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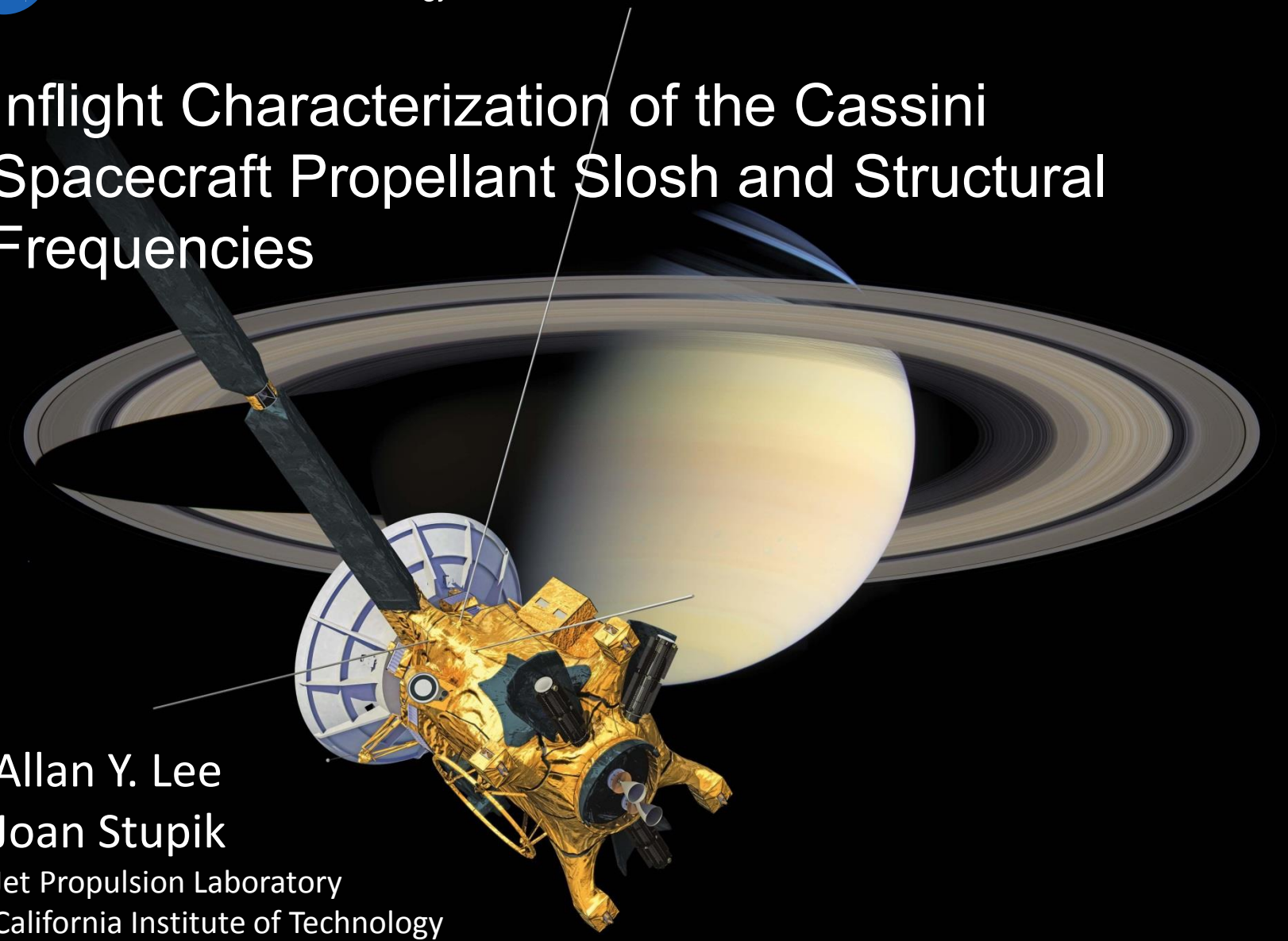
Inflight Characterization of the Cassini Spacecraft Propellant Slosh and Structural Frequencies



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1/5/2015

Topics to Cover

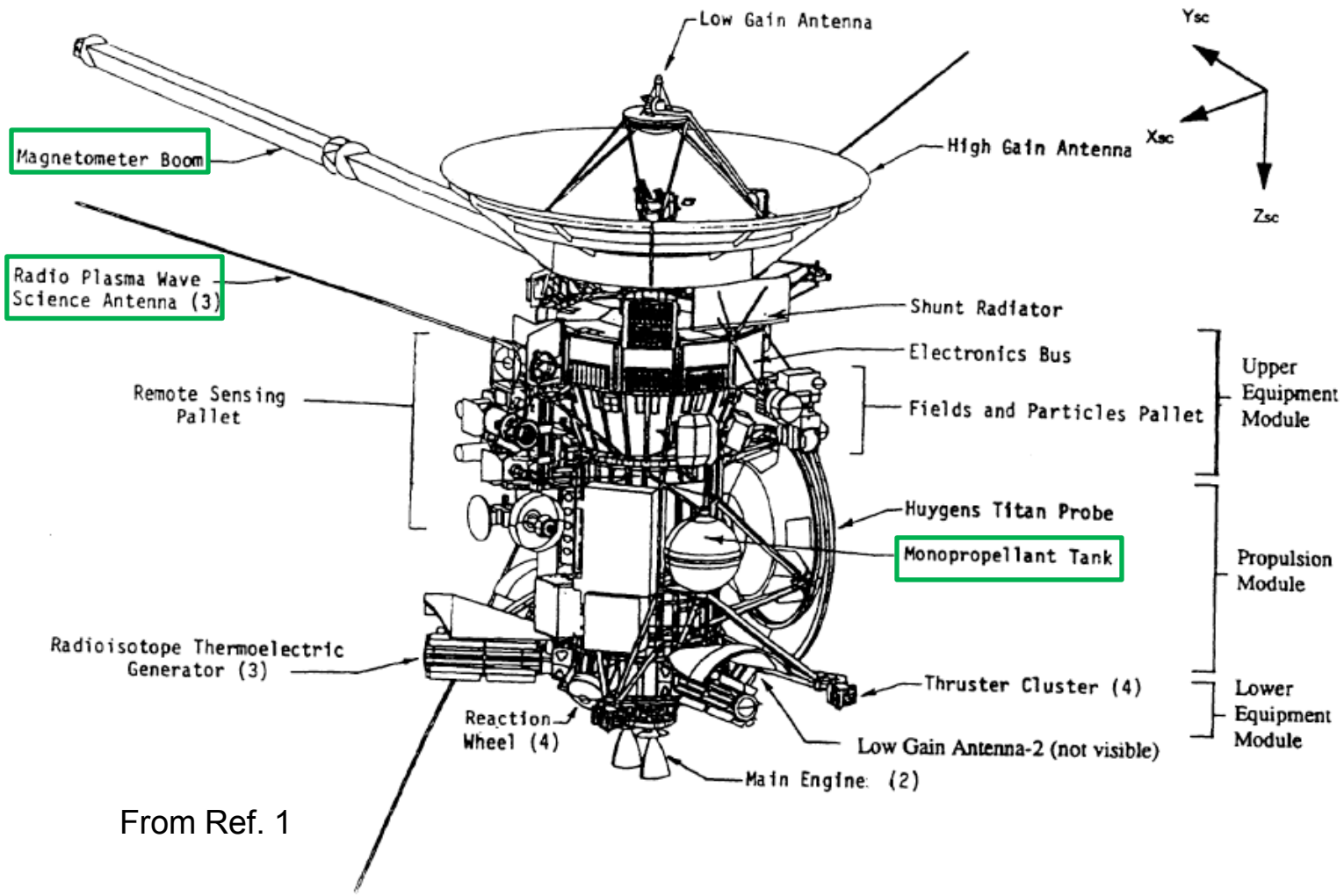
- Cassini Spacecraft
- Propellant Slosh
- Propellant Management Device (PMD)
- Theoretical Predictions
- Objective
- Magnetometer Boom
- High-g Fuel Slosh
- Conclusions

Cassini Spacecraft

From NASA/JPL Cassini website

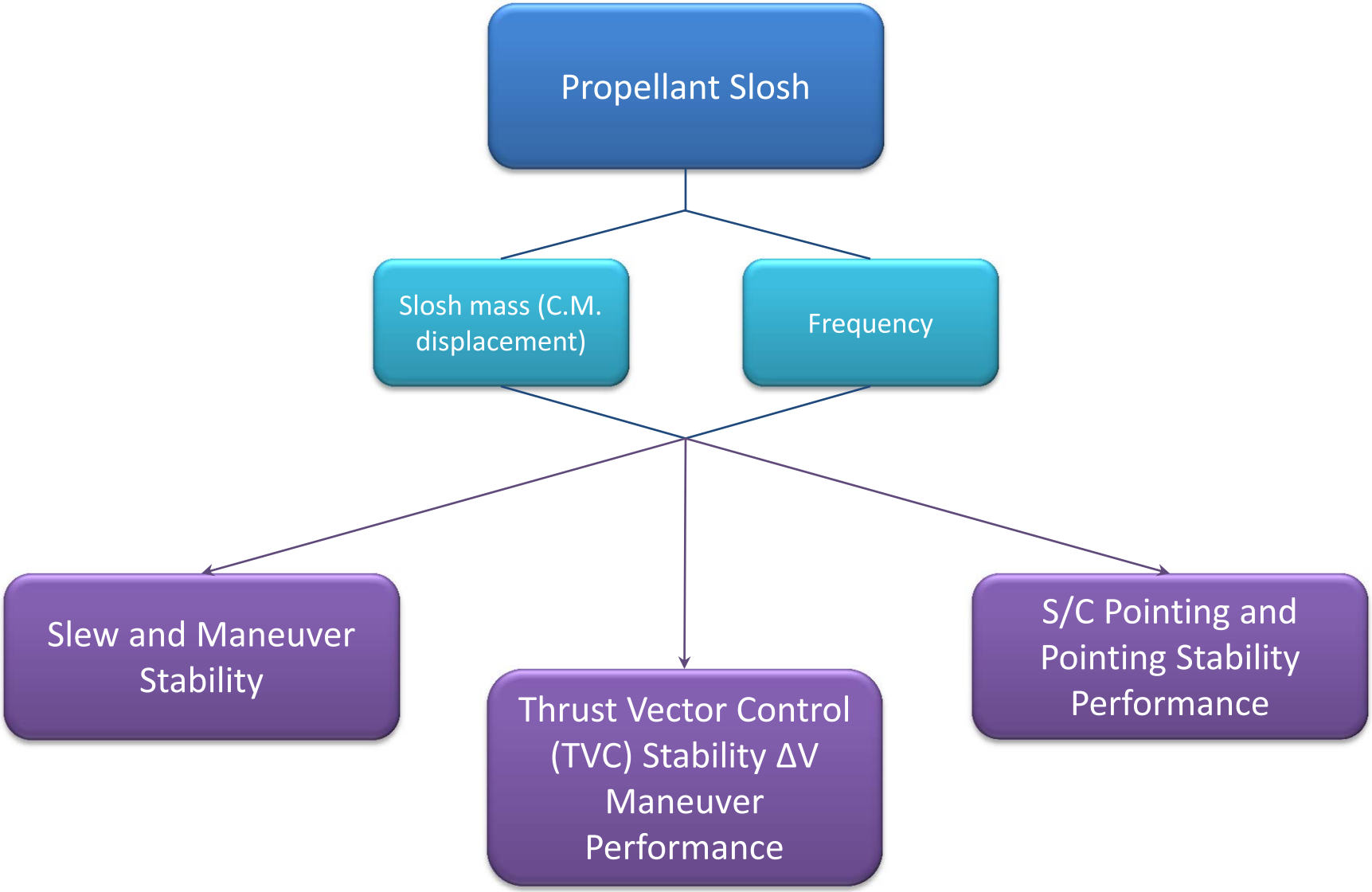
- Major science objectives of the Cassini mission include investigations of
  - The configuration and dynamics of Saturn's magnetosphere
  - The structure and composition of the rings
  - The characterization of several of Saturn's icy satellites (e.g., Enceladus)
  - Titan's atmosphere constituent abundance
- Spacecraft general parameters
  - Main engine: 445 N (2)
  - Thrusters: 1 N at launch (16)
  - Launch mass: 5,574 kg
  - Propellant mass: 3000 kg
    - Hydrazine: 132 kg
    - Fuel/Ox: 2868 kg
  - Flexible appendages
    - Magnetometer boom
    - RPWS Antennae (3)

Cassini Spacecraft



From Ref. 1

Propellant Slosh



Propellant Management Device (PMD)

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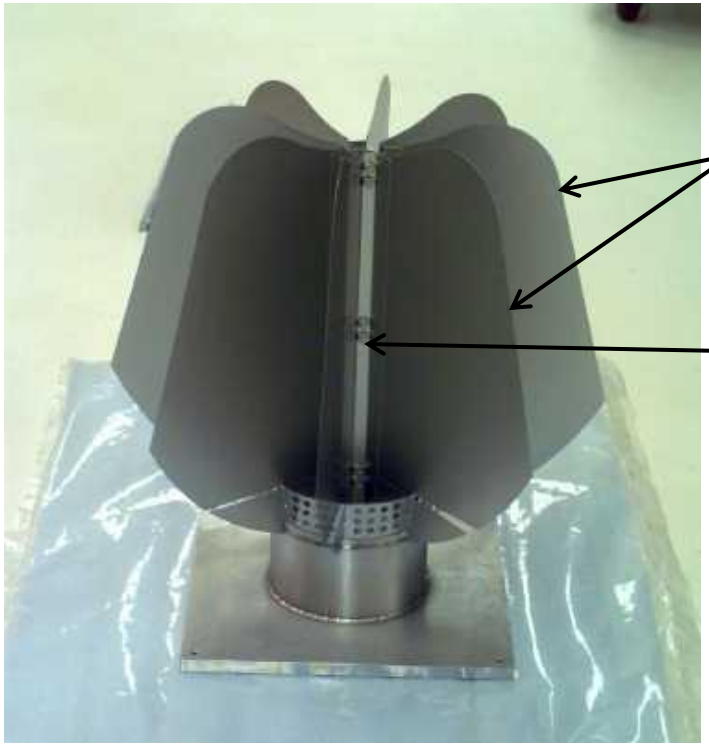
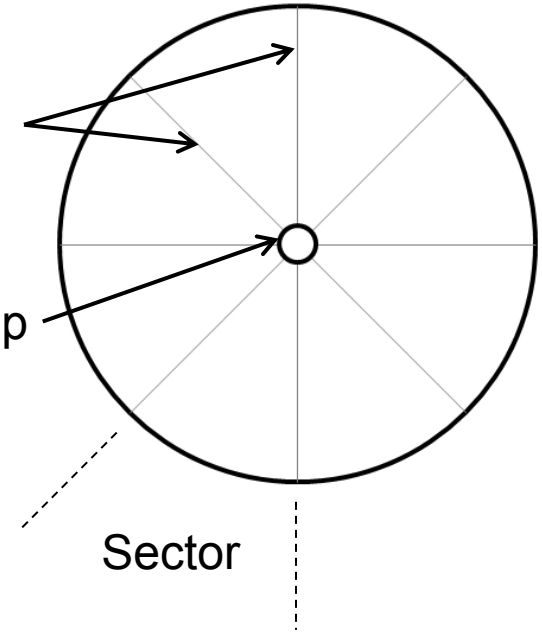
- Cassini fuel/oxidizer (MMH/NTO) tanks
- Hydrazine has comparably insignificant slosh mass, no PMD
  - 132 kg vs. 2868 kg
  - Instead, a polymeric rubber diaphragm was used
- Decrease participating slosh mass and control center of mass
- Create two slosh frequencies: sector and full tank



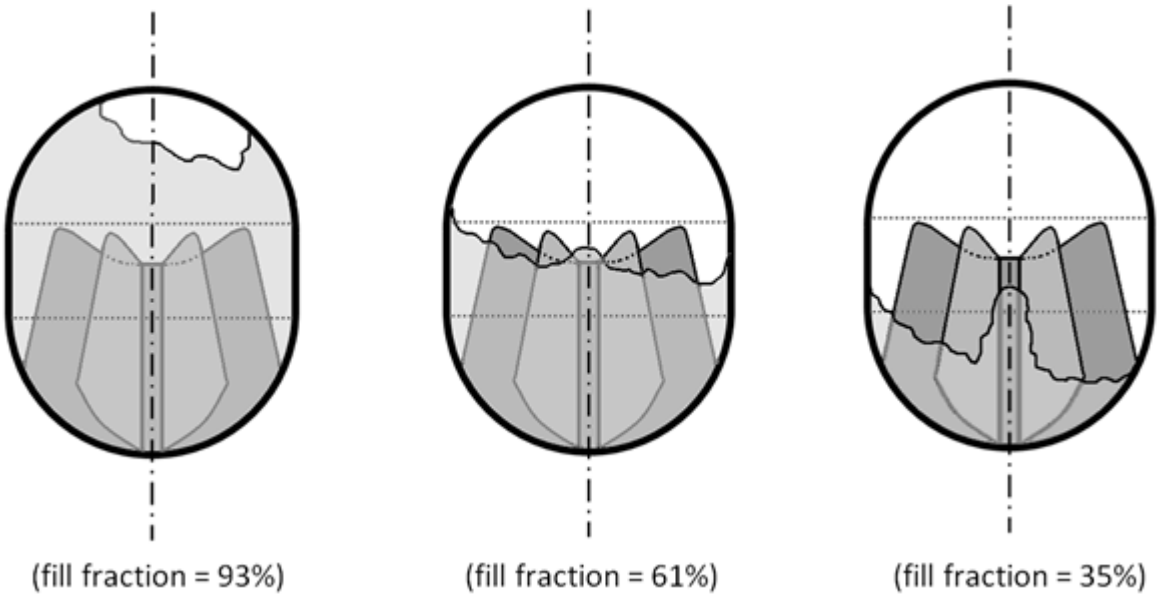
8 Vane panels
45° spacing

Supporting
structure/sump
cover



MGS PMD
From Ref. 2

PMD Continued



- When PMD is fully submerged, only expect to see full-tank frequency
- When PMD is not fully submerged, expect to see two frequencies: sector and full-tank

High-g vs. Low-g

- Applied acceleration and surface tension forces both contribute to slosh dynamics – but which dominates?

$$\mathrm{Bo} = \frac{\rho a R^2}{\sigma}$$

- Bond Number [dimensionless]
  - ρ = density of liquid at 20°C
  - a = applied acceleration
  - R = radius of tank
  - σ = surface tension parameter of propellant at 20°C

- Bo < 10 means surface tension forces dominate … low-g mode
- Bo > 10 means acceleration dominates … high-g mode

Theoretical Slosh Predictions: High-g

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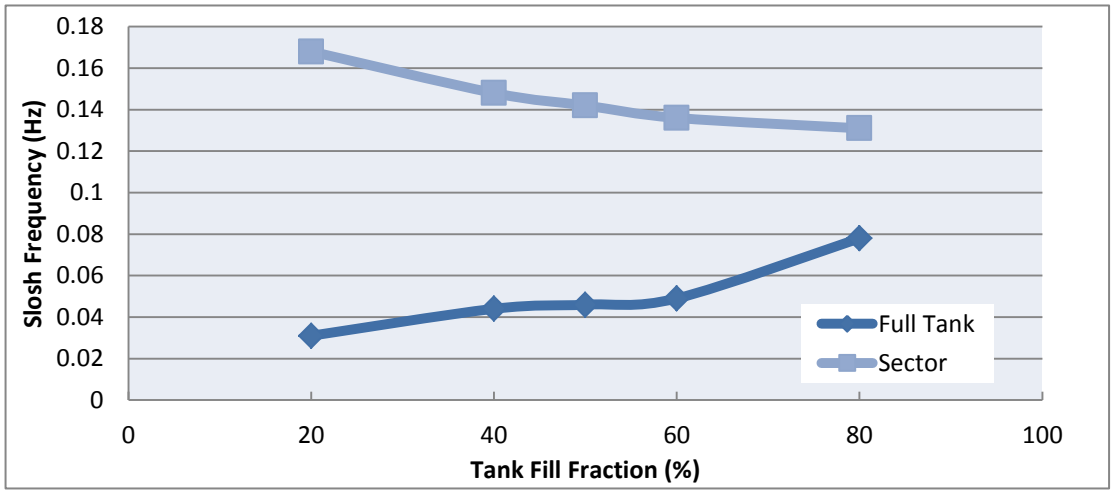
Table 1. Cassini Bipropellant High-g Slosh Frequency

Tank Fill Fraction [%]	Acceleration [m/s^2]	Full-tank Mode Slosh Frequency* [Hz]	Sector Mode Slosh Frequency* [Hz]
0	0.266	-	-
20	0.190	0.031	0.168
40	0.139	0.044	0.148
50	0.127	0.046	0.142
60	0.117	0.049	0.136
80	0.101	0.078	0.131
100	0.089	-	-

*True values are slightly different – see next page



- See paper for discussion regarding the calculation of these values

Theoretical Slosh Predictions

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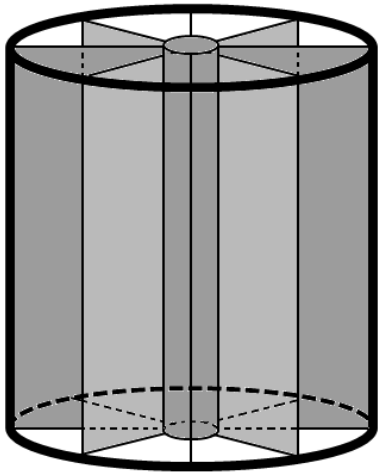
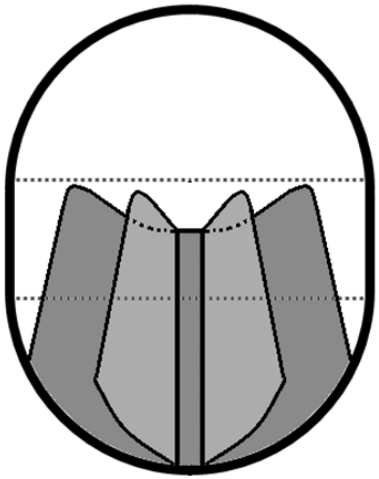
Analytical (1994)



- Thrust: 490 N
- Launch mass: 5,300 kg
- a = 0.009428 g's

Spacecraft at Launch (1997)



- Thrust: 445 N
- Launch mass: 5,574 kg
- a = 0.008141 g's

Theoretical Slosh Predictions: Low-g

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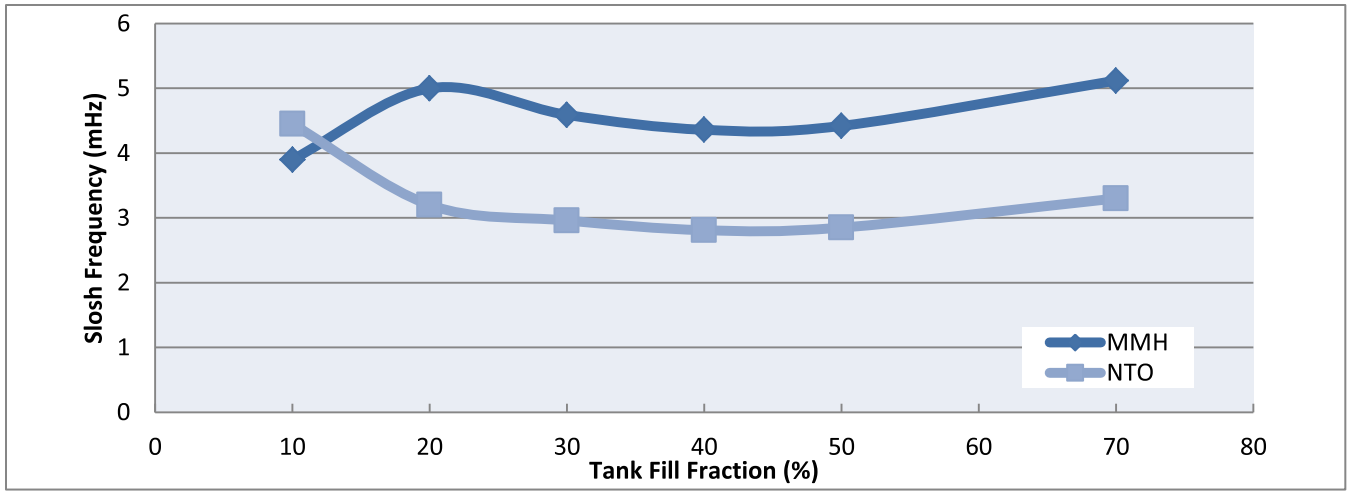
Table 2. Cassini Bipropellant Low-g Slosh Frequency

Tank Fill Fraction [%]	NTO Slosh Frequency [mHz]	MMH* Slosh Frequency [mHz]
10	4.45	6.90
20	3.20	5.00
30	2.96	4.59
40	2.81	4.36
50	2.85	4.42
70	3.30	5.12

*The MMH frequency can be obtained directly by multiplying the NTO slosh frequency by the square root of the ratio of kinematic surface tensions of MMH to NTO, which is 1.55.



Low-g slosh frequencies range from 3.3 – 6.9 mHz

Objective

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Using Cassini telemetry, characterize high-g and low-g propellant slosh frequencies across a range of fill fractions and compare with theoretical predictions

- Where can high-g and low-g slosh be expected to appear?

$$\mathrm{Bo} = \frac{\rho a R^2}{\sigma}$$

Event	Applied Acceleration	Bond Number*	High/Low
Main Engine Burn	0.09** m/s^2	877.5	High-g
Thruster (RCS) Control	0.000723** m/s^2	7.05	Low-g
RWA Control***	-	-	Low-g

*Given for MMH. NTO values are not exactly the same, but close enough for this purpose

**Representative minimum values – acceleration varies with thrust and mass

***Only applied forces are centrifugal forces due to static imbalance of the wheels

Cassini Frequencies

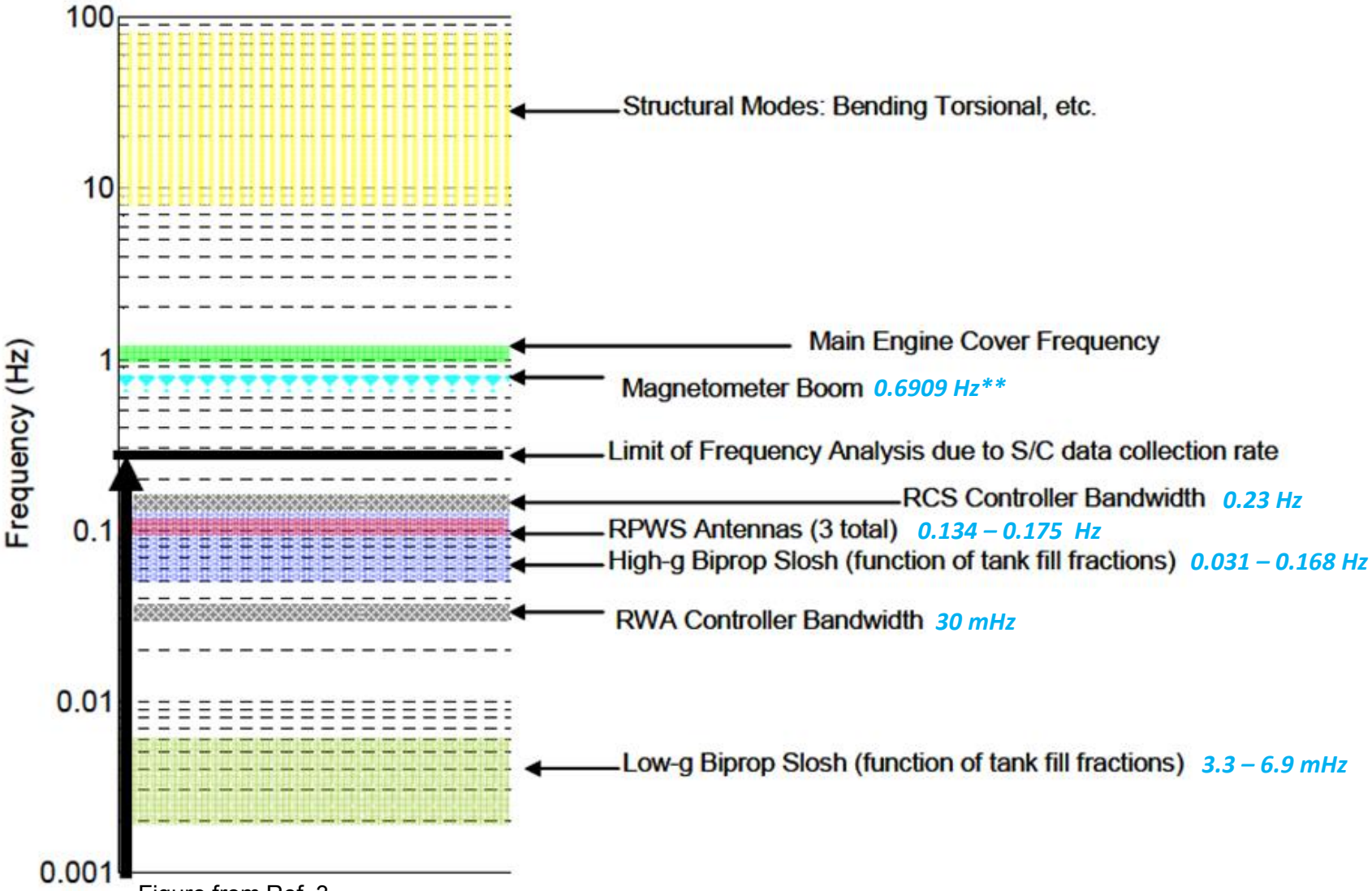
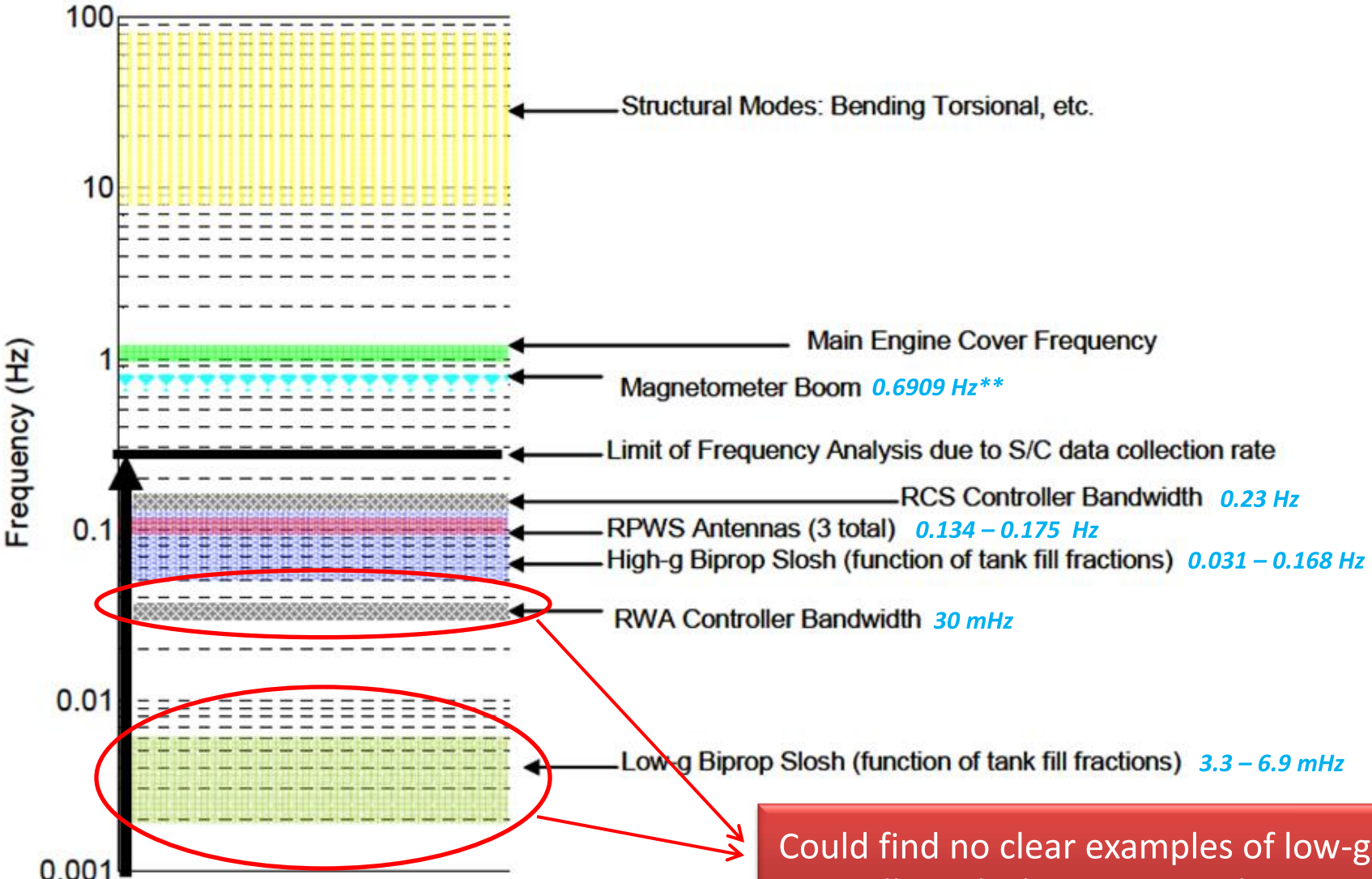


Figure from Ref. 3
**Ref. 4

Cassini Frequencies



Could find no clear examples of low-g propellant slosh in Cassini telemetry

Figure from Ref. 3
*Ref. 3
**Ref. 4

Cassini Frequencies

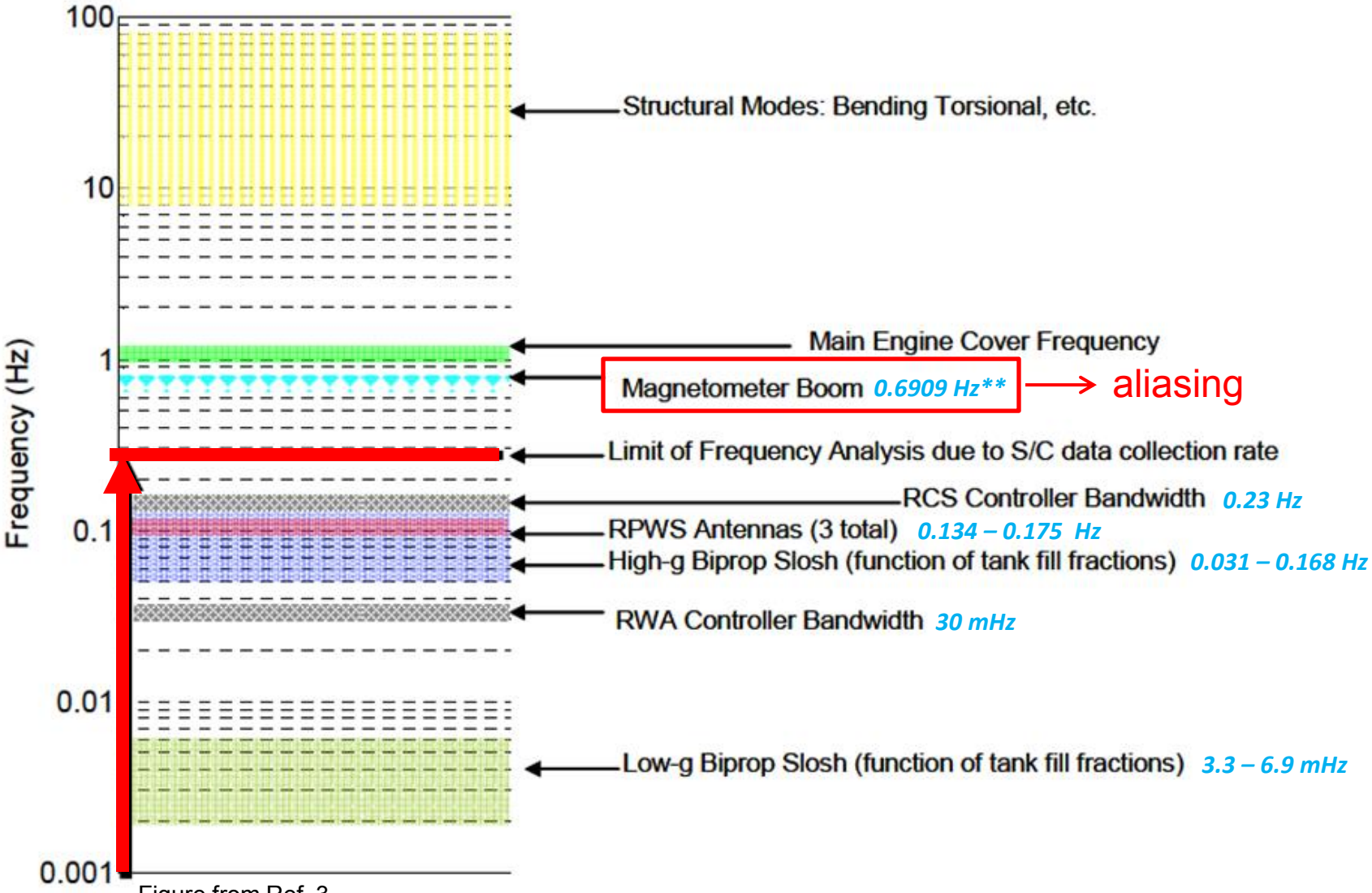
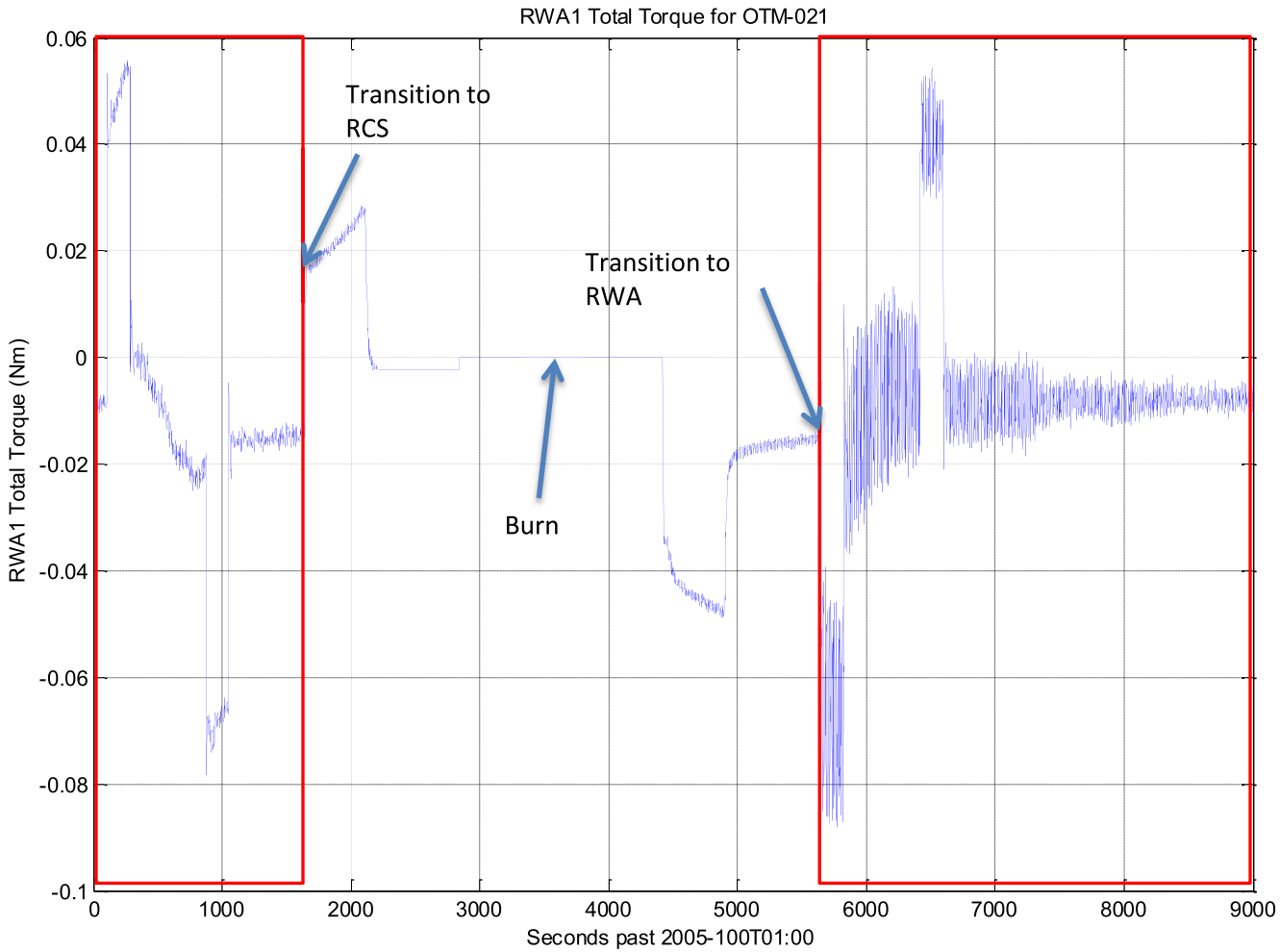


Figure from Ref. 3
*Ref. 3
**Ref. 4

OTM-21

- Main engine burn, 5.833 m/s that lasted 37.35 sec, executed on 4/10/2005
- Propellant slosh damping ~10%, boom ~1%



Cassini Magnetometer Boom

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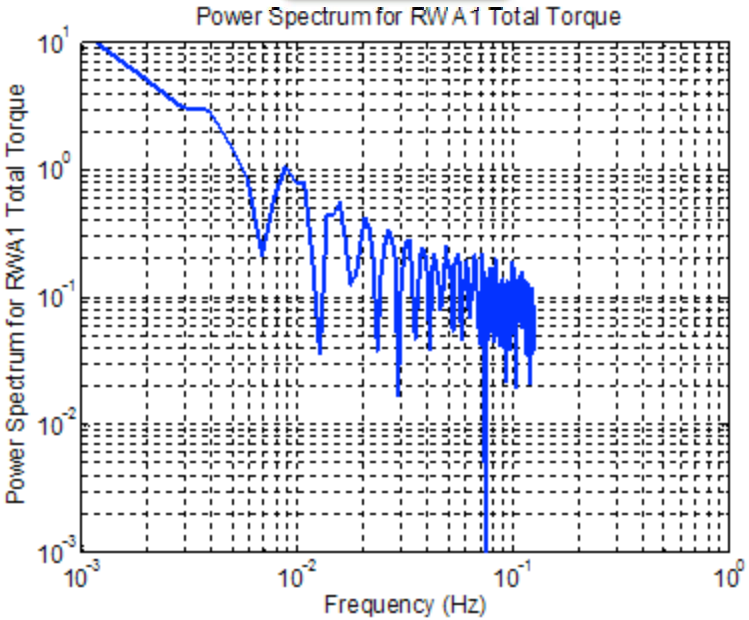
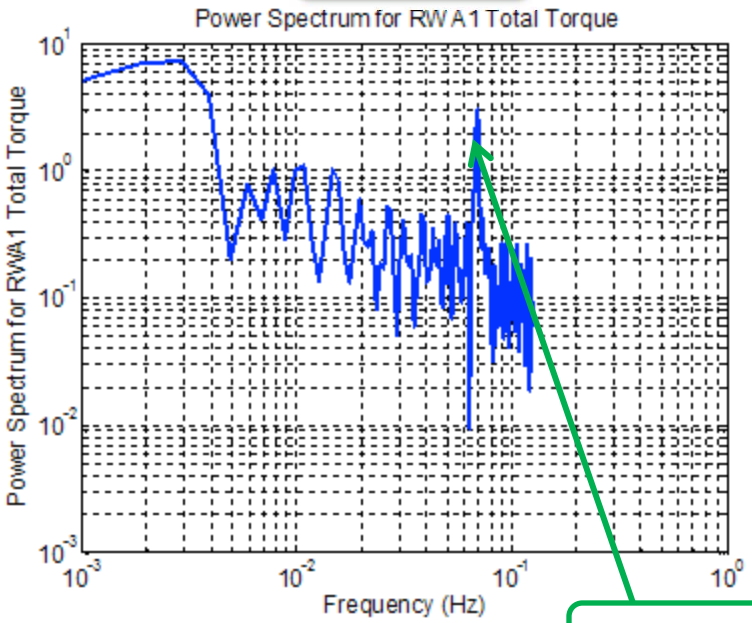
Before



After



0.06836 Hz

- RWA1 Total Torque sampled at 0.25 Hz
- Frequency that aliases to 0.06836 Hz:

0.6816 Hz

- 1% different from ground-measured value of 0.6909 Hz

High-g Fuel Slosh

- Need main engine burns of sufficient duration to get meaningful power spectrum
- Top 5 longest ME burns:

Maneuver	Date [UTC]	Burn Time [min]	NTO Fill Fraction	MMH Fill Fraction
TCM-05 (DSM)*	12/03/1998	86.95	92.6%	93.4%
TCM-09	07/06/1999	7.63	68.0%	68.5%
SOI**	07/01/2004	97.40	60.8%	61.2%
OTM-002 (PRM)***	08/23/2004	50.88	34.6%	34.8%
OTM-144	02/06/2008	3.80	11.2%	11.4%

*Deep Space Maneuver
**Saturn Orbit Insertion
***Periapsis Raise Maneuver

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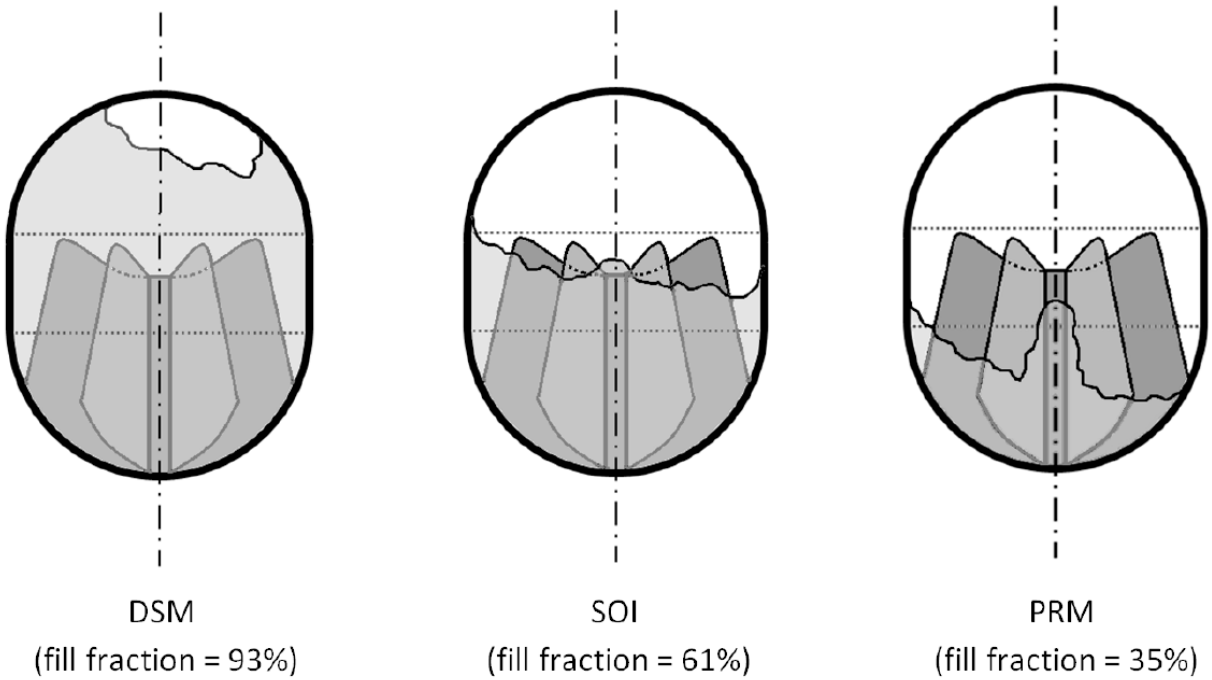
High-g Fuel Slosh



- Take the FFT of the X-axis body rate during the first ~5 minutes of each burn
- NOTE: In all “dynamics”-related telemetry for all “long” ME burns, there are observed limit cycles frequencies (~0.035 Hz) from a <u>stable</u> interaction between nonlinear elements of the engine gimbal and thrust vector control algorithm (see Ref. 1 of the paper for discussion of this limit cycling mode)

High-g Fuel Slosh in Telemetry

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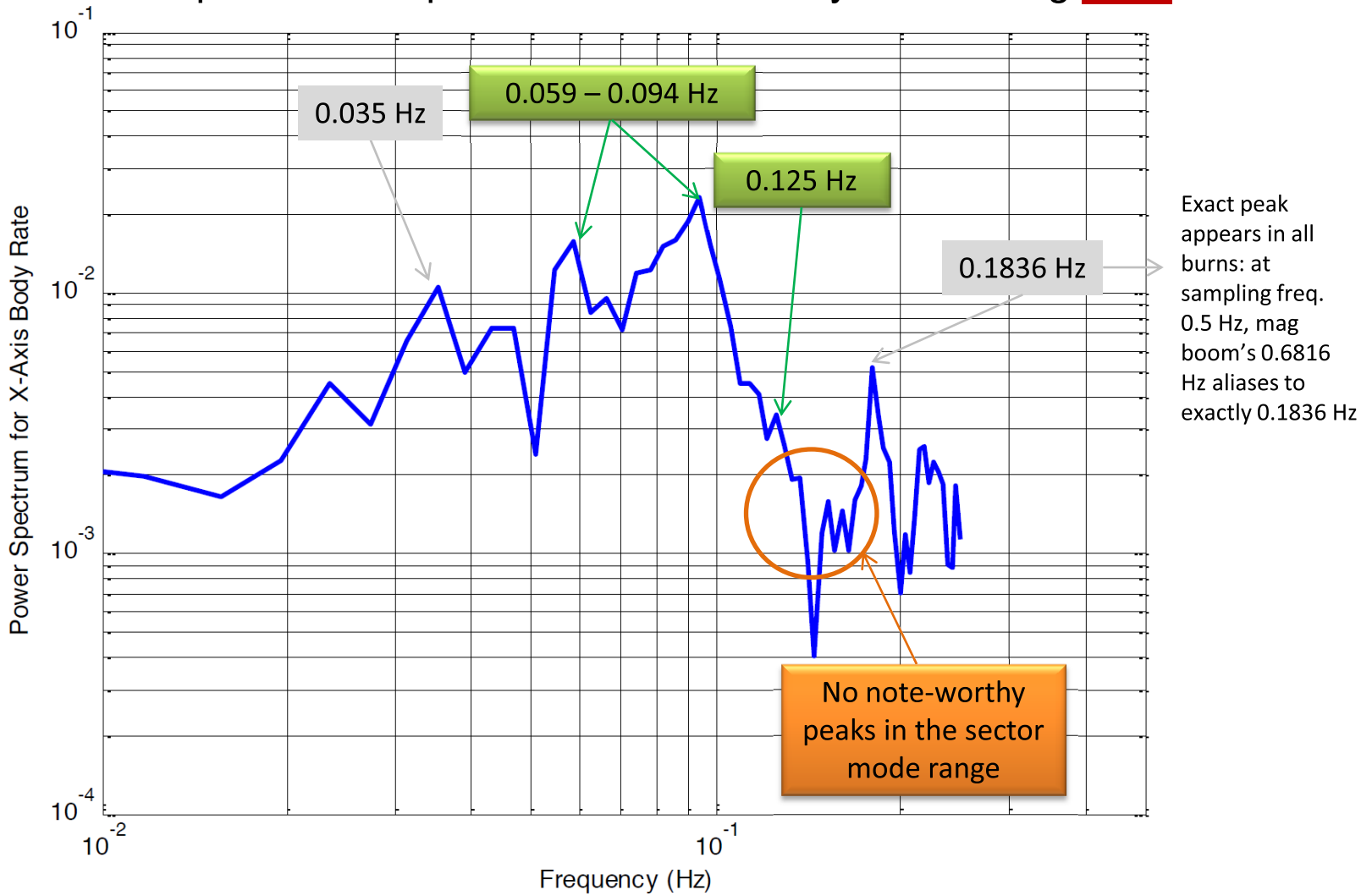
Power Spectrum of Spacecraft's X-axis Body Rate during **DSM**



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High-g Fuel Slosh in Telemetry

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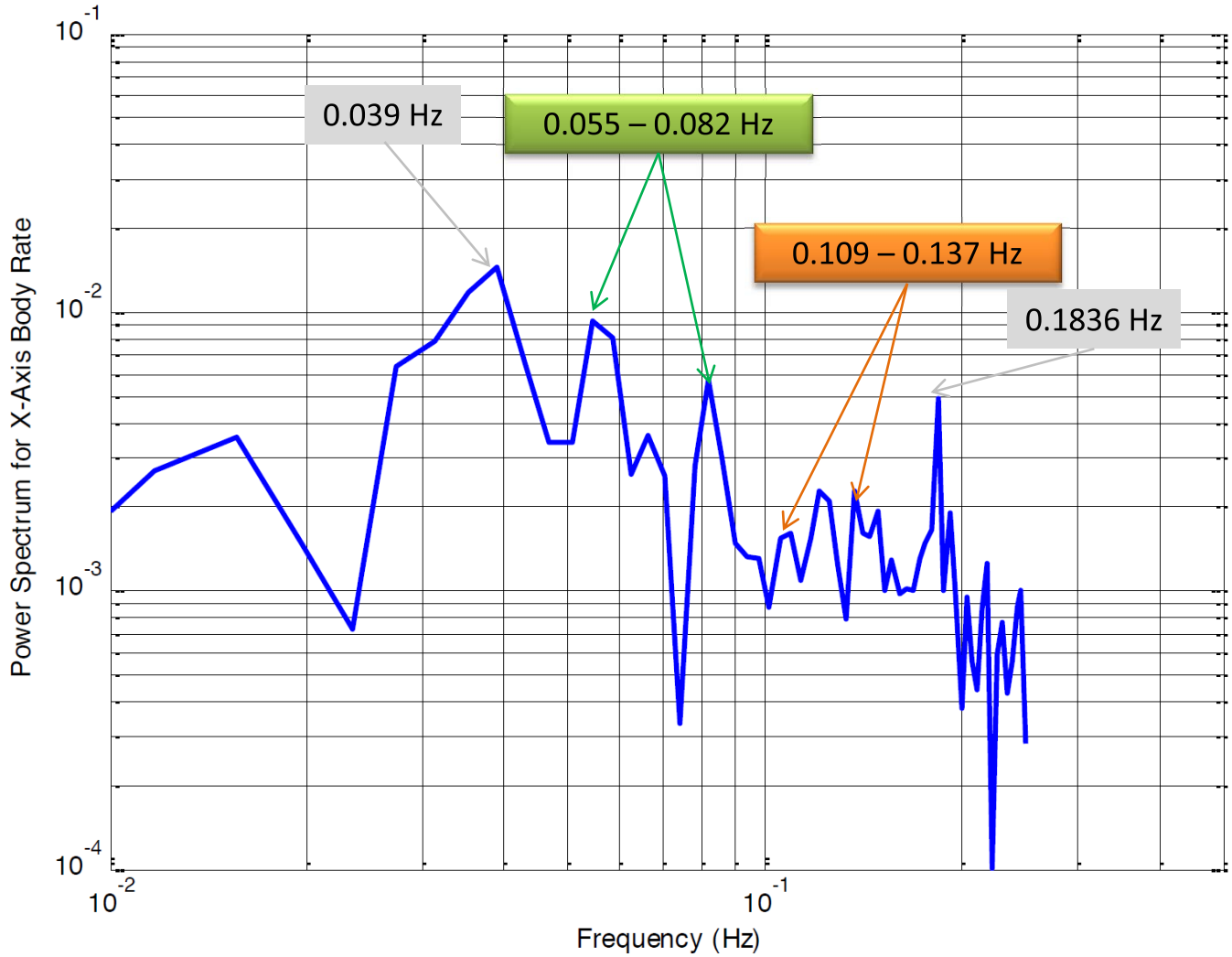
Power Spectrum of Spacecraft's X-axis Body Rate during **SOI**



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High-g Fuel Slosh in Telemetry

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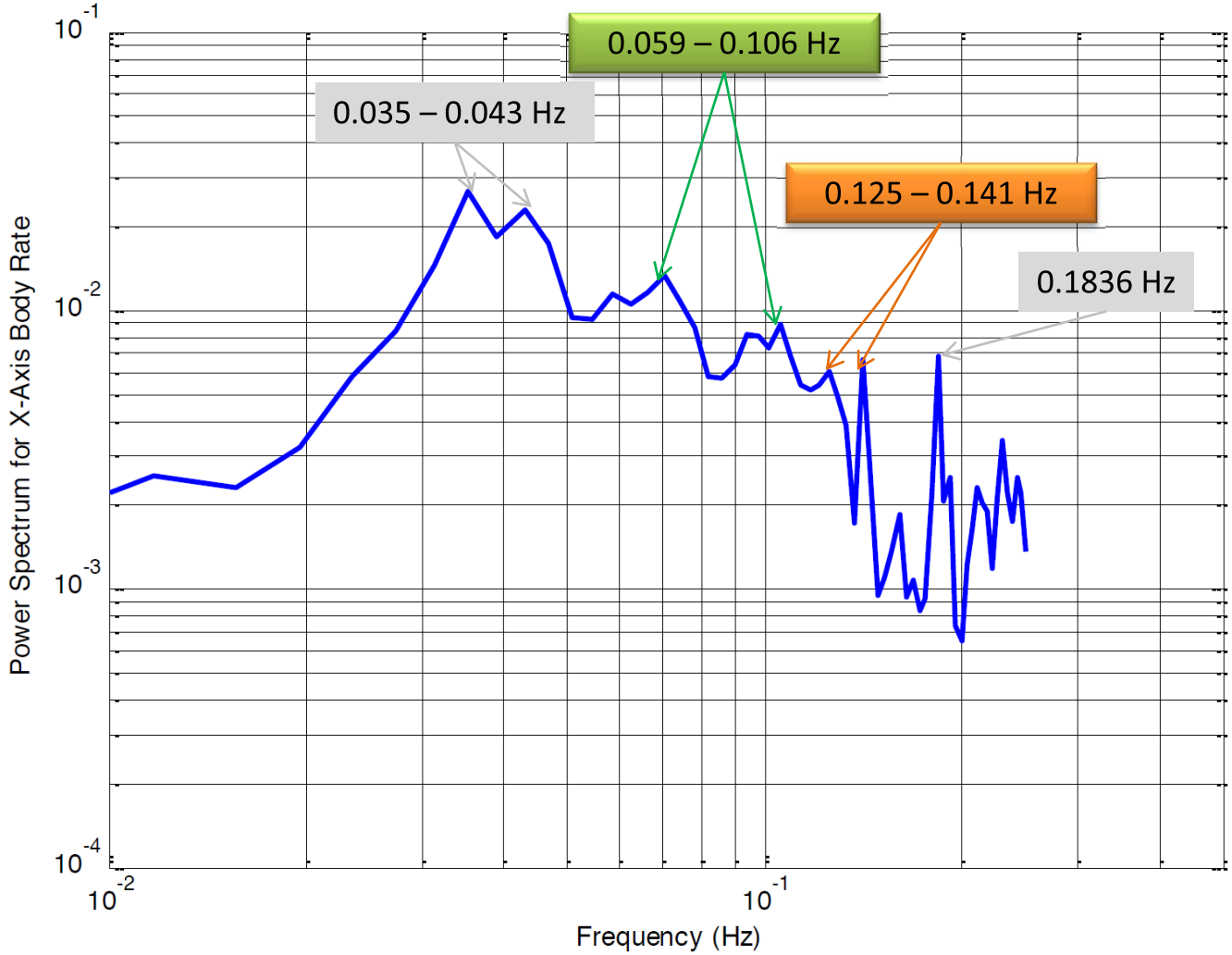
Power Spectrum of Spacecraft's X-axis Body Rate during **PRM**



NOTE: In all "dynamics"-related telemetry for all "long" ME burns, there is observed limit cycles frequencies from a stable interaction between nonlinear elements of the engine gimbal and thrust vector control algorithm (See Ref. 1)

High-g Predictions vs. Observed

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Table 3. Cassini Bipropellant Observed Frequencies for Three Large Main Engine Burns

Burn	Date	Burn Time [min]	Burn Start Fill Fraction [%]	Sector Mode Predicted [Hz]	Sector Mode Observed [Hz]	Full Tank Mode Predicted [Hz]	Full Tank Mode Observed [Hz]
DSM	12/3/98	86.9	93	*	*	0.077 (1st) 0.130 (2nd)	0.059–0.094 0.125
SOI	7/1/04	97.4	61	0.124 (1st) 0.146 (2nd)	0.109–0.137	0.0697	0.055–0.082
PRM	8/23/04	50.9	35	0.138 (1st) 0.162 (2nd)	0.125–0.141	0.077	0.059–0.106

*The Cassini PMD is completely submerged by the liquid at this fill fraction. In this condition, the sector mode disappeared. The full-tank mode frequency should approach that of a "clean tank".

Predictions are within a few percent (5 – 6%) for both sector and full-tank modes at high fill fractions

PRM has errors >10% for both sector and full-tank modes…but at PRM, all the fuel is in the spherical cap (not considered in predictions)

NOTE: See paper for discussion of *which* prediction methods produced the closest estimate to the observed

Conclusions

- Due to low telemetry sampling rate and effectiveness of the PMD, it was challenging to find examples of fuel slosh in telemetry
  - Gyro data at high frequency, if available, would be beneficial
- Low-g fuel slosh was unidentifiable because the frequencies are all well below the bandwidth of both RCS and RWA controllers
  - Low-g slosh disturbance did not degrade S/C pointing stability performance. The S/C stability requirements are met by a factor of >5 (see Ref. 3)
- Predictions for high-g full-tank and sector modes are good (5 – 6%) at higher fill fractions
  - More than 163 main engine burns (as per 2/24/14) were executed sucessfully and with high accuracy
- Predictions for high-g full-tank and sector modes deteriorate (>10%) at low fill fractions
  - At low fill fractions, all fuel is in the spherical cap, which the analytical models do not include
- Observed frequency of magnetometer boom was predicted within 1% of ground-based measurements

Presentation References

1. Lee, Allan Y. and Hanover, Gene, “Cassini Spacecraft Attitude Control System Flight Performance,” Paper AIAA-2005-6269, *Proceedings of the AIAA Guidance, Navigation, and Control Conference, and Exhibit*, San Francisco, CA, Aug. 15–18, 2005.
2. http://mars.jpl.nasa.gov/mgs/movpics/atlo_pics/comppics.html
3. Pilinski, E. and Lee, A.Y., “Pointing Stability Performance of the Cassini Spacecraft,” Journal of Spacecraft and Rockets, Volume 46, No. 5, September-October, 2009, pp. 1007–1015.
4. Norton, R.L., “Revised Cassini Magnetometer Boom Frequency Sensitivity Analysis,” Jet Propulsion Laboratory, IOM 3541-94-228 dated November 9, 1994.
5. Dodge, F. T., “The New “Dynamic Behavior of Liquids in Moving Containers,” Southwest Research Institute, San Antonio, Texas, 2000 (this is an update of NASA SP-106 whose original authors are Norm Abramson, Douglas Michel, George Brooks, and Helmut Bauer).

See paper for complete list of references. The numbering will not be the same.

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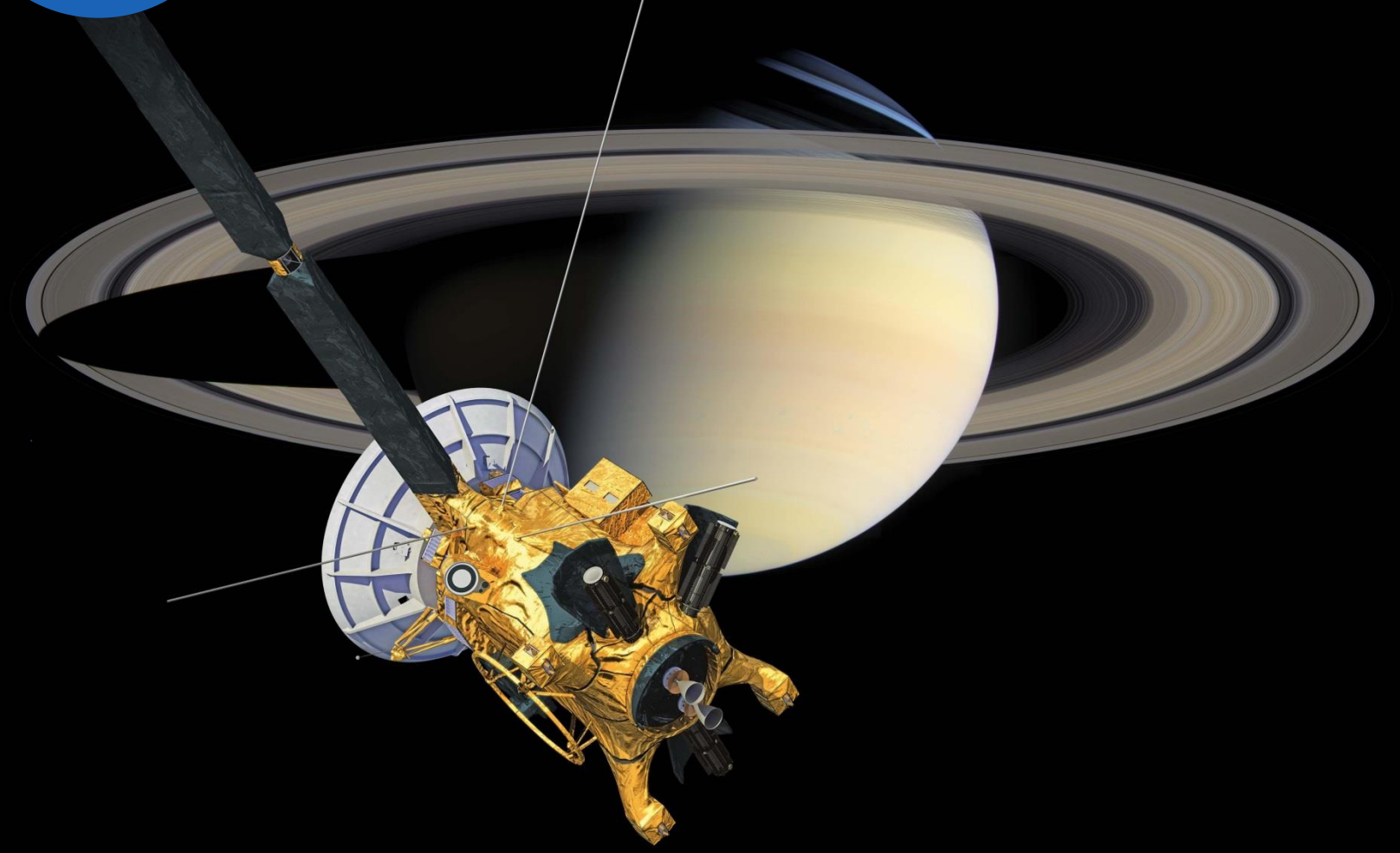
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