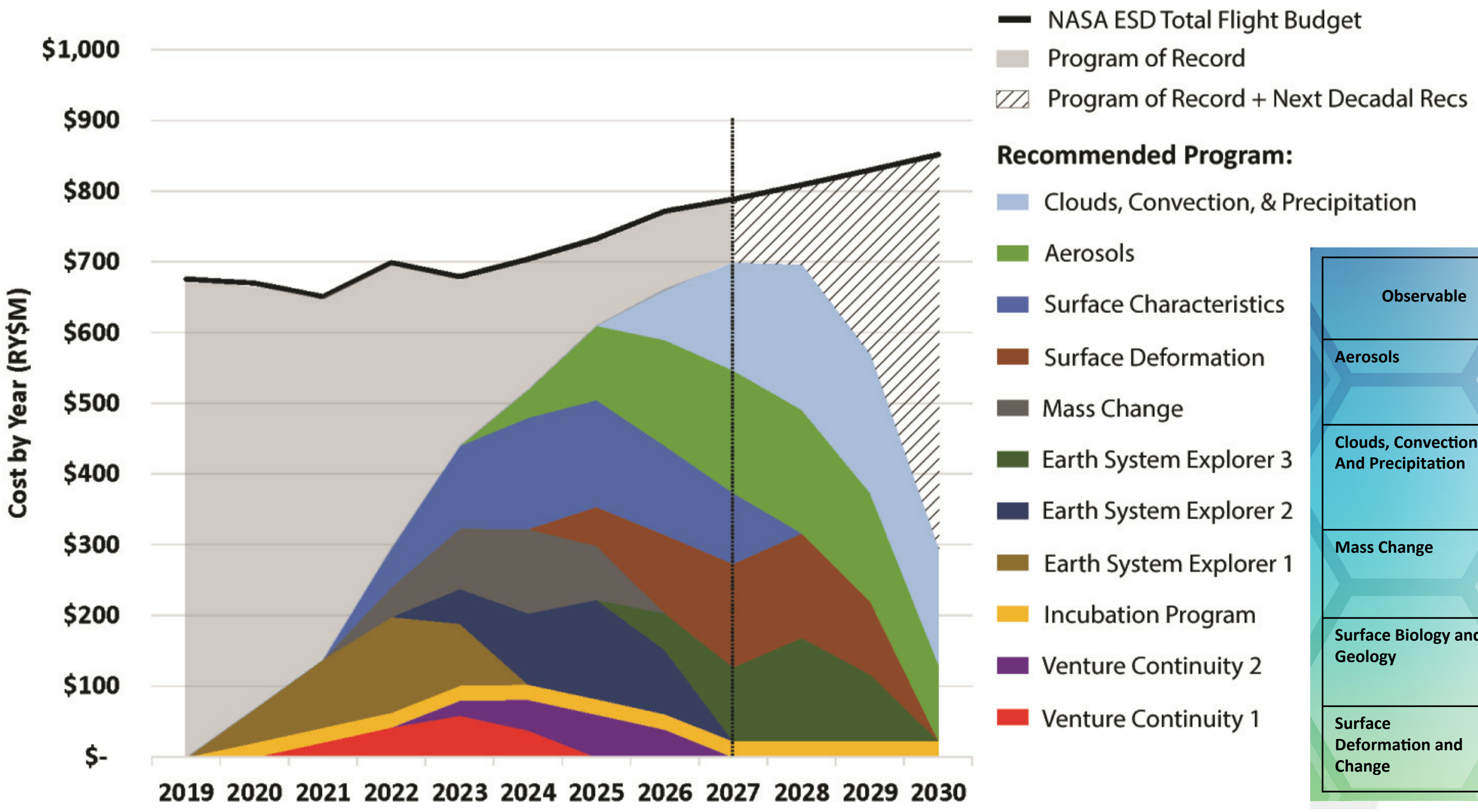
High Spectral Resolution Lidar (HSRL)





Iodine vapor filter absorbs photons. Only a fraction of the molecular backscatter is measured (e.g., 50%).

Designated Observables Proposed Budgets



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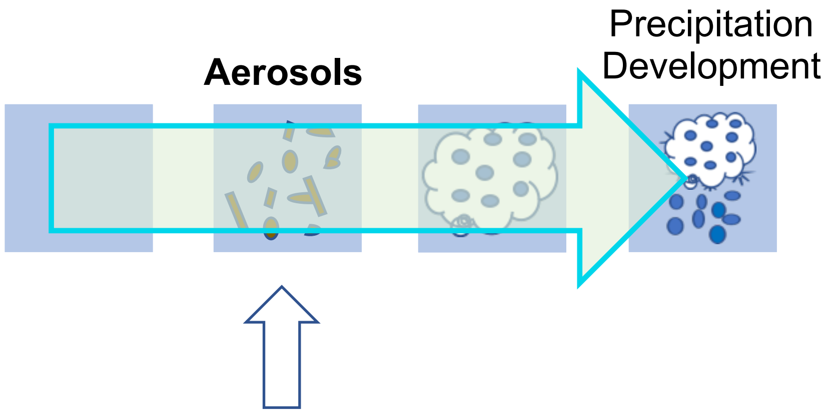
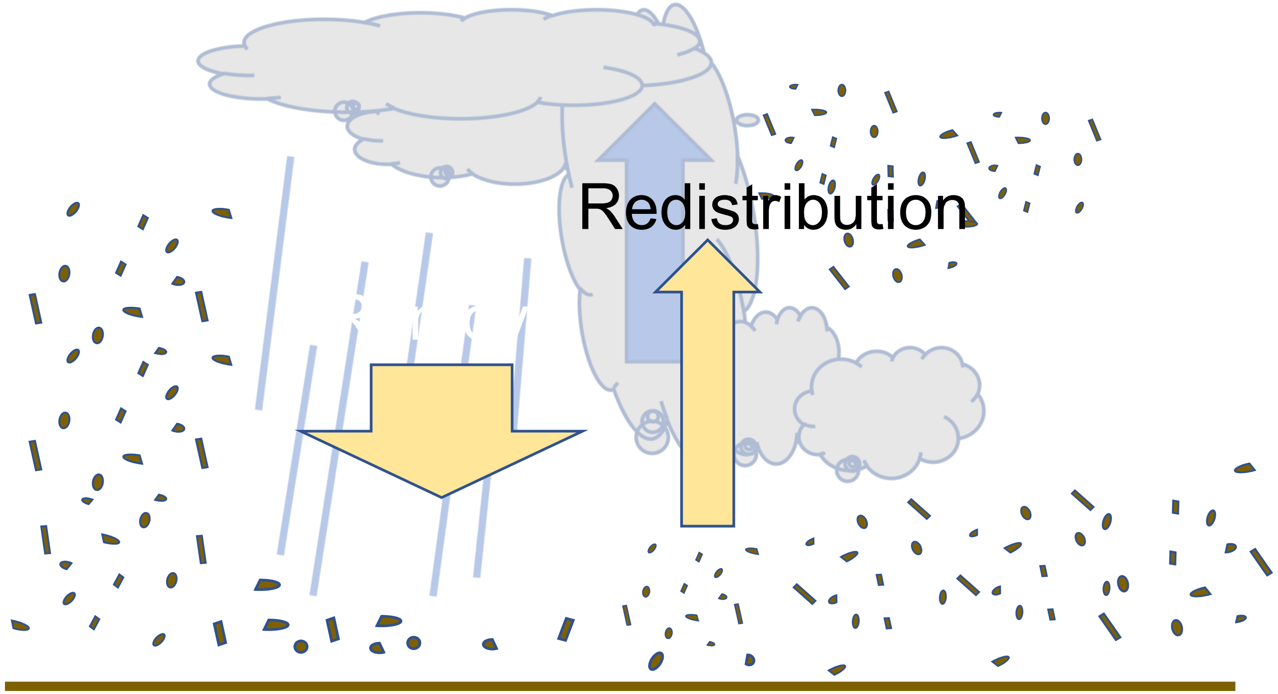
Science Links Beteween A & CCP

I. Cloud Nucleation



Aerosols are a fundamental and enabling component to the formation of clouds and precipitation.

II. Aerosol Removal and Redistribution



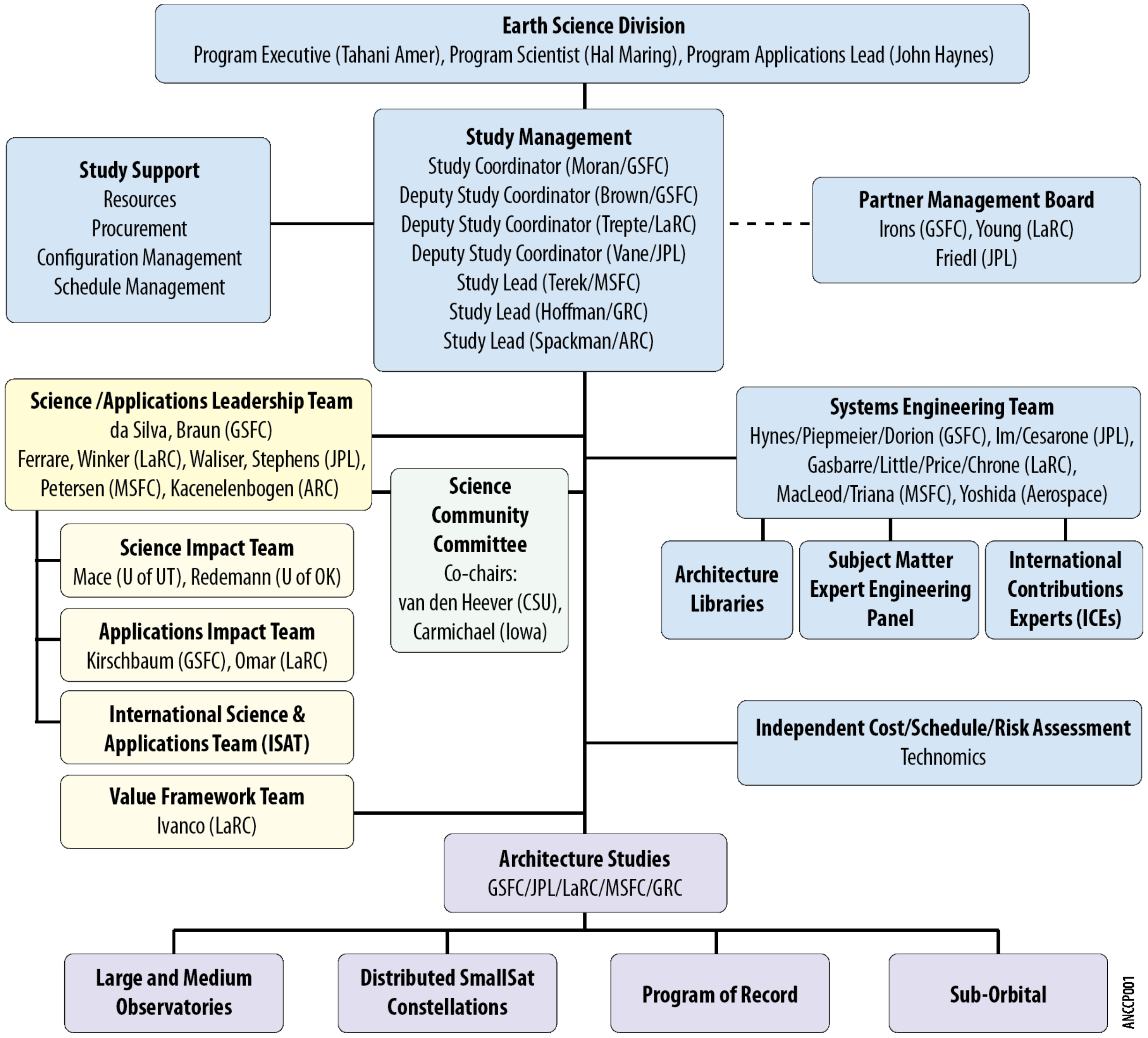
Precipitation removes aerosols and convection and storms loft and redistribute aerosols

ACCP Study Team

Study Management Team (SMT)
- Overall Leadership and Management of Study and Delivery of Study Report
- Community Engagement
- Assessment of Architectures
  - Cost Estimation & Validation
  - Programmatic Risk
  - Other Programmatic Factors

Science/Applications Leadership Team (SALT)
- Definition of Science & Applications Traceability Matrices
- Assessment of the Utility of the Geophysical Variables in Meeting Each Objective

Science & Applications Impact Teams (SIT and AIT)
- Assessing the Science & Applications Value of Architectures (Science Quality of Each Architecture wrt Meeting Geophysical Variables)



Science Community Committee
- Independent Assessment of SATM
- Independent Assessment of Science & Applications Benefit by Community of Users

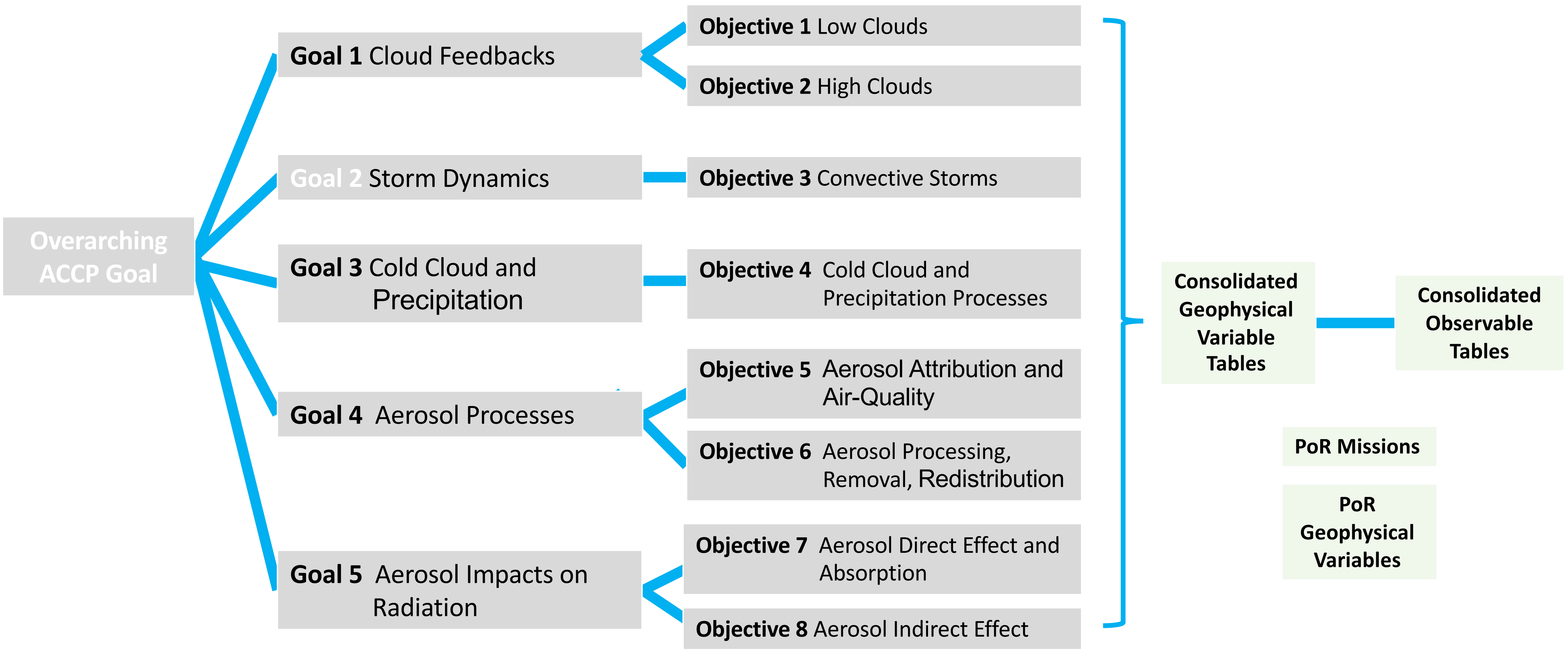
Systems Engineering Team (SET)
- Definition of Architectures
- Assessment of Architectures
  - Technology Readiness
  - Technical Risk

Value Framework Team
- Development of Standard and Systematic Approach to Science, Applications, and Programmatic Evaluations of Architectures to facilitate Down-Select Decisions

ACCP Science Objectives

1. Low Cloud Feedback
2. High Cloud Feedback
3. Convective Storm Systems
4. Cold Cloud & Precipitation
5. Aerosol Attribution and Air Quality
6. Aerosol Processing, Removal and Redistribution
7. Aerosol Direct Effect and Absorption
8. Aerosol Indirect Effect

A-CCP Science and Applications Traceability Matrix



SATM Traces Objectives to Geophysical Variables (GVs) to be Measured

A+CCP	A	CCP	Objectives
			O5 Aerosol Attribution and Air Quality **Minimum:** Quantify optical and microphysical aerosol properties in the PBL and free troposphere to improve process understanding, estimates of speciation, aerosol emissions and predictions of near-surface particulate concentrations. **Enhanced:** Characterize changes in vertical profiles of optical and microphysical properties over space and time in terms of 3D transport, spatially resolved emission sources and residual production and loss terms.

A	CCP	ODO	POR	Utility Score	Geophysical Variables (1 of 2) Minimum	Enhanced	Qualifiers
√				4.2	Aerosol Extinction (Total & Non-Spherical)		VIS & NIR Profile
√		S	(√)	5.0	Aerosol Optical Depth		UV to SWIR Column, PBL
√				4.4	Aerosol Absorption Optical Depth		UV & VIS Column, PBL
√				4.4	Aerosol Fine Mode Optical Depth		Column, PBL
√			(√)	3.6	Aerosol Real Index of Refraction		Column, PBL
√				4.8	Aerosol Non-Spherical AOD Fraction		Column, PBL
√				4.2	Aerosol Extinction to Backscatter Ratio		VIS & NIR Column, PBL
√				4.8	Aerosol-Cloud Feature Mask		
√			(√)	N/A	Planetary Boundary Layer Height		
			√	N/A	Environmental Temperature		Profile
			√	N/A	Environmental Humidity		Profile

Approach (1 of 2)

General Approach

a) Use ACCP measurements to estimate aerosol speciation using the following approaches:
   1) Optimal estimation algorithm using as prior aerosol state from an assimilation system that incorporates the aerosol PoR
   2) Empirical aerosol typing based on clustering of aerosol optical properties
b) Inverse calculations used to assess impact on emissions, and through revised emissions impact on forecasts of near-surface particulate concentrations
c) Model sensitivity studies, validated by ACCP data, used to gain insight into process parameterizations.
d) Complement and where possible expand on existing climate data records. Examine inter-annual variability of aerosol emissions, optical properties and impact on global AQ.

Role of Models – primary tool to integrate observations, test understanding & examine impacts and feedbacks.

Approach (2 of 2)

Role of Sub-orbital – cal/val variable retrievals, validate process interpretation, advance process understanding with enhanced property measurement. Linking of optical to chemical aerosol properties.

New and Improved

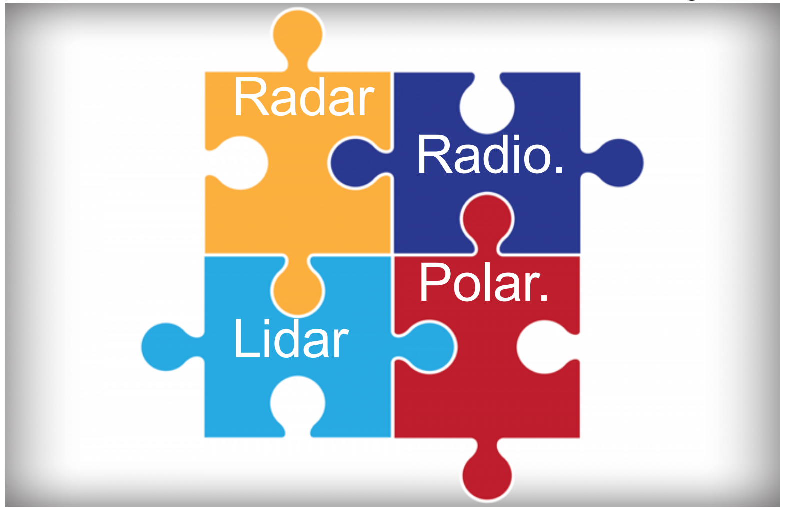
a) Significant improvements of key aerosol variables (vertically/spectrally resolved aerosol absorption and extinction, fine mode fraction over land, etc.)
b) Improved global emissions and near surface aerosol characterization, with benefits for AQ analysis and forecasts.

SATM Specifies GV Uncertainty & Resolution

Consolidated Geophysical Variables (4 of 17) – Minimum	Consolidated Geophysical Variables (4 of 17) – Enhanced	Science Objectives	Desired Capability: Range	Desired Capability: Uncertainty	Scales: XY	Scales: Z	Scales: T	Scales: Swath	Examples of Observables / *Notes*	Enabled Apps
		IMPORTANT: Desired Capabilities and Observables are preliminary. Click here for additional information.								
ANC.z	Aerosol Number Concentration Profile	O8	10-1000 cm^{-3}	50%	1 km					2, 3, 5
AOD.ℓ	Aerosol Optical Depth (Column and PBL)	O3, O5, O6, O7, O8	0.03 - 4	±0.02±0.05*AOT	2 km 1 km		I	100 km 300 km	Multi-angle radiance (UV,VIS), multi-angle DOLP - Multispectral radiance UV (aerosol absorption) & VIS (AOD, fine mode aerosol over water) - SWIR (surface properties and cirrus screening) *Swath refers to column; Nadir for PBL* *O7: column only* *O8: PBL only*	1, 3, 4, 5, 7 (12, 13, 14 for inference of PM from AOD)
APM25	Aerosol PM2.5 Concentration (surface)	O5	20-150 $\mu g/m^3$	+/-20-25%						12, 13, 14
ARIR.ℓ	Aerosol Real Index of Refraction (Column and PBL)	O5, O6,O7	1.33–1.7	±0.025	5 km 1 km		I			
ACF	Areal Cloud fraction	O1, O4, O7	0.0 - 1.0	0.1	200 m	N/A	I, M	Nadir	PoR: ABI, AHI, etc.; VIIRS * Lidar # Polarimeter	
		O8	0.0 - 1.0	0.1	100 m* 200 m#	N/A	I, M	Nadir* 100 km#		

Architecture Segment Libraries

Instrument Library



- Other Library Components
  - Spacecraft buses
  - Launch vehicles
  - Ground systems
  - Mission operations
  - Suborbital campaigns
  - Science team

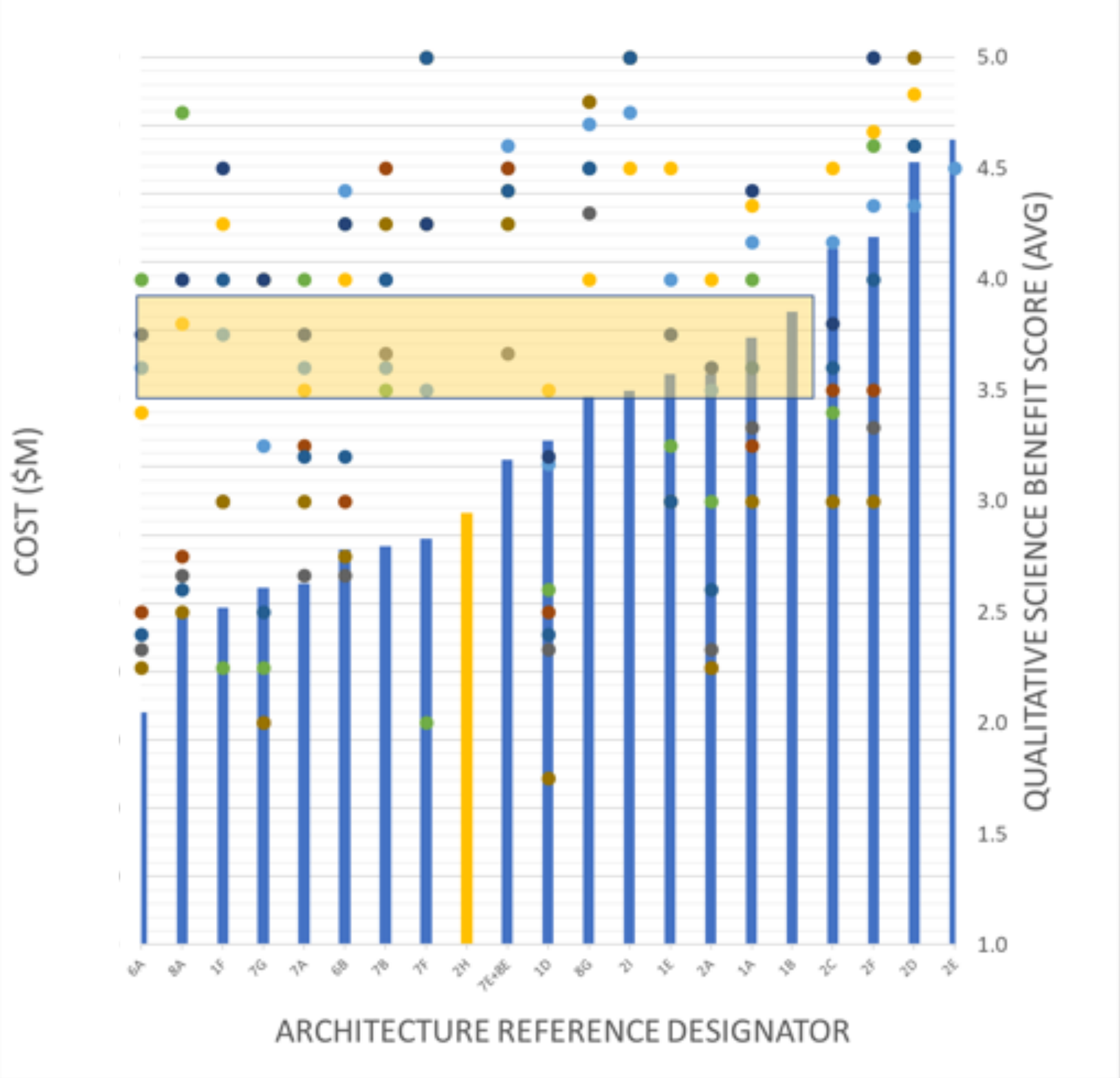
Radars	Radiometers	Lidars	Polarimeters	Spectrometers
W, Ka, Ku, scanning, Doppler	11, 19, 24, 37, 89, 166, 183	**532 bs, 1064 bs**	14 channels, 5 angles	**LWIR, 3 channels**
W, Ka, scanning, Doppler	11, 19, 24, 37, 89	532 bs, 1064 bs	**14 channels, 5-9 angles**	**VIS/NIR/SWIR, hyperspectral**
W, Ka, nadir, Doppler	**24, 31, 55, 89, 166, 183**	355 HSRL, 532 HSRL	Hyperspectral, 1 angle	**LWUV/VIS/NIR/SWIR, hyperspectral**
W, Ka, nadir, Ka Doppler	**19, 24, 34**	532 bs, 1064 bs	**Hyperspectral, 5 angles**	**LWIR/FIR, 8 channels**
W, Ka, nadir, no Doppler	118, 183	532 HSRL, 1064 bs	**10 channels, 60 angles**	LWIR=Longwave infrared LWUV=Longwave ultraviolet VIS=visible NIR=near IR SWIR=Shortwave IR FIR=Far IR
Ka, Ku, scanning, Ku Doppler	**87, 164, 174, 178, 181**	355 HSRL, 532 HSRL, 1064 bs	**11 channels, 60 angles**	
Ka, Ku, scanning, no Doppler	**118, 183, 240, 310, 380, 660, 880**	355 HSRL, 532 bs, 1064 bs	**12 channels, 60 angles**	
W, scanning, Doppler	**883**	**1064 bs**	**15 channels, 60 angles**	
W, nadir, no Doppler	**183**	**532 bs, 1064 bs**	**9 channels, 255 angles**	
Ka, nadir, Doppler	**183, 326**	bs=backscatter HSRL=High Spectral Resolution Lidar	Channels in VIS, VNIR, SWIR	
Ka, scanning, no Doppler	**670**			
Ka, nadir, no Doppler	**220, 680 GHz/ 8.6, 11, 12 microns**			
Ku, nadir, Doppler	**91, 118, 183, 205**			
Ku, scanning, no Doppler	Radiometer channels in GHz			

Small satellite capable sensors indicated in bold.

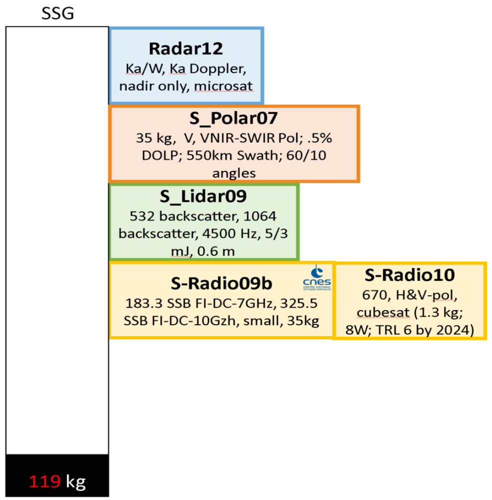
Preliminary Architecture Costing

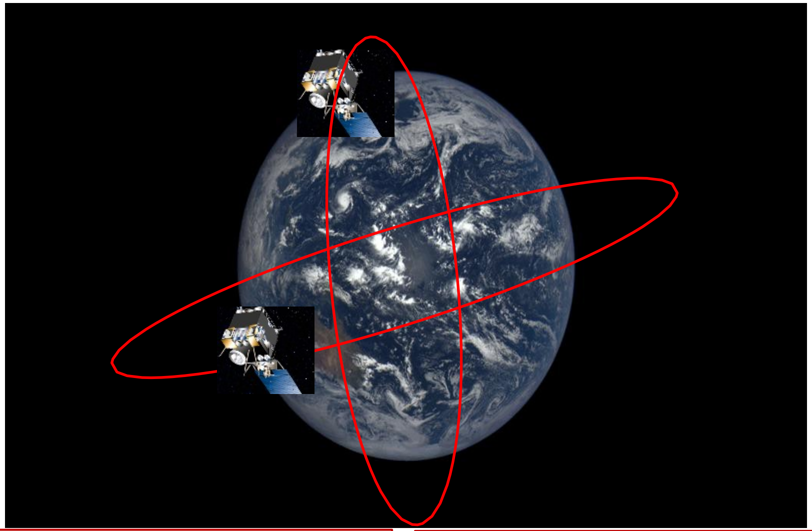
Architecture costs include EVERYTHING for the lifetime of the mission:

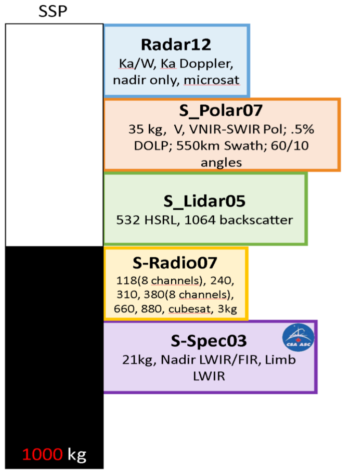
- Instrument
  - Research and Development
  - Integration
  - Cal/Val
- Spacecraft
- Launch Vehicle
- Ground Segment
- All people/labor
- 30% Reserves



Architecture 8G







GPM Orbit: Tropics & mid latitude coverage with diurnal cycle, complements and extends capabilities of GPM

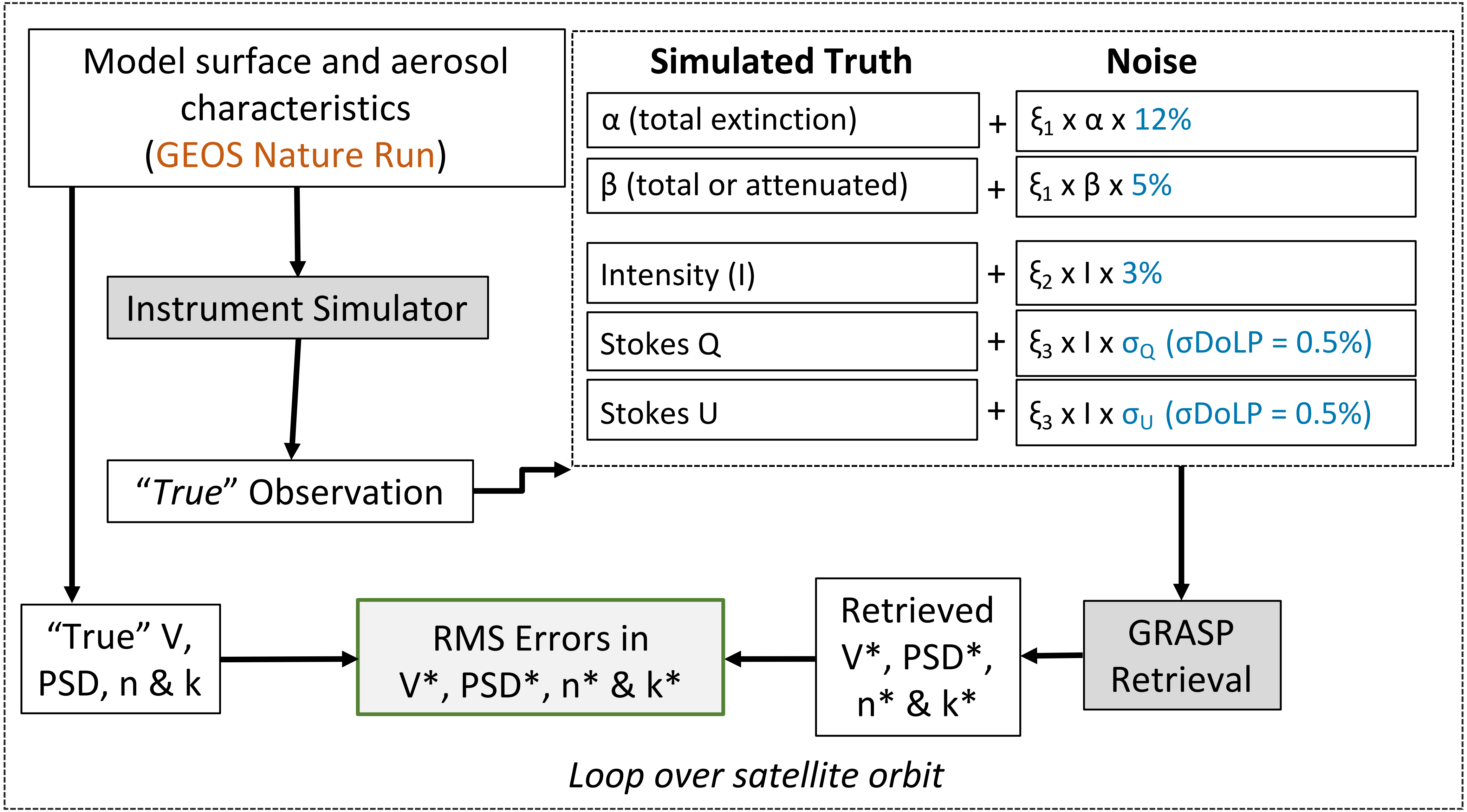
- Coupled cloud and precipitation profiling (including extremes) in context of GPM swath
- Coincident convective dynamics
- Improved capability for snowfall mapping
- Diurnal information on biomass burning aerosols from major source regions and on major pollution hotspots

Polar Orbit: Global coverage, higher fidelity aerosol measurements

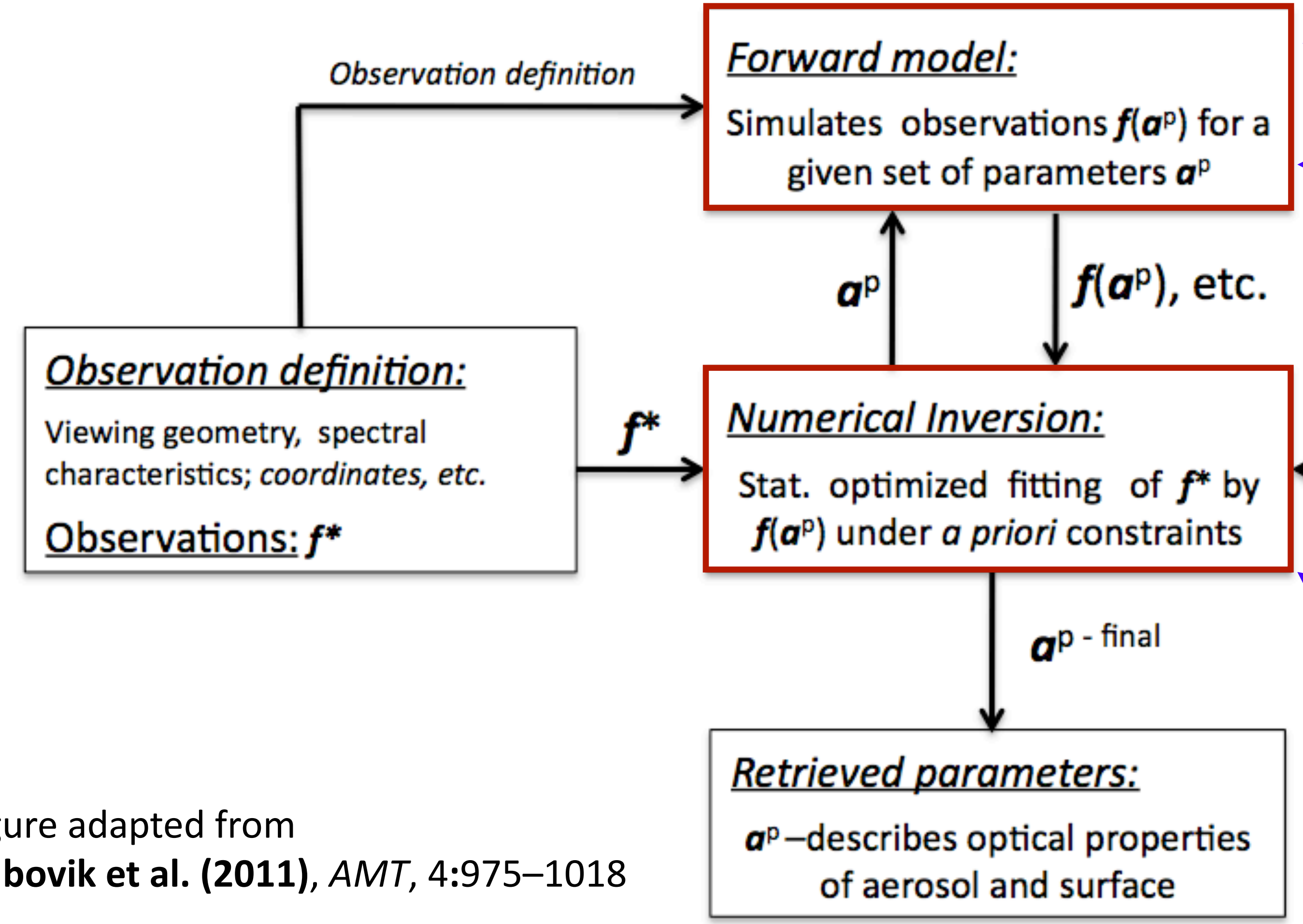
- Critical for cloud feedbacks, high latitudes
- Nadir-only active data on convective storms, cold clouds & precip
- Measurement of thin ice clouds
- Vertically-resolved aerosol microphysics and speciation
- Better insight into aerosol processes & impacts on radiation

- Enhanced spatial and temporal sampling with two satellites
- Global measurements with diurnal information at mid and lower latitudes
- High fidelity aerosol measurements on polar satellite anchors algorithms on GPM-orbit satellite

OSSE Framework



GRASP algorithm structure



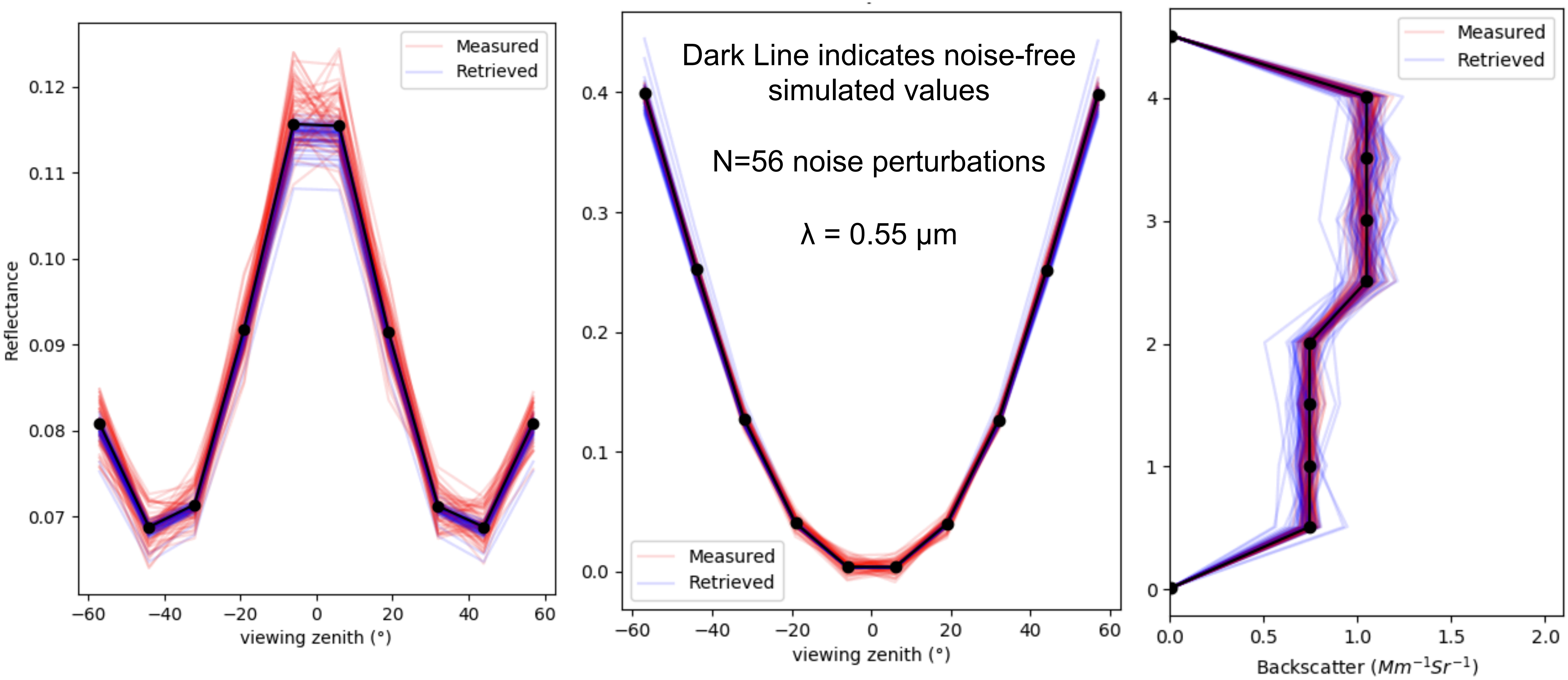
Single scattering sphere/spheroid LUT (Dubovik et al. 2006)

Successive orders of scattering RT code (Lenoble et al. 2007)

Multi-term least squares fitting (Dubovik et al. 2000, 2004, 2008)

Figure adapted from
Dubovik et al. (2011), *AMT*, 4:975–1018

Polarimeter Simulated Measurements and Fits



Uncertainty Estimates for Architectue 8G

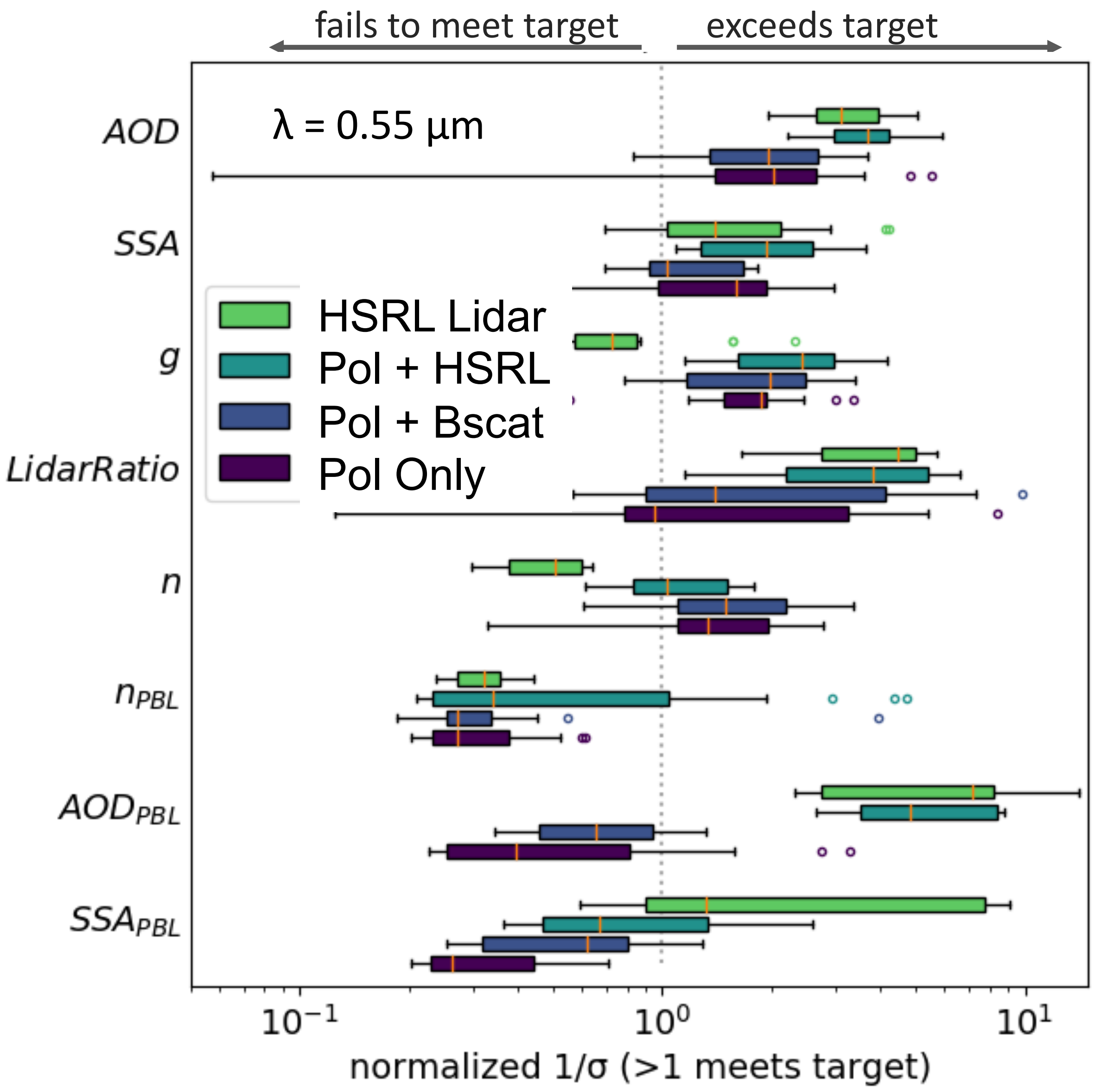
Simulation "Truth"

Retrieved Value on n^th trial

$$\sigma'_X = \sigma_X \Bigg/ \sqrt{\frac{1}{N}\sum_{n=1}^{N}(X - X_n{}')^2}$$

Target Uncertainty

Geophysical Variable (GV)	Plot Target Uncertainty
Total Aerosol Optical Depth	$\sigma_\tau = 0.02 + 0.05\,\tau$
Single Scattering Albedo	$\sigma_{SSA} = 0.03$
Lidar Ratio	$\sigma_S = 0.25\,S$
Real Refractive Index	$\sigma_n = 0.02$



Scoring the Science Benefits of Architectures

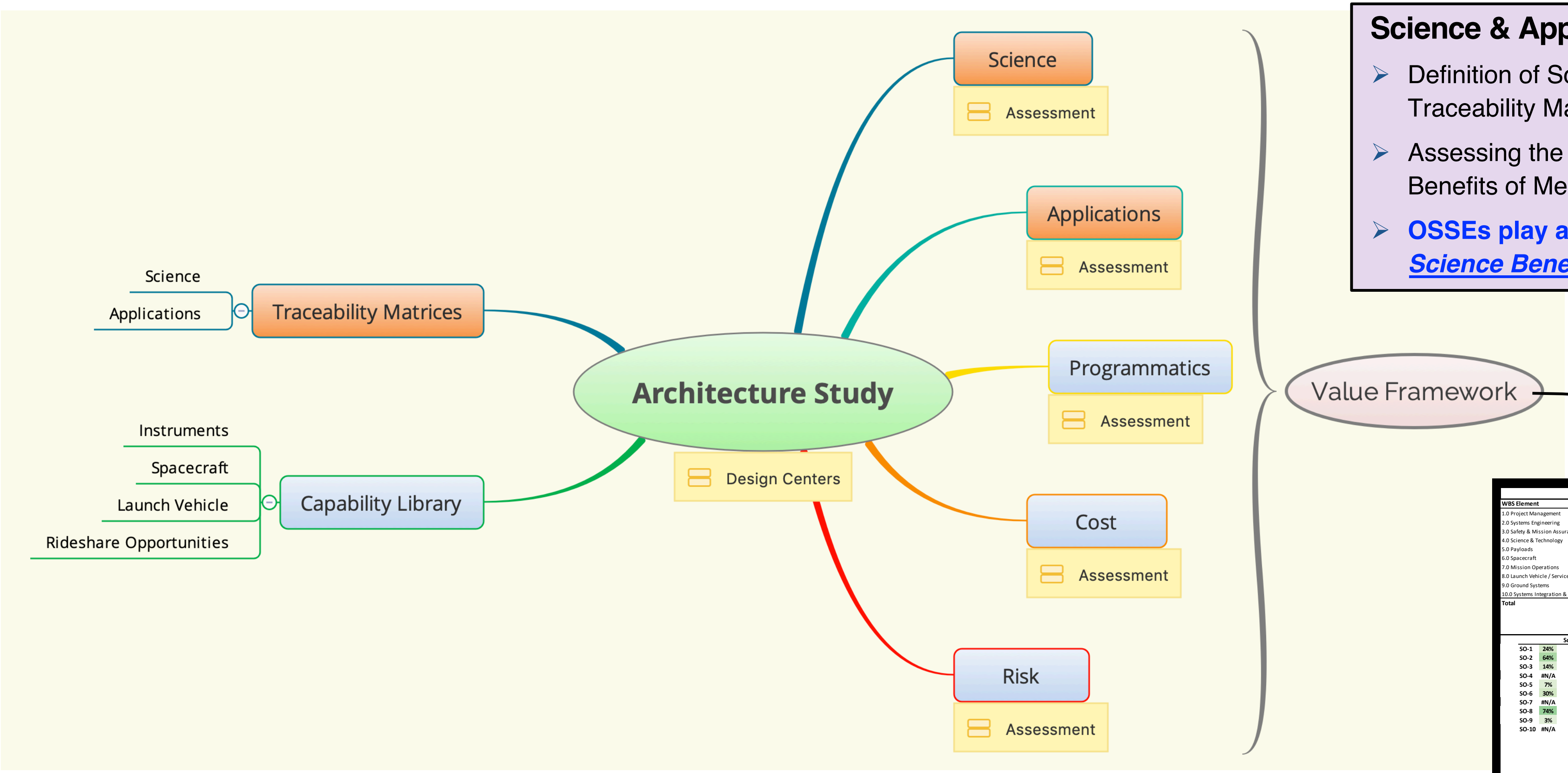
Utility: degree to which Geophysical Variable (GV) addresses the objective if it were measured perfectly.

$$\text{Science Benefit Score (for Objective)} = \frac{1}{N} \sum_{\text{GVs}} \text{Utility of GV for Objective (SALT)} \times \text{Quality of GV given Measurements (SIT)}$$

Quality: degree to which measurements provide the desired geophysical variable. OSSEs inform the quality assessment.

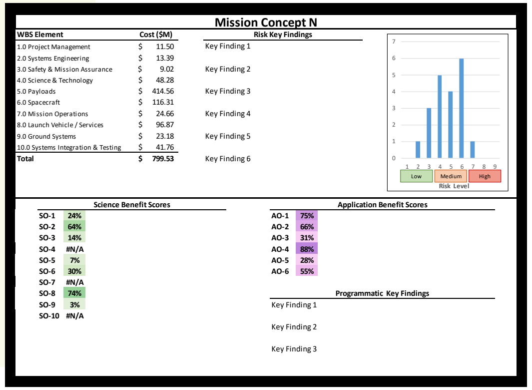
Similar to approach outlined on *Continuity of NASA Earth Observations from Space* report (NAS 2015)

Science Is Only One Part of the Overall Value Assesment



Science & Applications Activities

- Definition of Science & Applications Traceability Matrices
- Assessing the Science & Applications Benefits of Measurement Architectures
- **OSSEs play a critical role assessing the *Science Benefit* scores of Architectures**



VF Baseball Cards

Summary

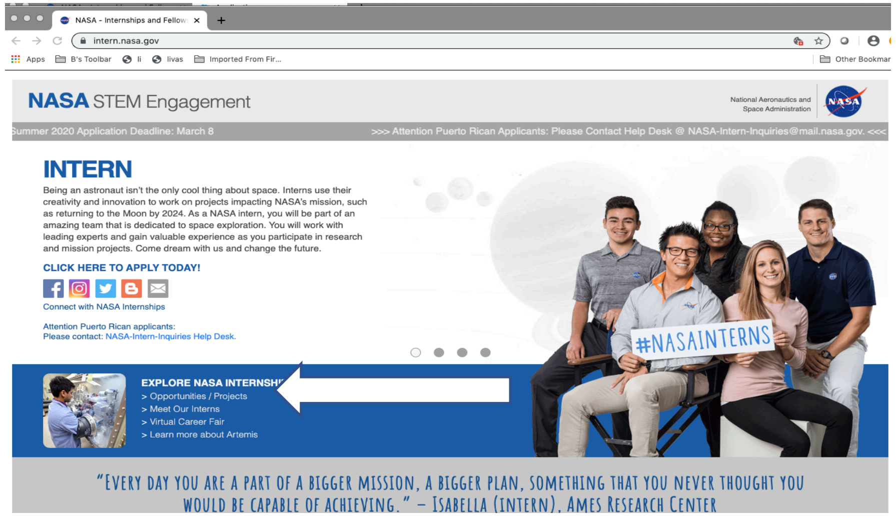
- Developing new satellite missions takes a large multi-disciplinary group of people
  - It’s a lot of work!
- NASA is trying to use OSSE frameworks to quantitatively evaulate science benefits of new mission concepts
  - GMAO provides high resolution nature runs and instrument simulations to support mission studies
- The lidar + polarimeter architecture concept is promising, and preliminary assesements show that it meets several GV target uncertainties
- This is all a work in progress…stay tuned

- If any of this sounds interesting, you should consider working with us!

Summer Internship Opportunities at NASA

Internships (NIAMS) https://intern.nasa.gov

- Fulltime (40 hr/wk)
- Paid
  - High School: $3.7K for 6 weeks
  - Under Grad: $7.3K for 10 weeks
  - Grad: $9K for 10 weeks
- No vacation (federal holidays only)
- Requirements
  - Full-time enrolled student
  - 3.0 GPA
- College start dates can depend on academic schedule
- Part-time internships during academic year are now available at GSFC
- Application
  - Students apply to individual projects, and mentors select from students who apply to their posted research opportunities
  - You can apply to more than one project with only one application
  - Summer 2020 Deadline is March 8



Summer Internship Opportunities at NASA

- ARC
  - 88 summer projects posted
  - Examples
    - Optical Sensing for Planetary Exploration
    - Development of Chem/Bio Sensors for Space Application
    - Airborne Remote Sensing of Particles
    - Urban Air Transport Research and Development
- GSFC (including GISS)
  - 280 summer projects posted
  - Examples
    - Spanish Language Journalism, Multimedia, and Social Media
    - Falling Snow Estimates from Ground Based Sensors
    - Cybersecurity
    - Flexible Cloud Masks from Space-borne Lidar

NASA Graduate Fellowships

Science Mission Directorate—"FINESST"

- Awards about 100 Fellowships a year (funds will double in FY20)
- Applications go through NSPIRES
- Deadline in February

Office of STEM Engagement—"NASA OSE Fellowship Activity 2020"

- Awards about 10 Fellowships a year
- Requires yearly 10-week research experience at a NASA center each year of fellowship
- All funding is for students who attend a minority serving institutions

Both

- Fellowship supports cost of graduate education for up-to-3 years; each call has a different funding cap
- Applicants write a research proposal
- Proposal reviewed externally

My Tips

- How does your project contribute to NASA's goals, and use NASA assets?
- Tell a good story and "sell" – proposals aren't just papers written in the future tense!