Satellite Constellation Mission Design using Model-Based Systems Engineering and Observing System Simulation Experiments

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Outline

- Introduction – Small Satellite Constellations, MBSE and OSSE
- Problem Statement – Earth Radiation Budget
- Proposed Mission Design Methodology using MBSE and OSSE
- Design Methodology applied to the Problem
- Preliminary Results for Full System Simulation
- Summary and Future Work

Introduction

- Small Sats as constellations have tremendous potential in **supplementing flagship missions** in Earth Observation (ESTO Earth Science Vision 2030)

- *"Synergies of complementary measurements...avoidance of engineering and management difficulties associated with integration on a common bus; and a more agile and cost-effective replacement of individual sensors...* ***moving away from a single parameter and sensor-centric approach*** *toward a systems approach that ties observations together to study processes important to understanding* ***Earth-system feedbacks***" – NRC Decadal Survey, 2007

Introduction

- *"Model-Based Systems Engineering is the normalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development"* – INCOSE, 2004
All the more **important for constellations as complex systems!**

- *"Observing System Simulation Experiments (OSSEs) are designed to mimic the process of data assimilation"* – NASA GSFC GMAO. E.g. OSSEs have been used in many journal papers to **show the shortcomings of all flagship radiative flux instruments** (TRMM,MODIS show uncertainties of 5-10W/m^2& 10-15W/m^2 in in short/longwave) **and in designing CLARREO**.

- Need to design small sat constellation missions in a language that the Earth Science community uses to designing flagship missions understands so that a **quantifiable gap is justified and filled quantifiably**.

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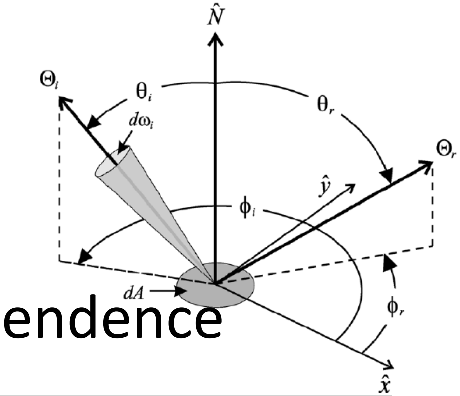
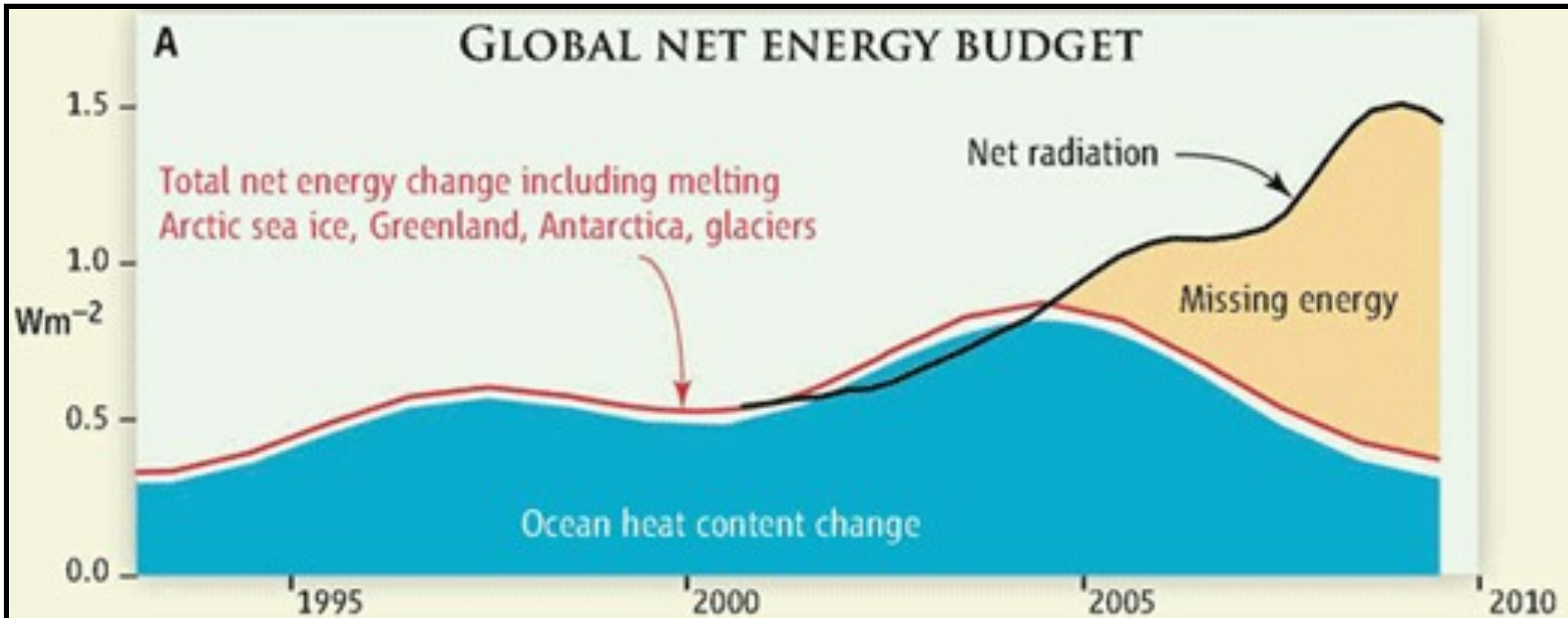
Earth Radiation Budget

Total Solar Incidence – Total Outgoing Radiation
– Heat Absorbed = 0

But TOR ~= 0.9 W/m^2 (-2/+7 [45],0.5[47],0.4-0.7)

Because TOR has spatial, temporal and angular dependence



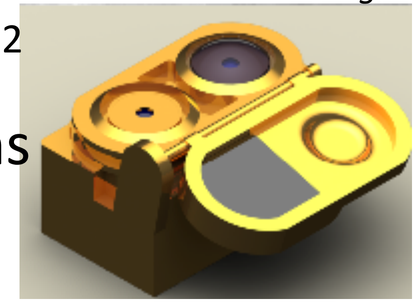


Specifically mentioned in NRC Decadal Survey

Image Credits: Trenberth and Fasullo, 2010

Improving the TOR Estimation

Image Credits: earthzine.org



Currently under development:

- Cubesat radiometers (RAVAN) with flux reso<0.3 W/m^2
- Technology demonstration to scale up to constellations

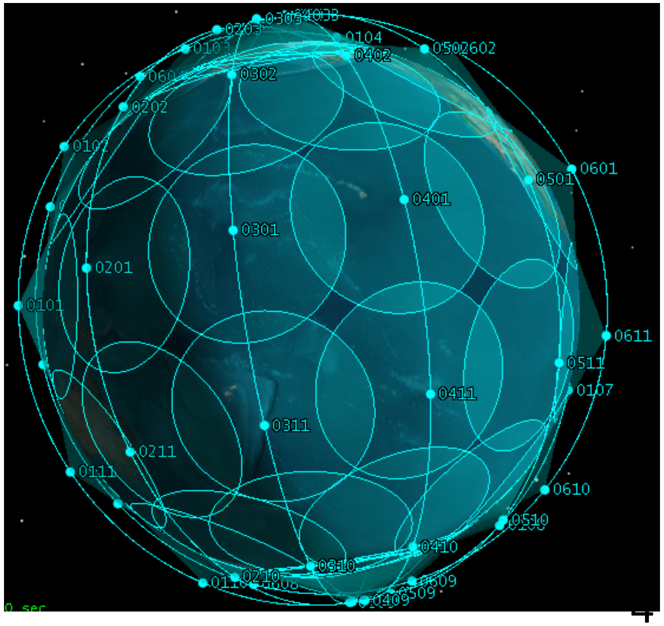
What is the "optimal" constellation architecture?

Constraints:

- Tech (within comm. cubesat subsystems)
- Programmatic (available launches)

Objectives: Science Metrics

- => Quantified by OSSE
- => NOT constraints
- => Flexible during decisions
- => Optimizable based on real constraints



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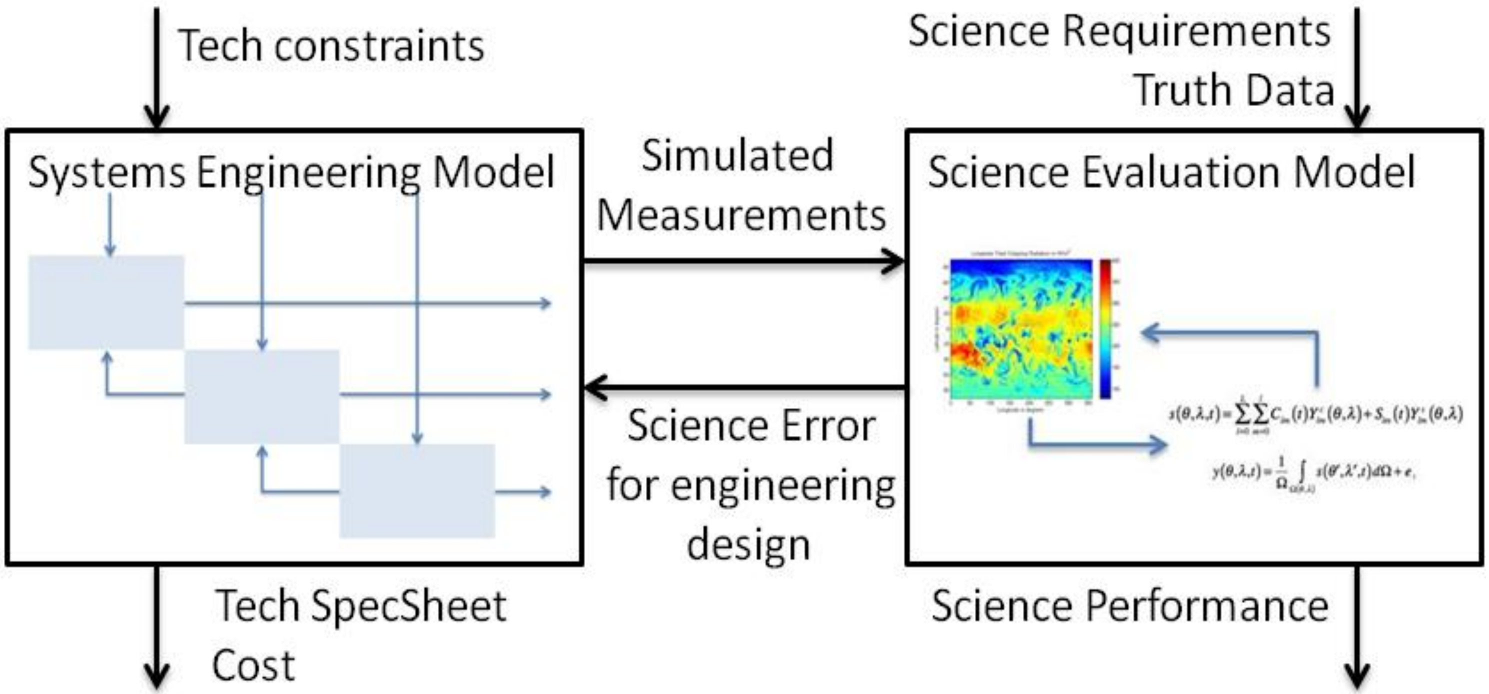
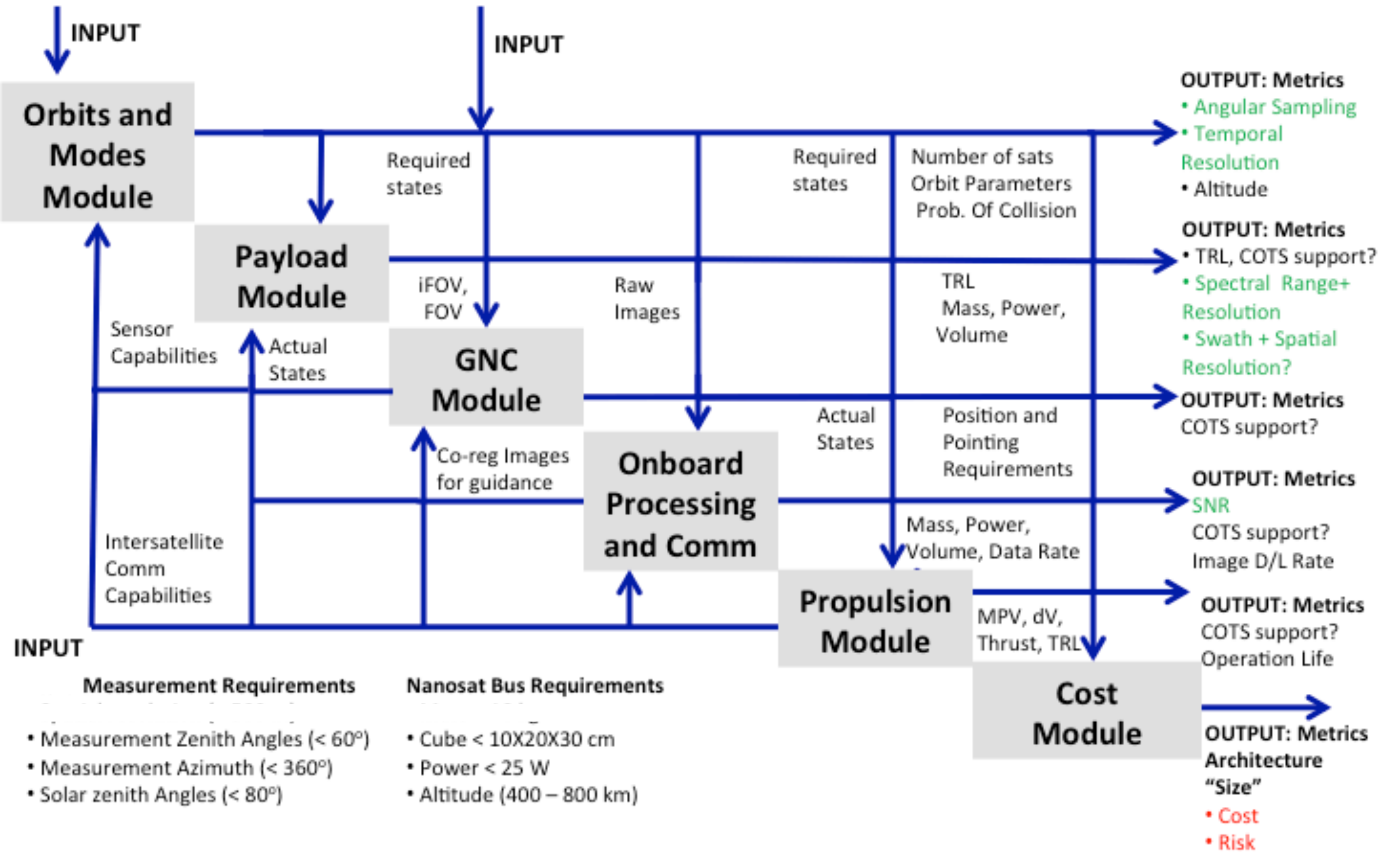
Mission Design Methodology

Coupled and iterative MBSE + OSSE



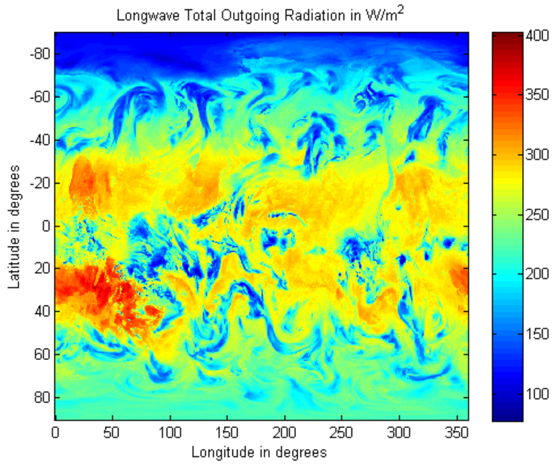
*as a function of tech requirements, biomes of interest, science applications

Architecture Gen, Support, Sizing with MBSE

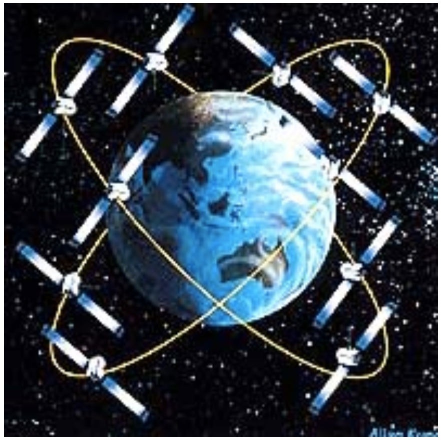


Science Performance Evaluation with OSSE

1. True TOR



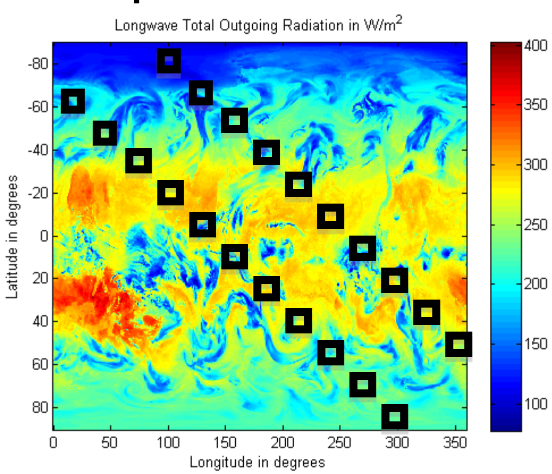
2. Temporal and Angular samples from any constellation architecture



Total Outgoing Radiation Error: Optimization Objective

6. Estimated TOR at all Earth grid points and times using parameters.

3. Select corresponding samples from "Truth"



4. Fit a Spherical Harmonics model and invert for model parameters

$$s(\theta,\lambda,t)=\sum_{l=0}^{L}\sum_{m=0}^{l} C_{lm}(t)Y_{lm}^{c}(\theta,\lambda)+S_{lm}(t)Y_{lm}^{s}(\theta,\lambda)$$

$$y(\theta,\lambda,t)=\frac{1}{\Omega}\int_{\Omega(\theta,\lambda)} s(\theta',\lambda',t)\,d\Omega+e,$$

5. Run forward model with inverted parameters

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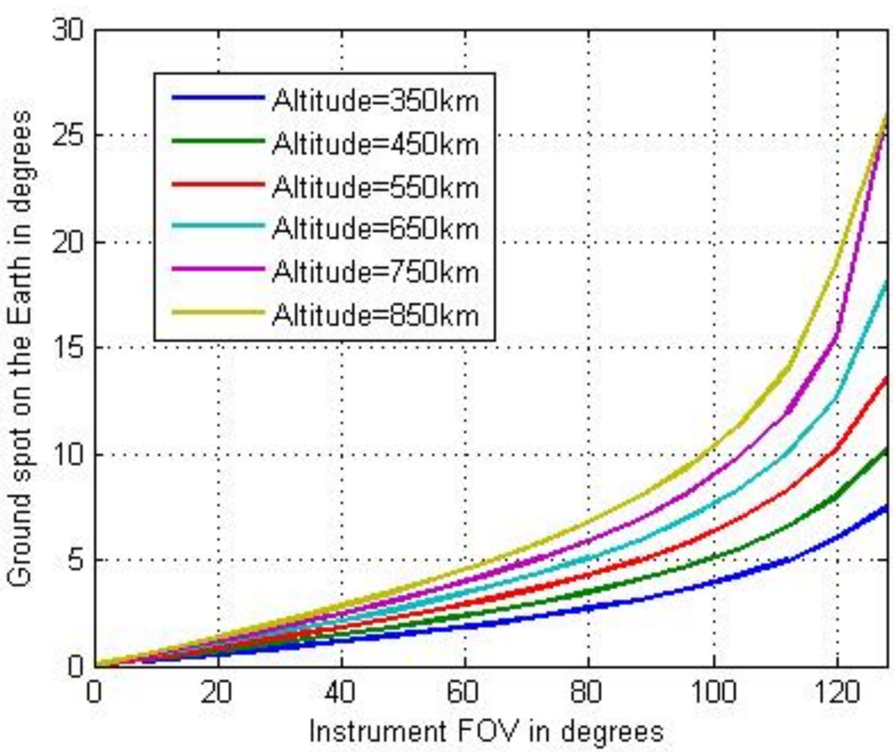
MBSE: Architecture Generation

Major Variables to generate architectures:

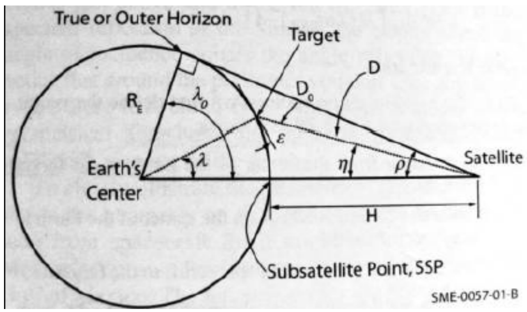
- Altitude (Baselined at the Landsat orbit from ERB instruments)
- FOV (assumed from RAVAN radiometer = 130 deg)
- Inclination (Baselined to Landsat)



$$\lambda = 90 - \eta - \varepsilon$$

$$\varepsilon = \cos^{-1}\frac{\sin(\eta)}{\sin(\rho)}$$

$$\rho = \sin^{-1}\frac{Re}{Re + h}$$

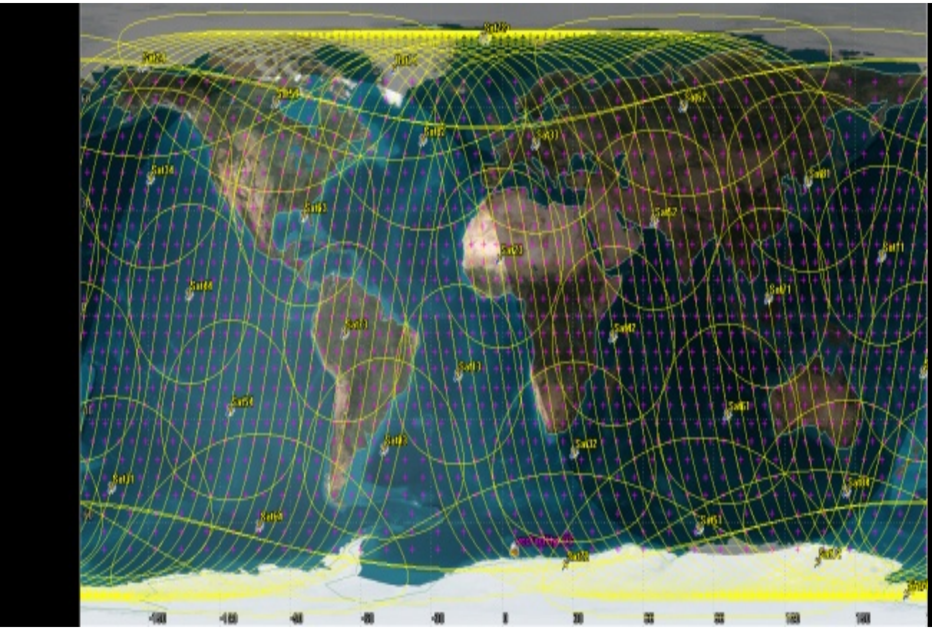


Inclination > 90-λ

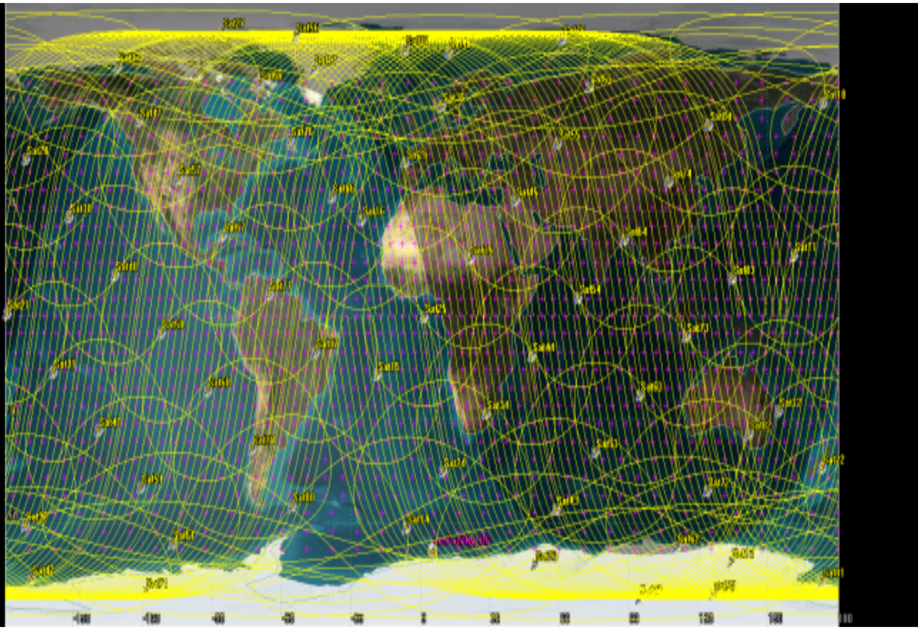
MBSE: Architecture Generation

Major Variables to generate architectures:

- Altitude (Baselined at the Landsat orbit from ERB instruments)
- FOV (assumed from RAVAN radiometer = 130 deg)
- Inclination (Baselined to Landsat)
- Number of satellites (arrangement varies = uniform, clustered)



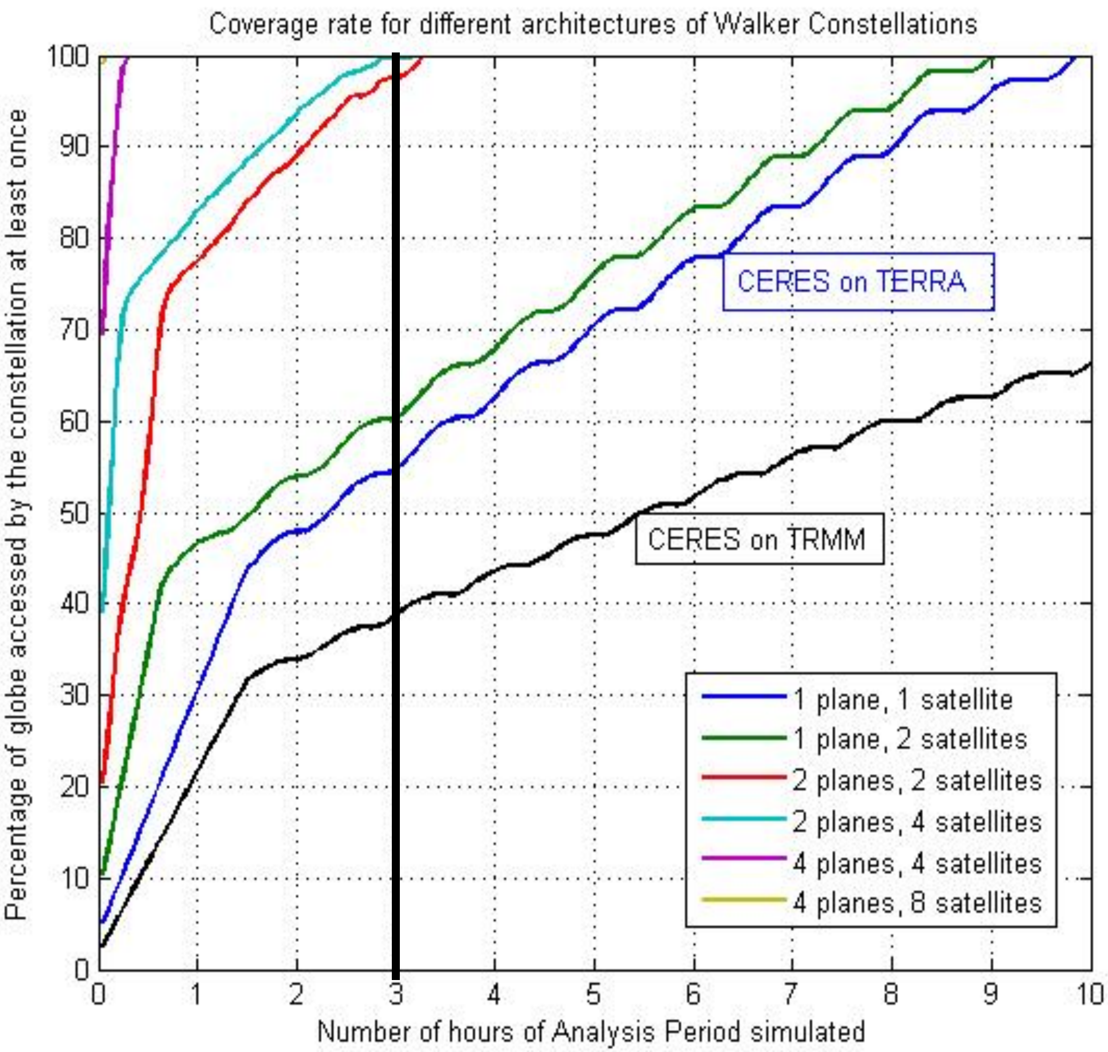
32 satellites = 8 planes X 4 satellites/plane

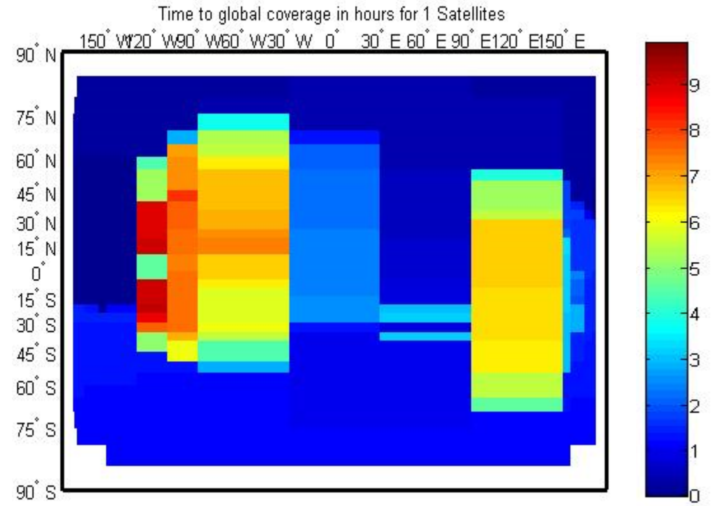


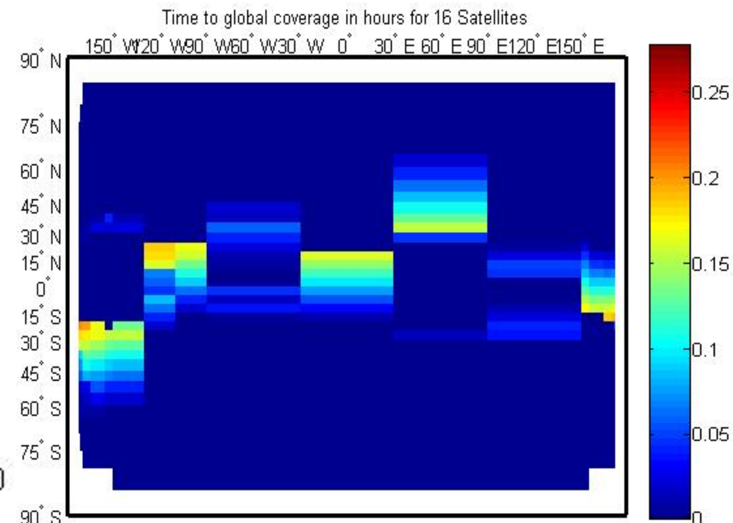
64 satellites = 8 planes X 8 satellites/plane

MBSE: Interim Metrics for Performance

Major metrics – Spatial and Temporal





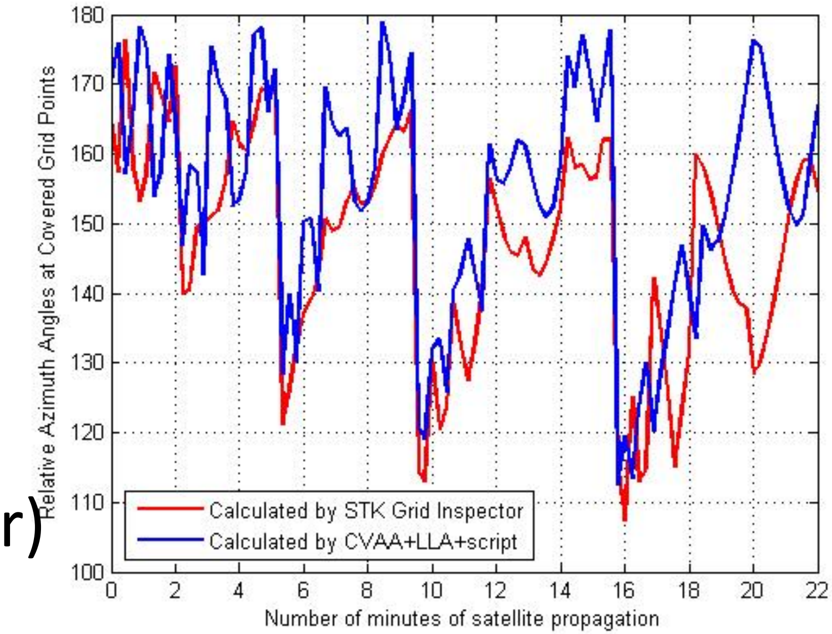


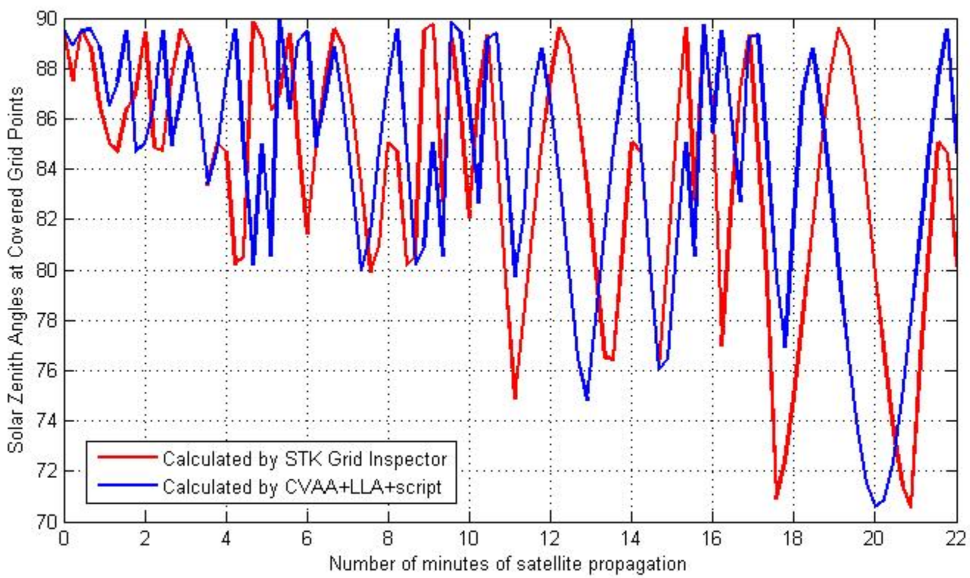
MBSE: Interim Metrics for Performance

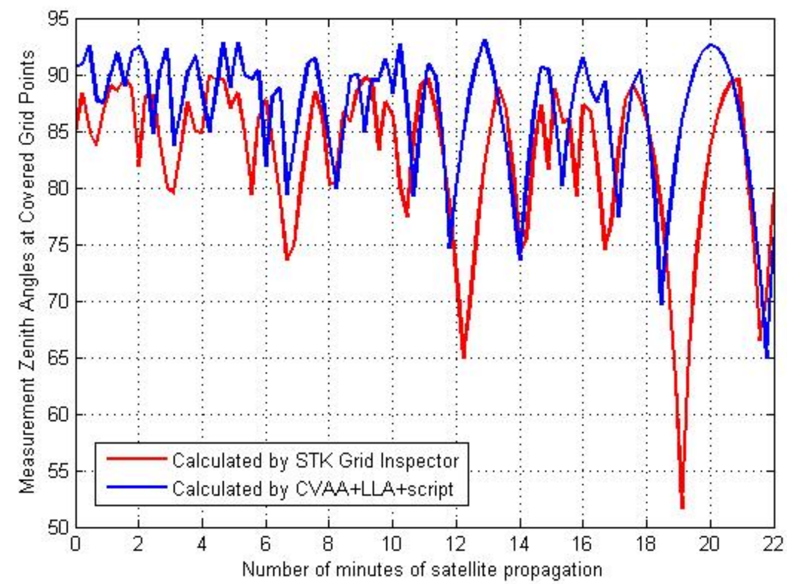
Major metrics – Angular

Calculate all 3 angles for
for every gridpoint+time

Compare developed algorithm
results with STK calculated
results (1500X faster, <4° error)



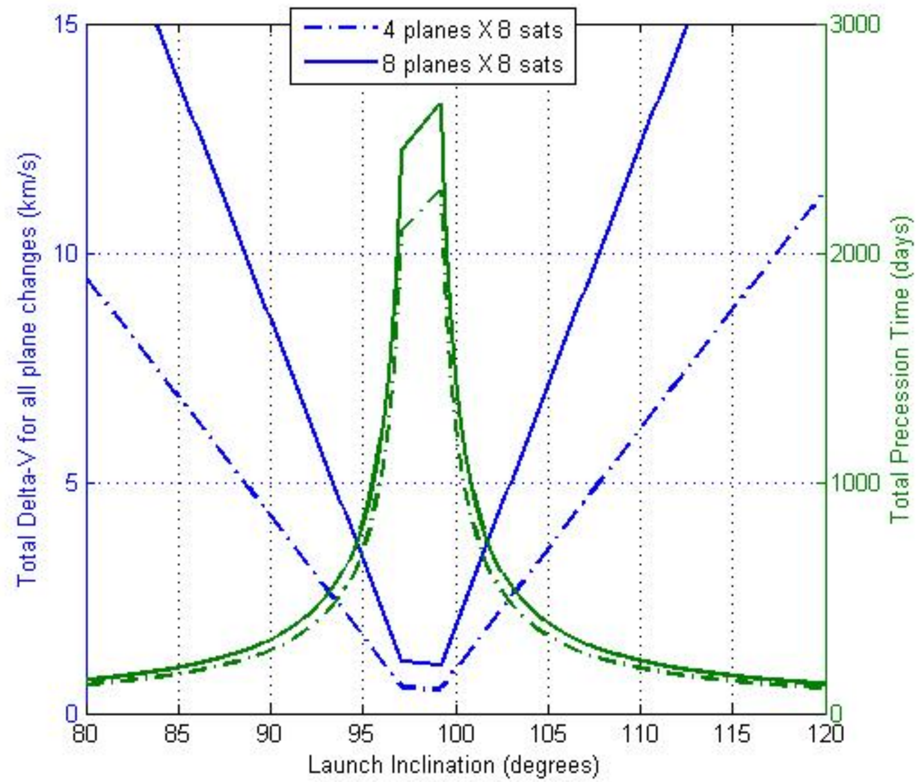




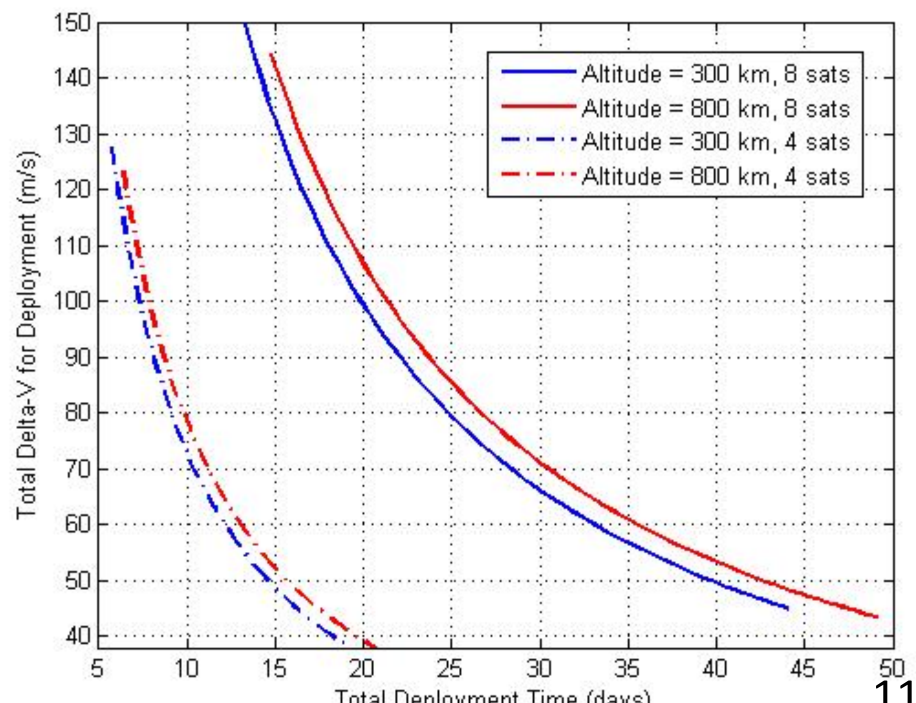
MBSE: Evaluating Support Capability

- Propulsion for orbit initialization and maintenance
- **Initialization** = (1) Secondary launch w/o propulsion OR (2) Secondary launch w/ propulsion to arrange into planes, and then arranging around the plane.

RAAN Spread –> Launch into different inc + use dV and precession time to move RAAN



TA Spread –> Use an elliptical transfer orbit to achieve the appropriate phasing before entering the final orbit.

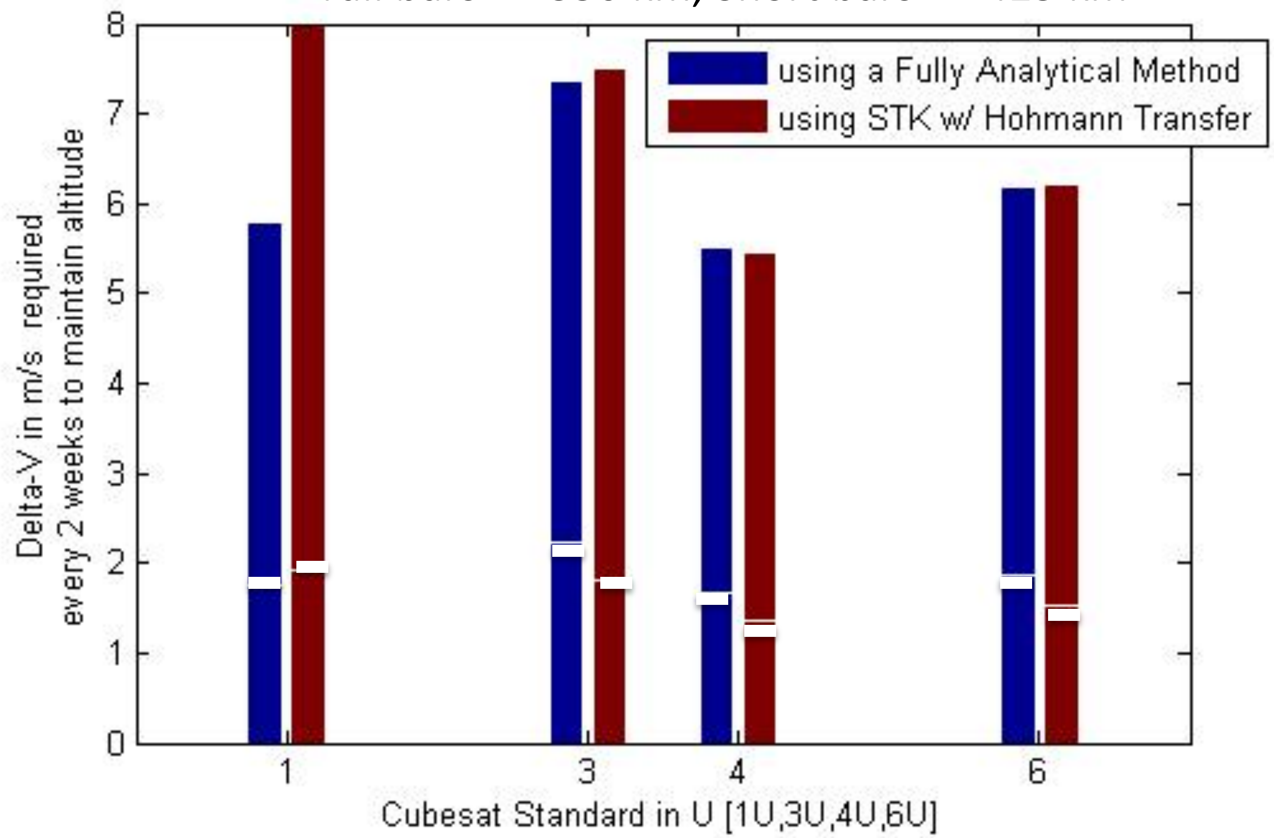


MBSE: Evaluating Support Capability

- Propulsion for orbit initialization and maintenance
- **Maintenance** = To counter altitude drop due to atmospheric drag only because all orbit params but RAAN and TA are the same for uniform constellations

Like before, an analytical automated algo was developed and compared to STK for plugging into the MSBE:

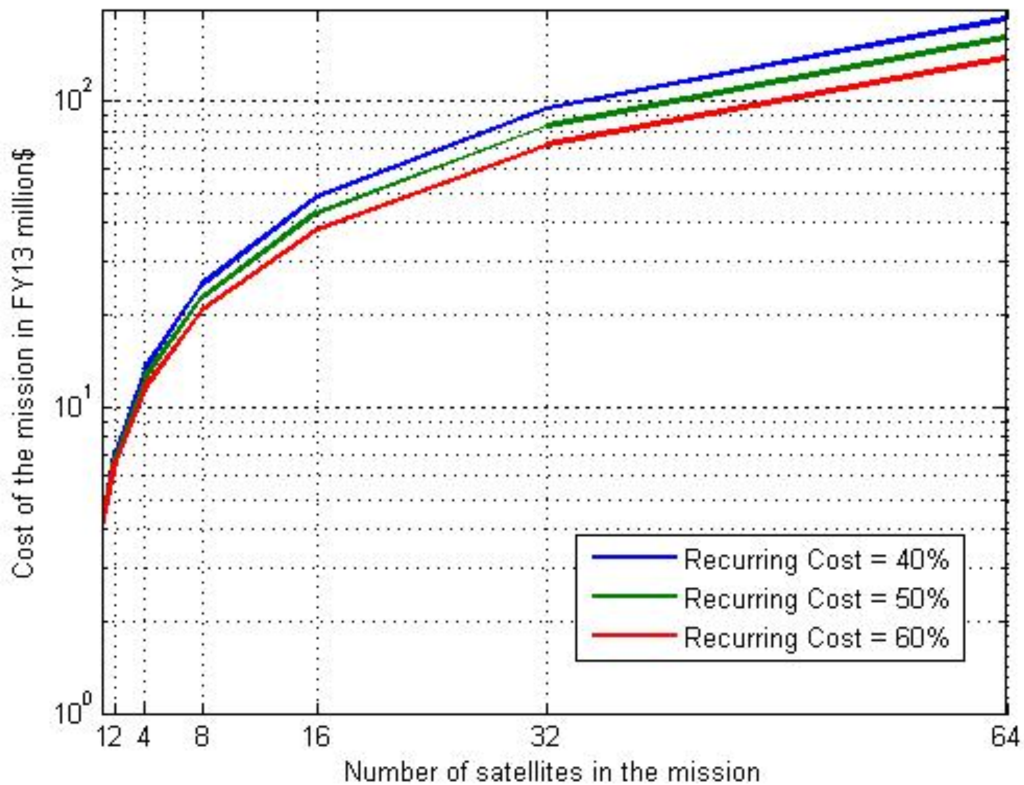
Tall bars => 350 km, Short bars => 425 km



MBSE: Sizing Costs

- Development costs
  - Single TFU cost estimated from RAVAN = $4 mill
  - Learning curve parameter calculated as 0.662 from APL published data of making multiple instruments
  - Recurring cost assumed variable within bounds
  - Cost capped within EVM
- Launch costs ignored
- Initialization and Maintenance costs
  - Function of delta-V alone
  - Ground system support ignored

Development Cost =

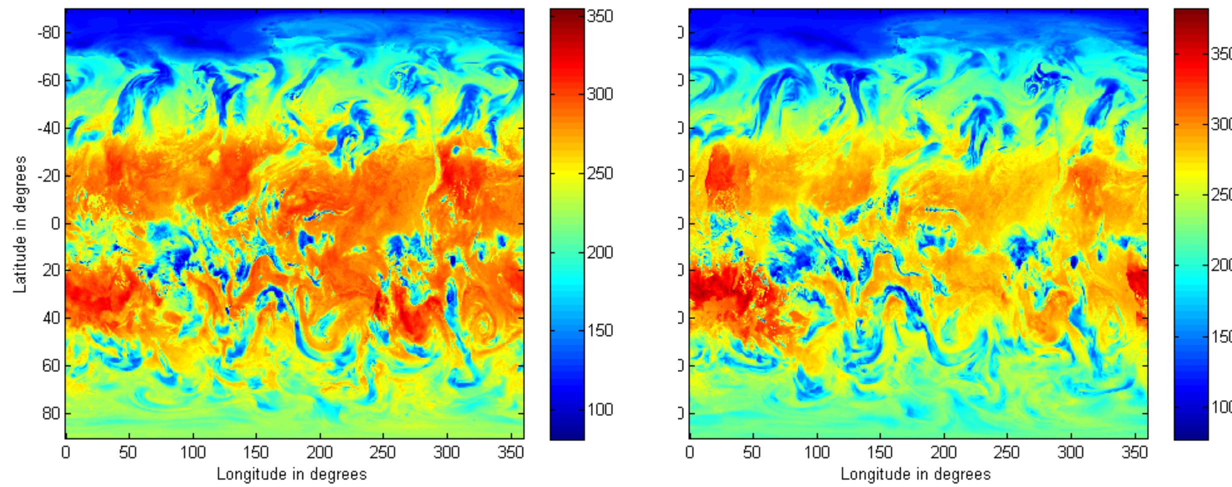


+ Init + Maint cost because they depend on init strategy (time to science trade) and maint strategy (lifetime trade)

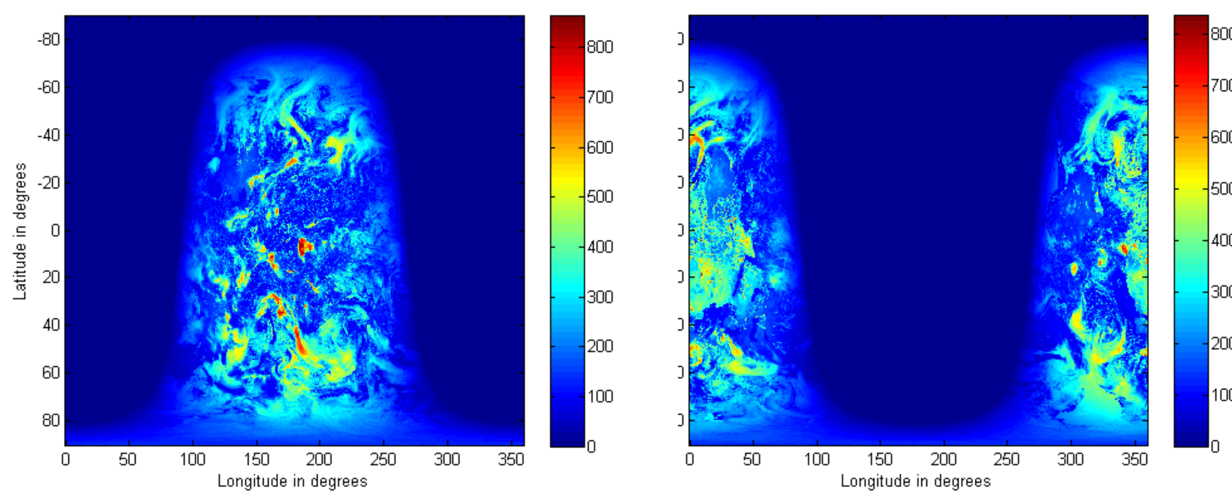
OSSE: Setting up the “Truth”

UMGLO Model Output

Find the global TOR (long and shortwave) every 3 hours:



LW (up) & SW (down) : 29 Aug 2010, 00:00 (left) & 12:00 (right)

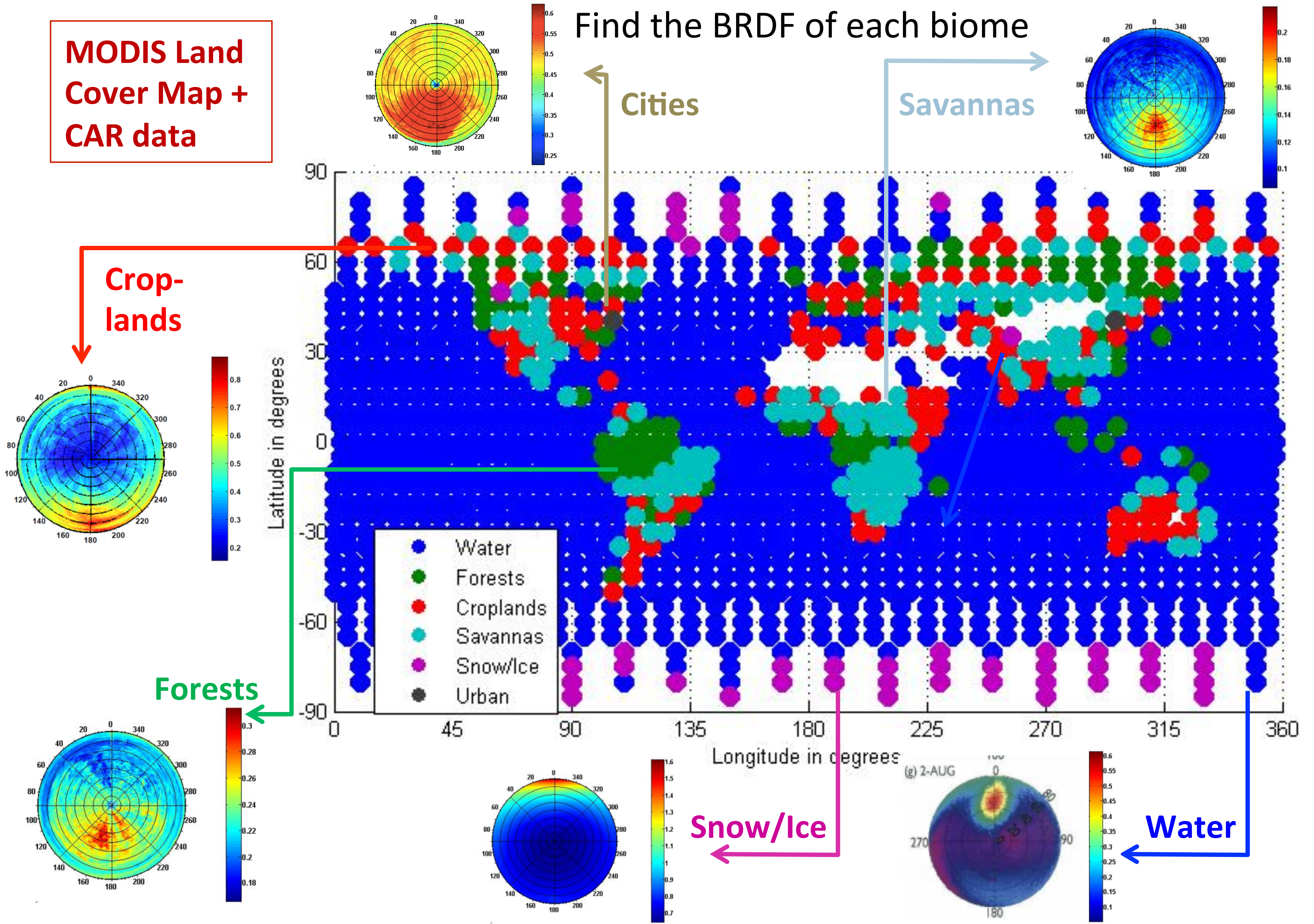


The Met Office global forecast model was used to generate the TOR data and obtained with permission from Christine Chu, University of Manchester.

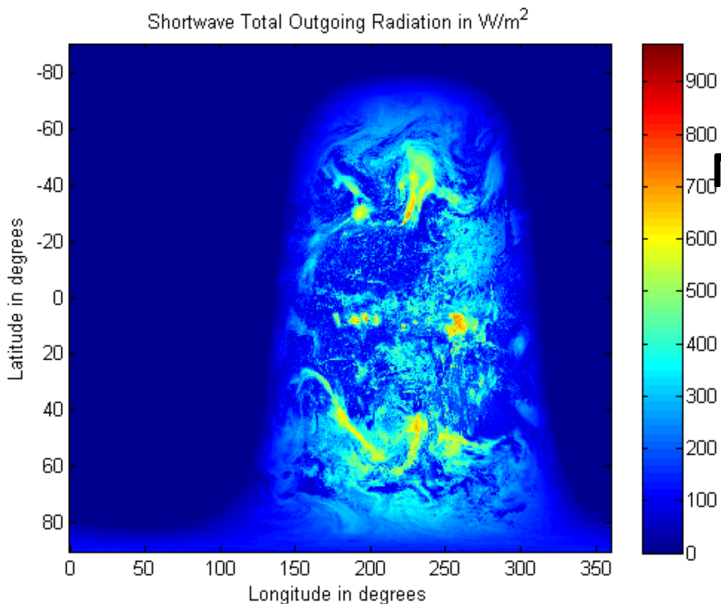
BUT the data is isotropic!

OSSE: Setting up the "Truth"

MODIS Land Cover Map + CAR data



OSSE: Setting up the "Truth"



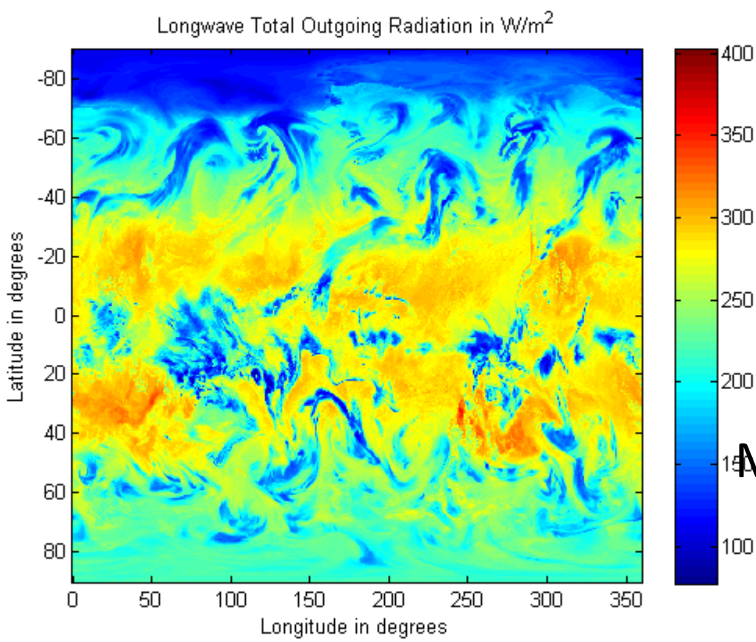
New Truth (time, lat-lon, MZA,RAZ)

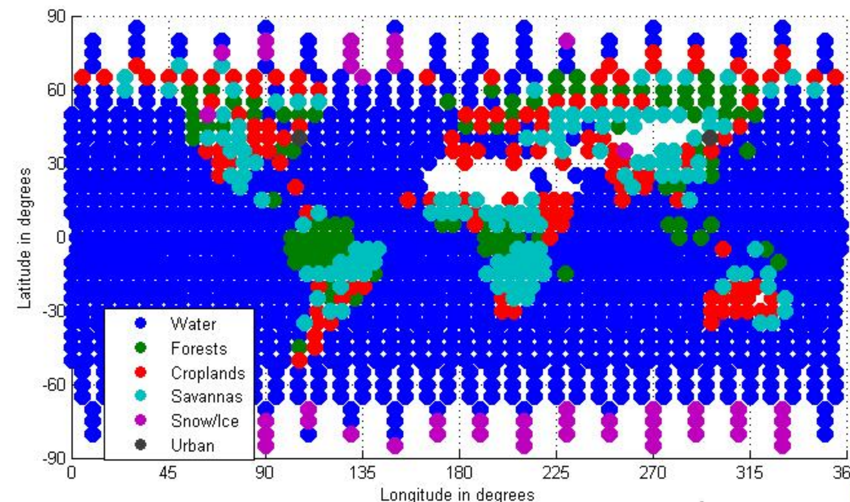
=

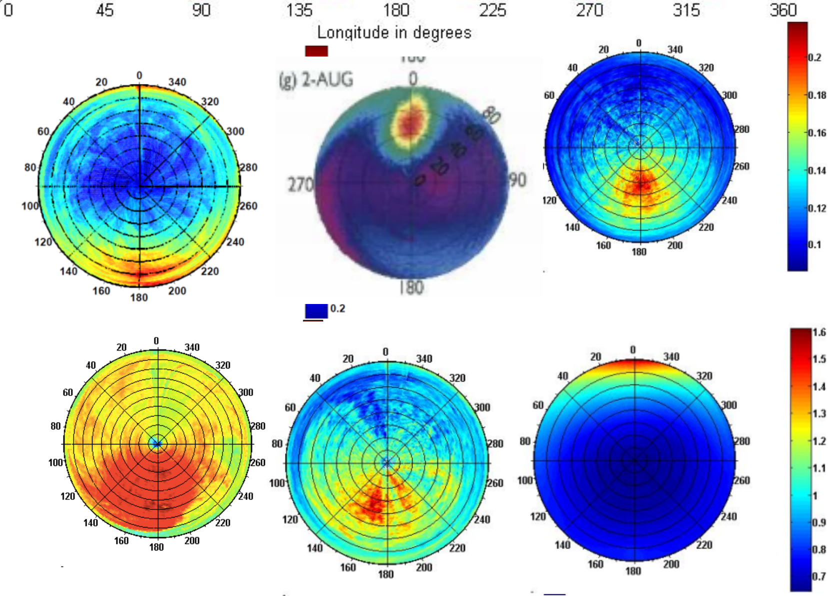
UMGLO (time, Lat-lon)

X

BRDF (lat-lon, MZA,RAZ)







MZA= Measurement Zenith Angle

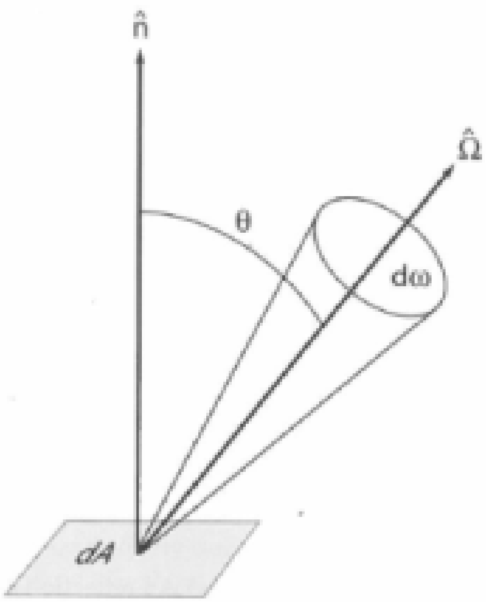
SZA = Solar Zenith Angle, assumed C

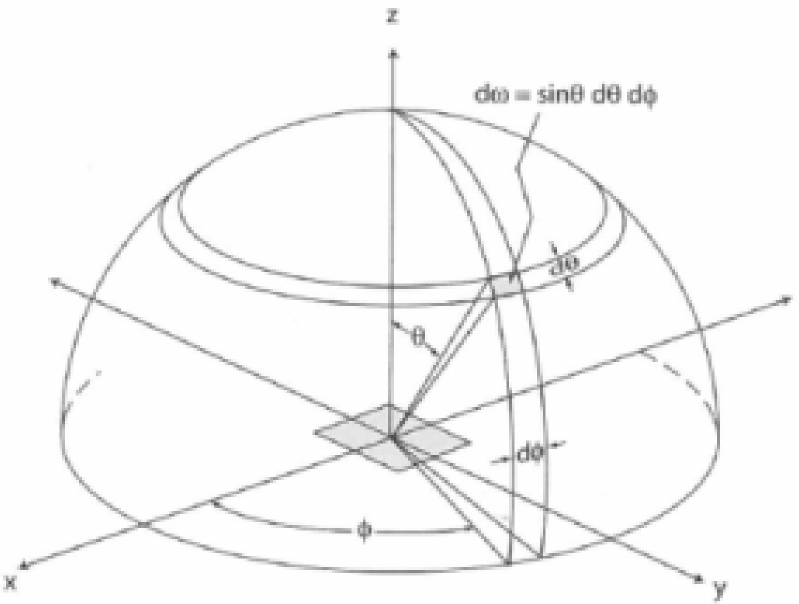
RAZ = Relative Azimuth wrt Sun

OSSE: Flux Integration over FOV

From Radiance to Flux over Field of View (FOV)

For each satellite at each time, treat each seen grid point (from MBSE model) as the center of a spherical triangle and adding all true radiances, weighted by angle & area.





$$Flux = \int_{2\pi} Radiance(\Omega)cos(\theta)d\omega =$$
$$\int_0^{2\pi} \int_0^{\pi/2} Radiance(\theta,\varphi)cos(\theta)sin(\theta)d\theta d\phi$$

OSSE: Spherical Harmonics Model

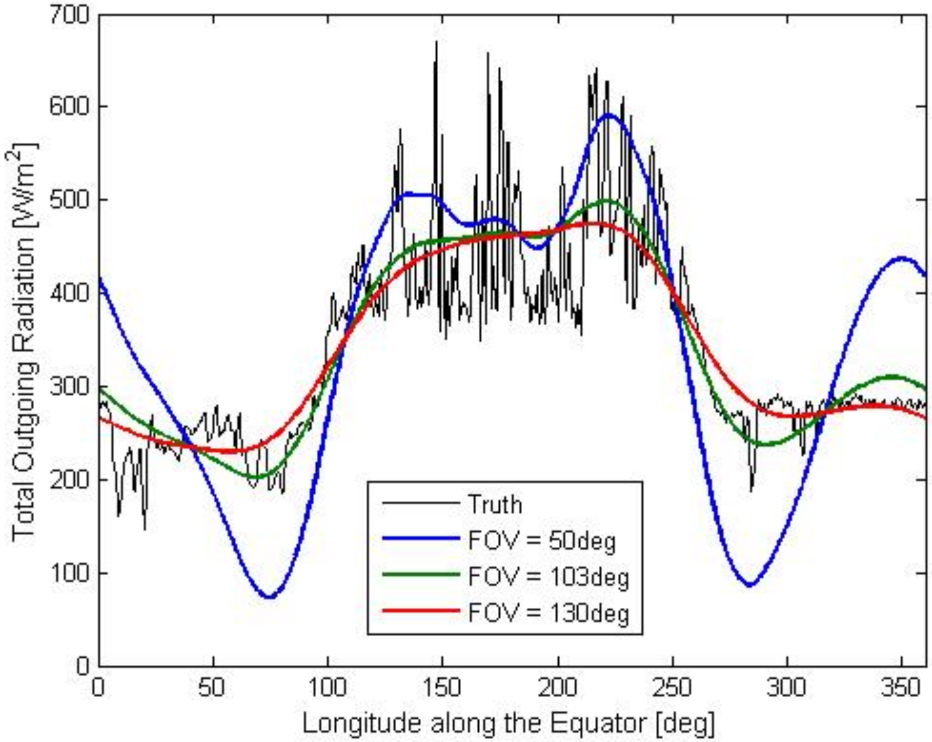
- True flux from each grid point (s) is a weighted sum of basis functions (Sph. Harms)

$$s(\theta,\lambda,t)=\sum_{l=0}^{L}\sum_{m=0}^{l}C_{lm}(t)Y_{lm}^{c}(\theta,\lambda)+S_{lm}(t)Y_{lm}^{s}(\theta,\lambda)$$

- Measured flux (y) is the FOV integration over s, and also has a Sph. Harm rep

$$y(\theta,\lambda,t)=\frac{1}{\Omega}\int_{\Omega(\theta,\lambda)}s(\theta',\lambda',t)\,d\Omega+e$$

$$y(\theta,\lambda,t)=\sum_{l=0}^{L}\sum_{m=0}^{l}\left[\bar{C}_{lm}\bar{Y}_{lm}^{c}(\theta,\lambda)+\bar{S}_{lm}\bar{Y}_{lm}^{s}(\theta,\lambda)\right]+e$$



- Coefficients of y and s are related by a Pellican cap parameter (smoothing operator)

$$\begin{Bmatrix}\bar{C}\\ \bar{S}\end{Bmatrix}=\beta_l\begin{Bmatrix}C\\ S\end{Bmatrix}$$

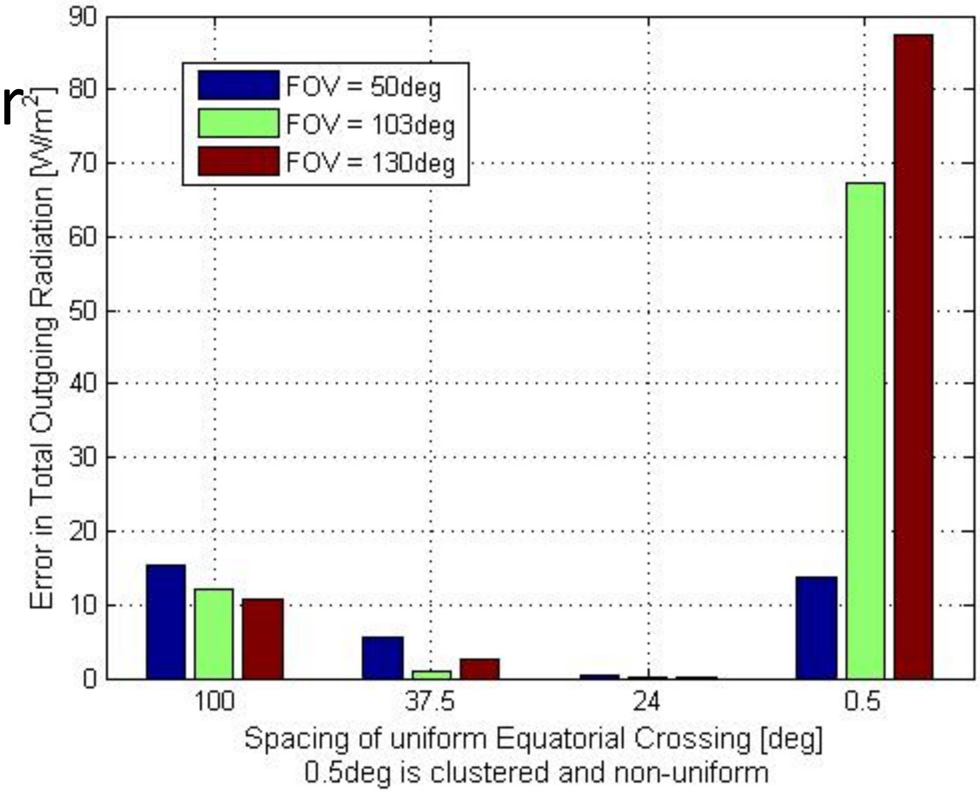
$$\beta_l=\frac{1}{1-\cos FOV}\frac{1}{l+1}\left[P_{l-1}(\cos FOV)-\cos FOV\,P_l(\cos FOV)\right]$$

$$\beta_1=\frac{1}{2}\left[\sin FOV\cot\frac{FOV}{2}\right]\qquad \beta_0=1$$

Model proposed by: Shinchan Han, NASA GSFC

OSSE: Spherical Harmonics Model

- Given truth, measured flux can be calculated per point analytically
- For any given constellation architecture, pick the points seen by the satellites (MBSE output)
- Run inverse model to estimate original spherical coefficients and compare with truth



Measurements with equal spacing arranged around Equator

Clustered Measurements Spread over 24°

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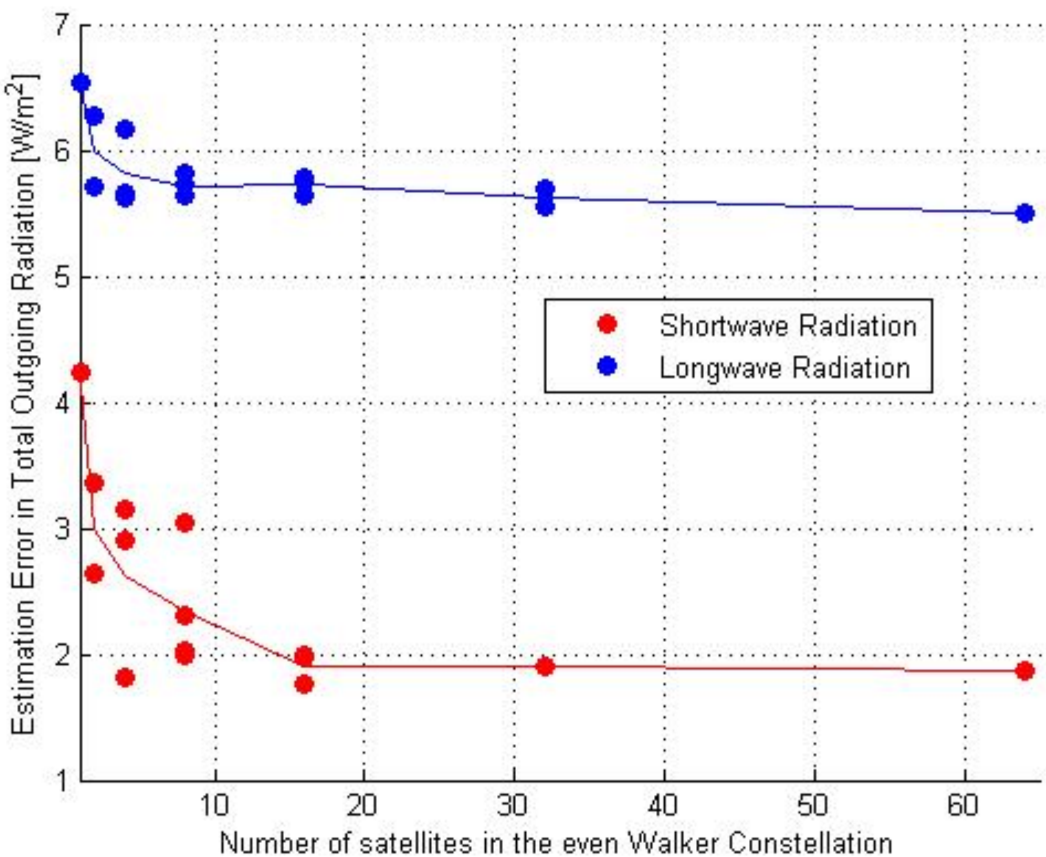
MBSE+OSSE: TOR Errors wrt Truth

When an ***isotropic*** truth is used, the errors reduce with the number of satellites, if evenly arranged, and then saturates after full coverage. If uneven, there may be oscillation before saturation.

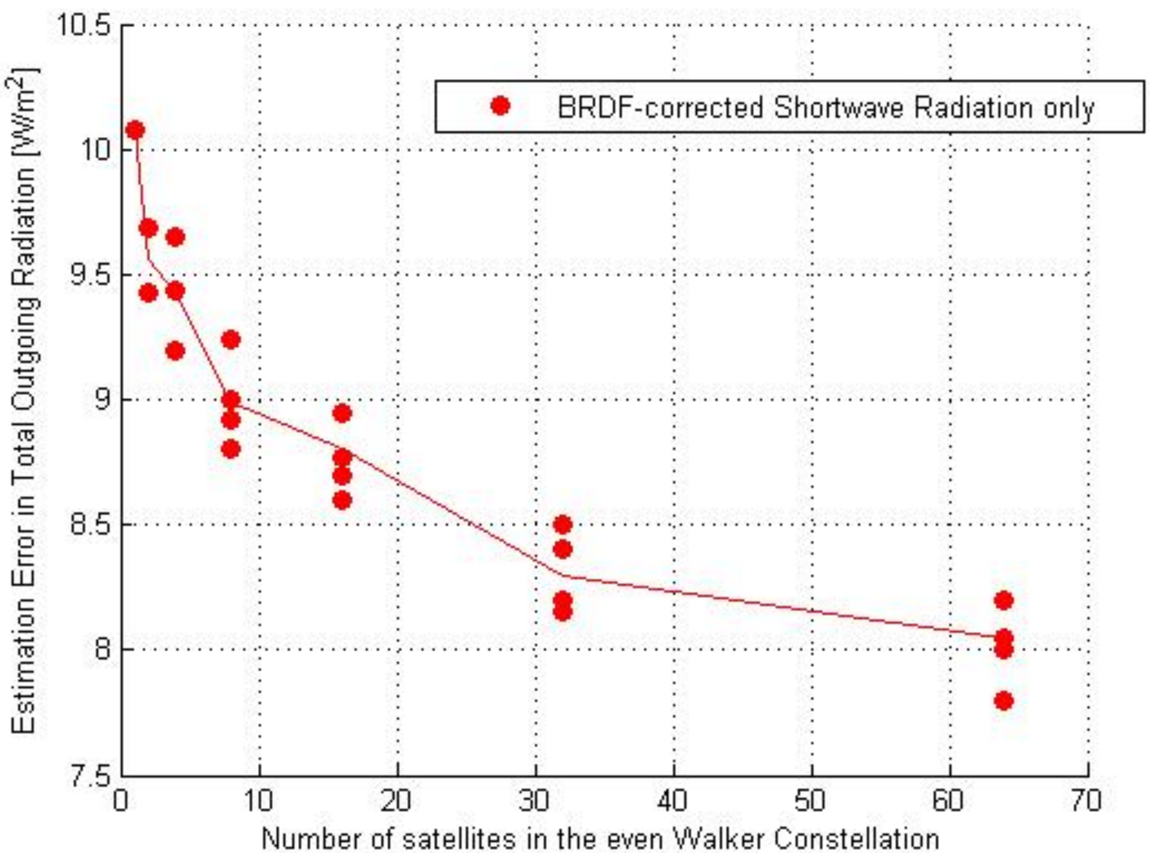


MBSE: 710 km, 130° FOV, 98.18° inc
OSSE: UMGLO truth, Averaging model

Comparison to another monolith (CERES on TRMM): Flux errors wrt UMGLO are *15.37 W/m^2 for shortwave radiation and 34.31 W/m^2 for longwave radiation.*

MBSE+OSSE: TOR Errors wrt Truth

If an ***anisotropic truth*** is used, errors increase overall BUT reduce with the number of satellites because more overlap allows better angular estimation. Need a functional model to represent TOR.



MBSE: 710 km, 130° FOV, 98.18° inc
OSSE: UMGLO + CAR truth, Averaging model

Anisotropic radiation field requires more satellites to for same performance because the angular variation of data needs to be captured along with the spatial and temporal variation

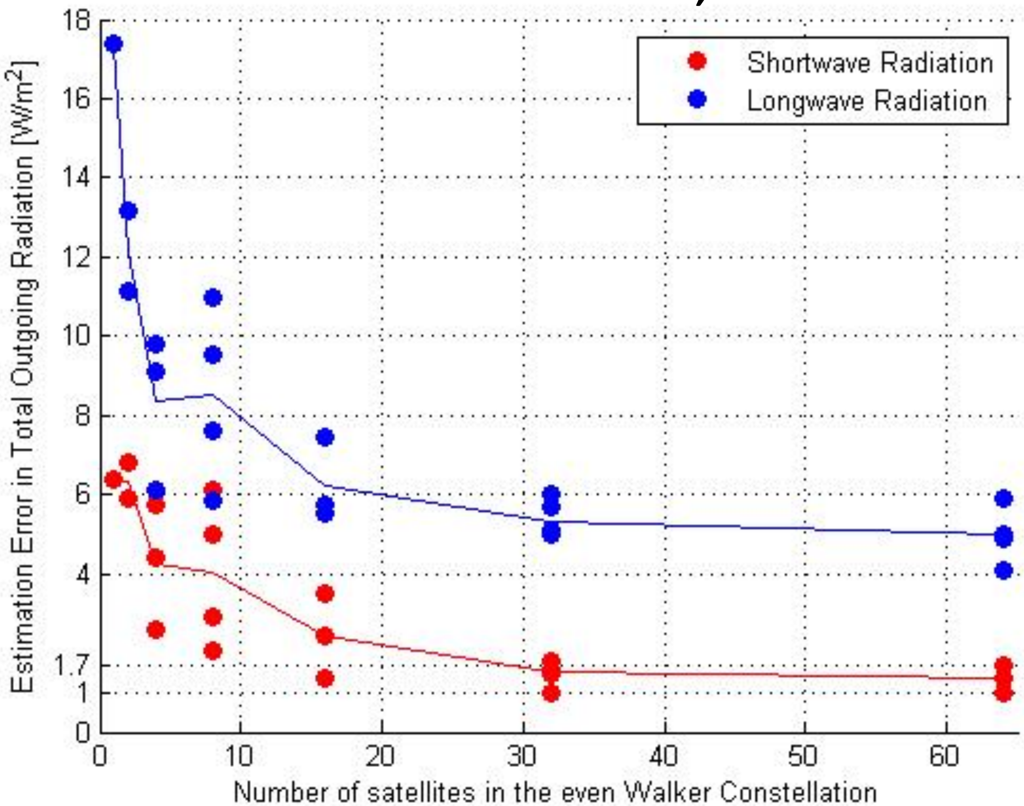
MBSE+OSSE: TOR Errors wrt Truth

When the ***spherical harmonic model*** is used, the number of satellites required is pushed down because of its higher fidelity and functional representation.

NOAA accuracies not reached within 64 satellites for 1D rep at Equator (worst case).

More will be needed globally!

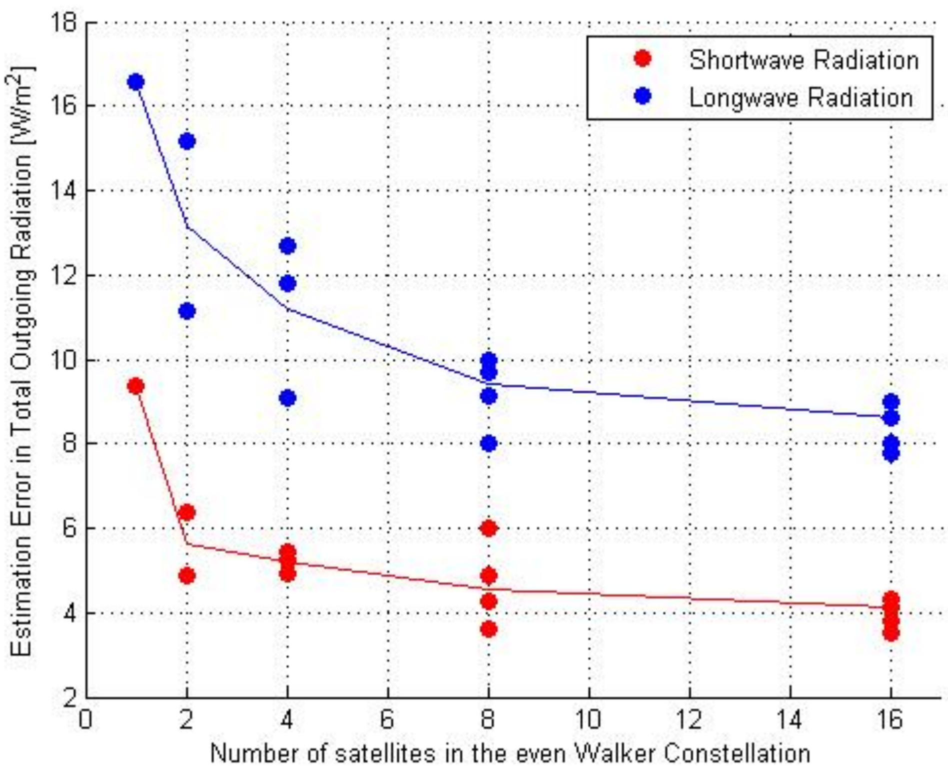
MBSE: 710 km, 130° FOV, 98.18° inc, even&uneven
OSSE: UMGLO + BRDF truth, SH Model

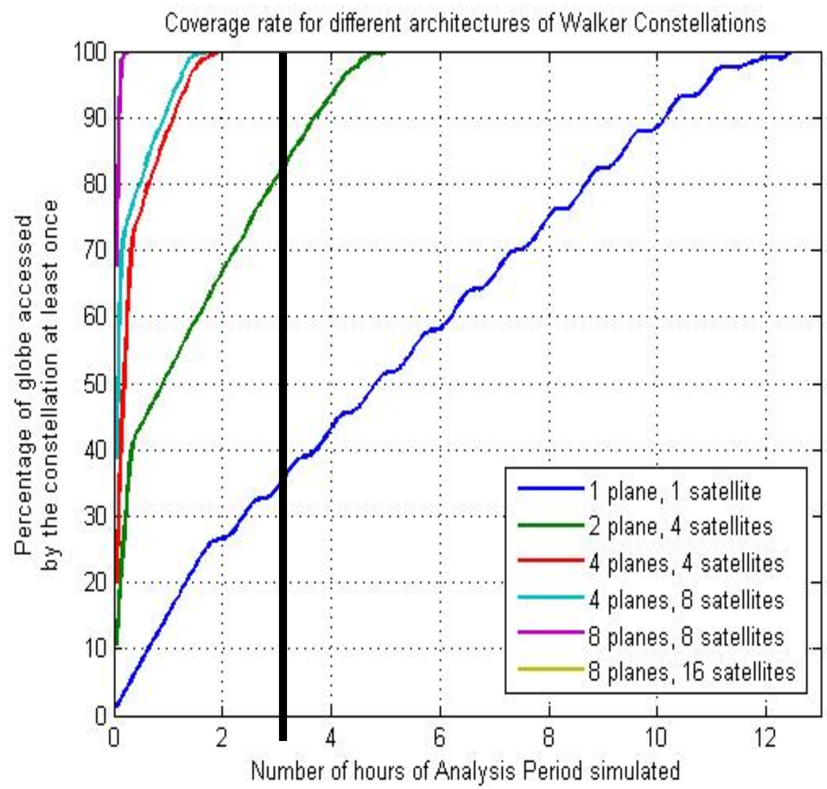


MBSE+OSSE: TOR Errors wrt Truth

When ***altitude is lowered*** (710km => 500 km), coverage rate drops and errors increase for the same satellite numbers.

Angular resolution increase is a benefit especially in anisotropic truth is used so complicated dependence on altitude is seen (***spatial – angular trade-offs***)





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Conclusions and Future Work

- MBSE + OSSE coupled model proposed for mission design of small sat constellations to ***fill specific, quantifiable gaps left by flagships***.
- All models are ***modular and flexible***. E.g. flagship is ERB and TOR
- MBSE model was coded in MATLAB, STK (mostly for validation) and truth + models constructed for the OSSE in MATLAB, Fortran.
- Some insights can be drawn from sub models to constrain trades (delta-V cap, cost cap, FOV and clustering influence on errors, etc.)
- Full simulations show ***50-70% improvement using 64 satellites and 10-20% using 16 satellites compared to monolith OSSEs***.
- 64 satellites at 710 km can achieve ***errors wrt truth of 1.5 and 5.2 W/m^2*** in short and longwave, when NOAA requires 1 and 1.7W/m^2.
- Spatio-angular trade-offs can be understood ***only with the OSSE***
- OSSE models to be improved (2D SH), cost models more detailed (C2C) & more launch/init strategies for Pareto front construction.

Acknowledgments

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Thank you!

Questions?

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