Aerosol remote sensing with small satellites in formation flight

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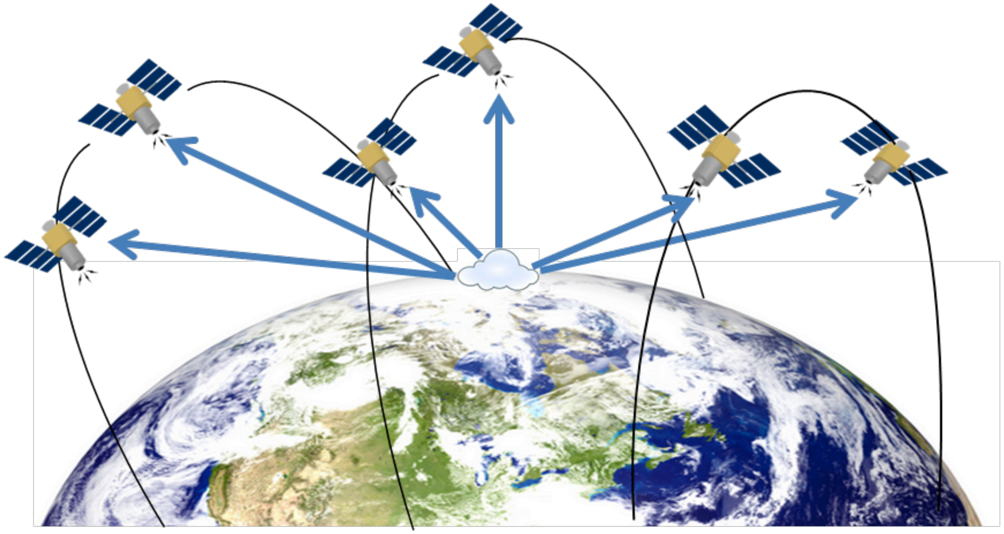


1 funding generously provided by the NASA New (Early Career) Investigator Program in Earth Science

Synopsis

Motivation potential of small satellite formations

Background

- Coupled Model Based Systems Engineering (MBSE) +
- Information content based Observing System Simulation Experiment (OSSE)

Approach

- Transform prior BRDF analysis for aerosol remote sensing
- Information content analysis details - sensor and simulations

Results

- Example BRDF results. Example Jacobian BRDF
- Degrees of Freedom
- Relative Aerosol Optical Thickness predicted uncertainty
- Fine mode effective radius predicted uncertainty

Conclusions

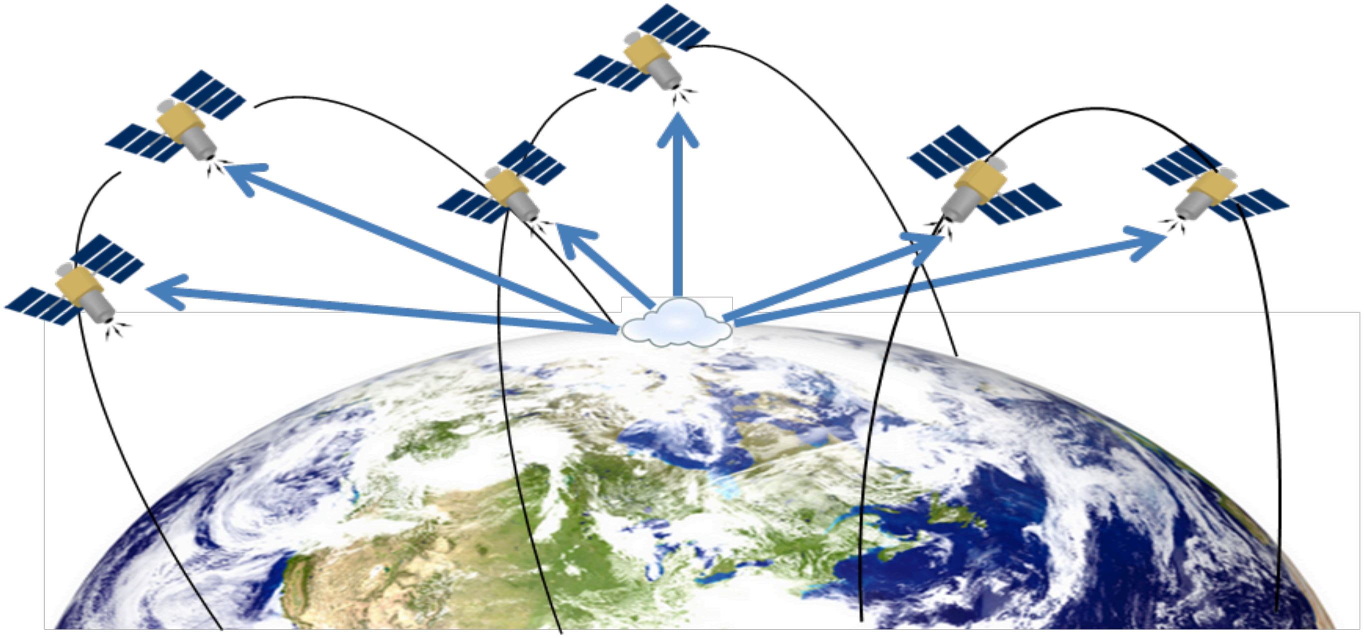
Formation flight – *alternate aerosol remote sensing paradigm?*

We need more information: *multiple spectra, multiple view angles, multiple polarization states*

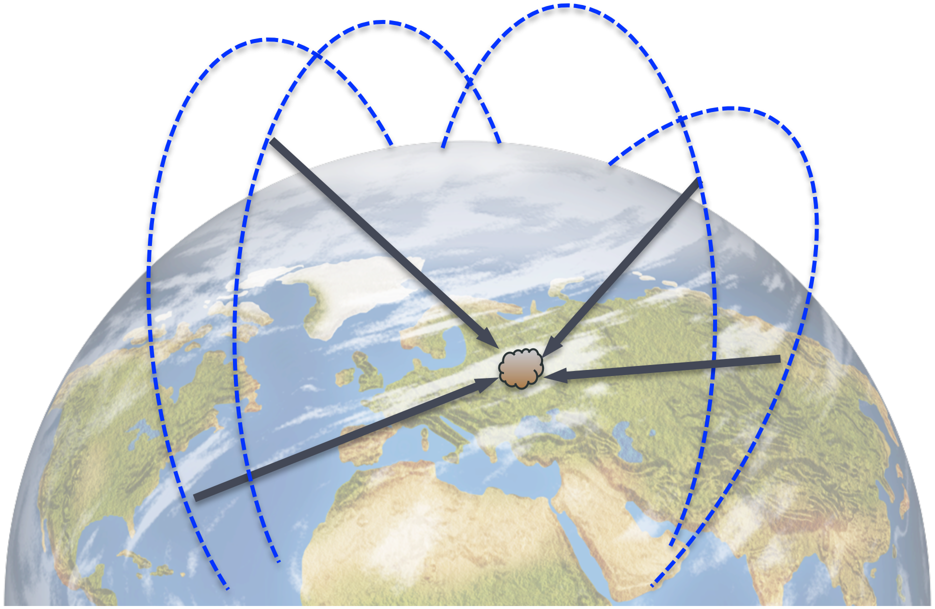
So far, we've put this all on a single instrument/platform

New cube/small satellite technology means observation can be dispersed…

… can there be a benefit to doing this?

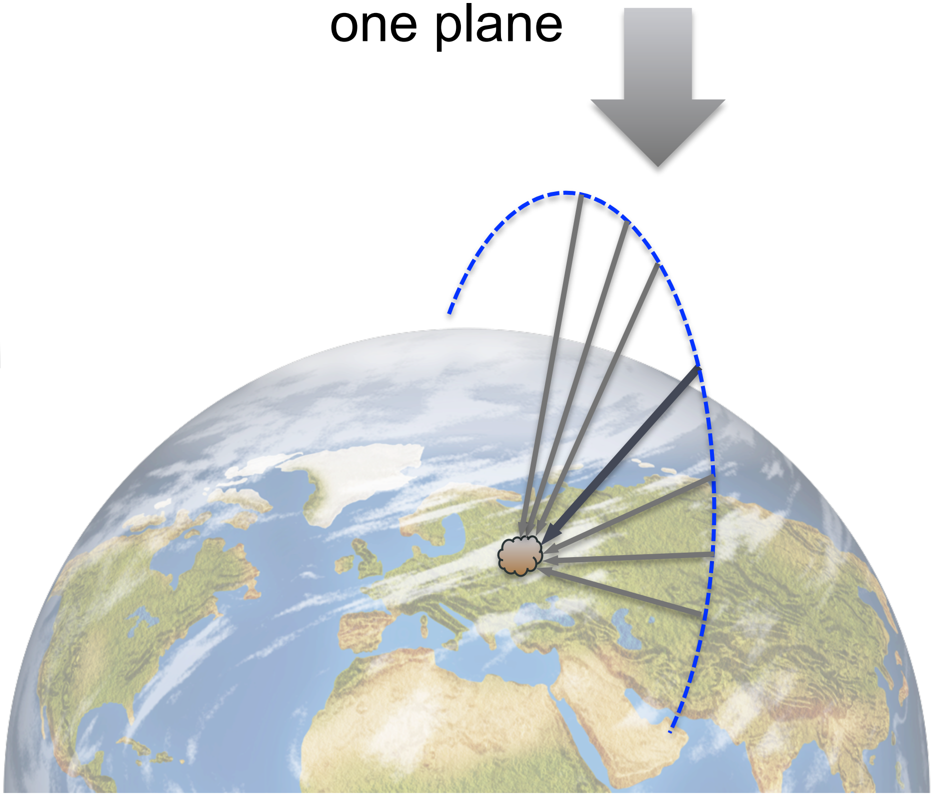


Formation flight: access alternate view geometries



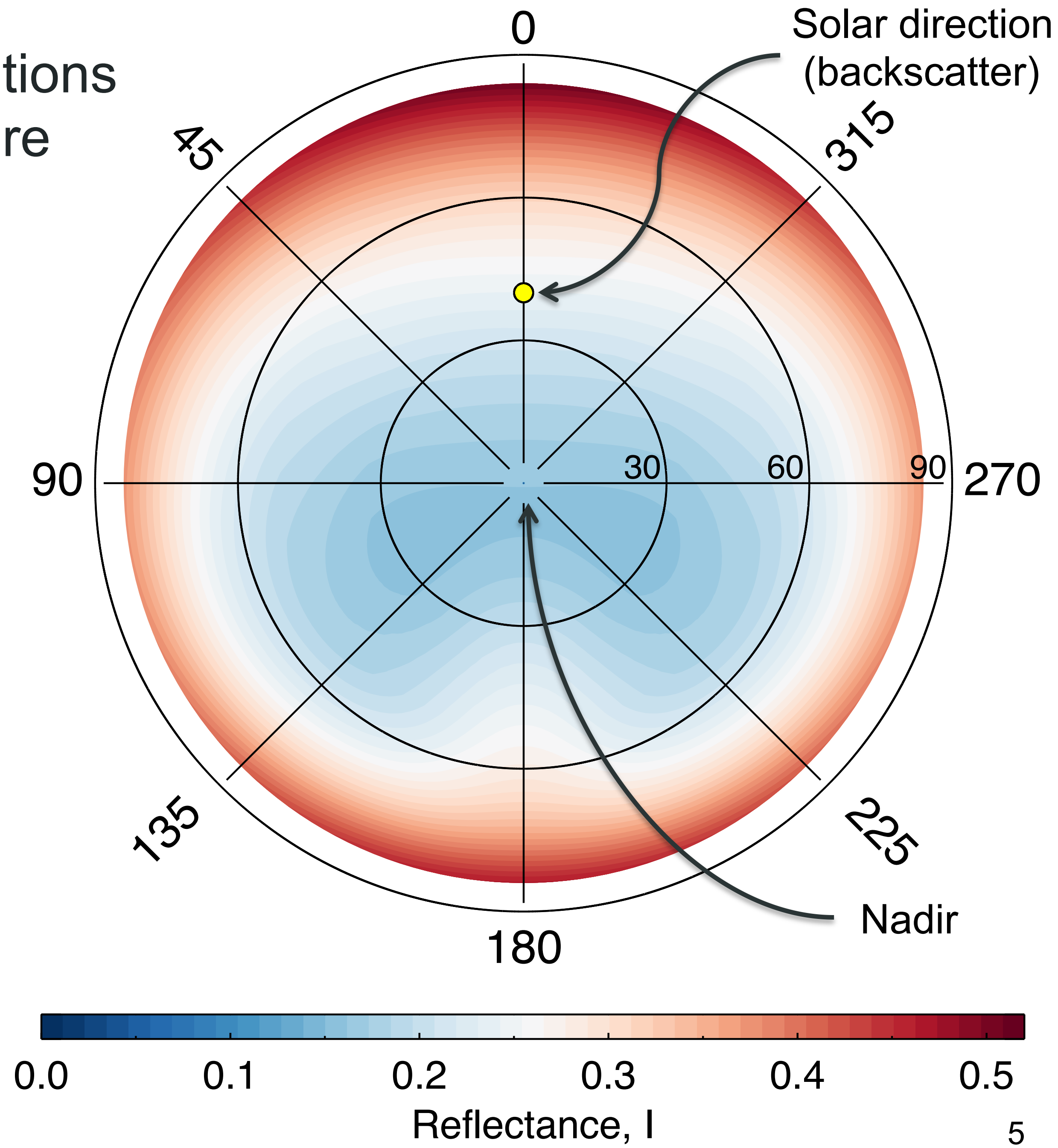
Distributed viewing geometry: Independent spacecraft observe a common location, variety of view zenith, azimuth angles

Single spacecraft Multiple views in one plane



Multi-angle observations at Top of Atmosphere (TOA) *sample* the:

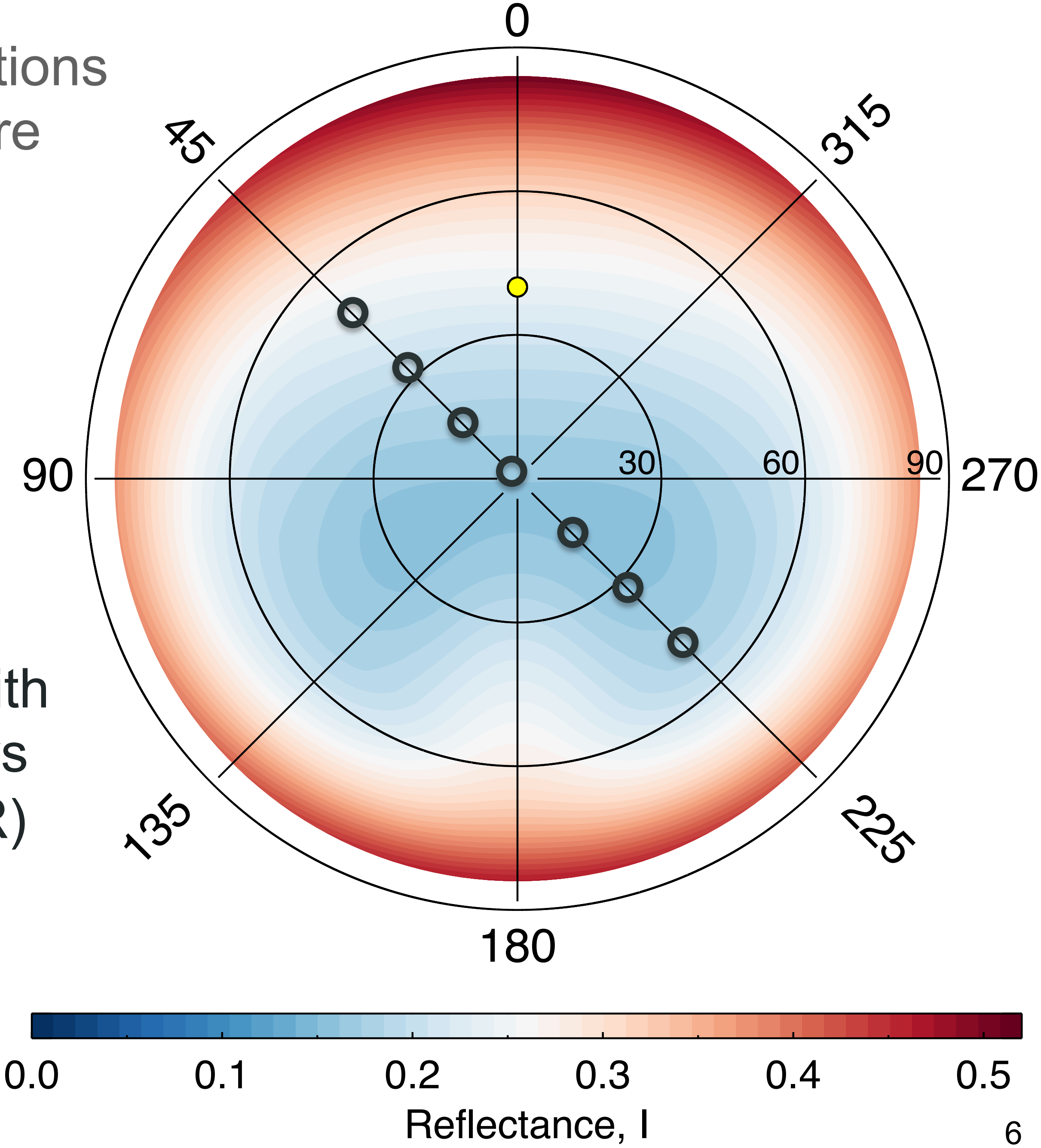
total Bidirectional Reflectance Distribution Function (BRDF)



Multi-angle observations at Top of Atmosphere (TOA) *sample* the:

total Bidirectional Reflectance Distribution Function (BRDF)

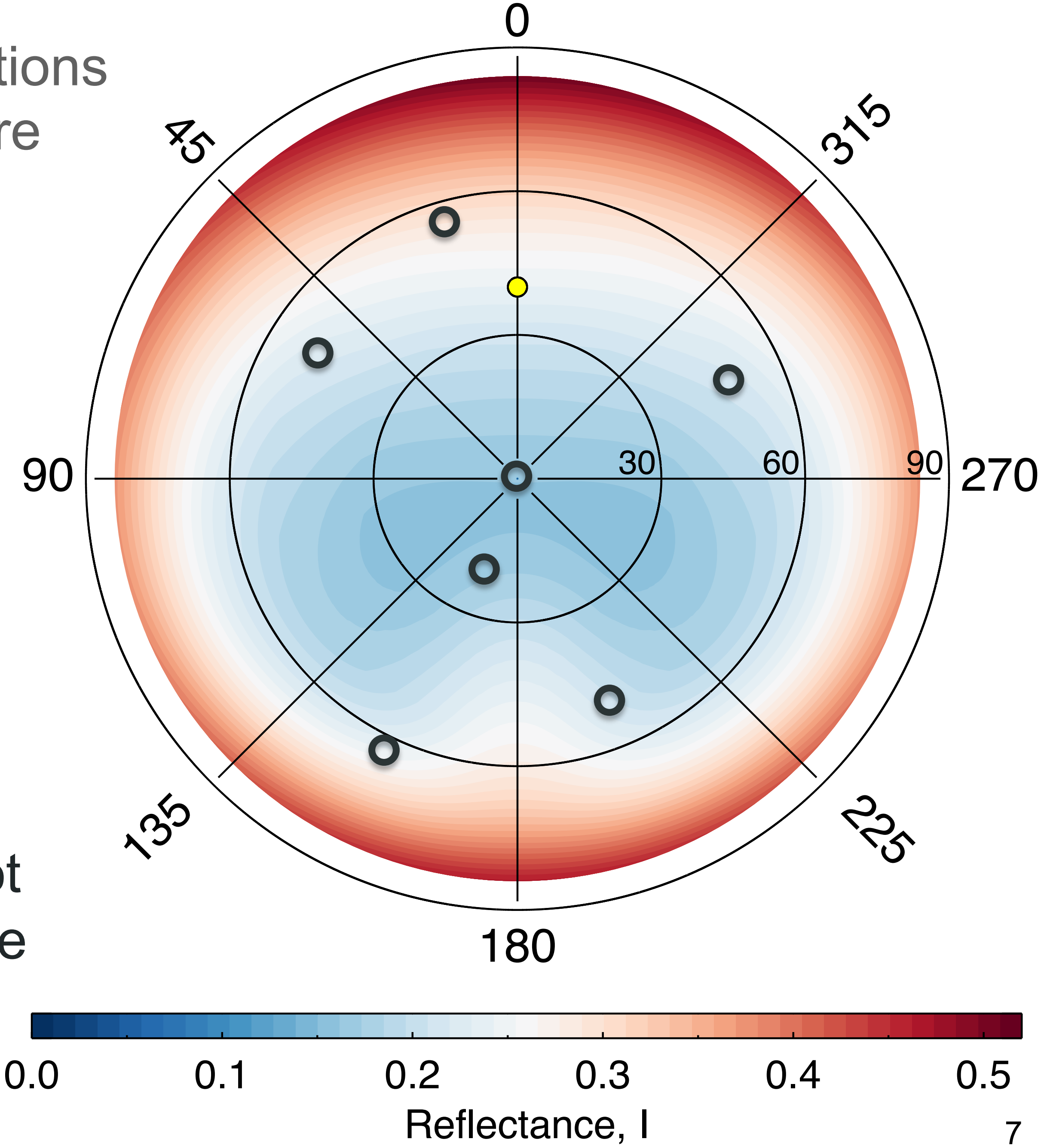
“single” platforms with multiple angle views (ie POLDER, MISR) sample in a plane



Multi-angle observations at Top of Atmosphere (TOA) *sample* the:

total Bidirectional Reflectance Distribution Function (BRDF)

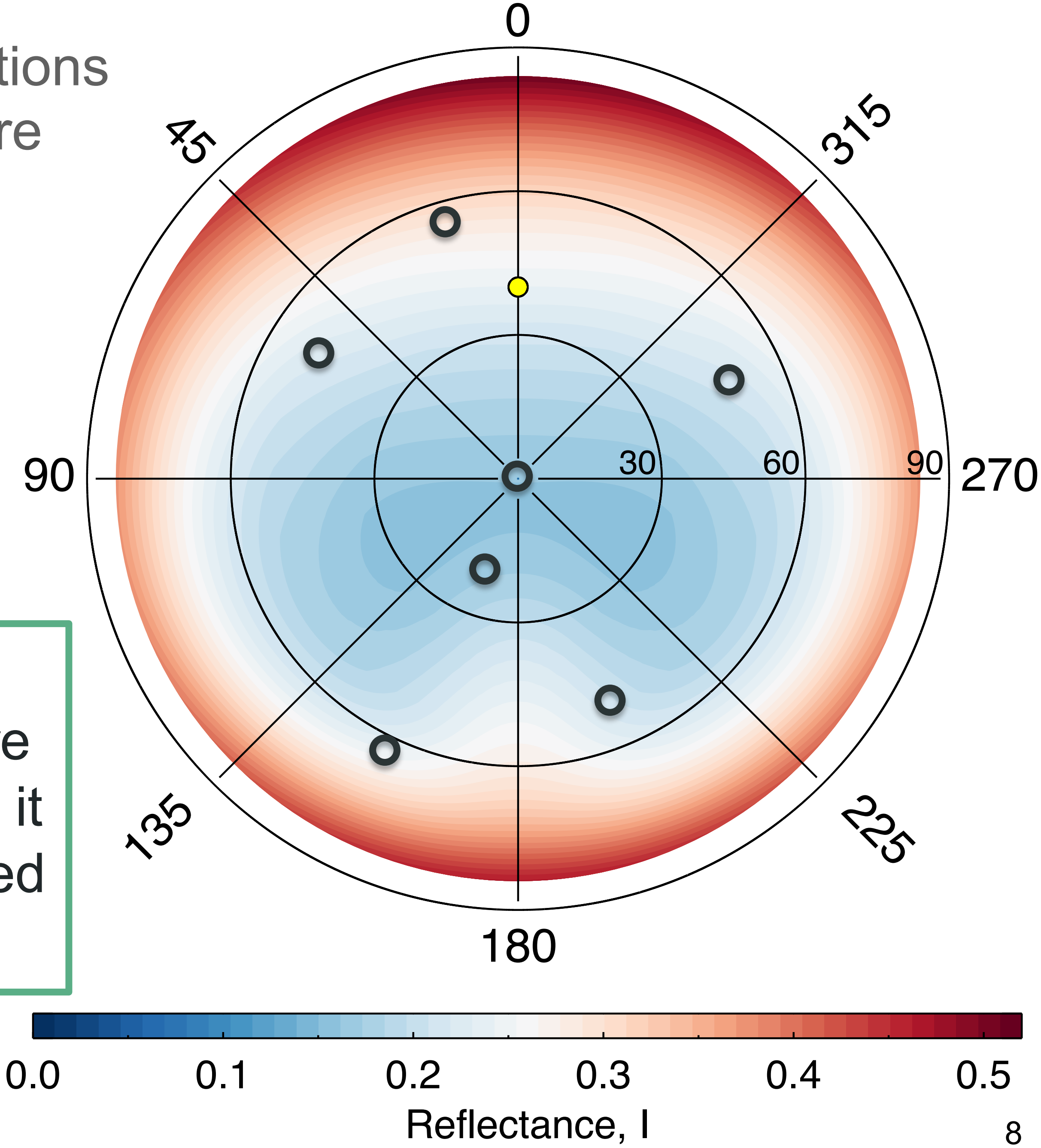
Samples from constellations of (single view) instruments are not restricted to a plane



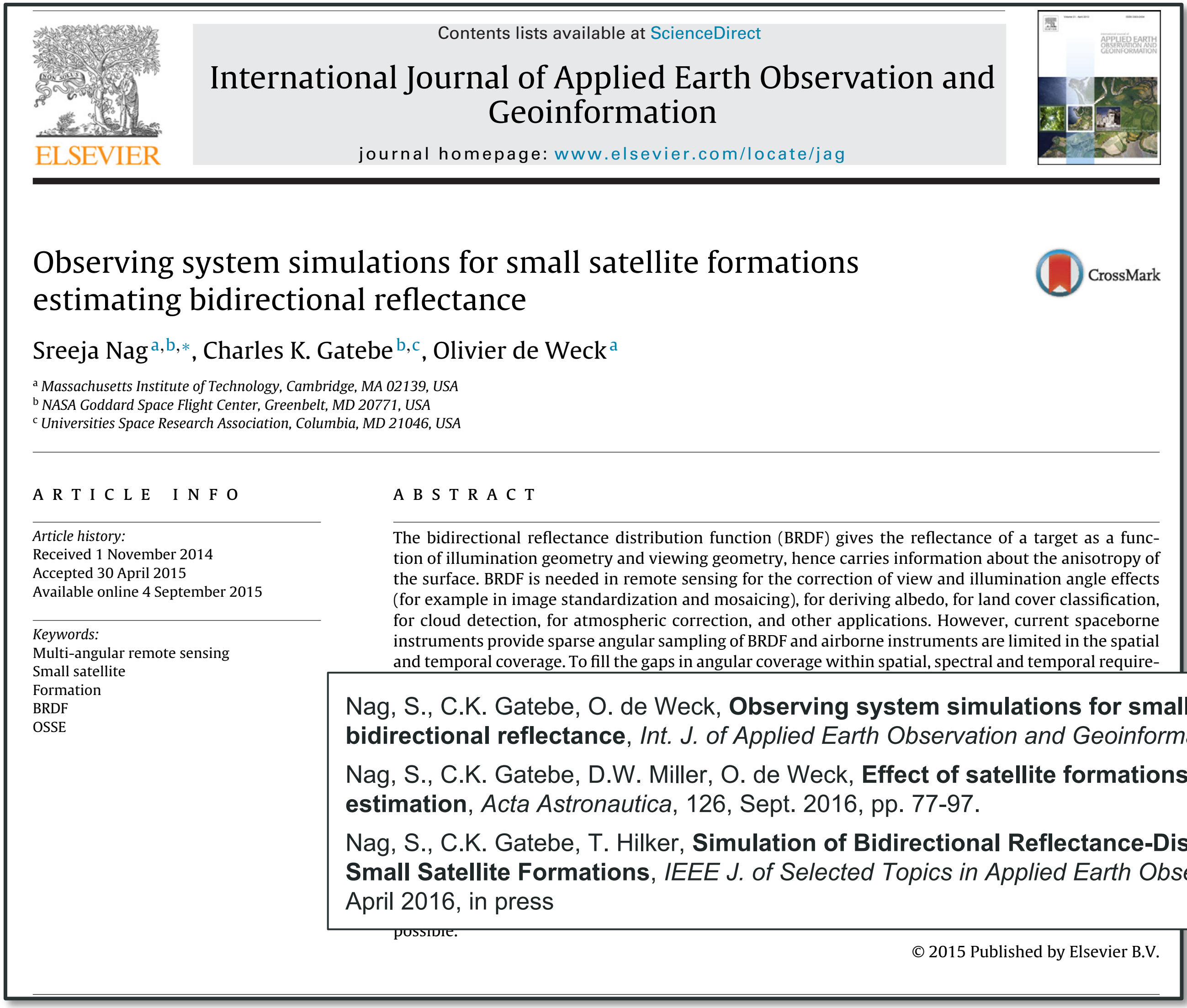
Multi-angle observations at Top of Atmosphere (TOA) *sample* the:

total Bidirectional Reflectance Distribution Function (BRDF)

Is this useful? Depends on nature of BRDF, and how it incorporates desired information



Conversion of Sreeja Nag's analysis for surface BRDF remote sensing to aerosol remote sensing



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Observing system simulations for small satellite formations estimating bidirectional reflectance

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ABSTRACT

The bidirectional reflectance distribution function (BRDF) gives the reflectance of a target as a function of illumination geometry and viewing geometry, hence carries information about the anisotropy of the surface. BRDF is needed in remote sensing for the correction of view and illumination angle effects (for example in image standardization and mosaicing), for deriving albedo, for land cover classification, for cloud detection, for atmospheric correction, and other applications. However, current spaceborne instruments provide sparse angular sampling of BRDF and airborne instruments are limited in the spatial and temporal coverage. To fill the gaps in angular coverage within spatial, spectral and temporal require-

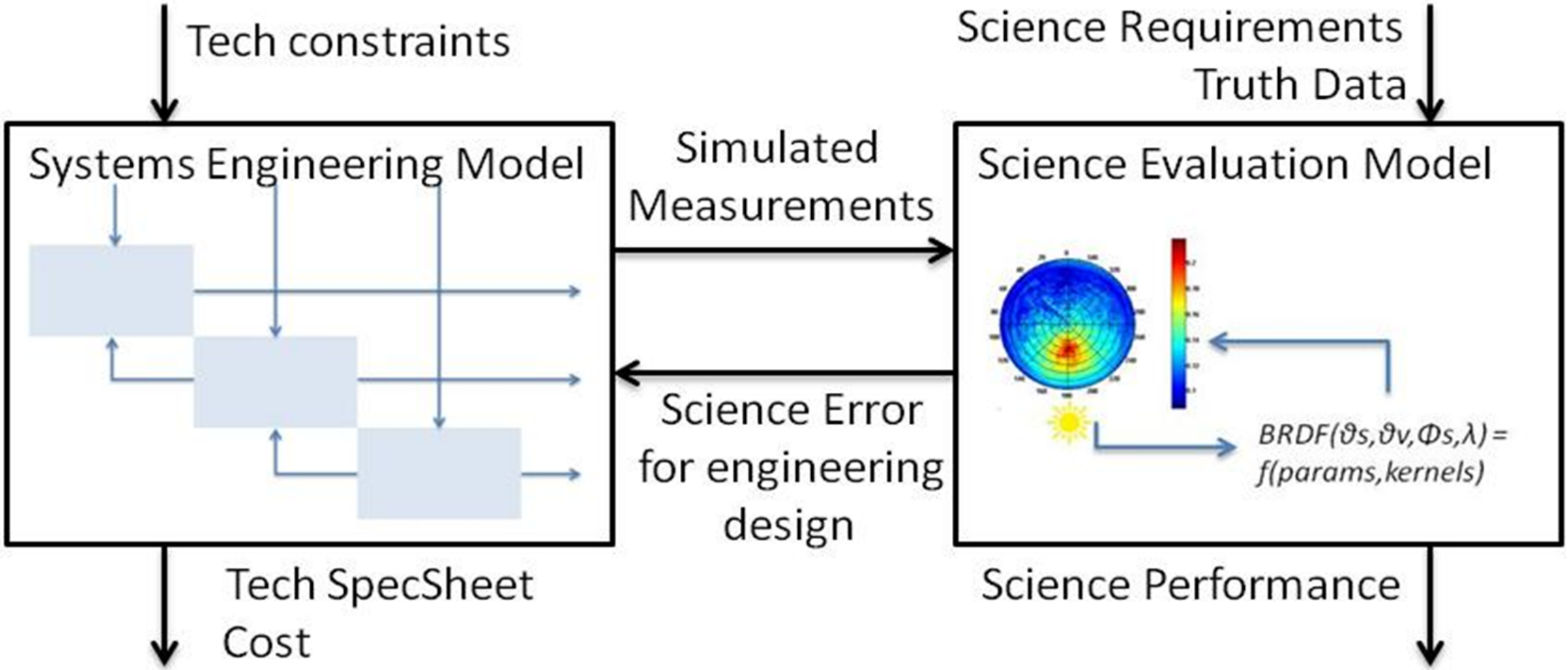
possible.

Nag, S., C.K. Gatebe, O. de Weck, **Observing system simulations for small satellite formations estimating bidirectional reflectance**, *Int. J. of Applied Earth Observation and Geoinformation*, 43, Dec. 2015, pp 102-118.

Nag, S., C.K. Gatebe, D.W. Miller, O. de Weck, **Effect of satellite formations and imaging modes on global albedo estimation**, *Acta Astronautica*, 126, Sept. 2016, pp. 77-97.

Nag, S., C.K. Gatebe, T. Hilker, **Simulation of Bidirectional Reflectance-Distribution Function Measurements using Small Satellite Formations**, *IEEE J. of Selected Topics in Applied Earth Observations and Remote Sensing*, accepted in April 2016, in press

Coupled Model Based Systems Engineering (MBSE) and Observing System Simulation Experiment (OSSE) tools



Tech constraints

Science Requirements
Truth Data

Systems Engineering Model

Simulated Measurements

Science Evaluation Model

Science Error for engineering design

$BRDF(\vartheta s,\vartheta v,\Phi s,\lambda) = f(params,kernels)$

Tech SpecSheet
Cost

Science Performance

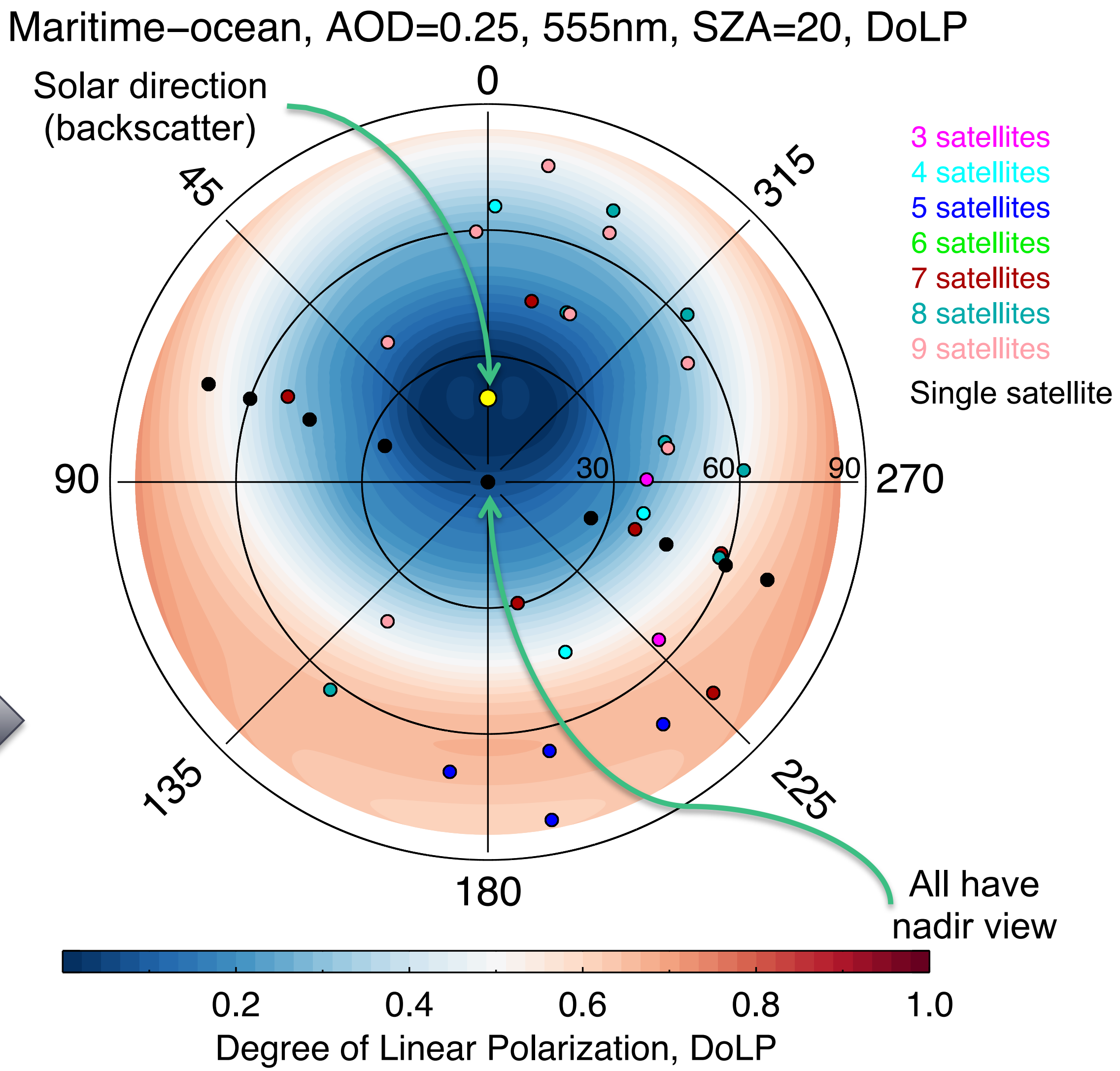
MBSE model predicted orbit geometries

MBSE model predicts 8 different configurations

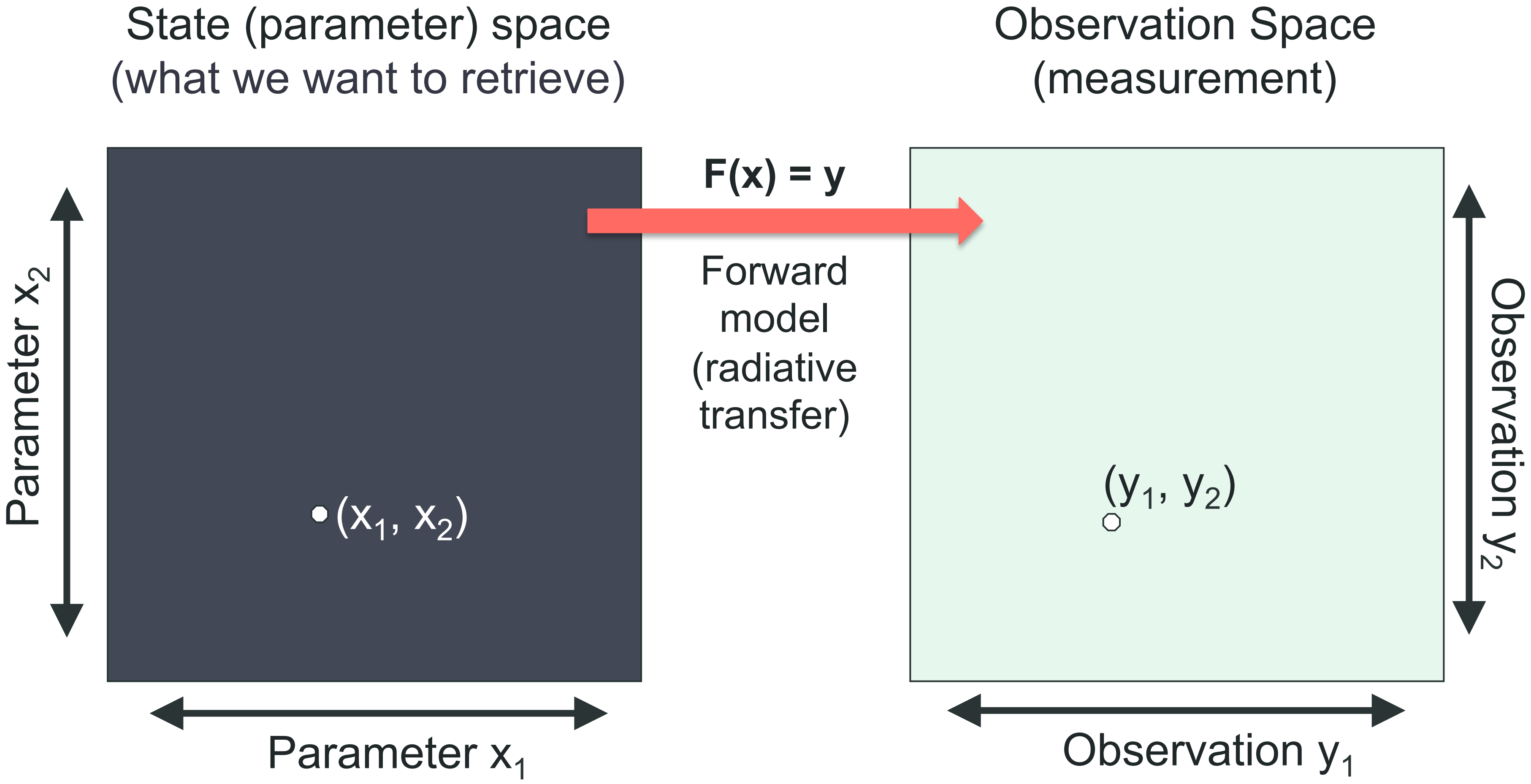
- 3 through 9 satellites flying in formation, tracking nadir observing satellite
- 9 view angle single satellite

Geometries for 100+ daytime observations

Example of a single observation



OSSE: information content assessment

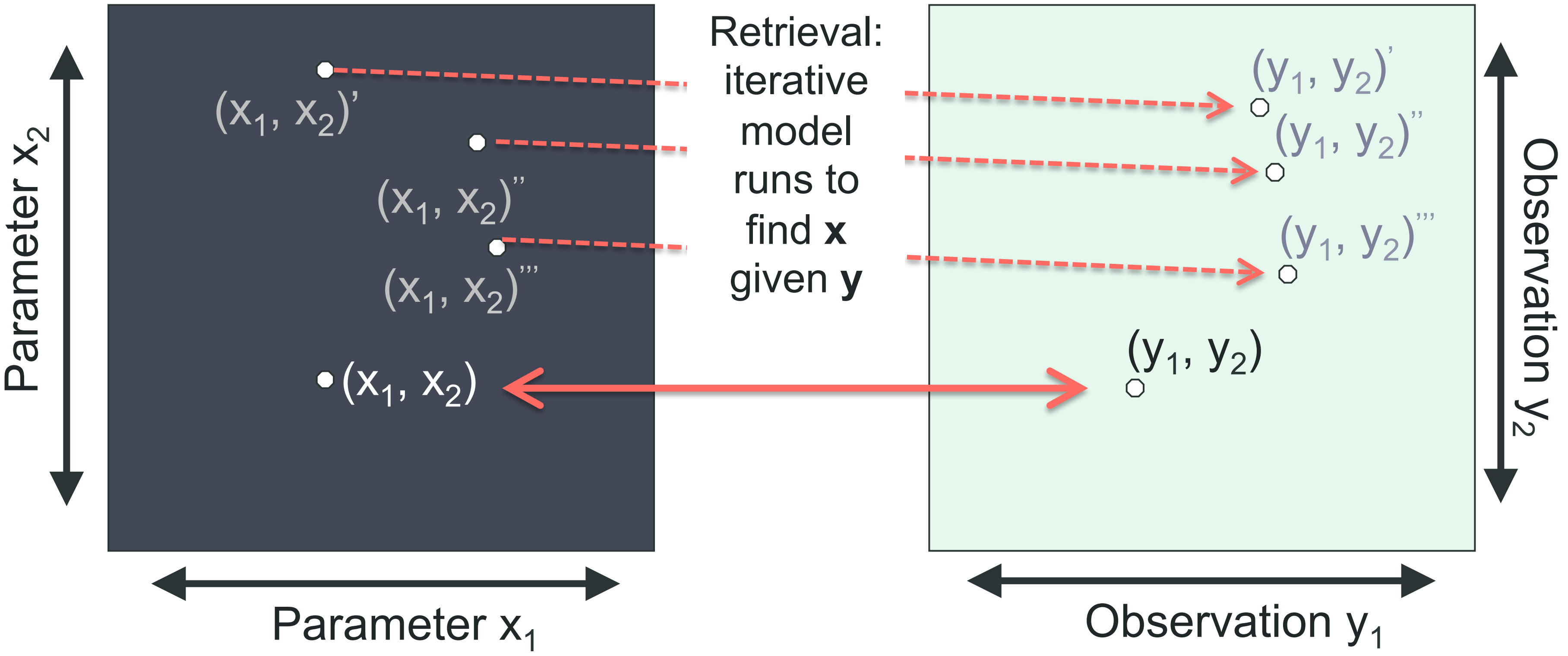


Knobelspiesse, K. et al. (2012) Analysis of fine-mode aerosol retrieval capabilities by different passive remote sensing instrument designs *Optics Express*, 20 (19).
Rodgers, C. D. (2000). Inverse Methods for Atmospheric Sounding: Theory and Practice, World Scientific, Singapore.

OSSE: information content assessment

State (parameter) space
(what we want to retrieve)

Observation Space
(measurement)



Retrieval: iterative model runs to find **x** given **y**

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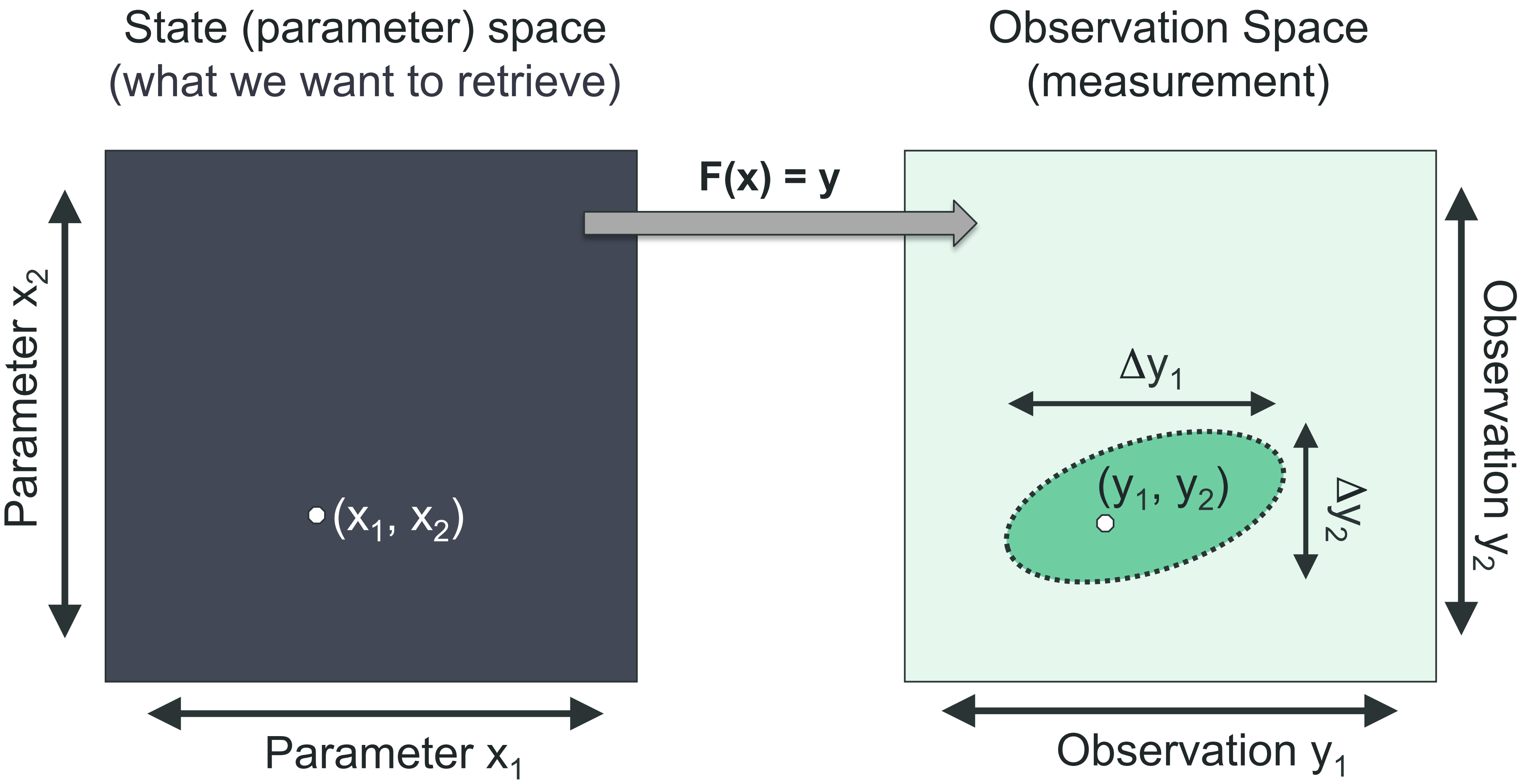

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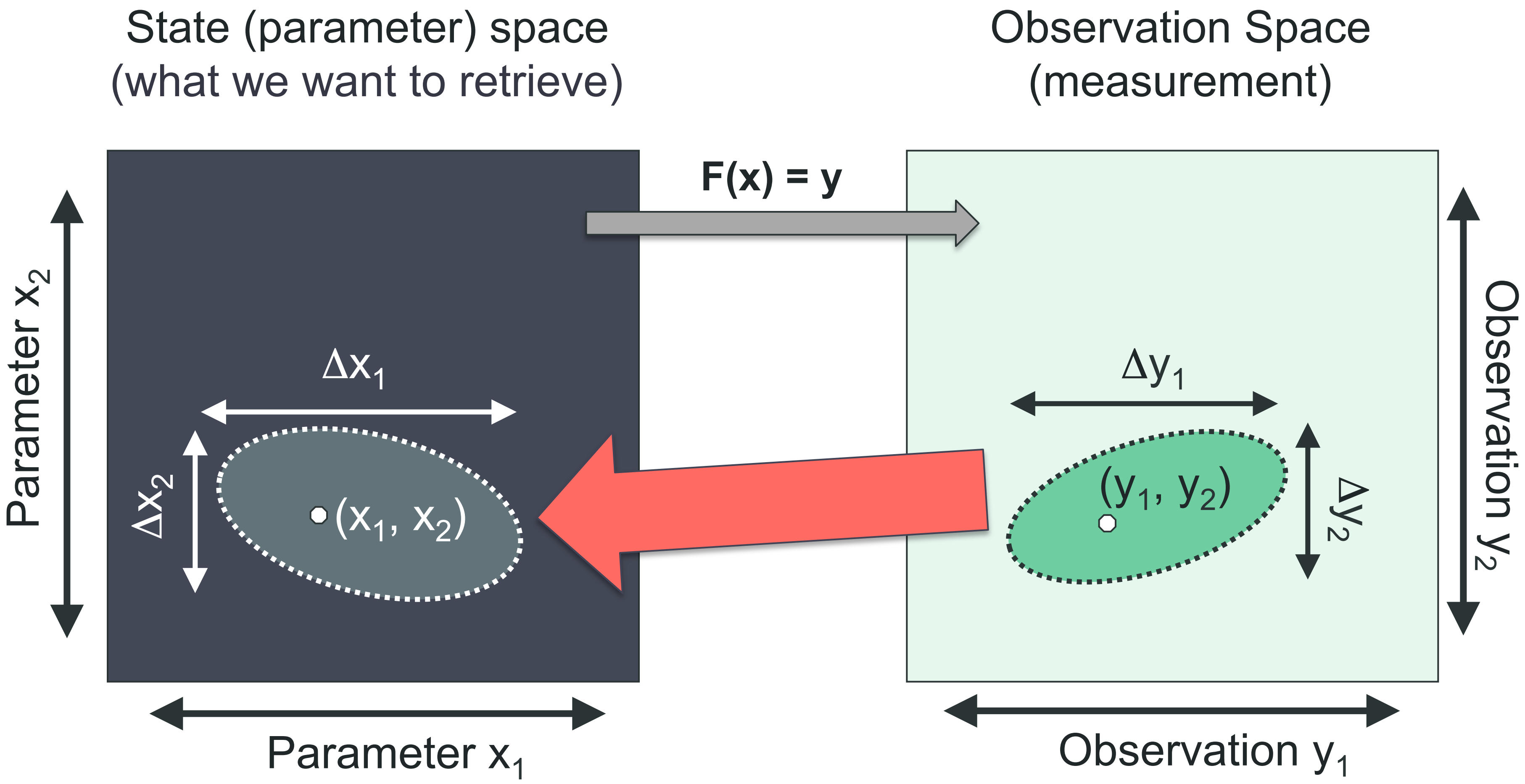

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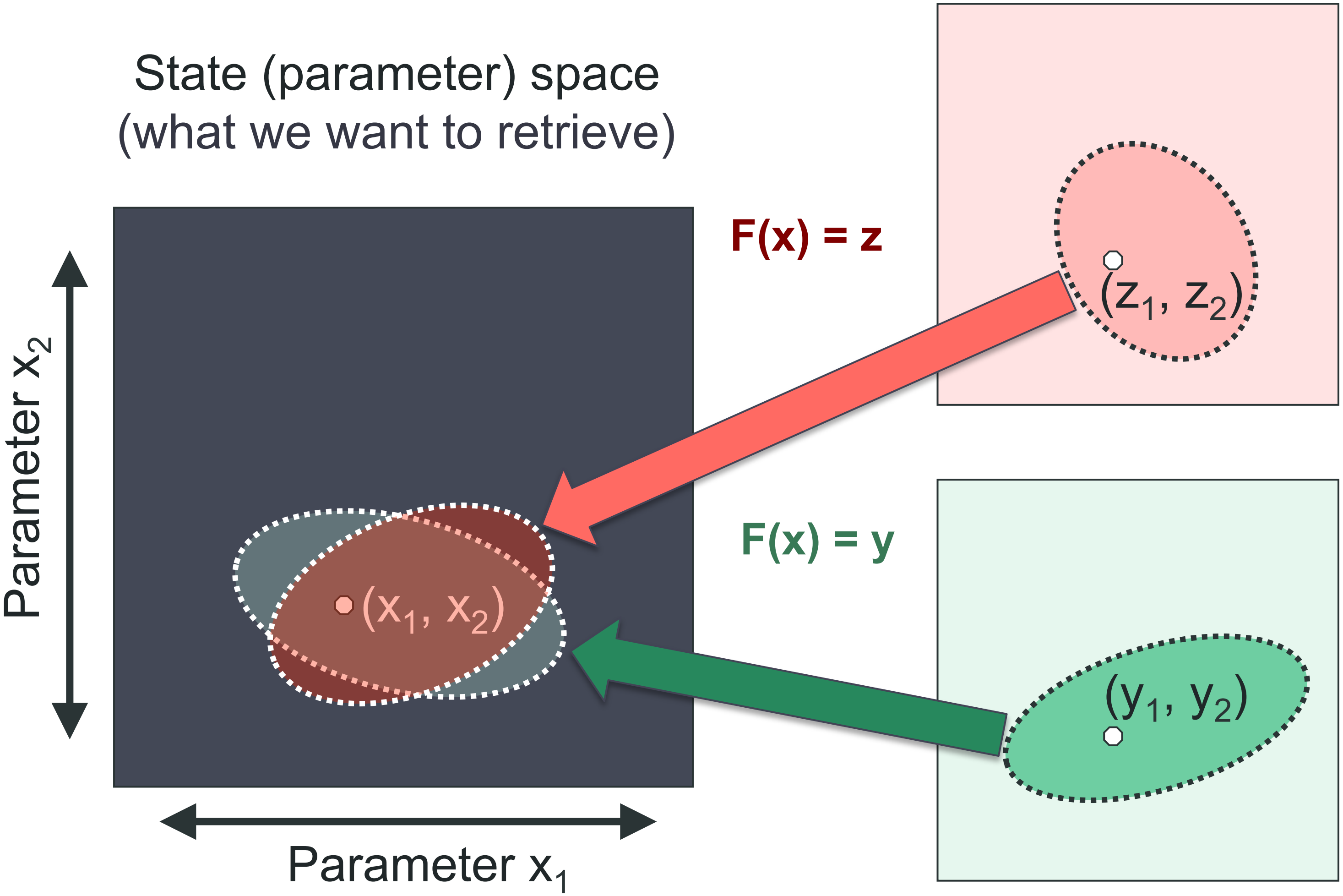

This formalism can be used to compare different types of observations

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OSSE: Information content assessment

Jacobian matrix: model calculated parameter sensitivity

$$K_{i,j} = \partial F_i(x) / \partial x_j$$

A priori matrix: parameter knowledge before observation

Measurement error covariance matrix: how we specify instrument characteristics

$$\hat{S} = \left[K^T S_\varepsilon^{-1} K + S_a^{-1} \right]^{-1}$$

Retrieval error covariance matrix: expected parameter uncertainty, overall metrics for info such as degrees of freedom

Degrees of Freedom (DoF) for signal

$$d_s = trace\left(\left[K^T S_\varepsilon^{-1} K + S_a^{-1} \right]^{-1} K^T S_\varepsilon^{-1} K \right)$$

> *"Essentially, all models are wrong, but some are useful"* – George Box

OSSE: Information content assessment

> *"Essentially, all models are wrong, but some are useful"* – George Box

Caveats

This method predicts retrieval uncertainty for a system with

- Perfect knowledge of observation uncertainty
- Perfect radiative transfer (forward) model
- Perfect ability to retrieve solution from observation

And we are far from perfect!

The results can be considered a '**best case scenario**'

Measurement system **can't do better than this** without adding information (such as constraints)

Considers an **unconstrained** retrieval over free parameters

This is a powerful technique for **relative** comparisons between measurement systems – assumptions are uniform

Simulation approach

Simulated instrument characteristics

Common to all

Wavelengths: **0.35**, **0.41**, **0.555**, **0.865**, **2.25** μm

Radiometric uncertainty: 3%, polarimetric uncertainty: 0.5%

Radiometers

- multi-angle (9) *vs.* distributed single view (3-9)

Polarimeters

- multi-angle (9) *vs.* distributed single view (3-9)

(16 observation systems in total)

Simulated scenes (based on AERONET, Dubovik et al 2002)

Maritime aerosol over an open ocean, AOT(555nm) **= 0.05, 0.15, 0.25**

Aerosol: Fraction of AOT(555nm) in fine mode: 36%

Refractive index: 1.37-i0.001

Fine size mode: r_{eff}=0.135µm, v_{eff}=0.193

Coarse size mode: r_{eff}=3.36µm, v_{eff}=0.704

Ocean: Cholorphyll-a = 0.03 mg/m3, Wind Speed = 8 m/s

6 retrieval parameters

Greenbelt aerosol over sparse vegetation, AOT(555nm) **= 0.05, 0.15, 0.25**

Aerosol: Fraction of AOT(555nm) in fine mode: 90%

Refractive index: 1.40-i0.003

Fine size mode: r_{eff}=0.170µm, v_{eff}=0.155

Coarse size mode: r_{eff}=5.52µm, v_{eff}=0.755

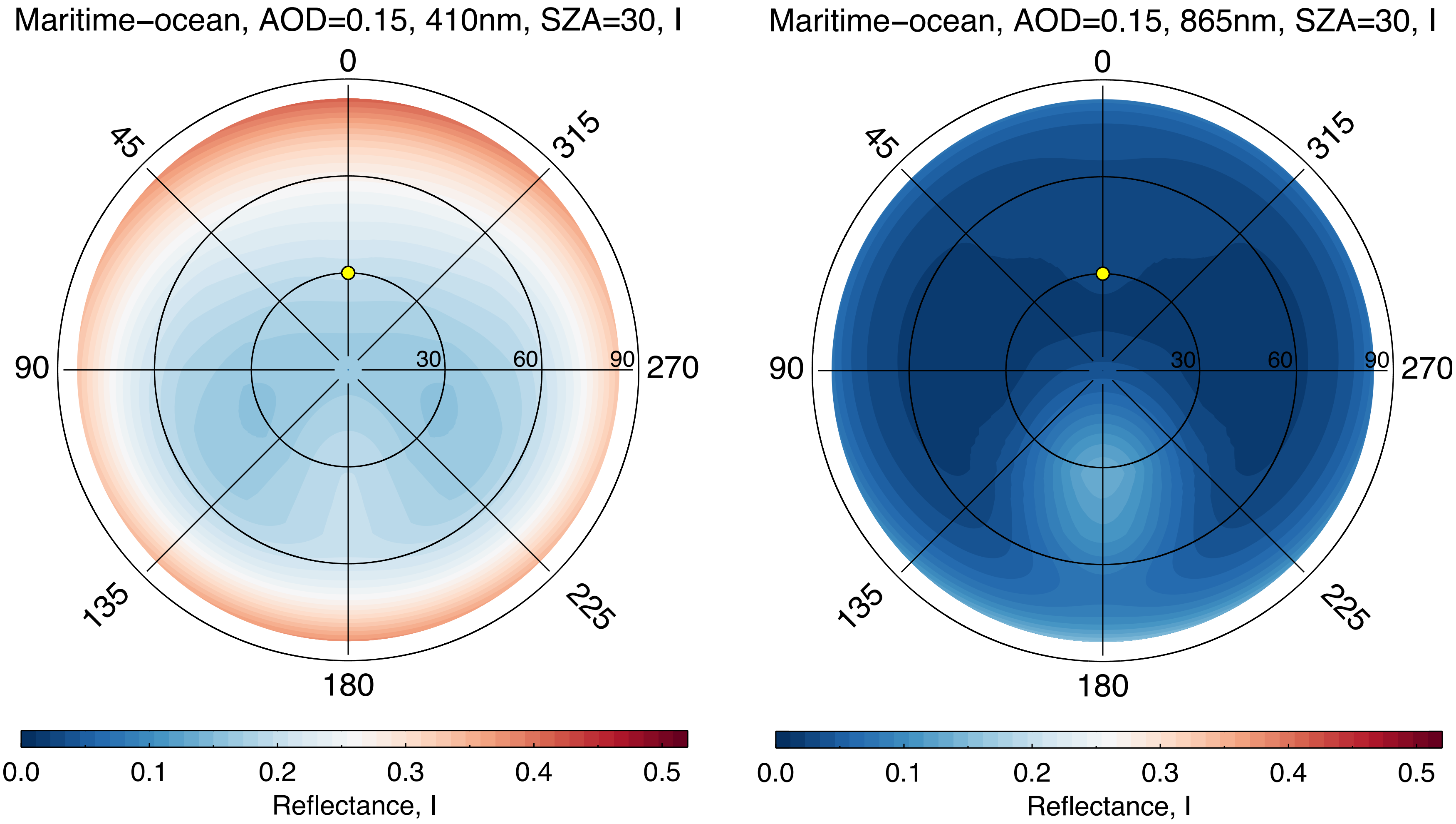
Ground: surface BRDF specified by 3 spectrally invariant kernels (fresnel, volumetric geometric) + spectrally varying isotropic values (5)

12 retrieval parameters

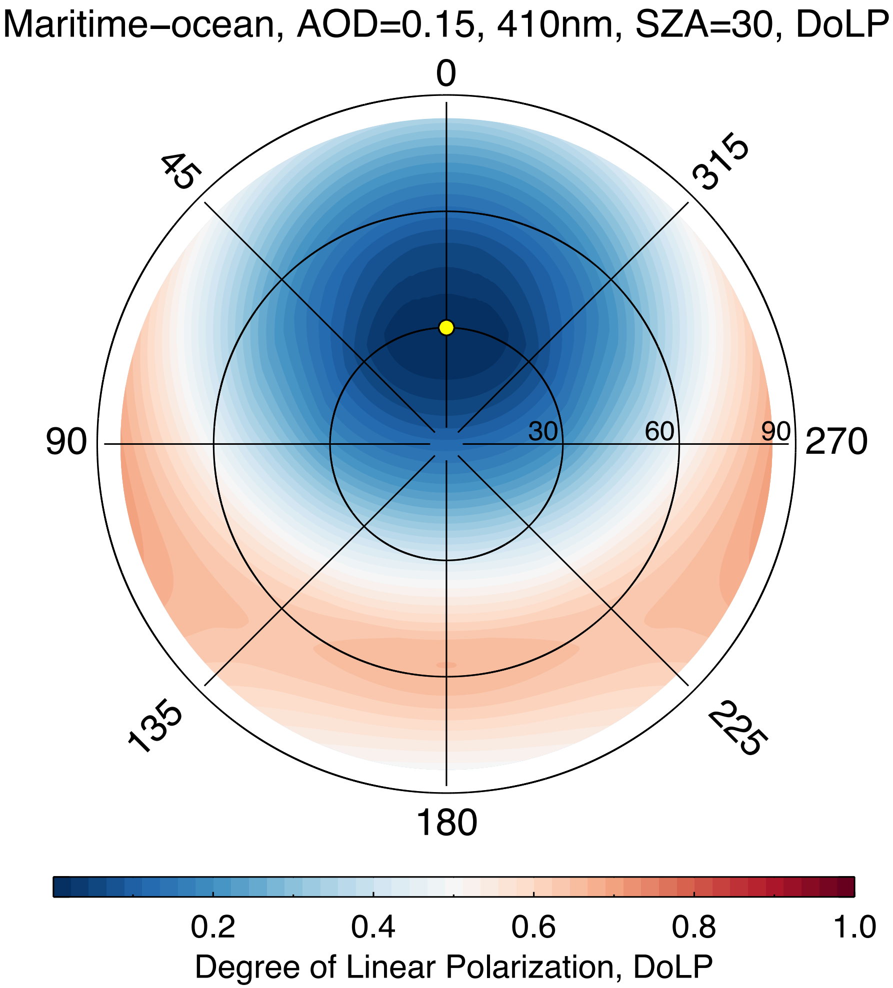
(6 scenes x 16 observation systems x 100+ geometries)

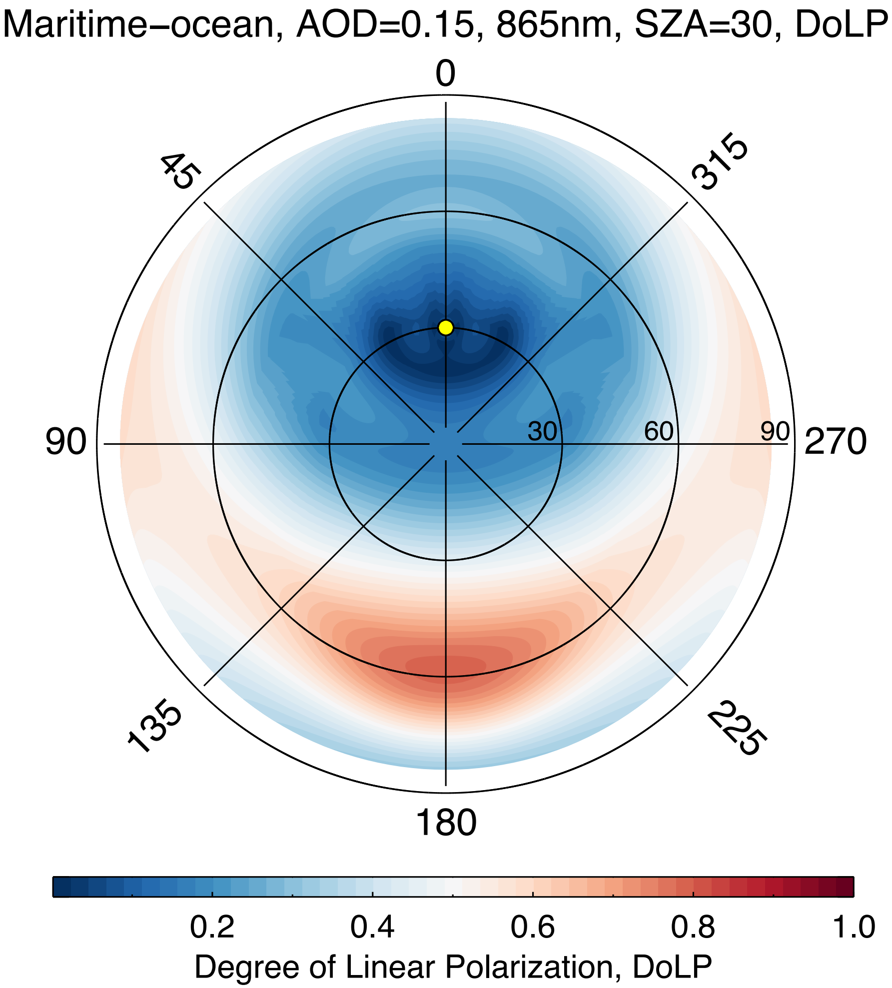
Simulation results

Maritime scene, AOT(555nm)=0.15, reflectance

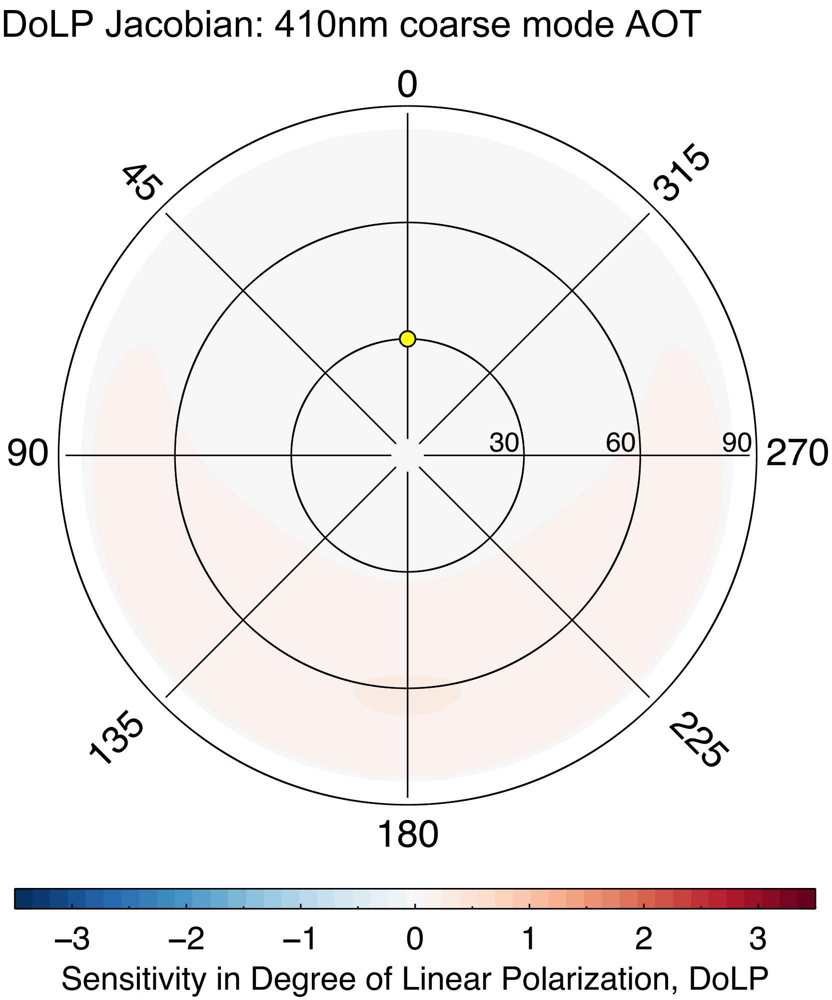


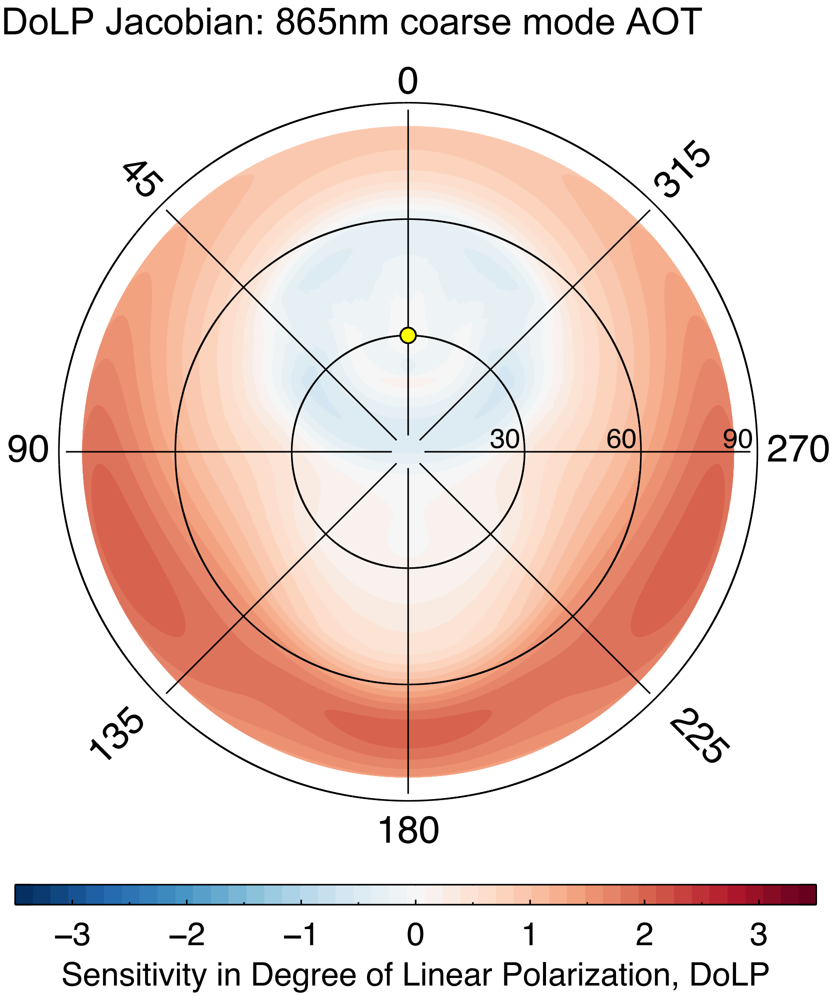
Maritime scene, AOT=0.15, Degree of Linear Polarization (DoLP)



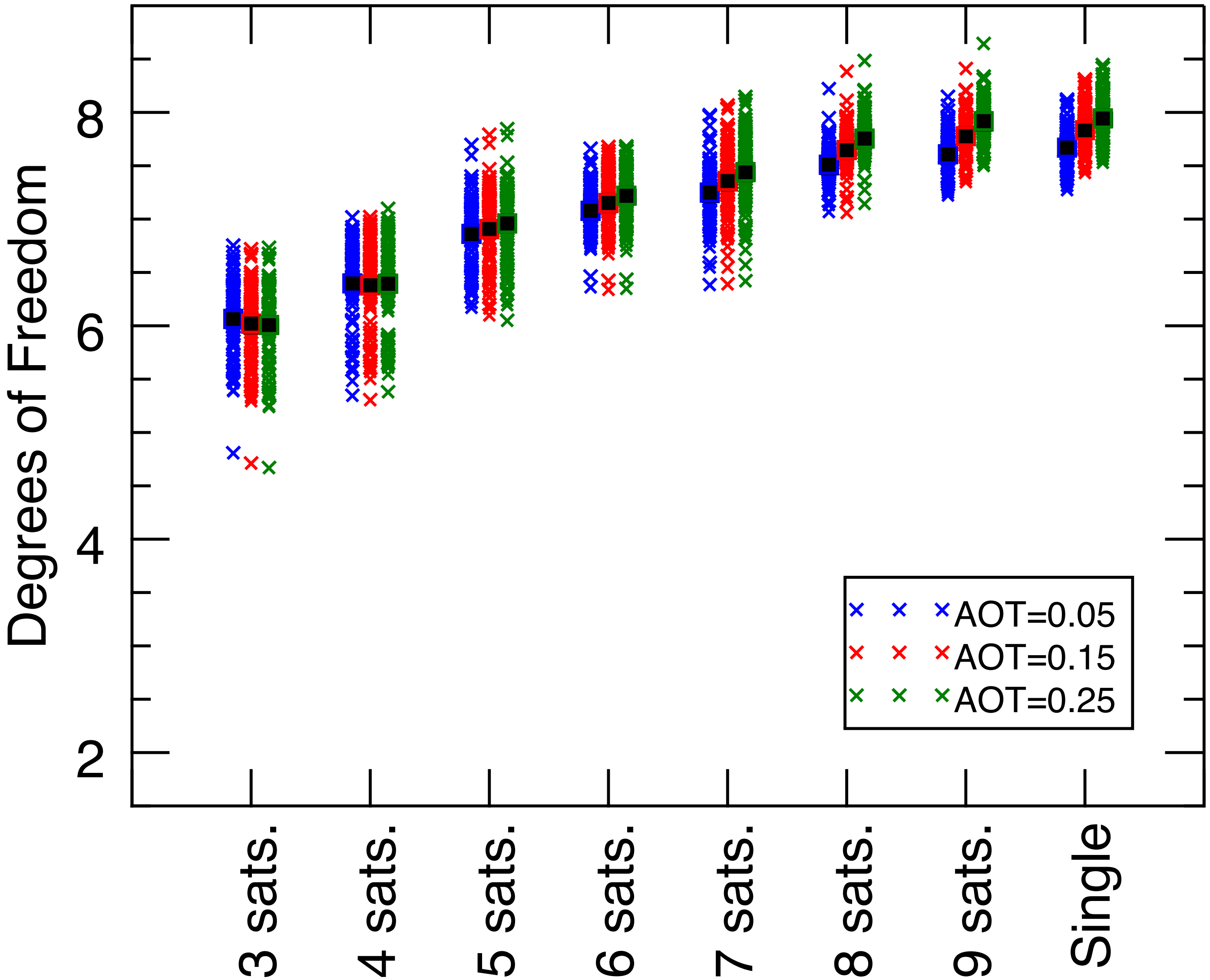


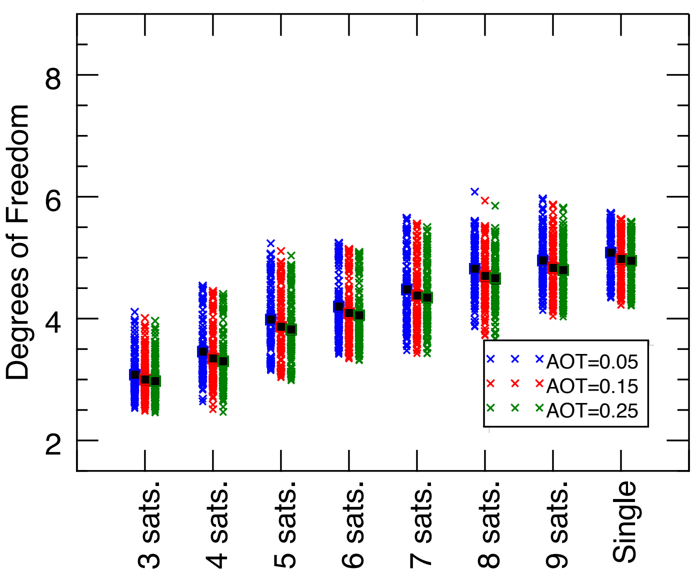
Maritime scene, AOT=0.15, Jacobian (DoLP)

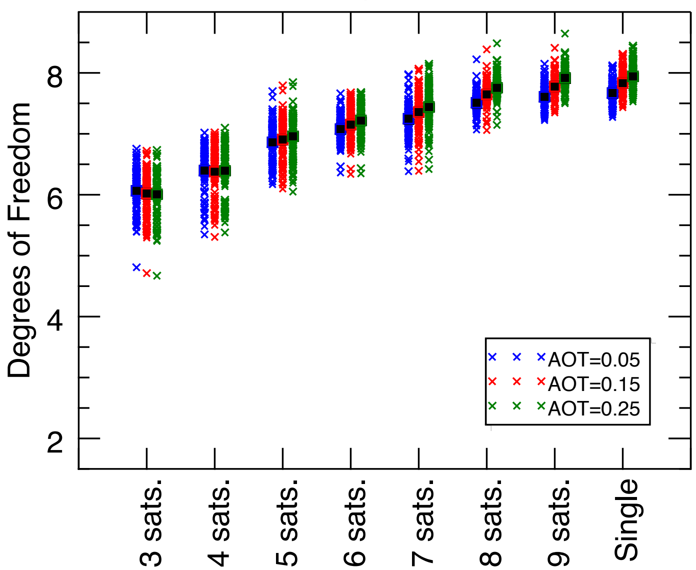


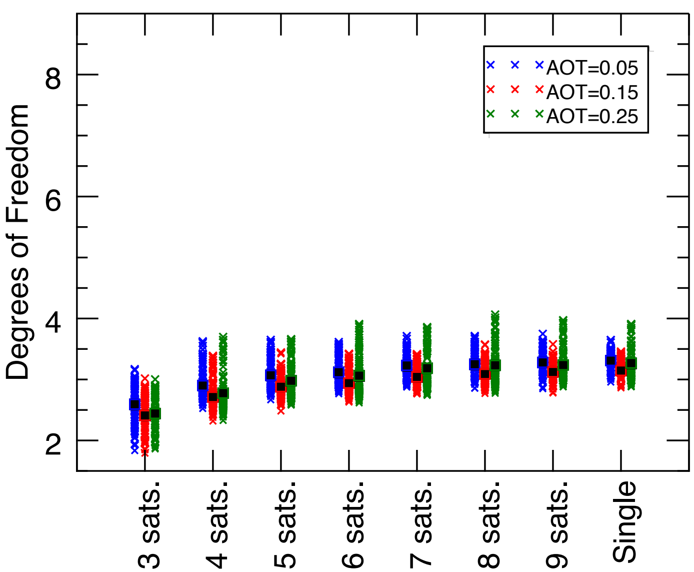


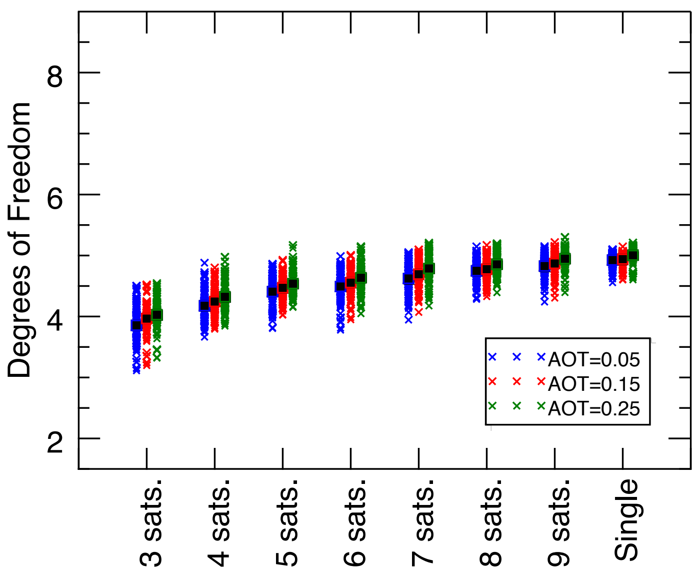
Degrees of freedom: aerosols over land, polarimeters



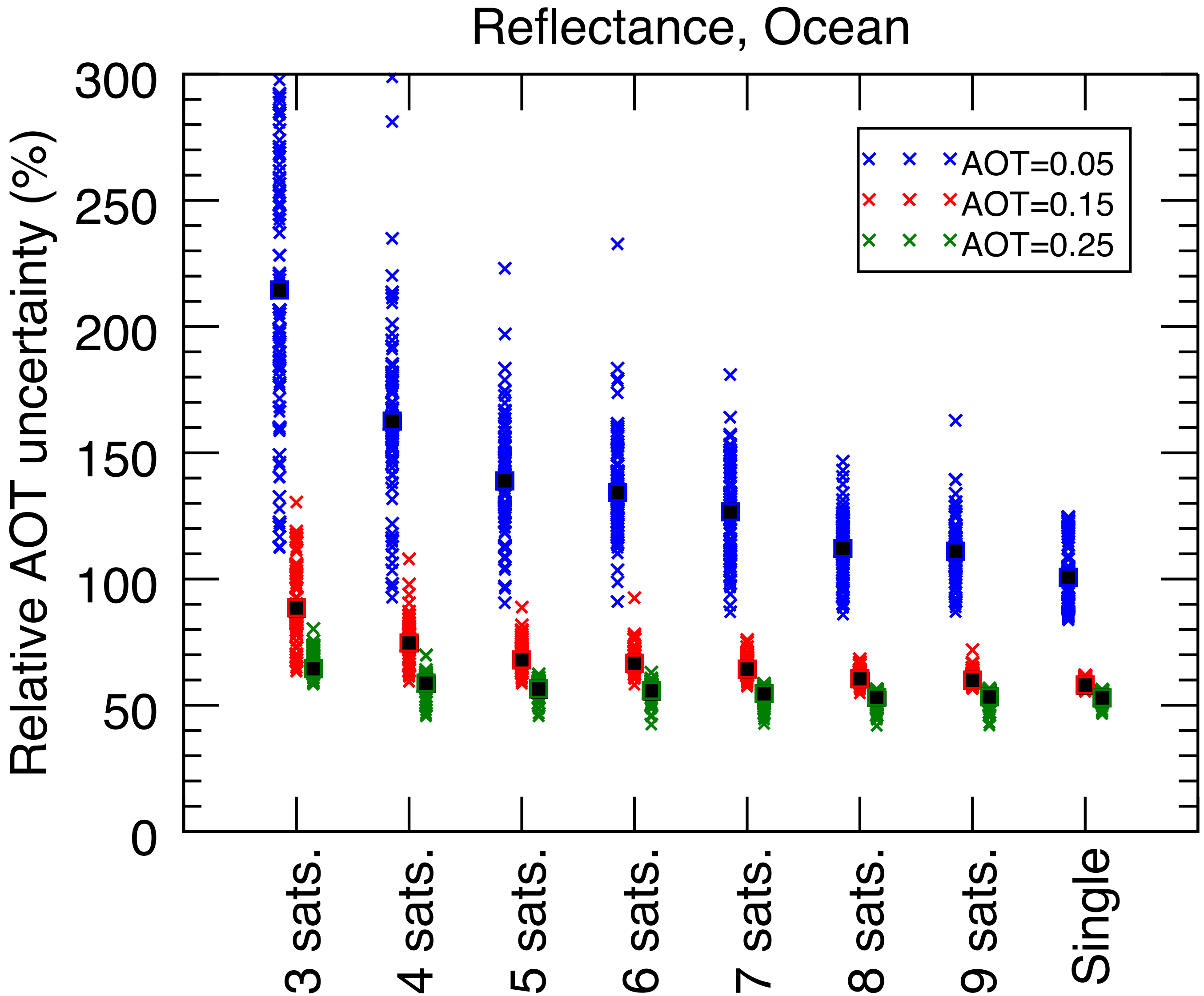

Reflectance, Land

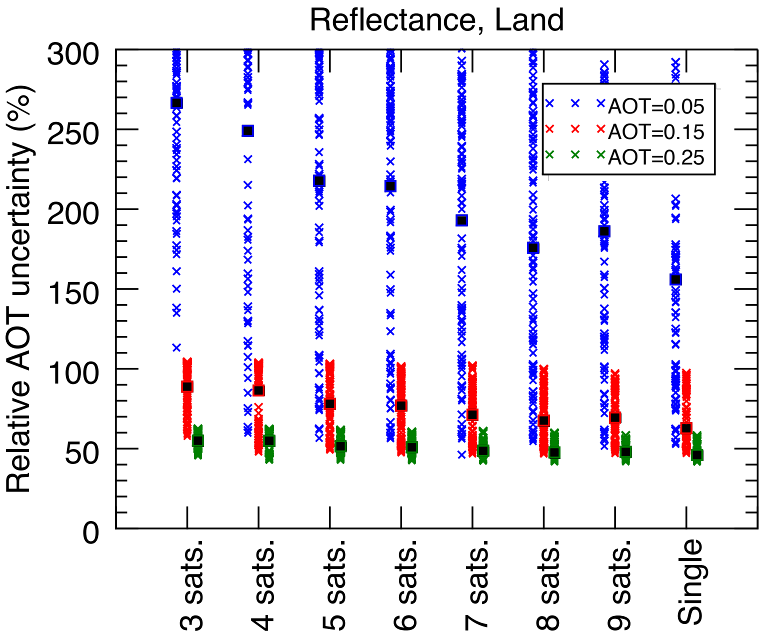

Reflectance + polarization, Land


Reflectance, Ocean


Reflectance + polarization, Ocean

Aerosol Optical Thickness results, reflectance only





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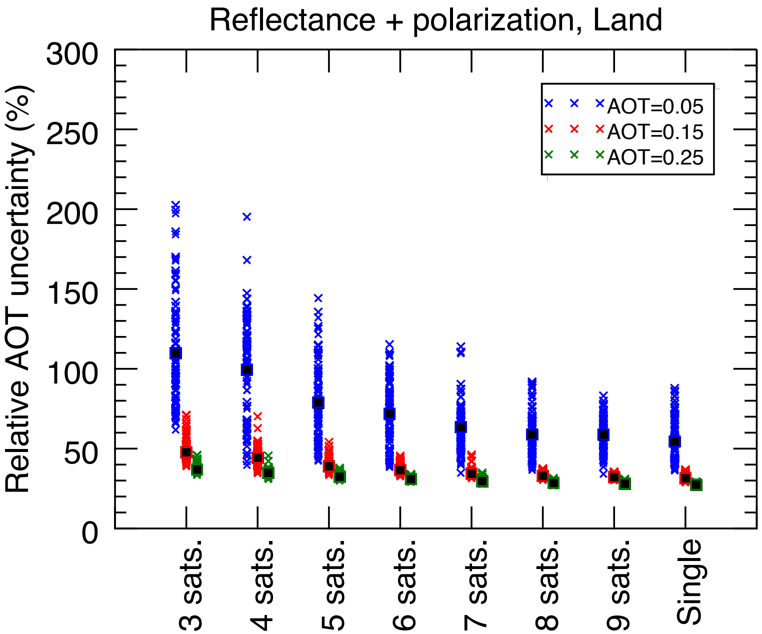
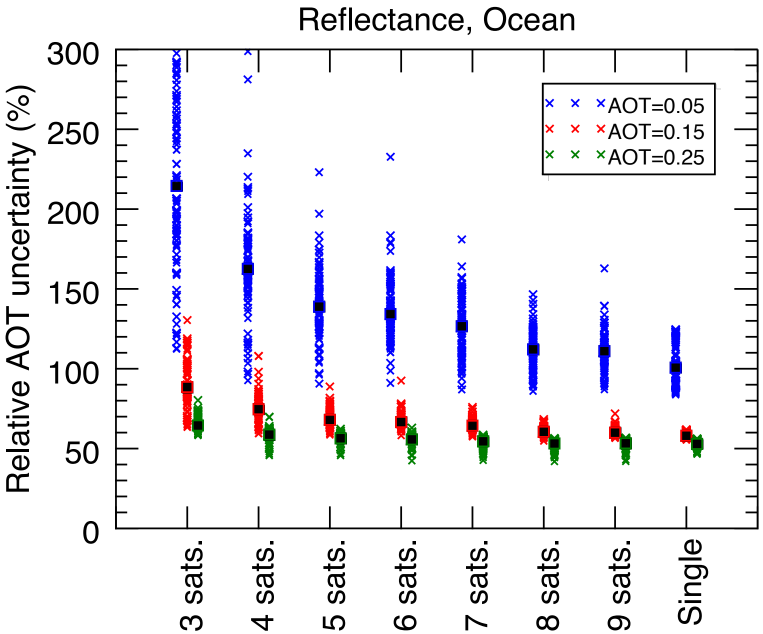


Reflectance + polarization, Land



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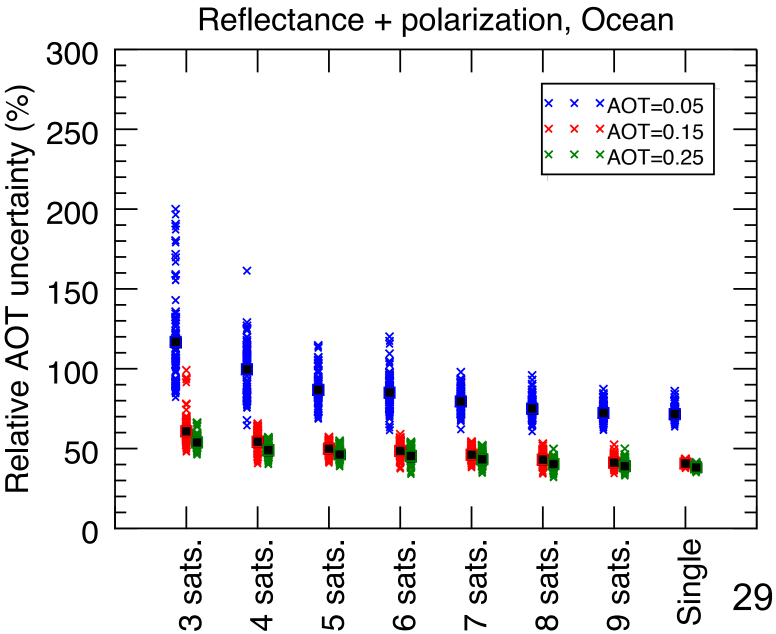
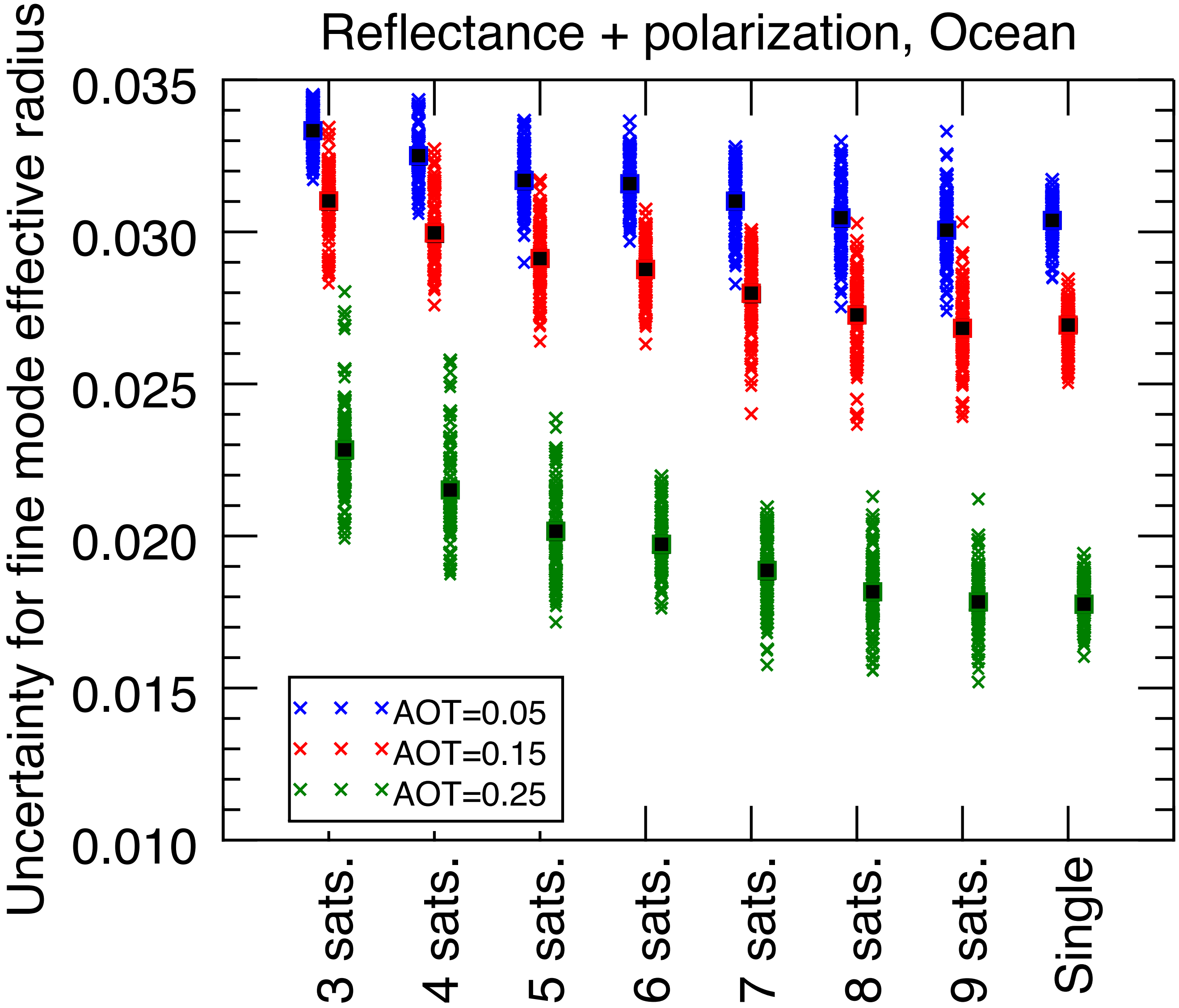
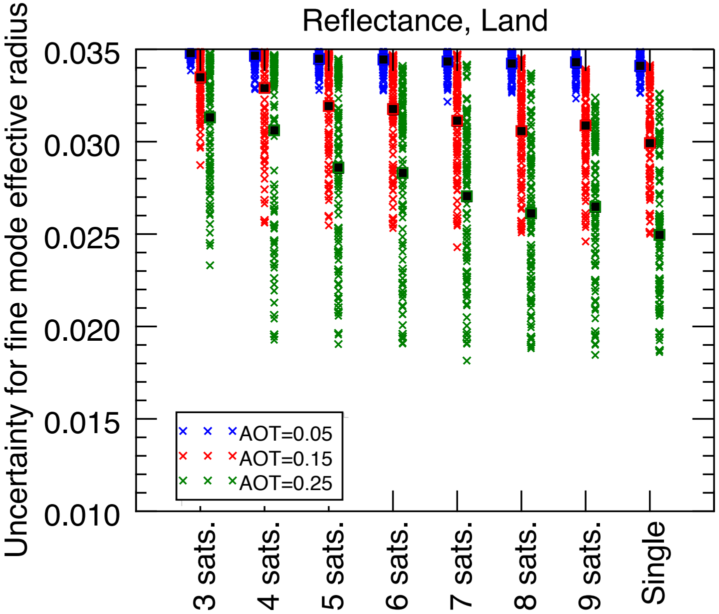
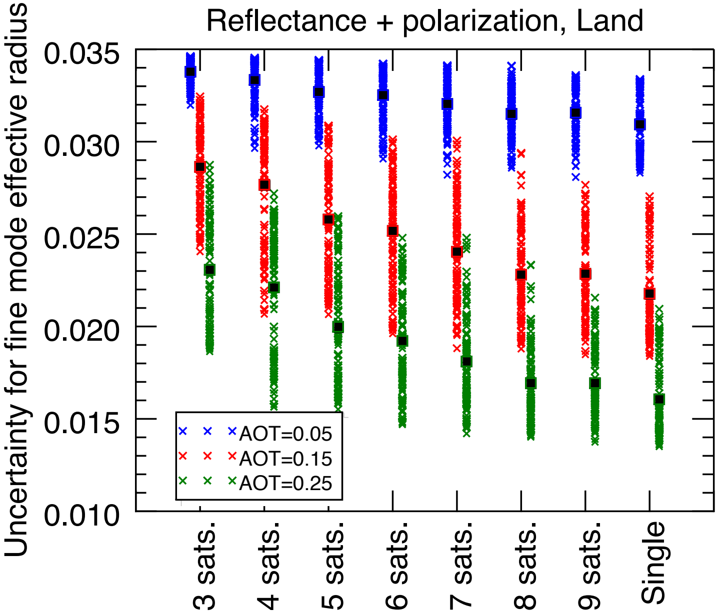


Reflectance + polarization, Ocean

Fine mode effective radius




Reflectance, Land
Uncertainty for fine mode effective radius
0.035
0.030
0.025
0.020
0.015
0.010
3 sats.
4 sats.
5 sats.
6 sats.
7 sats.
8 sats.
9 sats.
Single
AOT=0.05
AOT=0.15
AOT=0.25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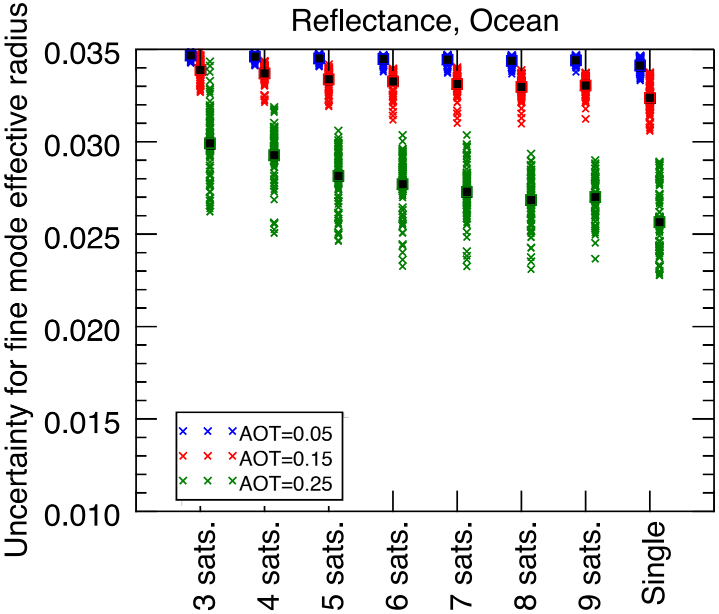
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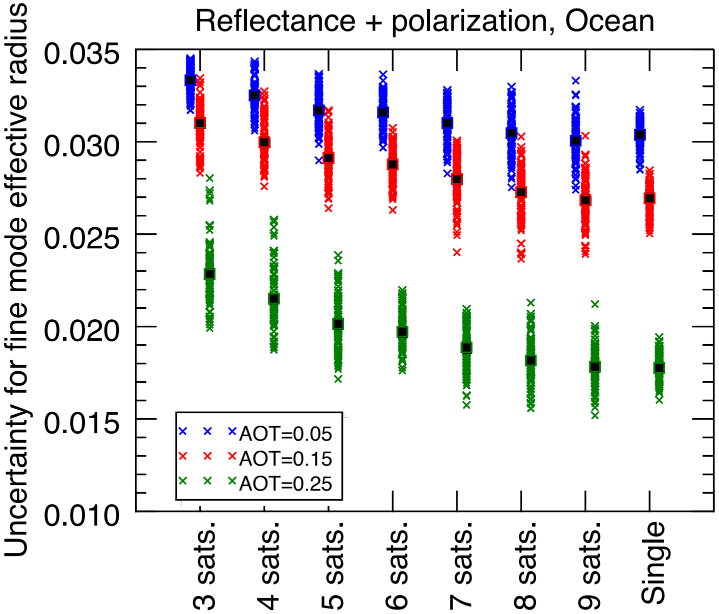
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Single
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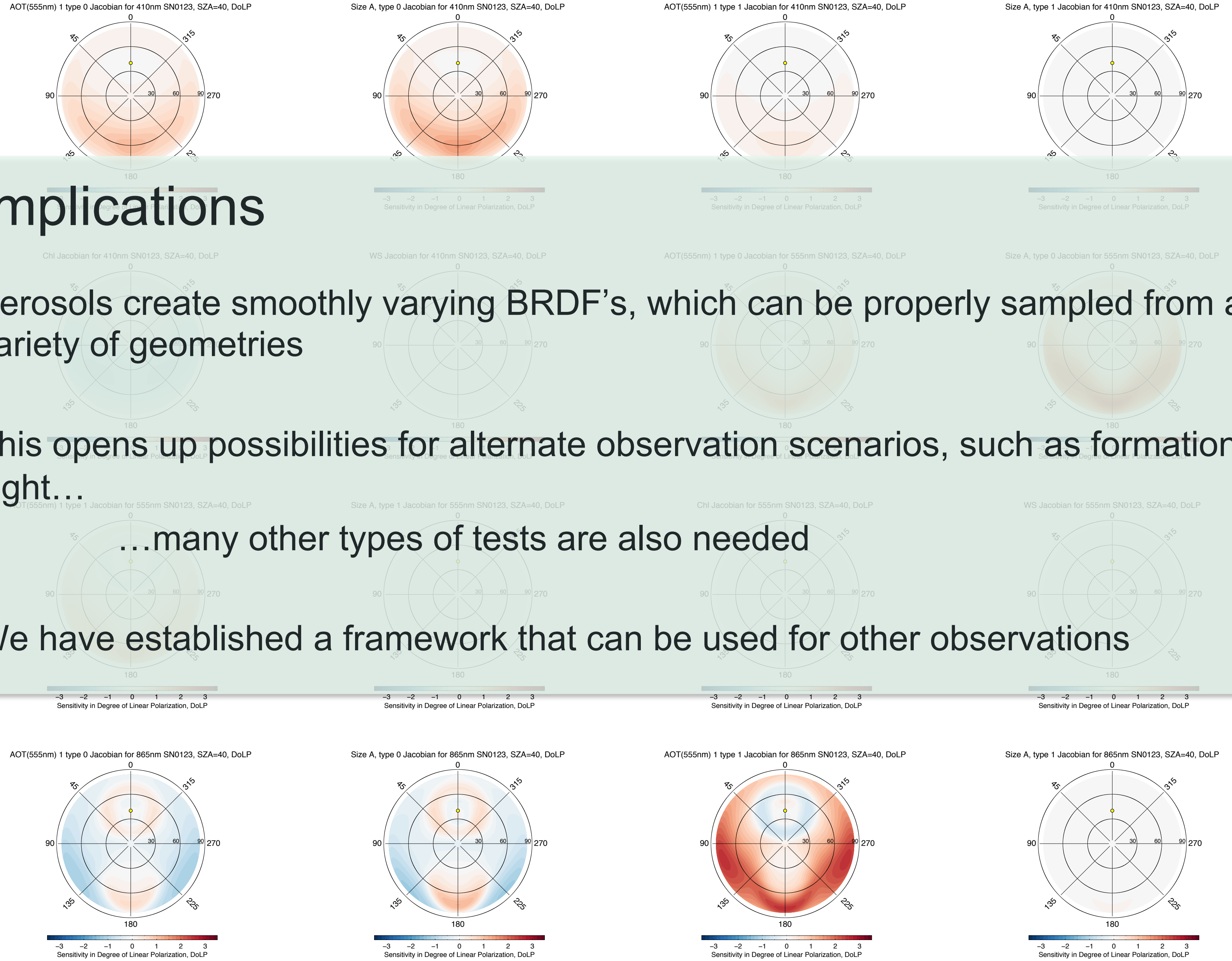
AOT=0.25

Conclusions

Obviously, more angles means more DoF, lower parameter uncertainty

- 9 satellites in formation ≈ 9 views on a single satellite
- Improvements are gradual – loss of single observation is not catastrophic
- At some point, additional views don’t improve AOT, but they do for other parameters
- Quantity of aerosols (AOT) controls ability to retrieve properties



Implications

Aerosols create smoothly varying BRDF’s, which can be properly sampled from a variety of geometries

This opens up possibilities for alternate observation scenarios, such as formation flight…

…many other types of tests are also needed

We have established a framework that can be used for other observations