The Power of Inexpensive Satellite Constellations

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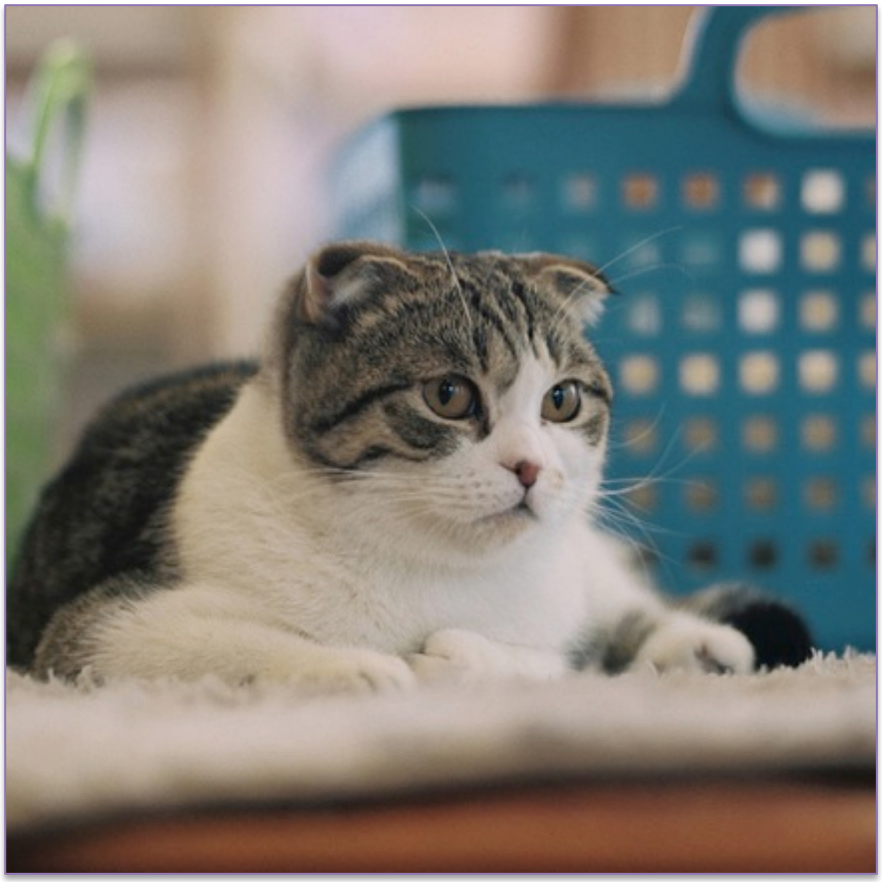
Why conduct science from Space?

Value Proposition of Space



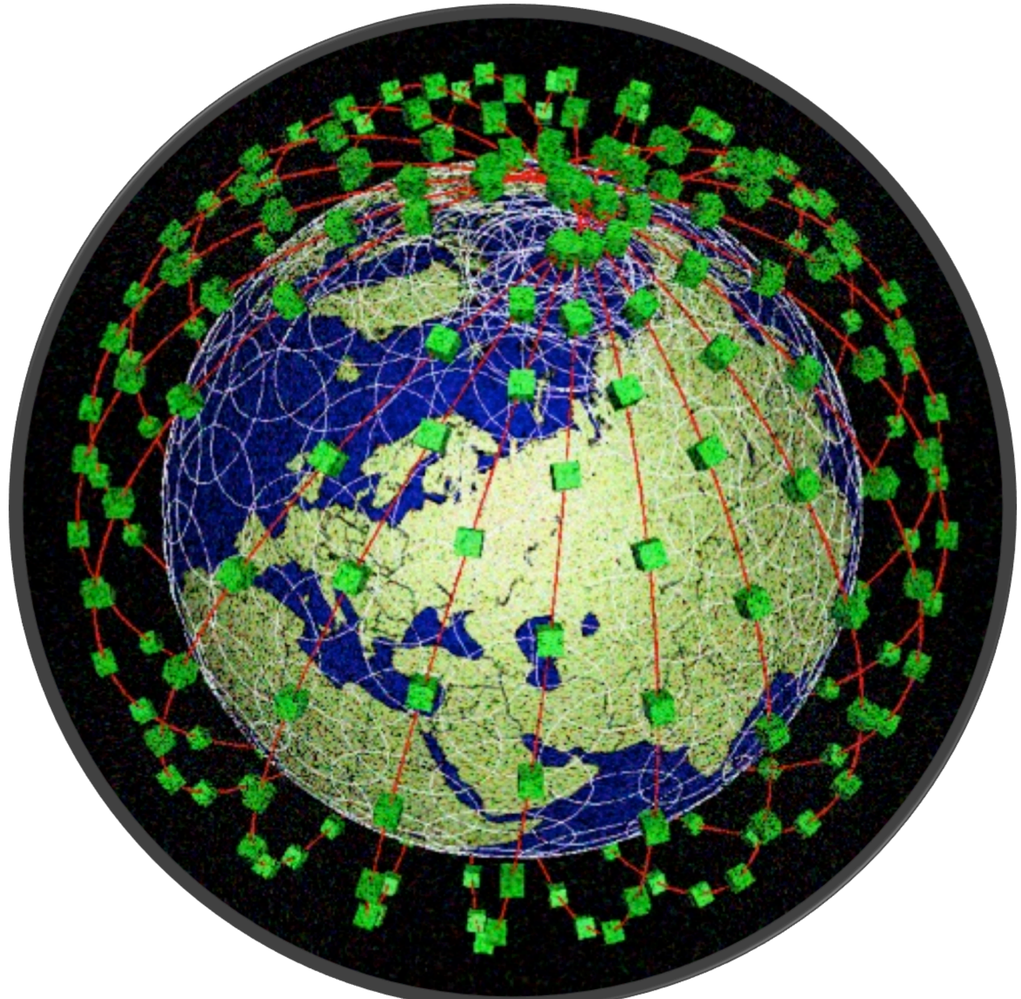
What is the value proposition of cube, small-sats, and hosted-payloads for Earth science?

Enabler

- Lowered binary cost of Launch $15M→$200k
  - Lowers barriers to entry → Expanded Participation
  - Creates a market for standardization
  - Increases risk tolerance
  - Faster iteration-Agile Processes
  - Lowered costs allow us re-envision how we design space missions – and solve science problems

Global satellite systems

A dense constellation of LEO satellites providing everywhere, all the time Earth and Cosmos awareness



Fundamental Drivers for Omnipresence Climate Science

- Quantities of interest are solar-time, Universal-time, spatial, and and angular (BRDF) dependence
- Multi-dimensional information-cube, *sampling only a sliver*
- Many science questions can not be answered without accurate global integration

What Earth Science Questions Need Omnipresence?

- **What is Earth's Radiation Balance**
- **How does terrestrial photo-synthetic production keep up with CO_2 Emissions, and will the Biosphere saturate?**
- **How does large amounts of water move regionally at daily scales?**
- **What is the relationship between land surface changes and the environment and economy?**
- How does the magnetosphere and ionosphere respond during storm-time
- How many Earth-like Exo-planets are in our local neighborhood?

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GEOScan

A Geoscience Facility from Space

http://www.facebook.com/GEOScanEarthScience

NSF

Space Dynamics Laboratory

APL

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THE AEROSPACE CORPORATION

MIT

Earth Radiation: Simple *and* complex

ERI = TSI/4 – TOR [in W/m^2]

Absolute ERI Uncertainty

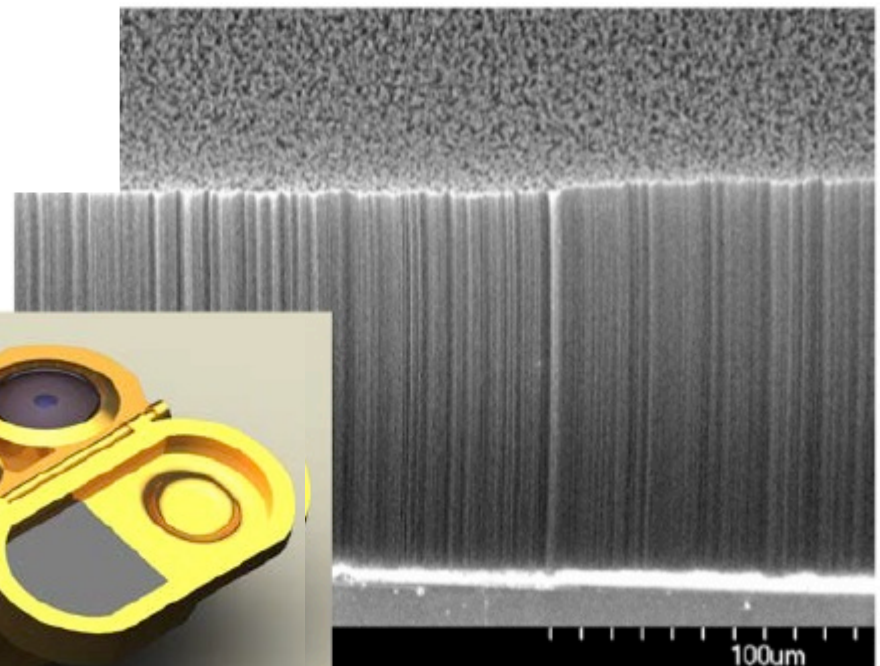
ERI (W/m^2)	Source of Estimate
0.9*	Climate model [Hansen et al., 2005]
0.9* ± 0.5	Best combination of models and observations [Trenberth et al., 2011]
6.5** (–2 to +7)	Satellite [Loeb et al., 2009, Table 2]
0.4 to 0.7	Oceanographers [Trenberth, 2009; Lyman et al., 2010; and von Schuckmann et al., 2009]
–1 to –8*	Re-analyses [Trenberth et al., 2011, Fig. 10] *(see also Fig. D-2 in this proposal)*

** One reanalysis gets a value of +11; also, MERRA range is +3 to –2 depending on time period.*
*** 5 year global mean*

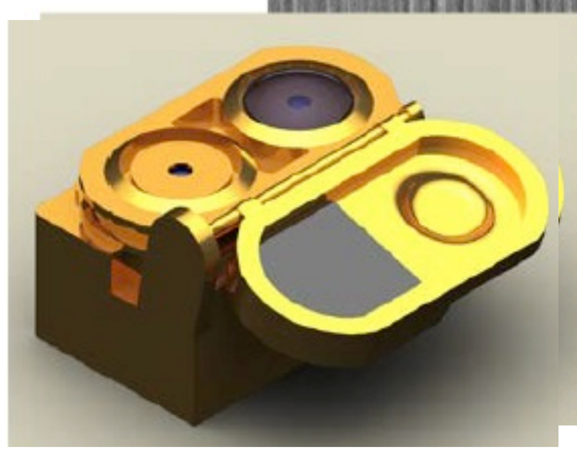
RAVAN

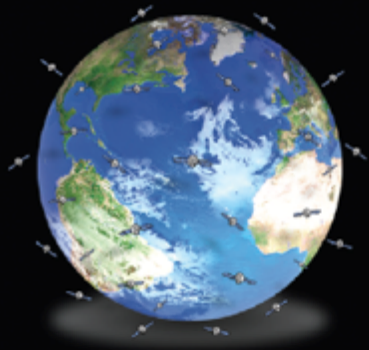
Radiometer Assessment Using Vertically Aligned Nanotubes

Lab-grown forest of Vertically Aligned Carbon Nano-Tubes



VACNT radiometer to be flight tested

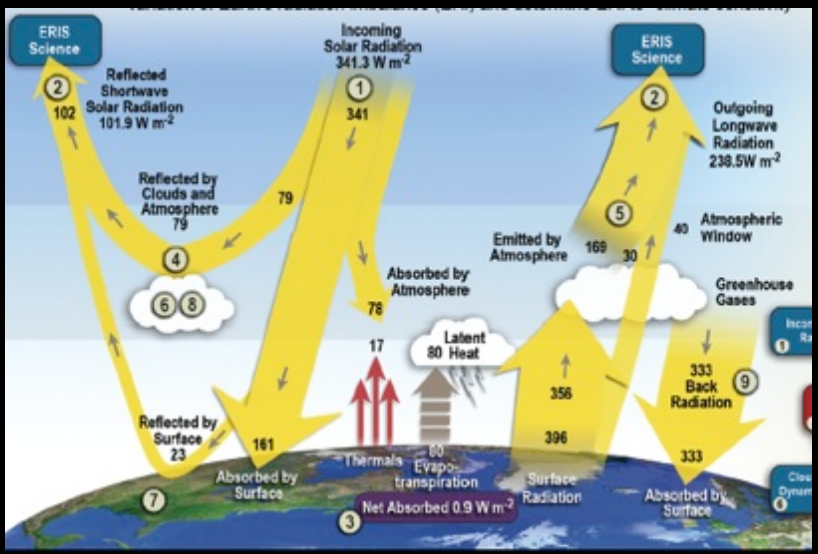




ERIS

Earth's Radiation Imbalance System

Understanding global change by measuring total outgoing radiation



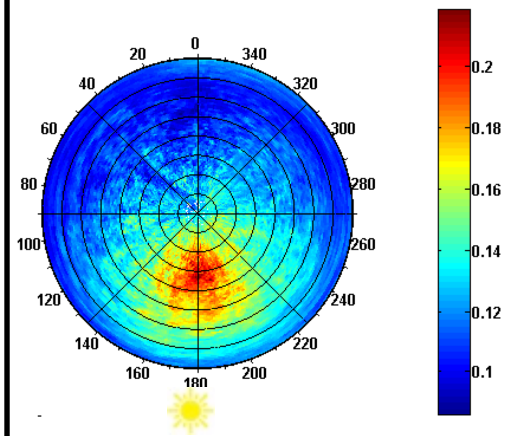
► Climate change is thought to result from a less than 1% imbalance between solar radiation coming and escaping out into space

►ERIS will measure this absolute imbalance for the first time!

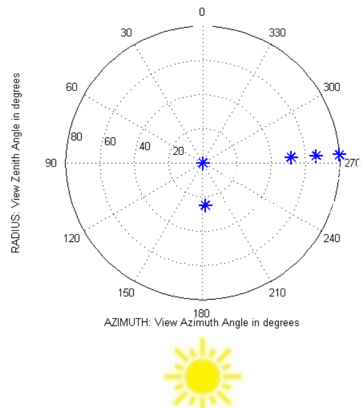
►ERIS will improve climate model performance

BRDF Simulations

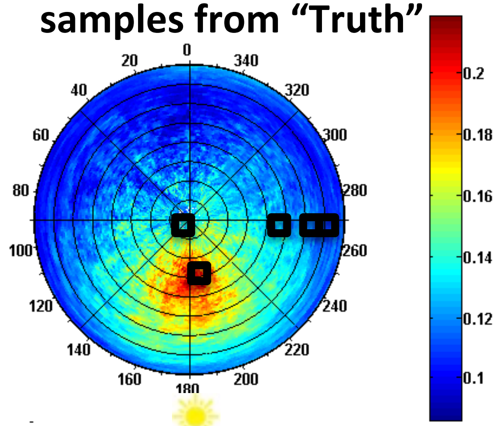
1. True BRDF (CAR data)



2. SE-Model Angular Sampling Outputs



3. Select corresponding samples from "Truth"

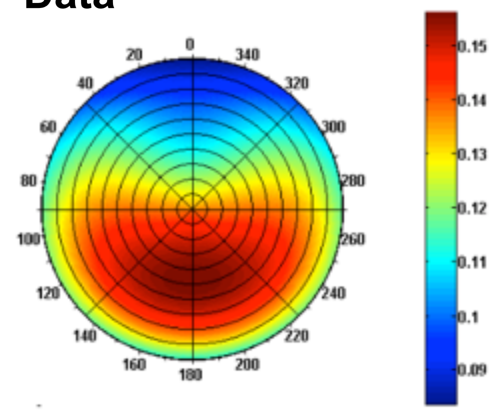


4. Fit known BRDF model and invert for model parameters

BRDF(θs,θv,Φs,λ) = f(params,kernels)

5. Run forward model with inverted parameters

6. Estimated BRDF using a sampling of True BRDF Data



7. Specific Applications (e.g. albedo)

Geophysical variable = f(BRDF)

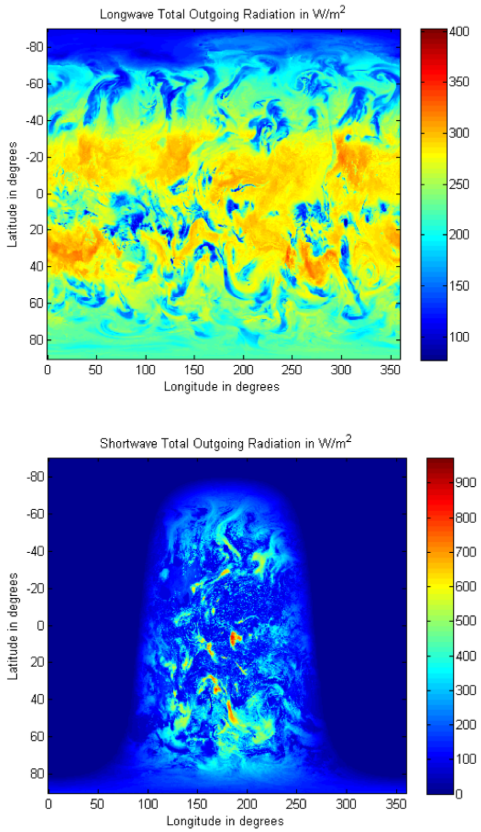
App Error

BRDF Error

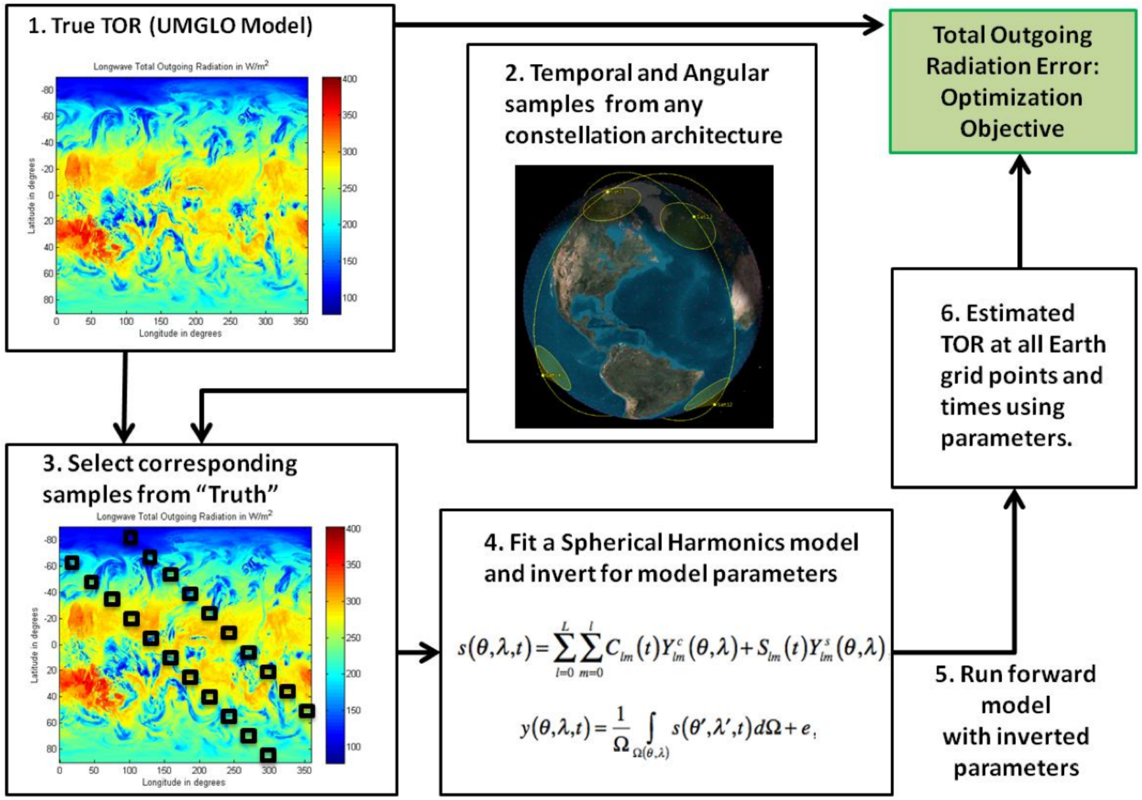
Courtesy Sreeja Nag

How many do we need?

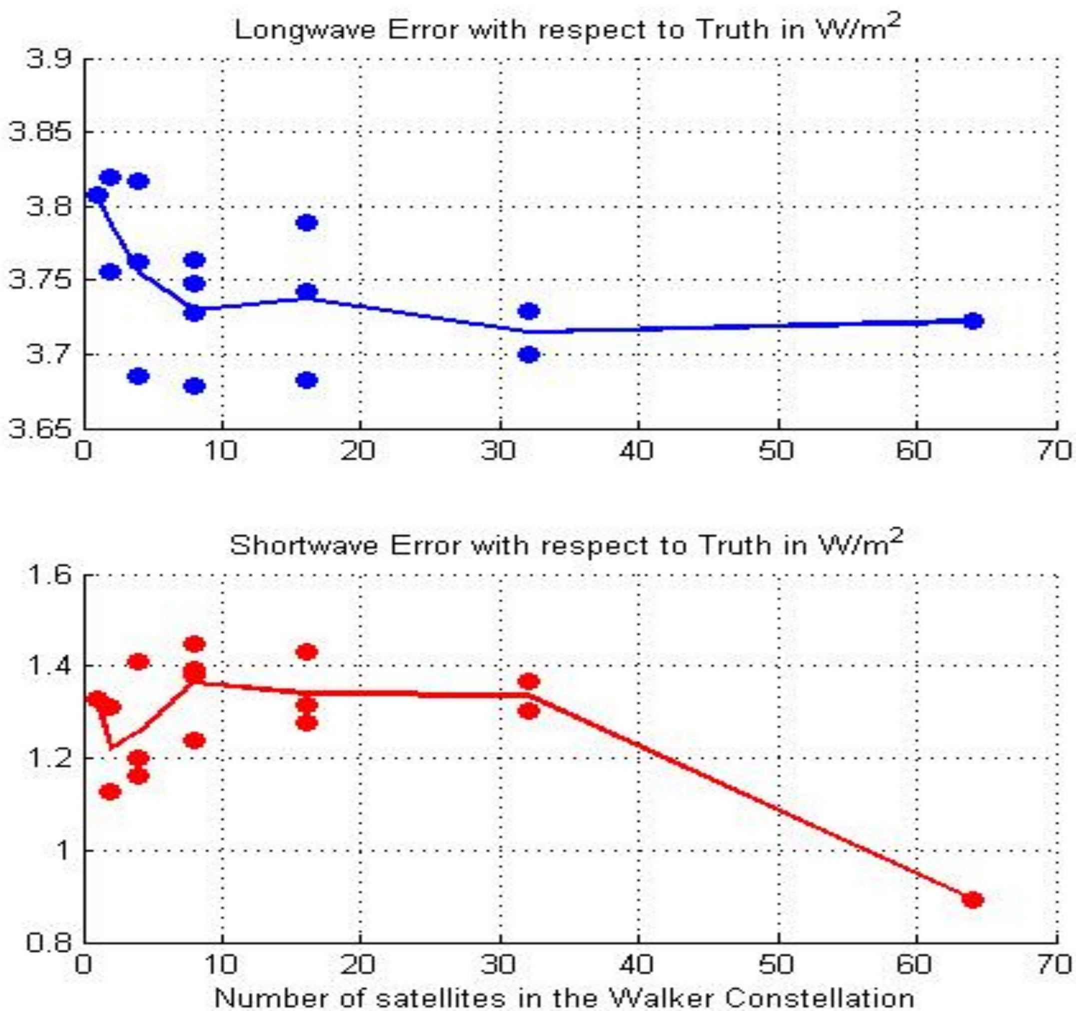
TRUTH AT MIDNIGHT



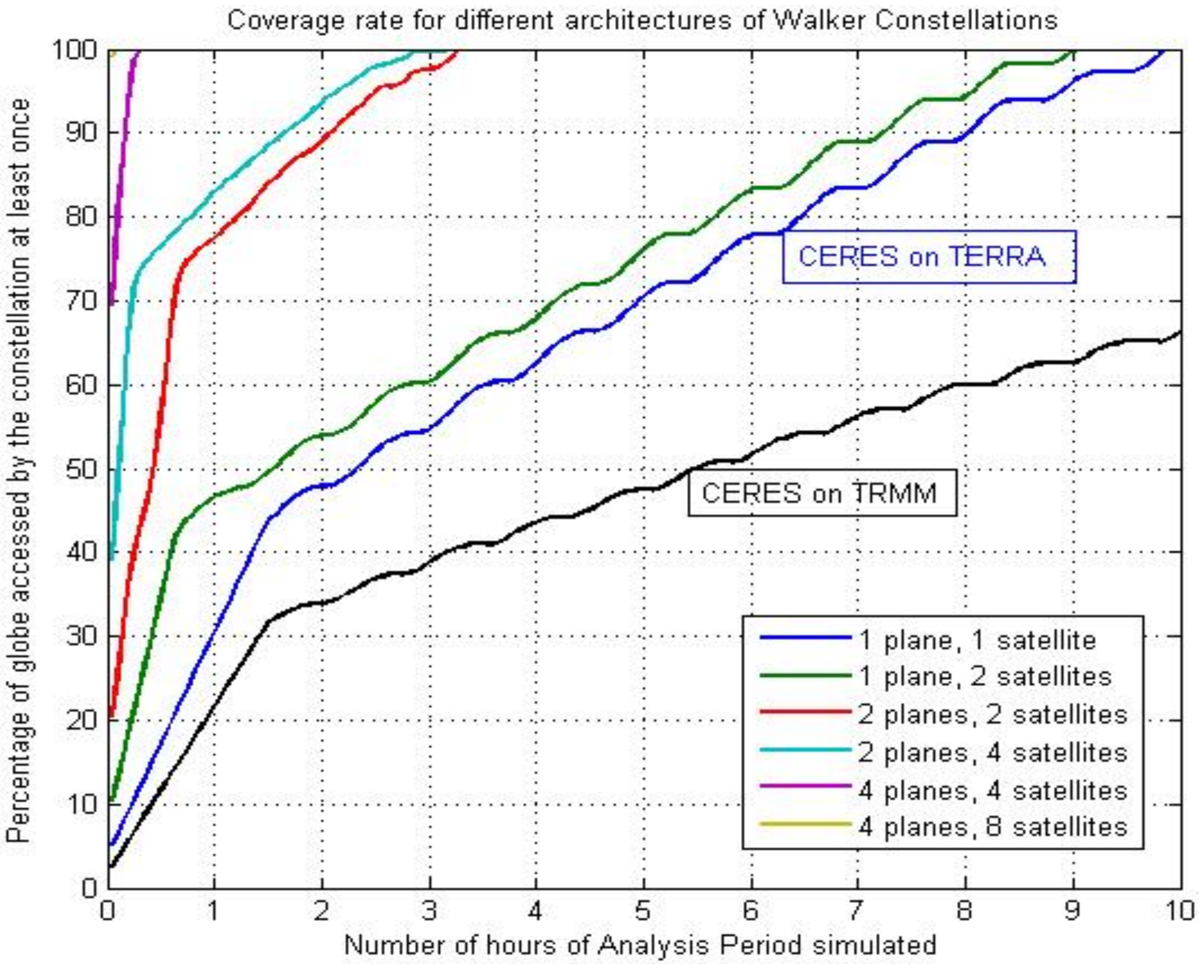
SCIENCE EVALUATION OF OSSE



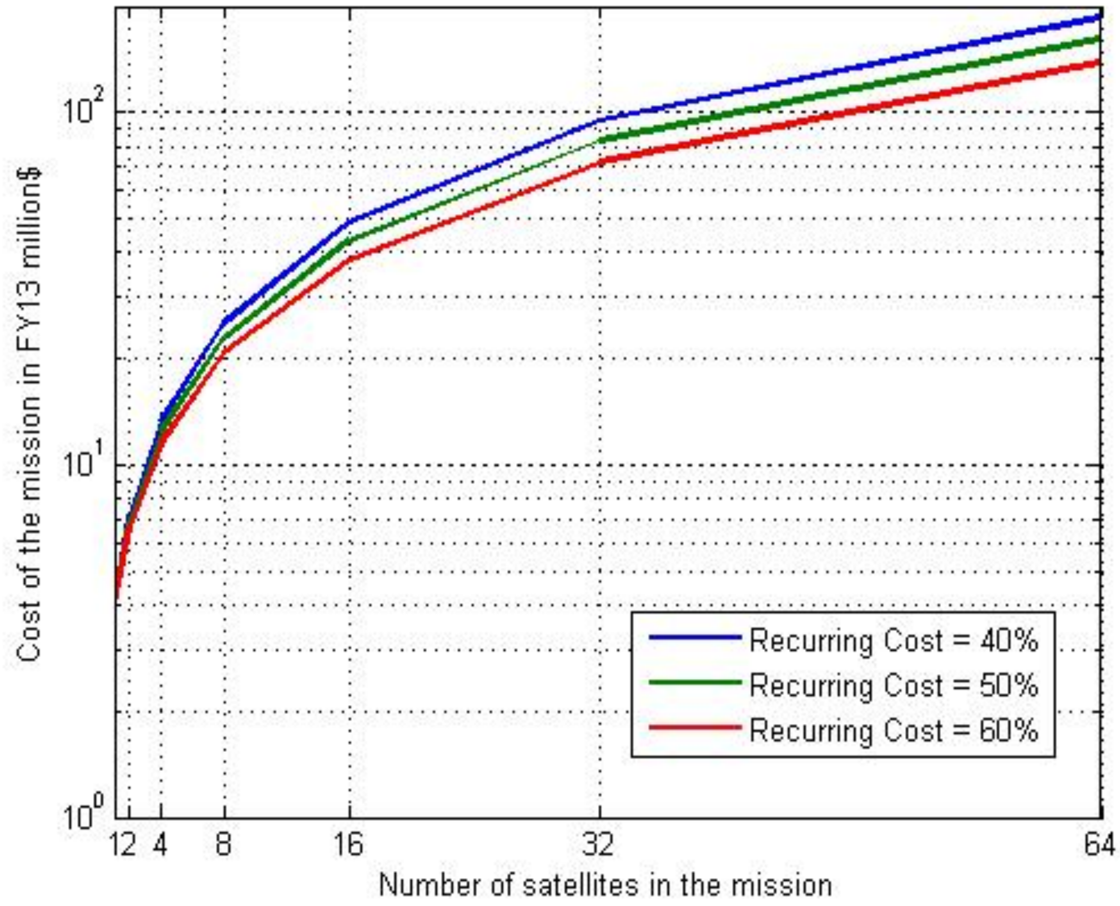
How many do we need?



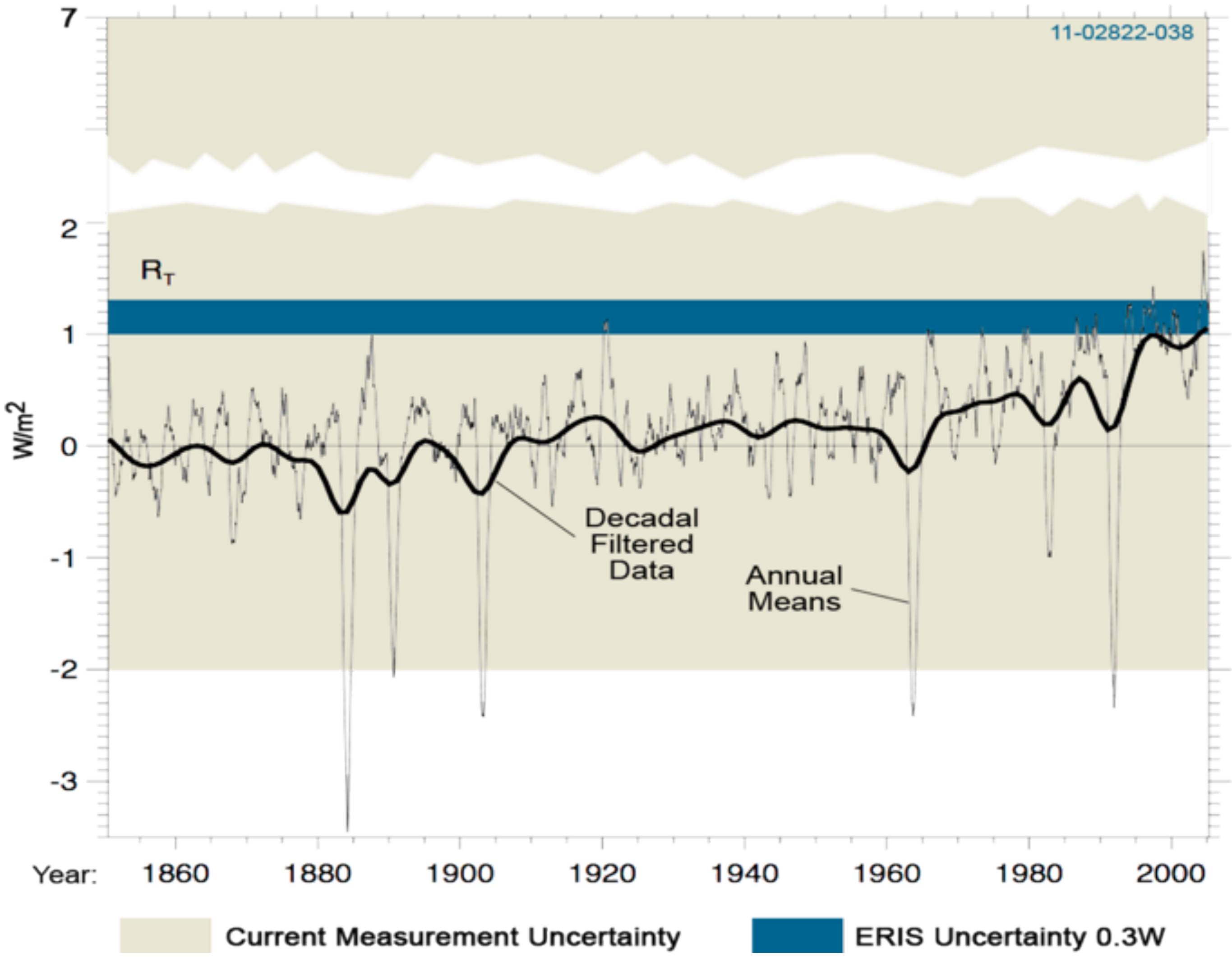
How many do we need?



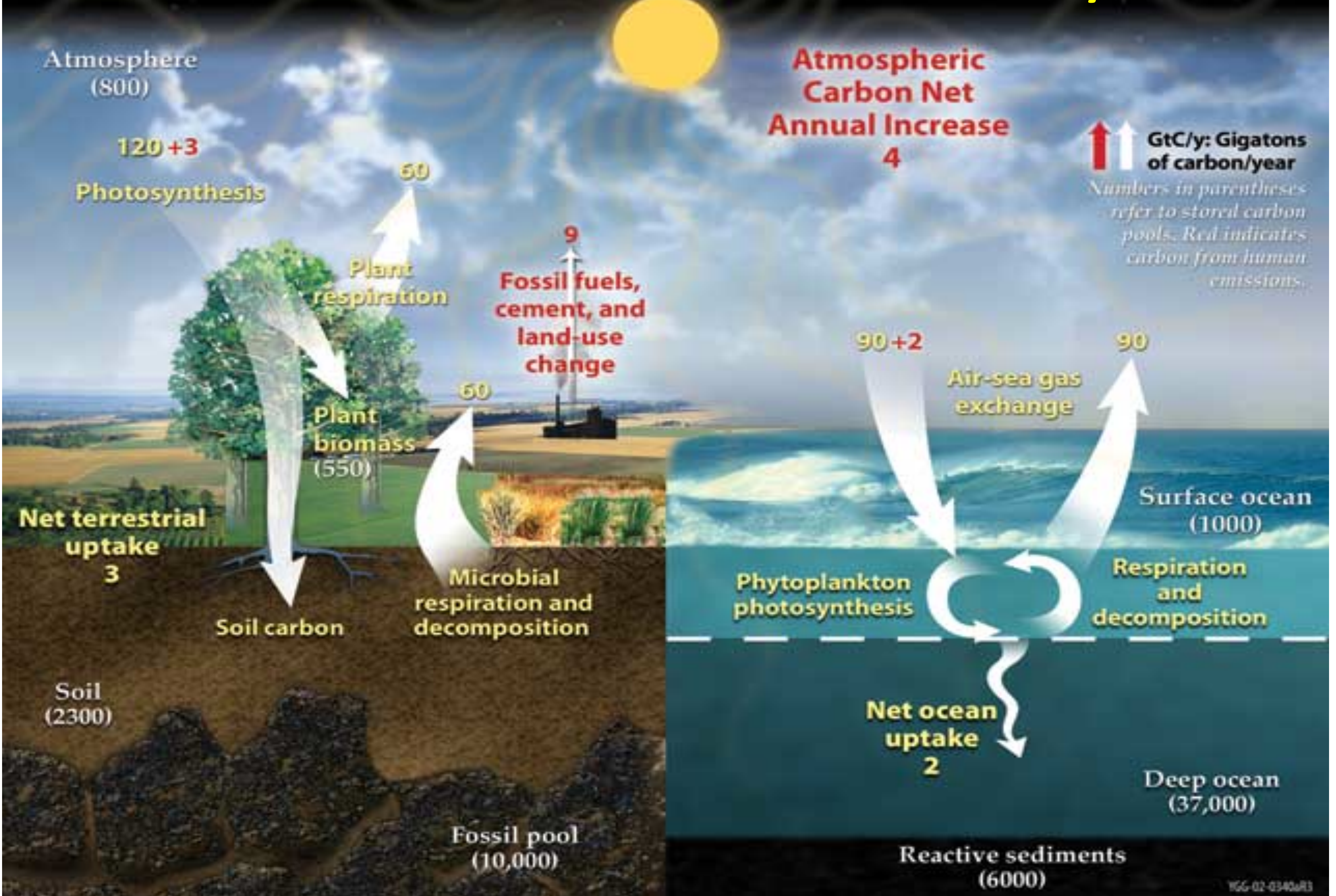
How much will that cost?



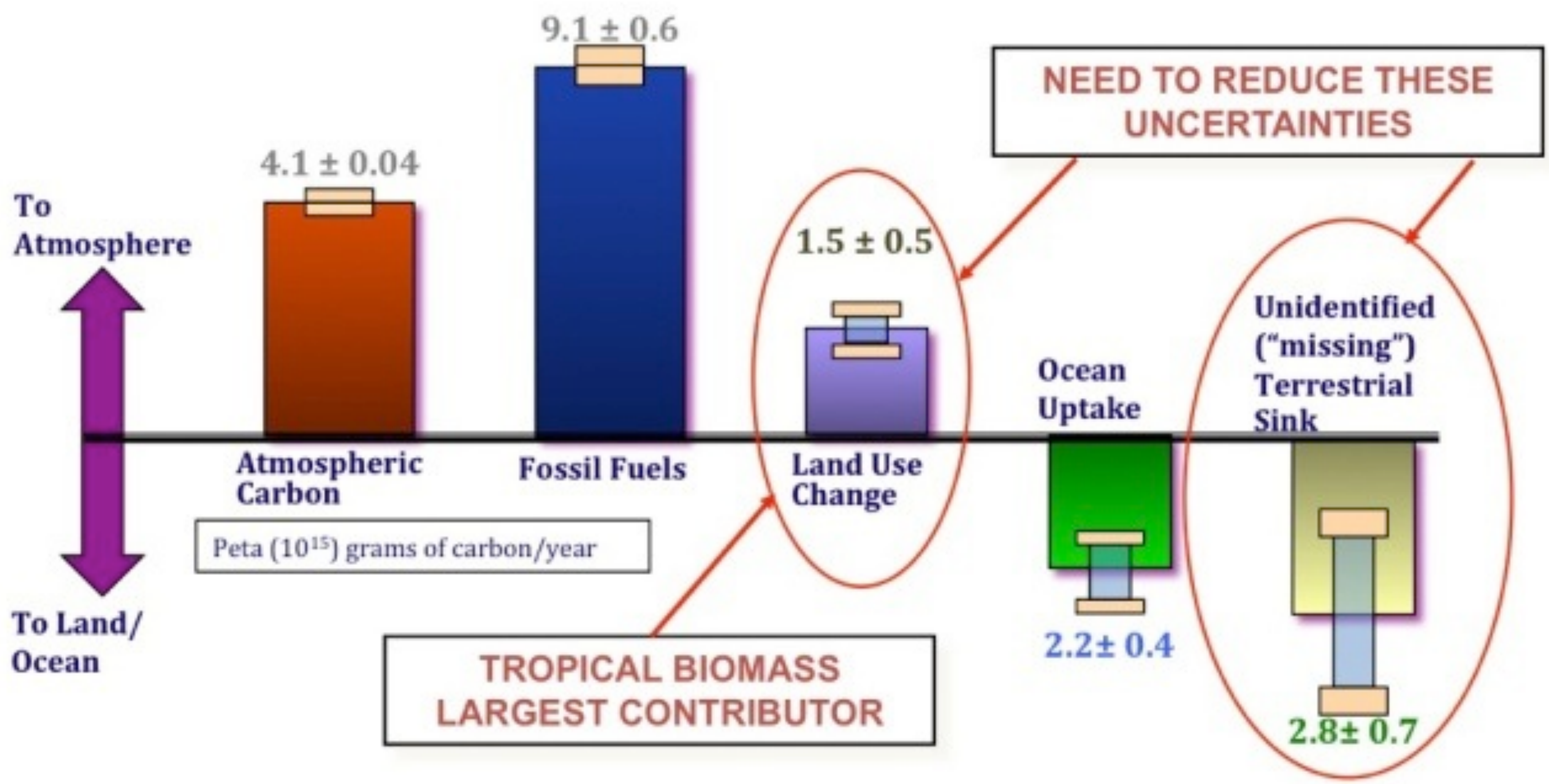
ERI-Modeled since Pre-Industrial



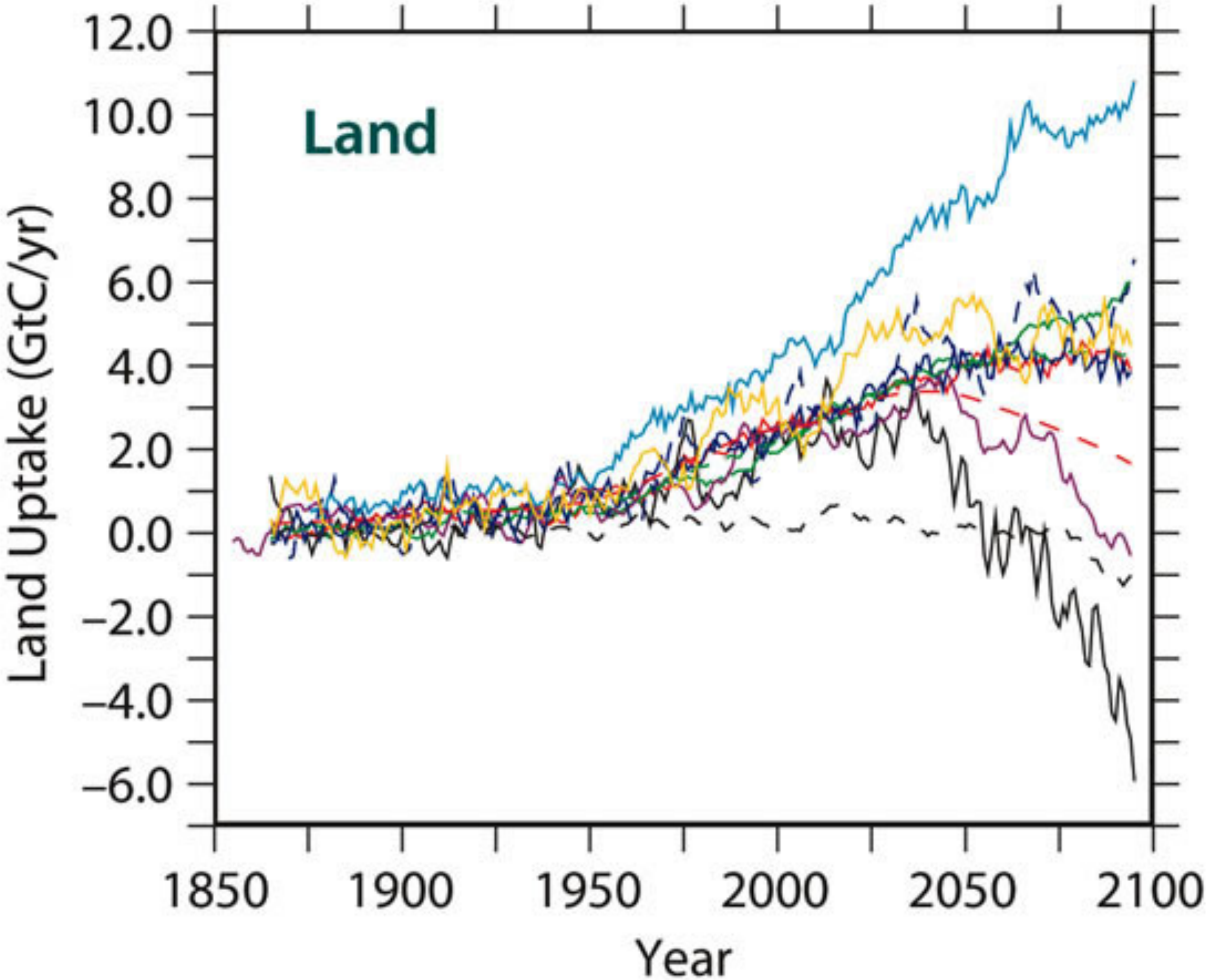
Climate and Global Carbon Cycle



Earth Global Carbon Cycle



Predictions of Carbon Cycle



Friedlingstein et al 2006

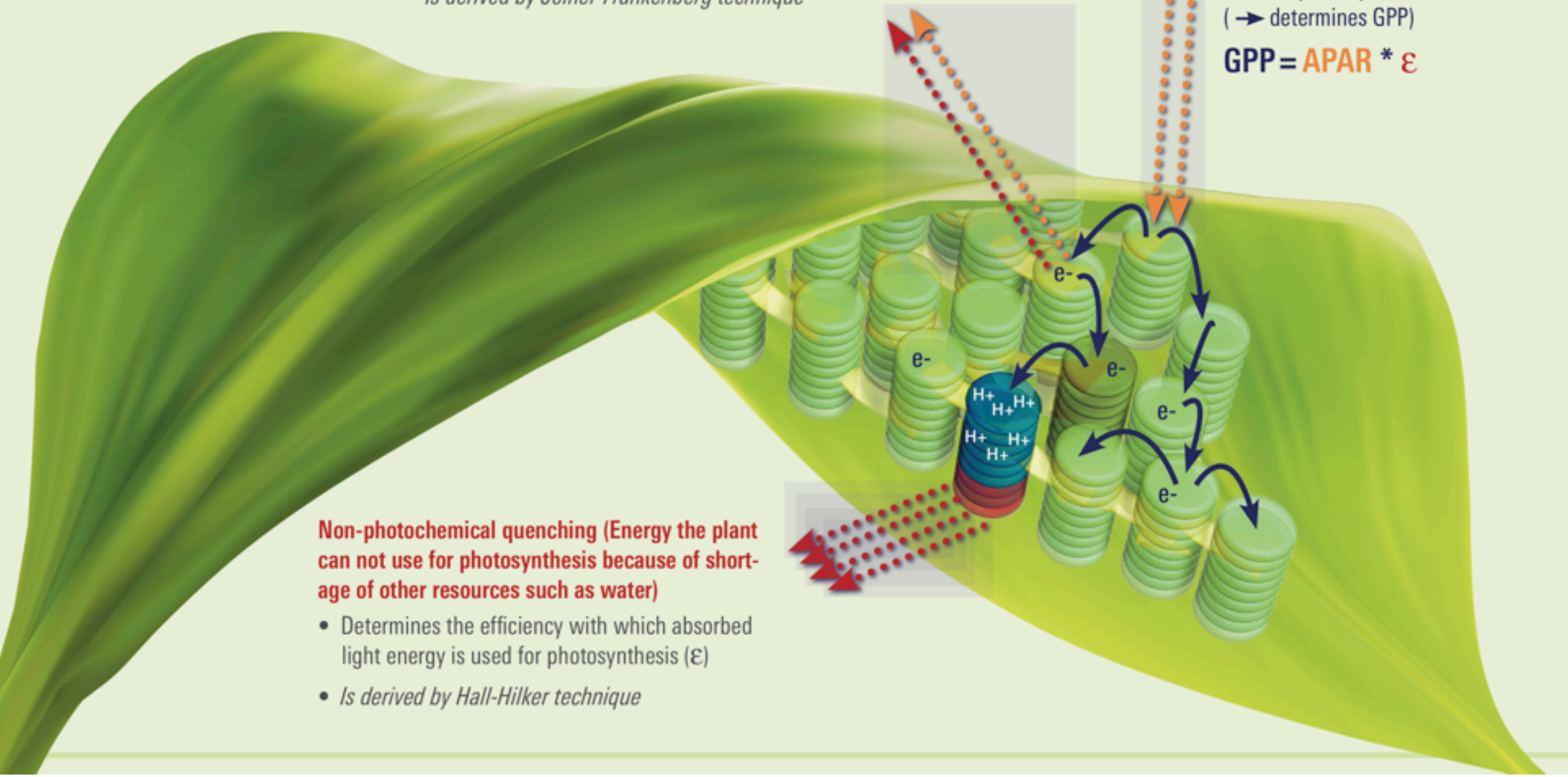
Chloropyll Fluorescence
(Emittance of photons as a result of photosynthesis)

- Is determined by the photon input (APAR) and the light use efficiency (ε)
- *Is derived by Joiner-Frankenberg technique*

Photon input (APAR)

Photochemical quenching
(The energy the plant actually uses for photosynthesis)
(→ determines GPP)

GPP = APAR * ε



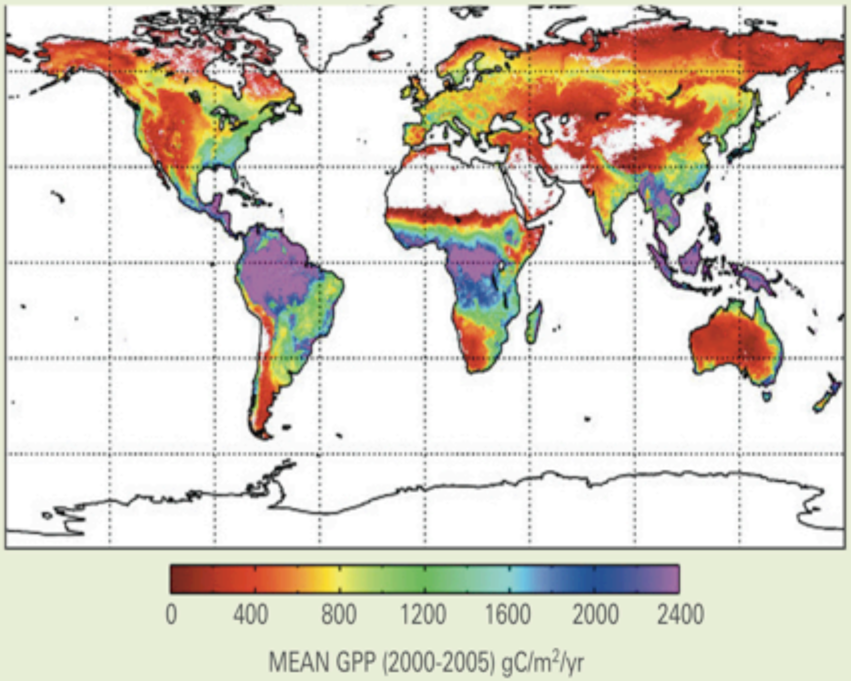
Non-photochemical quenching (Energy the plant can not use for photosynthesis because of shortage of other resources such as water)

- Determines the efficiency with which absorbed light energy is used for photosynthesis (ε)
- *Is derived by Hall-Hilker technique*

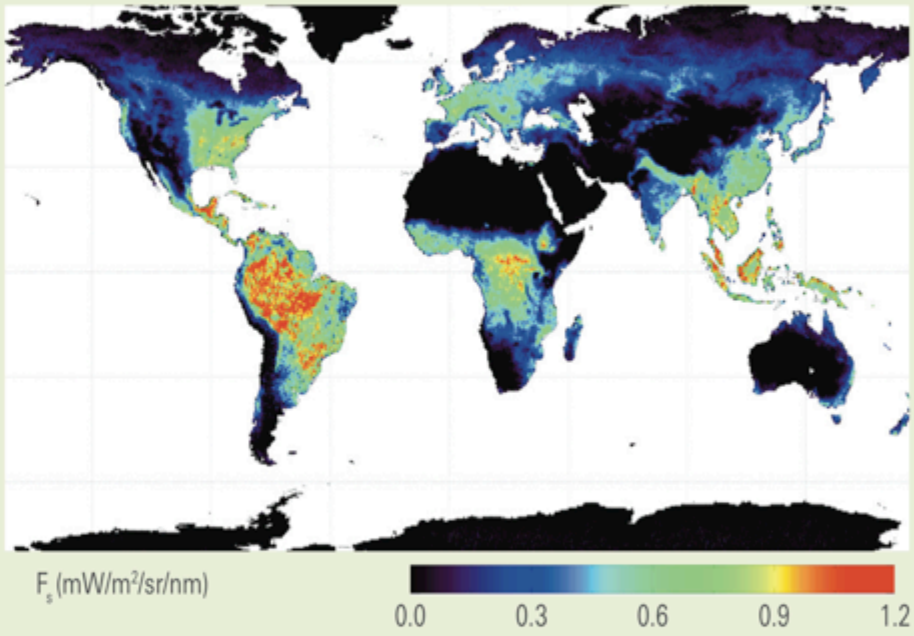
Science Objectives

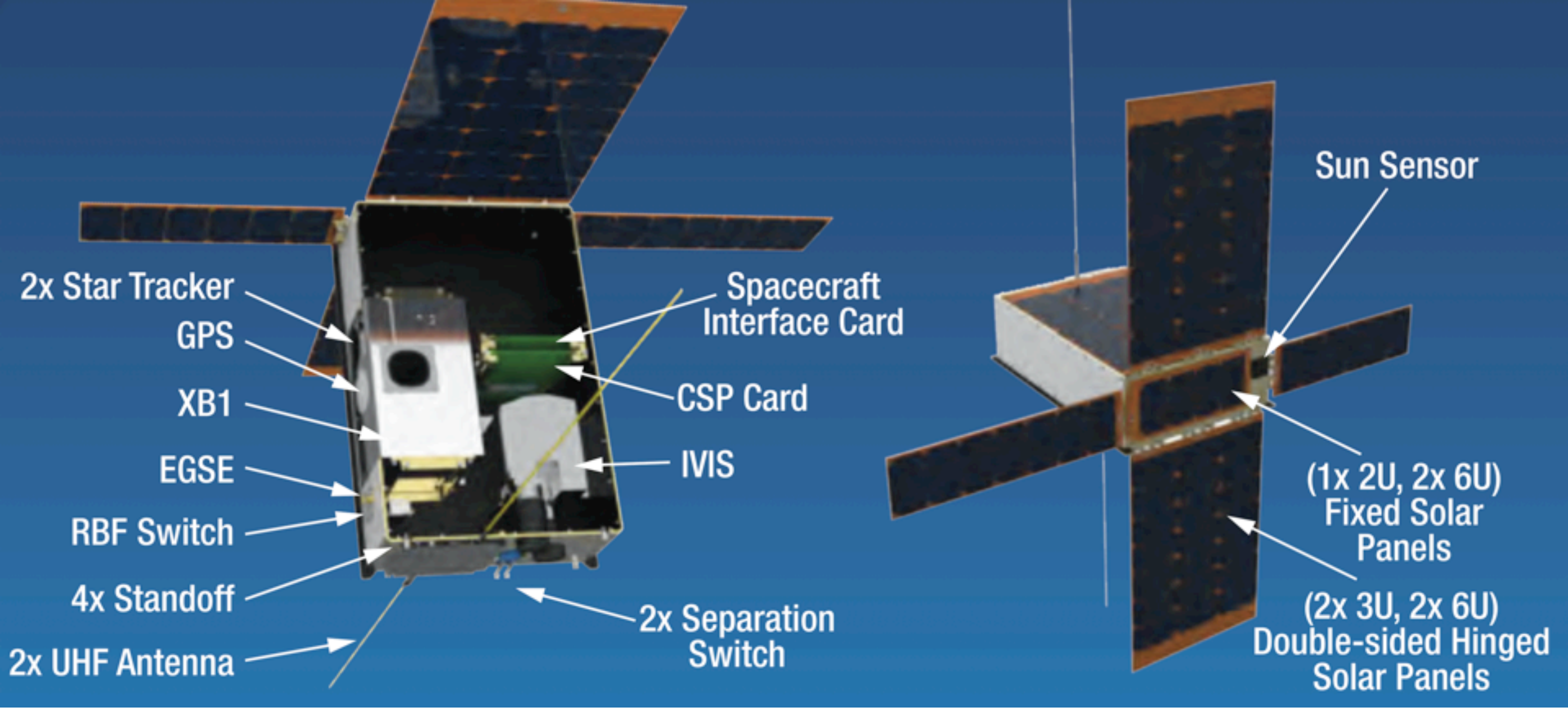
- Quantify plant production, Gross Primary Production (GPP) globally by spatially and temporally explicitly measuring its components and related quantities.
- Use EPIC data and models to improve our understanding of the relationship between photosynthetic production and environmental factors, such as soil moisture, temperature and nutrients.

Improvements of the MODIS terrestrial gross primary production global data set
(Zhao et al., 2005)



Annual average fluorescence from GOME-2 on MetOp (40 km X 80 km footprint)
(Joiner et al., 2013)





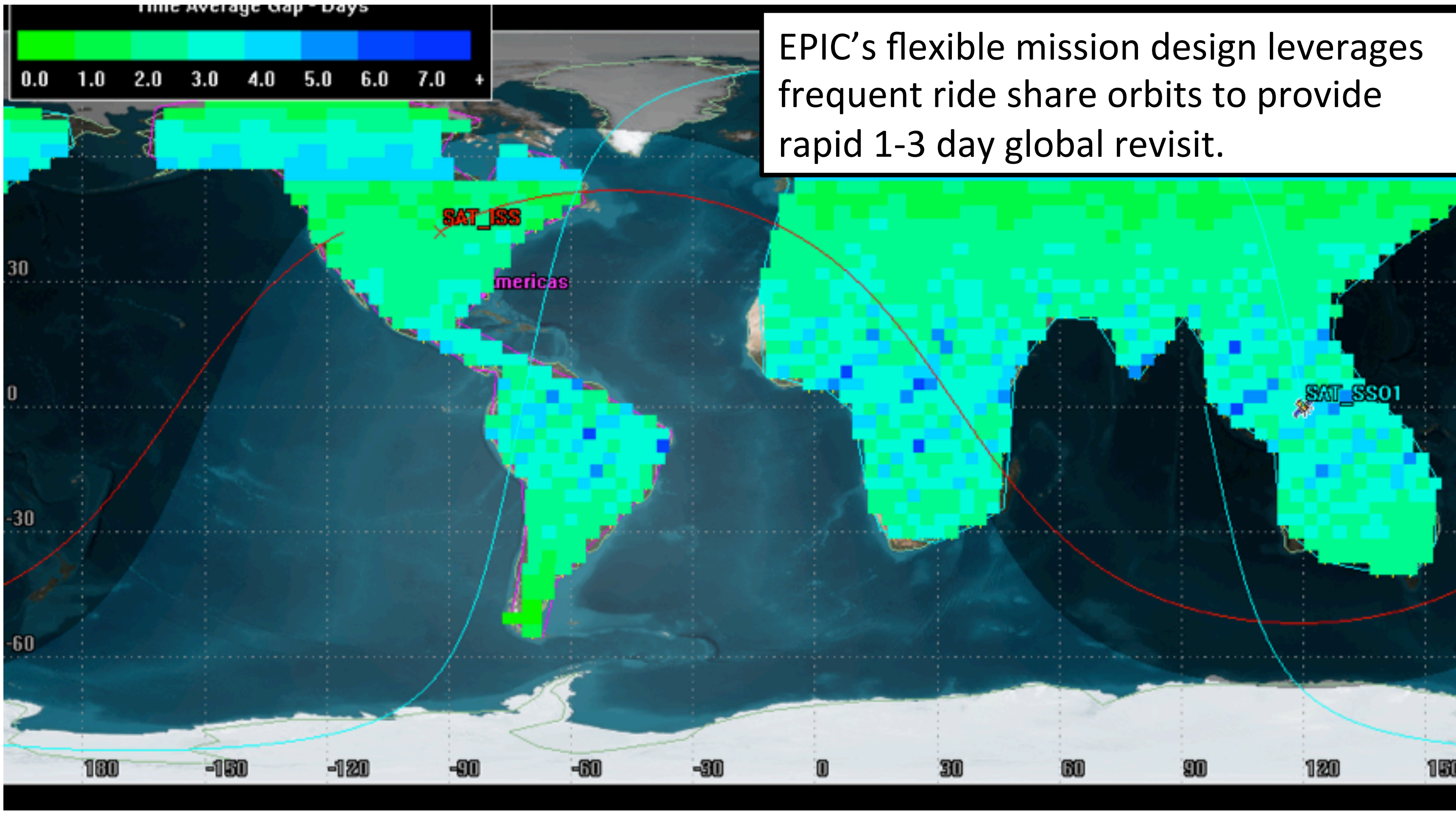
EPIC Team

EPIC's team leverages long-standing relationships and world-class expertise for project success.

Role	Name	Organization
Principal Investigator	Dr. Thomas Hilker	Oregon State University
Project Manager	Dr. Lars Dyrud	Charles Stark Draper Laboratory
Mission Systems Engineer	Mr. Stefan Slagowski	Charles Stark Draper Laboratory
IVIS Instrument	Dr. Dave Landis Dr. John Noto Dr. Steve Watchorn	Charles Stark Draper Laboratory SSI SSI
Satellite Bus/Ground	Mr. Scott Schaire	NASA GSFC/WFF

Role	Name	Organization
Science Team	Dr. Jung-Eun Lee Dr. Jack Mustard Dr. Gregory Asner Dr. Joe Berry Dr. Joanna Joiner Dr. Forrest Hall Dr. Alexei Lyapustin Dr. Christian Frankenberg	Brown University Brown University Carnegie Institute Carnegie Institute NASA GSFC NASA GSFC NASA GSFC JPL

Ride Share Orbits

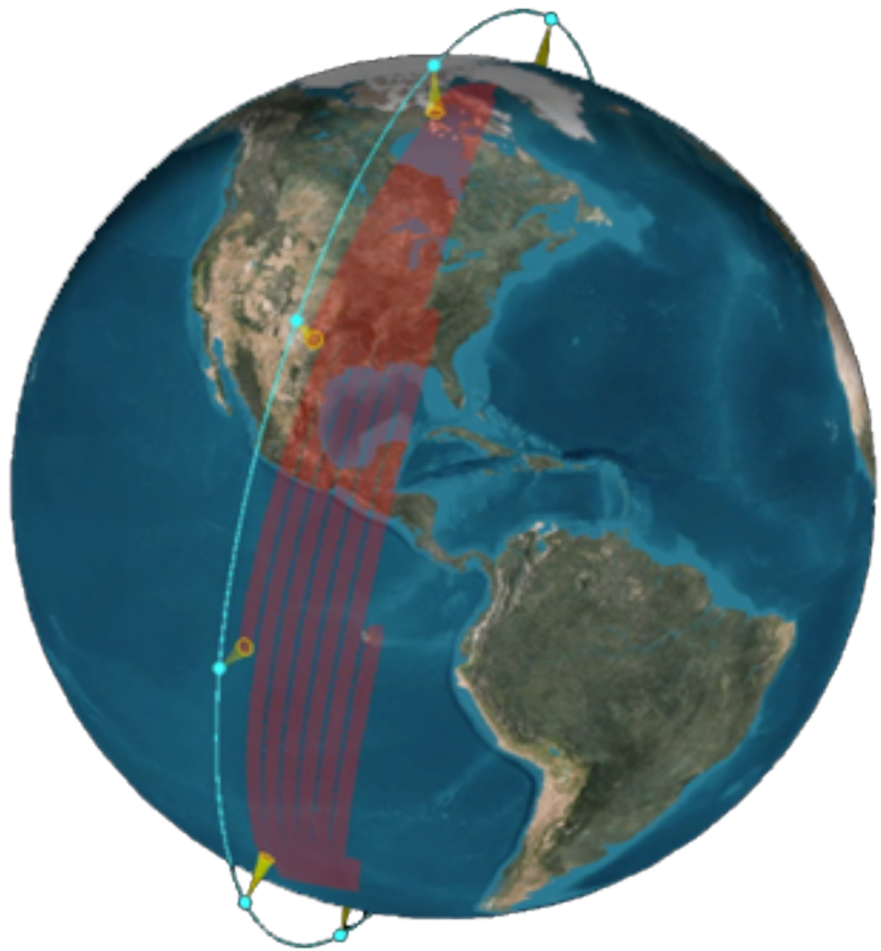


EPIC’s flexible mission design leverages frequent ride share orbits to provide rapid 1-3 day global revisit.

Land Cover Mapping

Commercial Constellations:

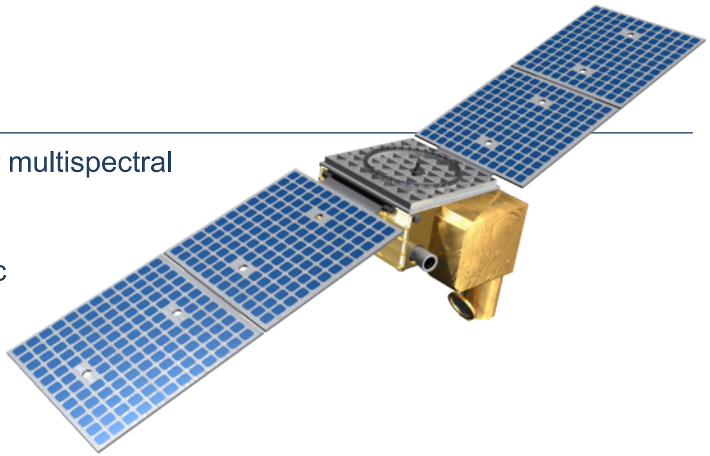
OmniEarth



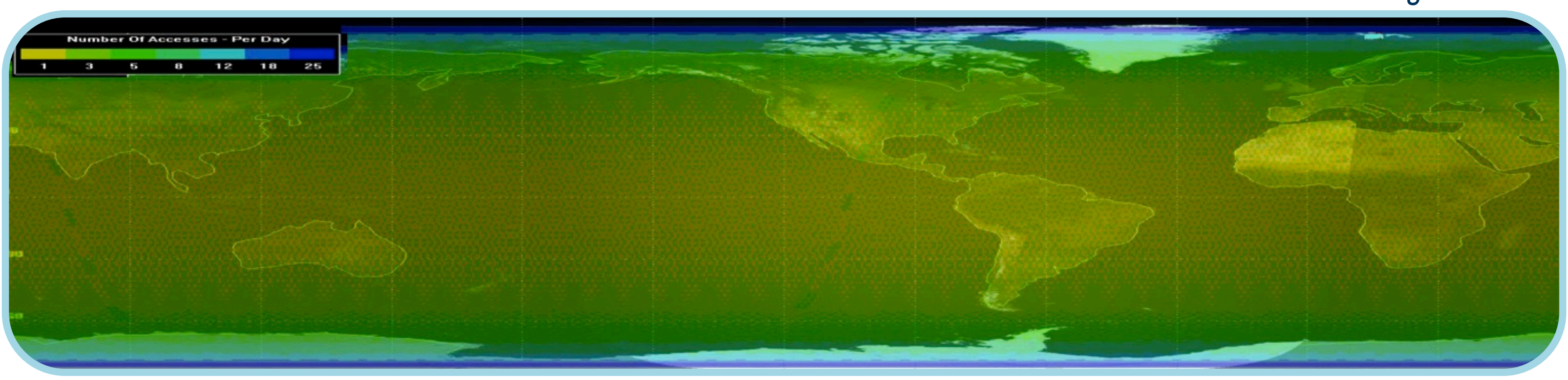
OmniEarth Constellation.

OmniEarth constellation design is driven by the imagery required to turn data into actionable intelligence.

Requirement	Value	Additional Notes
GSD	2–5 m	2 meter panchromatic, 5 meter multispectral
Field of View (“FOV”)	18°	
Number of Channels	7	6 multispectral, 1 panchromatic
Orbital Height	680 km	
Swath Width	200 km	
Phase I Revisit Rate	3 days	5 to 6 satellites
Phase II Revisit Rate	Daily	15 satellites + spares
Constellation Lifetime	7-10 years	Use of in orbit spares



1 visit per day at the equator with multiple visits at high latitudes



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Excessive Water Use Identification.

Using land classifications to determine water use baseline and identify excessive users on a rolling basis – with goal of 20% lower water usage by 2020. Based on flown imagery, parcel data, customer billing dates, and evaporative rate tables.

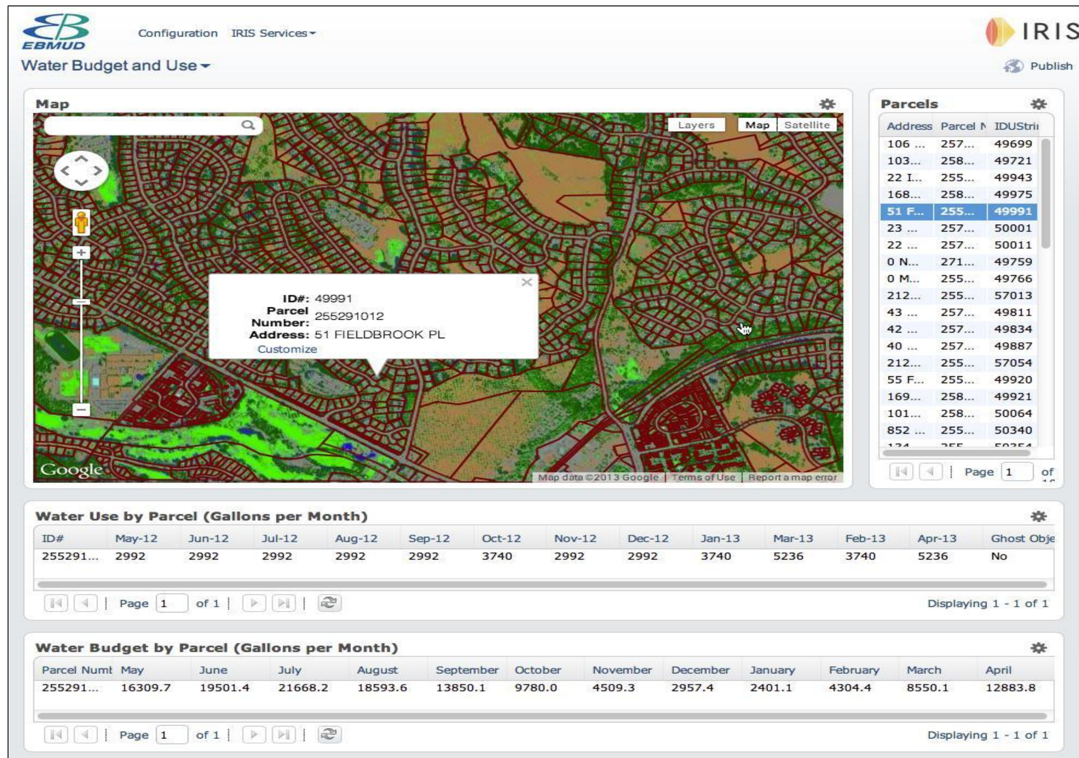
Processing

- Classify land types from flown imagery
  Calculate water budget by parcel
- Compare actual vs budget data by parcel by month

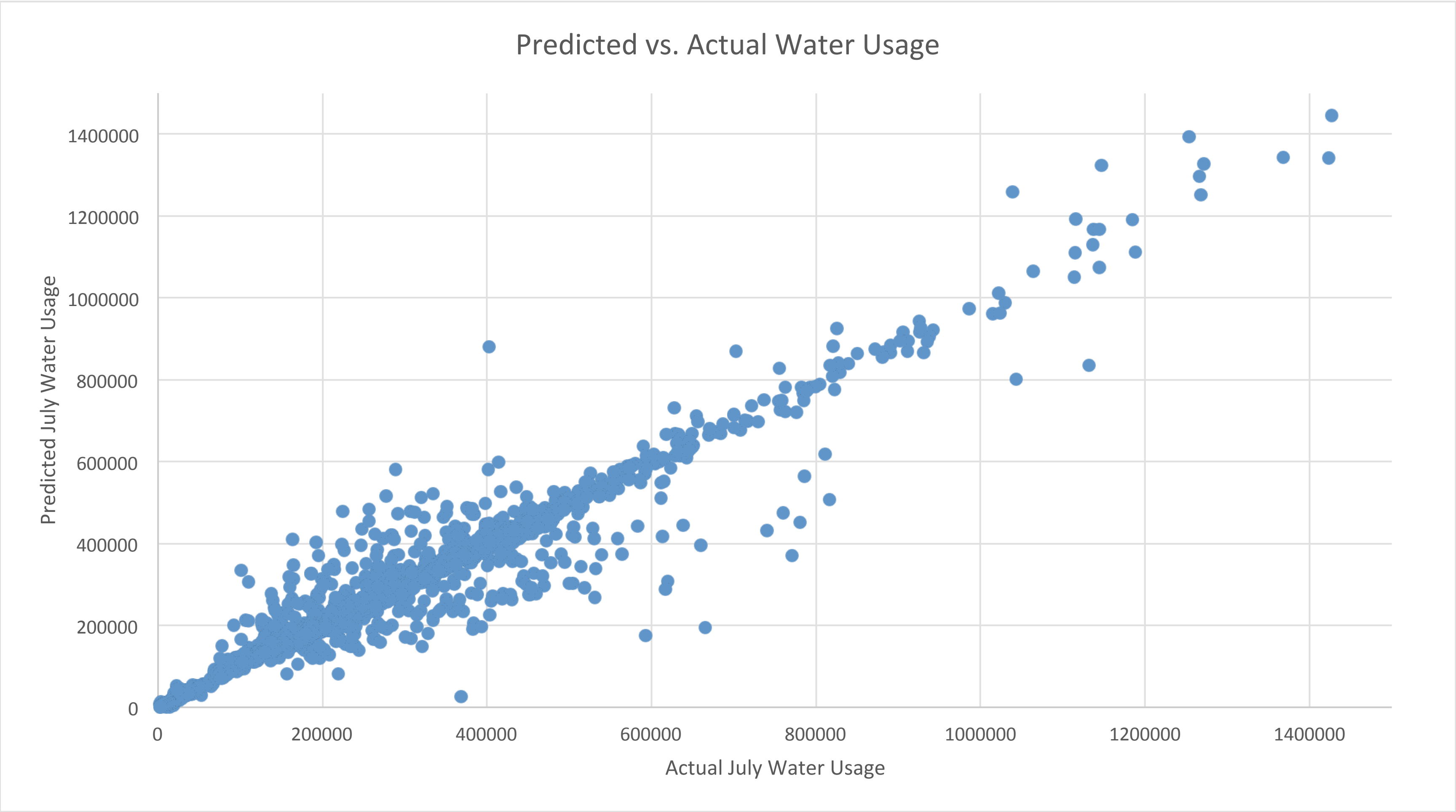
Services

- Import and link data sources
- Analytics" classify land types, calculate budget & actual water usage
- Visualize usage & budget by parcel
- Notify excessive use customers by email

Makes baseline budget possible and creates a repeatable water reduction campaign



Predictive Analytics Results

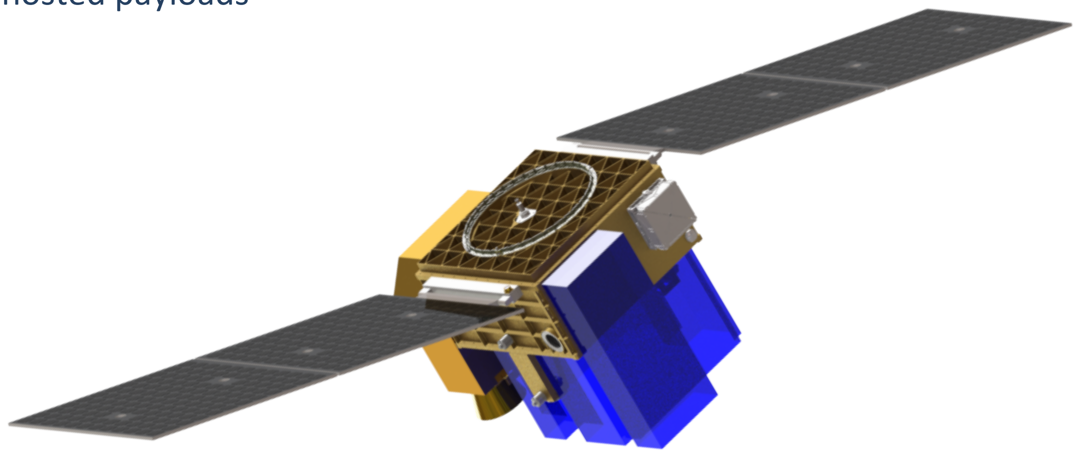


OmniEarth Hosted Payload Opportunity.

Leveraging proven hosted payload integrator experience and capabilities

- Harris Corporation will manage all of the hosted payload activities for OmniEarth. Harris is the provider of the Aireon ADS-B payload that will fly on the Iridium NEXT constellation.
- OmniEarth satellites will use the Harris AppStar hosted payload platform which is going to be used on all of the Iridium NEXT (> 80) spacecraft for the Aireon payloads.
- The AppStar platform provides an easily interchangeable, modular approach that cleanly separates the subsystem assembly and testing of the spacecraft and hosted payload deck, enabling parallel development of both systems until final integration and test.
- In addition to well defined allocations for volume, power, and mass, the AppStar platform also provides command and control, telemetry, and access to very high speed downlink facilities for hosted payloads

Firm Fixed Price offer at $80k per kg



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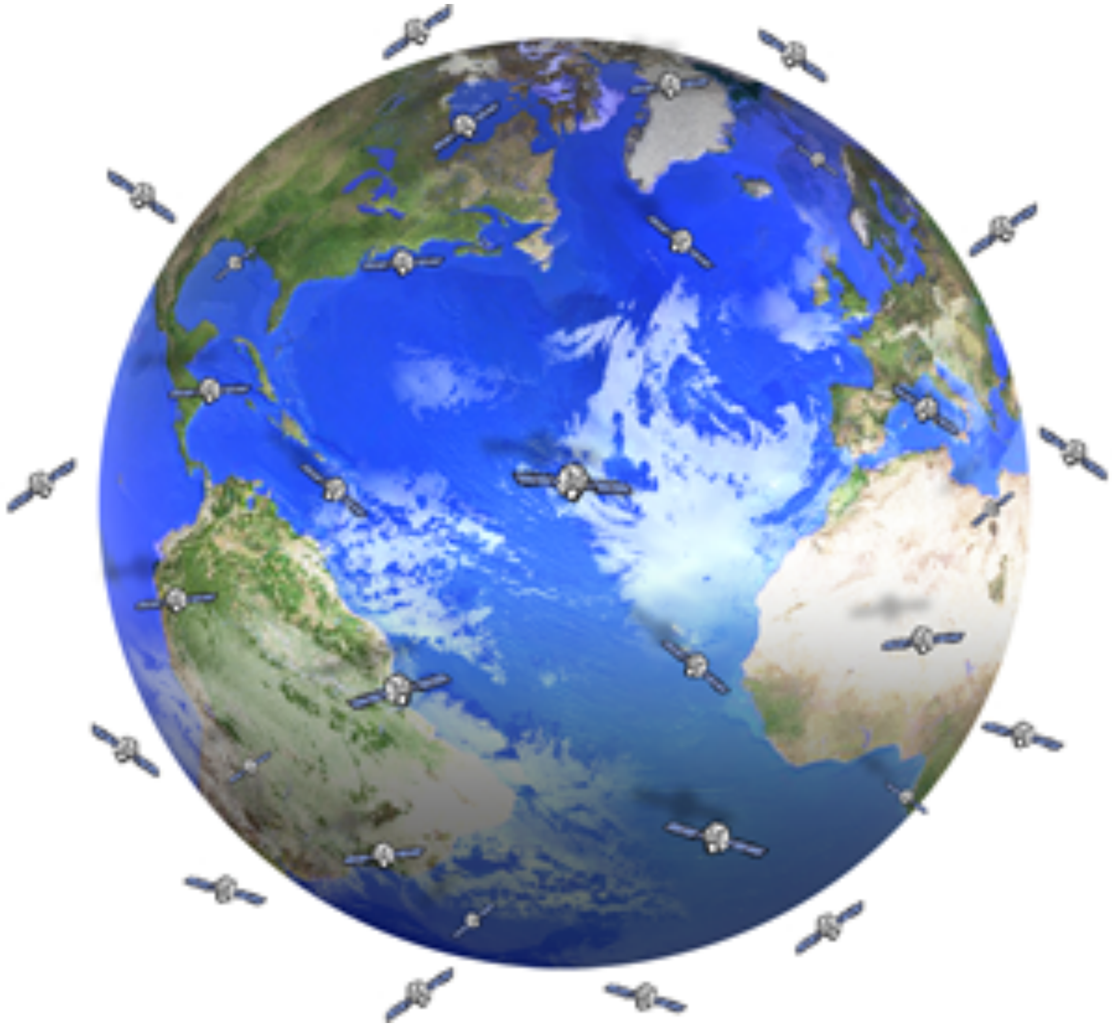
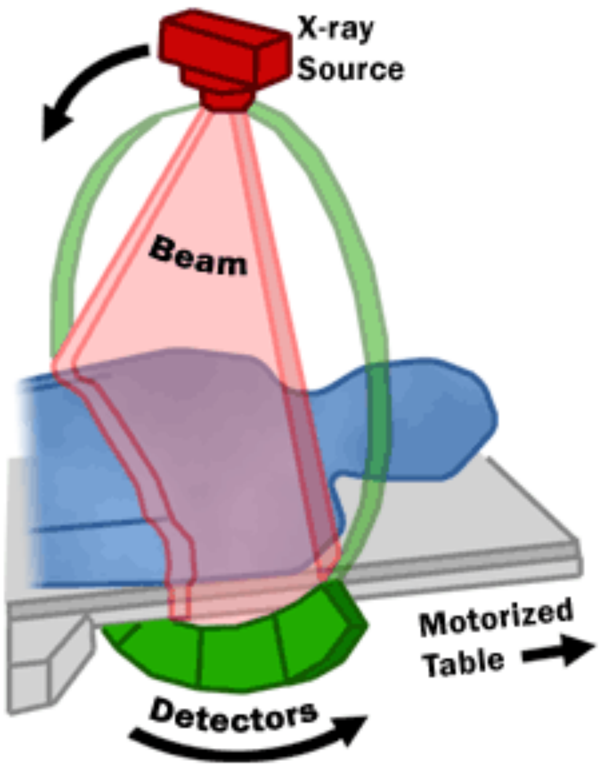
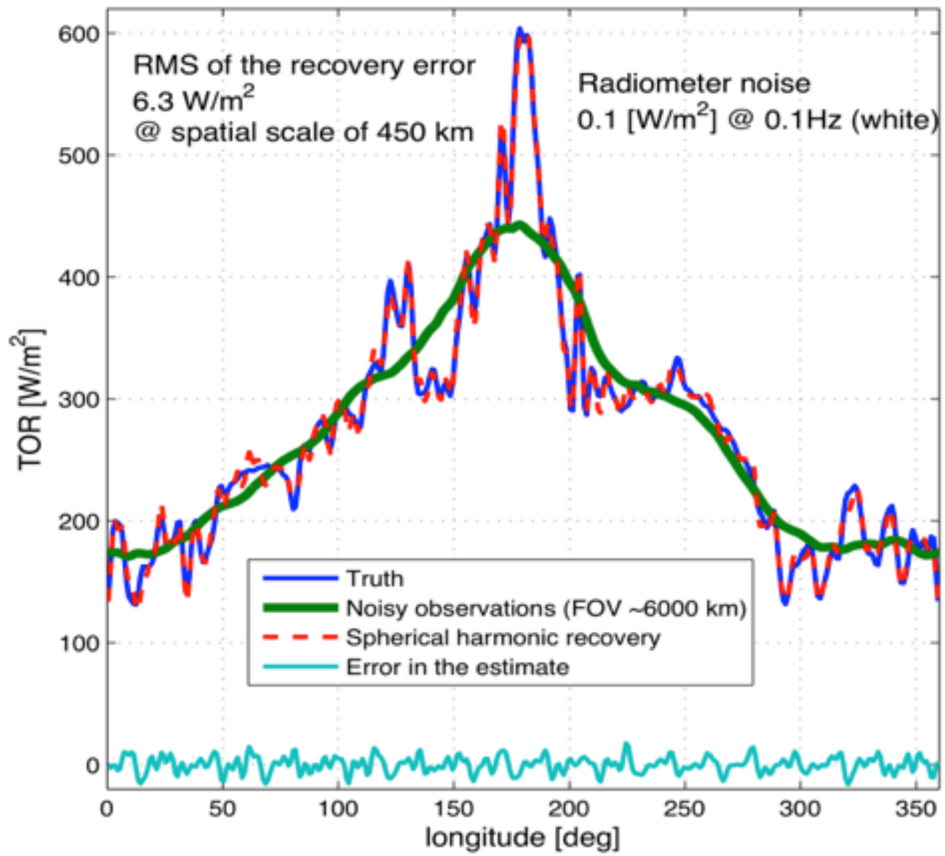


New Challenges and Opportunities

Retrieving spatial resolution from global constellations





From Shin Han Lin

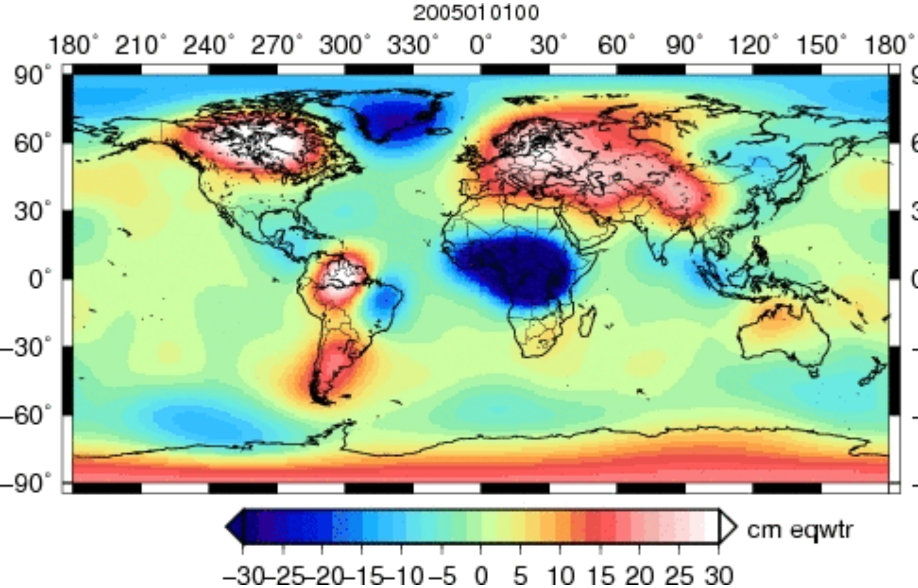
Easy Ad-Hoc International Constellations

- Ad-hoc constellations targeting same goal remove cooperation off the critical path
- Dramatically reduces program management/ negotiation overhead

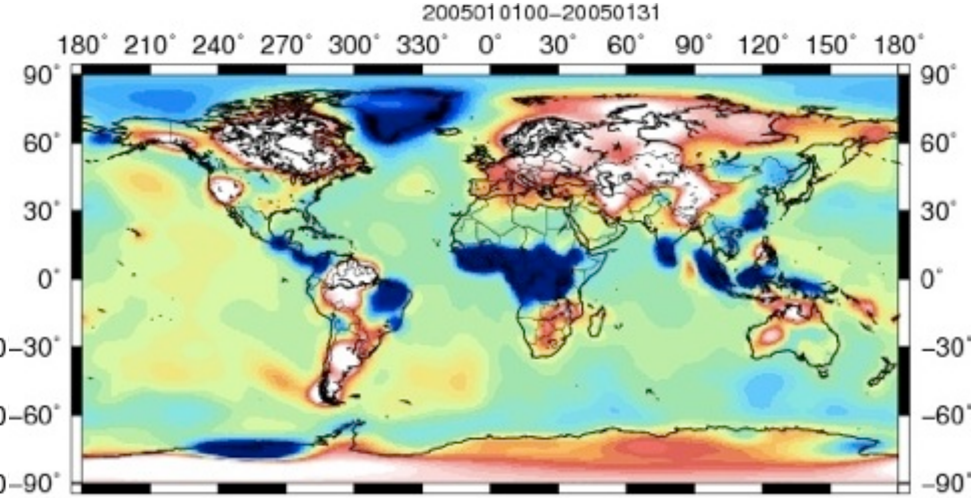
GRACE/GEOScan: One Month

- True and “observed” orbits were simulated, using positioning error spectrum derived from CHAMP mission data, equivalent to 2-3 cm 3D RMS uncertainty.
  - For more details, see
    - Ditmar et al., J. Geodesy, 2007
    - Gunter et al., J. Spacecraft & Rockets, 2011
- Accelerations derived using high-resolution, 6-hourly atmosphere, ocean, ice, hydrology, and solid-earth variations derived from a recent coupled Earth-system model.
  - See Gruber et al., ESSD, 2011

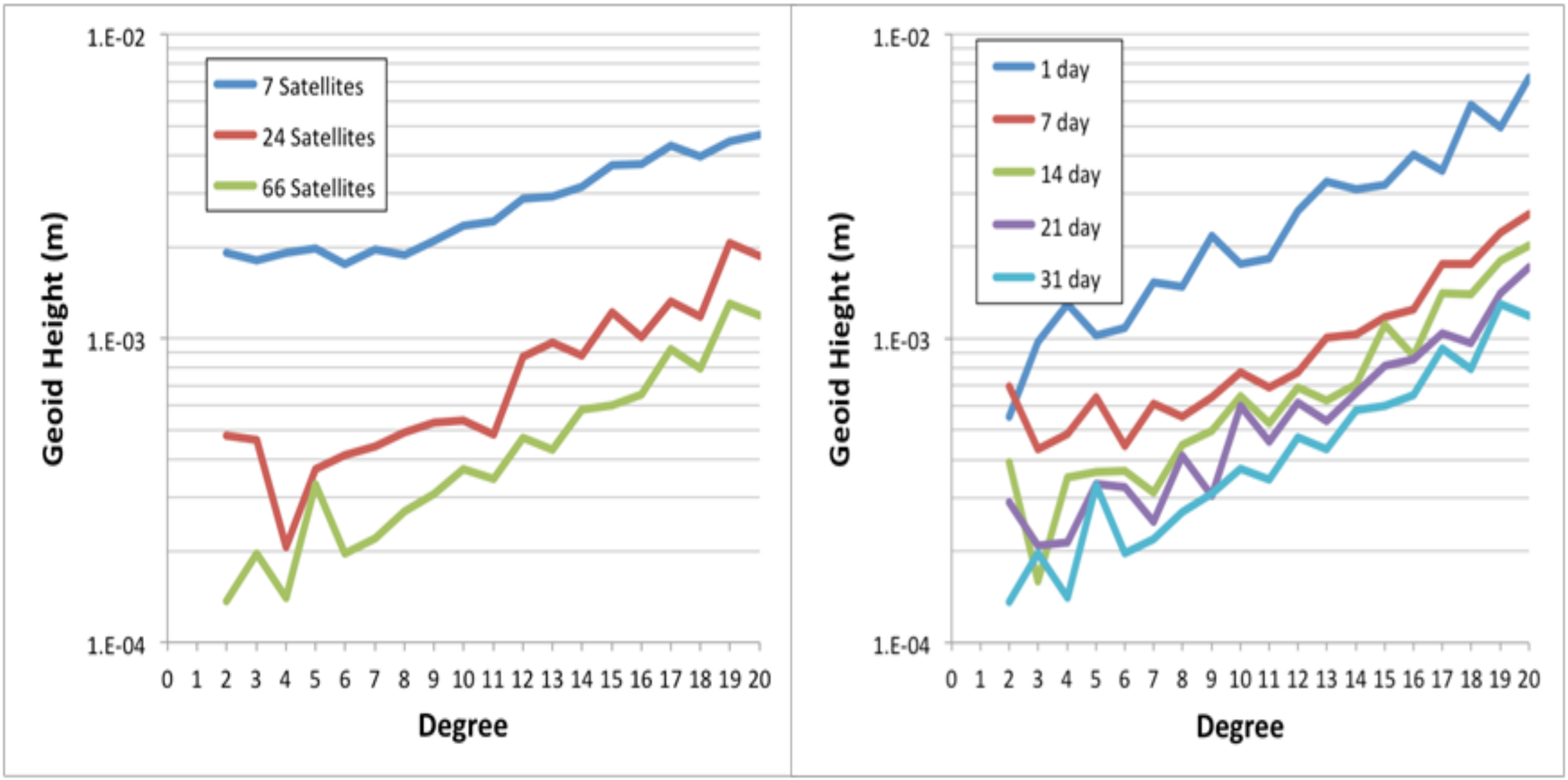
GEOScan



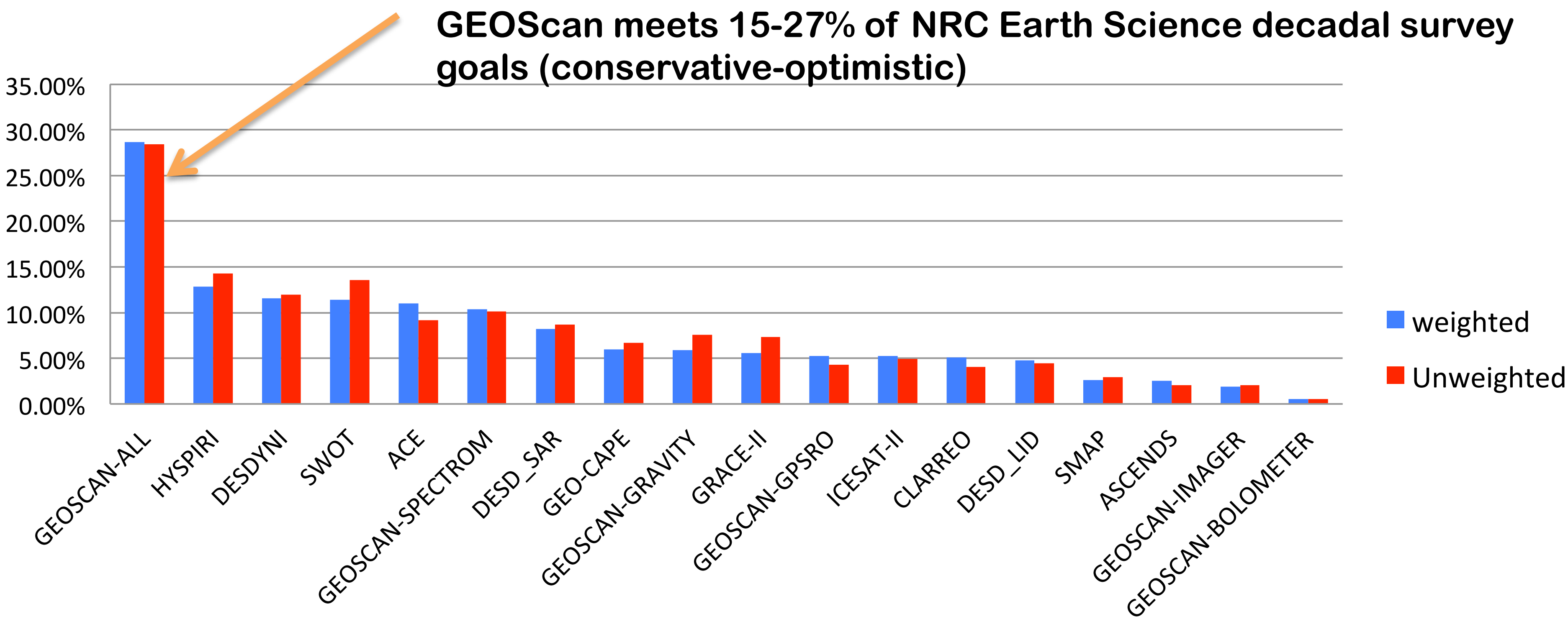
GRACE



How Many do We Need?



Meeting National Research Council Objectives at a Fraction of the Historical Cost



GEOScan's value far exceeds other NASA Earth Science Decadal Survey missions at a fraction of the cost. GEOScan (~$200M) is approximately 4-10 times more cost effective in terms of science per tax-payer dollar than any other Decadal mission.

From: Selva and Crawley, MIT, Rule-Based Optimization Framework

What is the Power?

- Reduce Costs
- Solve previously unsolvable problems