National Aeronautics and Space Administration
Jet Propulsion Laboratory
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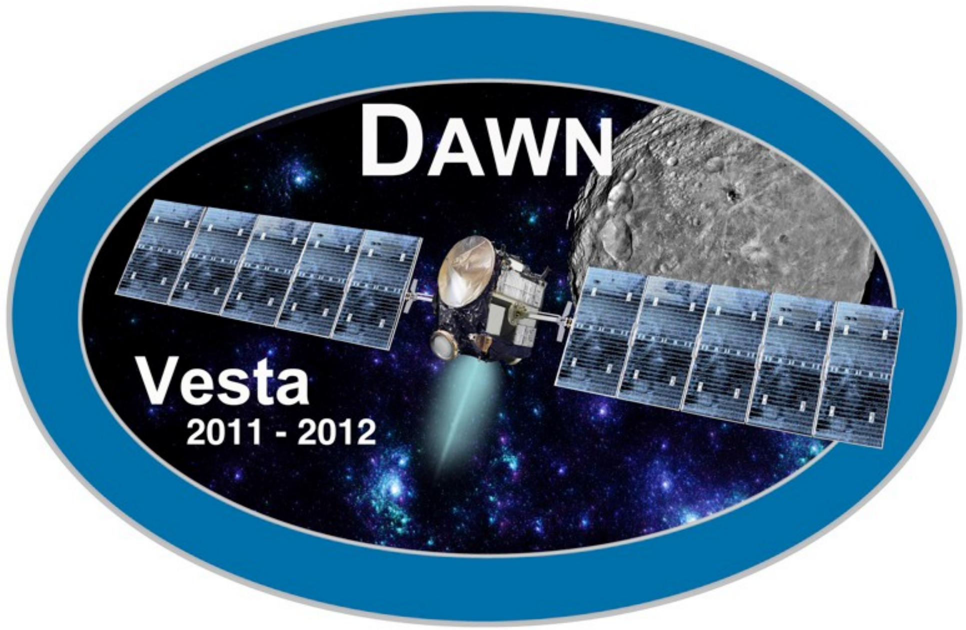
Understanding Spacecraft Agility for Orbit Transfers on the Dawn Low-Thrust Mission



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Understanding Spacecraft Agility for Orbit Transfers on the Dawn Low-Thrust Mission

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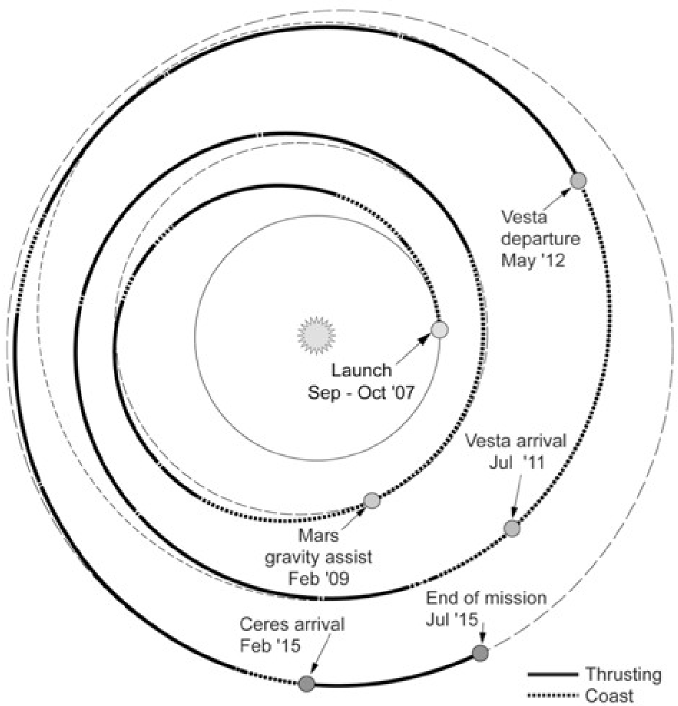
02/08/12

Dawn Mission at a Glance

- Interplanetary Cruise
  - Launched Sep. 2007 and Vesta Orbit capture July 2011
  - Will depart Vesta and Arrive at Ceres in Feb. 2015
    - Dawn will be the first mission to enter orbit around main-belt asteroids.
  - Solar Electric Propulsion (SEP)
    - Allows for the necessary delta-V

Mission Trajectory



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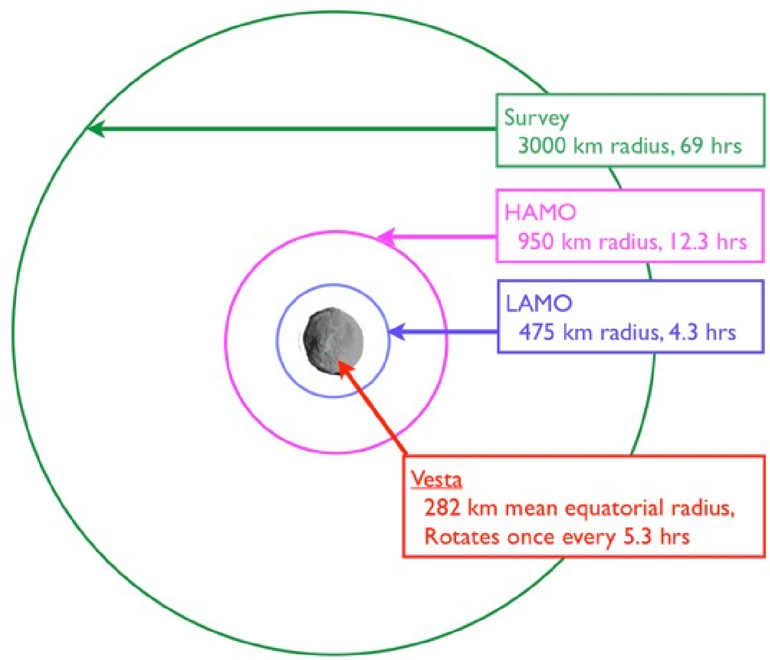
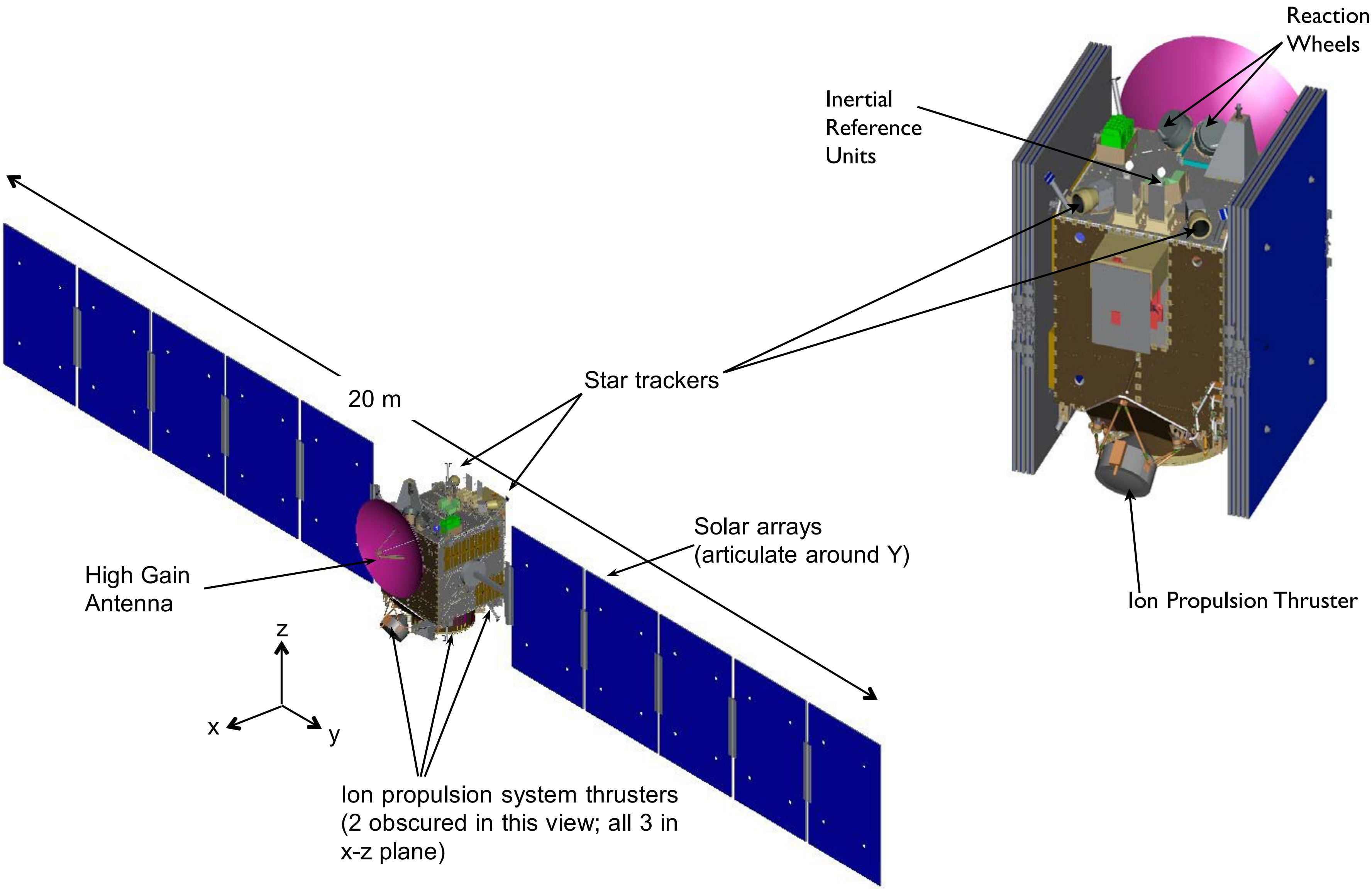
  - Solar Electric Propulsion (SEP)
    - Allows for the necessary delta-V
- Vesta Science Campaign
  - Three Different Science Orbits
    - Survey - 69 hr period
    - HAMO - 12.3 hr period
    - LAMO - 4.3 hr period
    - HAMO2 - 12.3 hr period
    - SEP transfer between each science orbit

Vesta Orbits



Dawn

Spacecraft Configuration



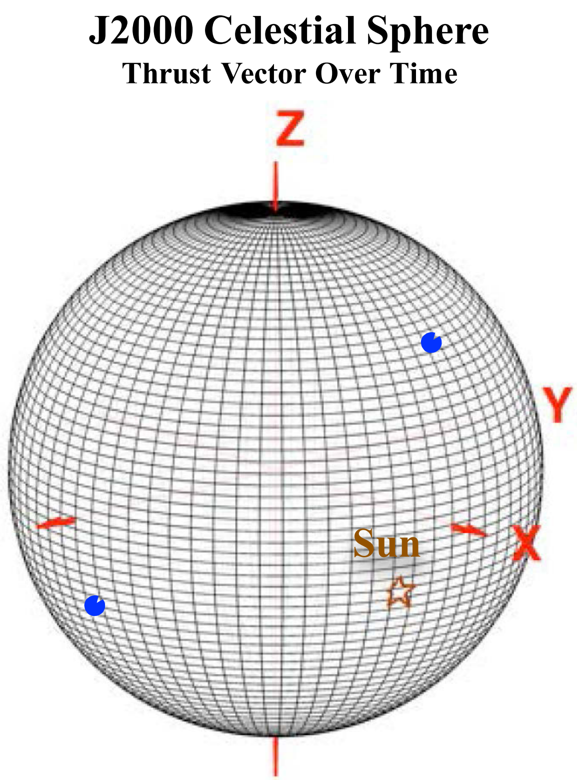
Dawn Spacecraft During Assembly

Why Use Solar Electric Propulsion

- Specific Impulse from 1900-3200 sec
  - Compare with typical 200-400 sec for conventional propulsion
- Means we can carry a LOT less fuel for the same Δv
  - Dawn will ultimately deliver about 11 km/s (already has the inflight record)
- Extraordinary flexibility in mission design:
  - choice of mission objectives and launch dates
- But all this comes with a price:
  - The thrust force is very weak (91mN maximum, at early mission)
    - Trajectory Correction Maneuvers ("burns") take a long time to accomplish
    - This has ramifications for how burns are designed and executed.
  - Safing events can result in failure to burn, so there is increased emphasis quickly returning to the capability to thrust

What is Different About Low-Thrust

- Conventional TCM structure
  - Thrust in 1 or 2 inertially fixed directions
  - Cruise Thrusting on Dawn worked in this fashion



What is Different About Low-Thrust

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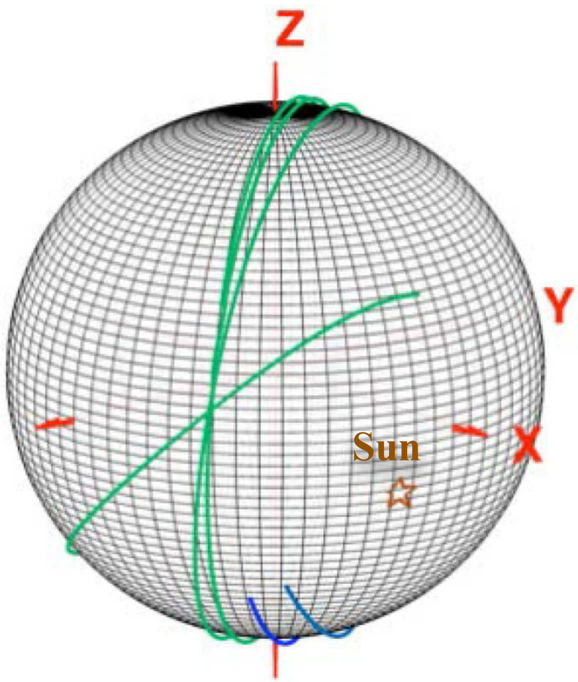
- Low thrust Orbit transfers
  - Overall Structure changes
    - Thrusting through significant portions of orbit
    - Cannot consider thrust as impulsive
    - Need to continuously change thrust direction
- Dawn Thrust Vector Control
  - Same actuator for ΔV and S/C control
  - How do you identify capability
    - What Can be done

J2000 Celestial Sphere
Thrust Vector Over Time



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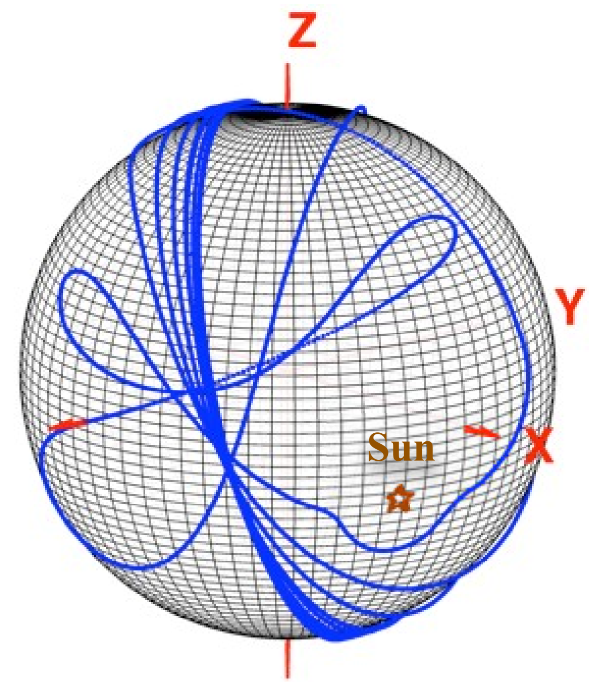
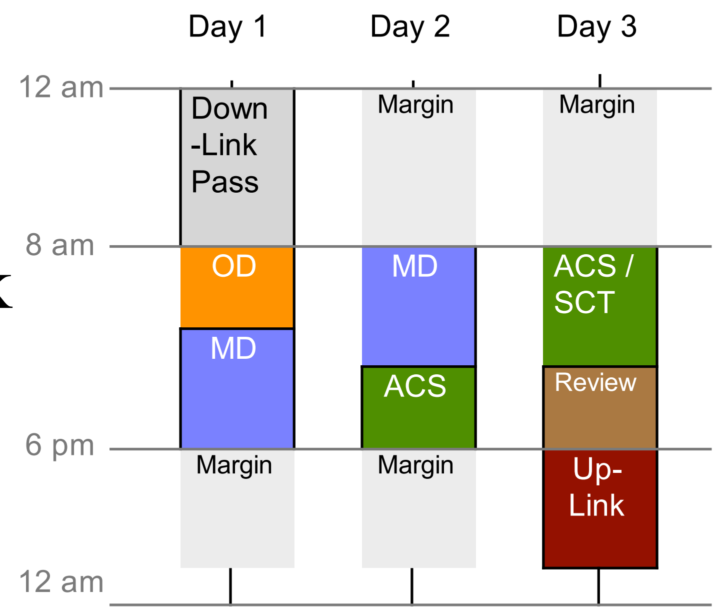
Thrust Vector Over Time



Dawn

Schedule / Timeline

- Design process done many times
  - 4 designs during S2H transfer
  - 10 Designs during H2L transfer
- Design Process must be done quick
  - One Pass Process
    - MD/NAV thrust profile (TVF) **must be correct**
      - not designed for a rework
    - Thrust profile is being designed before the previous design has completed
    - ACS time line is short
      - generation of momentum strategy 4-6 hours
      - ACS complexity dependent on NAV design

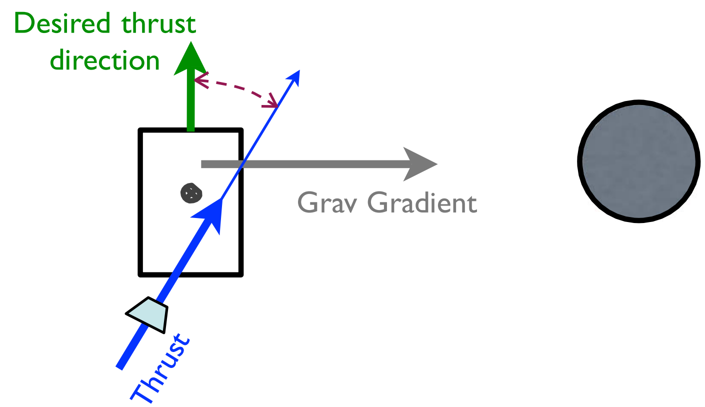


OD = Orbit determination Team
MD = Maneuver Design Team
ACS = Attitude Control Subsystem Team
SCT = Spacecraft Team

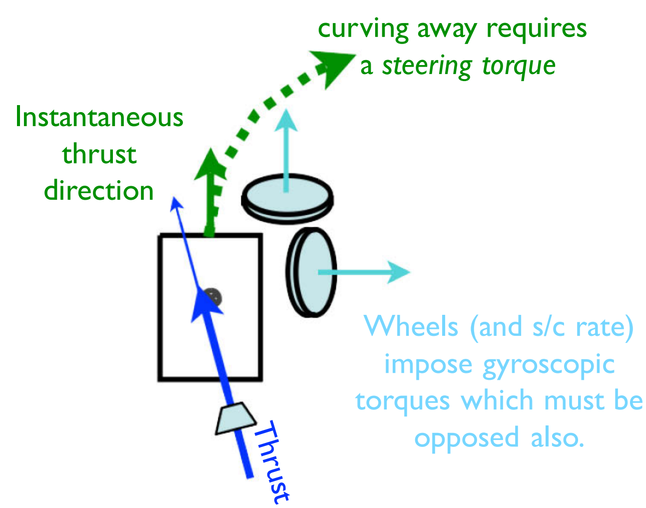
- We cannot fail!
  - Missing uplink could mean weeks of delay, mission re-design

Tight Coupling of ACS and NAV

- Thrust vector control (TVC)
  - control orthogonal to like of thrust
  - negligible dynamics in cruise



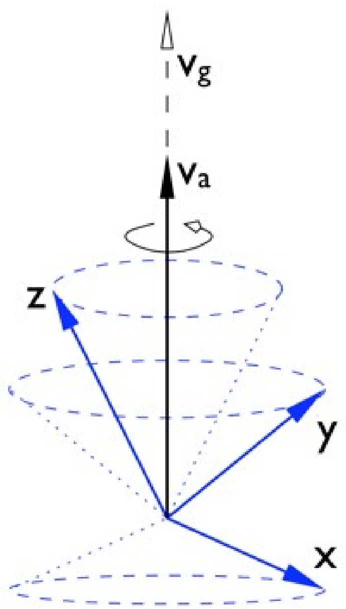
- TVC in orbit operations
  - Must counter gravity gradient torque
  - Provide torque to follow thrust profile
  - Must overcome gyroscopic torque of wheels
- IPS provides delta-V and Control
  - Thrust profile must consider control capabilities
  - Dynamic effects also couple into design of the thrust direction profile.



Attitude Commanding Provides a Limitation

- 3-axis controlled Spacecraft
- FSW only allows commanding of a single axis!
- FSW constructs a 3-axis attitude to optimize solar array power
  - Operator can command a body vector (v_a) to align with an inertial vector (v_g)
  - FSW rotates the S/C bus to maximize array power
  - FSW also prefers to keep the -x face away from the sun
  - Called "Power Steering Algorithm"

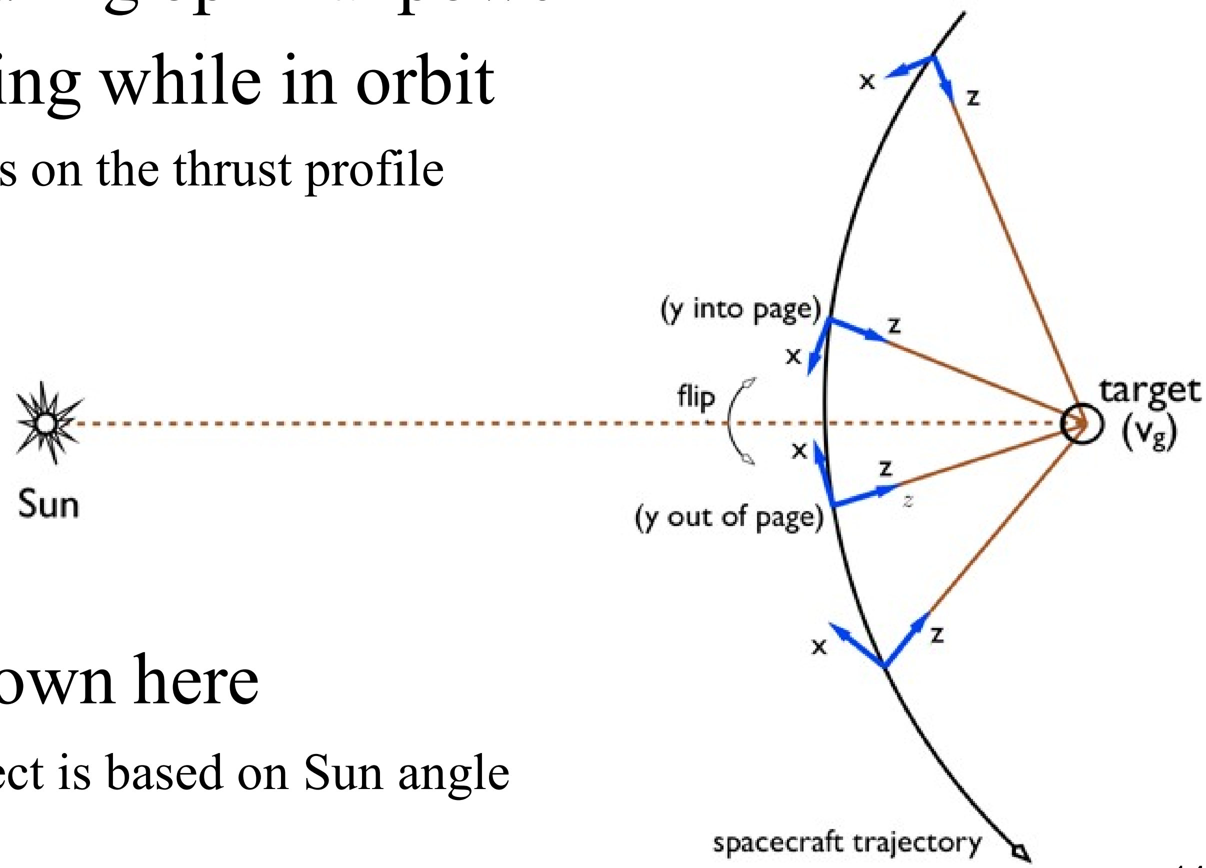
Power Steering Algorithm



- Generally works well, however:
  - Orientation is always changing
    - S/C moves relative to the sun
  - Singularity exists when the target points close to the sun

Power Steering "Flip-Over"

- Power steering is always optimizing array pointing
  - cannot be easily circumvented
- Works well for ensuring optimal power
- Complicates thrusting while in orbit
  - Complicates constraints on the thrust profile



- Singularity case shown here
  - The amount of this effect is based on Sun angle

Orbit Transfer Challenge

- Conventional thrust design process is insufficient
  - Time-varying thrust arcs
  - Dynamic effects are coupled into thrust design
  - Thrust direction and attitude are coupled
- How can we ensure a thrust design is flyable?
  - within the build timeline
  - allowing for the necessary time varying thrust directions
  - based on spacecraft capabilities

Defining Thrusting Constraints for MD/NAV

Constraints

- **Geometric**
- Continuity
- Control Authority
- Thrust Delivery

- Geometric
  - Typical pointing constraint seen in TCM's
    - Keep the sun away from some spacecraft axis
    - Dawn constraints
      - Keep thrust vector away from sun
      - Keep -X axis away from sun

Defining Thrusting Constraints for MD/NAV

Constraints

- Geometric
- **Continuity**
- Control Authority
- Thrust Delivery

- Continuity and Smoothness
  - Dawn's attitude commanding results in a thrust direction defines the three axis attitude
    - Power steering always in play
  - Thrust vector profile must maintain continuity
    - Each thrust arc must be smooth
  - Attitude continuity must be considered in thrust design

Defining Thrusting Constraints for MD/NAV

Constraints

- Geometric
- Continuity
- **Control Authority**
- Thrust Delivery

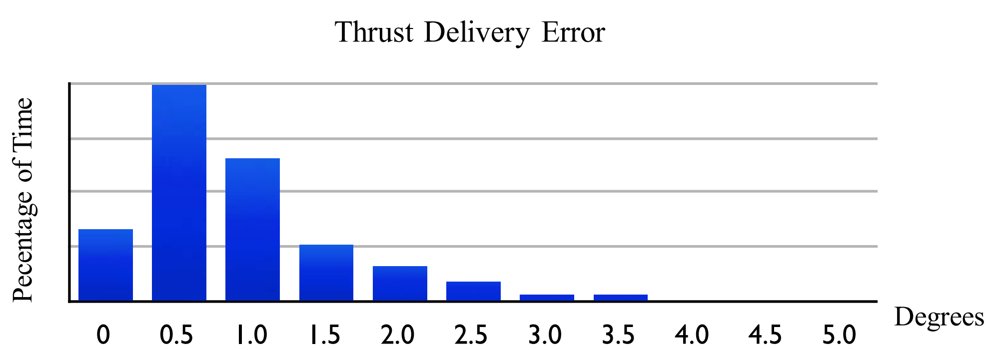
- Control Authority
  - ACS Dynamic constraints become thrust profile constraints
    - Rate
    - Acceleration
    - RWA Momentum Capacity
    - IPS Gimbal range of motion
  - Some geometric constraints are dynamic
    - The thrust-sun geometric constraint changes based on S/C rate.
      - The faster the S/C the farther the thrust profile must stay from the sun.

Defining Thrusting Constraints for MD/NAV

Constraints

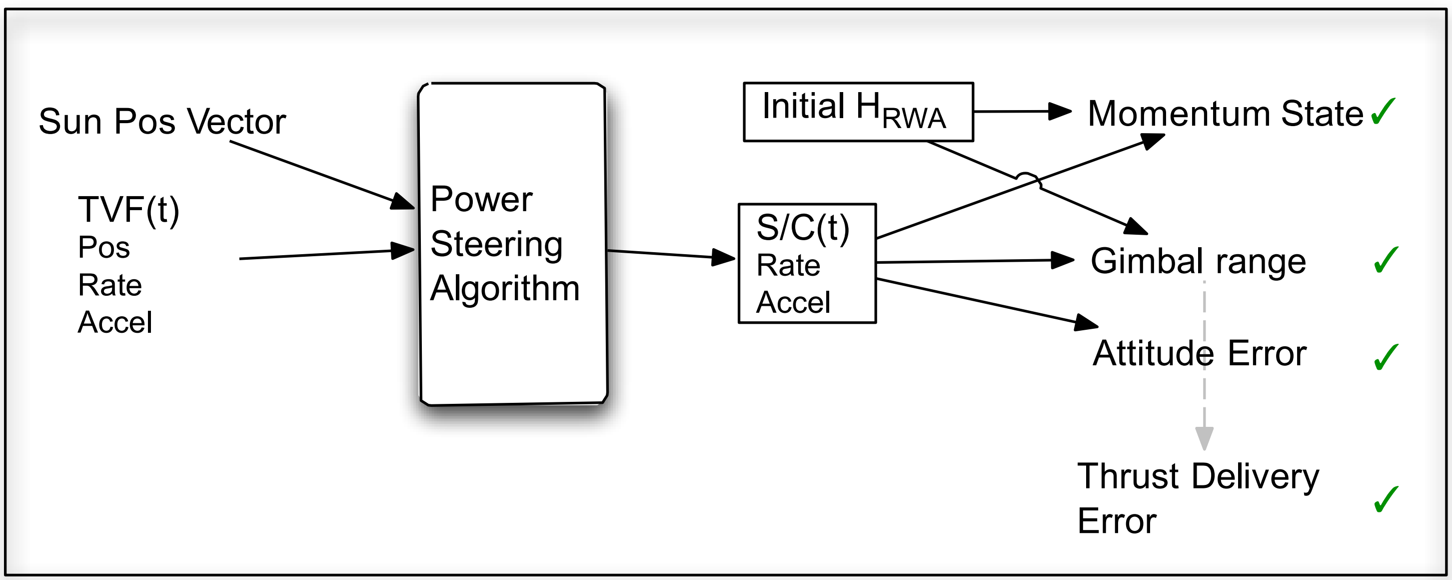
- Geometric
- Continuity
- Control Authority
- **Thrust Delivery**

- Thrust Delivery
  - Execution error is now time varying
    - Function of attitude error and IPS gimbal actuation
    - No longer a single number for execution error
  - Thrust vector profile can affect thrust delivery
    - More aggressive thrust profile results in larger thrust delivery error



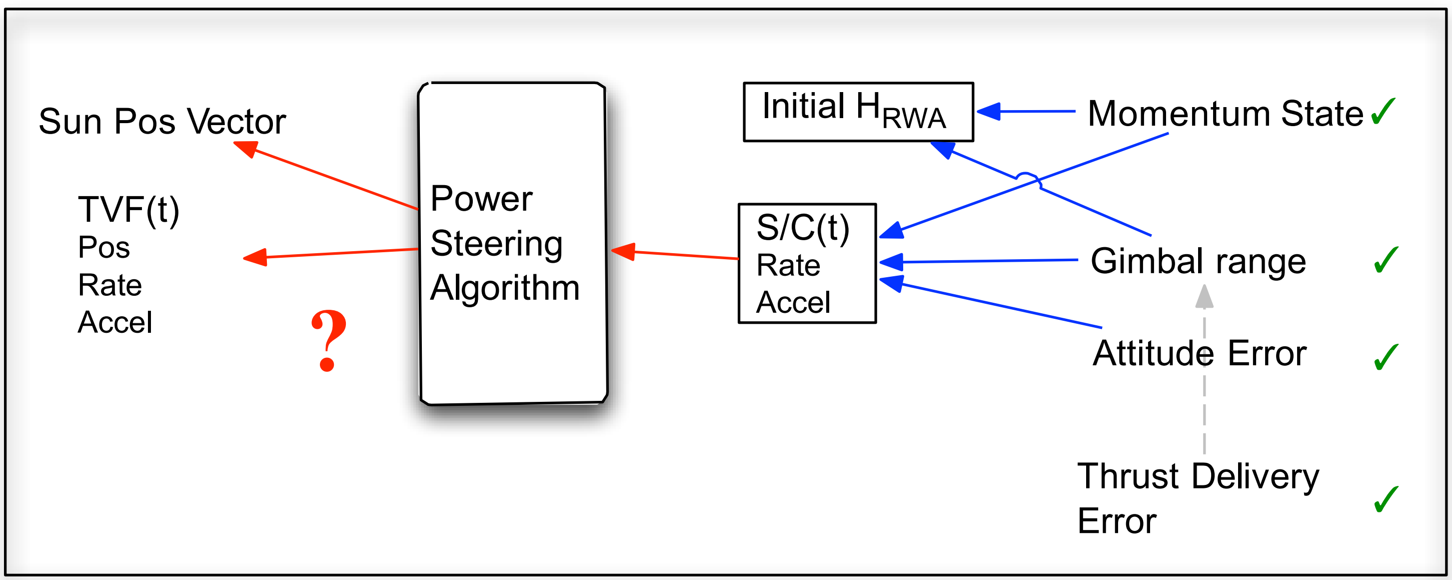
Mapping Constraints from ACS to MD/NAV

- The desire was to have simple constraints that if the thrust profile met them, it was good to fly.
  - We tried many different ways to convert spacecraft constraints to thrust vector file (TVF) design constraints



Mapping Constraints from ACS to MD/NAV

- The desire was to have simple constraints that if the thrust profile met them, it was good to fly.
  - We tried many different ways to convert spacecraft constraints to thrust vector file (TVF) design constraints
    - Could not map backwards through the 1-to-Many problem



A Different Approach

- What we needed
  - Fast method to verify a thrust profile is achievable

- The concept we came up with:

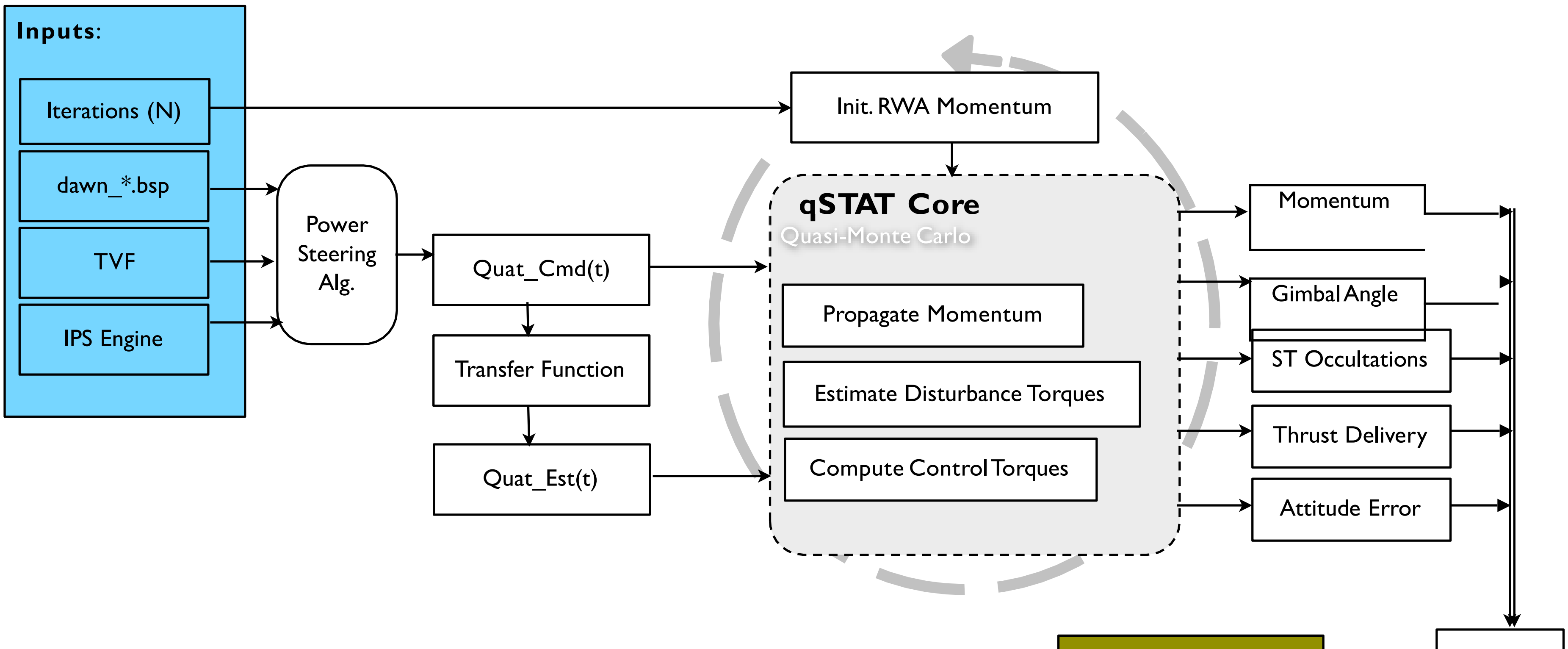
  quick and Simple TVF Analysis Tool (qSTAT)
  - A fast and simple simulation
    - Not High Fidelity (better is the enemy of the good)
    - Very few inputs to keep it simple
    - An indication of a PASS definitely means it will work
  - MD/NAV can use to verify designs before delivery
    - Puts a limited ACS brain in a box that the NAV team can utilize

qSTAT Overview

- Inputs / Outputs and what it Provides
  - Inputs: TVF, S/C Trajectory, IPS Engine
  - Outputs: Plots and Constraint Checks
    - S/C rate
    - S/C acceleration
    - Attitude Error
    - IPS Gimbal Range
    - ST Occultation Duration
    - Thrust Delivery Error
    - RWA Momentum
  - Provides a fast approximation (< 1 min)
    - Models thrusting portion only
- Simplified Model Assumptions
  - Needs to work for the desired operational range case
    - extreme cases break down but are flagged by the tool as unusable
  - Mostly linear and algebraic assumptions
  - Transfer-Function represents the dynamics
    - Not a closed loop simulation
  - VnV'd against full dynamic simulation tool (Softsim)

Dawn

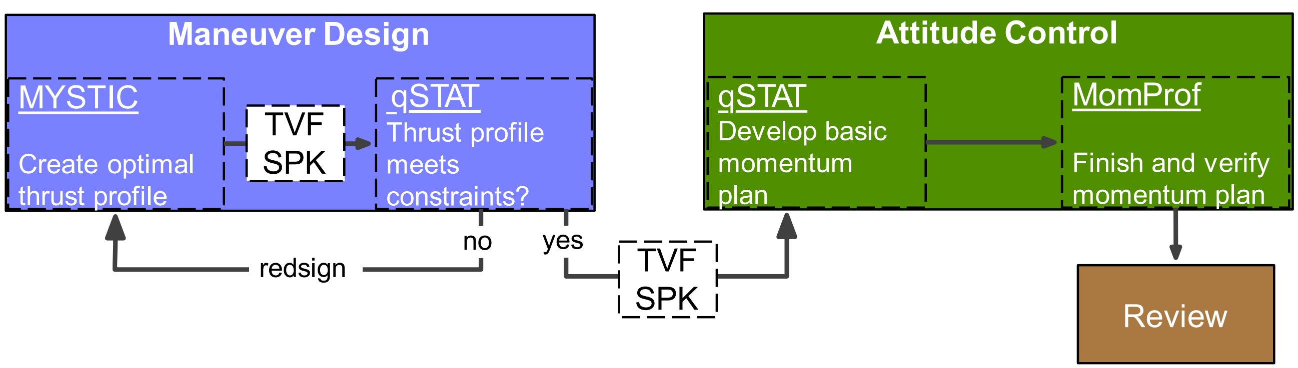
qSTAT Block Diagram



Cost Function:
MIN(Gyroscopic torque)
MIN(# forced desats)

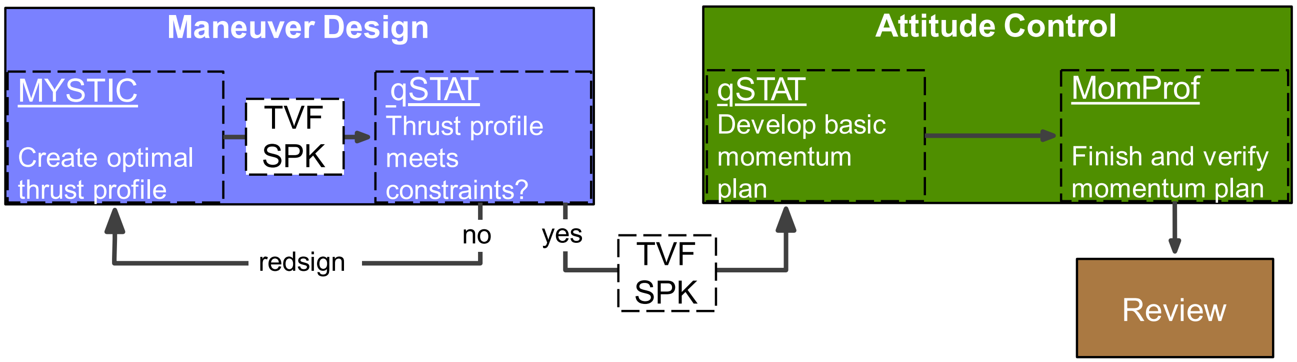
qSTAT for NAV

- NAV can run the tool with small number of inputs
  - MD folks do not need to know the inner details of the ACS system to simulate a thrust profile design
  - qSTAT makes some assumptions about the momentum management strategy and evaluates a number of cases to provide a result
    - NAV usually runs qSTAT with 30 - 100 initial RWA momentum combinations
- Verify and investigate
  - NAV can use qSTAT both to verify a flight TVF design but also explore future scenarios and look for ways to make thrust profiles provide better thrust delivery error.



Momentum Management

- qSTAT is used by ACS as well as NAV
  - Since qSTAT runs a bunch of different initial momentum states and sorts them based on a cost function
  - ACS can use this to get a head start on a momentum strategy
    - The large attitude changes and rates make momentum management not straight forward
  - qSTAT has ability to insert a momentum adjust and quickly show the results
    - Graphical interaction to let ACS engineers find a good solution for the entire thrust arc
  - A tight timeline requires ACS to respond to the thrust design quickly.



Survey to HAMO (S2H) Transfer Results

- qSTAT modeling worked very well
- Survey to HAMO transfer provided first real step into the regime of rapidly changing thrust profiles
  - Not real stressing on the system or the tools
  - Provided confidence and experience needed to do the next transfer

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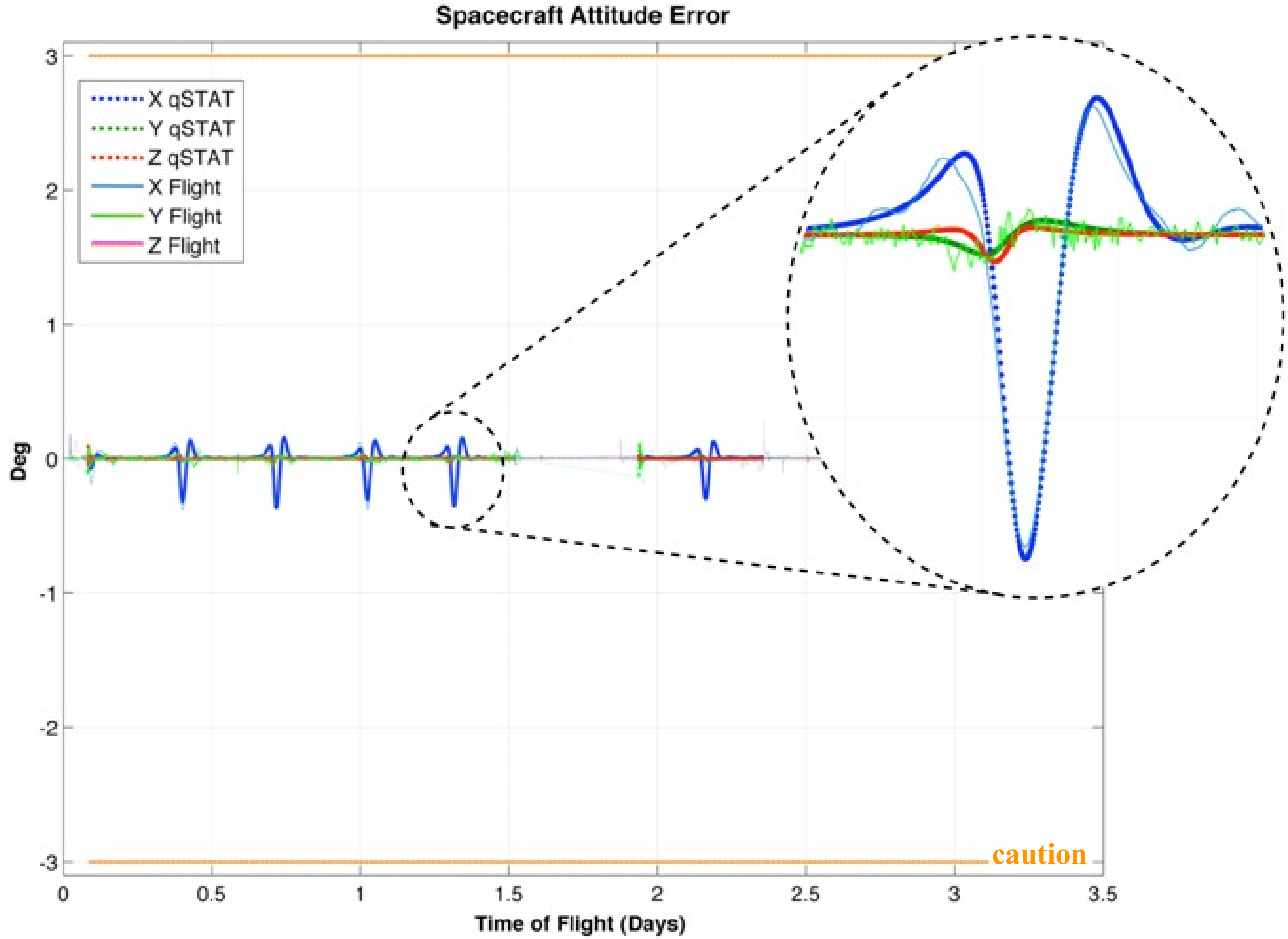
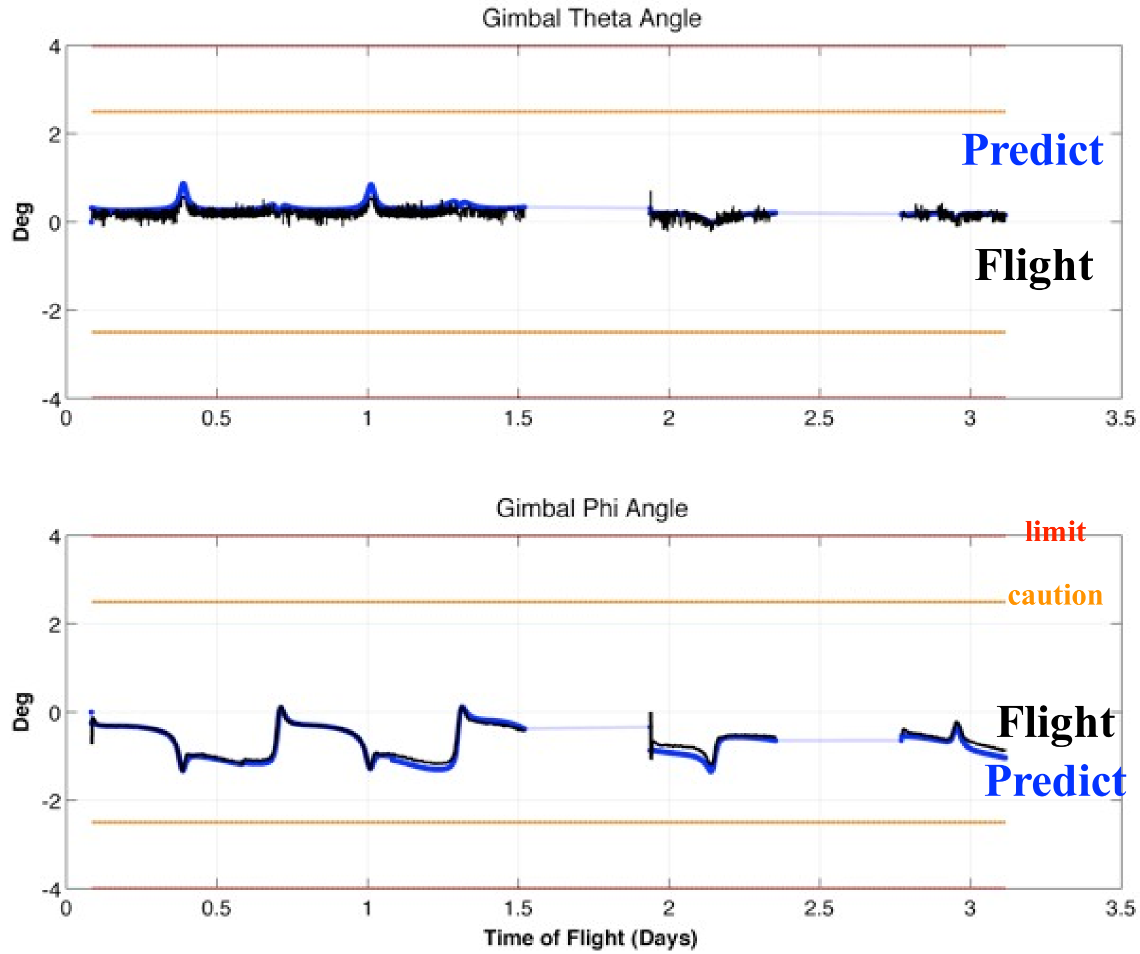
S2H Attitude Error

- Very good modeling of Attitude error



S2H Gimbal Angle

- Gimbal angle predictions match flight very well



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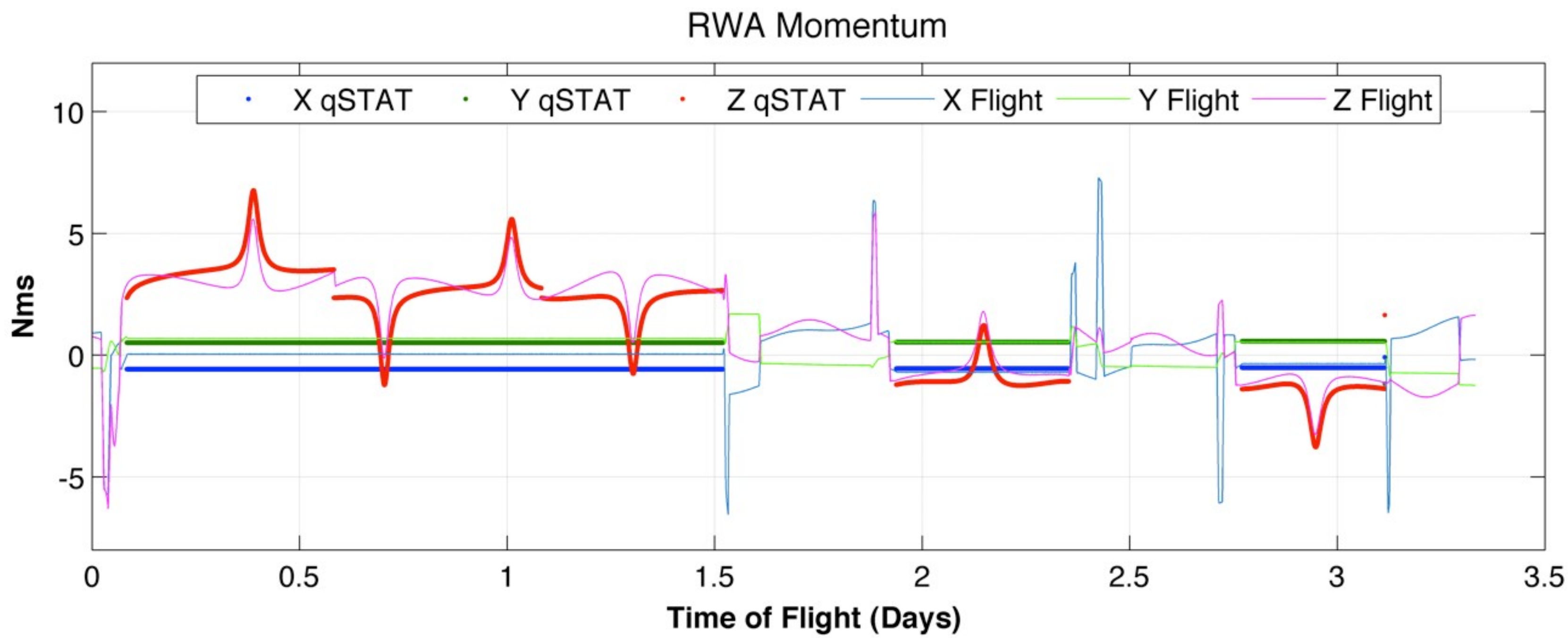
S2H Momentum

- Momentum modeling is always the most challenging
  - qSTAT only models thrusting portions
  - Un-modeled momentum aspects that happen prior to thrusting affect predict.
    - Higher fidelity MomProf tool more accurately models entire sequence



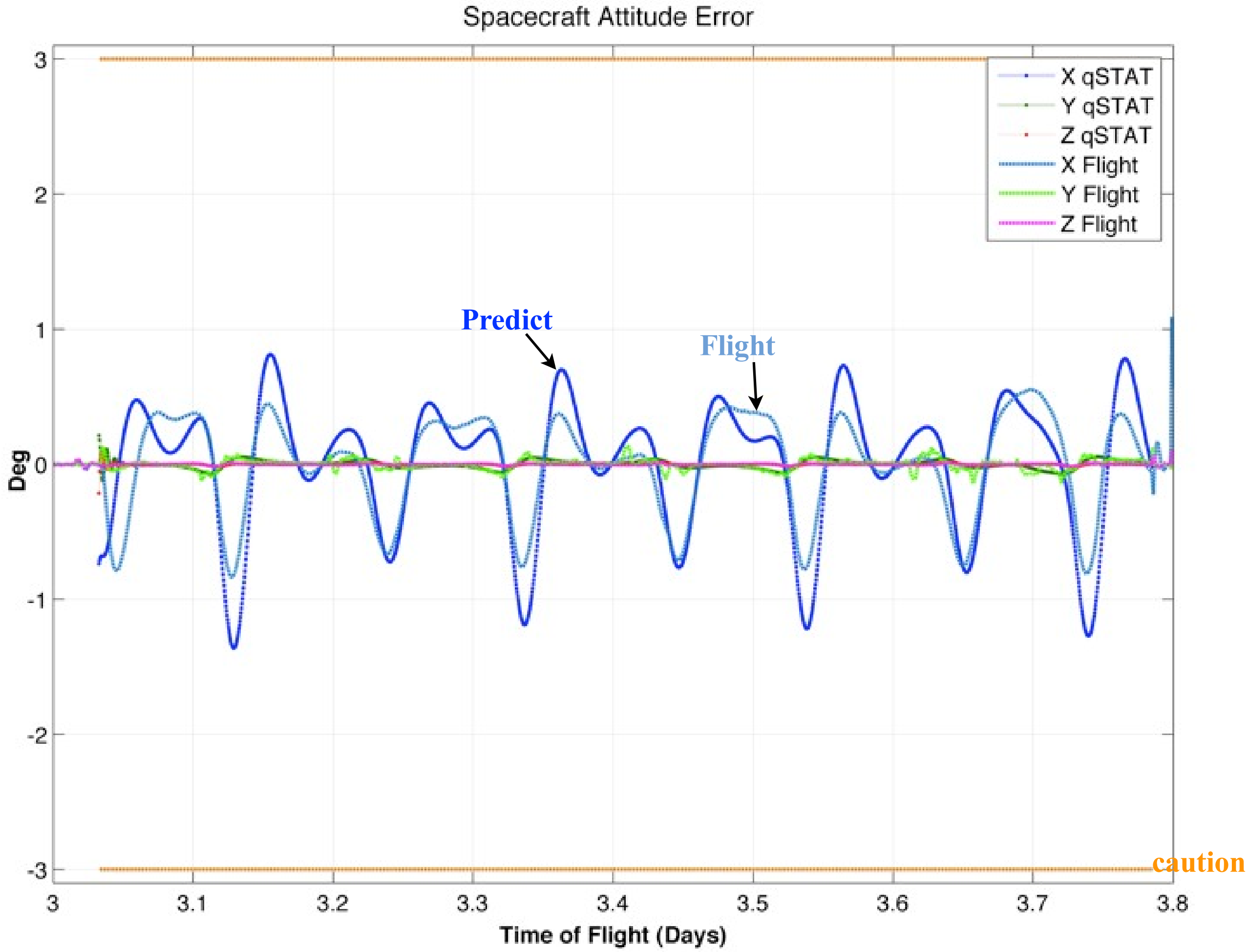
HAMO to LAMO (H2L) Transfer

- Much more challenging Transfer
  - Short orbit period
  - Larger gravity gradient torque
- qSTAT modeling worked well
  - Some of the model simplification begin to show up
  - Operational changes were made to reduce un-modeled behavior
    - Sequence timing
- Provided the necessary task of identifying unflyable thrust profile designs

Dawn

Attitude Error

- Good Match while being conservative
  - Simplified transfer function doesn't capture all dynamics



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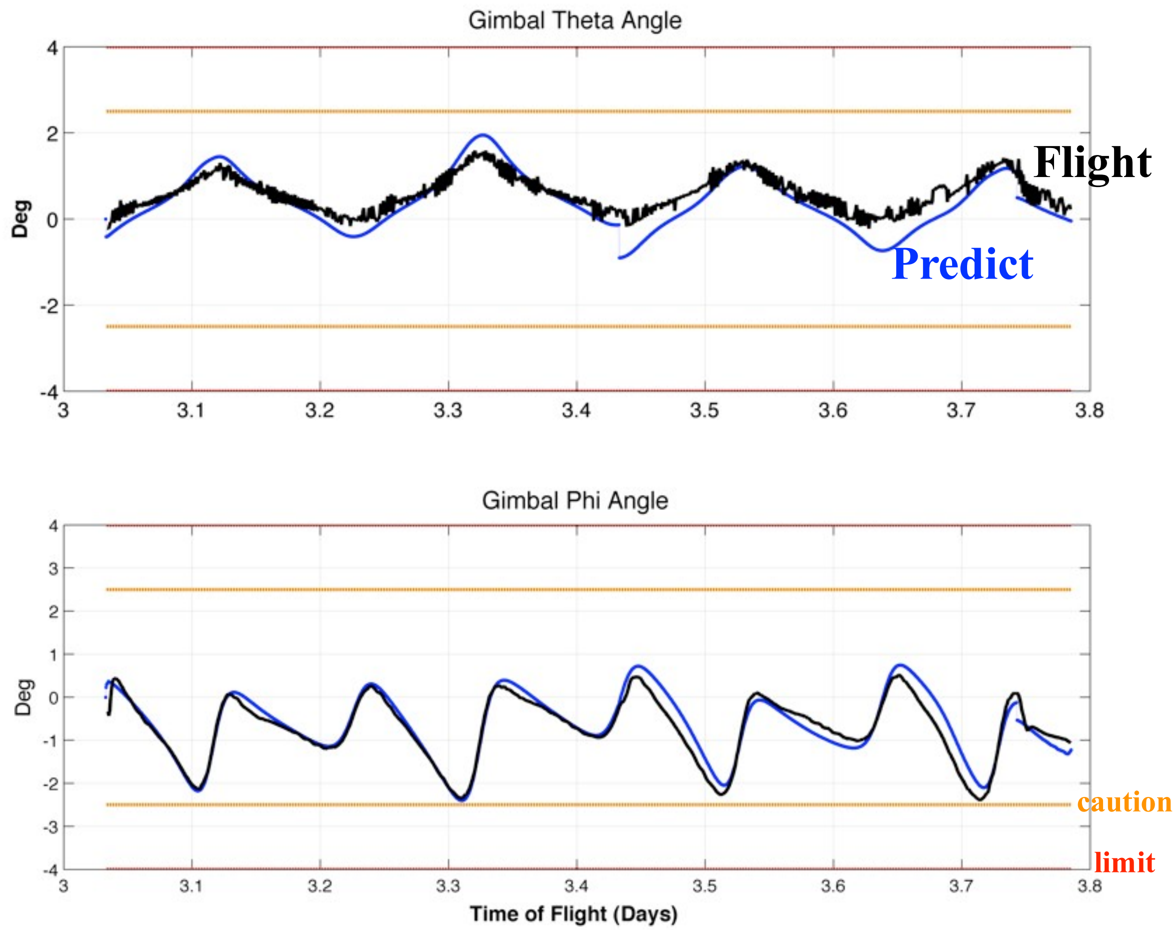
H2L Gimbal Angle

- Gimbal prediction good
  - errors come from momentum prediction and corresponding gyroscopic torque



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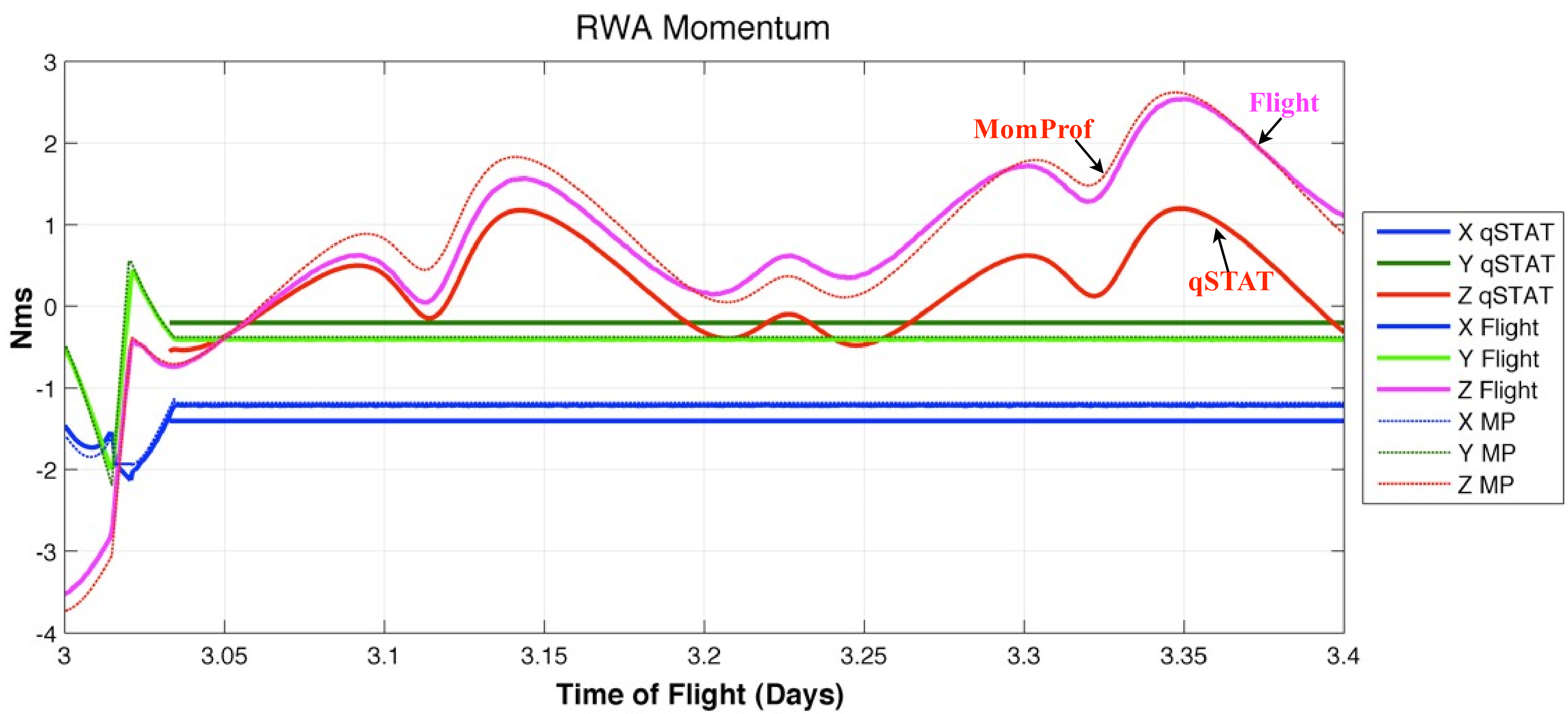
H2L Momentum

- Momentum modeling was most challenging
  - small errors in initial state resulted in large errors over time.
  - qSTAT still provided sets of desirable momentum states
    - Higher fidelity tools included non-thrusting portions and matched flight more accurately



Conclusions

- Conventional maneuver design processes were inadequate
  - Long thrusting durations with the small force of SEP
  - Increased coupling between ACS and NAV teams
- Definition of quantifiable constraints proved impractical
  - Specifically for the Dawn mission, because of the attitude steering algorithm
- A time-efficient simulation tool, qSTAT, was developed
  - allowed fast verification of candidate thrust profile designs
- This approach allowed Dawn to overcome the complications of low-thrust orbit transfers

Dawn

Lessons For Future Low Thrust Missions

- Navigation and ACS elements are deeply coupled on a SEP mission
  - Traditional trajectory design by finding mass-optimal or time-optimal solutions may not be suitable for low-thrust orbit transfers
  - Well-integrated tools in the ACS/NAV systems will be key in reducing risk and improving the capabilities of future low-thrust missions
- Language of Communication between the NAV and ACS worlds must be improved, for low-thrust transfers
  - New methods and techniques produce new language
  - Intuition based on conventional orbit transfer activities may not apply
- Strong system engineering is needed early-on
  - Make sure system-wide interactions are fully appreciated
  - Having people who are strong in both the NAV and ACS domains will help

Questions?