Lidar-Polarimeter Retrieval OSSEs in Support of NASA's Aerosols and Clouds-Convection-Precipitation (ACCP) Study

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Richard Ferrare, David Winker, Ali Omar (LaRC)

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Science/Applications Leadership Team (SALT)

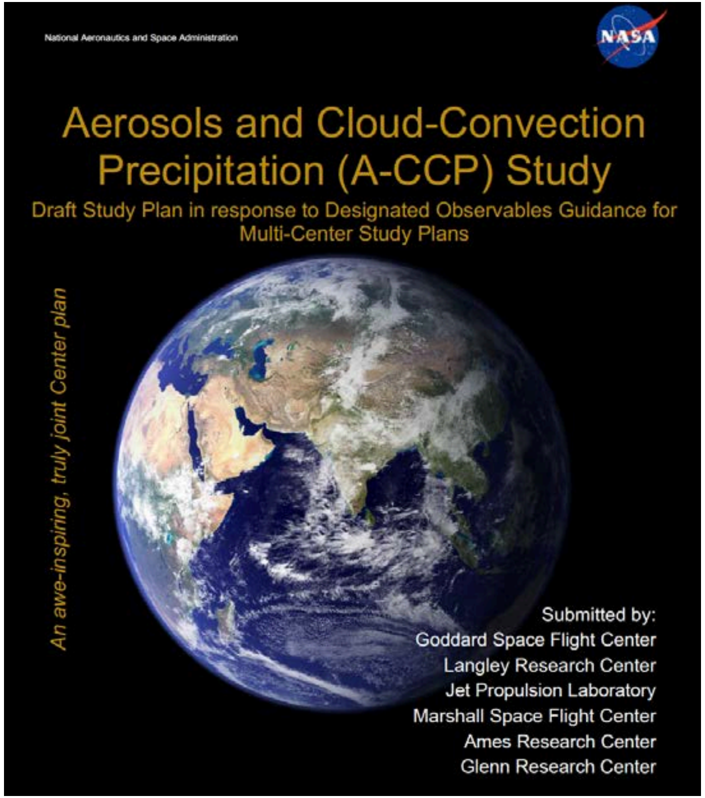
With Contributions from: Jens Redemann, Jay Mace, Reed Espinosa, Patricia Castellanos, Pete Colarco, Ed Nowottnick, and the rest of the ACCP Team

AGU Fall Meeting – San Francisco, CA

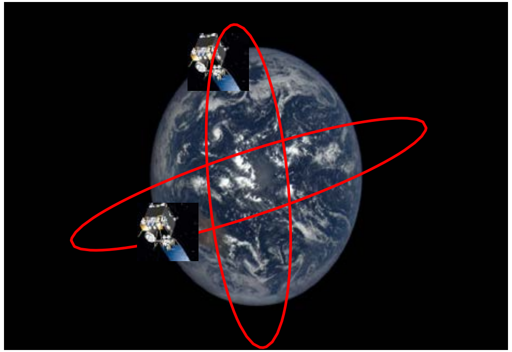
9–13 December 2019

Outline

1. ACCP Science Overview
2. Architecture Studies
   - Science Objectives
   - Instrument Library
   - Value Framework
3. Evaluating Science Benefits
   - Utility and quality scores
   - Simulation approach
   - Examples (preliminary)
4. Concluding Remarks

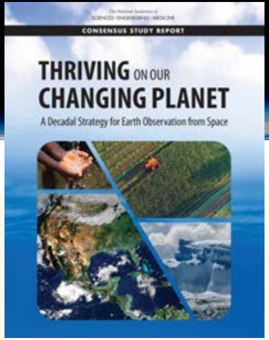


ACCP at a Glance



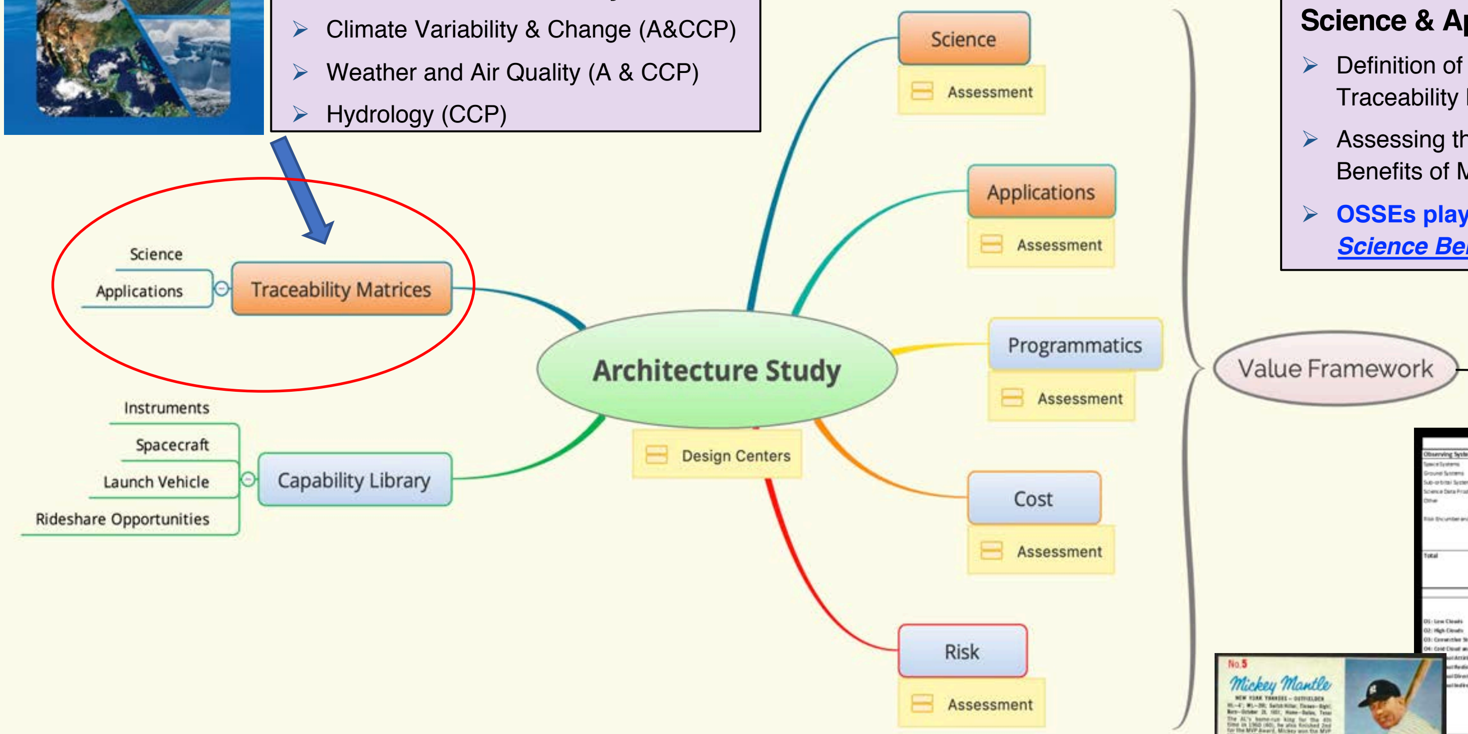
- ACCP is a combined Aerosols and CCP process-oriented Earth Observing System
- ACCP is an Earth Observing System potentially consisting of
  - a) A space-based mission (payload, spacecraft, launch vehicle)
  - b) A fully integrated, sustained sub-orbital component
  - c) Models, data assimilation and synergistic algorithms needed to extract maximum benefits from the ACCP measurements
- Payload may consist of:
  - a) Active sensors (lidars and radars) are the cornerstones of the payload, complemented by
  - b) Several passive radiometers (multi-angle, multi/hyper-spectral, with some polarized channels, from UV to sub-mm)
- Being a process-oriented mission, some of the instruments may have a narrow swath needed to provide context to the measurements (as opposed to wide swath needed for mapping)

ACCP Study: Approach



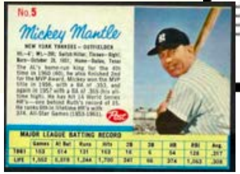
Relevant Decadal Survey Themes

- Climate Variability & Change (A&CCP)
- Weather and Air Quality (A & CCP)
- Hydrology (CCP)



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**



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ACCP Science Objectives

ACCP SATM Navigation Map

Click on Blue Lines or Text

Overarching ACCP Goal

- **Goal 1** Cloud Feedbacks
  - **Objective 1** lower Clouds
  - **Objective 2** upper Clouds
- **Goal 2** Storm Dynamics
  - **Objective 3** Convective Storms
- **Goal 3** Cold Cloud and Precipitation
  - **Objective 4** Cold Cloud and Precipitation Processes
- **Goal 4** Aerosol Processes
  - **Objective 5** Aerosol Attribution and Air-Quality
  - **Objective 6** Aerosol Processing, Removal, Redistribution
- **Goal 5** Aerosol Impacts on Radiation
  - **Objective 7** Aerosol Direct Effect and Absorption
  - **Objective 8** Aerosol Indirect Effect

Consolidated Geophysical Variable Tables — **Consolidated Observable Tables**

PoR Missions

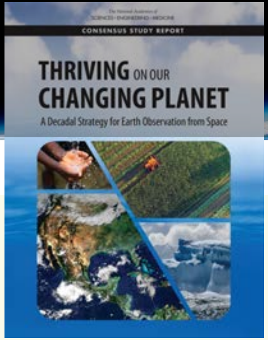
PoR Geophysical Variables

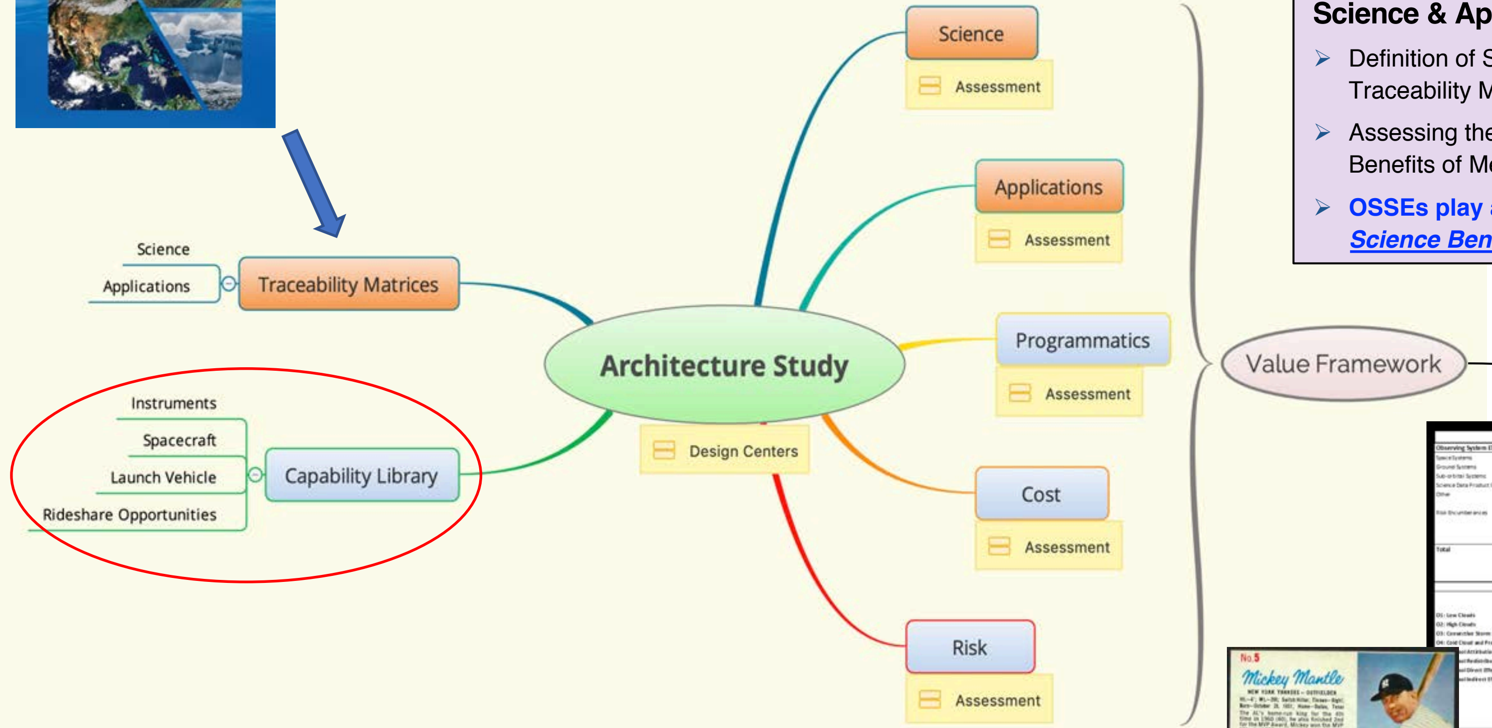
Links to :
- Geophysical Variable Tables
- Observable Tables
- Enabled Application Tables
- Decadal Survey Tables
- Acronyms

Navigation buttons on next slides: Help | Last slide viewed | Return to here

Work in Progress

ACCP Capability Library





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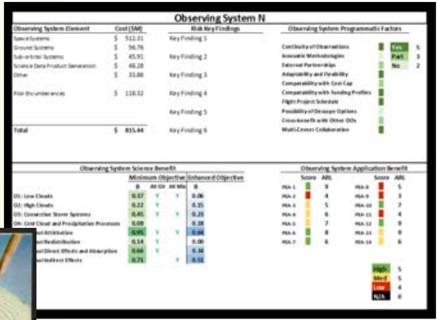

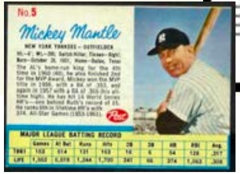

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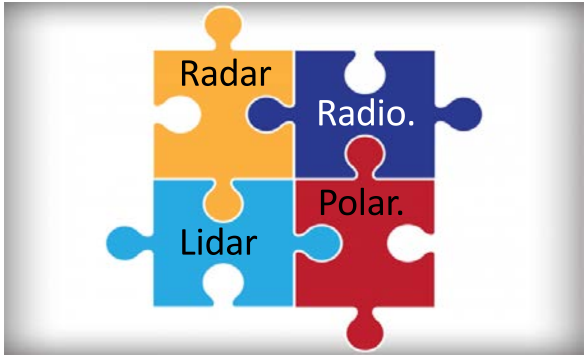
Capability Libraries

- **Instrument Library**



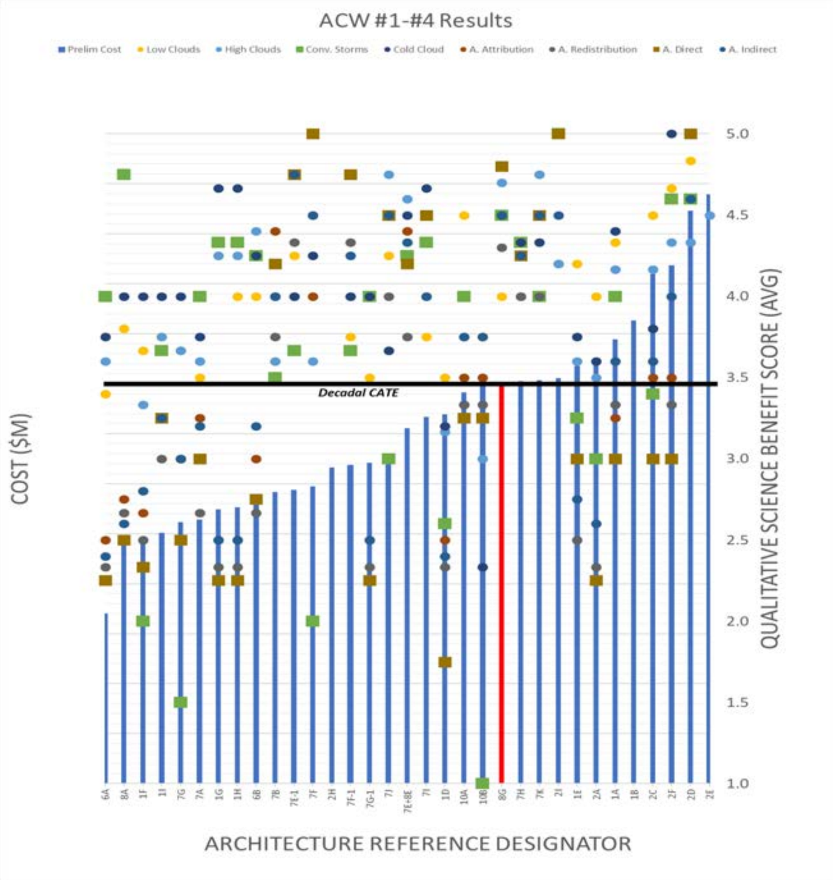
- **Other Library Components**
  - Spacecraft buses
  - Launch vehicles
  - Ground systems
  - Mission operations
  - Suborbital campaigns
  - Science team

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**	
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**			
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	bs=backscatter HSRL=High Spectral Resolution Lidar	Channels in VIS, VNIR, SWIR	LWIR=Longwave infrared LWUV=Longwave ultraviolet VIS=visible NIR=near IR SWIR=Shortwave IR FIR=Far IR

Small satellite capable sensors indicated in bold.

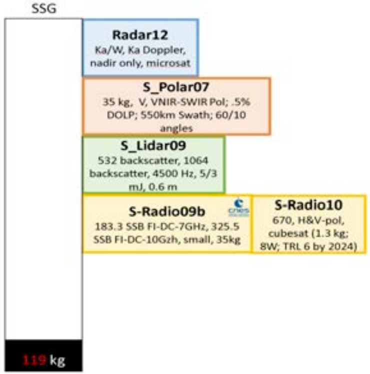
Architecture Construction Workshops: Preliminary Cost & Qualitative Science Benefit

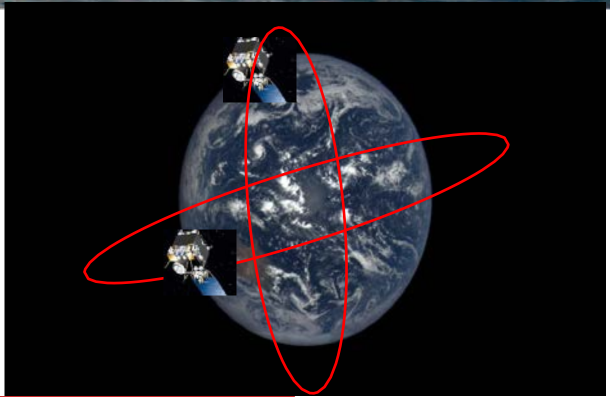
- ***Type of Architectures***
  - *Single, Dual, or Multiple spacecrafts*
  - *Large, Medium, Small-Sats and CubeSats combinations*
  - *Single and/or Multiple Orbital planes*
- ***Orbits***
  - *Polar sun-synchronous @ 450km, 1:30 PM equatorial crossing time*
  - *Precessing (65o/36o inclination) @ 407km – same as GPM*
- ***Preliminary Evaluation***
  - *Used to select ~6 architectures for deep-dive study*
  - *Parametric costing exercise used for relativistic assessment*
  - *Qualitative science evaluation for each science objective*
- First Architecture (8G) was taken for detailed study in early October 2019



First Architecture Selected for CDC (Deep Dive)

GPM Orbit





Polar Orbit

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

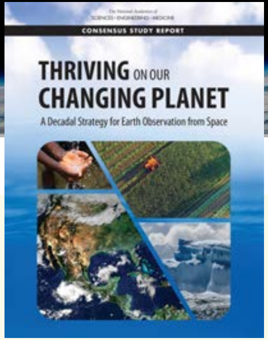
- Coupled cloud and precipitation profiling (including extremes) in context of GPM swath
- Coincident convective dynamics
- Improved capability for snowfall mapping
- Diurnal information on biomass burning aerosols from major source regions and on major pollution hotspots

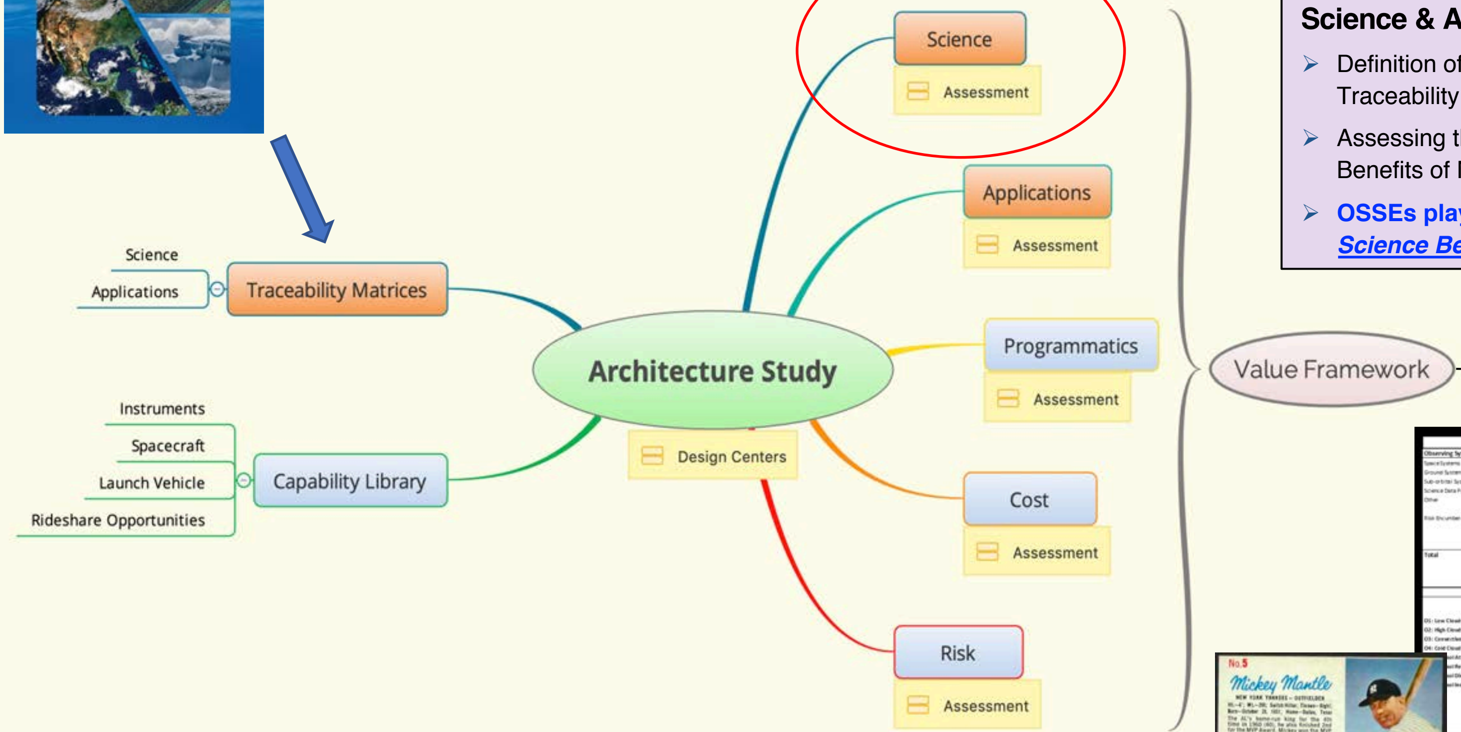
Polar Orbit: Global coverage, upperer fidelity aerosol measurements

- Critical for cloud feedbacks, upper 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 lowerer latitudes
- upper fidelity aerosol measurements on polar satellite anchors algorithms on GPM-orbit satellite

A-CCP Science Benefit Evaluation





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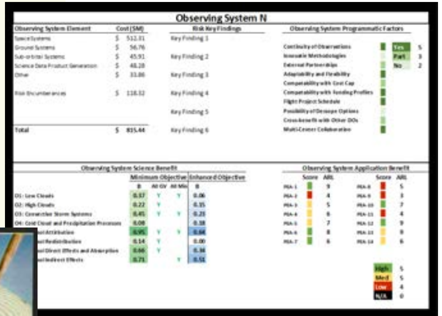

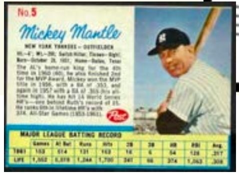

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Scoring the Science Benefits of Architectures

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

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

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)

Utility Scores

A+CCP	A	CCP	Objectives
			O3 Convective Storm Systems **Minimum:** Relate vertical motion within deep convective storms to their a) cloud and precipitation structures, b) microphysical properties, c) local environment thermodynamic and kinematic factors such as temperature, humidity, and large-scale vertical motion, and d) ambient aerosol loading. **Enhanced**: Improve measurements of convective storm vertical motion and storm characteristics in (a) and (b) of the Minimum objective. Further relate items in the Minimum objective to latent heating profiles, storm life cycle, ambient aerosol profiles, and surface properties.

Approach

General Approach - Establish global convective structure climatologies that statistically characterize deep convective processes through measurement of convective scale vertical motion, cloud, precipitation, and surrounding column aerosol properties. Leverage temporal/spatial coverage of GEO and LEO PoR with ground-based observations and global/regional analysis systems.

Role of models - testing and evaluation of ACCP observational impacts on improved model physical representation of convective cloud processes.

Role of Sub-orbital - In situ and improved space-time sampling of convective processes, especially for strong to severe storms, and perturbations in the ambient cloud environment. Cal/val for satellite measurements and retrieval algorithms.

New and Improved - a) global convective scale vertical motion profiles and correlated process metrics, and b) measurements of hydrometeor structure and environment aerosol properties, PoR measurements and capabilities, and global model analysis resolution/physics.

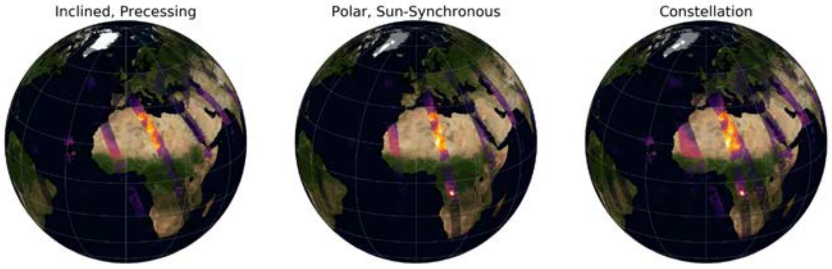
A	CCP	ODO	POR	Utility Score	Geophysical Variables (1 of 2)		Qualifiers
					Minimum	Enhanced	
	√			5.0	In-Cloud Vertical Air Velocity Profile		measure above melting layer at a minimum; Velocity minimum |>2 m/s|
√	√		(√)	5.0	Hydrometeor vertical feature mask		Cloud top height
√	√		(√)	4.5	Cloud geometric-top temperature		
√	√		(√)	3.5	Cloud top phase		
			√	N/A	Diurnally resolved cloud cover		PoR Primary; Context
			√	N/A	Diurnally resolved cloud top height		PoR Primary; Context
	√		(√)	5.0	Precipitation rate profile		
	√		(√)	4.0	Precipitation phase profile		Liquid/mixed/frozen
	√		(√)	4.3	Ice water path		
	√		√	N/A	Convective classification		Org./intensity/depth; PoR for org. context
	√		(√)	4.5	Precipitation Discrimination (stratiform/convective)		
			√	N/A	Environmental temperature profile		Used for stability parameters as well
			√	N/A	Environmental humidity profile		Used for stability parameters as well
			√	N/A	Environmental horizontal wind profile		Used for shear calculation

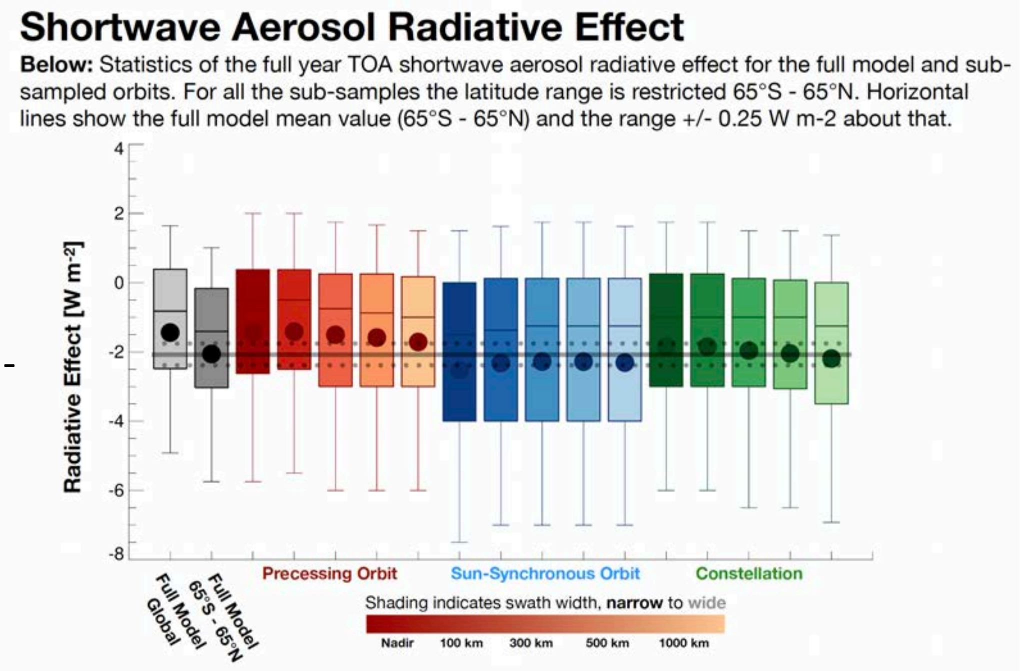
Target SATM Uncertainties

Consolidated Geophysical Variables (4 of 17)		Science Objectives	Desired Capability						Examples of Observables *Notes*	Enabled Apps
			Range	Uncertainty	Scales					
					XY	Z	T	Swath		
Minimum	**Enhanced**	**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	Layer	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%**		N/A				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	Layer	I			

Uncertainty needed to meet Science Objective

Spatial and Temporal Sampling





Nature Run: GEOS-5 Nature Run (Global, 7km, non-hydrostatic)

Sampling along candidate orbits:

- A 65° inclined precessing orbit, similar to GPM
- A sun-synchronous polar orbit, similar to Aqua, with a local equator crossing time of 1:30 AM/PM
- A constellation the combines both

Courtesy: Pete Colarco, see Poster A23R-3045

Example Aerosol Canonical Cases

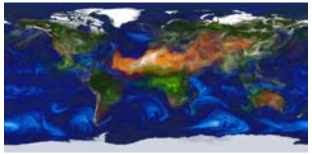
type	550 nm AOD		
	Mode 1	Mode 2	Total
Smoke (upper) over marine (lower)	0.2165	0.0335	0.2500
	0.0287	0.0713	0.1000
Smoke (lower) over marine (upper)	0.0866	0.0134	0.1000
	0.0719	0.1781	0.2500
Smoke (upper) over pollution (lower)	0.2165	0.0335	0.2500
	0.0918	0.0082	0.1000
Smoke (lower) over pollution (upper)	0.0866	0.0134	0.1000
	0.2295	0.0205	0.2500
Dust (upper) over marine (lower)	0.1293	0.1207	0.2500
	0.0287	0.0713	0.1000
Dust (lower) over marine (upper)	0.0517	0.0483	0.1000
	0.0719	0.1781	0.2500

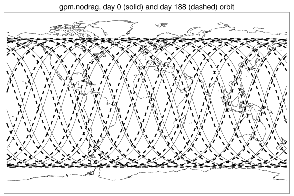
Ensemble of Uncertainties

Ensemble of prescribed Aerosol States

- From “***canonical cases***”
  - Statistical sampling of noisy observations
  - Range of solar and viewing geometries
  - Range of aerosol species and mixtures

- From **Nature Run Sampling**
  - Sample Nature Run at the satellite specific orbits for at least 1 year
  - Simulate retrievals at each sampled profile





Ensemble of Uncertainties: either

- Simulate retrieval for each realization and assess uncertainty by subtracting the specified ground truth (fewer assumptions), OR
- Estimate *a posteriori* error covariance and sample from it (assumes optimality and perfect knowledge of prior/observational error covariances)

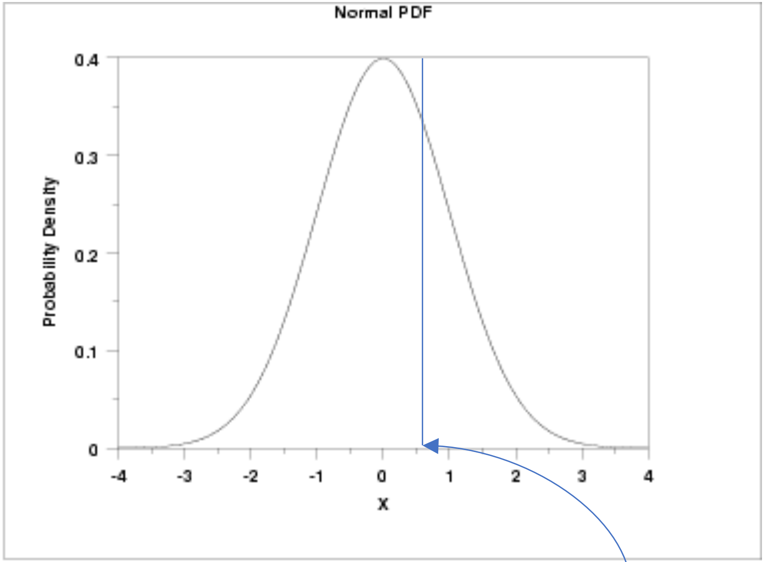
Quality Scores

- **Goal**: Assess how well a given architecture (instruments on a given orbit) delivers the required Geophysical Variables
- **Approach**:
  - From an ensemble of simulations, calculate a PDF of uncertainties
  - Using the target uncertainties in the SATM as reference, calculate the percentual of ensemble members that meet the target uncertainties

Q-Score

% of uncertainties that meets SATM target

PDF of Simulated Uncertainty of Ensemble of Retrievals

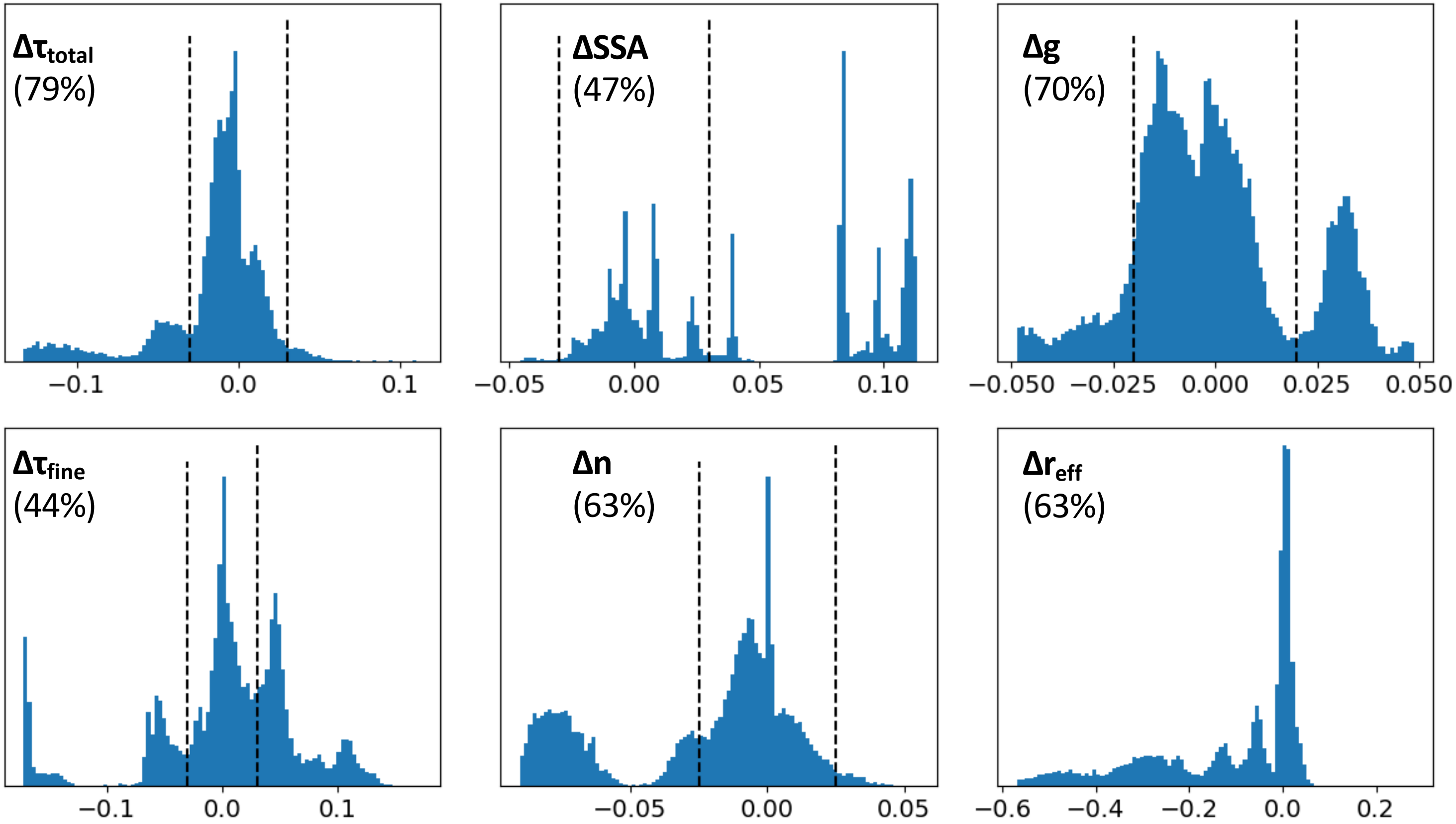


SATM Target Uncertainty For this Science Objective

Example: PDF of Uncertainties (Polarimeter Only)

Dashed lines show SATM target uncertainties

Value in parenthesis is the number of cases meeting target



Example: 2-Layer Retrieval Simulations for Canonical Cases (Preliminary)

Simulation "Truth"

Retrieved Value on n^{th} trial

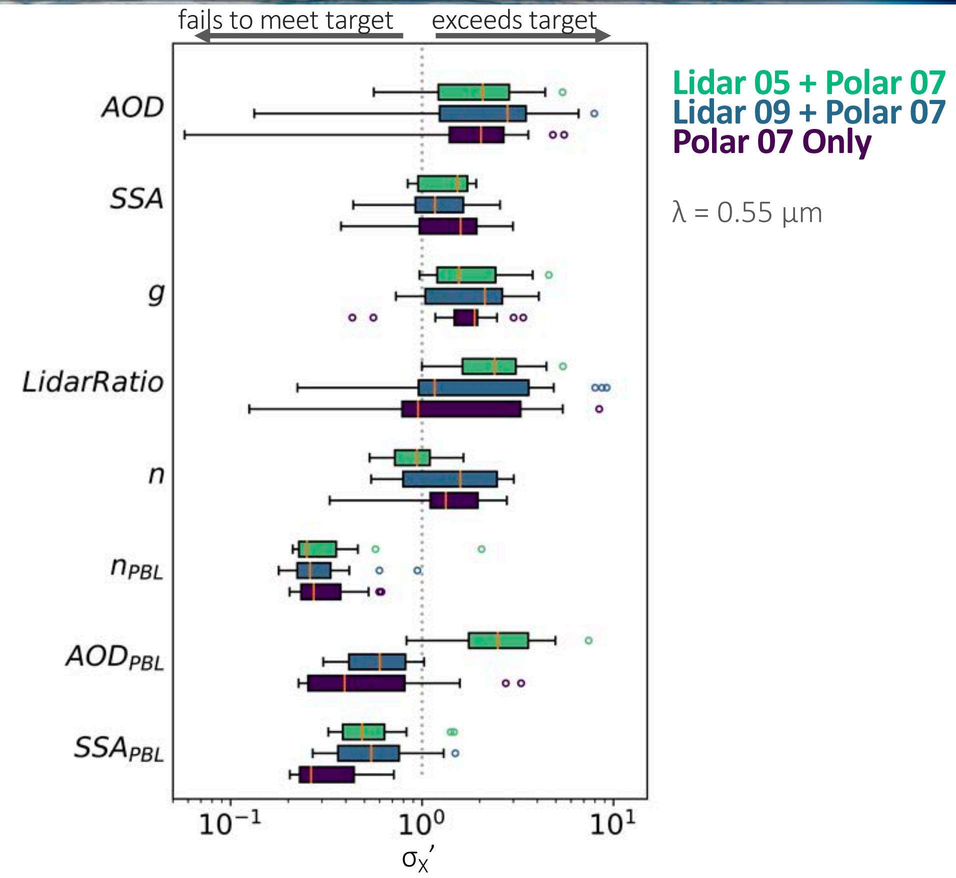
$$\sigma'_X = \sigma_X \Big/ \sqrt{\frac{1}{N}\sum_{n=1}^{N}(X - X_n')^2}$$

SATM Target Uncertainty

n = 0,1,2,…,140 trials over 18 cases
(2,520 total retrievals per instrument)

Geophysical Variable (GV)	Target Uncertainty
Total Aerosol Optical Depth	$\sigma_\tau = 0.02 + 0.05\ \tau$
Single Scattering Albedo	$\sigma_{SSA} = 0.04$
Lidar Ratio	$\sigma_{LRf} = 0.25$ LR
Real Refractive Index	$\sigma_n = 0.025$
Asymmetry Parameter (g)	$\sigma_g = 0.02$

The column and PBL σ_X both use the same target uncertainty values



ACCP Splinter Meetings: Tuesday 12/10 and Wednesday 12/11 – 5:30 PM

- **Where**:

SFSU College of Extended Learning's Downtown Campus

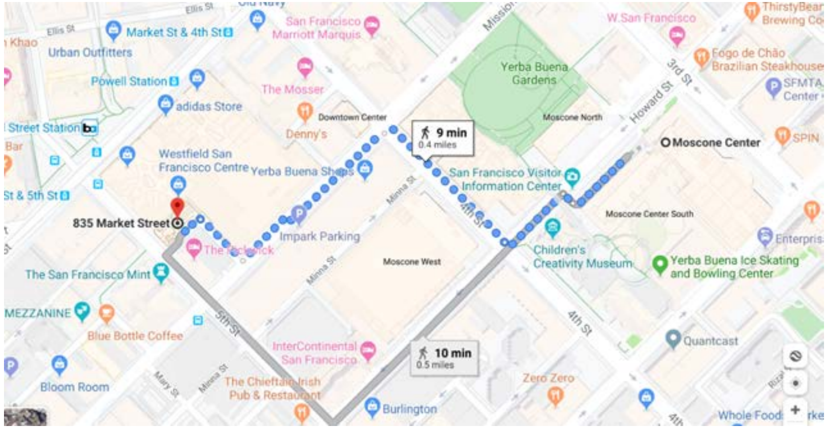
835 Market St. 6th Floor San Francisco, CA 94103

Please enter at 835 Market Street (between Walgreens and Timberland). The Bart/Muni station is Powell St. Enter on the Market St. entrance.

Dates: Tuesday 12/10 and Wednesday 12/11

Time: 5:30 pm

Meeting room is DTC 619, located on the 6th floor.

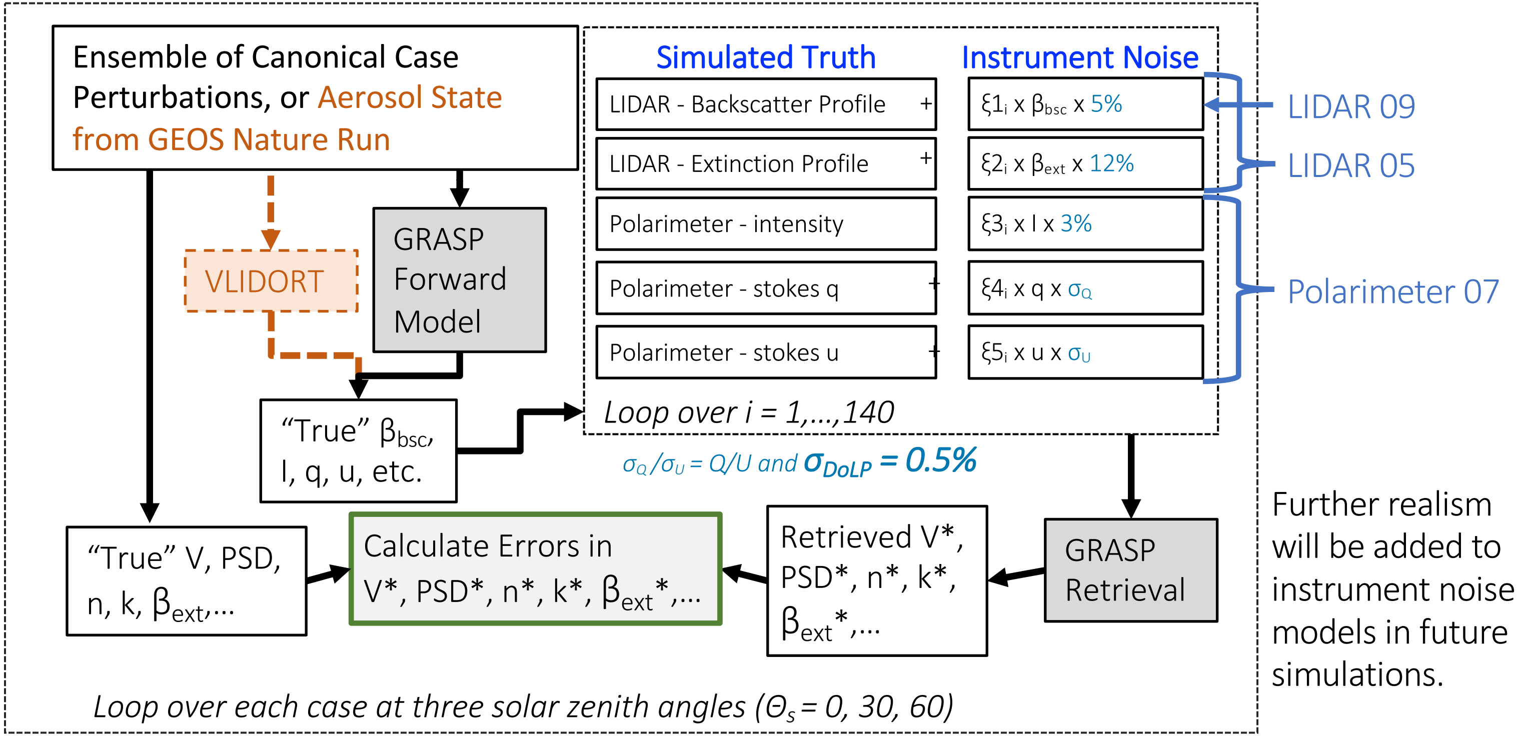


Concluding Remarks

- Global estimates of vertical motion in convective storms will enable transformative science related to storm development and life cycle, hydration of the upper troposphere and precipitation extremes.
- Aerosol absorption is a key, transformative ACCP measurement for assessing the impact of aerosols on radiation.
- Aerosol speciation is the linchpin for improving aerosol emissions and for gaining insight into aerosol processes such as vertical transport, wet removal and cloud processing
  - Goal 4 (Aerosol Processes) cannot be fully addressed with remotely-sensed observations alone –– earth system models play a critical role be it in data assimilation/inverse calculations or systematic upscaling from LES to the climate scales.
- Simultaneous observations of the aerosol and clouds/precipitation states are not easily (if at all) realized from space — an integrated space/sub-orbital approach is necessary to fully address many of the A-CCP objectives.
- The Geostationary PoR will play a critical role for all process oriented objectives in ACCP.

Extra Slides

Ensemble of Uncertainties



Further realism will be added to instrument noise models in future simulations.

ξN_i corresponds to random value pulled from a standard normal distribution

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

Science and Applications Traceability Matrix

Public Release E

23 October 2019

Note to Reviewers: Please use this on-line form to provide your comments: https://goo.gl/forms/RbSbNez4lNjjEjun2

OSSE Capabilities for ACCP

Aerosol Nature Runs

- 2-year global, non-hydrostatic mesoscale simulation for the period June 2005 through May 2007 with a 7 km horizontal resolution.
- Other upperer resolution experiments (3 km globally)
- Supplemental experiments including cloud and aerosol microphysics.

Library of Aerosol Canonical Cases

- Aerosol profiles for basic aerosol types and mixtures

Polarimeter Simulators

- VLIDORT (GSFC), MAPP, C-VDISORT, PCRTM, GISS Add-doubling (LaRC), CMPI , Markov Chain RT (University of Oklahoma)

Lidar Simulators

- GSFC (CATS/CPL heritage), LaRC (CALIPSO, HSRL heritage)

Joint lidar-polarimeter Retrieval Simulators

- GRASP (GSFC), MAPP (LaRC), extension of AirMSPI algorithms (U. Oklahoma)

Aerosol forecast and data assimilation system

- GEOS based system at GMAO

Cloud and Precipitation Process Nature Runs

- Large eddy simulations of cumulus and stratocumulus
- Convection resolving simulations of shallower to deep convection
- Large domain regional simulations of tropical convection and extratropical cyclones

Radar Simulators

- Time dependent 2-stream multiple scattering (GSFC), NEOS3 (JPL), Hogan and Battaglia multiple scattering (JPL)

Microwave Radiometer Simulators

- Delta-eddington 2-stream polarized (GSFC,JPL)

Visible/Near-IR simulators

- RADIANT multi-stream vis/nir solver (JPL, Univ. Utah)

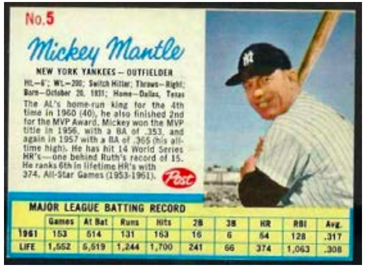
Bayesian Retrieval Algorithms

- Optimal Estimation (JPL, Univ. Utah), Markov chain Monte Carlo (JPL, Univ. Utah)

Convection-Resolving Ensemble Data Assimilation

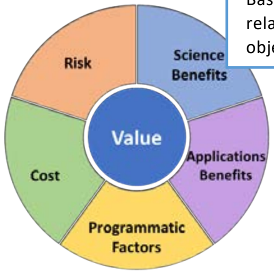
- WRF-based Ensemble Kalman Filter (EnKF)

Science Benefit in the Value Framework



Example Baseball Card for OS 1-5

For each **Observing System (OS)**, a **Science Benefit (B)** score is determined for each **Science Objective** and incorporated in the OS's Football Trading Card.



Based on each OS's capabilities relative to each SATM objective

Science Benefit is one of five contributions to an OS's Value

	OS 1	OS 2	OS 3	OS 4	OS 5
O1: Low Clouds	0.37	0.13	0.37	0.64	0.33
O2: High Clouds	0.22	0.34	0.89	[illegible]	0.11
O3: Convective Storms	0.45	0.67	0.53	[illegible]	0.19
O4: Falling Snow Processes	0.08	0.59	[illegible]	[illegible]	0.59
O5: Aerosol Redistribution	0.95	0.67	[illegible]	0.24	0.29
O6: Aerosol Attribution	0.14	[illegible]	[illegible]	0.42	0.83
O7: Air Quality	0.66	0.44	[illegible]	0.13	0.36
O8: Absorbing Aerosols	0.71	0.86	0.34	0.75	0.40
O9: Aerosol Direct Effect	0.89	0.77	0.88	0.20	0.06
O10: Aerosol Indirect Effect	0.55	0.47	0.04	0.09	0.19

Notional scores for example only

Example comparison of Science Benefit (B) across OSs 1-5

For a given OS and Science Objective

$$B = \sum UQ$$

U – Utility (0-1) – quantifies how important a Geophysical Variable (GV) is to address the Science Objective

Q – Quality (0-1) – quantifies how well an Observing System obtains a Geophysical Variable.

Decadal Survey Aerosol Themes and Objectives

Table 1-1: Most Important (MI) Decadal Survey Science Objectives of relevance to the Aerosol Designated Observable.

Theme	Science Objectives
Climate Variability and Change	• Reduce aerosol radiative forcing uncertainty by a factor of two (C-2h) • Quantify the contribution of the upper troposphere and stratosphere to climate feedbacks and change (C-2g) • Improve estimates of the emissions of natural and anthropogenic aerosols and their precursors via observational constraints (C-5a) • Quantify the effects of aerosols on cloud formation, height, and properties (C-5c) • Reduce uncertainties in low and high cloud feedback by a factor of two (C-2a)
Weather and Air Quality	• Determine the effects of key boundary layer processes on weather, hydrological, and air quality forecasts (W-1a) • Improve the observed and modeled representations of natural, low-frequency modes of weather/climate variability (W-2a) • Improve our understanding of the processes that determine air pollution distributions and reduce uncertainties in PM concentrations (W-5a)

Decadal Survey CCP Themes and Objectives

Table 1-2: Most Important (MI) Decadal Survey Science Objectives of relevance to the Cloud-Convection-Precipitation Designated Observable.

Theme	Science Objectives
Hydrology	• Develop and evaluate an integrated Earth System analysis with sufficient observational input to accurately quantify the components of the water and energy cycles and their interactions, and to close the water balance from headwater catchments to continental-scale river basins (H-1a) • Quantify rates of precipitation and its phase (rain and snow/ice) worldwide at convective and orographic scales suitable to capture flash floods and beyond (H-1b) • Quantify rates of snow accumulation, snowmelt, ice melt, and sublimation from snow and ice worldwide at scales driven by topographic variability (H-1c)
Climate Variability and Change	• Reduce uncertainties in low and high cloud feedback by a factor of two (C-2a) • Quantify the contribution of the upper troposphere and stratosphere to climate feedbacks and change (C-2g)
Weather and Air-Quality	• Determine the effects of key boundary layer processes on weather, hydrological, and air quality forecasts (W-1a) • Improve the observed and modeled representations of natural, low-frequency modes of weather/climate variability (W-2a) • Determine how spatial variability in surface characteristics modifies regional cycles of energy, water, and momentum (stress) (W-3a) • Measure the vertical motion within deep convection to improve model representation of extreme precipitation and determine convective transport and redistribution of mass, moisture, momentum, and chemical species (W-4a)

A+CCP	A	CCP	Goal	Example Science Questions	Objectives
			G1 Cloud Feedbacks *Reduce the uncertainty in lower- and upper-cloud climate feedbacks by advancing our ability to predict the properties of lower and upper clouds*	*1) To what extent can the properties of lower clouds be determined by environmental factors?* *2) How do the properties and formation of upper clouds relate to (i) deep convection and (ii) large-scale environmental factors?*	**O1** lower Clouds **Minimum:** Determine the sensitivity of boundary layer *bulk* cloud physical and radiative properties to large-scale and local environmental factors including thermodynamic and dynamic properties. **Enhanced**: Adds to Minimum cloud *microphysical* properties and enhanced bulk cloud properties.
					O2 upper Clouds **Minimum:** 1) Relate the vertical structure, horizontal extent, ice water path, and radiative properties of *convectively generated* upper clouds to convective vertical transport 2) Relate the vertical structure, horizontal extent, ice water path, and radiative properties of *large scale* upper clouds to environmental factors. **Enhanced**: Adds to Minimum microphysical properties of ice clouds.

A+CCP	A	CCP	Goal	Example Science Question	Objectives
			G2 Storm Dynamics *Improve our physical understanding and model representations of cloud, precipitation and dynamical processes within deep convective storms*	1) *How does convective mass flux relate to the vertical distribution and microphysical properties of clouds and precipitation in deep convection?* 2) *How do different convective storm systems contribute to vertical transports of heat, water, and other constituents within the atmosphere and how do these transports relate to storm environment and lifecycle?*	**O3** Convective Storm Systems **Minimum:** Relate vertical motion within deep convective storms to their a) cloud and precipitation structures, b) microphysical properties, c) local environment thermodynamic and kinematic factors such as temperature, humidity, and large-scale vertical motion, and d) ambient aerosol loading. **Enhanced:** Improve measurements of convective storm vertical motion and storm characteristics in (a) and (b) of the Minimum objective. Further relate items in the Minimum objective to latent heating profiles, storm life cycle, ambient aerosol profiles, and surface properties.

A+CCP	A	CCP	Goal	Example Science Questions	Objectives
			G3 Cold Cloud and Precipitation *Improve understanding of cold (supercooled liquid, ice, and mixed phase) cloud processes and associated precipitation and their coupling to the surface at mid to upper latitudes and to the cryosphere.*	*1) What is the distribution and phase of surface precipitation (rain, mixed phase, frozen and snowfall) and how does it influence the surface water and energy balance?* *2) What are the processes that govern phase partitioning and precipitation formation in cold clouds?* *3) What are the processes that govern the vertical structure of microphysics of cold-cloud precipitation from cloud top to near-surface?*	**O4** Cold Cloud and Precipitation Processes **Minimum:** Detect and quantify vertical profiles of ice and liquid condensate (including precipitation), and relate these to cloud physical properties (including mixed-phase precipitation and snowfall), meteorological forcing and regime, orography, and surface properties. **Enhanced:** Enhancement of Minimum with an additional focus on: 1) cloud physical processes related to the density and microphysical characterization of snowfall and frozen precipitation in the column and near surface; 2) characterization of atmospheric contributions to the surface water mass and energy balance at upperer latitudes.

A+CCP	A	CCP	Goal	Example Science Questions	Objectives
			G4 Aerosol Processes *Reduce uncertainty in key processes that link aerosols to weather, climate and air quality related impacts.*	1) *What are the major anthropogenic and natural sources of aerosol and how do they vary spatially and temporally?* 2) *What are the factors that relate aerosol microphysical and optical properties to surface PM concentrations?* 3) *To what extent does long-range transport of smoke, dust, and other particulates impact regional near-surface air quality?*	**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 aerosol emissions, speciation, and predictions of near-surface particulate concentrations. **Enhanced:** Characterize variations 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.
					O6 Aerosol Processing, Removal and Vertical Redistribution **Minimum:** Characterize the processing and removal of aerosols by clouds and light precipitation (<2 mm/hr). **Enhanced:** Characterize the processing, removal and vertical redistribution of aerosols by clouds and heavy precipitation (> 2 mm/hr).

<table>
<tr><th>A+CCP</th><th>A</th><th>CCP</th><th>Goal</th><th>Example Science Questions</th><th>Objectives</th></tr>
<tr><td rowspan="2"></td><td></td><td rowspan="2"></td><td rowspan="2">G5 Aerosol Impacts on Radiation

Reduce the uncertainty in Direct (D) and Indirect (I) aerosol-related radiative forcing of the climate system.</td><td rowspan="2">1) How do changes in anthropogenic aerosols affect Earth's radiation budget and offset the warming due to greenhouse gases?

2) What is the role of absorbing aerosols in the Earth's radiation budget and thermodynamics?

3) Under what conditions do aerosols impact the albedo or coverage of shallower clouds and by how much?</td><td>O7 Aerosol Direct Effects and Absorption

Minimum: Reduce uncertainties in estimates of: 1) global mean clear and all-sky shortwave direct radiative effects (DRE) to ±1.2 W/m2 at TOA and the anthropogenic fraction, 2) regional TOA and surface DRE, and 3) Quantify the impacts of absorbing aerosol on atmospheric stability.

Enhanced: Quantify the impact of absorbing aerosols on vertically resolved aerosol radiative heating rates and DRE commensurate with the uncertainties in global mean at TOA and surface.</td></tr>
<tr><td></td><td>O8 Aerosol Indirect Effect

Minimum: Provide measurements to constrain process level understanding of aerosol-warm cloud interactions to improve estimates of aerosol indirect radiative forcing.

Enhanced: Provide measurements to constrain process level understanding of interactions of aerosol with cold and mixed-phase clouds to improve estimates of aerosol indirect radiative forcing.</td></tr>
</table>

DS Traceability Goals 1-2

2017 Decadal Survey Goals (from Appendix B)	ACCP Goals
C-2a Reduce uncertainty in lower and upper cloud feedback. **W-1a** Determine the effects of key boundary layer processes on weather, hydrological, and air quality forecasts at minutes to subseasonal time scales. **W-2a** Improve the observed and modeled representation of natural, lower-frequency modes of weather/climate variability. **C-2g** Quantify the contribution of the UTS to climate feedbacks and change.	**G1** Cloud Feedbacks *Reduce the uncertainty in lower- and upper-cloud climate feedbacks by advancing our ability to predict the properties of lower and upper clouds.*
C-5c Quantify the effect that aerosol has on cloud. **C-2g** Quantify the contribution of the UTS to climate feedbacks and change. **H-1b** Quantify rates of precipitation and its phase (rain and snow/ice) worldwide at convective and orographic scales suitable to capture flash floods and beyond. **W-1a** Determine the effects of key boundary layer processes on weather, hydrological, and air quality. **W-2a** Improve the observed and modeled representation of natural, lower-frequency modes of weather/climate variability. **W-4a** Measure the vertical motion within deep convection to within 1 m/s and heavy precipitation rates to within 1 mm/hour to improve model representation of extreme precipitation and to determine convective transport and redistribution of mass, moisture, momentum, and chemical species.	**G2** Storm Dynamics *Improve our physical understanding and model representations of cloud, precipitation and dynamical processes within storms.*

Most Important   Very Important

DS Traceability Goals 3-5

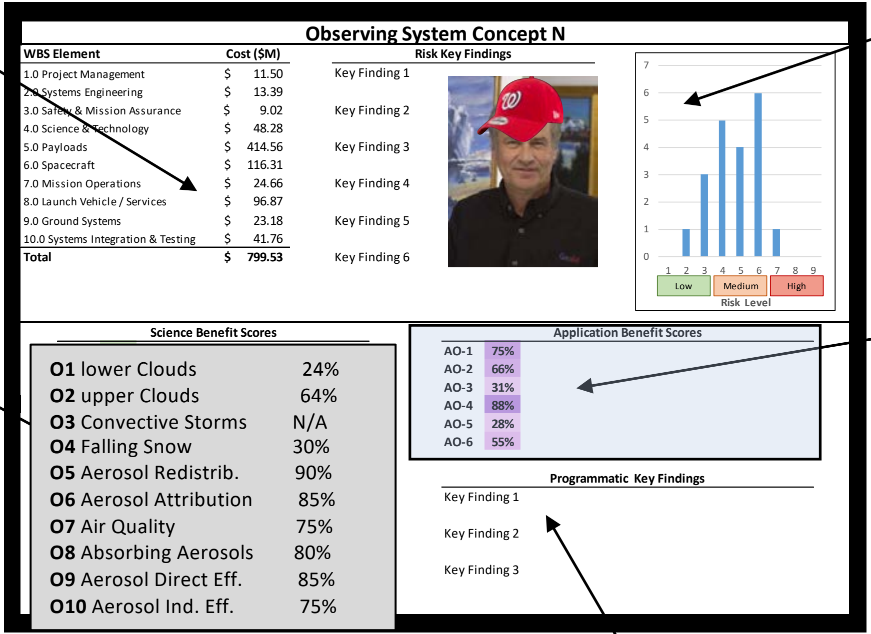
2017 Decadal Survey Goals (from Appendix B)	ACCP Goals
H-1b Quantify rates of precipitation and its phase (rain and snow/ice) worldwide at convective and orographic scales suitable to capture flash floods and beyond. **S-4a** Quantify global, decadal landscape change produced by abrupt events and by continuous reshaping of Earth's surface due to surface processes, tectonics, and societal activity. (Recommended measurement of rainfall and snowfall rates). **W-1a** Determine the effects of key boundary layer processes on weather, hydrological, and air quality. **W-3a** Determine how spatial variability in surface characteristics modifies region cycles of energy and water	**G3** Cold Cloud and Precipitation *Quantify the rate of falling snow at middle to upper latitudes to advance understanding of its role in cryosphere-climate feedbacks.*
W-1a (boundary layer processes) **W-5a** (air pollution and health) **C-5a** Improve estimates of the emissions of natural and anthropogenic aerosols	**G4** Aerosol Processes *Reduce uncertainty in key processes that link aerosols to weather, climate and air quality related impacts.*
C-2a Reduce uncertainty in lower and upper cloud feedback. **C-2h** Reduce aerosol radiative forcing uncertainty **C-5c** Quantify the effect that aerosol has on cloud	**G5** Aerosol Impacts on Radiation *Reduce the uncertainty in Direct (D) and Indirect (I) aerosol-related radiative forcing of the climate system.*

Most Important Very Important

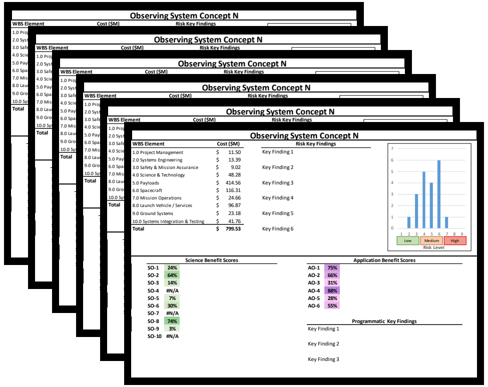
Value Output: Baseball Cards for Concept N

Cost Estimate Summar y

Science Benefit Scores



Risk Estimate Summary



Applications Benefit Scores

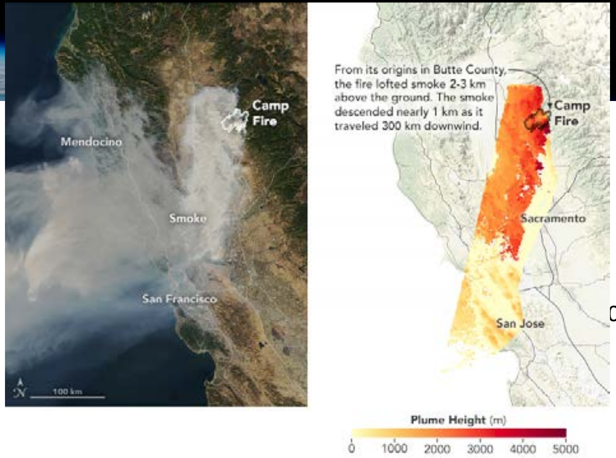
Programmatic Factors

The VF Baseball Card allowers for simultaneous comparisons across observing system concepts on the basis of cost, risk, science and applications benefits, and programmatic factors.

Objective 5: Aerosol Attribution/AQ

Potential Enabled Application Example

- **AQ Forecasting & Decision-Making:** Observations of speciated aerosol enable initial conditions, plume tracking (e.g., volcanoes, forest fires), and estimation of emissions for AQ forecasting, as well as, for AQ decision-making, such as State Implementation Plan development and Exceptional Event support.
- **Relevant Geophysical Properties:** AOD, Aerosol Extinction Profiles, Aerosol Speciation, Aerosol layer height
- **Partners**: NOAA, EPA, state AQ agencies, National Forest Service, FAA, VAACs



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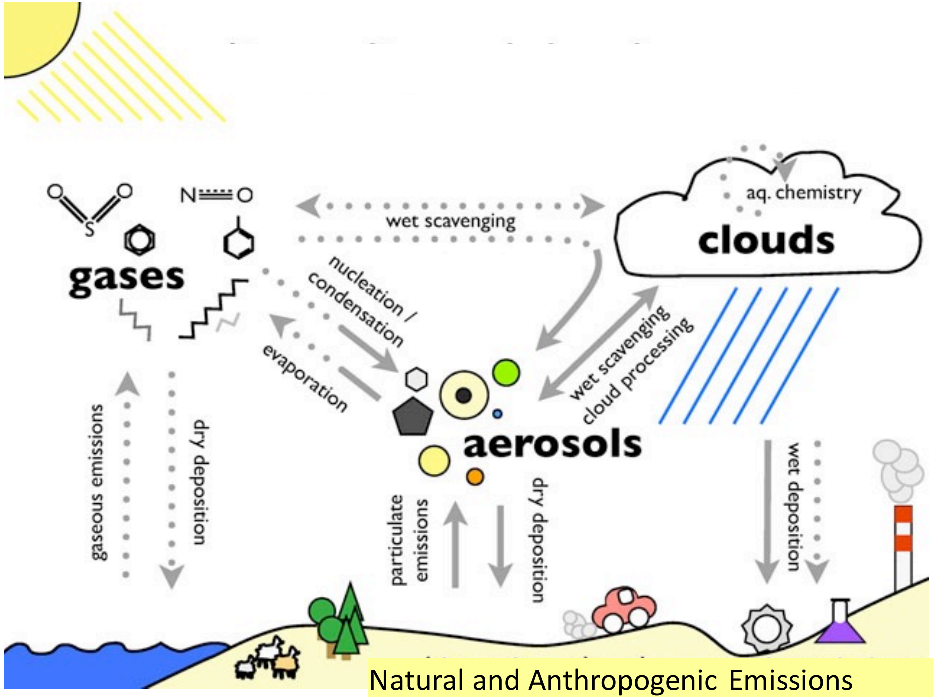
A+CCP has the potential to provide more and better information to characterize the 3-D structure of speciated aerosols within the boundary layer and to quantify emission sources

Objective 5: Aerosol Redistribution
Potential Enabled Application Example

- **Operational Air Quality Forecasting**: Aerosol observations are used for operational AQ forecasting (e.g., forecast initialization), tracking dust plumes, and issuing AQ alerts
- **Relevant Geophysical Properties:** Aerosol Optical Depth, Aerosol Extinction Profiles, & Aerosol Speciation
- **Partners**: NOAA, EPA (e.g., AirNOW) and state AQ agencies

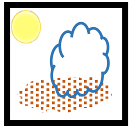


Courtesy of EMPA

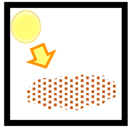
The Aerosol Science of ACCP

Advanced Science Enabling Observations

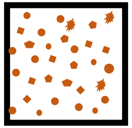
Collocated Aerosol and Cloud Observations



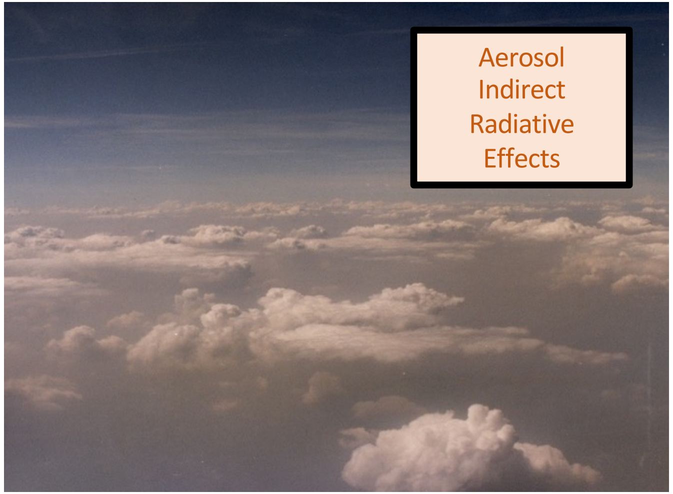
Aerosol Absorption (Heating)



Aerosol Speciation



Aerosol Direct Radiative Effects



Aerosol Indirect Radiative Effects

Aerosol Attribution, Redistribution and Air Quality