Design of Nano-Satellite Cluster Formations for Bi-Directional Reflectance Distribution Function Estimations

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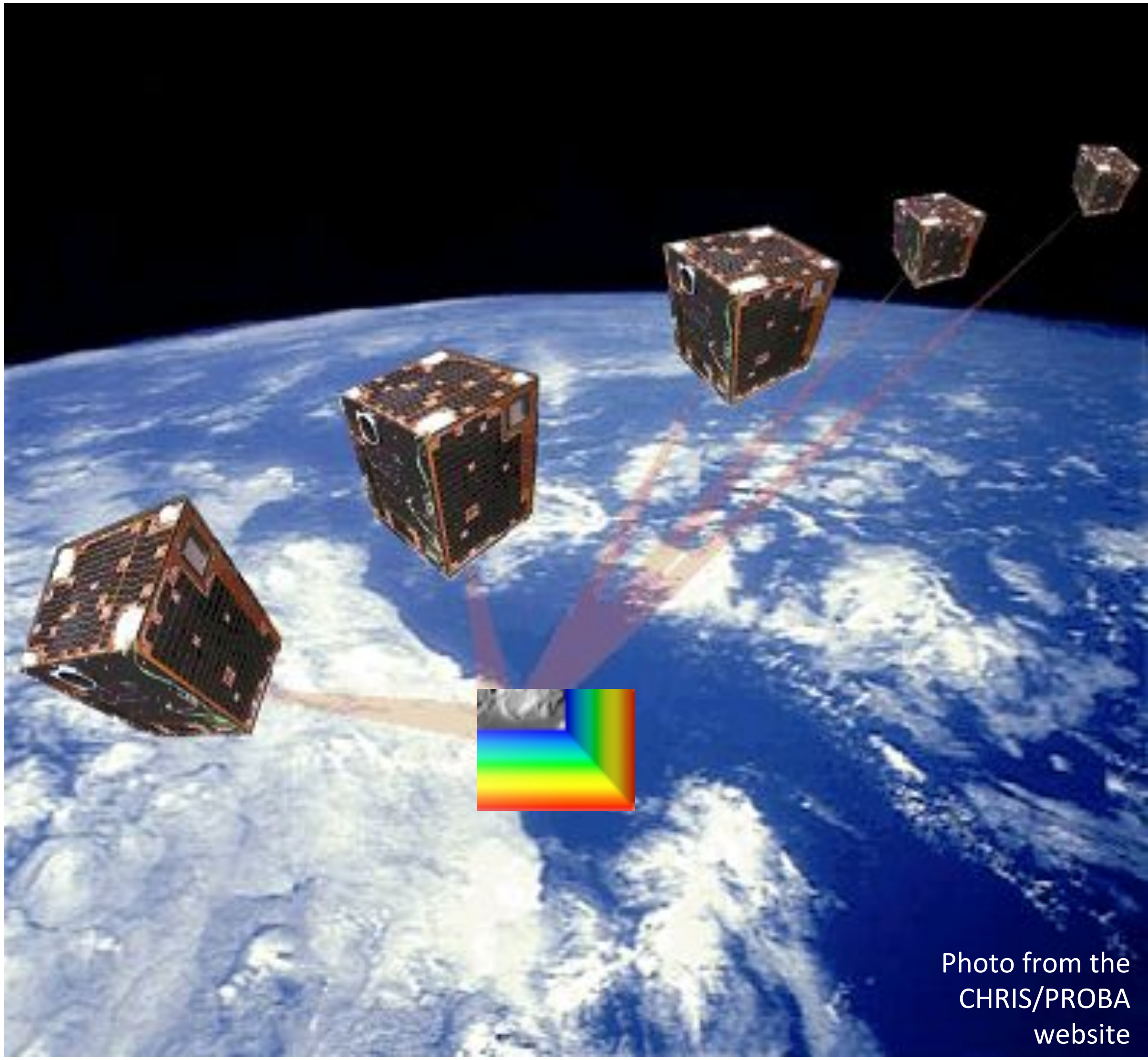
August 14, 2013

Introduction

Bi-Directional Reflectance Function (BRDF) Estimations

falls under the broad topic of

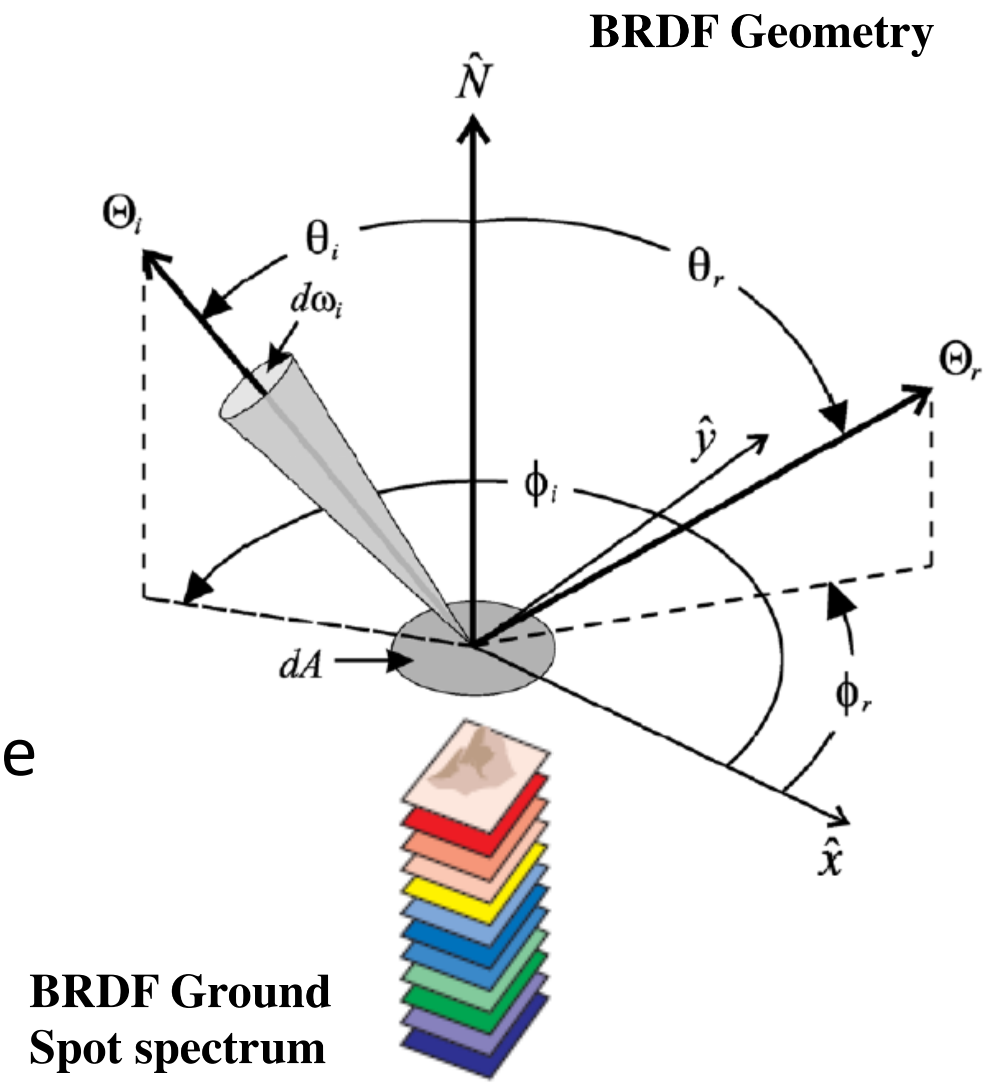
<u>Multi-Angular</u>, <u>Multi-Spectral</u> Remote Sensing of the Earth



Background

BRDF Definition

- Bi-directional reflectance distribution function
- Anisotropic (angle-dependent) and multispectral (near-solar spectrum) reflectance of clouds and ground surface
- R (Θi, Θr, ϕi, ϕr, λ)

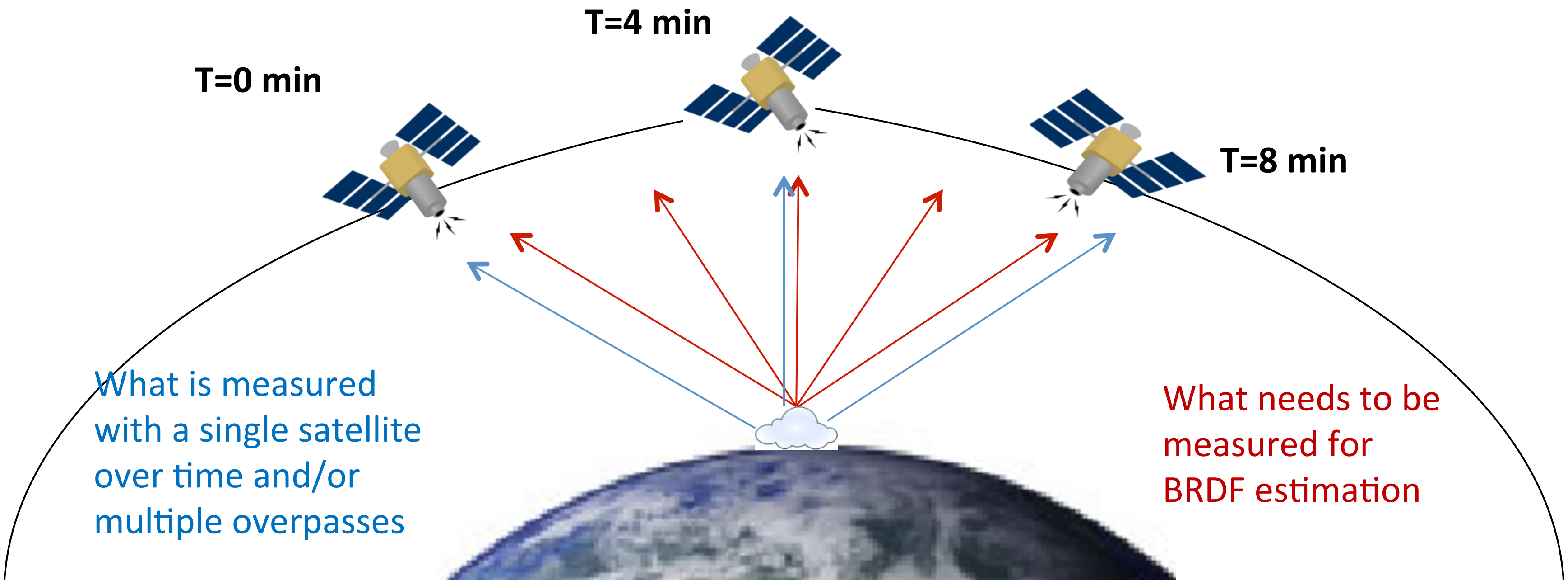


Angular Challenge

BRDF Estimation by combining the consecutive measurements

Problem: 1. Restrictive plane with respect to the sun

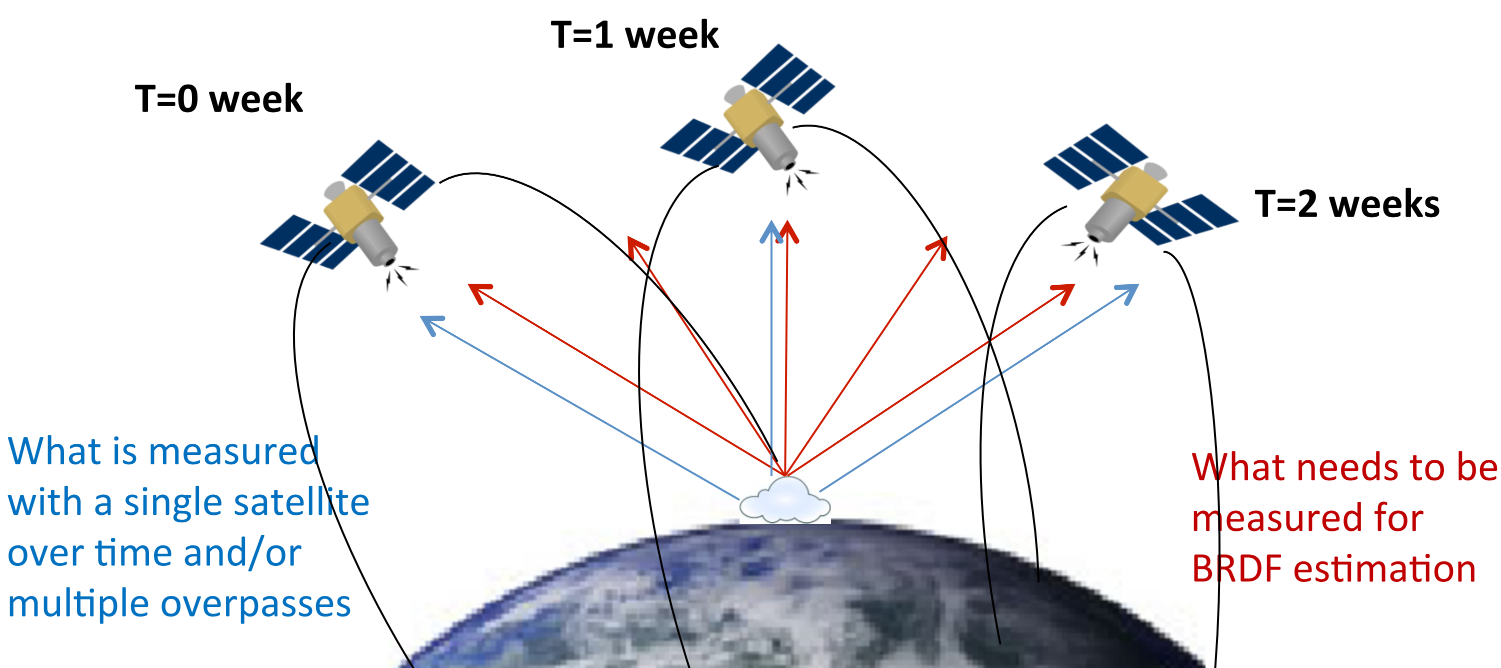
2. Up to 10 minutes between measurements



Angular Challenge

BRDF Estimation by combining measurements over consecutive overpasses

Problem: 1. Restrictive plane with respect to the sun
2. Up 2 weeks between measurements



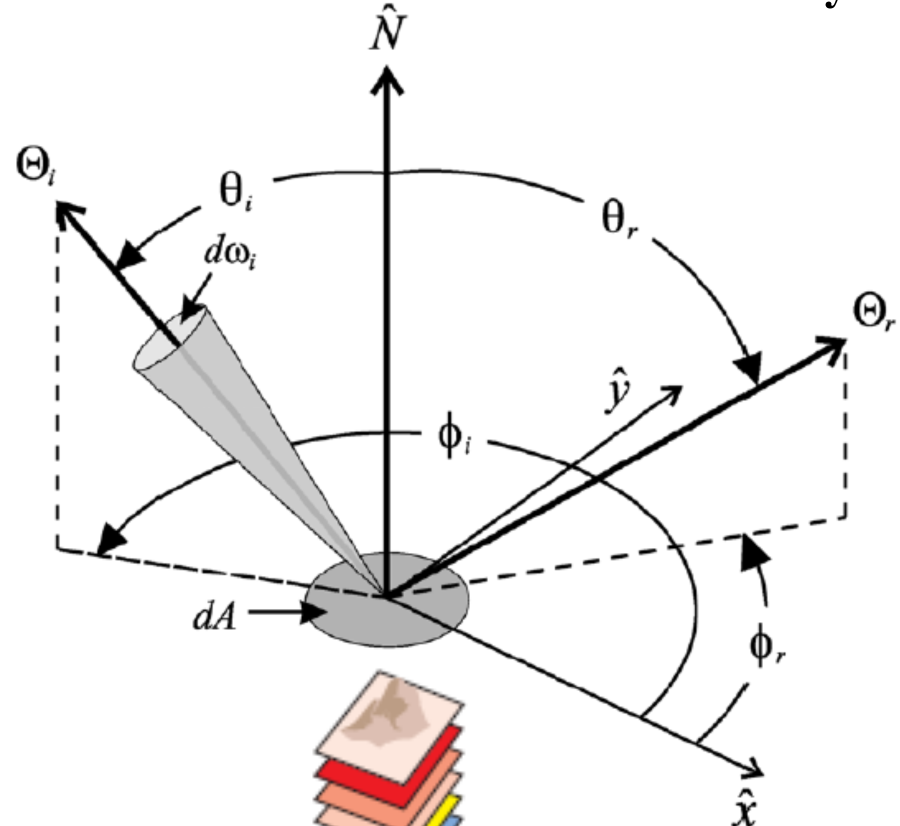
BRDF Importance

Theoretical function, very important applications

Mentioned in many science and policy docs

- *"Responding to the challenge of Climate and Environmental Change";"enhance understanding of the role of CO2 in the global carbon cycle" –* ***NAS Decadal Survey 2007***
- *"To provide data on variables (surface BRDF and albedo) that have wide application… (especially those) designed primarily for cloud and aerosol studies" -* ***Ecosystems Structure and Biomass panel on Multi Angle Remote Sensing***

BRDF Geometry



BRDF Ground Spot spectrum

BRDF Importance

BRDF effects on important applications such as **albedo** radiative forcing, gross primary productivity is stark

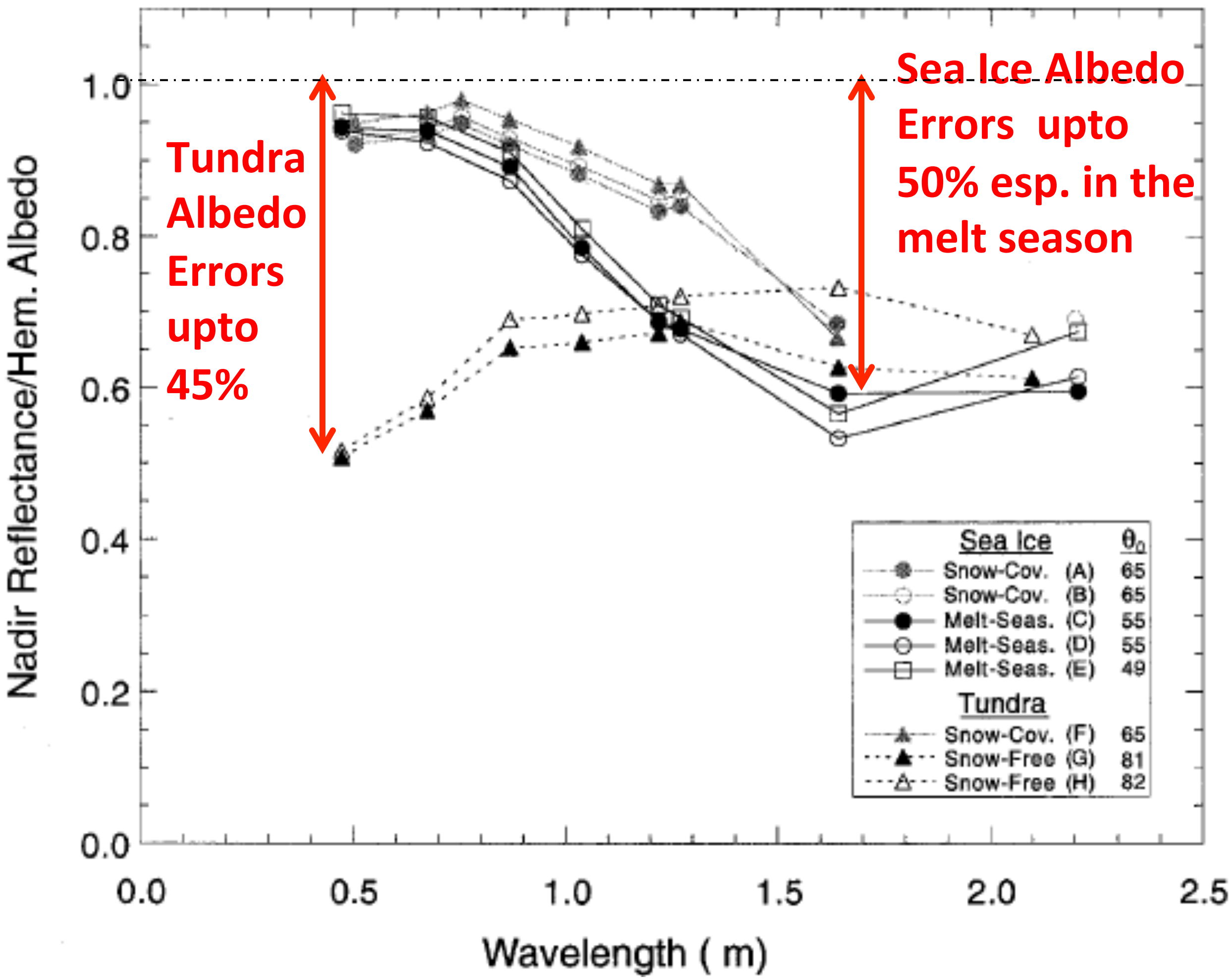


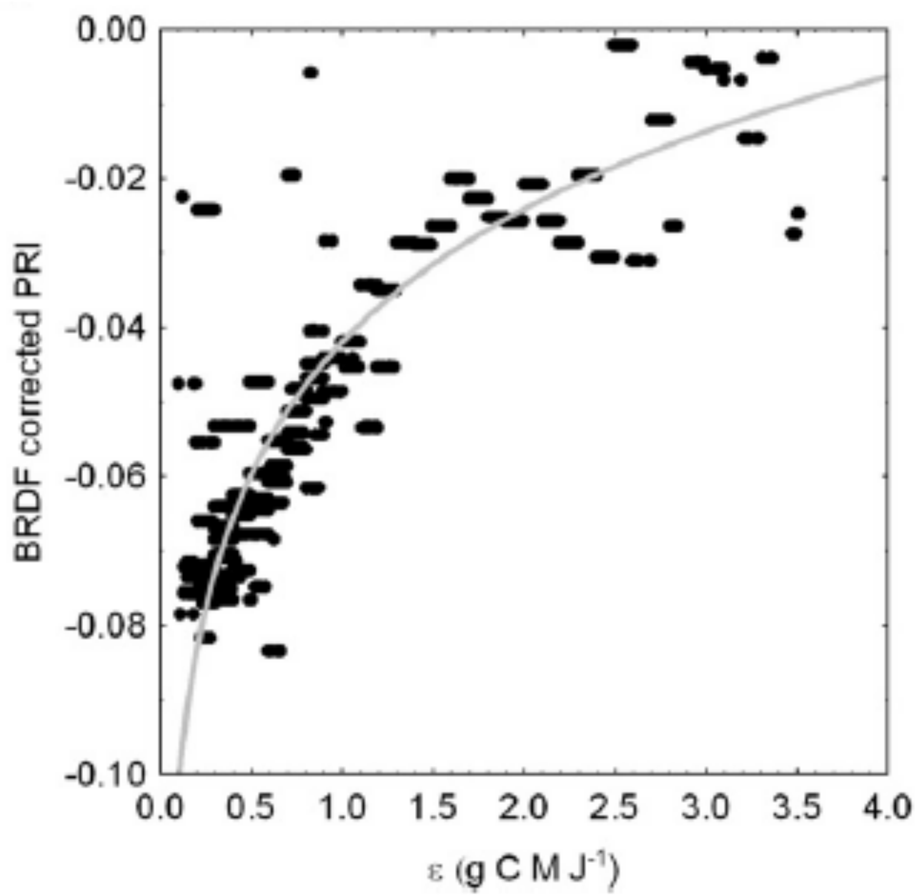
Image Credits: Arnold et. al, 2002

Figure uses thousands of angular measurement data from the airborne Cloud Absorption Radiometer taken during the ARMCAS campaign in 1998.

BRDF Importance

BRDF effects on important applications such as albedo radiative forcing, **gross primary productivity** is stark

BRDF corrected PRI



Photosynthetic Efficiency

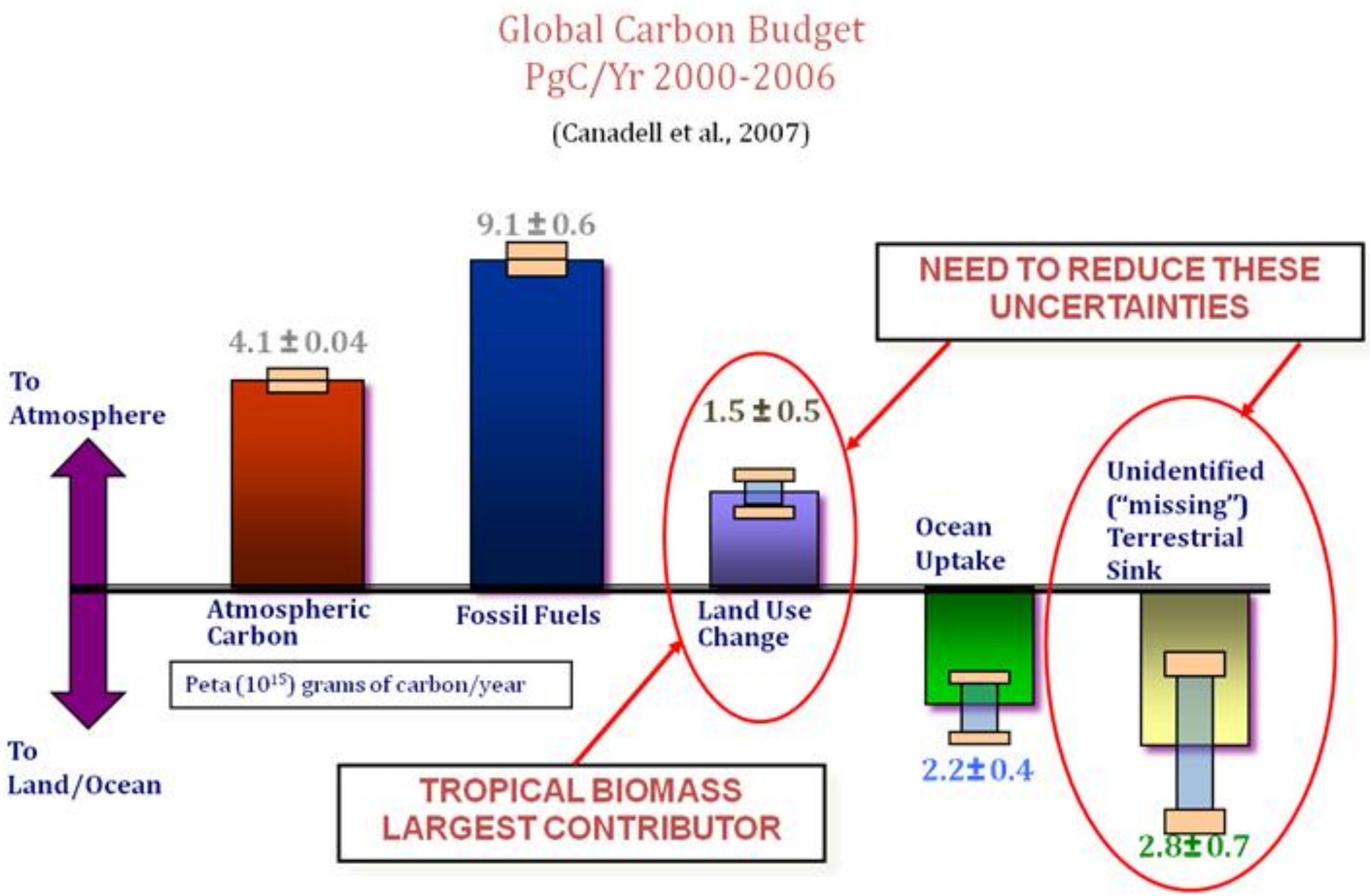
*GPP => Extent to which **vegetation acts as a Carbon Dioxide Sink***

GPP α Photosynthetic Efficiency α BRDF corrected Photosynthetic Refractive Index

Image Credits: Hilker et. al., 2008

BRDF Importance

BRDF effects on important applications such as albedo radiative forcing, **gross primary productivity** is stark



40% errors in current budget estimates shown in *Canadell et al. 2007*

Reduced to 10% errors using CHRIS multi-angular data shown in *Hall and Tucker 2010*

Monolithic Measurement Gaps

Airborne: Very accurate for local BRDF estimation
e.g. Cloud Absorption Radiometer (CAR)

BUT no global or continuous coverage, expensive to scale up area and time

Geometrical Requirements

Spectral Requirements

BRDF-Science Metrics	Number of angles	Ground Pixel Size in km X km	Revisit [illegible]e (any view [illegible]ays	Spectral Range	# of spectral bands

Monolithic Measurement Gaps

Spaceborne: Angular coverage through Large swath or FOV[1], Fwd-Aft sensors[2], autonomous maneuverability[3]

BUT fall short in terms of science metric/s + nearing EOL

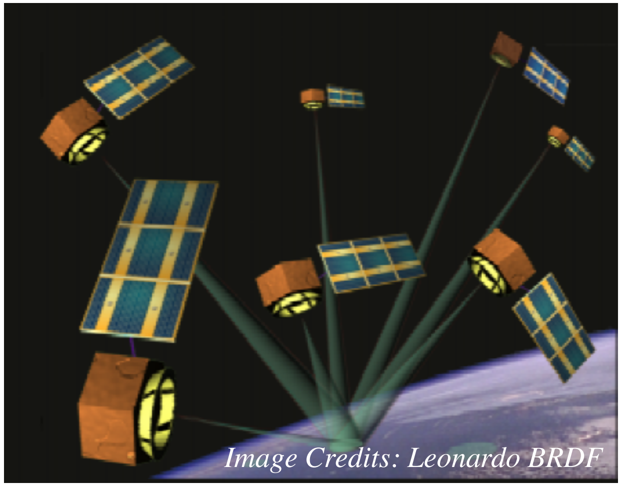
Geometrical Requirements

Spectral Requirements

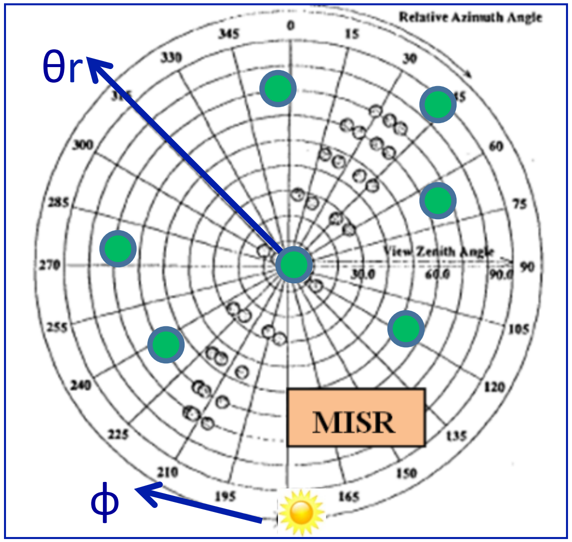
BRDF-Science Metrics → Current Instruments ↓	Number of angles	Ground Pixel Size in km X km	Revisit Time (any view) in days	Spectral Range	# of spectral bands
[1]MODIS	1	0.25 to 1	~2(16day RGT)	0.4-14.4 μm	36
[1]POLDER	14	6 X 7	~2(16day RGT)	0.42-0.9 μm	9
[1]CERES	1	10 to 20	~2(16day RGT)	0.3-12 μm	3
[2]MISR	9	0.275 to 1.1	9(16 day RGT)	0.44-0.87 μm	4
[2]ATSR	2	1 to 2	3-4	0.55–12 μm	7
[2]ASTER	2	0.015 to 0.09	~2(16day RGT)	0.52–11.65 μm	14
[3]CHRIS	5-15	0.017 to 0.5	As per command	0.415-1.05 μm	18-63

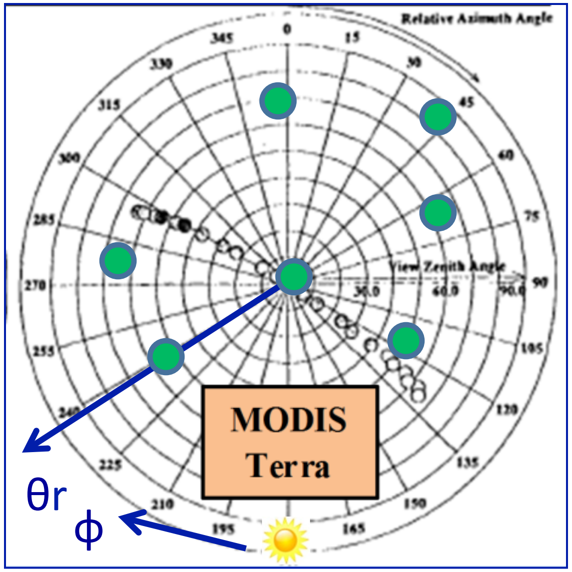
Filling in the Monolithic Gaps

Major Gap: Angular undersampling (θs,θr,ϕ)
Potential Solution: Clusters of nano-satellites since each sat will be small



Additional advantages:- 6U cubesats under development, Standard bus, Secondary payload launches, Cubesat GS network
Disadvantages:- Restrictive h-i combinations, mass/volume constraints





Approach

Build a Systems engineering (SE) model integrated with traditional BRDF Estimation models to finalize the ideal cluster architecture, satellite design, subsystem design and primary instrument

BRDF Systems Engineering -SE- Model
(dependent on satellite subsystems)

Simulated measurements/ sampling of the BRDF function →

Software for Space, Defense & Intelligence

GCC

← Errors in BRDF Estimation + other application specific metrics

BRDF Science Evaluation Model
(dependent on application)

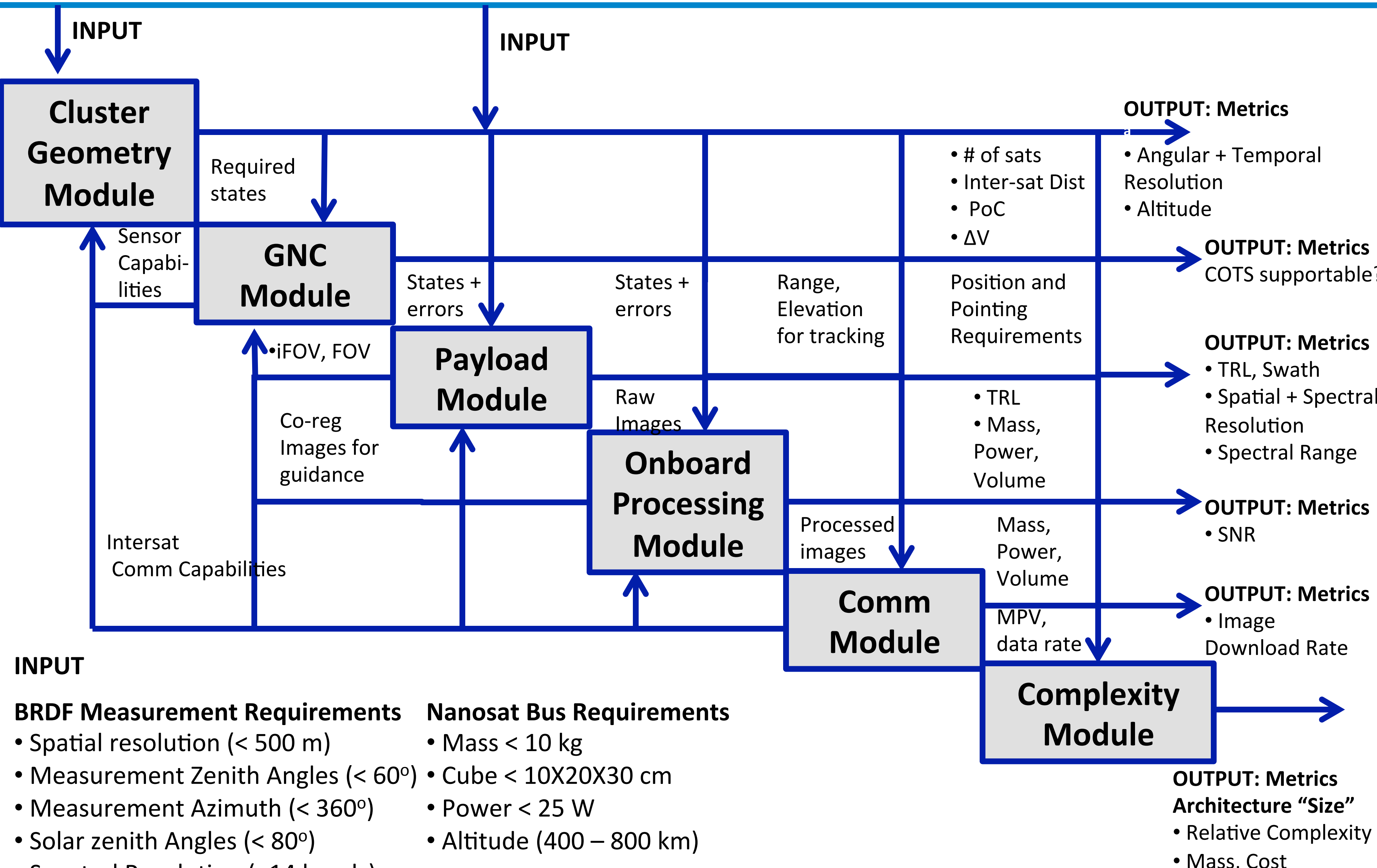
Measurement Requirements from Science Traceability Matrix Goals Layer

INPUT

Estimated BRDF + errors; other application specific metrics

OUTPUT

SE Model as an N2 Diagram



INPUT

BRDF Measurement Requirements
- Spatial resolution (< 500 m)
- Measurement Zenith Angles (< 60°)
- Measurement Azimuth (< 360°)
- Solar zenith Angles (< 80°)
- Spectral Resolution (>14 bands)
- Spectral Range (350-2300 nm)

Nanosat Bus Requirements
- Mass < 10 kg
- Cube < 10X20X30 cm
- Power < 25 W
- Altitude (400 – 800 km)

Cluster Geometry Models

Computational Ease of Tradespace Exploration and Optimization

LINEARIZED HILL CLOHESSY WILTSHIRE EQUATIONS

DUAL SPIRAL EQUATIONS

GLOBAL ORBIT PROPAGATION USING STK

Model Fidelity/Reliability

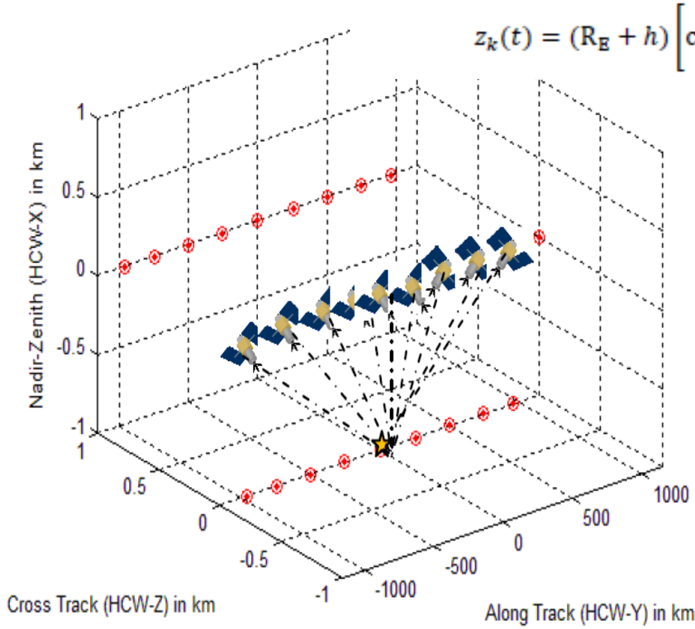
Cluster Geometry Models

LINEARIZED HILL CLOHESSY WILTSHIRE EQUATIONS

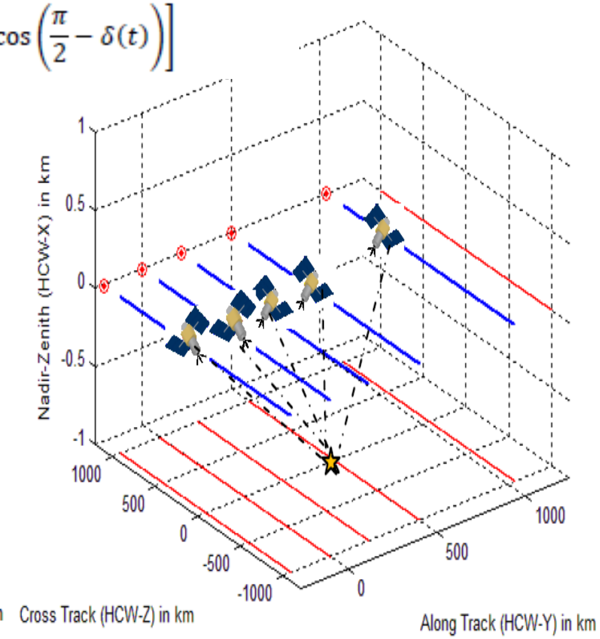
$$x_k(t) = (R_E + h)\left[\cos(\Phi_k + \alpha(t))\sin\left(\frac{\pi}{2} - \delta(t)\right) - 1\right]$$

$$y_k(t) = (R_E + h)\left[\sin(\Phi_k + \alpha(t))\sin\left(\frac{\pi}{2} - \delta(t)\right)\right]$$

$$z_k(t) = (R_E + h)\left[\cos\left(\frac{\pi}{2} - \delta(t)\right)\right]$$



String of Pearls (SOP)



Cross Track Scan (CTS)

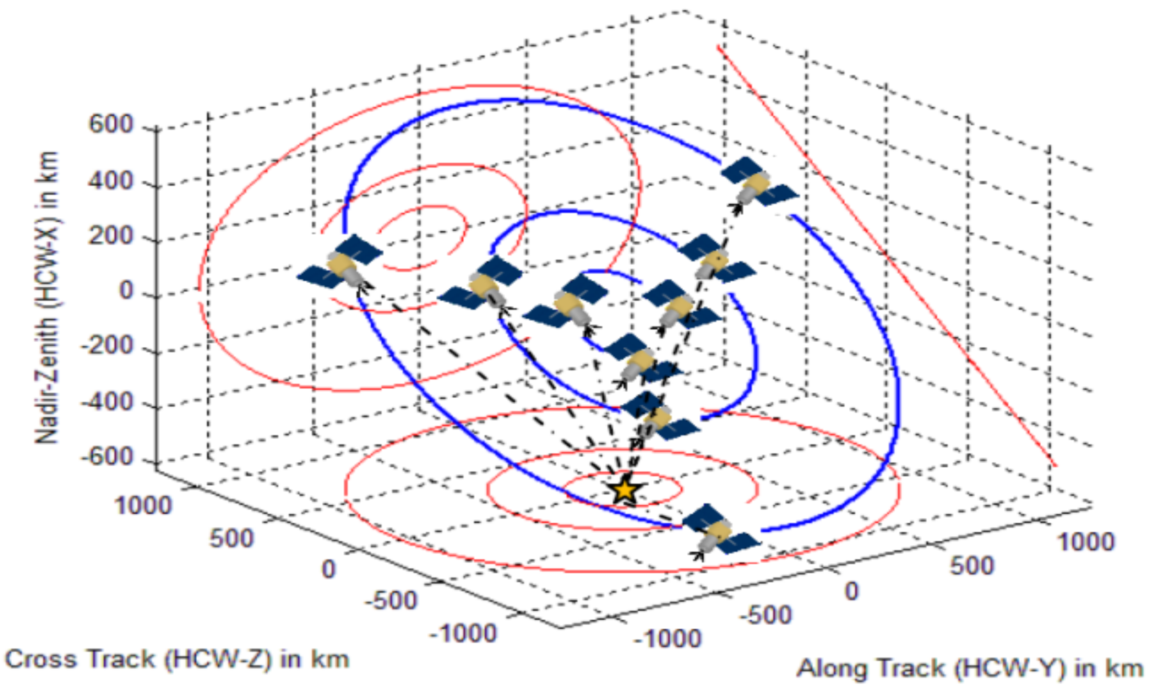
Computational Ease of Tradespace Exploration and Optimization

Model Fidelity/Reliability

Cluster Geometry Models

Computational Ease of Tradespace Exploration and Optimization

LINEARIZED HILL CLOHESSY WILTSHIRE EQUATIONS



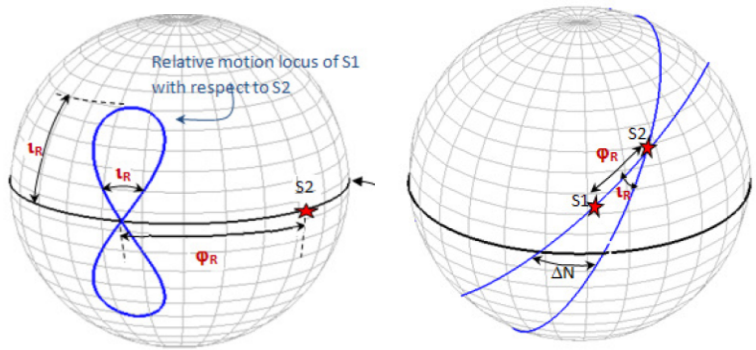
Free Orbit Ellipse (FOE)

Model Fidelity/Reliability

Cluster Geometry Models

Computational Ease of Tradespace Exploration and Optimization

Special Case for the Dual Spiral model : Relative Analemma



$$\sin\delta = \sin i_R \sin nt$$

$$\alpha = nt - \operatorname{atan}(\cos i_R \tan nt)$$

$$\Delta\Phi = \Phi_2 + \Phi_R - \Phi_1$$

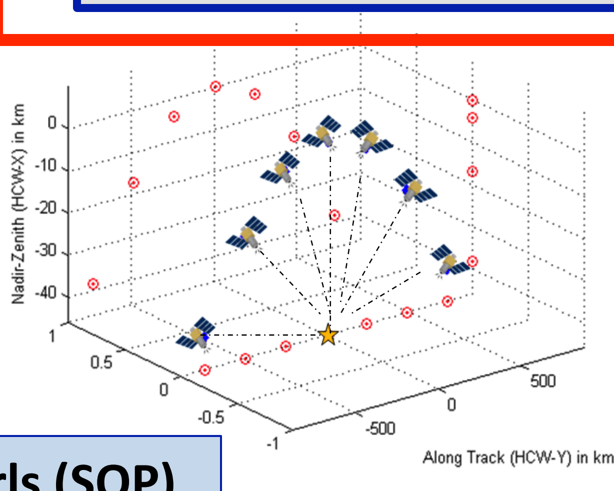
$$\cos\Phi_1 = \frac{\cos i_2 - \cos i_1 \cos i_R}{\sin i_R \sin i_2}$$

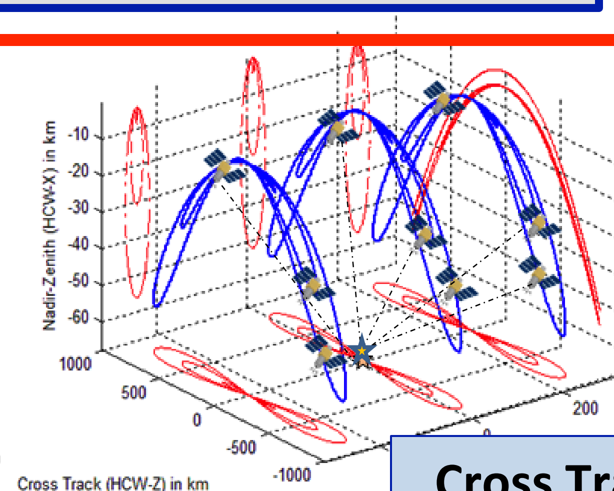
$$\cos\Phi_1 = \frac{\cos i_2 - \cos i_1 \cos i_R}{\sin i_R \sin i_2}$$

$$\cos i_R = \cos i_1 \cos i_2 + \sin i_1 \sin i_2 \cos\Delta N$$

$$\Phi_R = (T_2 - T_1)n + \Delta\Phi$$

DUAL SPIRAL EQUATIONS





Model Fidelity/Reliability

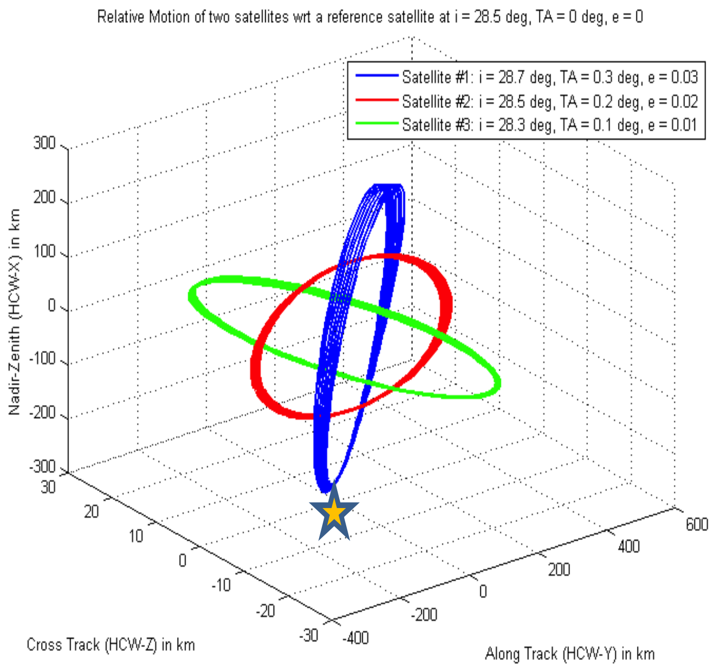
String of Pearls (SOP)

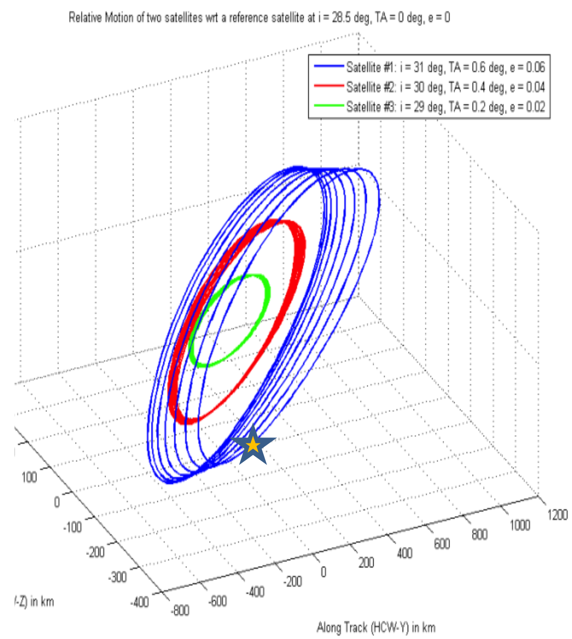
Cross Track Scan (CTS)

Cluster Geometry Models

Computational Ease of Tradespace Exploration and Optimization

Free Orbit Ellipse(FOE)





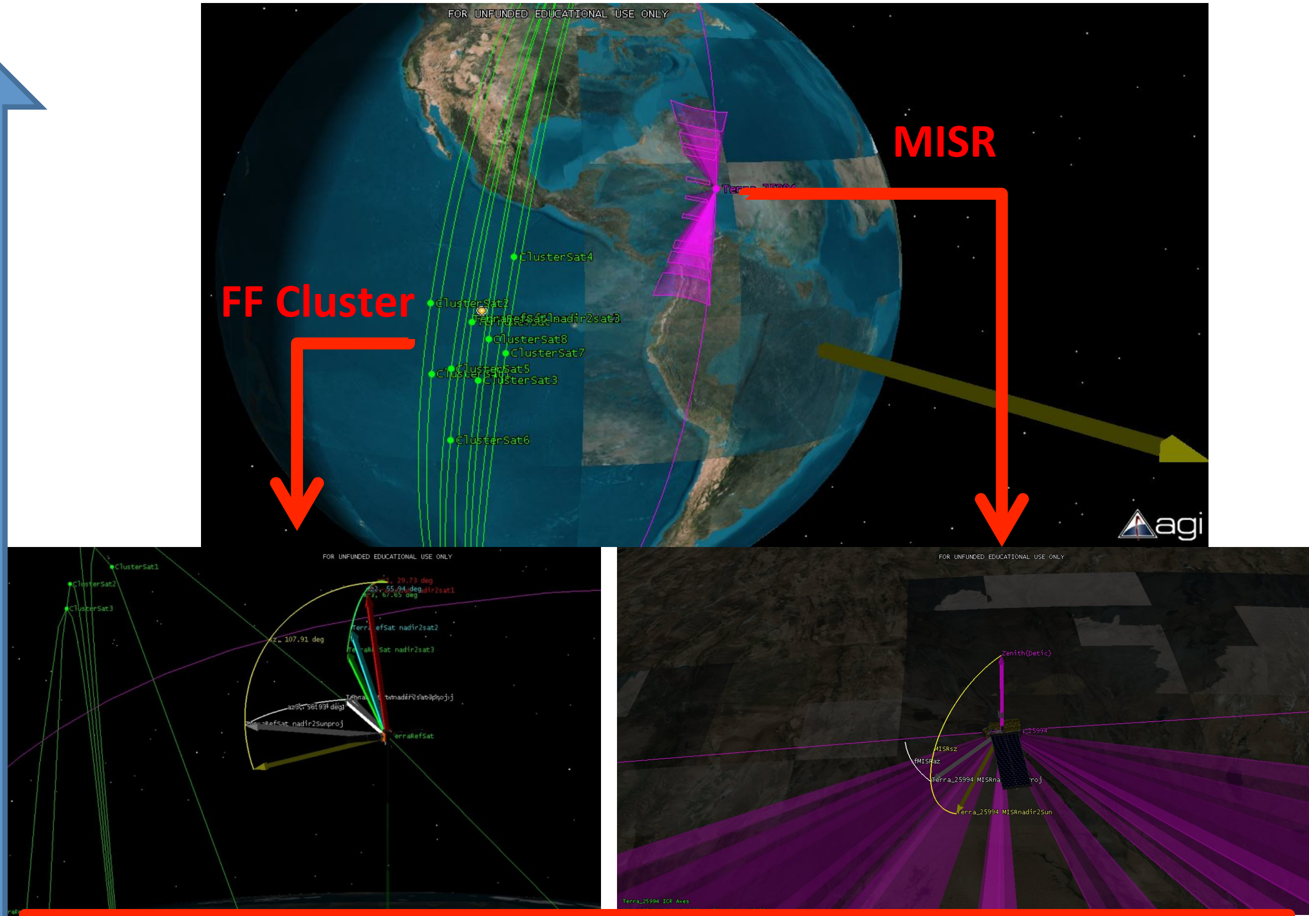
GLOBAL ORBIT PROPAGATION USING STK

Trajectories in the LVLH frame of orbits propagated for one day

Model Fidelity/Reliability

Cluster Geometry Models

Computational Ease of Tradespace Exploration and Optimization



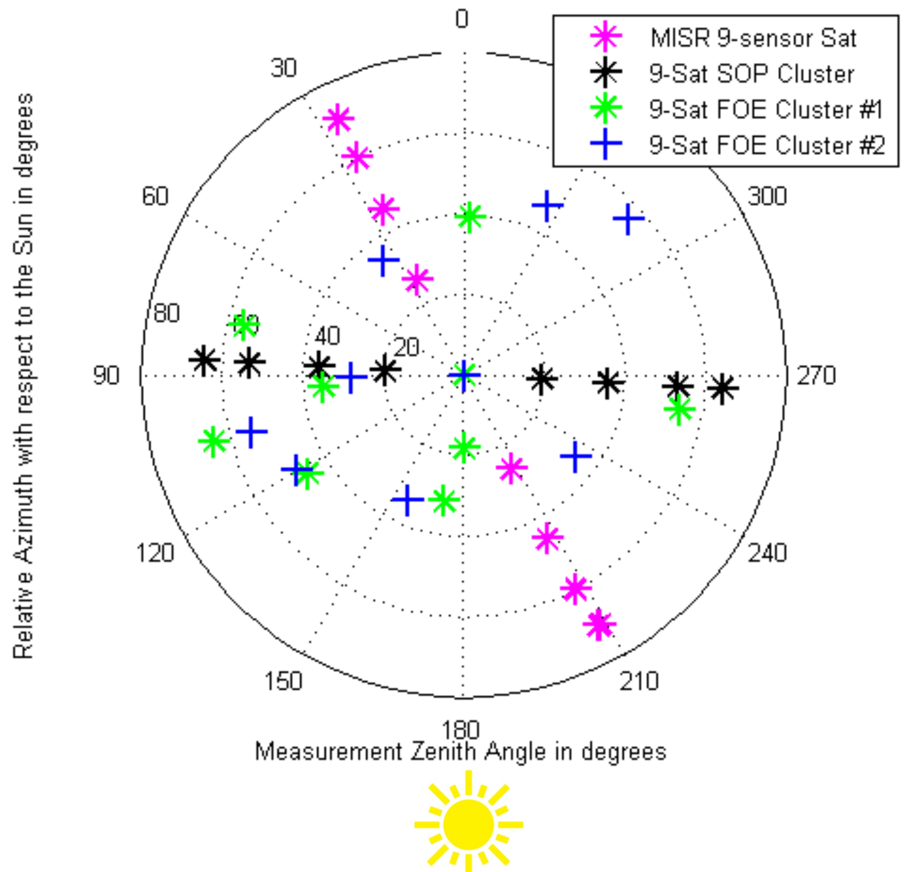
Model Fidelity/Reliability

GLOBAL ORBIT PROPAGATION USING STK

Target (yellow) imaged at multiple angles by cluster (green), MISR (pink)

Cluster Geometry Models

Computational Ease of Tradespace Exploration and Optimization



GLOBAL ORBIT PROPAGATION USING STK

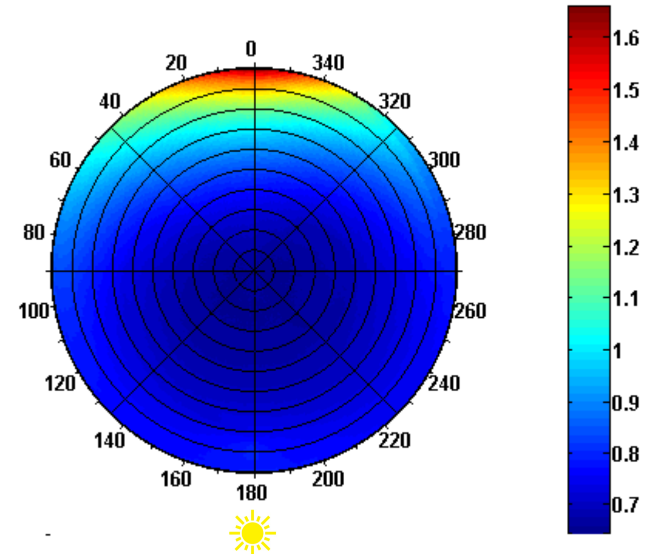
Target (yellow) imaged at multiple angles by cluster (green), MISR (pink)

Model Fidelity/Reliability

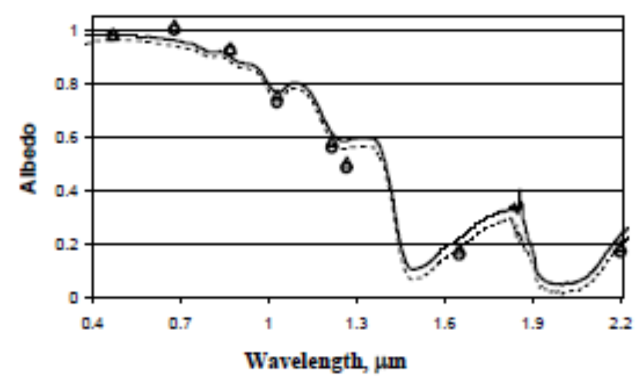
Snow Albedo Application

- ***Snow environment*** selected because of lack of aerosol effects, less clouds, important for climate change, melt season needs >1 day temporal repeat, availability of campaign.
- Used ***BRDF data as "truth"*** from the ARCTAS (Arctic) campaign at Elson Lagoon (71.3 N, 156.4 W), Alaska, which was studied by the NASA P-3B carrying the Cloud Absorption Radiometer (CAR).
- Data available at all 360 azimuth and 90 zenith angles, so ***easy to select any angular sampling combination*** for trades.
- Used the ***RossThick-LiSparse (RLTS) model*** because it is linear, suited for spatial scales, used for MODIS products and tested appropriate for snow *[Lyapustin et al, 2010]*

TRUE BRDF



RADIUS: View Zenith Angle in degrees
AZIMUTH: View Azimuth Angle in degrees
Wavelength = 1.02 microns (atm window)
Acquisition height = 1.69 km



Black Sky Albedo at solar zenith angle = 30.72 deg

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$$BRDF(\theta_s,\theta_v,\Delta\phi,\lambda) \cong R(\theta_s,\theta_v,\Delta\phi,\Lambda) = f_{iso}(\Lambda) + f_{vol}(\Lambda)K_{vol}(\theta_s,\theta_v,\Delta\phi) + f_{geo}(\Lambda)K_{geo}(\theta_s,\theta_v,\Delta\phi,P_4,P_5)$$

where:

$$K_{vol} = \frac{(\pi/2-\xi)\cos\xi + \sin\xi}{\cos\theta_s + \cos\theta_v} - \frac{\pi}{4}$$

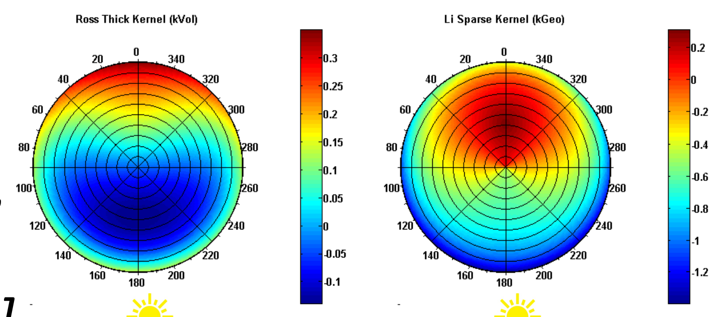
$$\cos\xi = \cos\theta_s\cos\theta_v + \sin\theta_s\sin\theta_v\cos\Delta\phi$$

$$K_{geo} = \frac{1 + \sec\theta'_s\sec\theta'_v + \tan\theta'_s\cos\Delta\phi}{2} + \left[\frac{t - \sin t\cos t}{\pi} - 1\right](\sec\theta'_s + \sec\theta'_v)$$

$$\cos^2 t = \min\left\{\left[\frac{P_4}{\sec\theta'_v + \sec\theta'_s}\right]^2\left[D^2 + (\tan\theta'_v\tan\theta'_s\sin\Delta\phi)^2\right], 1\right\}$$

$$\tan\theta'_x = P_5\tan\theta_x; \quad x = v \text{ or } s$$

$$D = \sqrt{\tan^2\theta'_s + \tan^2\theta'_v - 2\tan^2\theta'_s\tan\theta'_v\cos\Delta\phi}$$



RADIUS: View Zenith Angle in degrees
AZIMUTH: View Azimuth Angle in degrees
SZA = 30.72 deg

Snow Albedo Application

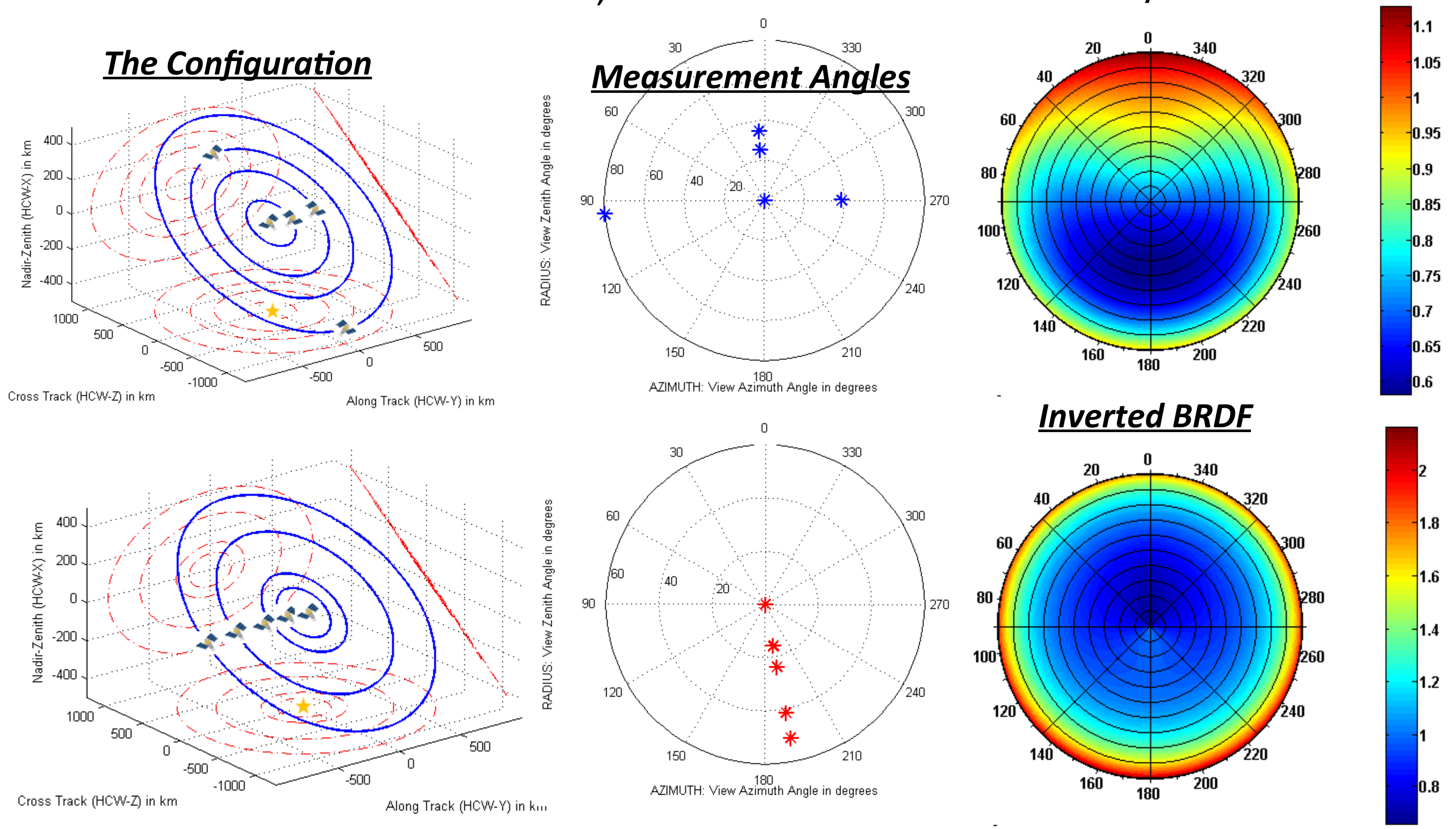
KEY TRADE VARIABLES: Cluster Geometry (<u>HCW-FOE</u>), FOE Orientation (22deg to LVLH-XY), # Rings (2-4), # Satellites (**<u>5, 9,</u>** 13), Angle subtended by rings at chief orbit (20-60deg), Orbit Orientation (<u>normalized to Sun</u>) , Angular Coverage

INTEGRATED MODEL: <u>Modified HCW for FF + RLTS for BRDF Estimation</u>

KEY METRICS: RMS error wrt true BRDF, Albedo error wrt true black sky albedo

Best Case
RMS err=0.08
Albedo err=0.0015

Worst Case
RMS err=0.3892
Albedo err=0.2928



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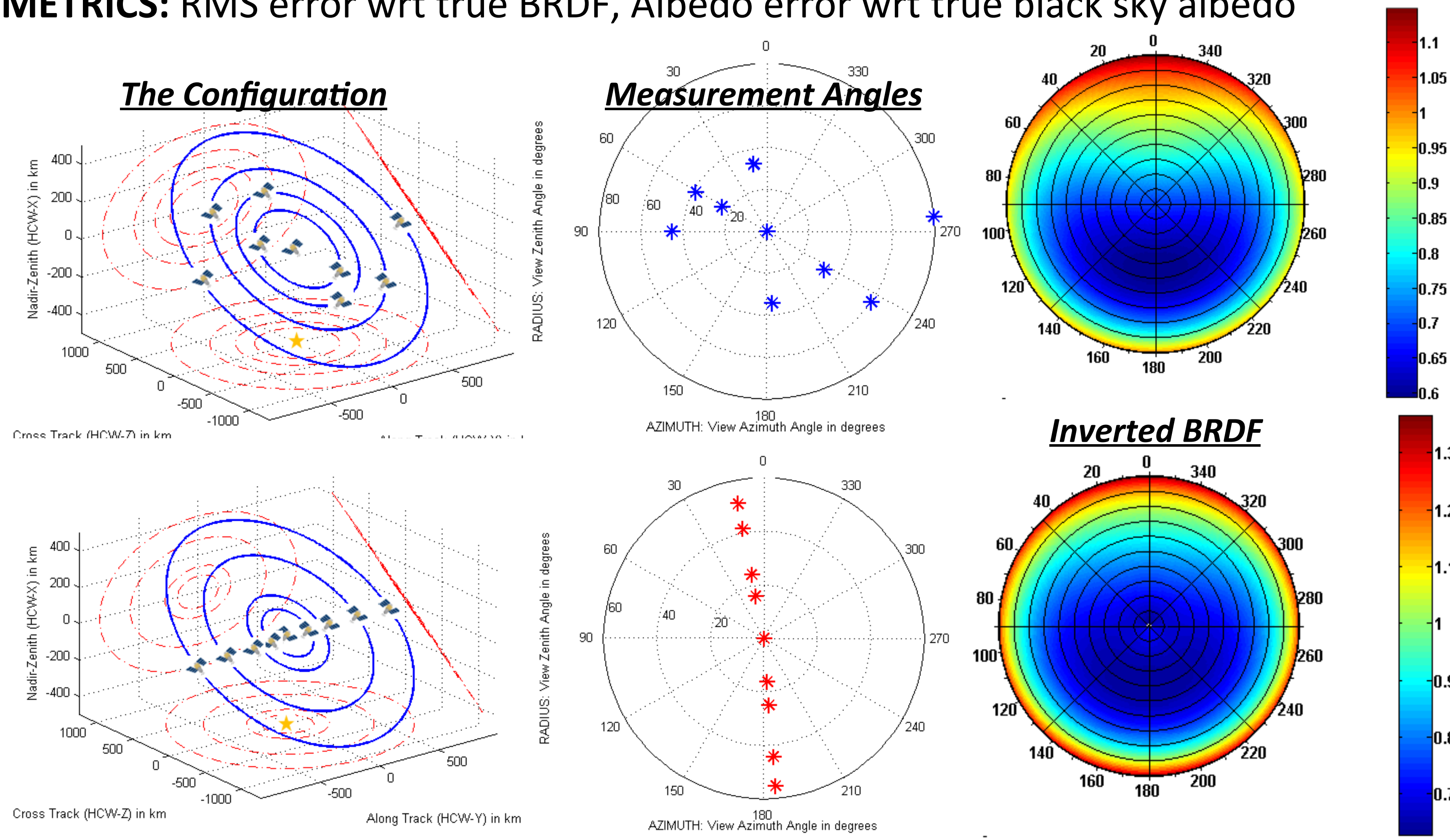
Best Case
RMS err=0.0707
Albedo err=0.001

Worst Case
RMS err=0.1137
Albedo err=0.045



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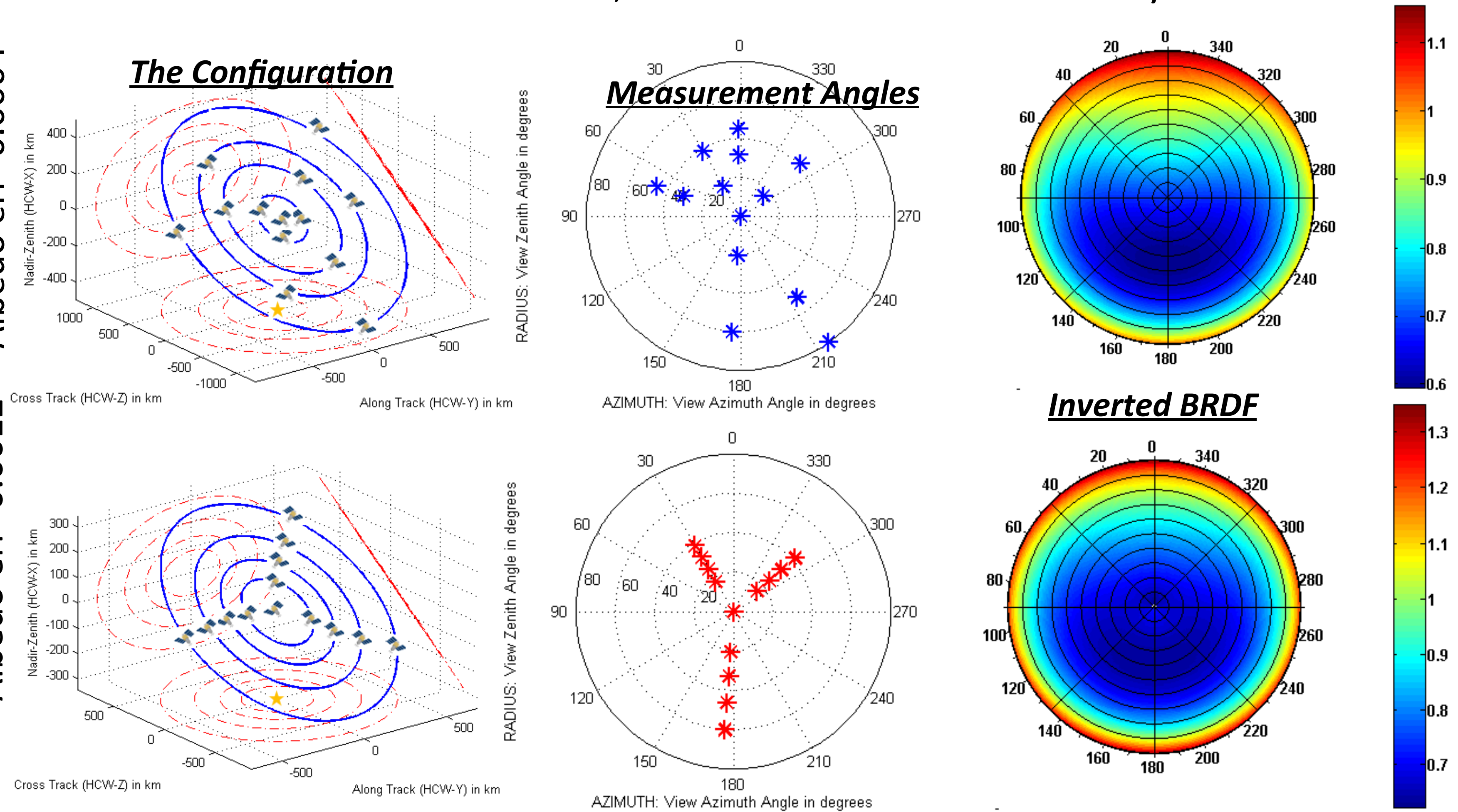
KEY METRICS: RMS error wrt true BRDF, Albedo error wrt true black sky albedo

Best Case
RMS err=0.07
Albedo err=0.0004

Worst Case
RMS err=0.109
Albedo err=0.0012



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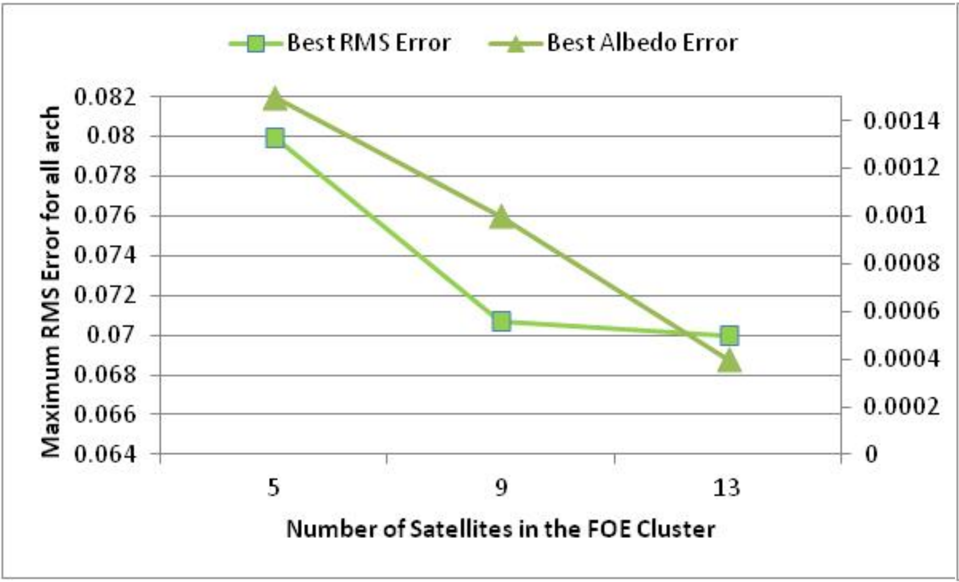
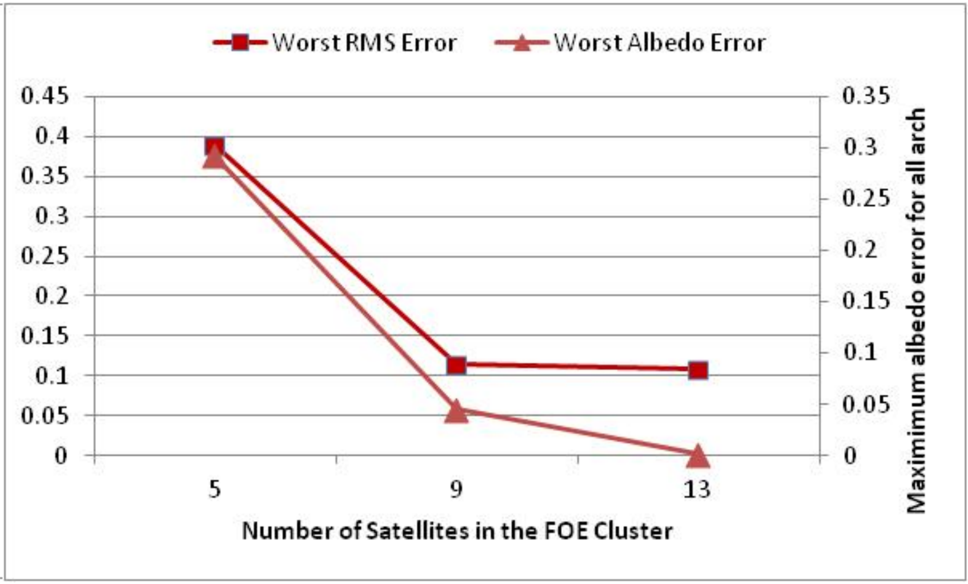




BRDF and Black Sky Albedo errors compared to 'Truth'/CAR Values as a function of #satellites

Important quantification of value to trade against cost of a growing cluster size!

Linearized HCW Analysis

Angular/Area variation for the ***BEST FOE geometry***:

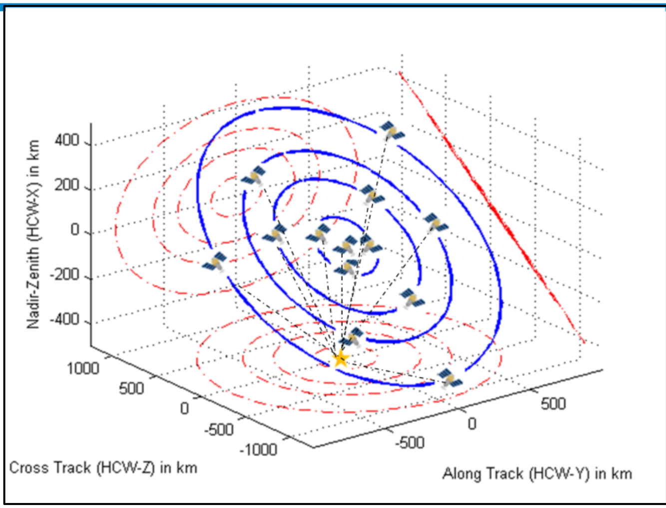
H = 600 km, N = 13 satellites in 4 rings

x0/z0 ratio = 0.4 = 21.8 deg

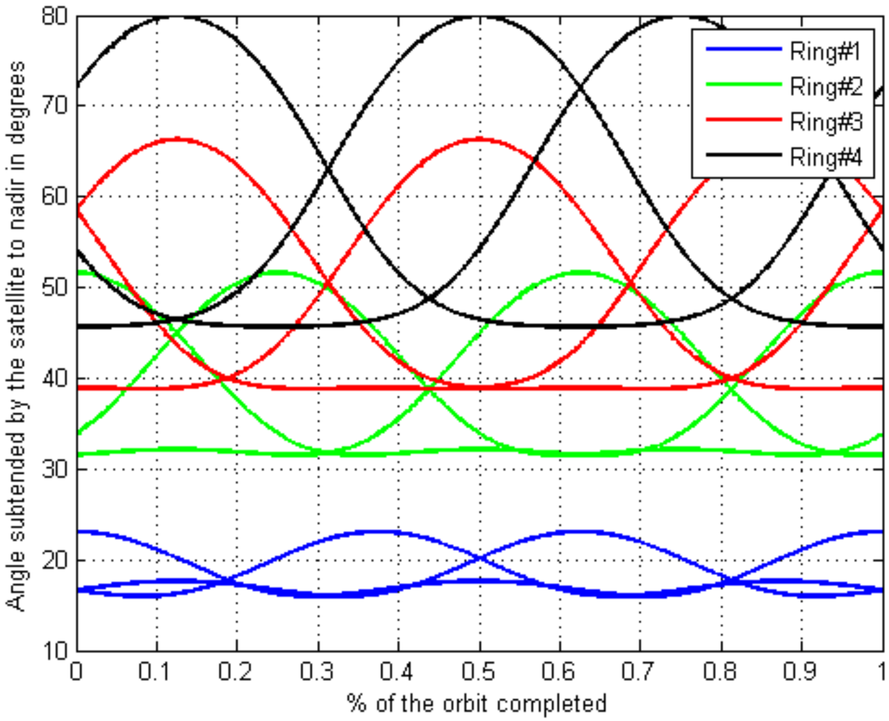
FOV assumed = 10 deg

Nominal boresight angle = 0, 20, 40, 50, 60 deg

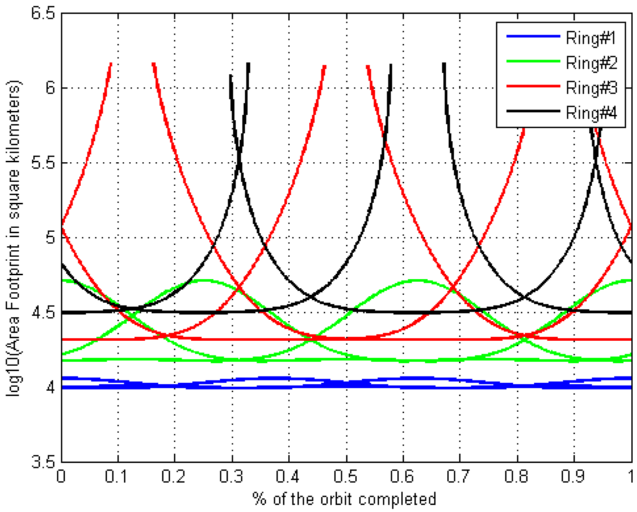
Nominal azimuthal angle = Variation optimized per ring



ANGULAR SAMPLING ***Required Boresight angle*** variation:

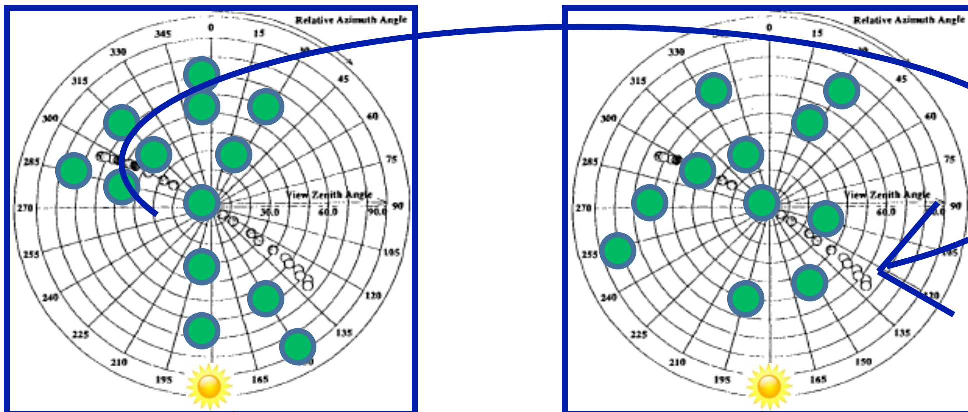


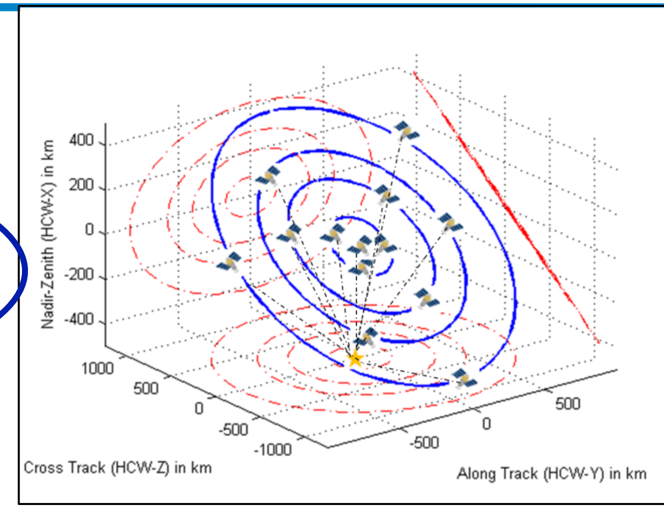
SPATIAL SAMPLING ***Footprint Area v****ariation*:



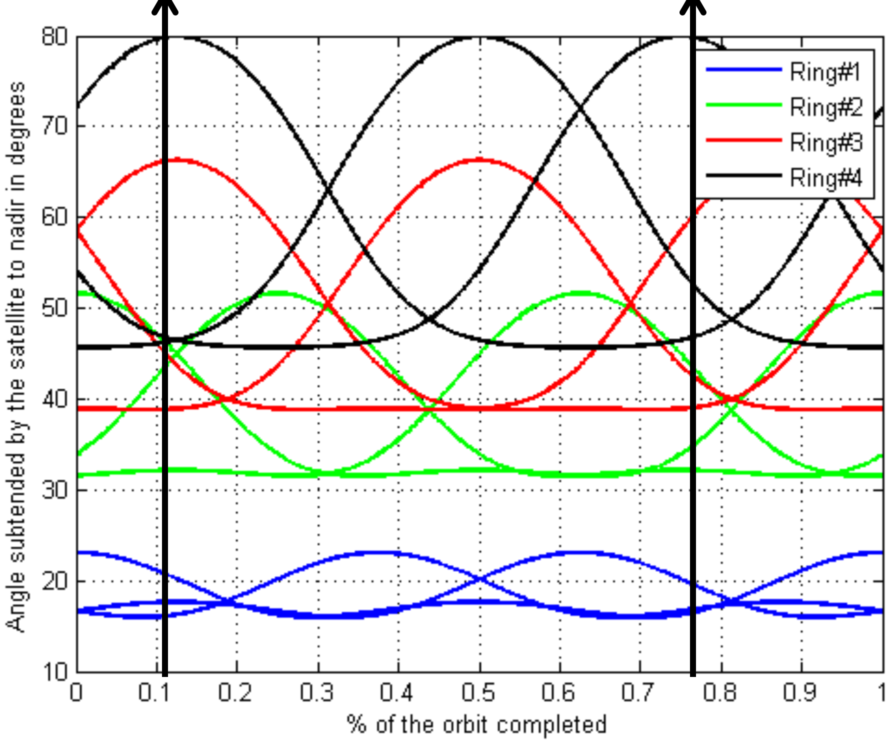
Linearized HCW Analysis

Zenith/Azimuth variation for the ***BEST FOE geometry***:

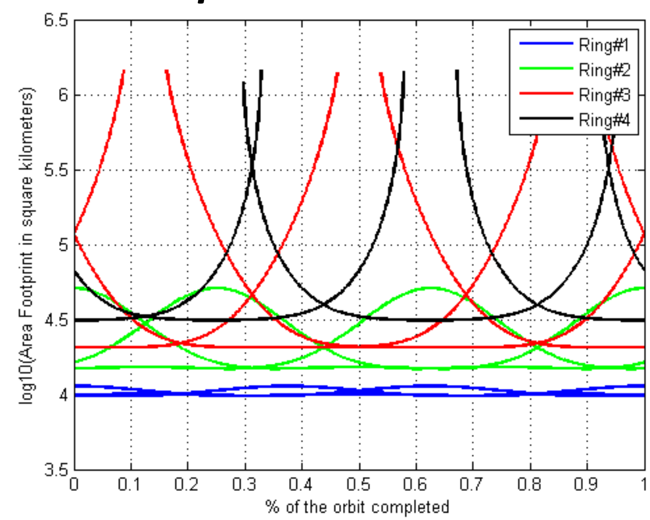




ANGULAR SAMPLING ***Required Boresight angle*** variation:



SPATIAL SAMPLING ***Footprint Area v****ariation*:



Linearized HCW Analysis

*ACDS variation for the **BEST FOE geometry***:

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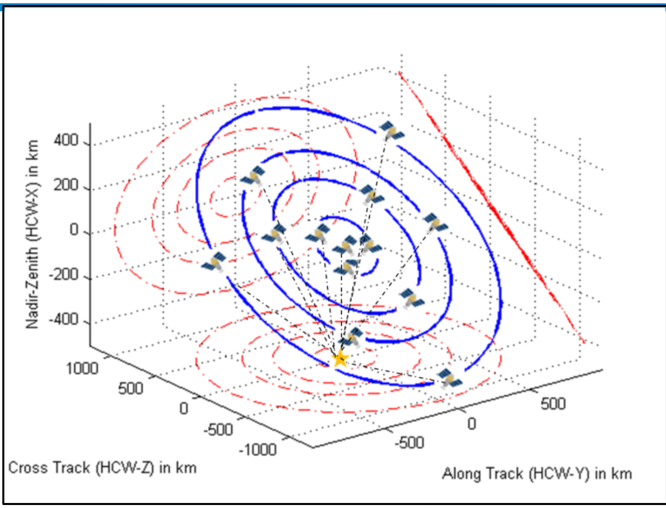
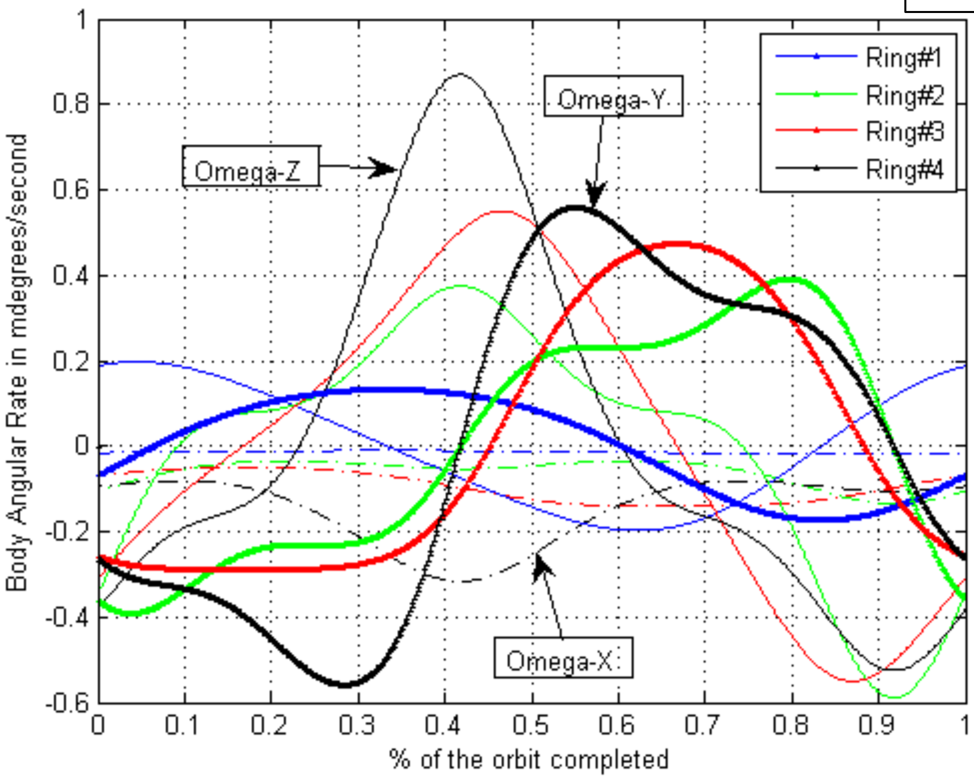


Required Slew Rate:

(I = 0.15 kg-m^2 assuming a cubic nanosat)



MAI-400 (Maryland Aerospace) RW

P ~ 3W

m < 0.7 kg

V ~ 0.5 cube

Max H = 11.8 mNms

Max T = 0.625 mNm

Linearized HCW Analysis

*ACDS variation for the **BEST FOE geometry***:

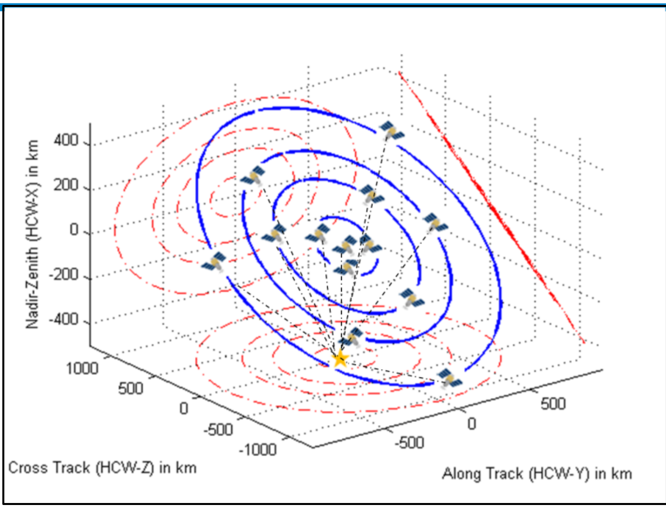
H = 600 km, N = 13 satellites in 4 rings

x0/z0 ratio = 0.4 = 21.8 deg

FOV assumed = 10 deg

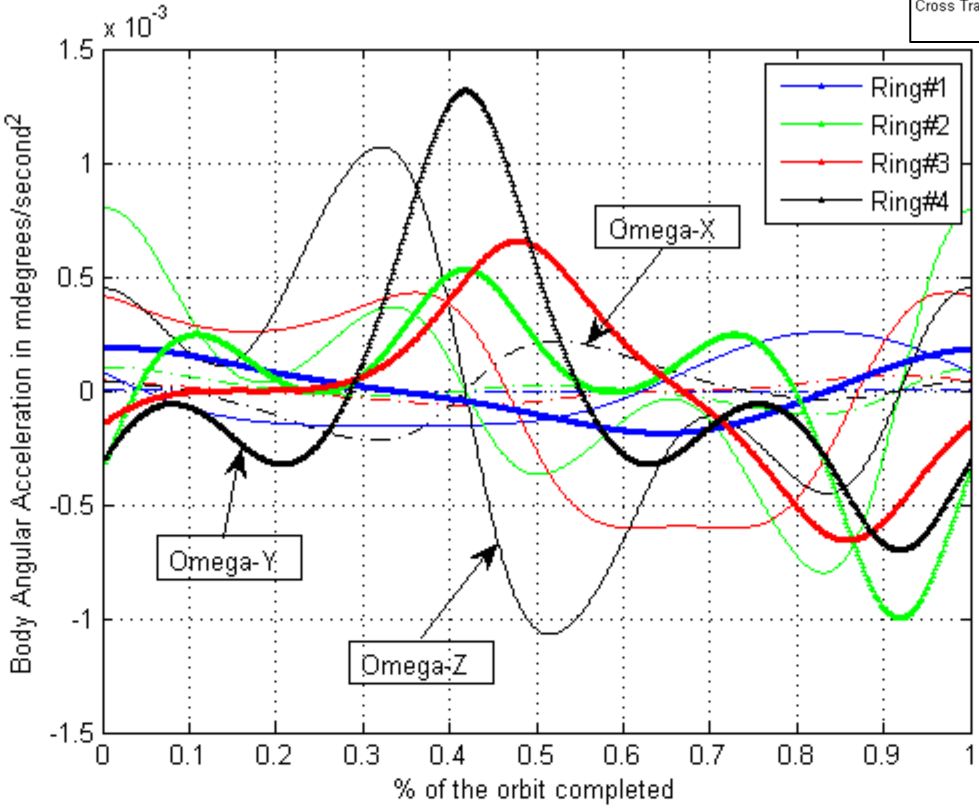
Nominal boresight angle = 0, 20, 40, 50, 60 deg

Nominal azimuthal angle = Variation optimized per ring



Required Angular Acceleration:

(I = 0.15 kg-m^2 assuming a cubic nanosat)



MAI-400 (Maryland Aerospace) RW

P ~ 3W

m < 0.7 kg

V ~ 0.5 cube

Max H = 11.8 mNms

Max T = 0.625 mNm

Conclusions and Future Work

- ***Proposed nanosatellite clusters in formation flight*** with VNIR spectrometers to sample the BRDF function as a complement to existing monolithic data products
- Designed a physics-based, ***integrated science + systems engineering model*** for tradespace exploration to find the "optimal design" for the cluster geometry that will maximize specific BRDF science goals
- Identified ***snow albedo*** as a critical BRDF application
- Used the tradespaces to ***quantify the significance on albedo and BRDF errors*** of cluster geometry and orientation, # of Satellites, orbit orientation and azimuthal coverage Showed that the optimal cluster configuration's subsystem requirements (e.g. ADCS) is COTS supportable
- ***Future Work*** includes heuristic optimization of clusters (both modified linearized and global propagation) for albedo accuracy over mission lifetime (cluster dynamics and orbit maintenance). Other critical applications such as GPP will also be realized.

Acknowledgements

- MIT
  - Prof. Olivier de Weck
  - Prof. Kerri Cahoy
  - Prof. David Miller
- NASA GSFC
  - Charles Gatebe
  - Warren Wiscombe
  - Jacqueline Lemoigne
  - Alexei Lyapustin
  - Ralph Kahn
  - Miguel Roman
  - John Mather Nobel Scholar Award Committee

Questions?