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

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**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
**Dawn**

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- **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
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Spacecraft Configuration

- High Gain Antenna
- Ion propulsion system thrusters (2 obscured in this view; all 3 in x-z plane)
- Solar arrays (articulate around Y)
- Star trackers
- Reaction Wheels
- Inertial Reference Units
- Ion Propulsion Thruster

20 m
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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
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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
• **Typical TCM structure**
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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
**Dawn**

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  - How do you identify capability
    - What Can be done and Cannot be done
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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

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

- 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
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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
• 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
Constraints

• **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
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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

Thrust Delivery Error

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</table>
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.
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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
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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
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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)
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qSTAT Block Diagram

**Inputs:**
- Iterations (N)
- dawn_*.bsp
- TVF
- IPS Engine

**Power Steering Alg.:**
- Quat_Cmd(t)
- Transfer Function
- Quat_Est(t)

**qSTAT Core**
- Init. RWA Momentum
- Propagate Momentum
- Estimate Disturbance Torques
- Compute Control Torques

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

**Outputs:**
- All Data
- Plots w/ constraints

**Cost Function:**
- Momentum
- Gimbal Angle
- ST Occultations
- Thrust Delivery
- Attitude Error

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24
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**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.

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**Maneuver Design**

- MYSTIC
  - Create optimal thrust profile
- TVF
- SPK

**qSTAT**

- Thrust profile meets constraints?
  - no: redesign
  - yes: Finish and verify momentum plan

**Attitude Control**

- qSTAT
  - Develop basic momentum plan
- MomProf
  - Finish and verify momentum plan

Review
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 straightforward
  - 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.
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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
• Gimbal angle predictions match flight very well
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
• **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**
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Attitude Error

- Good Match while being conservative
  - Simplified transfer function doesn’t capture all dynamics
• 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
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?