Cassini Spacecraft Attitude and Articulation Control System: Overview and Flight Experience

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The Ringed Planet

Saturn’s diameter is 120,000 km. It has >31 moons
One Page in the Family Album of Saturn

Mimas

Enceladus

Tethys

Dione

Iapetus

Hyperion

Rhea

Titan

Surface of Titan

HST - WFPC2
History of Discoveries

• 1608
  Telescope was invented

• 1610
  Galileo Galilee discovered a “triple” planet (“a large body with two smaller bodies beside it”)

• 1659
  Christian Huygens was the first to conjecture that Saturn is not physically connected to its rings. He also discovered Saturn’s largest moon, Titan

• 1675
  Jean Dominique Cassini discovered four of Saturn’s moons and a gap in Saturnian rings. That gap is now called the “Cassini Gap”

300+ years later

• 1980-81
  Two JPL spacecraft, the Voyagers’, returned detailed photographs of the planet

• 1997
  NASA/ESA launched Cassini
The Cassini/Huygens Mission to Saturn: Overview

• The CRAF/Cassini missions were proposed by the President and approved by the U.S. Congress in the NASA appropriation for fiscal year 1990:
  – CRAF (Comet Rendezvous Asteroid Flyby) was cancelled in mid-1991

• Cassini carries scientific instruments to support 27 different investigations to probe the mysteries of the Saturnian system

• Benefits derived from the Cassini mission:
  – Rewards of international cooperation
  – Excitement of scientific discoveries
  – Technology spin-off's from solving “real-life” and hard problems
  – To inspire a new generation of young scientists/engineers
The Cassini Spacecraft and the Huygens Probe

6.8 m height
5800 kg at launch

2.7 m dia.
320 kg
Earth → Venus → Venus → Earth → Jupiter → Saturn

LV: Titan IV-B/Ceutaur upper stage
Attitude and Articulation Control System

• **AACS Functions:**
  - Maintain three-axis attitude knowledge in an inertial frame at all time
  - Pointing of Science Instruments. For example:
    • Narrow angle camera
  - Pointing of Communication Antennas
  - Slewing the spacecraft: Using thrusters or reaction wheels
  - Large and small trajectory correction maneuvers (called $\Delta V$ burns)
    • Large $\Delta V$ performed by a rocket engine
    • Small $\Delta V$ performed by thrusters
  - Detumble the spacecraft:
    • After separation from the Centaur upper stage
    • After the Probe was released
  - Overcome atmospheric torque imparted on the S/C during 21 low-altitude Titan flybys
  - Autonomous avoidance of conditions such as *Sun is too close to camera bore-sight*
CASSINI
Attitude and Articulation Control Subsystem

- Accelerometer
- Inertial Reference Unit
- Sun Sensor Assembly
- Valve Driver Electronics
- Stellar Reference Unit
- Reaction Wheel Assembly
- Engine Gimbal Actuator
- Engine Gimbal Electronics

Attitude Flight Computer
Cassini Pointing Engine

- **Primary pointing goal:**
  - Align primary body vector (e.g., antenna) to primary inertial vector (e.g., Earth)

- **Secondary pointing goal:**
  - Bring secondary body vector (e.g., +X-axis) as close as possible to secondary inertial vector (e.g., J2000-z)

- **Body vector example:**
  calibrated camera b/s vector

- **Inertial vector example:**
  Cassini-to-Earth vector
  - Relative motion of objects that satisfies the following equation could be modeled accurately as Conics (conic section)

\[
\ddot{\mathbf{r}} = -\frac{\mu}{|\mathbf{r}|^3} \mathbf{r}
\]
Inertial Vector Propagation

- **Vector Tree:**
  - Often time, it is more accurate to determine a vector by adding several “tree branches”. For example,
    - Cassini-to-Earth vector:
      \[
      \vec{P}_{\text{Earth Cassini}} = \vec{P}_{\text{Earth Sun}} - \vec{P}_{\text{Saturn Sun}} - \vec{P}_{\text{Saturn Cassini}}
      \]

- **Tree branches:**
  - Some could be propagated accurately over a long time by a conic section
    - \(\vec{P}_{\text{Earth Sun}}\) and \(\vec{P}_{\text{Saturn Sun}}\)
  - Others are propagated by Chebyshev polynomials (up to 12 degrees):
    - Best “Mini-Max” fit
      \(\vec{P}_{\text{Cassini Saturn}}\)
Inertial Attitude Estimation Design

• Attitude Determination modes:
  – **Nominal mode:**
    Combine data from Stellar Reference Unit (SRU) and Inertial Reference Units (IRU)
    • Stellar Reference Unit (SRU, Prime and Backup): Stellar reference via:
      – Five stars captured by star tracker
      – An on-board star catalog
      – Star Identification (SID) algorithm
    • Inertial Reference Unit (Prime and Backup): Propagate attitude knowledge from star update to update
      – Hemispheric Resonator Gyroscopes
      – Each IRU contains four gyros

  – **SID Suspend mode:**
    During Tour, Saturn, rings, etc. might fall inside the tracker’s FOV
    • They will confuse the SID algorithm
    • SID must be “suspended”
    • Attitude knowledge is propagated by gyros alone
Attitude Control Systems

• **Reaction Control System (Thrusters):**
  - Eight *A-branch* thrusters (prime) and eight *B-branch* thrusters (Backup)
  - Blow-down (1.1 N at launch)
  - Control system: Bang-Off-Bang (BOB), BW ≈ 0.15 Hz
  - Functions:
    - Small trajectory correction burns (ΔV)
    - RWA Biasing
    - Low-altitude Titan flybys
    - Detumble S/C

• **Reaction Wheel Assembly (RWA):**
  - Three prime RWAs and an articulate-able backup RWA
  - They are used to achieve small attitude control error and good pointing stability
  - Control system: PD controller, BW ≈ 0.029 Hz
Trajectory Correction Maneuvers (ΔV Burns)

- Large and small ΔV burns:
  - Large ΔVs are executed using a 445-N main engine (prime and B/U)
  - Small ΔVs are executed using four Z-facing thrusters (Blow-down)

- Since Launch:
  - Main engine ΔV burns:
    - More than 46 ΔV burns
    - Cutoff by an accelerometer
  - RCS ΔV burns:
    - More than 15 ΔV burns
    - Cutoff by a Timer

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.
Critical Events: Faultlessly Executed

• Launch (October 15, 1997)
  – Titan-4B/Centaur upper stage

• Saturn Orbit Insertion (June 30, 2004)
  – It lowered the Saturn-relative S/C velocity by >600 m/s, and allowed the S/C to be captured by Saturn gravity field

• Release of Huygens Probe (December 24, 2004)
  – To release the probe in a pre-determined inertial attitude, and to give it a spin

• Probe Relay Tracking (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 the ground
Time Line of Saturn Orbit Insertion (SOI)

A “gap” between The F and G rings

To Ascending ring plane attitude

To burn attitude

Settling

Burn time ≈ 1.6 hours

ΔV > 600 m/s

Settling

Science Observations
Ejection of the ESA-Built Huygens Probe

- Post-release S/C rate telemetry were used to reconstruct the Probe kinematics
- Results were given to ESA on Dec 25, 04

\[ \Delta V \approx 0.4 \text{ m/s} \]

\[ \Omega \approx 8 \text{ rpm} \]
Rhea
26 Nov. 2005
1000 km flyby

Old, battered surface with little evidence for geologic activity
Tectonic Activity on Titan

White linear features SAR data may represent ridges
First indication of possible tectonic activity on Titan’s surface
• Cassini AACS is one of the most complex and most capable of all interplanetary spacecraft

• Performance of attitude control design over the past 8 years has been superb. All key mission and science requirements are met with margins

• Factors contributing to success
  – Quality of the S/C flight operations team
  – Availability of Test beds and trained test teams
  – Availability of Ground software tools
  – Pay attention to details and Triple checks your results
Some Members of the Cassini Attitude Control Team