Flight Experience of Cassini Spacecraft Attitude Control at Saturn

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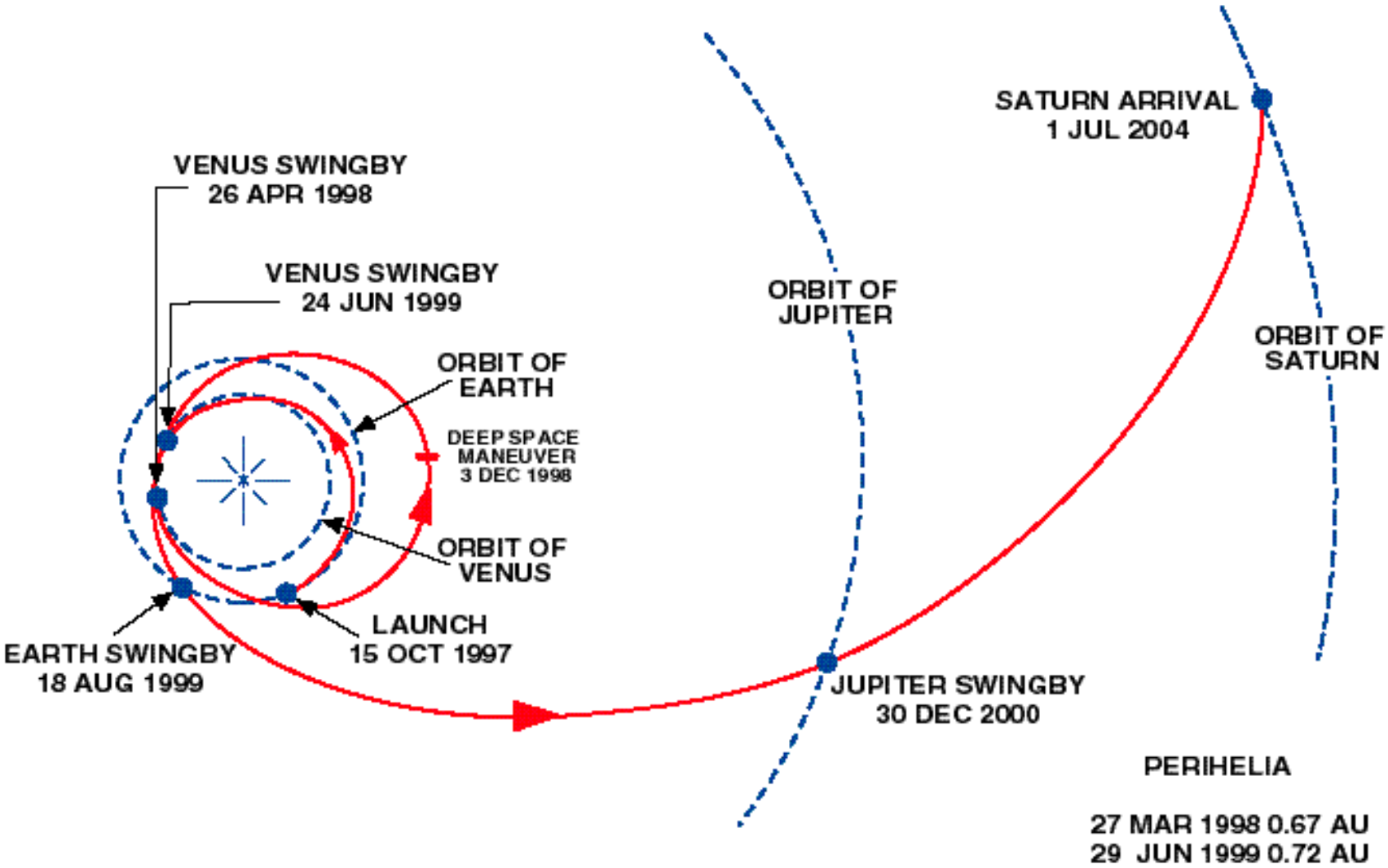
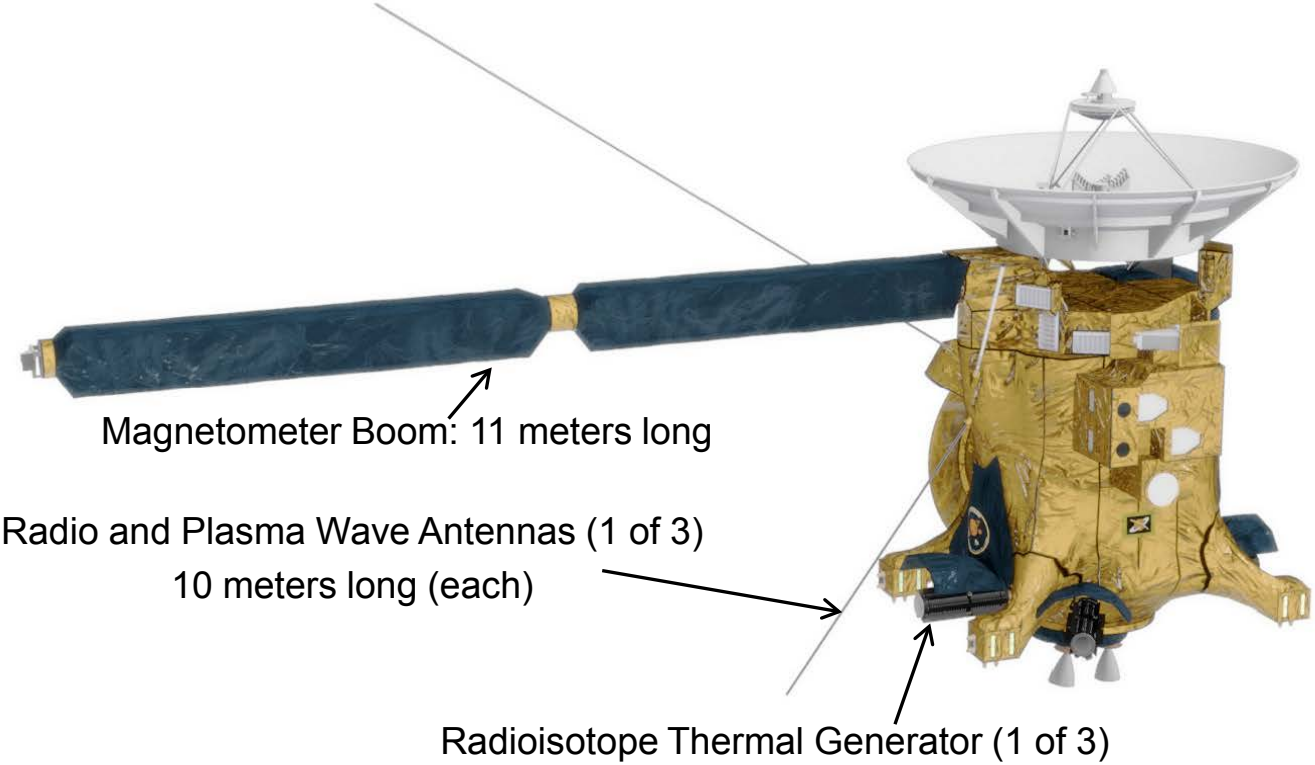
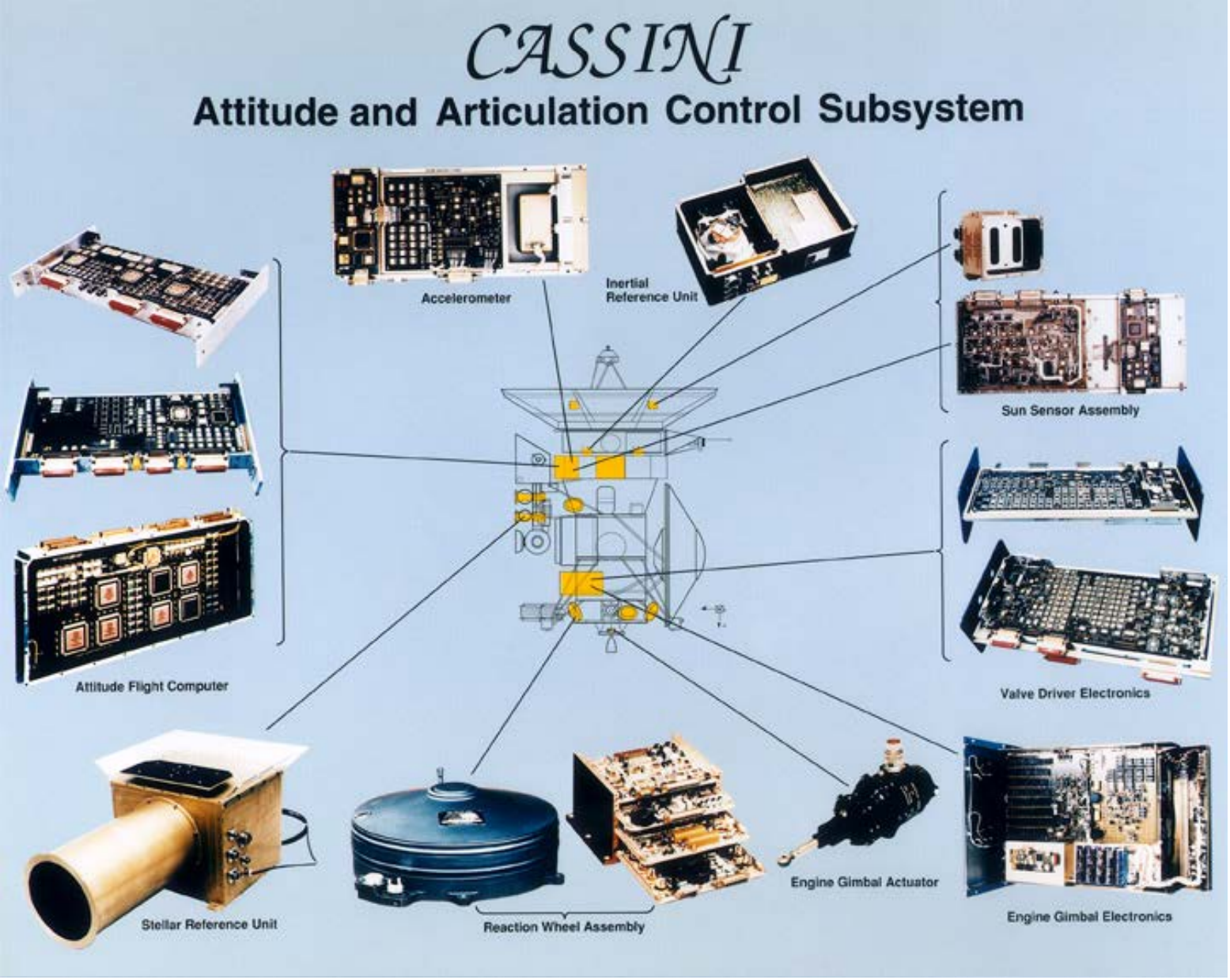
CASSINI INTERPLANETARY TRAJECTORY



Cassini Spacecraft



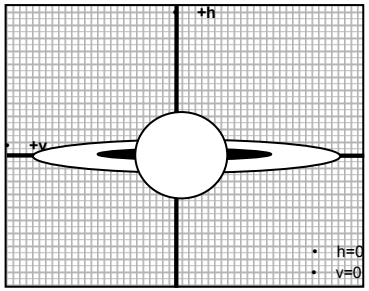
- RTGs produced 880W of power at launch in 1997. Today: 665 W
- Spacecraft Mass at Launch: 5600 kg. Today: 2325 kg
  - Bi-Propellant Load at Launch: 3000 kg. Today: 142 kg (5%)
  - Hydrazine Load at Launch: 132 kg. Today: 62 kg (47%)


CASSINI
Attitude and Articulation Control Subsystem
Accelerometer
Inertial Reference Unit
Sun Sensor Assembly
Attitude Flight Computer
Valve Driver Electronics
Stellar Reference Unit
Reaction Wheel Assembly
Engine Gimbal Actuator
Engine Gimbal Electronics

Attitude Estimator Design (Extended Kalman-Bucy Filter)

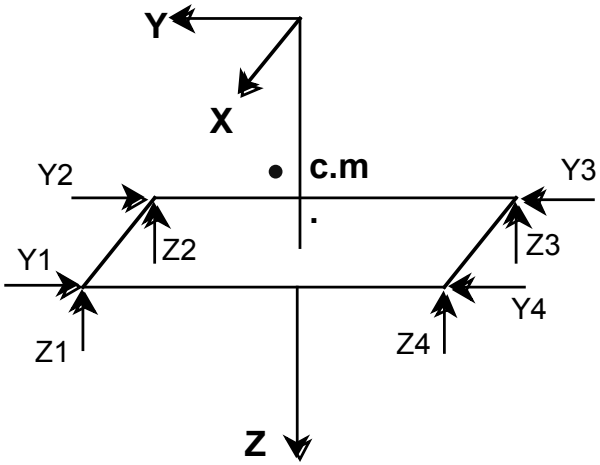
- **Attitude Determination modes:**
  - **Nominal mode**: Combine data from Stellar Reference Unit (SRU) and Inertial Reference Units (IRU)
    - Stellar Reference Unit (SRU, Prime and B/U): Stellar reference via:
      - Five stars captured by star tracker, provides 3-axis attitude knowledge
      - An on-board star catalog
      - Star IDentification (SID) algorithm
    - Inertial Reference Unit (Prime and B/U): Propagate attitude knowledge from star update to update
      - Hemispheric Resonator Gyroscopes
      - Each IRU contains four gyros
      - Prime IRU used continuously since launch

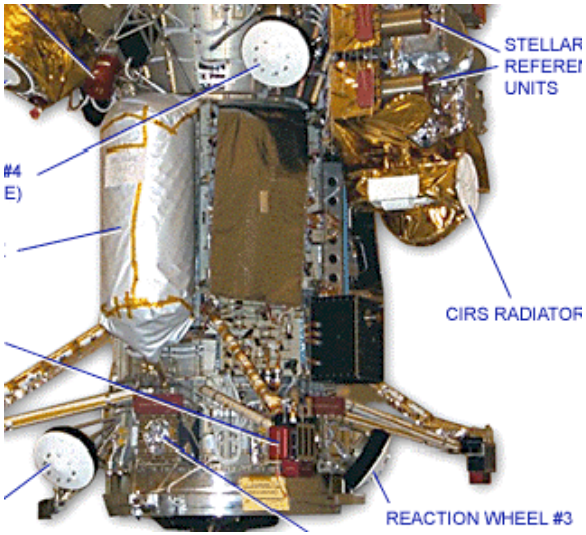
  - **SID Suspend mode**: During Tour, Saturn, rings, etc. might fall inside the star tracker's field-of-view
    - They will confuse the SID algorithm
    - SID must be suspended
    - Attitude knowledge is propagated by gyros alone



Cassini Attitude Control Systems

- Reaction Control System (RCS) [Hydrazine Thrusters]
  - Eight Prime Thrusters / Eight Backup Thrusters
    - In March, 2009, ground controllers swapped the prime thruster branch
  - Blow-down (0.97 N at launch, currently 0.7 N)
  - Control system: Bang-off-Bang
    - Commandable deadbands (0.5 to 20 mrad each axis)
  - Functions:
    - Small ΔV burns (0.01 m/s to 0.3 m/s)
    - RWA Momentum Biasing
    - Low-altitude Titan flybys (atmospheric torque)
    - Slews at higher rates/accels than RWA can perform
- Reaction Wheel Assembly (RWA):
  - Three prime RWAs and an articulatable RWA-4
    - In July, 2003, ground controllers brought RWA-4 On-line to replace RWA-3 in the "prime set"
  - RWAs are used to achieve small attitude control error and good pointing stability
    - Slew rates from very small to several mrad/s



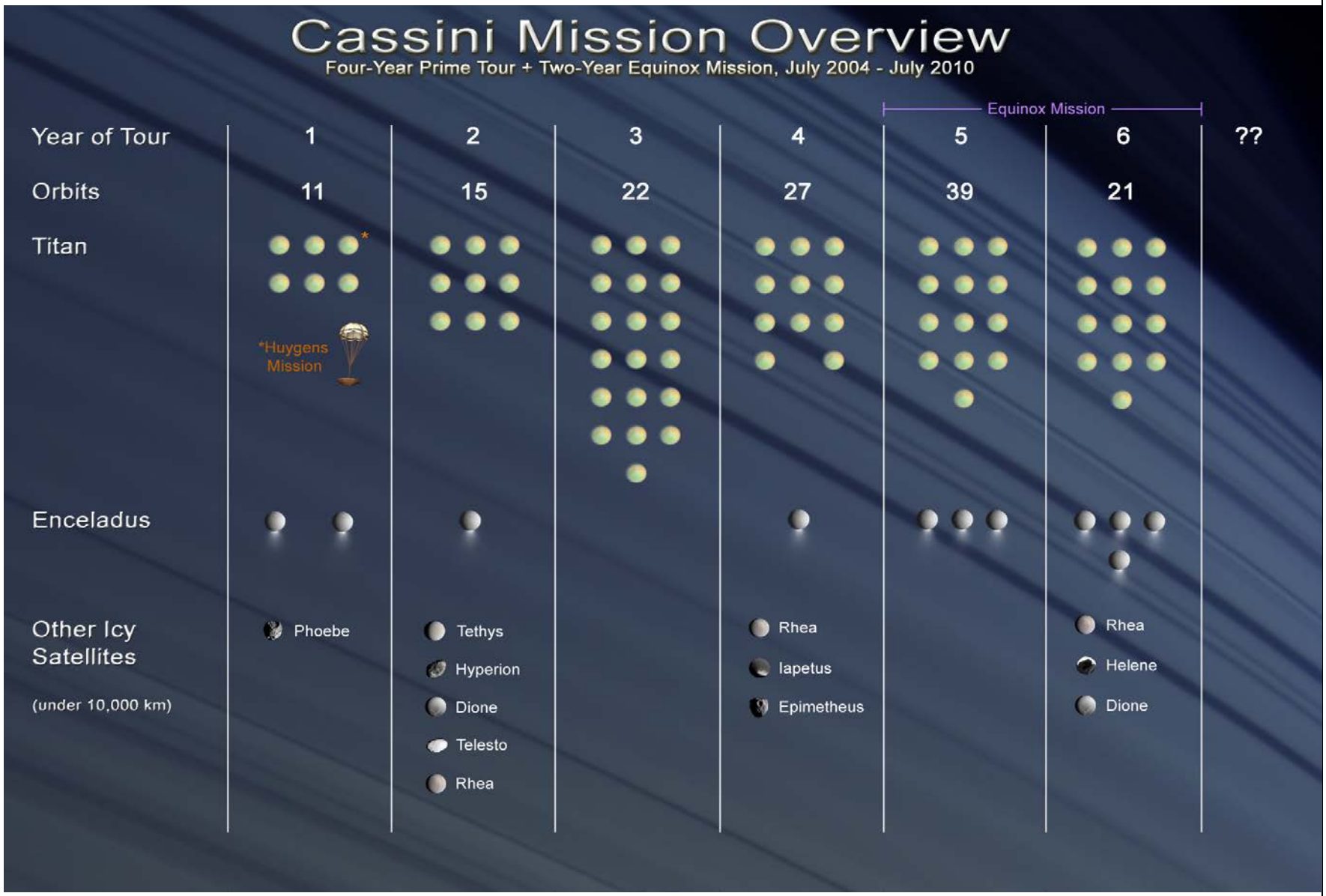


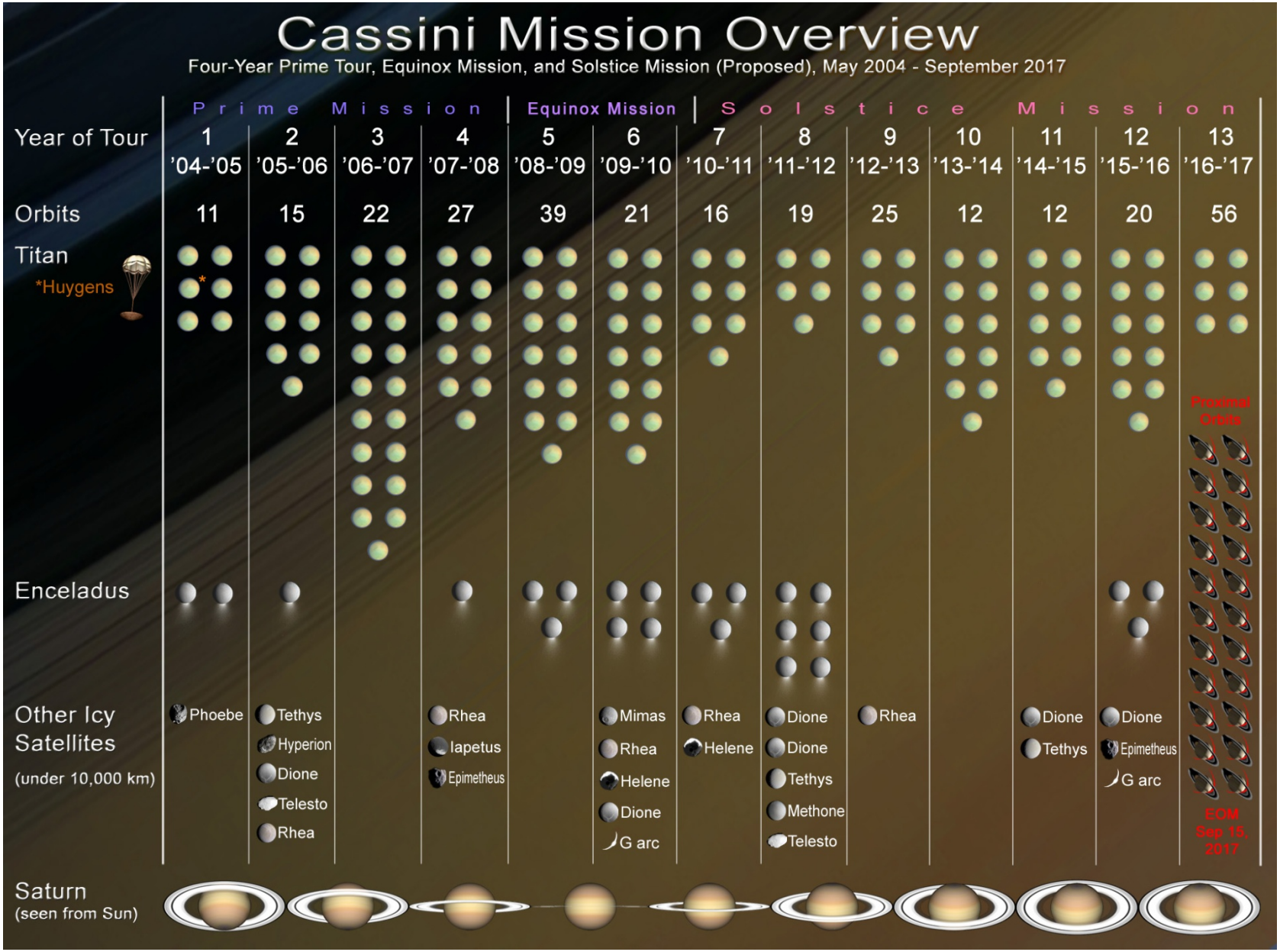
Critical Events Successfully Completed

- Launch (October 15, 1997)
  - Titan-4B/Centaur: Peak tip-off rate was ≈ 0.75 °/s
- Saturn Orbit Insertion (June 30, 2004)
  - This was a 96 min main engine-based burn
  - It lowered the Saturn-relative S/C velocity by 626.2 m/s, and allowed the spacecraft to be captured by Saturn gravity field
- Release of Huygens Probe (December 24, 2004)
  - Probe was released at a pre-determined inertial attitude and spinning
    - Peak Cassini post-release tumble rate was ≈ 0.95 °/s
    - Thrusters detumbled S/C and slewed it to an Earth-pointed attitude in <16 min.
- Probe Relay Tracking at Titan (January 14, 2005)
  - Science data was collected during the Probe descent for 2 h 27 m plus another 1 h 12 m while the Probe was on Titan's surface

Cassini Mission at Saturn

- July 2004 through June 2008 – Nominal mission completed
  - 73 orbits of Saturn completed
- July 2008 through Sept 2010 – Equinox Extended Mission (XM)
  - 65 additional orbits of Saturn completed
- Oct 2010 through Sept 2017 – Solstice Extended-Extended Mission (XXM)
  - 155 additional orbits of Saturn planned

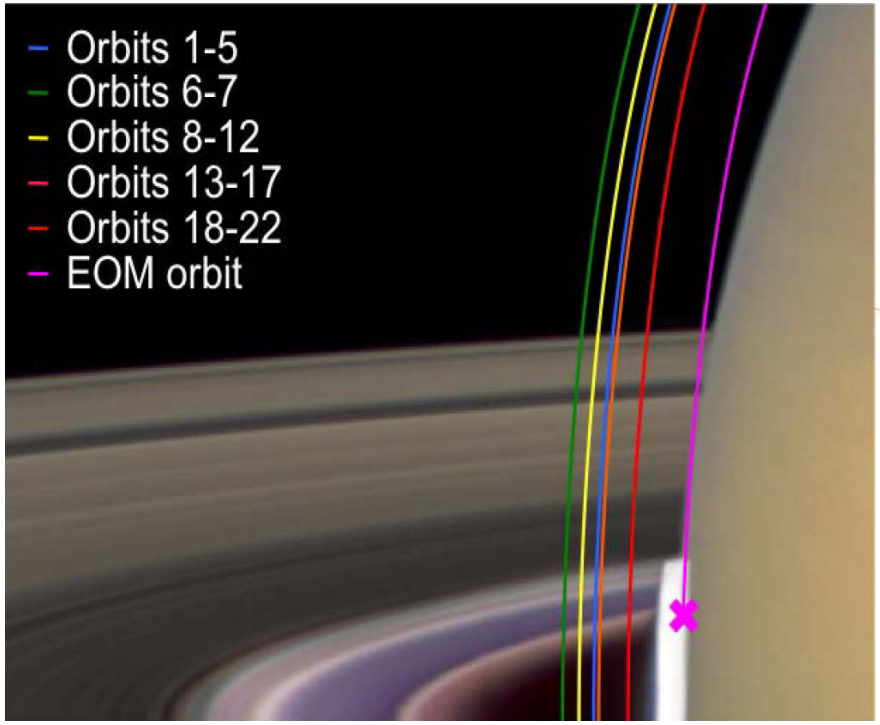

Cassini Mission Overview
Four-Year Prime Tour + Two-Year Equinox Mission, July 2004 - July 2010
Equinox Mission
Year of Tour
1
2
3
4
5
6
??
Orbits
11
15
22
27
39
21
Titan
*Huygens Mission
Enceladus
Other Icy Satellites
(under 10,000 km)
Phoebe
Tethys
Hyperion
Dione
Telesto
Rhea
Rhea
Iapetus
Epimetheus
Rhea
Helene
Dione

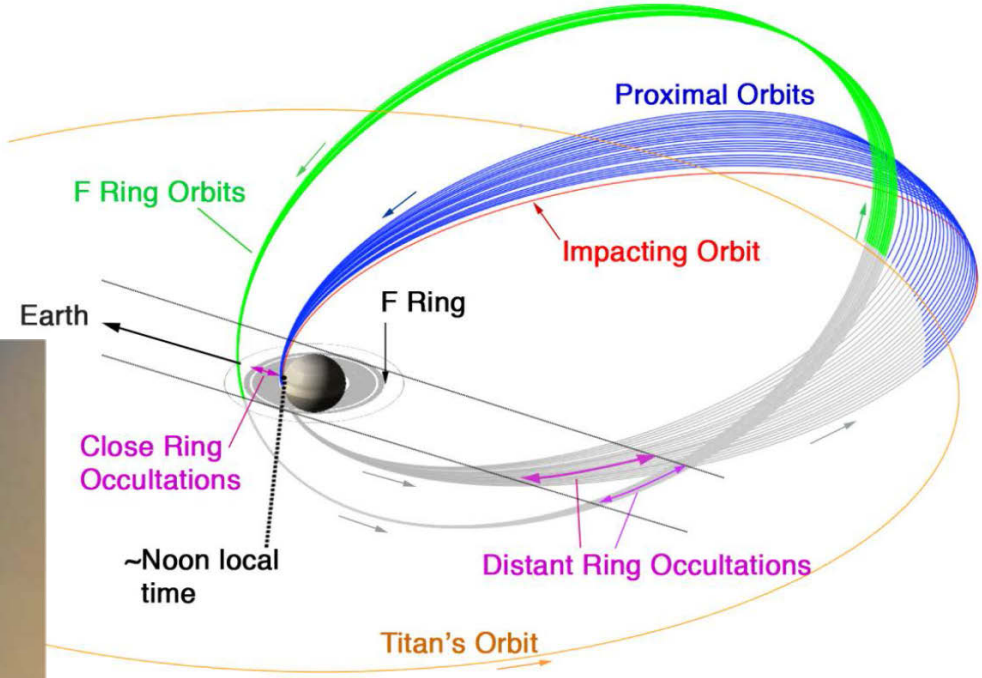

Cassini Mission Overview
Four-Year Prime Tour, Equinox Mission, and Solstice Mission (Proposed), May 2004 - September 2017
Prime Mission
Equinox Mission
Solstice Mission
Year of Tour
1 '04-'05
2 '05-'06
3 '06-'07
4 '07-'08
5 '08-'09
6 '09-'10
7 '10-'11
8 '11-'12
9 '12-'13
10 '13-'14
11 '14-'15
12 '15-'16
13 '16-'17
Orbits
11
15
22
27
39
21
16
19
25
12
12
20
56
Titan
*Huygens
Proximal Orbits
Enceladus
Other Icy Satellites
(under 10,000 km)
Phoebe
Tethys
Hyperion
Dione
Telesto
Rhea
Rhea
Iapetus
Epimetheus
Mimas
Rhea
Helene
Dione
G arc
Rhea
Helene
Dione
Dione
Tethys
Methone
Telesto
Rhea
Dione
Tethys
Dione
Epimetheus
G arc
EOM Sep 15, 2017
Saturn
(seen from Sun)

Proximal Trajectory April-Sept 2017

- 22 orbits with each periapsis inside Rings
  - Orbital Period 6.5 Days
- Ballistic Entry Into Saturn

  September 15, 2017





Cassini Orbit Trim Maneuvers at Saturn An Overview

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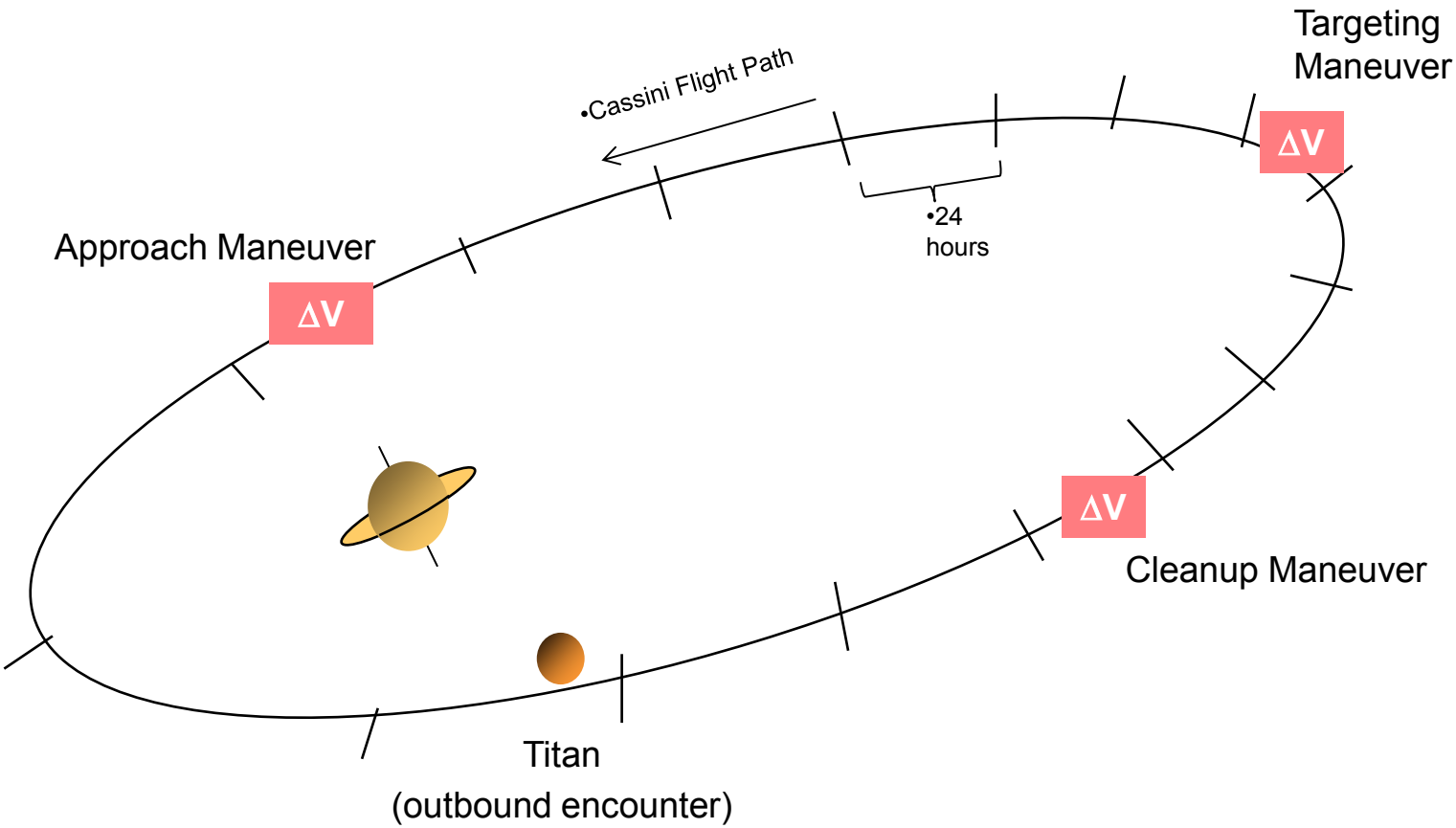
3 Orbit Trim Maneuvers Per Encounter

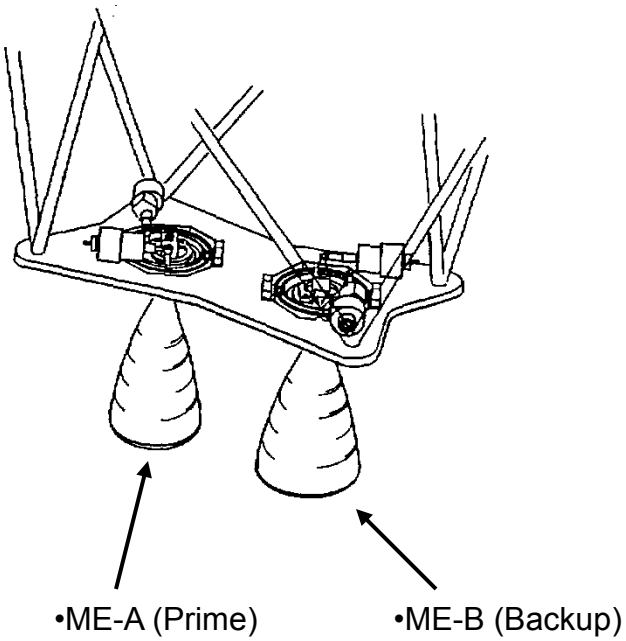


$\Delta V > 0.3$ m/s, use Main Engine

$\Delta V < 0.3$ m/s, use RCS Thrusters

ME Burns – Thrust and Control

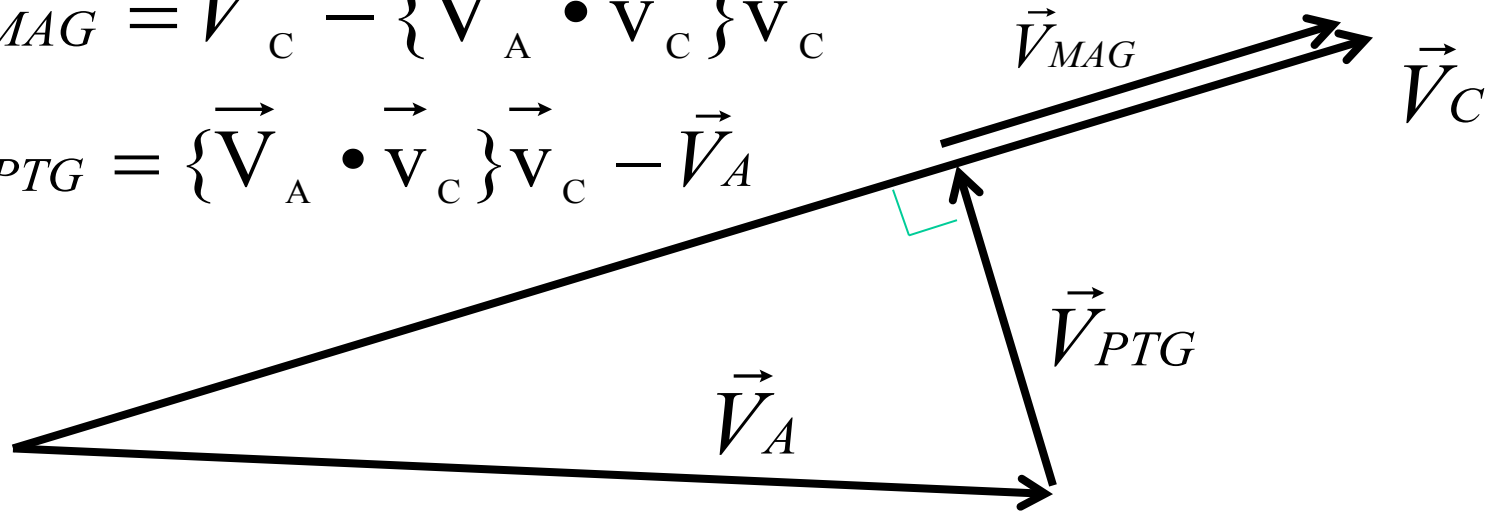
- The main engine provides between 400 N and 450 N of thrust (function of tank pressure)
- Two linear engine gimbal actuators (called “P” and “Q”) provide 2-axis control during the ME burn and the third axis (roll about the thrust vector) is controlled by the Y-facing RCS thrusters
- The main engine is physically mounted about 24 cm away from the Z-axis spacecraft “centerline” (in the +Y-axis direction).
- The effective “thrust vector” during ME burns makes an angle of about 7 degrees with the -Z-axis.



Execution Error Has Magnitude and Pointing Components

$$\vec{V}_{MAG} = \vec{V}_C - \{\vec{V}_A \bullet \vec{v}_C\}\vec{v}_C$$

$$\vec{V}_{PTG} = \{\vec{V}_A \bullet \vec{v}_C\}\vec{v}_C - \vec{V}_A$$



$$\vec{V}_A + \vec{V}_{PTG} + \vec{V}_{MAG} = \vec{V}_C$$

Where:

$\vec{V}_C$ Commanded (desired) velocity vector

$\vec{V}_A$ Achieved velocity vector

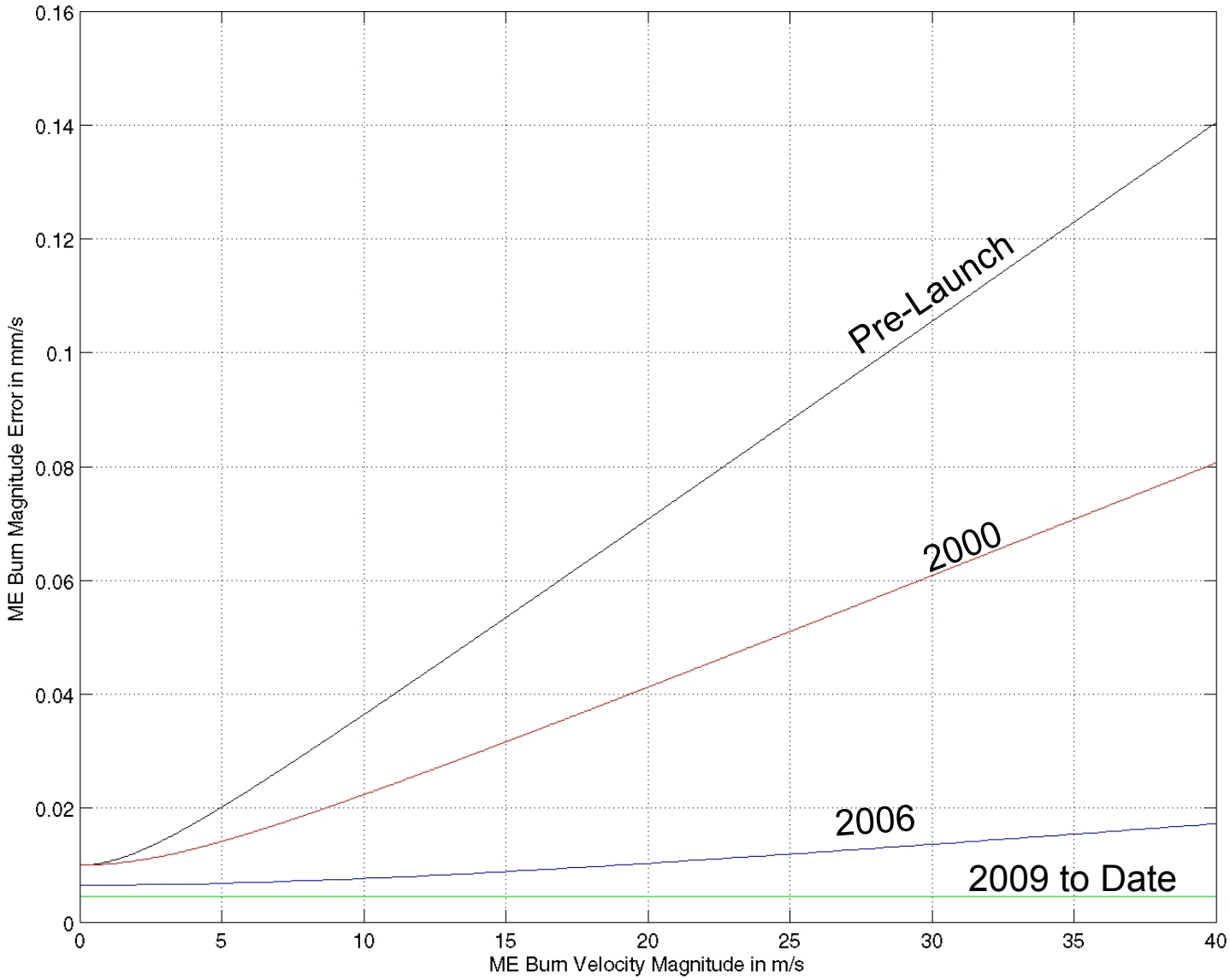
$\vec{V}_{PTG}$ Pointing error vector

$\vec{V}_{MAG}$ Magnitude error vector

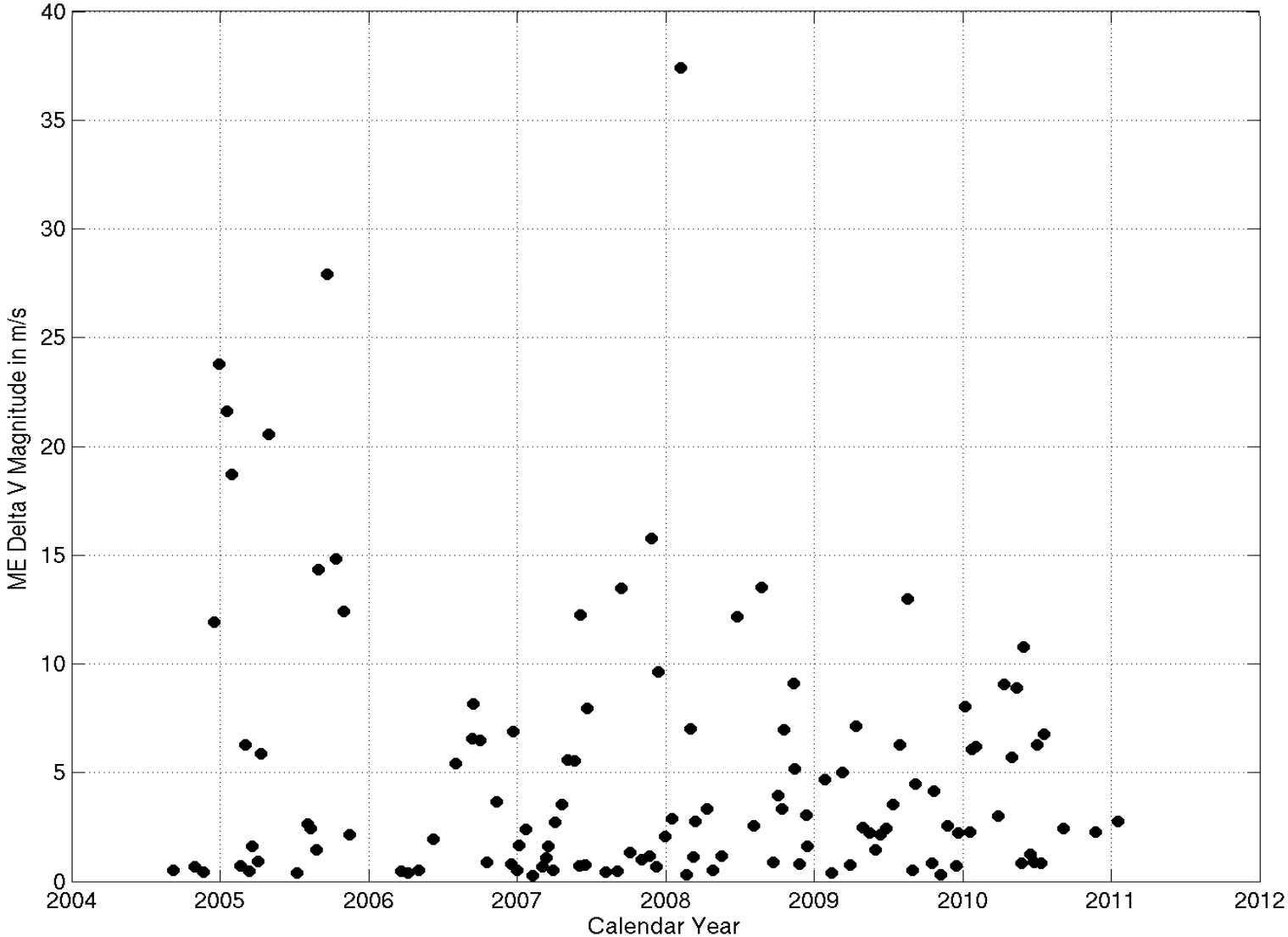
$$\vec{v}_C = \frac{\vec{V}_C}{\|\vec{V}_C\|} =$$

Unit vector of $\vec{V}_C$

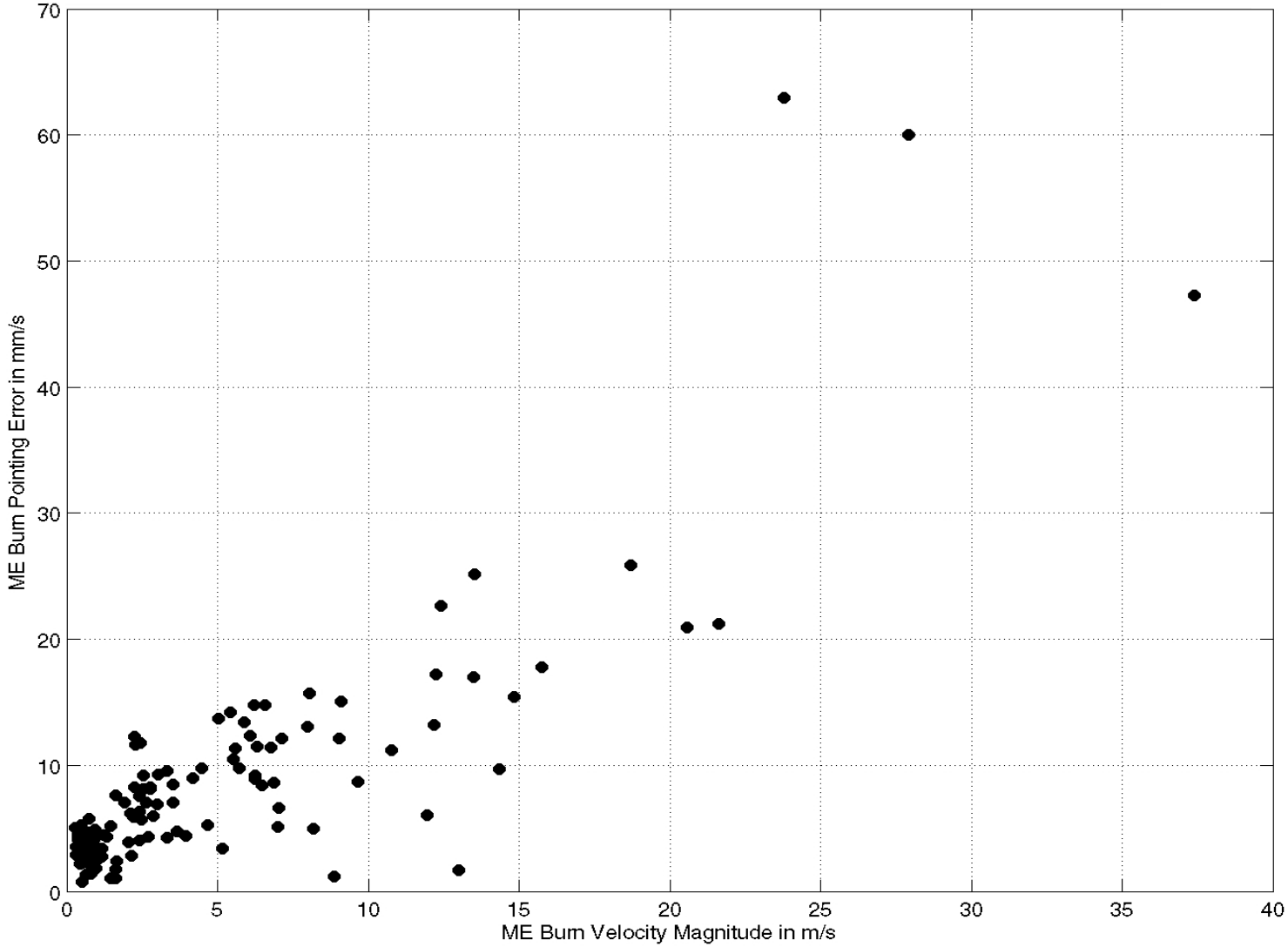
Main Engine Execution Error Has Improved Since Launch



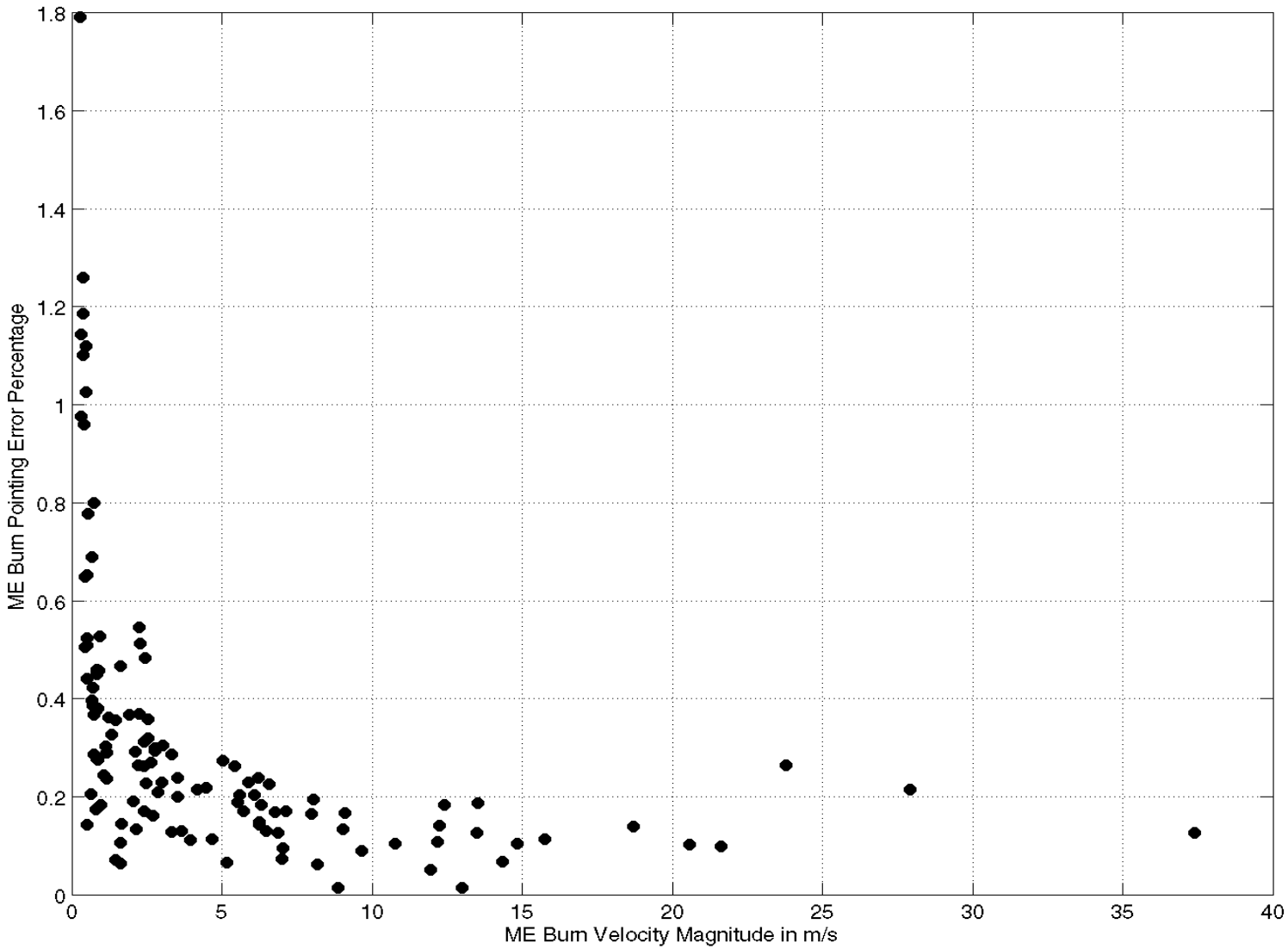
122 Main Engine Maneuvers at Saturn to Date



ME Pointing Error Versus Burn Magnitude



ME Pointing Error Percent Versus Burn Magnitude



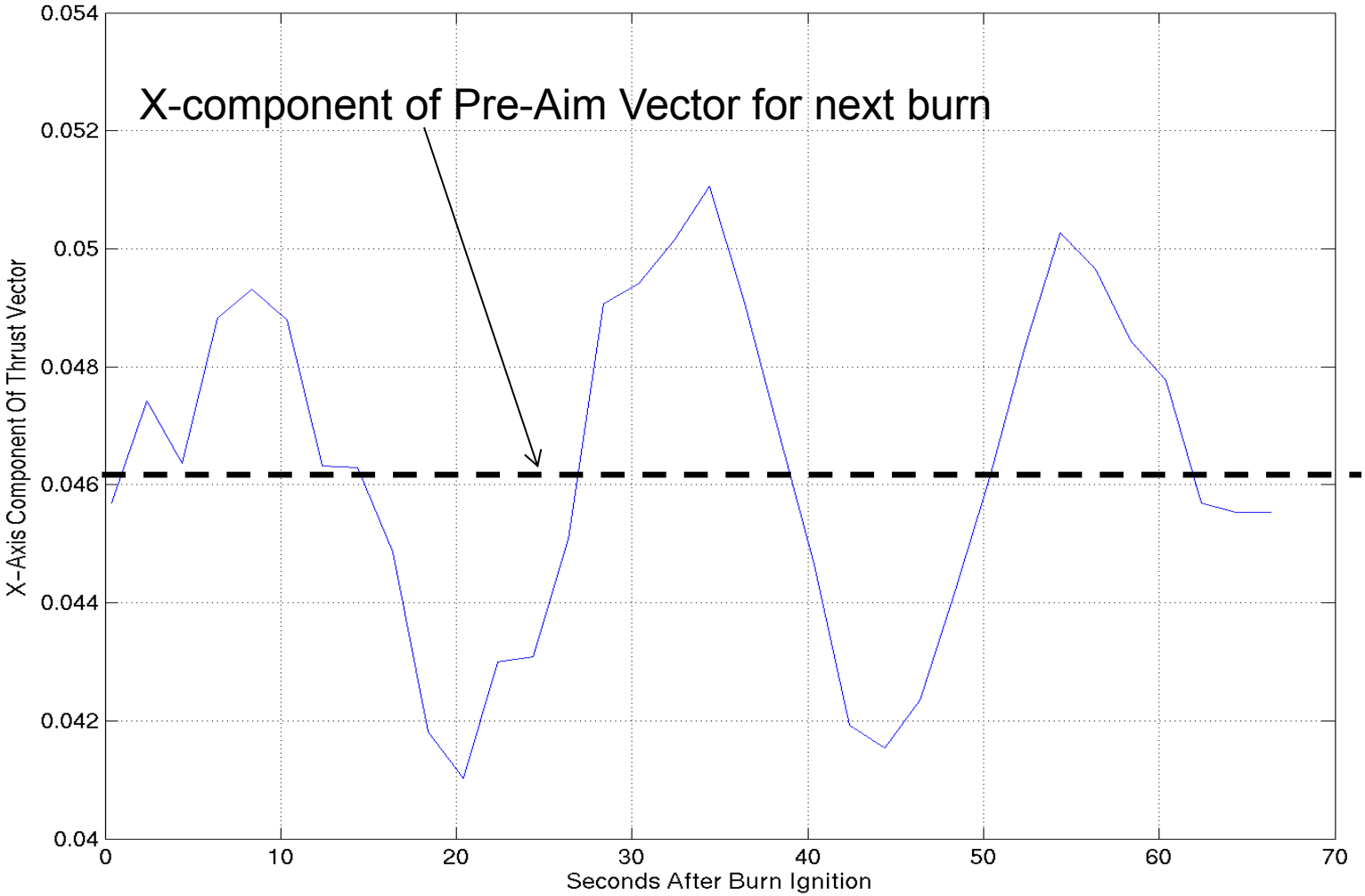
Main Engine Pointing Error and Pre-Aim Vector

- The Main Engine Pre-Aim Vector is the best estimate of the thrust vector during the burn, expressed in body-frame coordinates
- The commanded burn attitude aligns the Pre-Aim Vector with the desired ΔV direction
- A good Pre-Aim Vector estimate minimizes the pointing disturbance after ignition
  - The thrust vector controller essentially points the engine in the direction of the center-of-mass
- An error in the Pre-Aim Vector direction will lead to bigger pointing execution error and bigger ignition transients

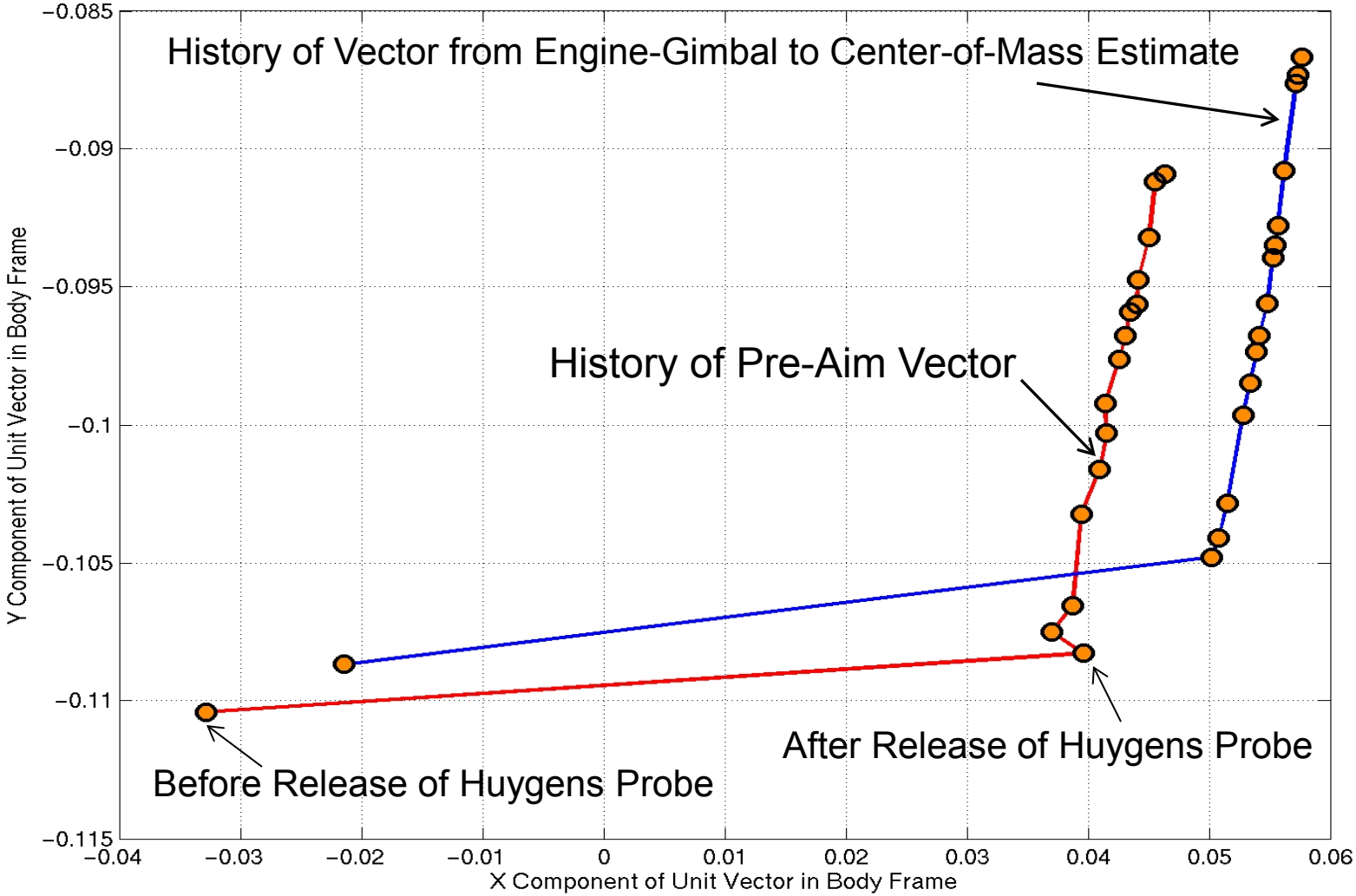
Estimating the Pre-Aim Vector

- Thrust vector telemetry is used to determine the Pre-Aim Vector direction for the next burn
- The oscillatory nature of the thrust vector requires that care be taken in constructing the Pre-Aim Vector for next burn
- The strategy used is to find the average of the thrust vector telemetry over an entire oscillation period of about 20-25 seconds
  - If the previous burn is at least this long, select the period nearest the end of the burn
  - If the previous burn is short (1-20 seconds), do not update the Pre-Aim Vector

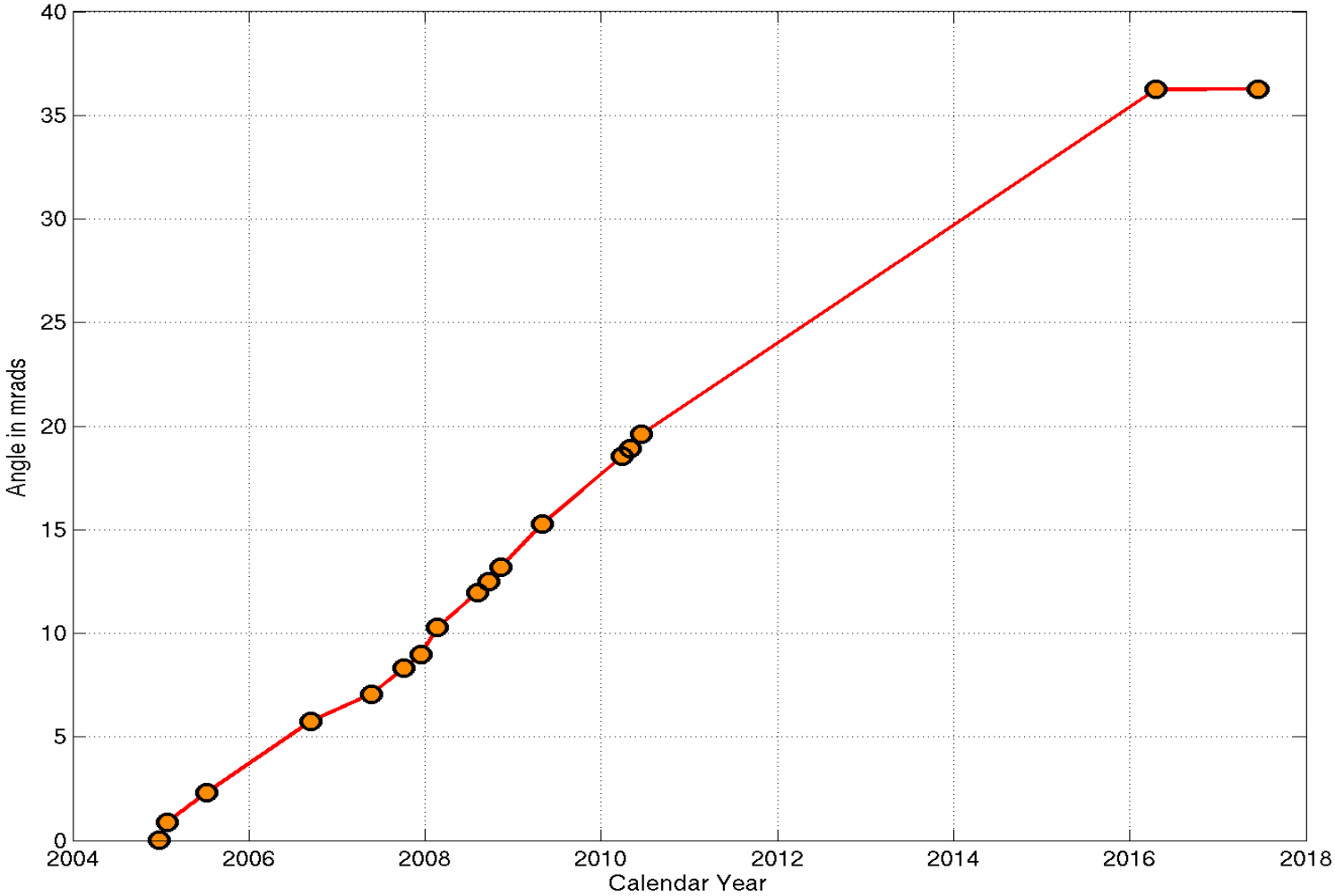
Estimating Pre-Aim Vector from Thrust Vector Telemetry



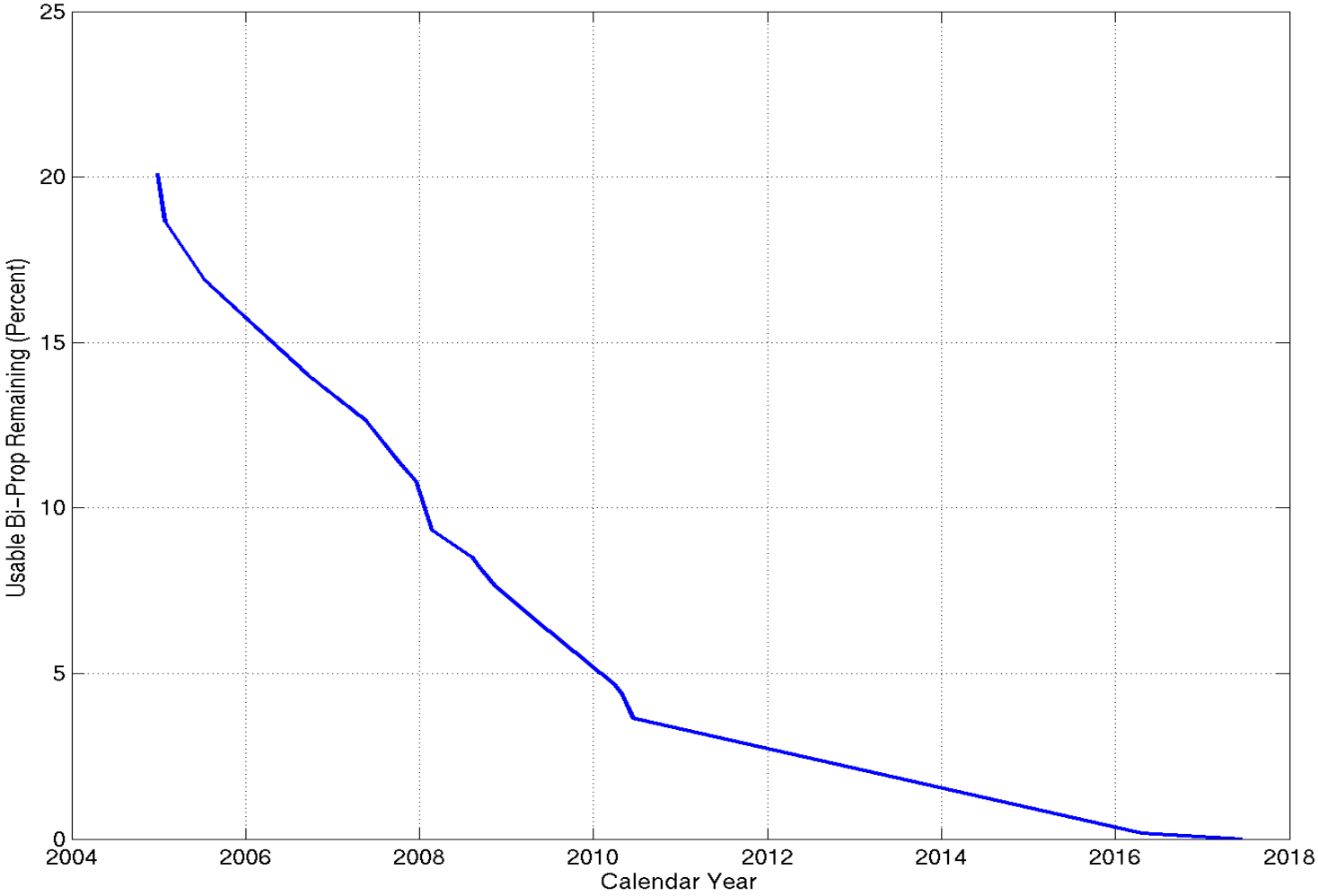
Trend in Pre-Aim is Offset from Gimbal-to-CM



Accumulated Pointing Change in Gimbal to Center-of-Mass Since 2005



Percentage of Usable Bi-Propellant Remaining Since 2005



Attitude Control Performance Has Been Excellent

- Main Engine Execution Error has improved during the mission
  - Accelerometer scale factor adjustments have helped
  - Pre-Aim Vector estimation using telemetry and center-of-mass trending is important
- All Main Engine Burns have used hardware Accelerometer for ΔV estimation
  - Keeps magnitude execution error small
- Future Main Engine burns will be smaller, on average
  - Pre-Aim Vector updates keep ignition transients small
  - Some Pre-Aim Vector updates may be made based on center-of-mass prediction
  - Thrust vector telemetry will continue to be the primary method of Pre-Aim Vector update