Astrodynamics Analysis, Control and Simulation Developments in the AVS Lab

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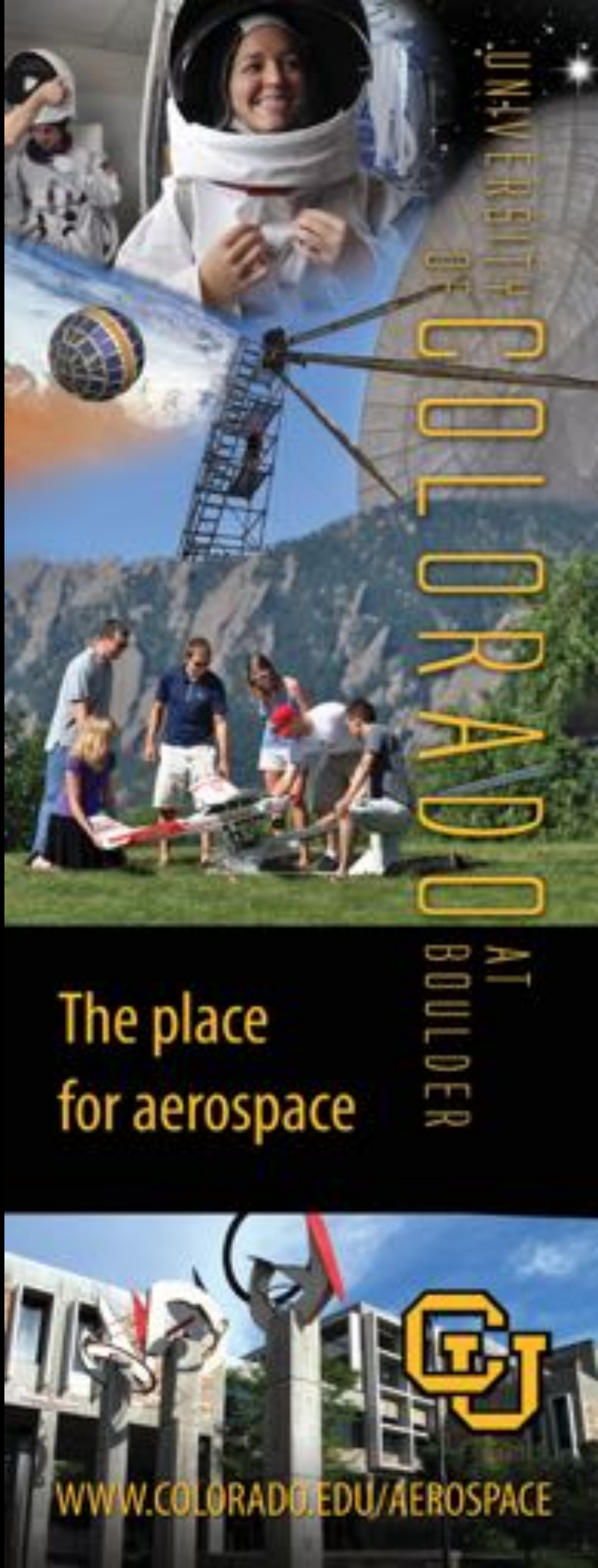
Aerospace Engineering Sciences Department

- Students
  - ~600 undergraduate students
  - ~300 graduate students
- 3600 Alumni/ 1600 in Colorado

- 36 Tenure-Track Faculty (2.5 budgeted elsewhere)
- $21.8M in research expenditures (FY12)
- 4.5 Instructors, Senior Instructors, Scholars in Residence
- 6 Research Faculty; numerous Research Associates
- 8.5 Support Staff, not including Research Centers



Ranked among the top aerospace Ph.D. programs, ranked as high as 2nd by the National Research Council in 2010

2008 University of Colorado President's Award for:

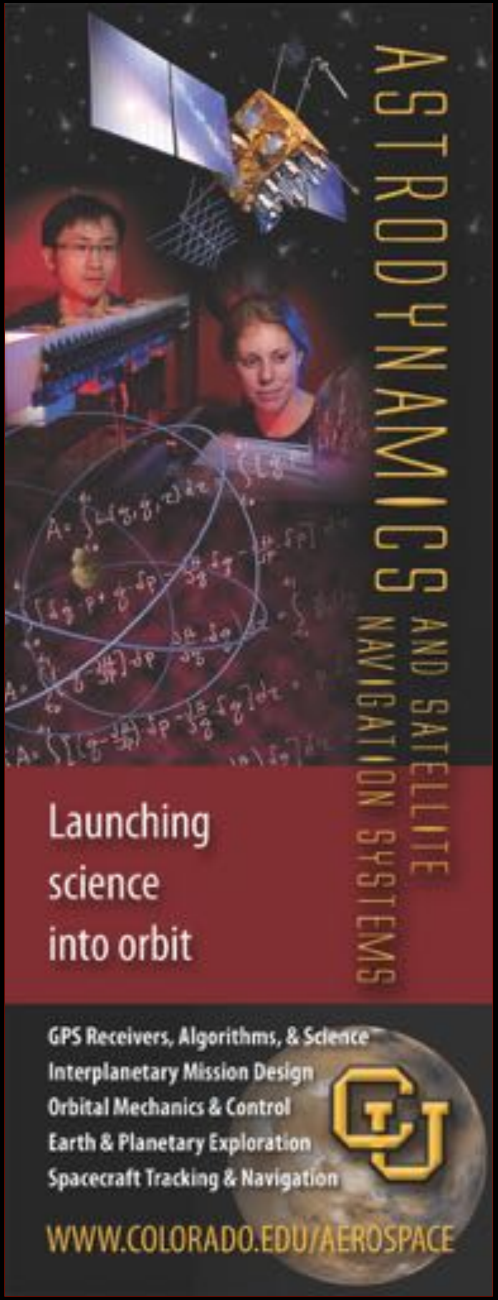
1st Outstanding Academic Leadership in Undergraduate Student Success

2nd Outstanding Academic Leadership in Graduate and Professional Student Success

Ranked 1st in both percent and absolute graduate female participation

Focus Areas for Research & Graduate Study

Astrodynamics &
Satellite Navigation



ASTRODYNAMICS AND SATELLITE NAVIGATION SYSTEMS

Launching
science
into orbit

- GPS Receivers, Algorithms, & Science
- Interplanetary Mission Design
- Orbital Mechanics & Control
- Earth & Planetary Exploration
- Spacecraft Tracking & Navigation

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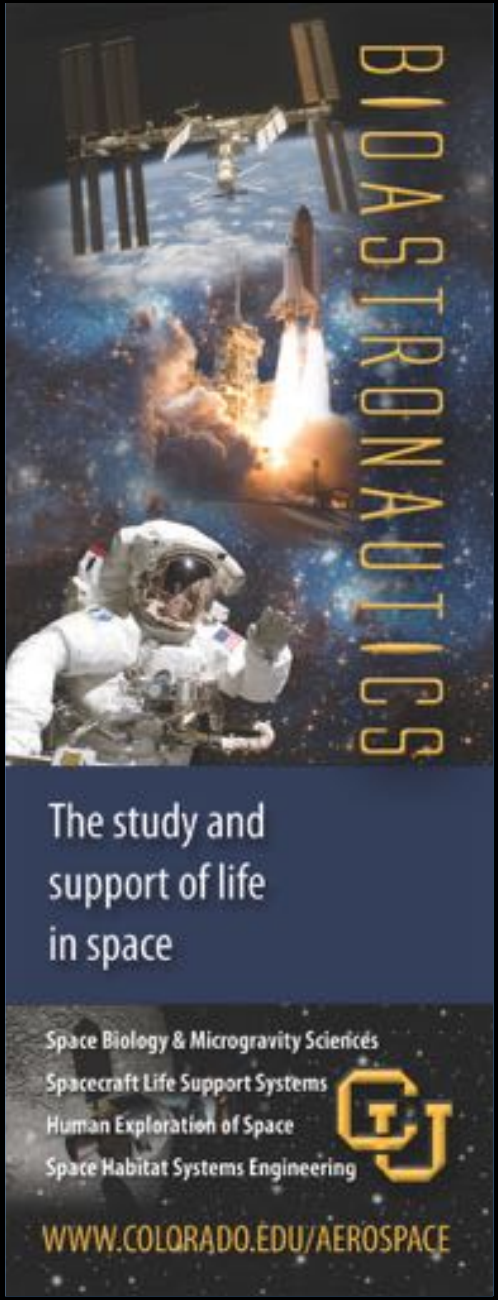
Bioastronautics



BIOASTRONAUTICS

The study and
support of life
in space

- Space Biology & Microgravity Sciences
- Spacecraft Life Support Systems
- Human Exploration of Space
- Space Habitat Systems Engineering

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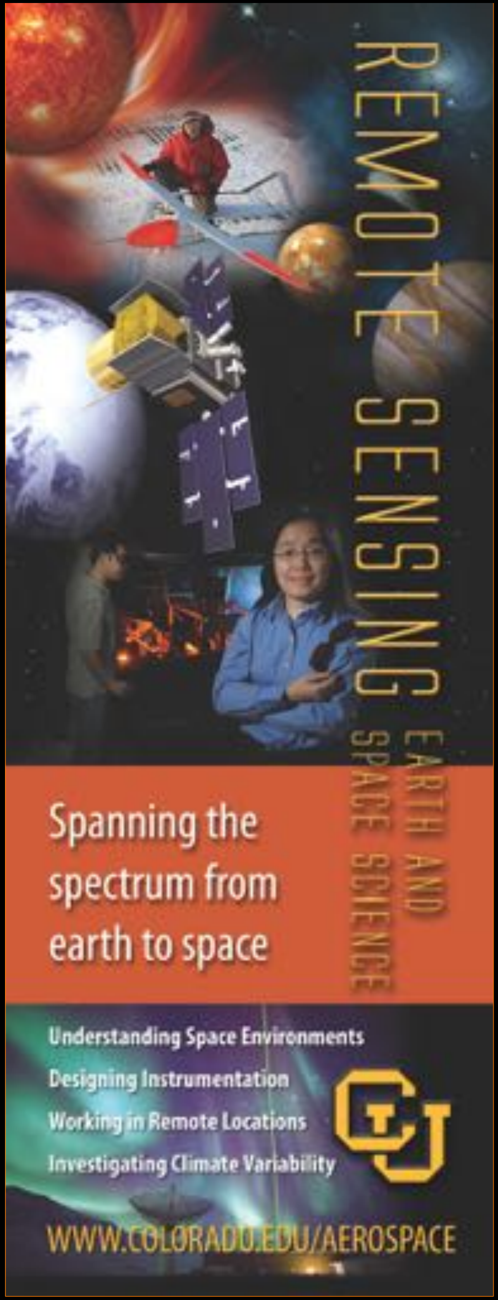
Remote Sensing, Earth
& Space Sciences



REMOTE SENSING EARTH AND SPACE SCIENCE

Spanning the
spectrum from
earth to space

- Understanding Space Environments
- Designing Instrumentation
- Working in Remote Locations
- Investigating Climate Variability

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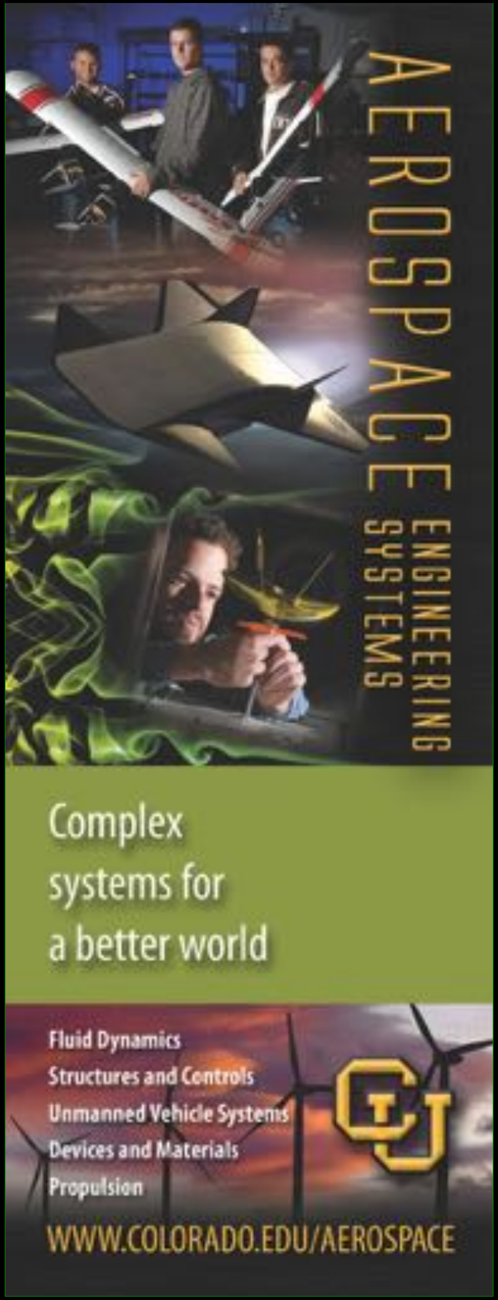
Aerospace
Engineering Systems



AEROSPACE ENGINEERING SYSTEMS

Complex
systems for
a better world

- Fluid Dynamics
- Structures and Controls
- Unmanned Vehicle Systems
- Devices and Materials
- Propulsion

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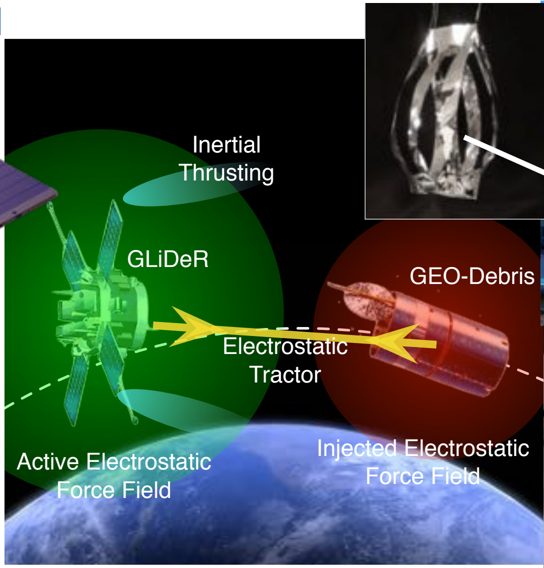
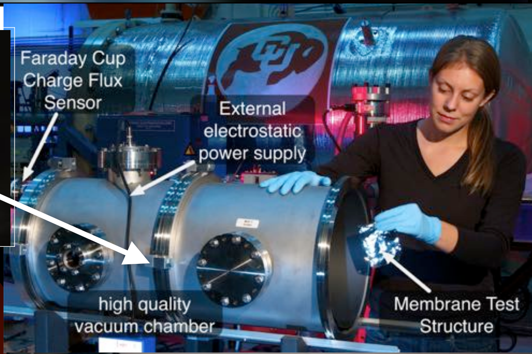
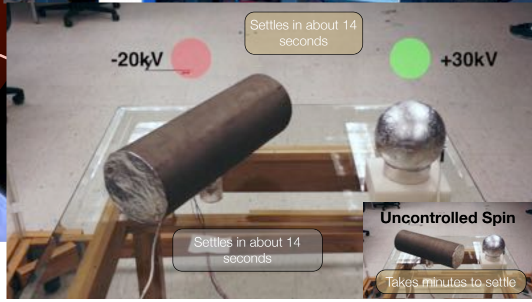
Dr. Schaub's Research Group
Autonomous Vehicle Systems (AVS) Lab

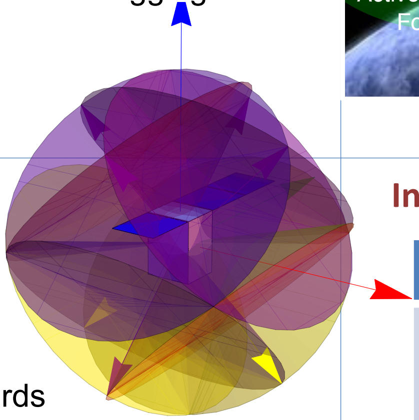
Objectives and Description

- Spacecraft formation flying and rendezvous and docking
- Nonlinear dynamics and control
- Attitude dynamics and control
- Fault tolerant, autonomous control
- Space debris mitigation and remediation
- Visual relative motion control
- Touchless despinning of passive space objects
- Gossamer structure dynamics such as tethered tugging or charged membrane structures



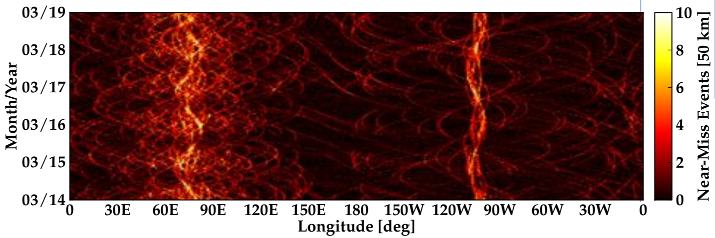






Status and Approach

- Research has led to 175 conference and 117 journal papers
- Graduate researchers have received 16 national fellowships, plus numerous awards
- Internationally recognized program for:
  - spacecraft control developments
  - hardware-in-the-loop simulations
  - complex dynamic simulations
  - experimental research on space actuation and sensing



Industry Application

Strengths	Capability
- Nonlinear dynamics, estimation and control - Advanced spacecraft attitude and relative motion control - Sensor modeling and estimation integration - Experimental astrodynamics - Space debris dynamics and analysis - Space debris mitigation	- Dynamic analysis of complex space concepts - Fast numerical simulations in C and OpenCL - Hardware experiments and simulations - Virtual reality dynamic simulations - Force/torque modeling due to spacecraft charging

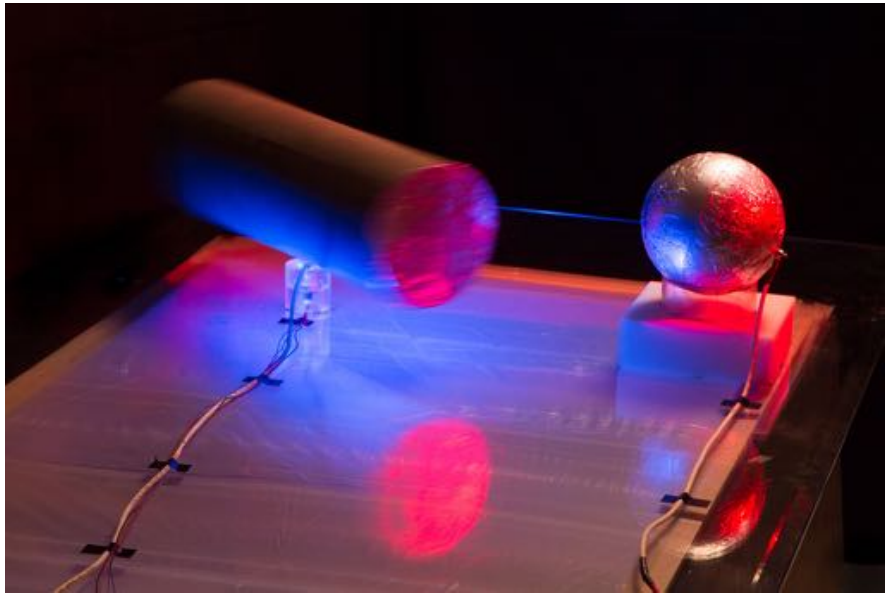
Be Boulder.

AeroSpace Ventures
UNIVERSITY OF COLORADO BOULDER

Aerospace Engineering Sciences
University of Colorado, **Boulder**

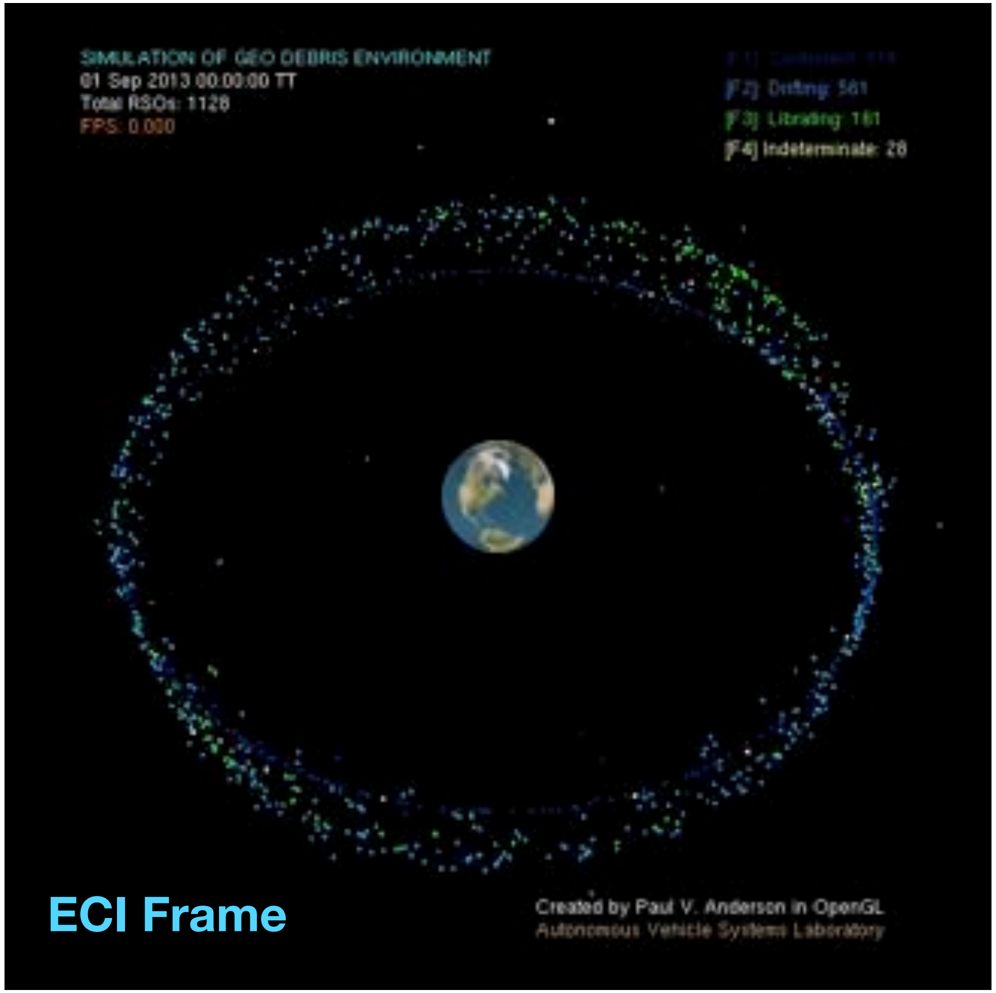
Outline

- GEO Debris Environment
- Electrostatic Forces and Torque
- Three-Dimensional Spin Control
- Basilisk Astrodynamics Simulation Framework
- Conclusions

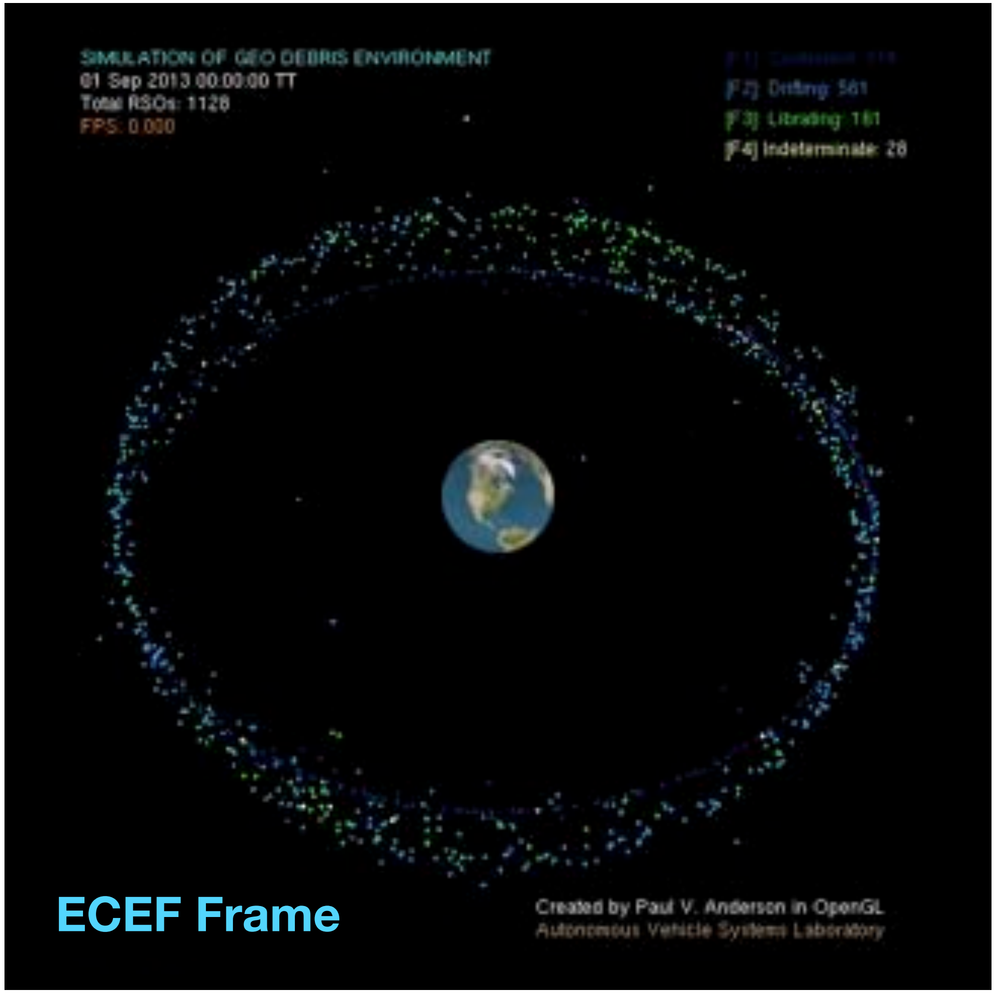


GEO Debris Environment

Visualization of GEO Debris



ECI Frame

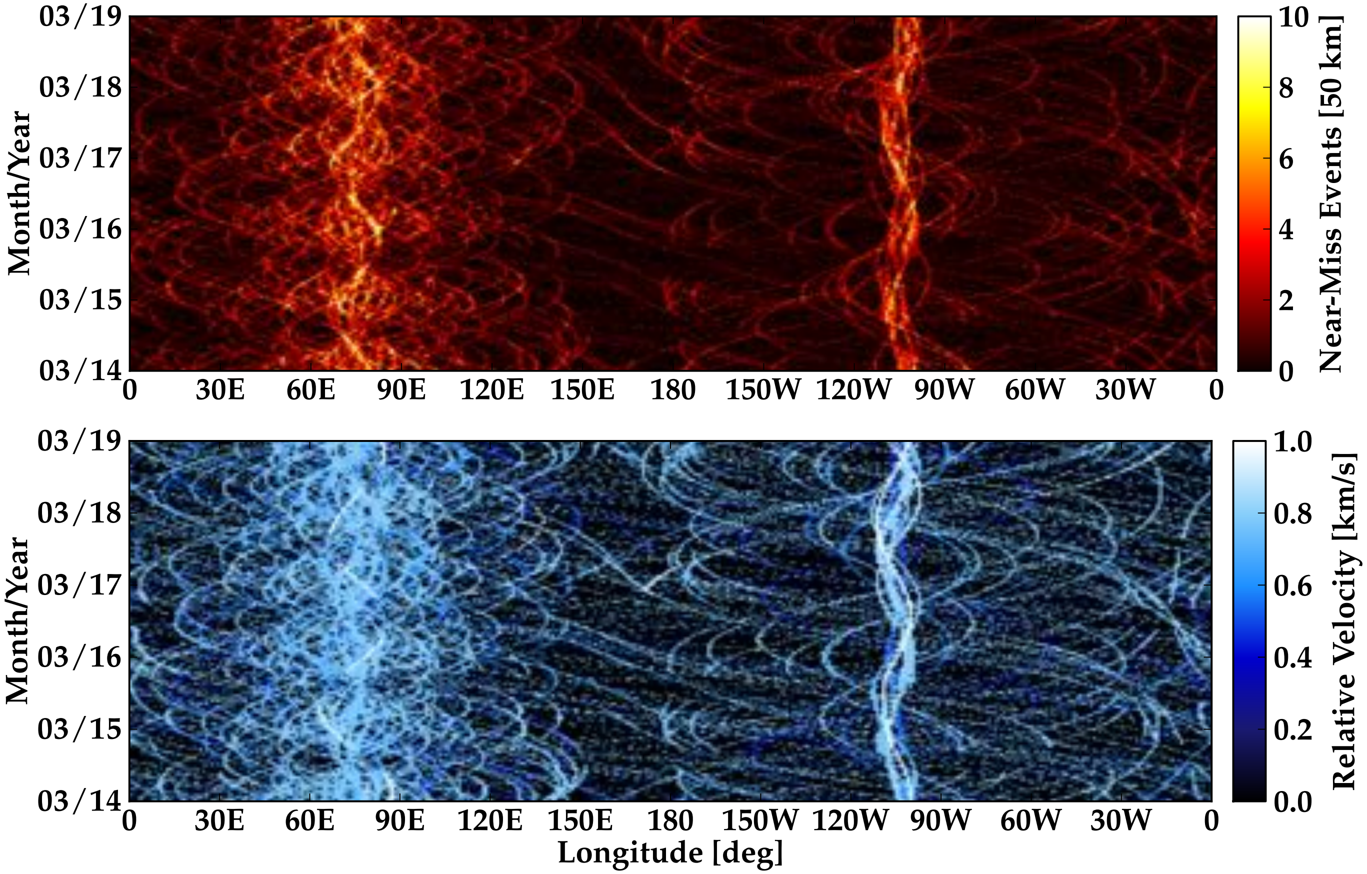


ECEF Frame

Complex relative motion of uncontrolled GEO debris readily visualized from the Earth-fixed frame

Localized GEO Debris Congestion

- **1145 objects** extracted from 02/28/14 TLE set (760 uncontrolled RSOs)
    - Nominal launch traffic, fragmentation events, SRM, MLI not considered here



Localized congestion forecast for five years: ***near-misses each day.***

Relative velocities of congestion forecast: ***speed of near-misses.***

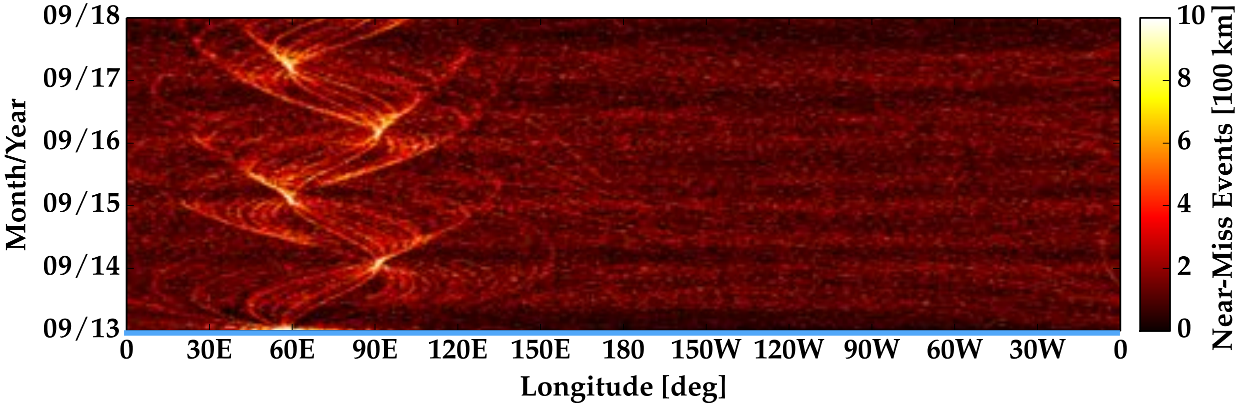
P. V. Anderson and H. Schaub, "Local Orbital Debris Flux Study in the Geostationary Ring," Advances in Space Research, Vol. 51, No 12, 2013, pp. 2195–2206.

GEO Rocket Body Explosion

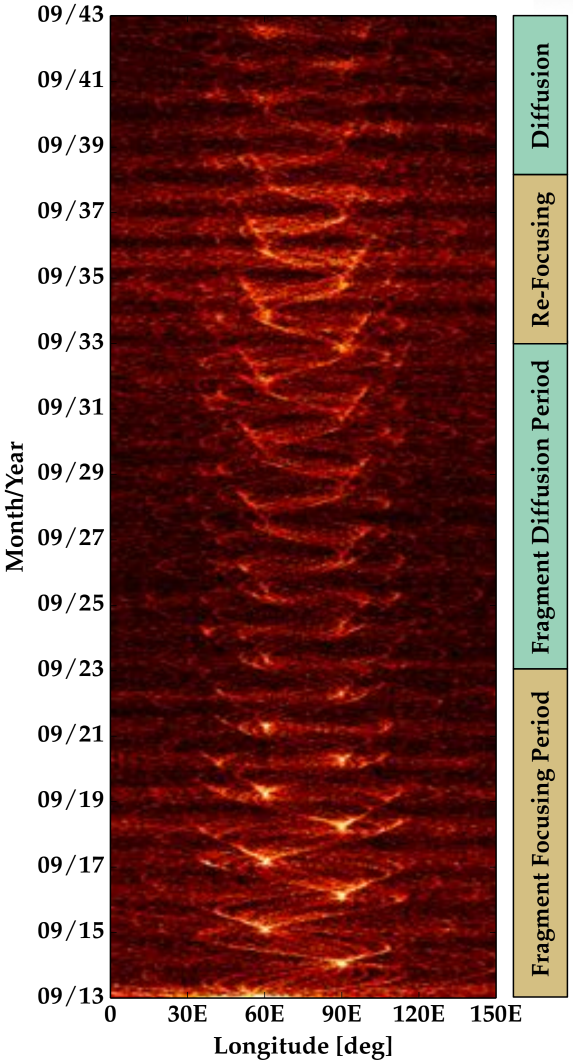
P. V. Anderson and H. Schaub, "Longitude-Dependent Effects Of Fragmentation Events In The Geosynchronous Orbit Regime," Acta Astronautica, Vol. 105, No. 1, Dec. 2014, pp. 285–297.

SIMULATION OF PROTON R/B EXPLOSION
Elapsed Days: 0
Total RSOs: 724
FPS: 0.000

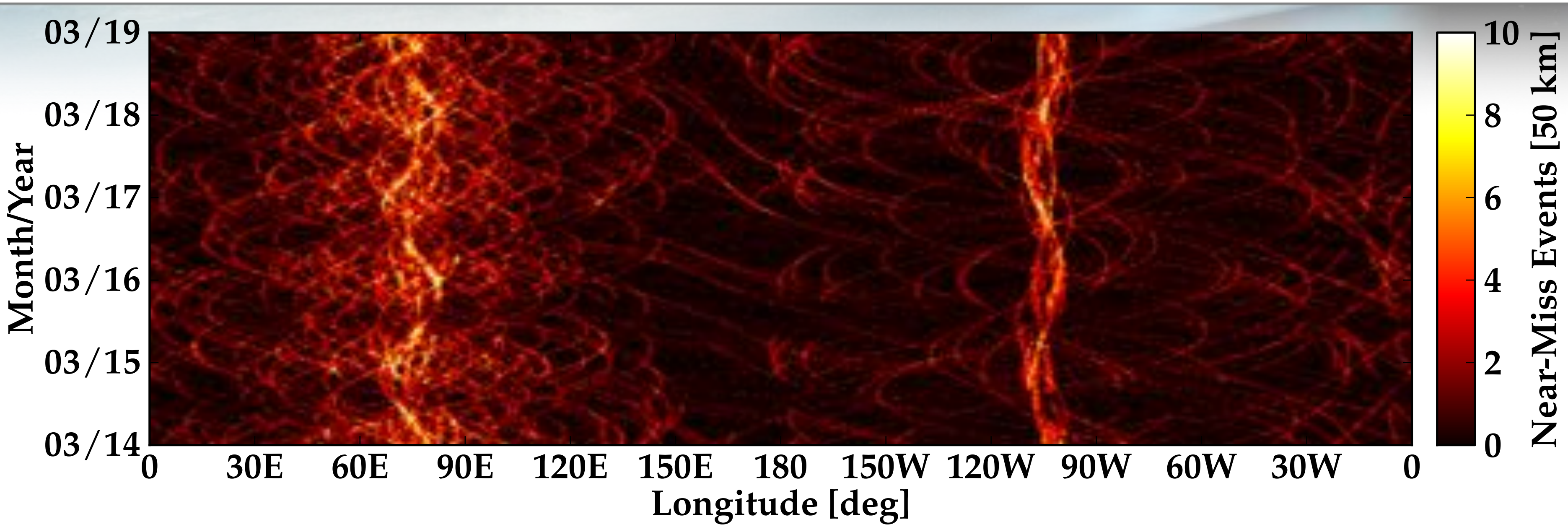
[F3] Librating: 80
[F4] Indeterminate: 0

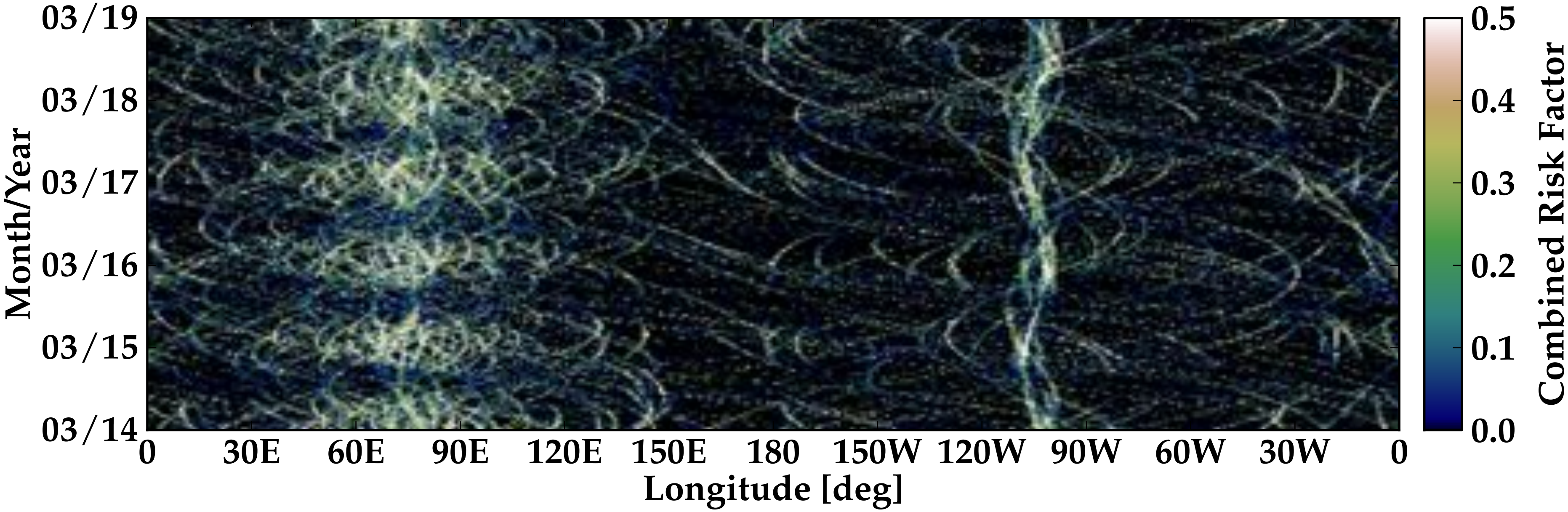


Long-term forecast.

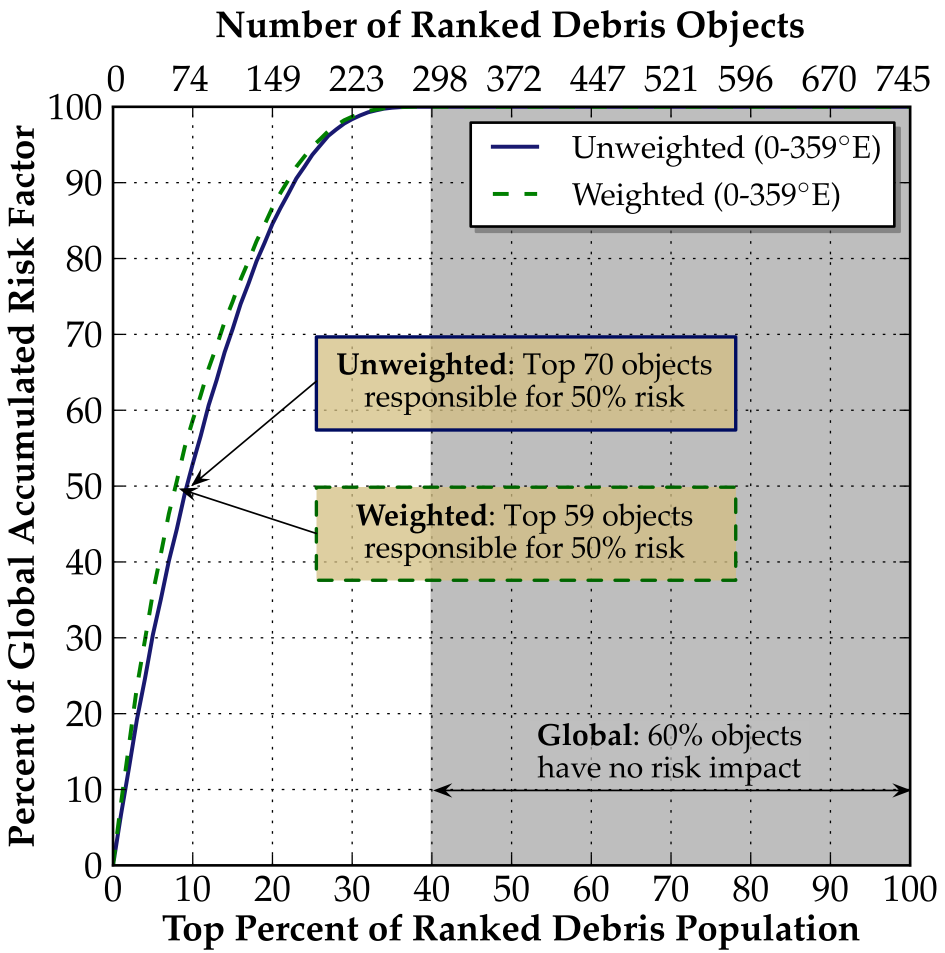


GEO Debris Risk Metric



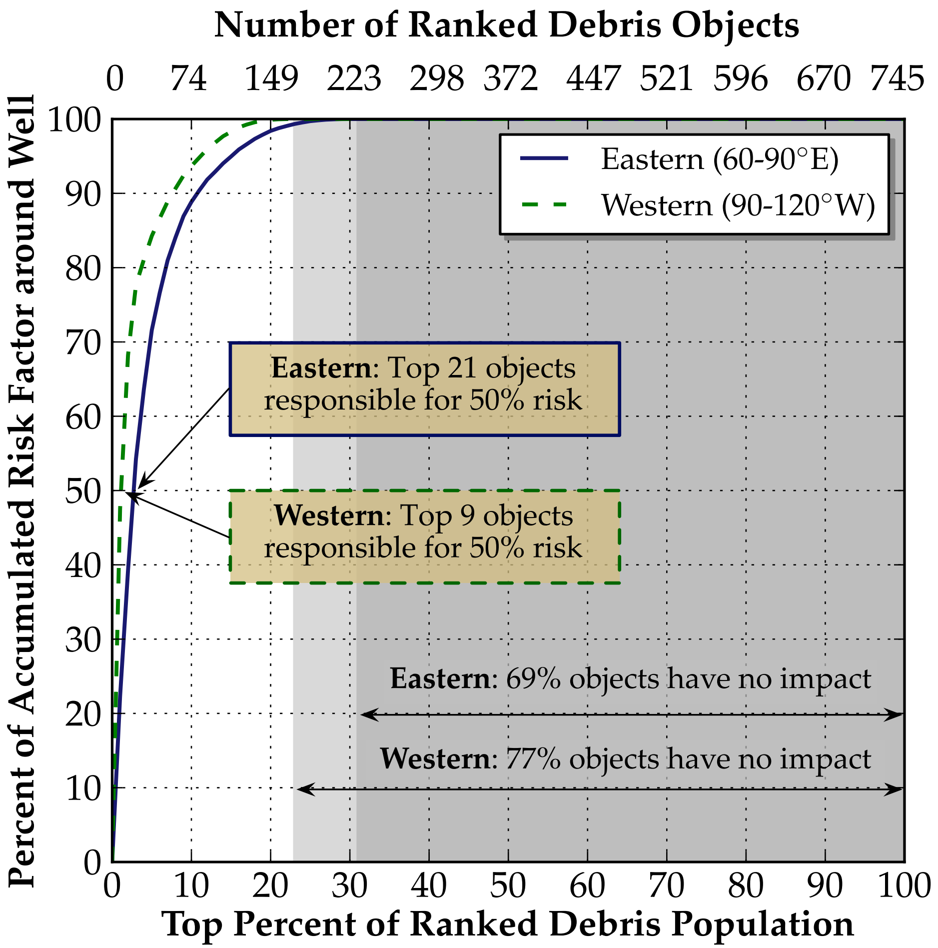


GEO Debris Risk Summary


Unweighted: Top 70 objects responsible for 50% risk

Weighted: Top 59 objects responsible for 50% risk

Global: 60% objects have no risk impact


Eastern: Top 21 objects responsible for 50% risk

Western: Top 9 objects responsible for 50% risk

Eastern: 69% objects have no impact

Western: 77% objects have no impact

Electrostatic Tug Concept

Video clip from the documentary “Collision Point, the Race to Clean up Space.”

Electrostatic Force and Torque Modeling

Charge Transfer Study

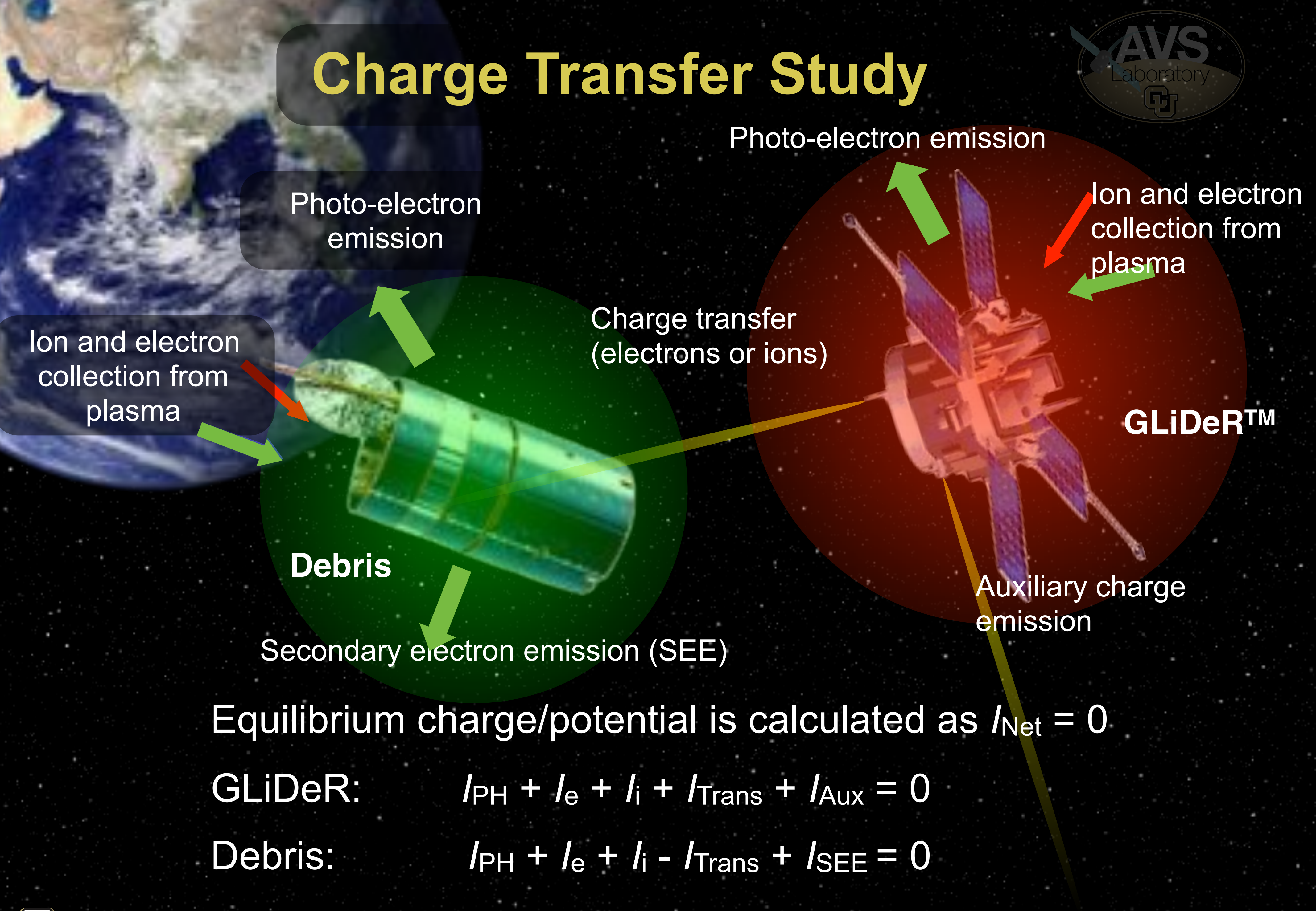


Photo-electron emission

Ion and electron collection from plasma

Photo-electron emission

Ion and electron collection from plasma

Charge transfer (electrons or ions)

GLiDeR^{TM}

Debris

Auxiliary charge emission

Secondary electron emission (SEE)

Equilibrium charge/potential is calculated as $I_{Net} = 0$

GLiDeR: $I_{PH} + I_e + I_i + I_{Trans} + I_{Aux} = 0$

Debris: $I_{PH} + I_e + I_i - I_{Trans} + I_{SEE} = 0$

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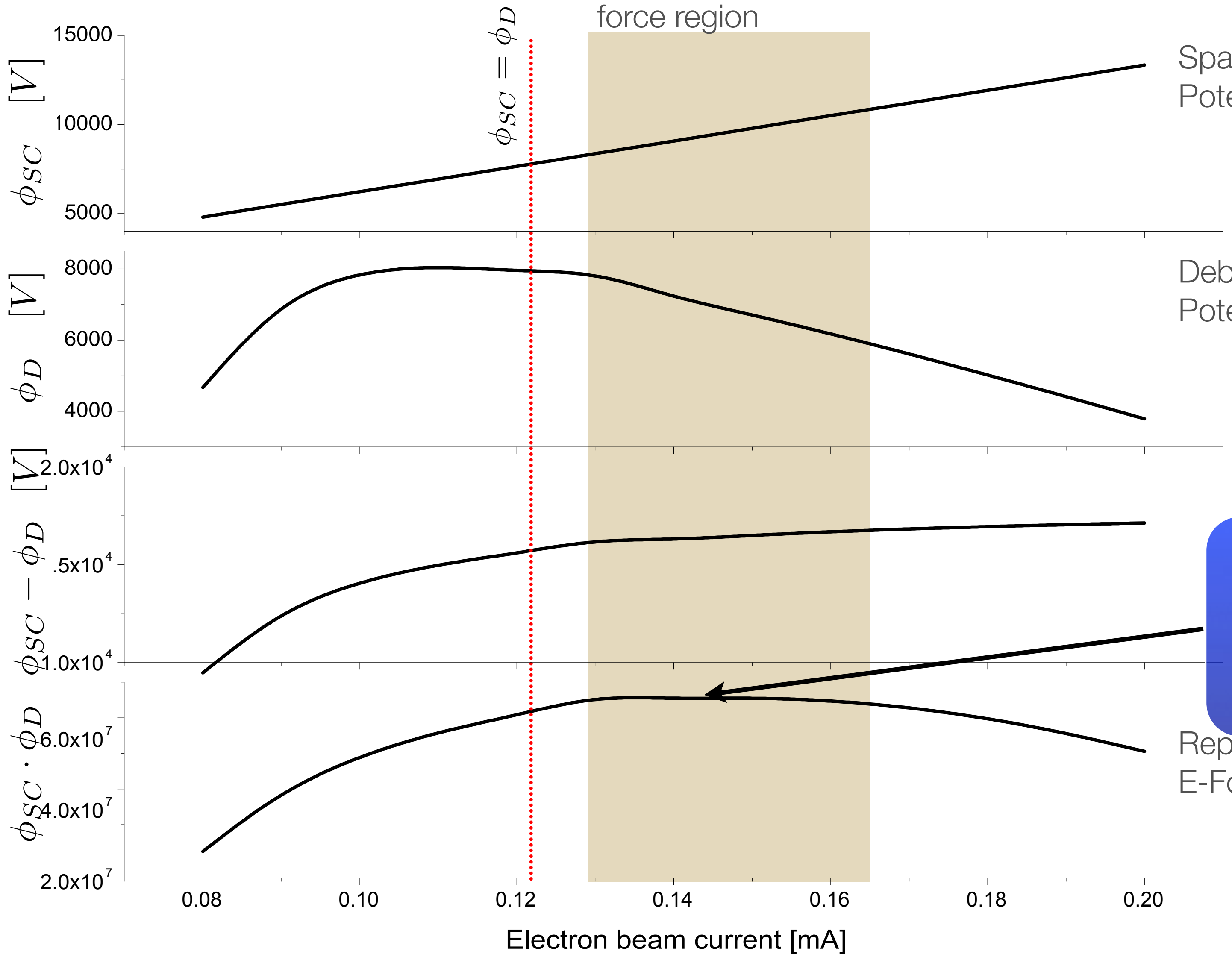
Electron Beam Current Variations



approximate max force region

Spacecraft Potential

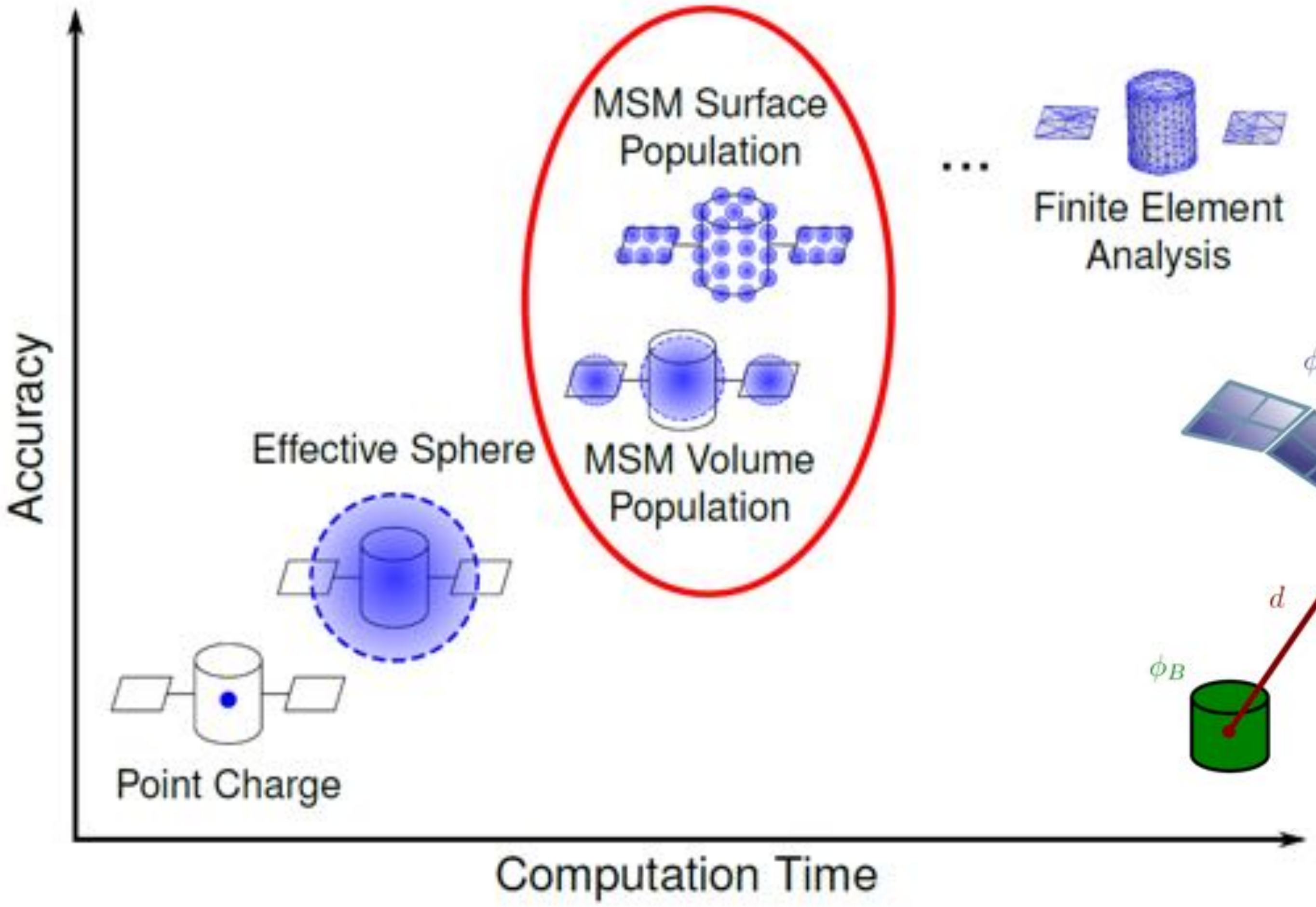
Debris Potential

Represents E-Force

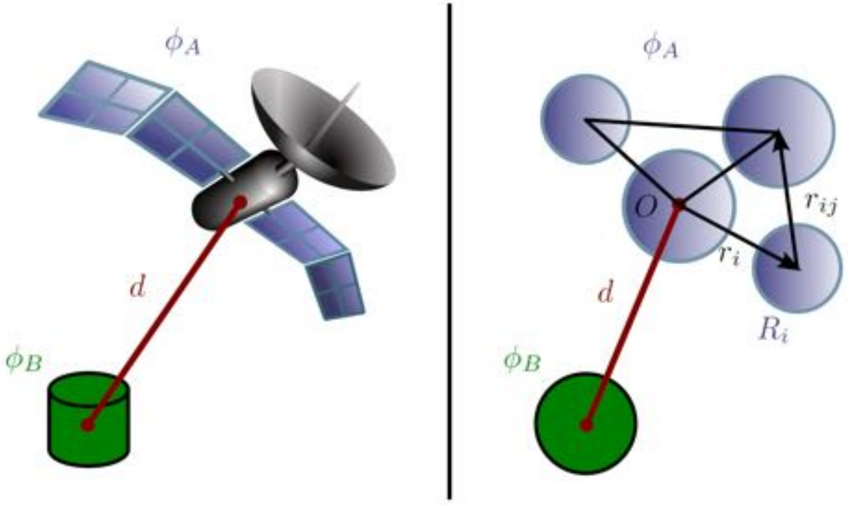
Electrostatic tractor force is robust to current variations.

H. Schaub and Z. Sternovksy, “Active Space Debris Charging for Contactless Electrostatic Disposal Maneuvers,” Advances in Space Research, Vol. 53, No. 1, 2014, pp. 110–118.

Multi-Sphere-Method (MSM)

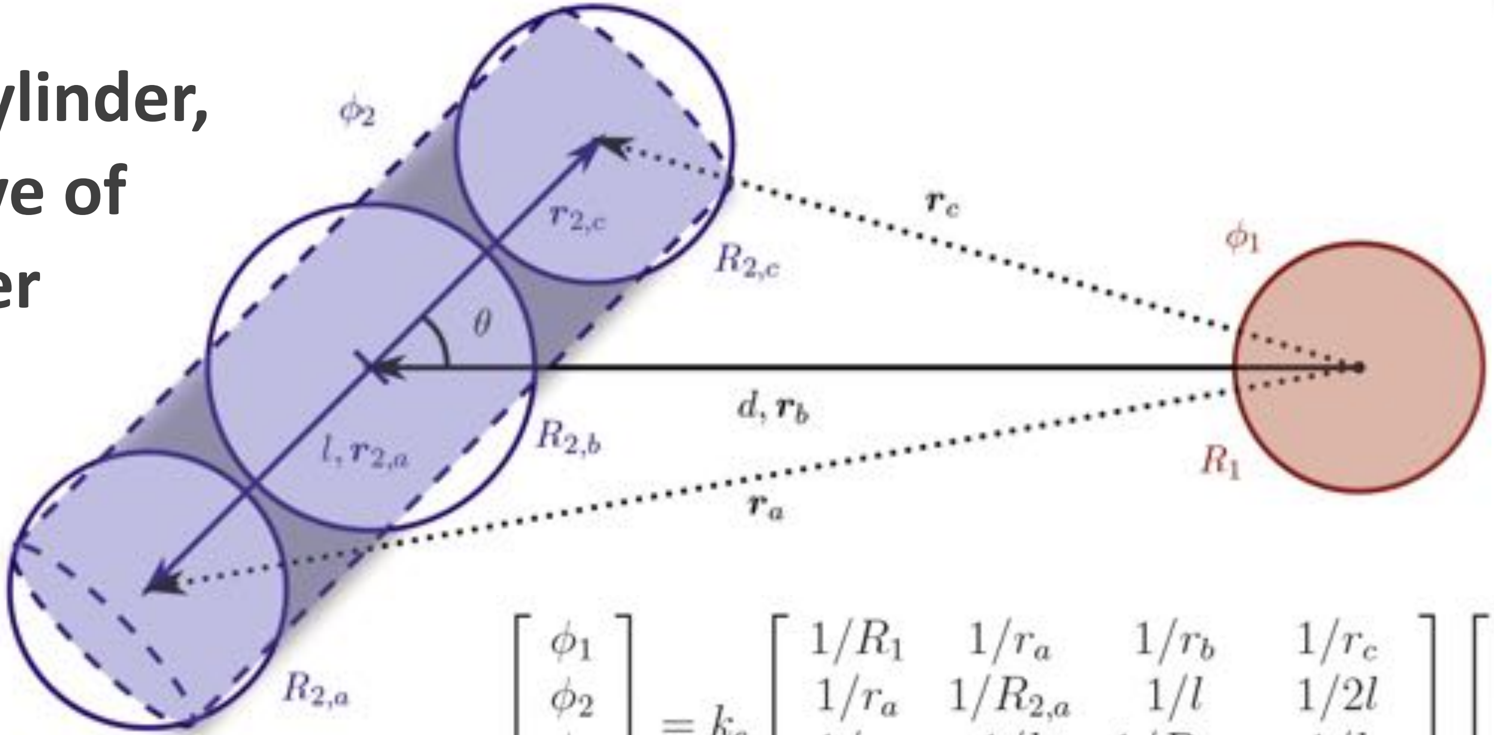


$$\phi_i = k_c \frac{q_i}{R_i} + \sum_{j=1, j\neq i}^{m} k_c \frac{q_j}{r_{i,j}}$$



Electrostatic Modeling

Simple 3x1 cylinder, representative of Centaur upper stage rocket



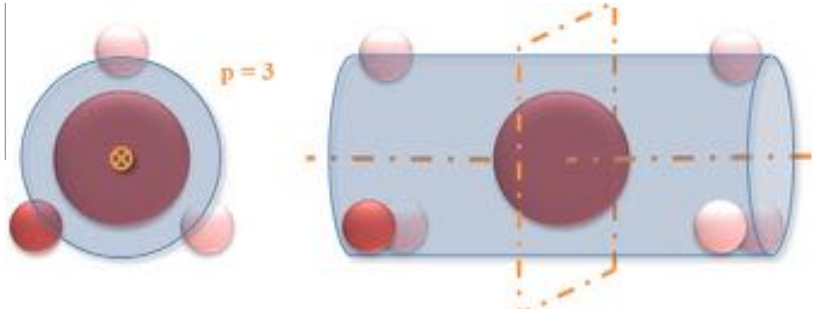
$$\begin{bmatrix} \phi_1 \\ \phi_2 \\ \phi_2 \\ \phi_2 \end{bmatrix} = k_c \underbrace{\begin{bmatrix} 1/R_1 & 1/r_a & 1/r_b & 1/r_c \\ 1/r_a & 1/R_{2,a} & 1/l & 1/2l \\ 1/r_b & 1/l & 1/R_{2,b} & 1/l \\ 1/r_c & 1/2l & 1/l & 1/R_{2,c} \end{bmatrix}}_{[C_M]^{-1}} \begin{bmatrix} q_1 \\ q_a \\ q_b \\ q_c \end{bmatrix}$$

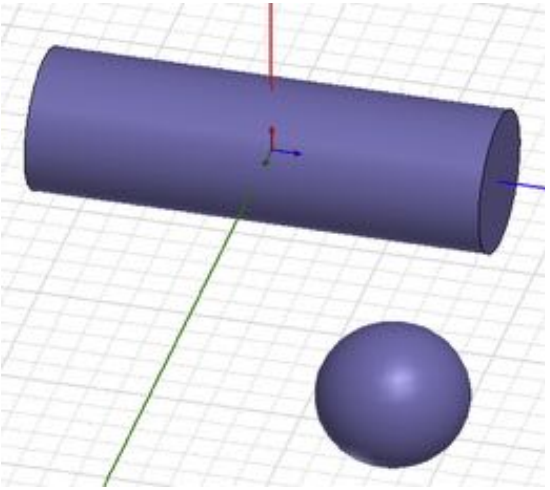
$$M_2 = k_c q_1(d,\theta) l d \sin\theta \left(\frac{q_c(d,\theta)}{r_c^3(d,\theta)} - \frac{q_a(d,\theta)}{r_a^3(d,\theta)} \right)$$

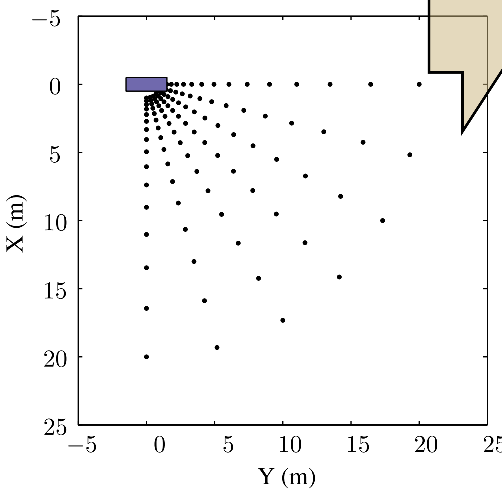
Parameter	Value	Units	Description
m_{cyl}	156.8	g	Cylinder mass
I_{cyl}	2.867	g·m^2	Cylinder transverse moment of inertia
d	45	cm	Object center-to-center separation
l	17.353	cm	MSM Parameters
R_a, R_c	8.8634	cm	MSM Parameters
R_b	9.7664	cm	MSM Parameters

D. Stevenson and H. Schaub, “Multi-Sphere Method for Modeling Electrostatic Forces and Torques,” Journal of Advances in Space Research, Vol. 51, No. 1, Jan. 2013, pp. 10–20.

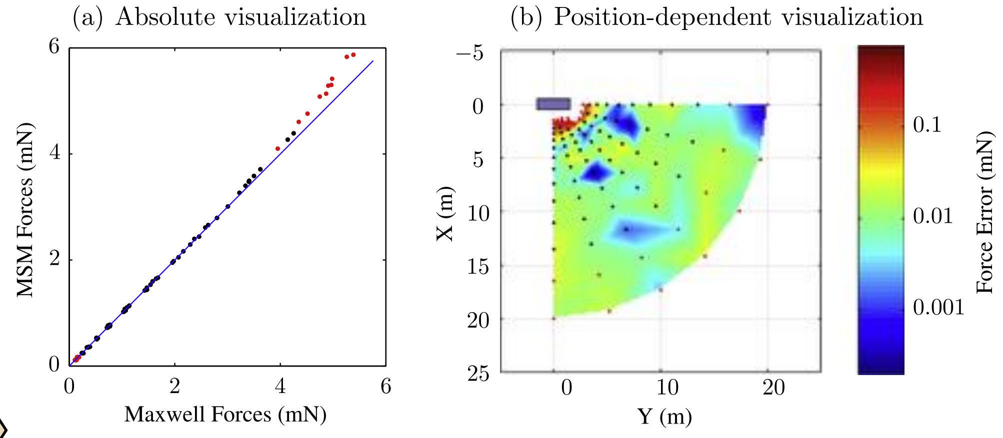
Volume MSM

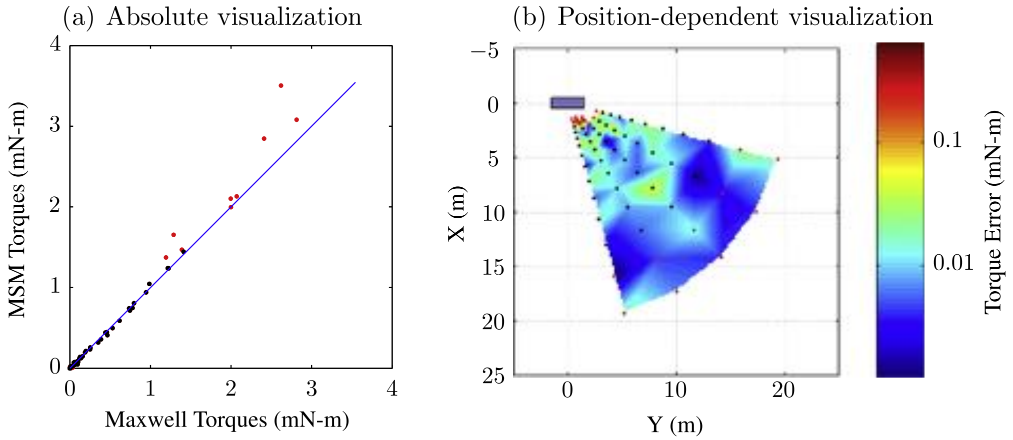



(a) Maxwell 3D model

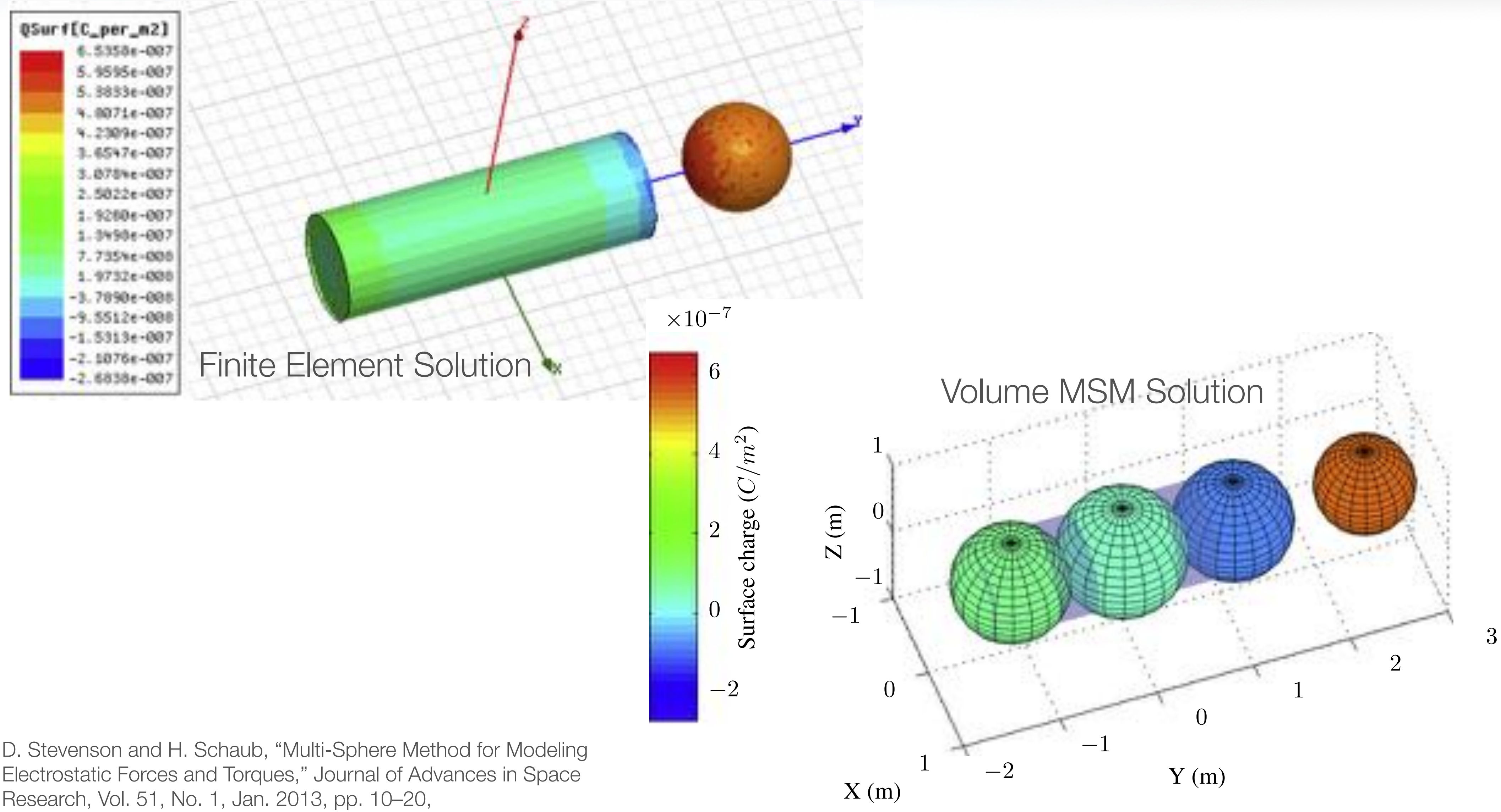


(b) Maxwell parameter sweep





Cylinder Volume MSM

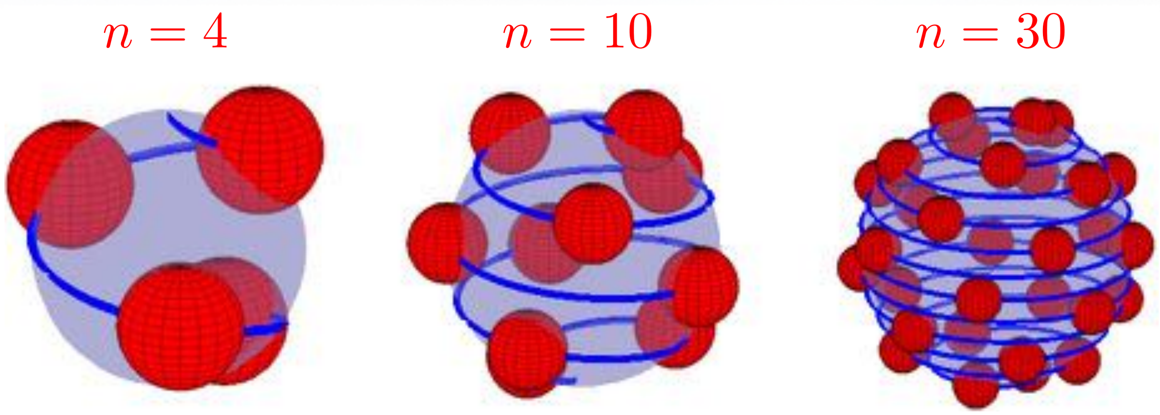


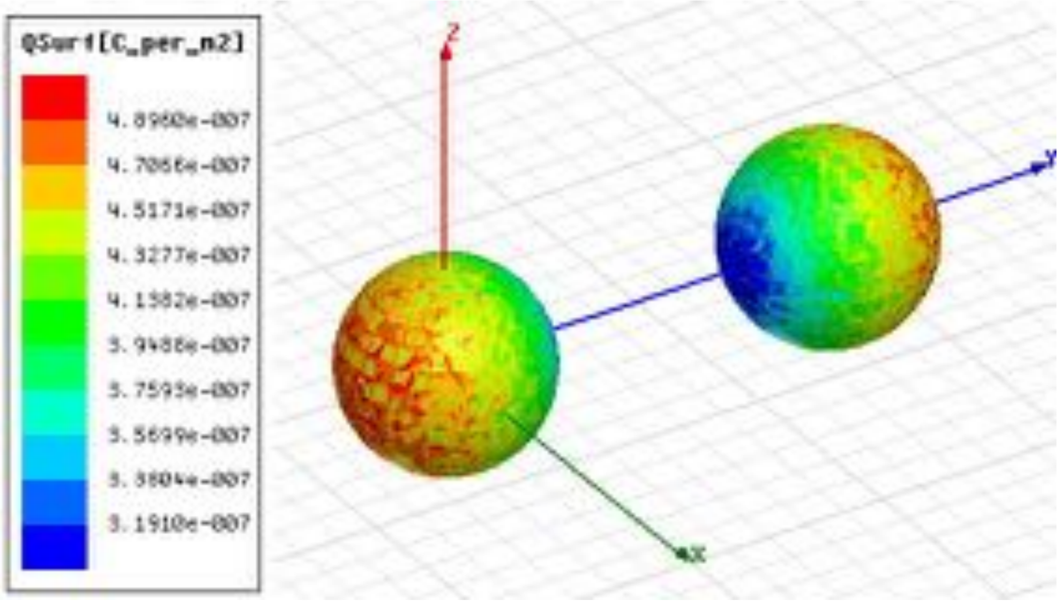
Finite Element Solution

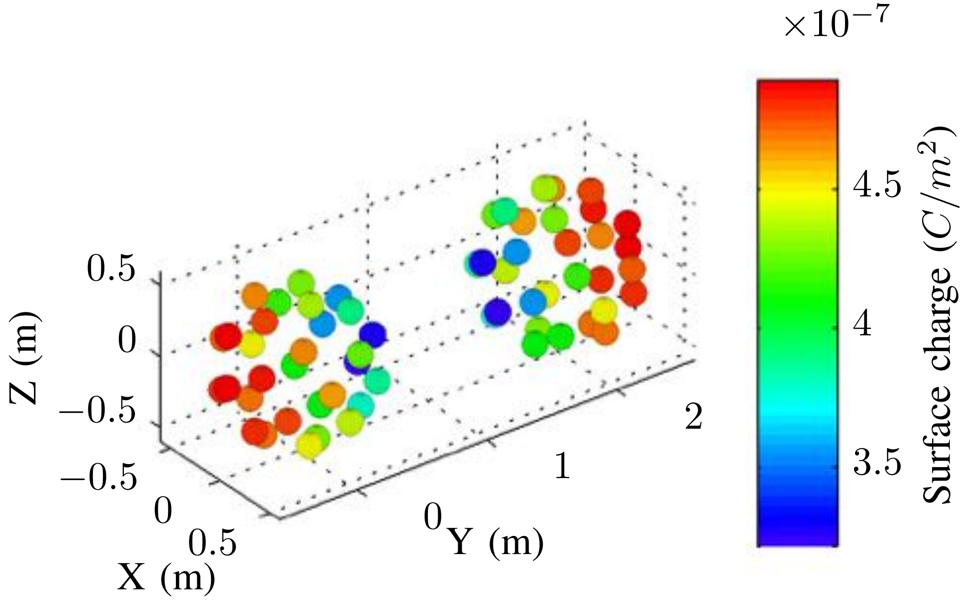
Volume MSM Solution

D. Stevenson and H. Schaub, “Multi-Sphere Method for Modeling Electrostatic Forces and Torques,” Journal of Advances in Space Research, Vol. 51, No. 1, Jan. 2013, pp. 10–20,

Surface MSM

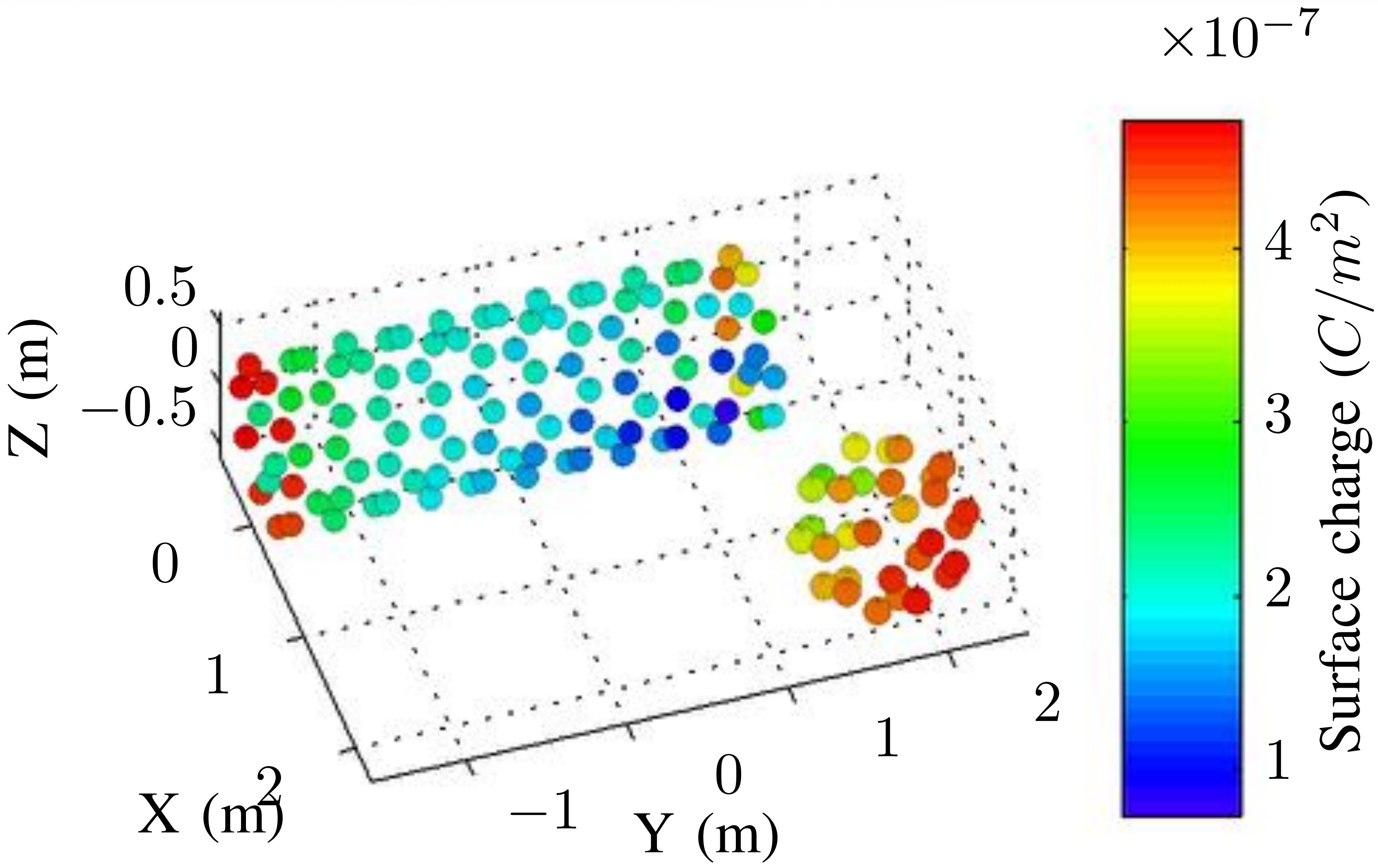




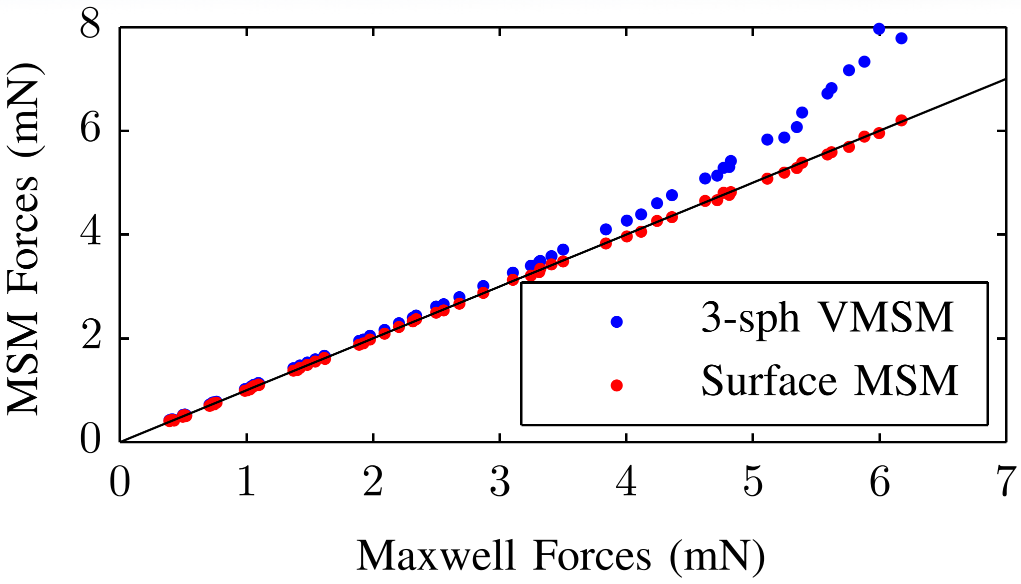


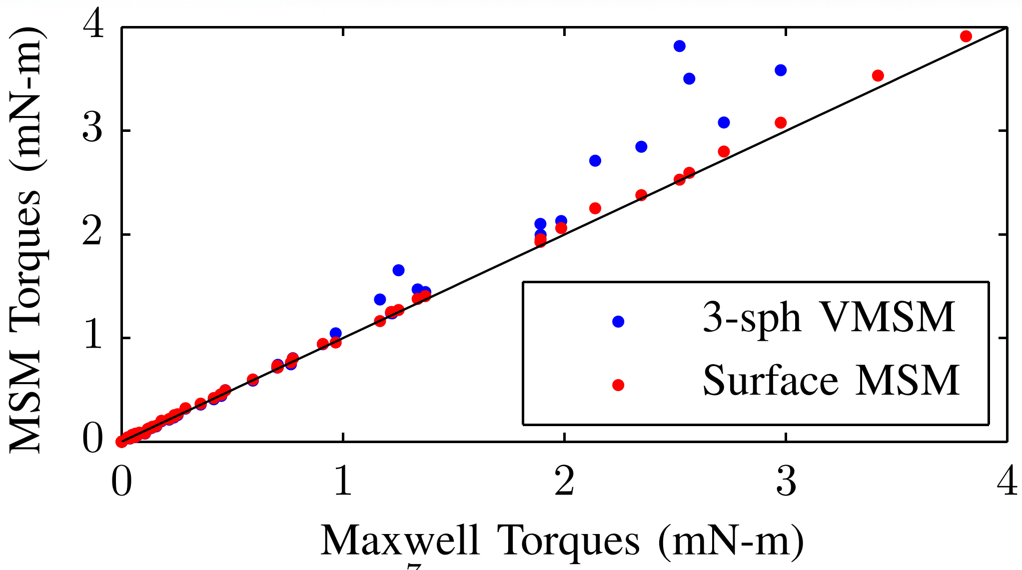
D. Stevenson and H. Schaub, "Optimization of Sphere Population for Electrostatic Multi-Sphere Method," IEEE Transactions on Plasma Science, Vol. 41, No. 12, Dec. 2013, pp. 3526-3535.

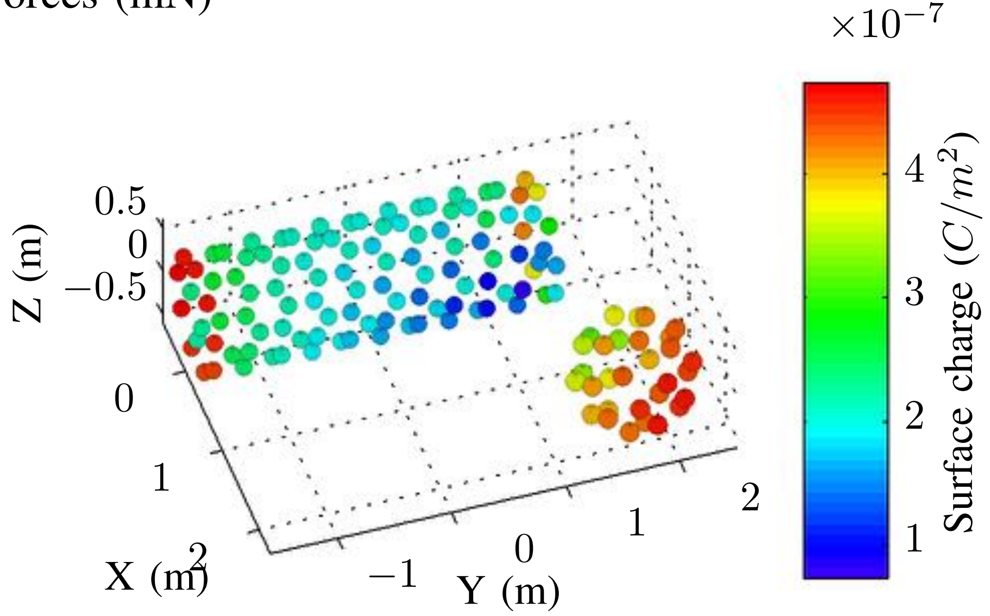
Rocket-Body Detumble Application



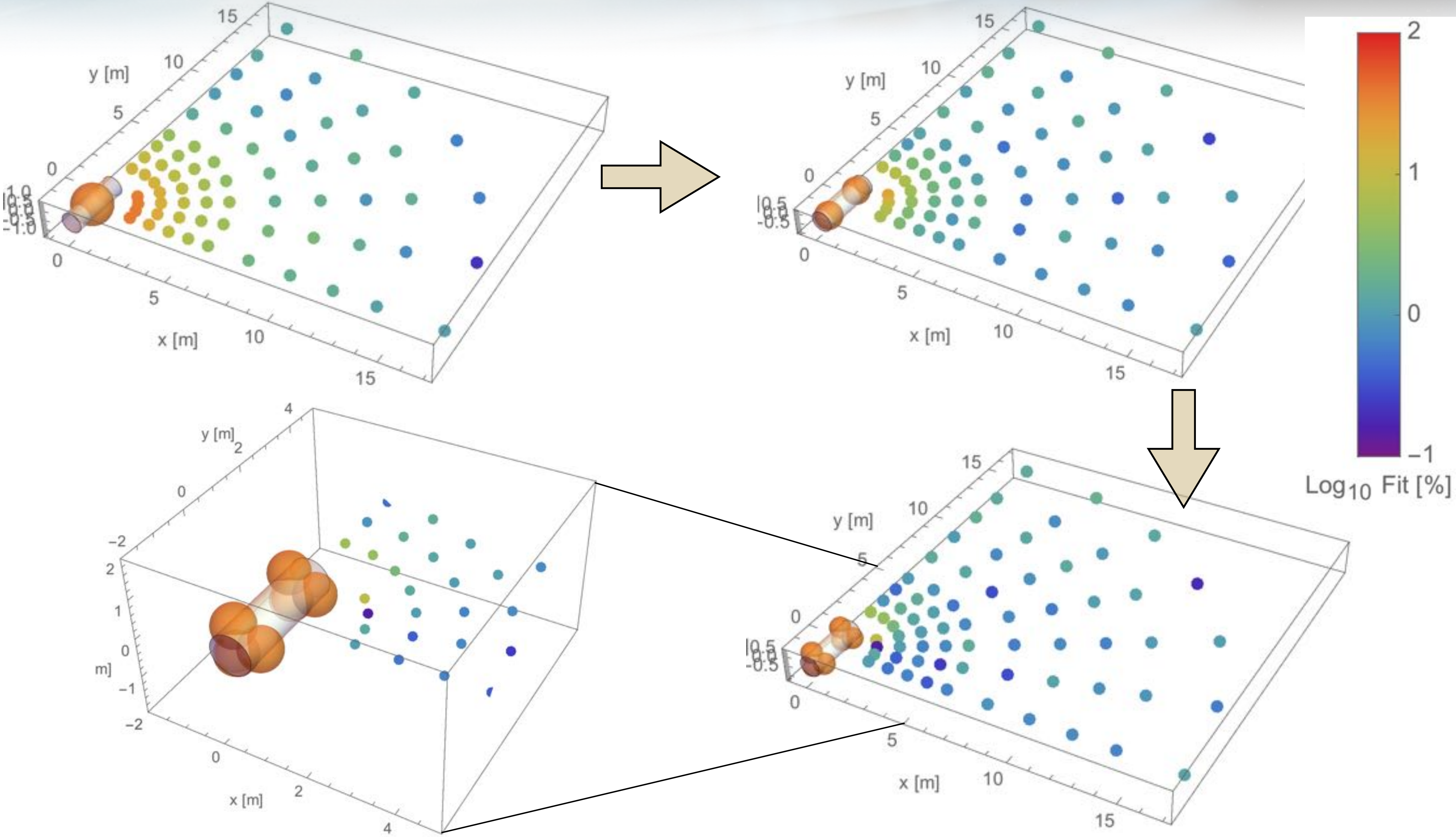
VMSM vs SMSM Accuracy Comparison



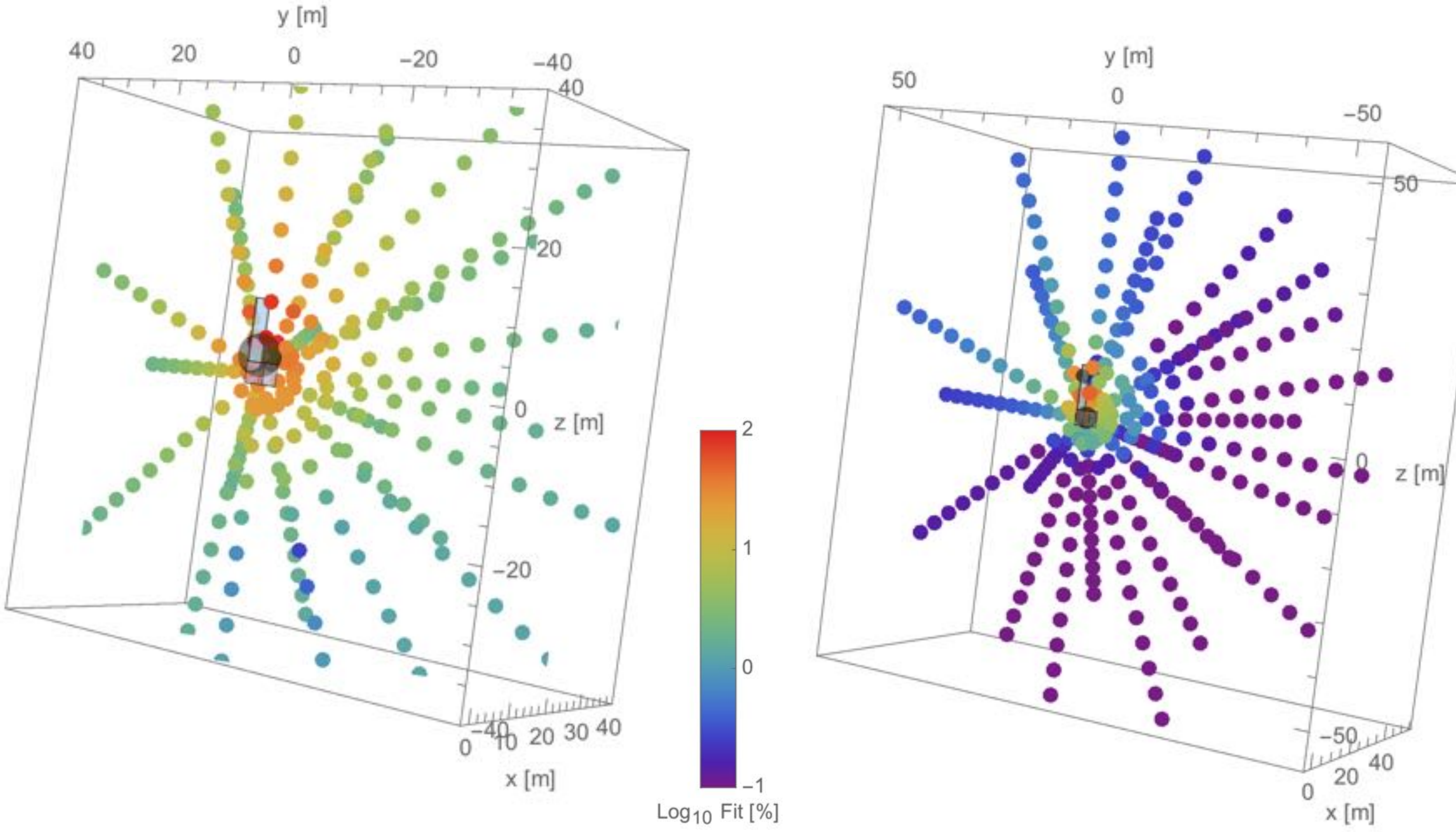




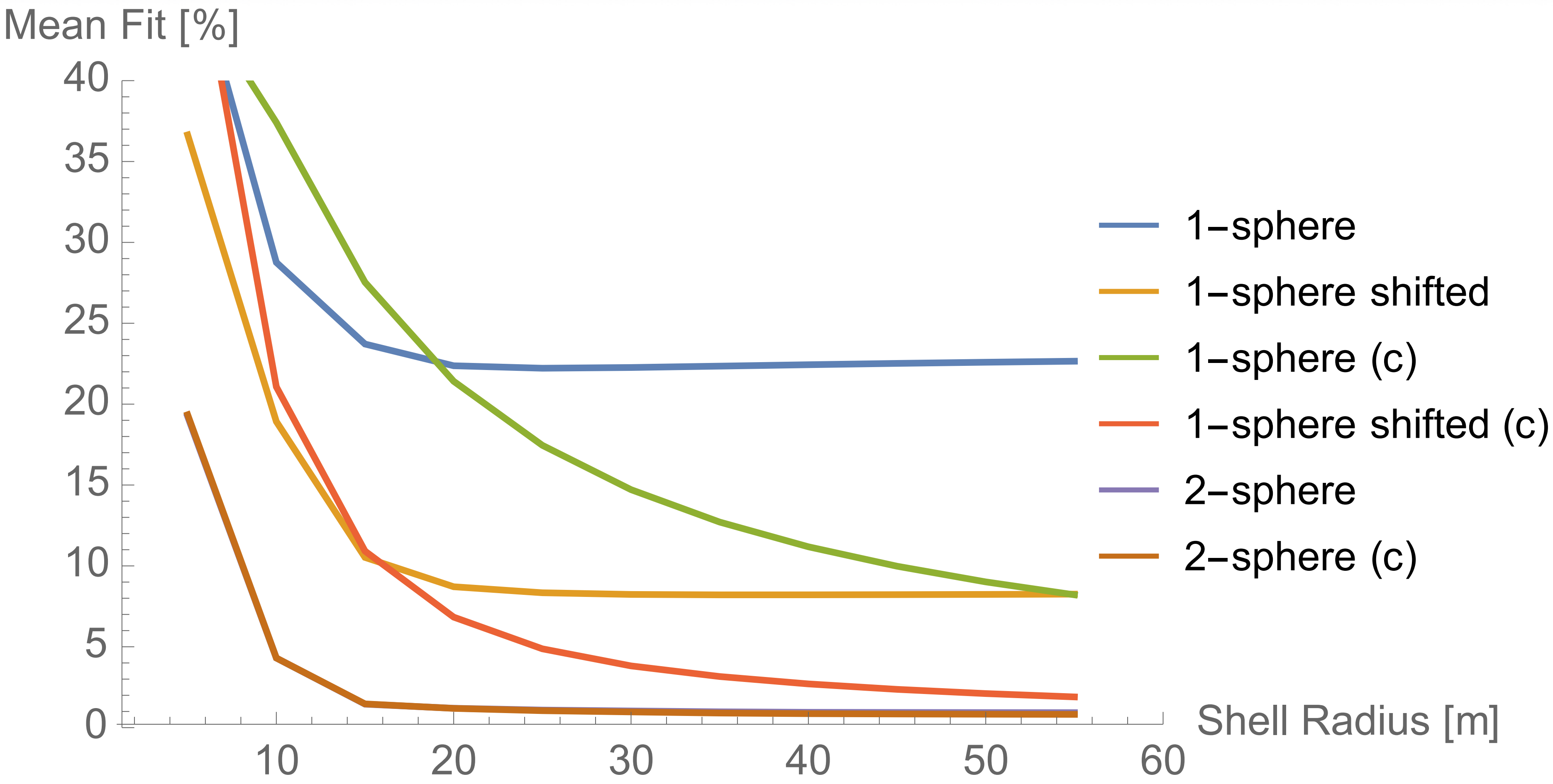
Cylinder Example



Box-Wing Example of GOES using SMSM Generated Models

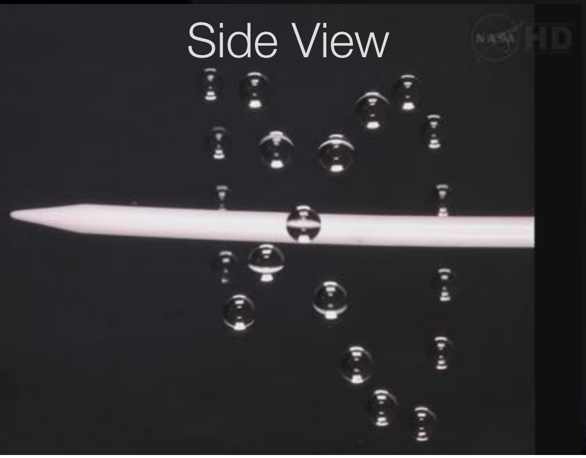


Comparison of SMSM fitted VMSMs



Needle/Droplet Experiment on ISS

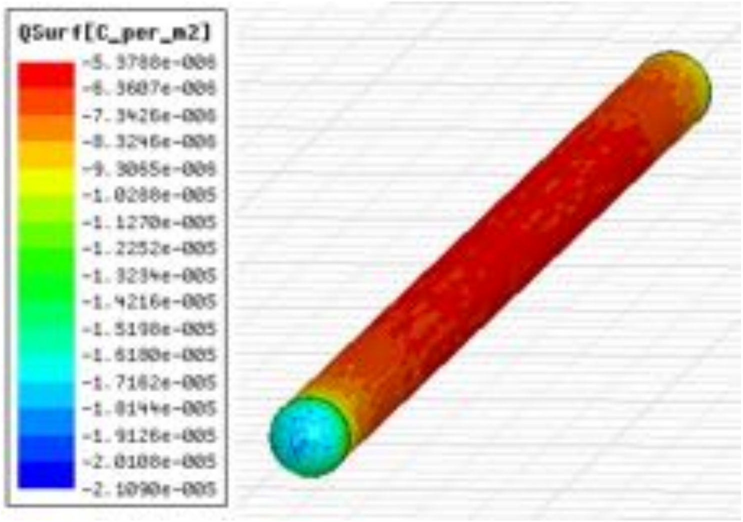
Front View

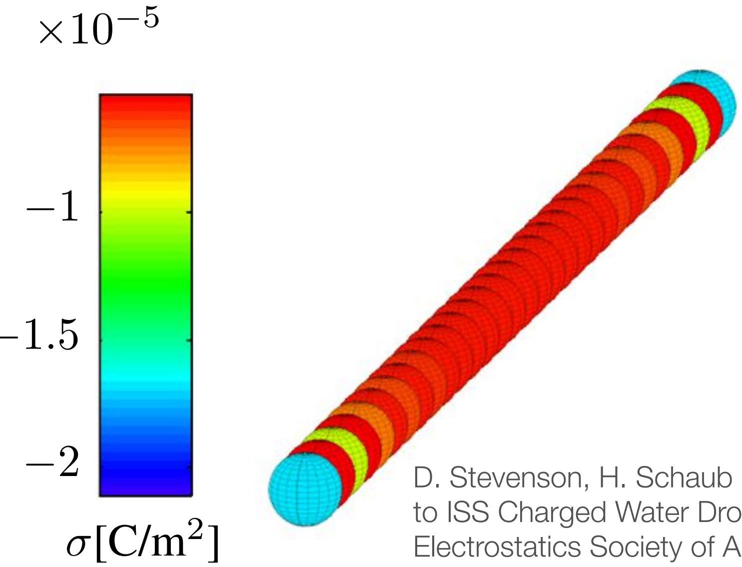


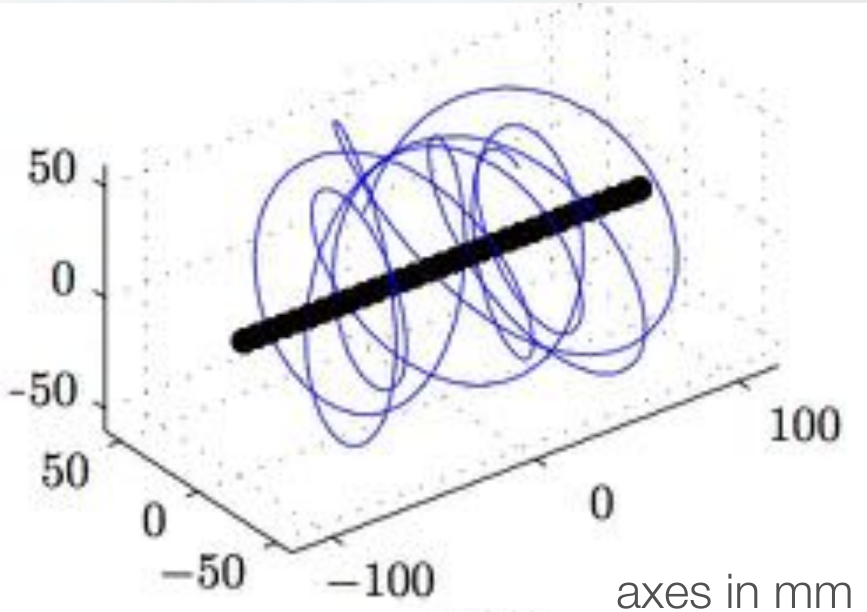
Side View

Video Curtesy of Astronaut Don Pettit, NASA

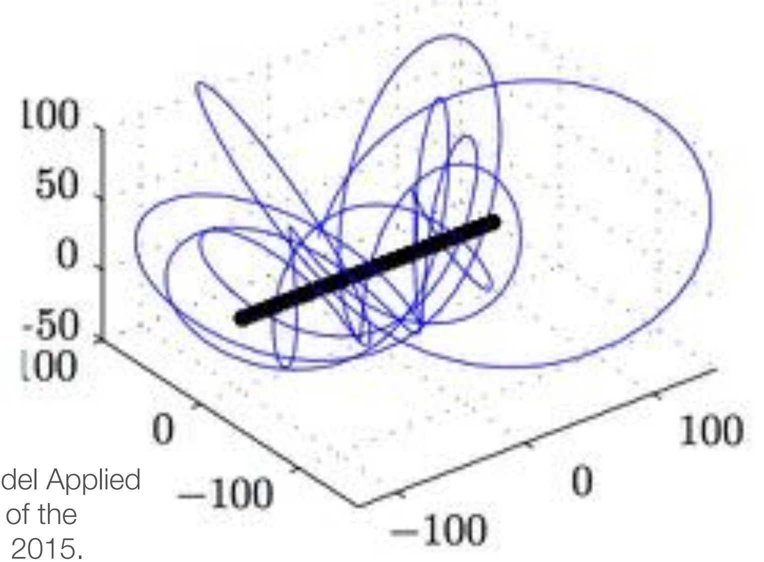
Numerical Needle/Droplet Simulation







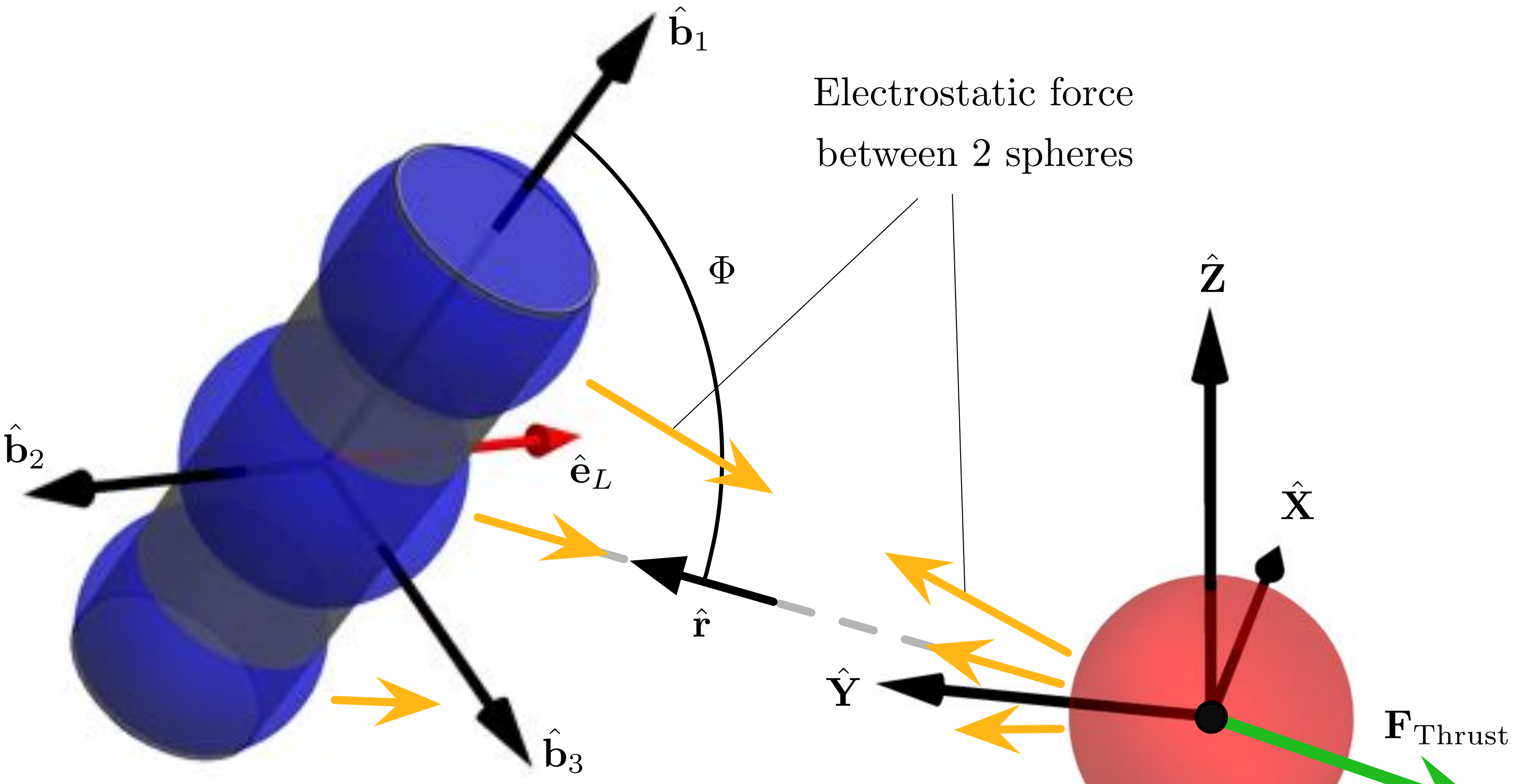
axes in mm



D. Stevenson, H. Schaub and D. R. Pettit, “Electrostatic Model Applied to ISS Charged Water Droplet Experiment,” Annual Meeting of the Electrostatics Society of America, Paloma, CA, June 16–18, 2015.

Electrostatic
3-D Spin Control

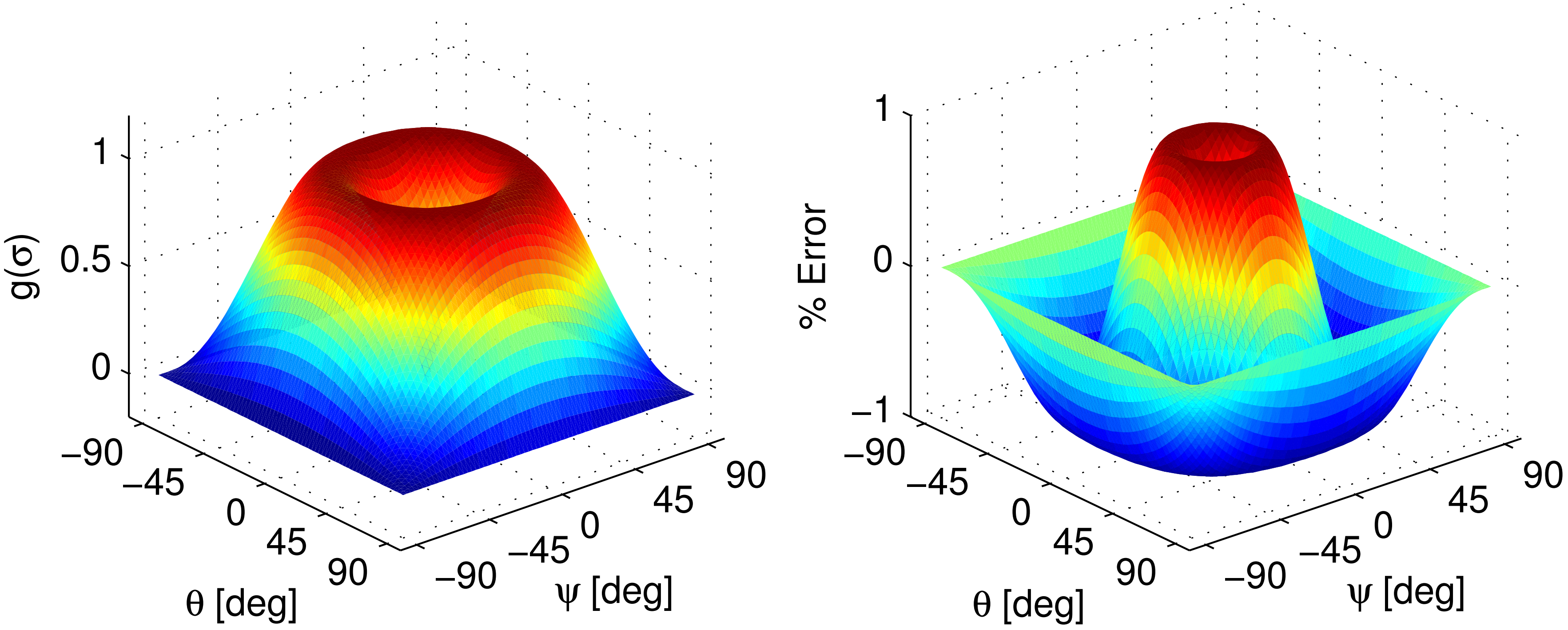
3D Relative Rotations



T. Bennett and H. Schaub, "Touchless Electrostatic Three-Dimensional Detumbling of Large GEO Debris," AAS/AIAA Spaceflight Mechanics Meeting, Santa Fe, New Mexico, January 26–30, 2014

Simplied 3D E-Torque Model

$$g(\boldsymbol{\sigma}) = \sin(2\Phi)$$

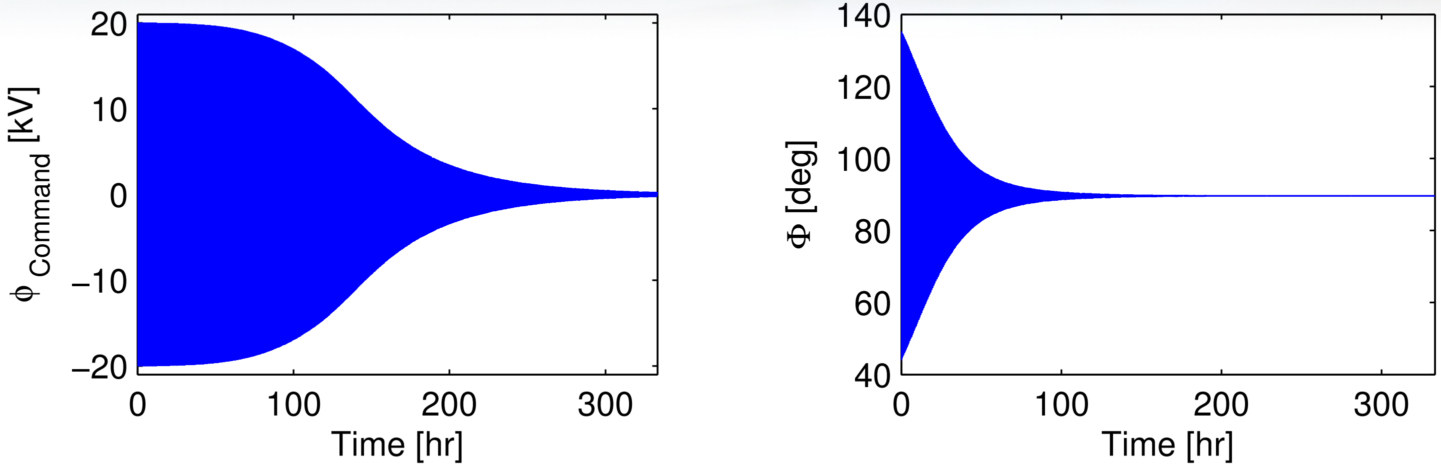


(a) Base function as a function of attitude

(b) Error between base function and MSM

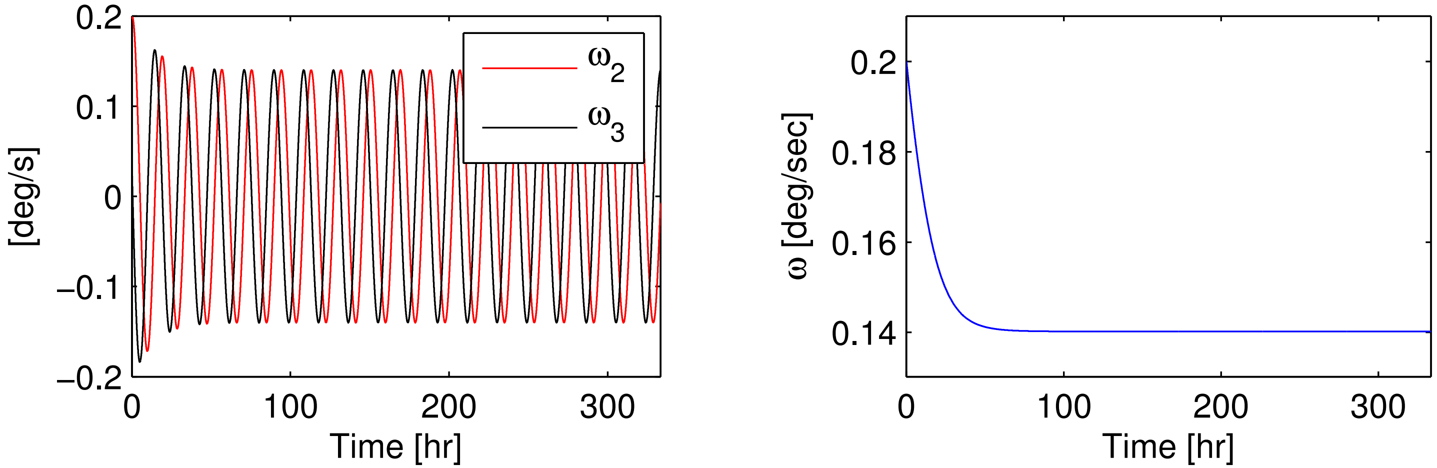
Figure 3. Normalized torque surface and corresponding error at a separation distance of $d = 15\ m$ **for** $V_1 = -30\ kV$ **and** $V_2 = 30\ kV$**.**

Numerical Simulation of 3D Detumble



(a) Commanded Potential, ϕ_1

(b) Projection Angle, , Φ

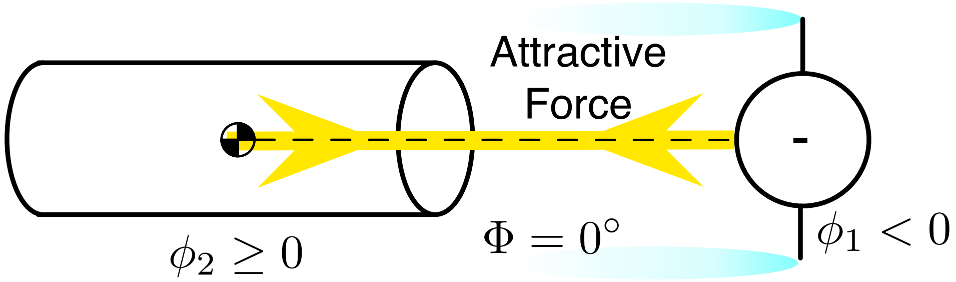


(c) Angular velocity components, $\boldsymbol{\omega}$

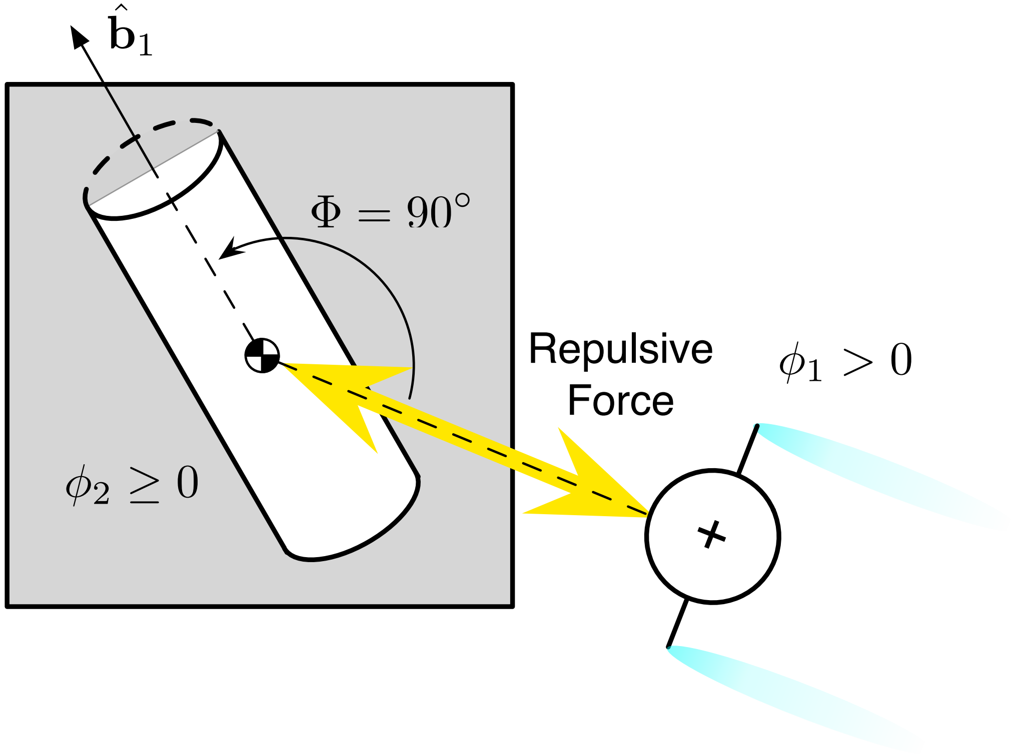
(d) Angular velocity magnitude, $|\omega|$

Figure 6. Numerical simulation with initial conditions: $|\omega| = 0.2$**,** $d = 15$ **m,** $\Phi_0 = 45°$**, with** $V_{\mathbf{max}} = 20\ kV$**.**

3D Detumbling While Tugging or Pushing in Deep Space

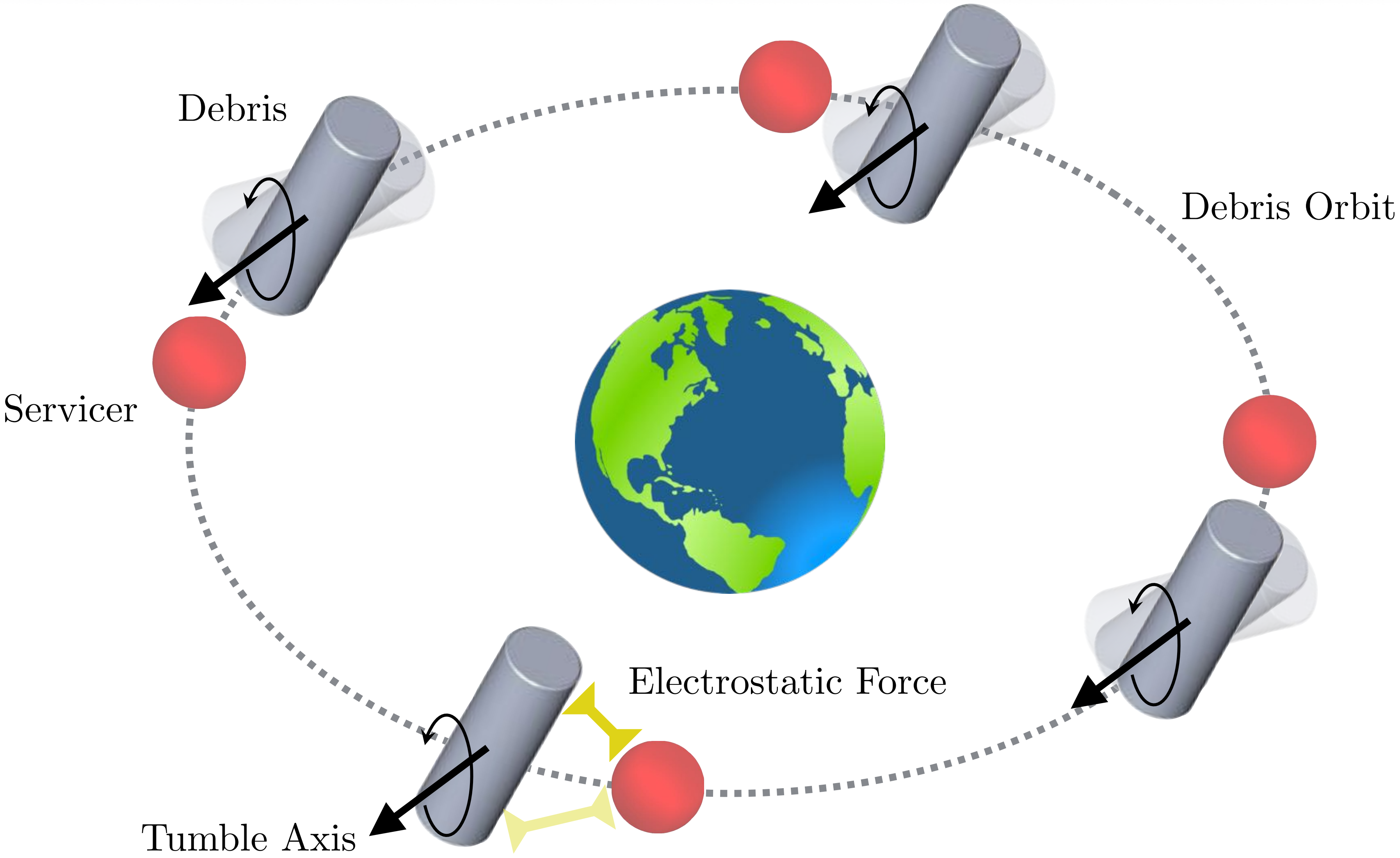


Tugging Configuration



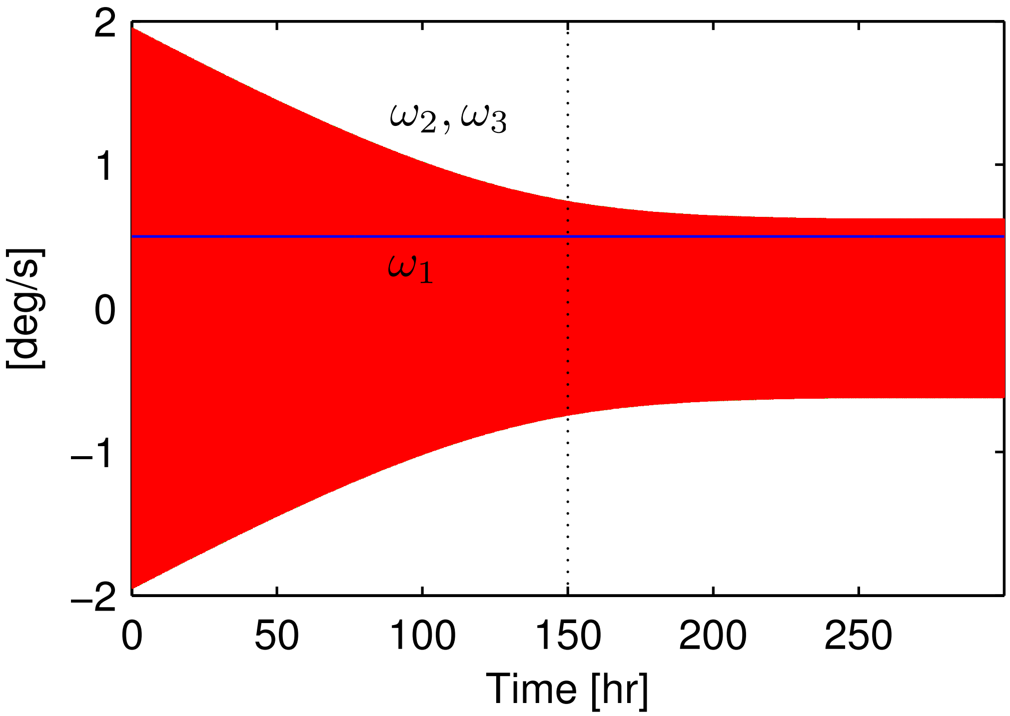
Pushing Configuration

Inertial Relative Motion in Orbit

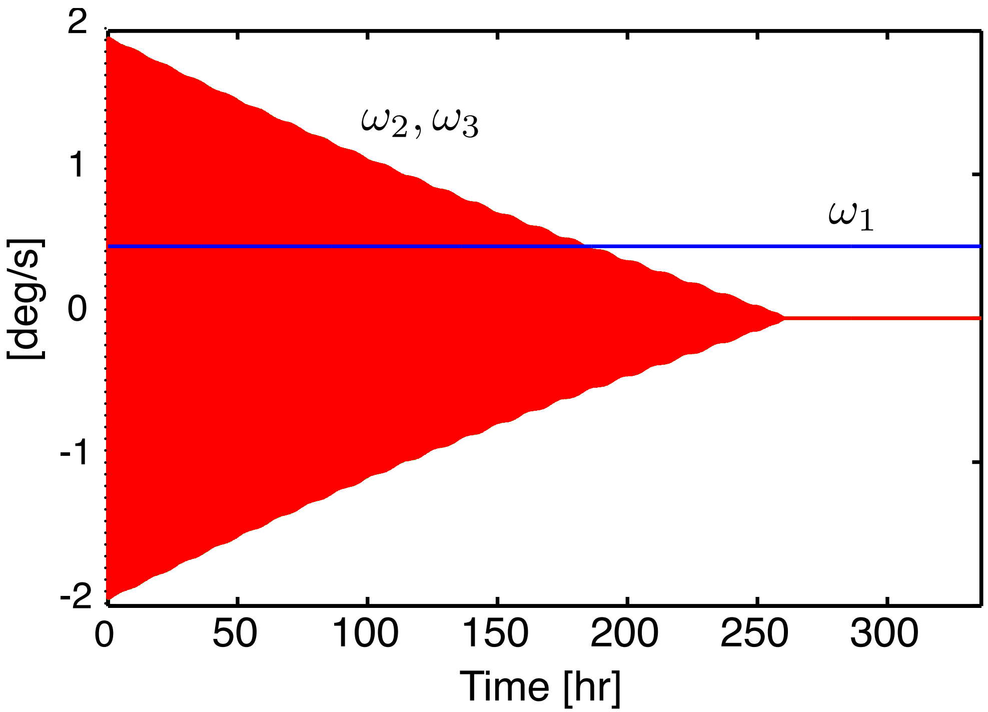


T. Bennett and H. Schaub, "Touchless Electrostatic Detumbling While Tugging Large Axi-Symmetric GEO Debris," AAS/AIAA Space Flight Mechanics Meeting, Williamsburg, VA, January 11–15, 2015.

Deep Space vs On-Orbit Performance



(a) Angular Velocities, Deep Space



(b) Angular Velocities, On Orbit

Basilisk – A Modular Spacecraft Simulation and Analysis Tool

Basilisk

Scott Piggott
Laboratory for Atmospheric and Space Physics

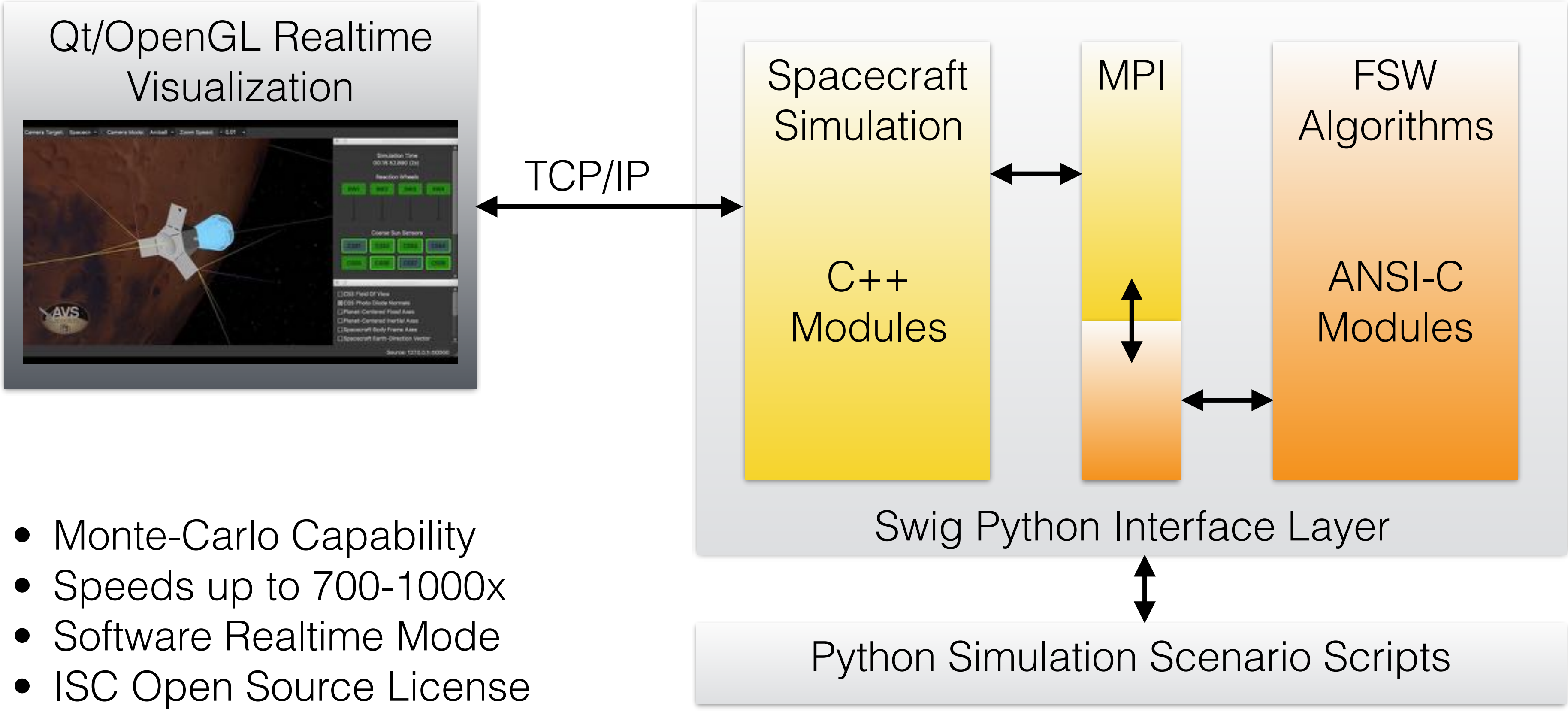
Prof. Dr. Hanspeter Schaub
Aerospace Engineering Sciences Department
Director of Autonomous Vehicle Systems (AVS) Lab

LASP
Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

AVS
Laboratory

July 2, 2016

Software Architecture (Analysis)



Qt/OpenGL Realtime Visualization

TCP/IP

Spacecraft Simulation

C++ Modules

MPI

FSW Algorithms

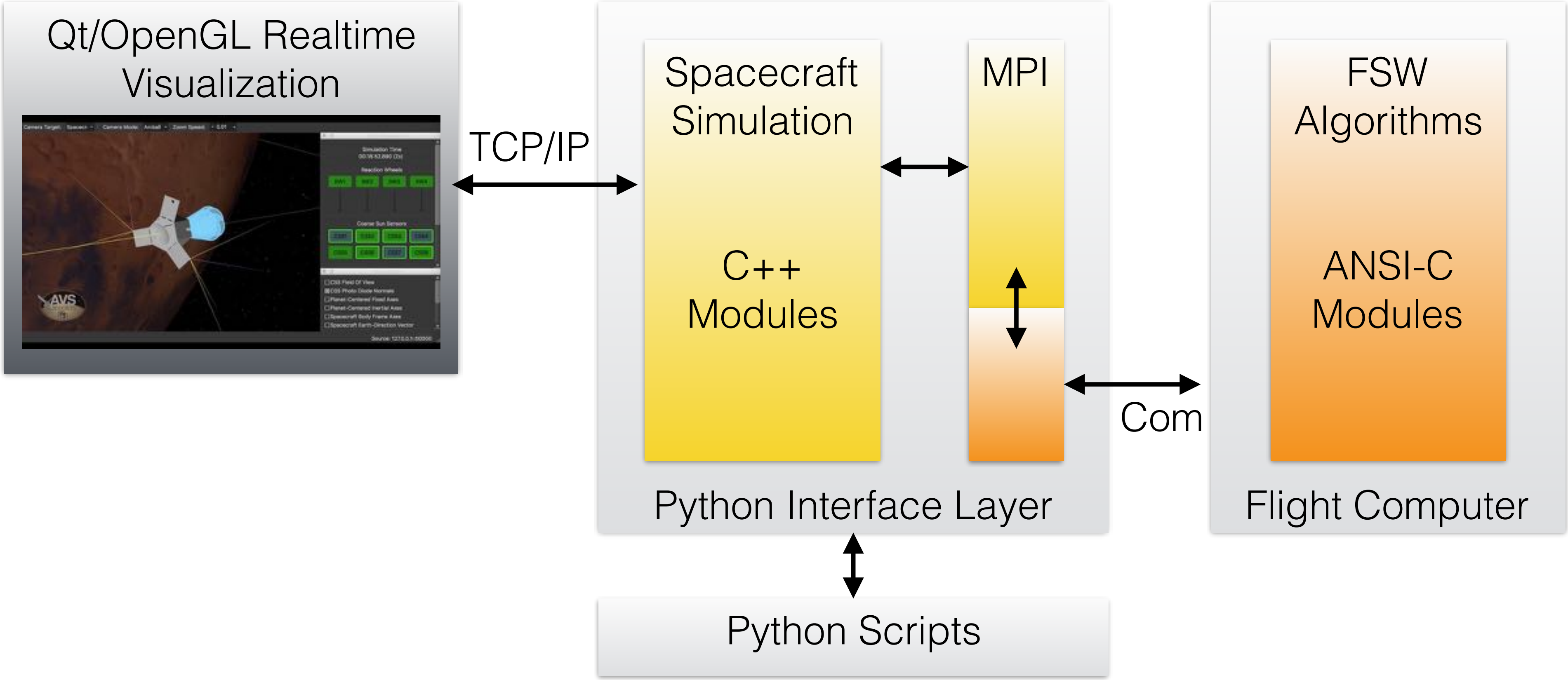
ANSI-C Modules

Swig Python Interface Layer

Python Simulation Scenario Scripts

- Monte-Carlo Capability
- Speeds up to 700-1000x
- Software Realtime Mode
- ISC Open Source License

Software Architecture (Flatsat)



Qt/OpenGL Realtime Visualization

TCP/IP

Spacecraft Simulation

C++ Modules

MPI

Com

Python Interface Layer

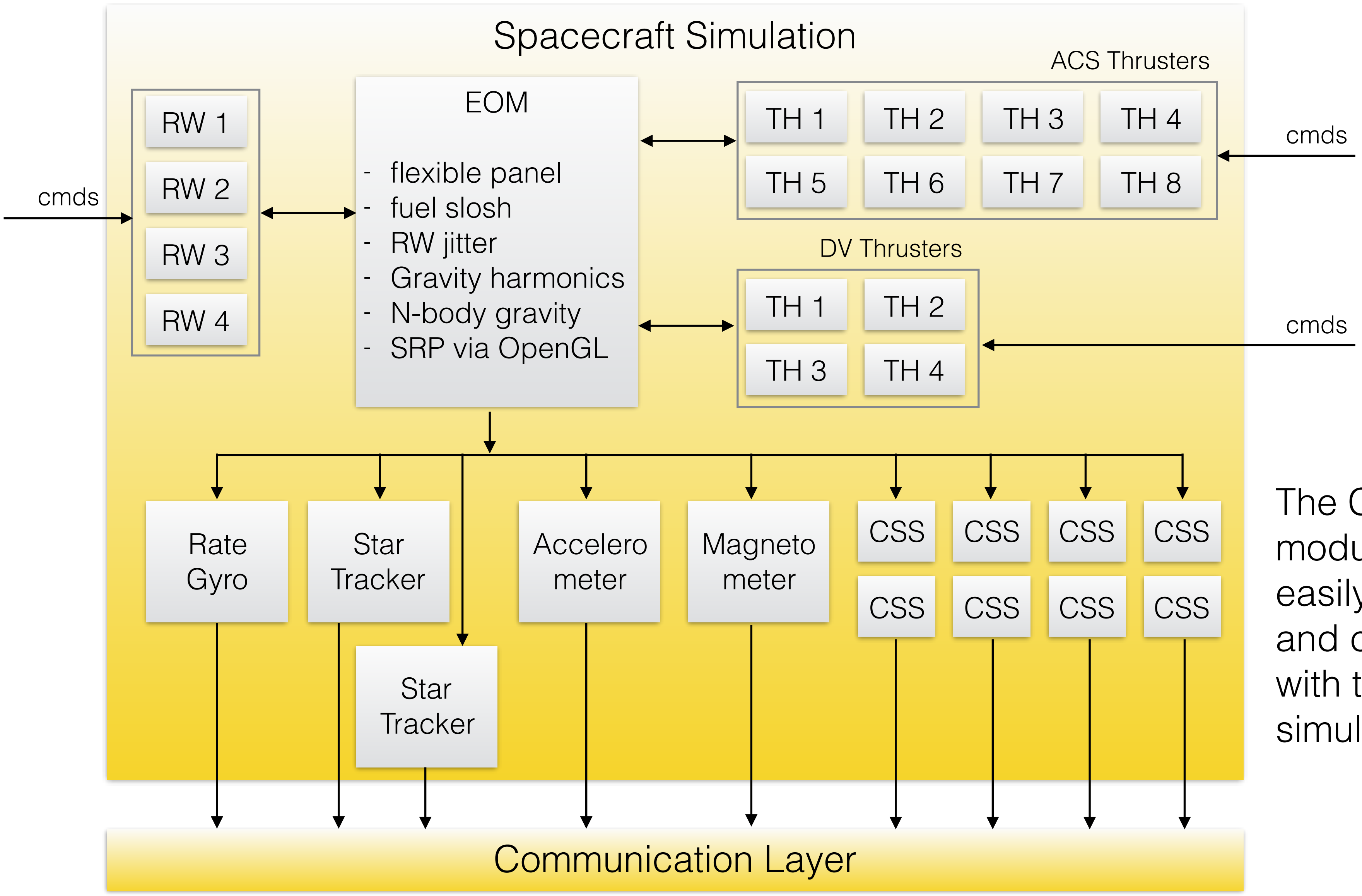
FSW Algorithms

ANSI-C Modules

Flight Computer

Python Scripts

Sample Spacecraft Simulation Setup



Spacecraft Simulation

cmds

RW 1
RW 2
RW 3
RW 4

EOM

- flexible panel
- fuel slosh
- RW jitter
- Gravity harmonics
- N-body gravity
- SRP via OpenGL

ACS Thrusters

TH 1 TH 2 TH 3 TH 4
TH 5 TH 6 TH 7 TH 8

cmds

DV Thrusters

TH 1 TH 2
TH 3 TH 4

cmds

Rate Gyro

Star Tracker

Star Tracker

Accelero meter

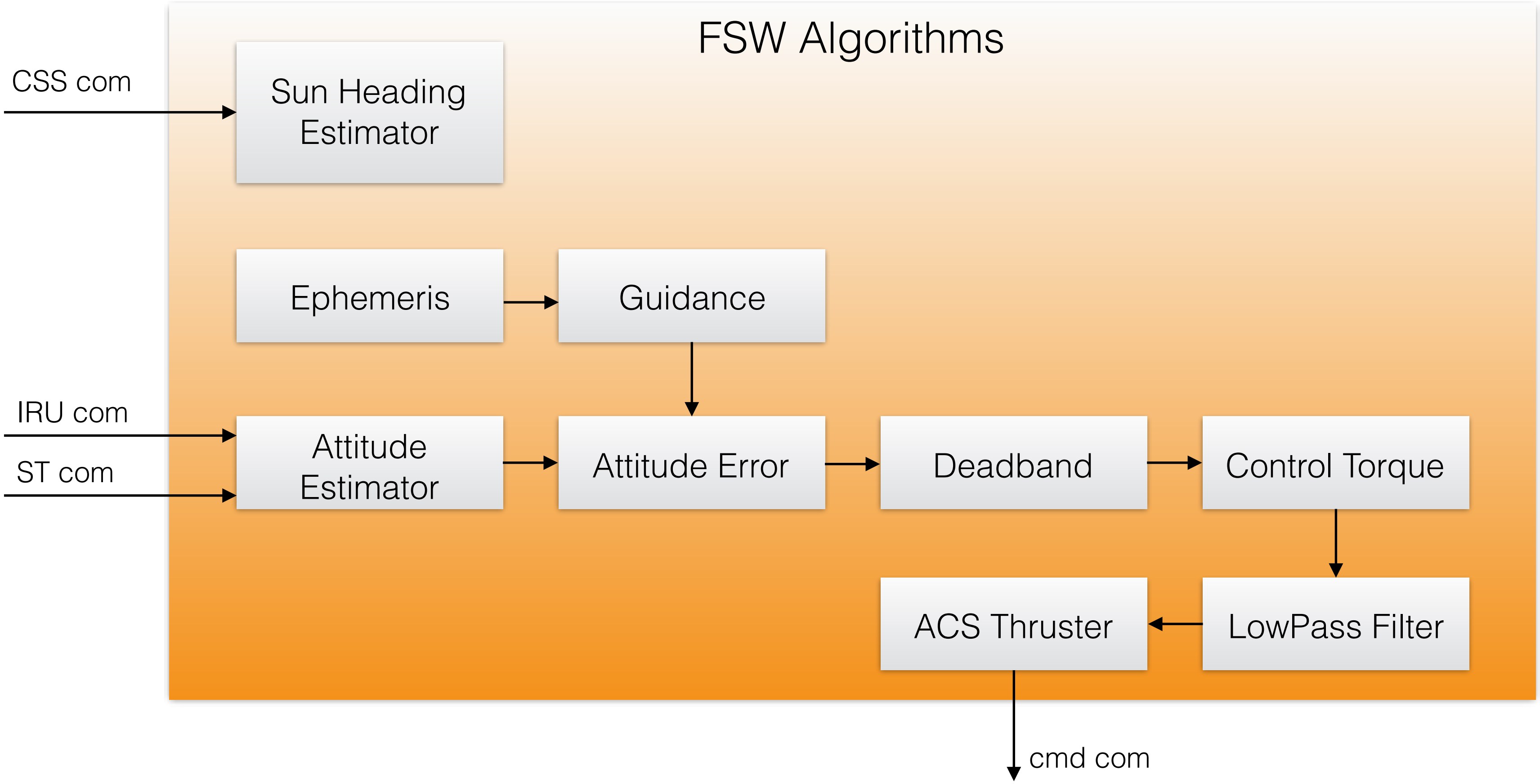
Magneto meter

CSS CSS CSS CSS
CSS CSS CSS CSS

Communication Layer

The C++ device modules can easily be added and connected with the the simulation.

Sample FSW Algorithm Setup

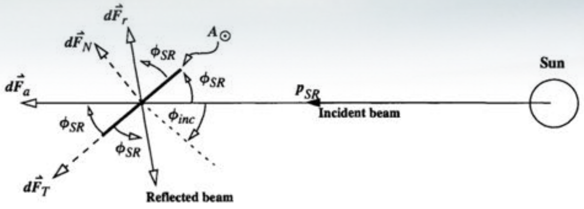


The ADCS algorithms are written in a modular format in C what allows the data to flow between them. This allows for the base modules to be interconnected to create complex control behaviors.

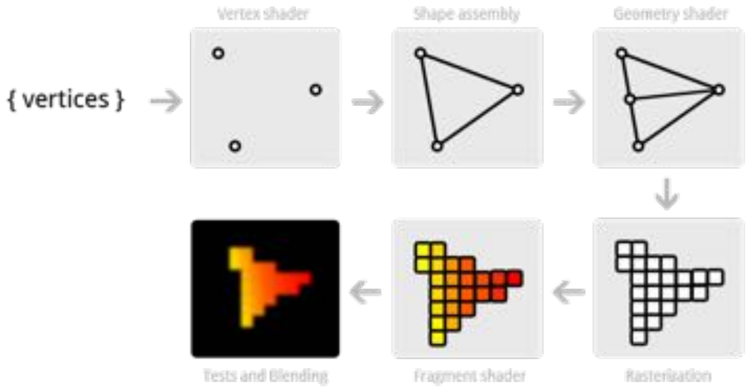
GPU Based Solar Radiation Pressure Modeling

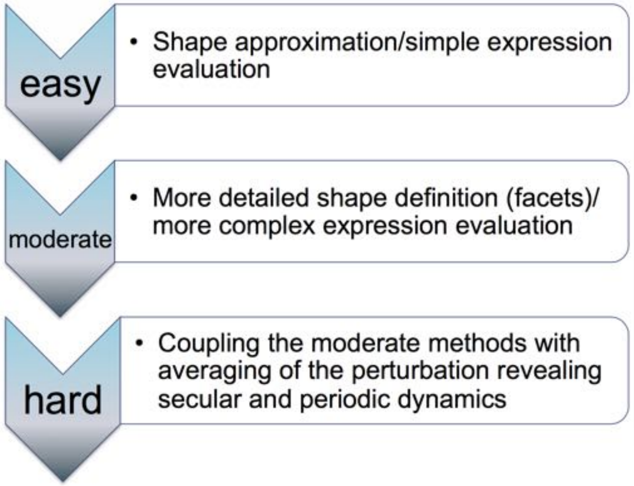
Prof. Hanspeter Schaub and Patrick Kenneally (Phd GRA)

A basic SRP model evaluates the force transmitted to the spacecraft due to impacting photons.
A truly high-fidelity model would implement an electromagnetic energy balance.

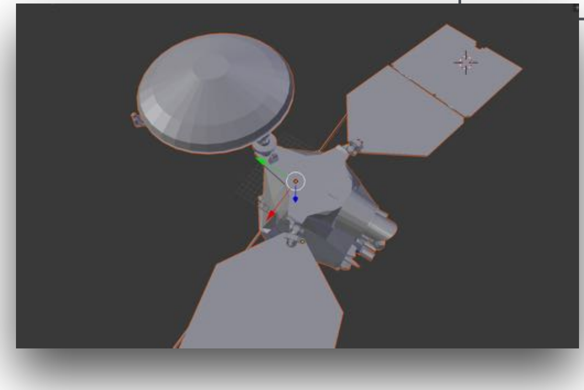


Shaders are ‘mini-programs’ that run on the GPU as part of the OpenGL pipeline. Operate on each per-vertex/shape primitive

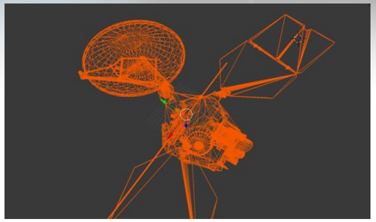




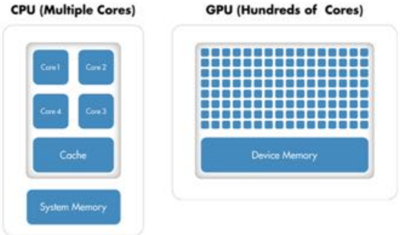
- Shape approximation/simple expression evaluation
- More detailed shape definition (facets)/ more complex expression evaluation
- Coupling the moderate methods with averaging of the perturbation revealing secular and periodic dynamics



- Evaluation of an increased fidelity geometry allows us to:
  - Leverage existing techniques present in computer graphics tools such as OpenGL to calculate the total SRP energy balance across a detailed CAD model.

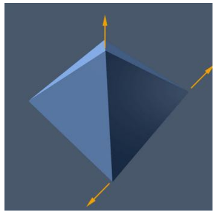


- The evaluation is an easily parallelized operation allowing use of the highly parallel processing capabilities of modern GPU.
  - Current high-end GPU’s perform 10E12 floating point operations per second.
  - Perfomance goal: 1year mission in 1day

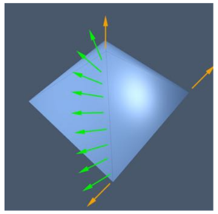


What Shaders do:

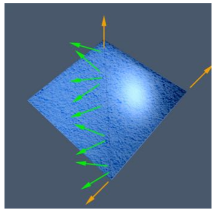
Single Face Lighting



Multi Vertex Lighting



Vertex Interpolation

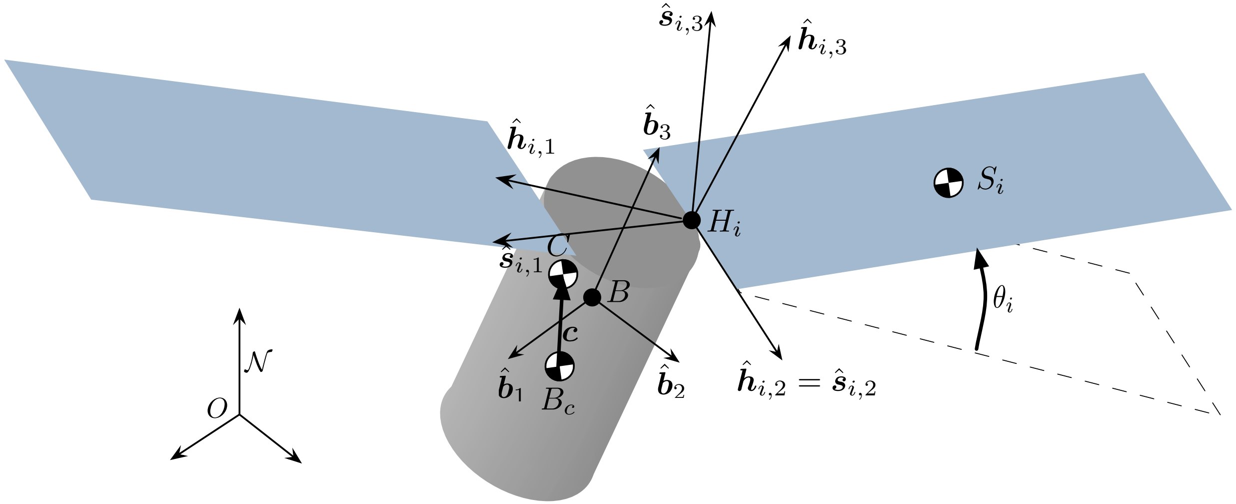


Resolving Textures

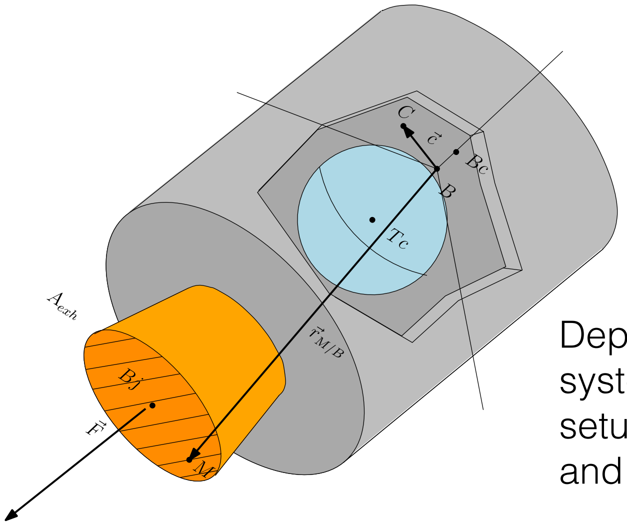
Using the OpenGL shader pipeline one can develop an algorithm which accounts for:

- Including spacecraft material properties assigned to the CAD model
- Material absorption and re-radiation at other location of the spacecraft

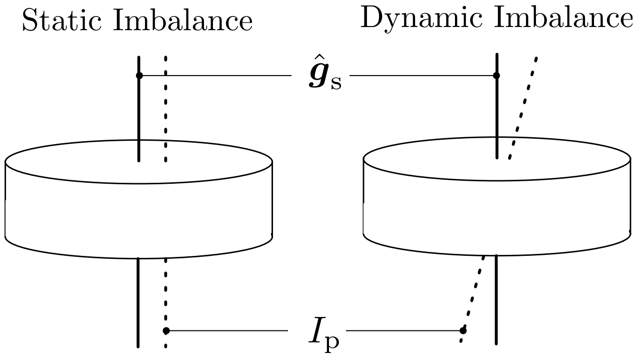
High-Fidelity Spacecraft Dynamics



Solved the spacecraft dynamics in a general, closed-form manner for a series of hinged panels.



Depletable mass system with general setup of tanks, thrusters and connections



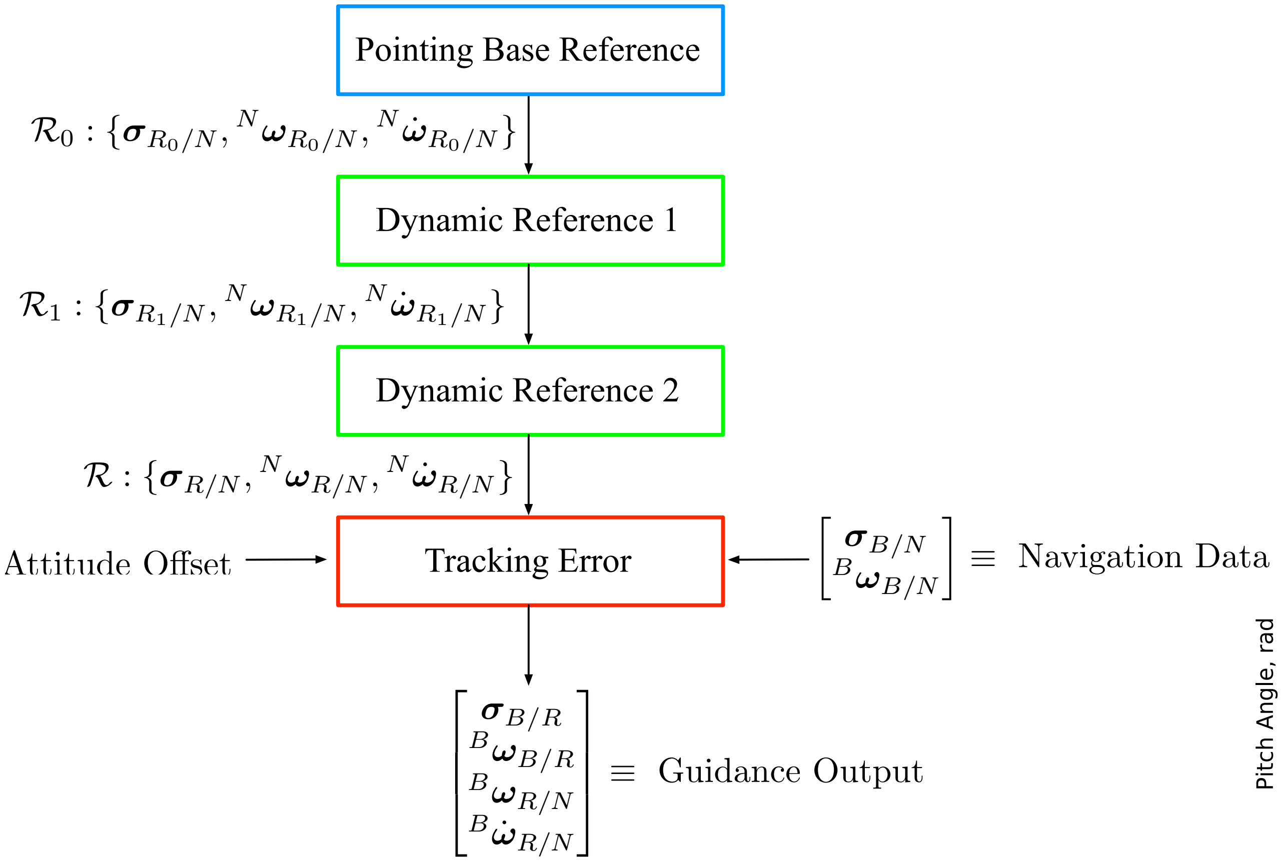
Solved the imbalanced RW spacecraft dynamics in a manner that complies with power rate and angular momentum conservation.

Be Boulder.

AeroSpace Ventures
UNIVERSITY OF COLORADO **BOULDER**

Aerospace Engineering Sciences
University of Colorado, **Boulder**

Modular Attitude Guidance Solution



Pointing Base Reference

$\mathcal{R}_0 : \{\boldsymbol{\sigma}_{R_0/N}, {}^N\boldsymbol{\omega}_{R_0/N}, {}^N\dot{\boldsymbol{\omega}}_{R_0/N}\}$

Dynamic Reference 1

$\mathcal{R}_1 : \{\boldsymbol{\sigma}_{R_1/N}, {}^N\boldsymbol{\omega}_{R_1/N}, {}^N\dot{\boldsymbol{\omega}}_{R_1/N}\}$

Dynamic Reference 2

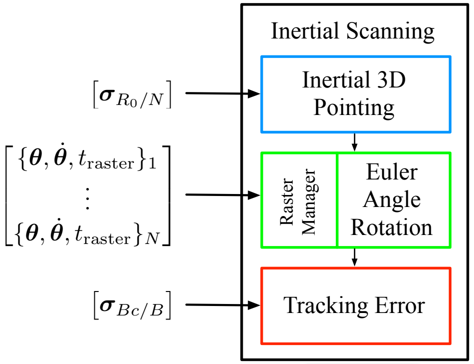
$\mathcal{R} : \{\boldsymbol{\sigma}_{R/N}, {}^N\boldsymbol{\omega}_{R/N}, {}^N\dot{\boldsymbol{\omega}}_{R/N}\}$

Attitude Offset

Tracking Error

$\begin{bmatrix} \boldsymbol{\sigma}_{B/N} \\ {}^B\boldsymbol{\omega}_{B/N} \end{bmatrix} \equiv$ Navigation Data

$\begin{bmatrix} \boldsymbol{\sigma}_{B/R} \\ {}^B\boldsymbol{\omega}_{B/R} \\ {}^B\boldsymbol{\omega}_{R/N} \\ {}^B\dot{\boldsymbol{\omega}}_{R/N} \end{bmatrix} \equiv$ Guidance Output

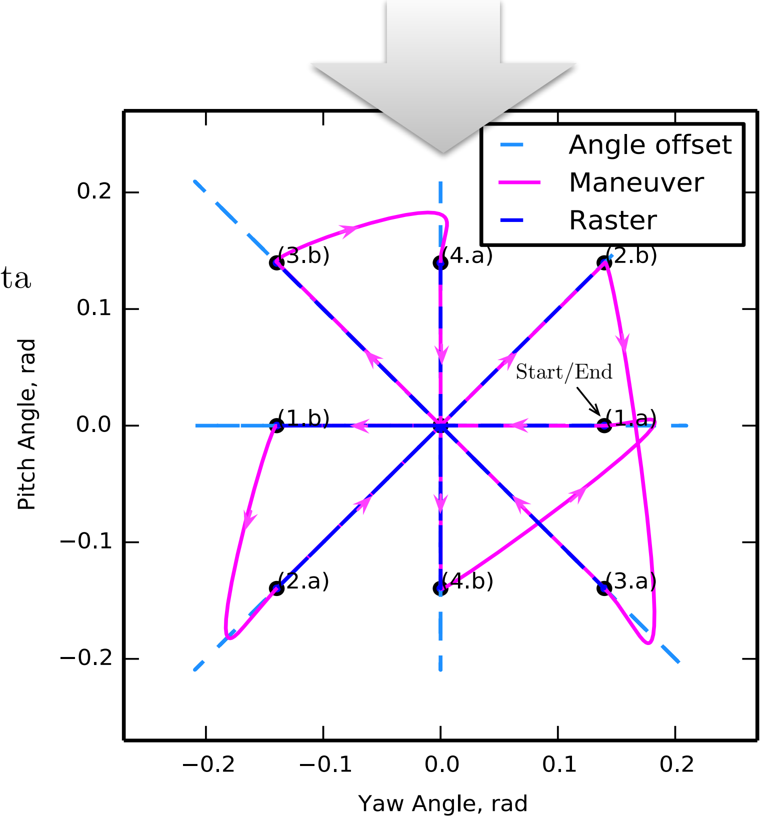


Inertial Scanning

$[\boldsymbol{\sigma}_{R_0/N}]$ → Inertial 3D Pointing

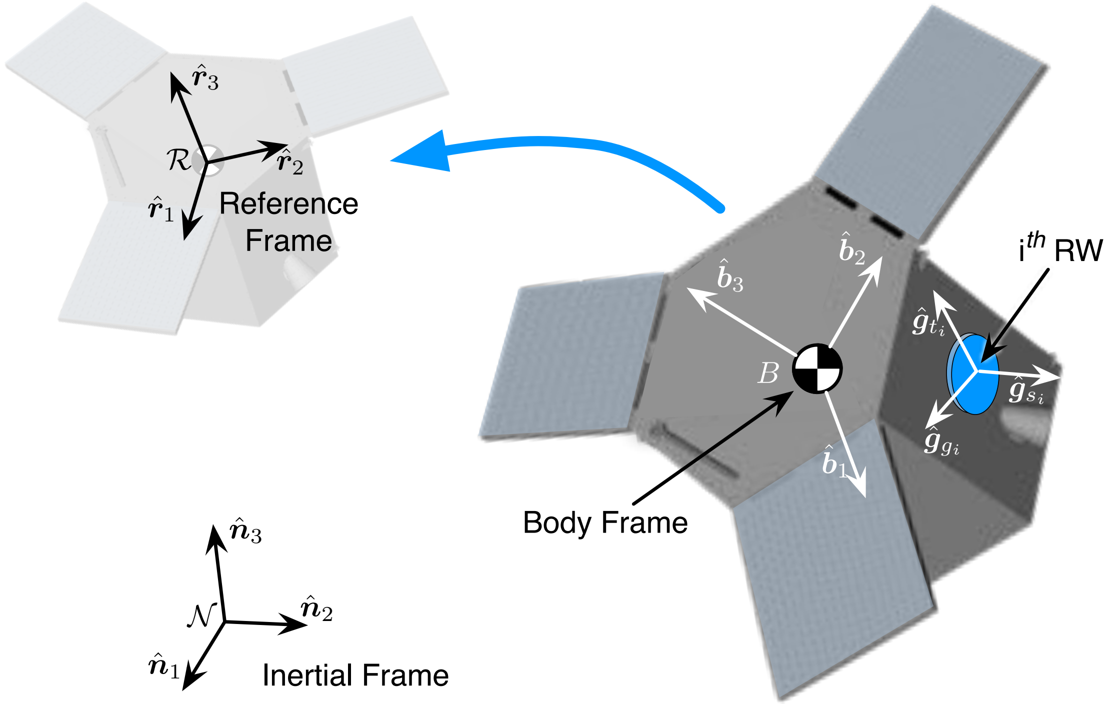
$\begin{bmatrix} \{\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}, t_{\text{raster}}\}_1 \\ \vdots \\ \{\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}, t_{\text{raster}}\}_N \end{bmatrix}$ → Raster Manager | Euler Angle Rotation

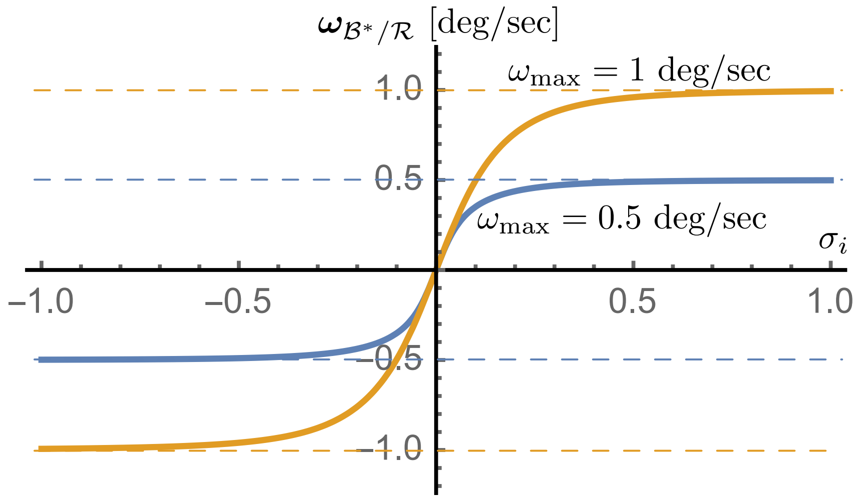
$[\boldsymbol{\sigma}_{Bc/B}]$ → Tracking Error

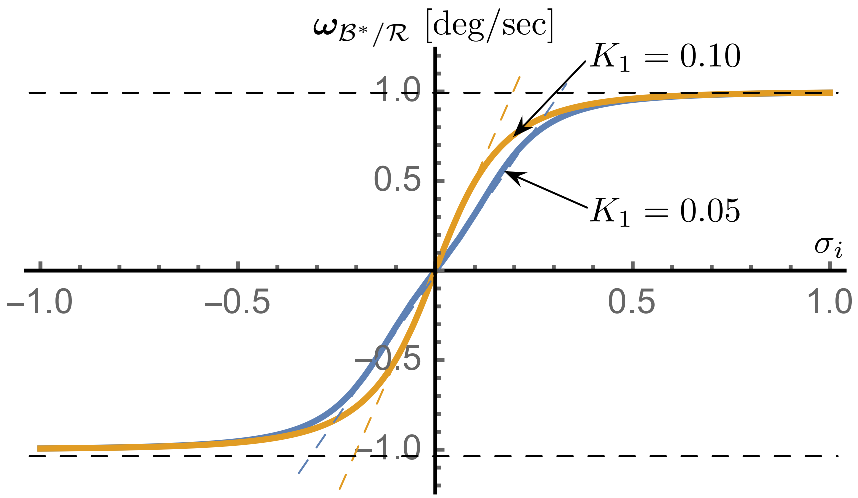


Create the attitude reference states through a modular sequence of atomic behavior modules.

MRP Steering Law







Design globally stable attitude steering laws that treat the angular velocity as the control variable. A rate sub-servo system is design to track the desired rates. This allows for rate constraints to be readily implemented.

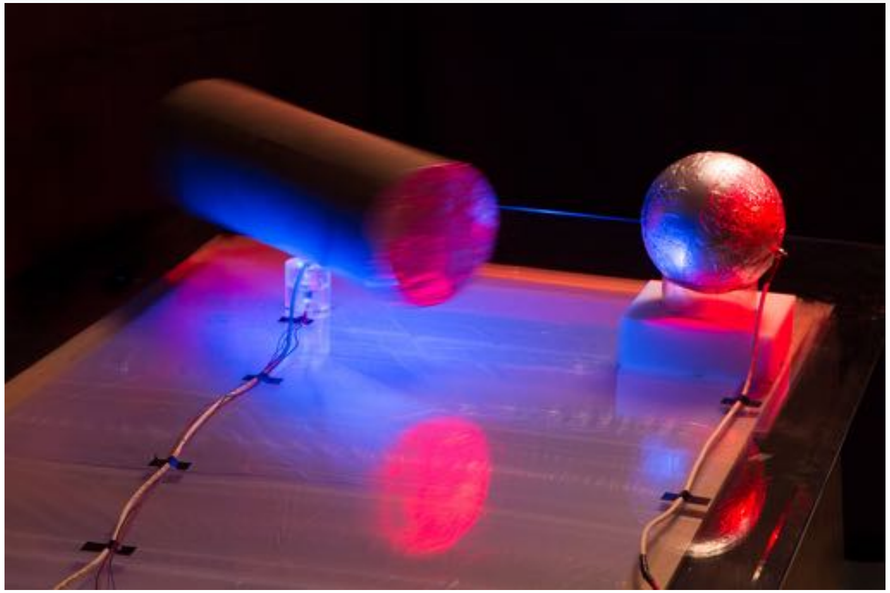
This allows for general attitude behaviors, such as sun-avoidance, to be super imposed on the control solution.

On-Going Basilisk Efforts

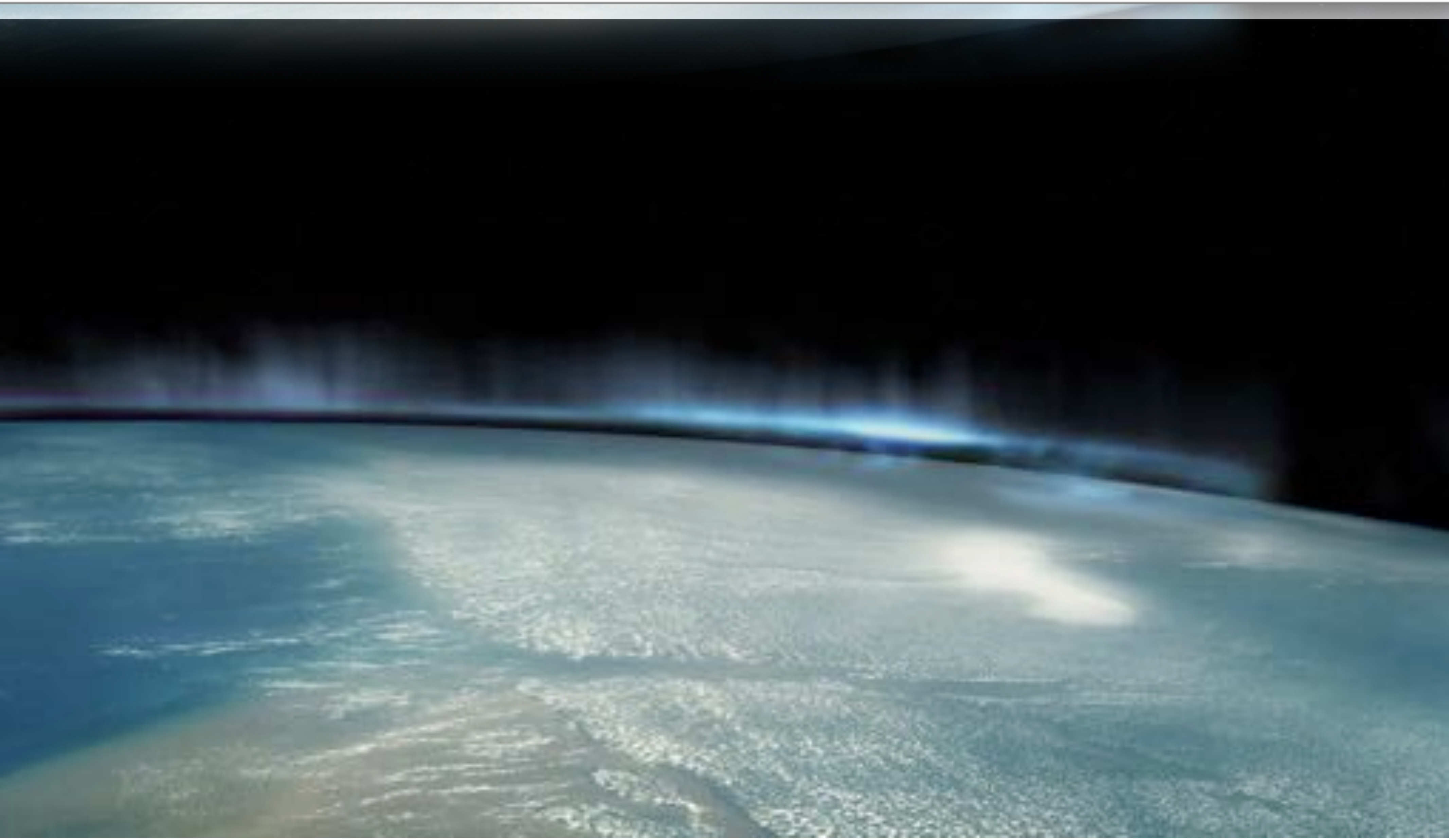
- Make the software framework for an open-source alpha release by December 2016
- Enhance dynamics to include
  - Fully coupled imbalanced RW, CMG and VSCMG
  - Atmospheric drag models, including GPU-based evaluation of a CAD model
  - SRP and drag with flexible shapes
  - Adding a range of leading atmospheric neutral density and wind models
  - Adding a very general depletable mass model
  - Adding magnetic field models
  - Adding MSM modeling
- Enhancing the Visualization components
- Adding Hardware in the loop capabilities

Conclusions

- Electrostatic Forces show promise to control the relative orientation of a passive GEO objects
- Only 10’s of Watts of electrical power is required to detumble an upper stage from 2°/s to zero over about a week
- The open-source Basilisk project enables highly reusable dynamics and flight software algorithm components
- The novel simulation architectures included cutting-edge GPU accelerations of SRP and drag evaluations.



Questions?



More information available at http://hanspeterschaub.info