Estimation of Titan Atmosphere Density By Cassini SCO AACS Operations Team†

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Acronyms

AACS	Attitude and Articulation Control Subsystem
CAD	Computer-aided Design
DSMC	Direct Simulation Monte Carlo
EME	Earth Mean Equator (J2000)
FSW	AACS Flight Software
GG	Gravity Gradient Torque
GSW	Ground Software
HASI	Huygens Atmospheric Science Instruments
INMS	Ion and Neutral Mass Spectrometer
ITAR	International Traffic in Arms Regulations
MEA	Main Engine Assembly
MLI	Multi-layer Insulation
RSS	Root Sum (of) Squares
RTG	Radio-isotope Thermo-electric Generator
RTI	Real Time Interrupt (125 msec)
S/C	Spacecraft
SCO	Spacecraft Operations Office
TCA	Titan Closest Approach
TMC	Target Motion Compensation

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Agenda

- Introduction
- Density reconstruction methodology – Underlying principles
  - Error Analysis – Uncertainty of the estimated density
- AACS data from two selected Titan flybys:
  - Titan-16 (950 km) – Prime science was Radar
  - Titan-21 (1000 km) – Prime science was INMS
- Estimated Titan atmosphere density of all low-altitude† Titan flybys
  - Empirical modeling of density as a function of altitude
- Estimated Titan atmosphere density of all INMS-centric low-altitude Titan flybys
  - Empirical modeling of density as a function of altitude
- Summary and Conclusions
- Backup materials
  - HASI data (Jan 14, 2005, Refs. 14–15)
  - NASA Langley assessment of Titan-A data

†Altitude ≤1290 km

History: Detection of Leaky Thrusters

- The Cassini spacecraft flew-by the Earth in 1999
  - If one of the eight prime thrusters leak (e.g., stuck open), the expulsing hydrazine will impart angular momentum on the S/C. In response to the resultant attitude control error, appropriate thrusters will be fired to maintain the commanded attitude:
    - Obviously, the draining of hydrazine cannot be allowed to persist indefinitely
    - The trajectory of the S/C might also be altered by these thrusters' firing
- A requirement in the Cassini Project Policy and Requirement document (CAS-699-004):
  - Section 4.2.9.6 *Earth Swing-by Requirements*
    - "Spacecraft fault protection shall be designed to detect and correct thruster level leakage that would otherwise generate a spacecraft translational velocity increment of ≥0.5 m/s for any continuous five day cruise..."
- In response to this requirement, Cassini AACS has in its Launch FSW a capability to estimate external torque imparted on the S/C
  - The external torque could come from the leaky thruster (see Ref. 4)
  - Or it might come from the Titan atmospheric drag during a Titan flyby

AACS Reconstruction of Titan Atmospheric Torque and Density

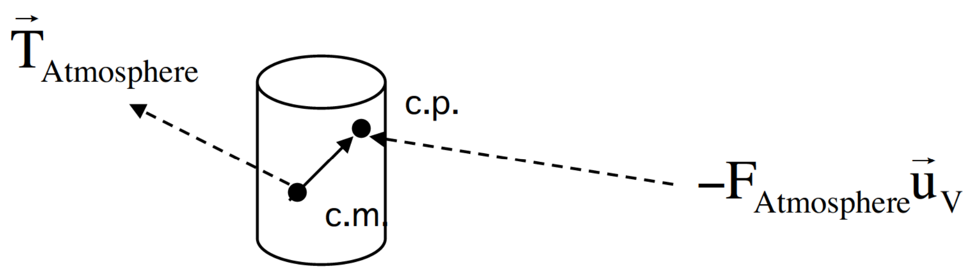
- One first estimate the magnitude of the Titan atmospheric torque imparted on the spacecraft during a Titan flyby
  - Attitude control data used is either thrusters' on-time or reaction wheel spin rates. See Refs. 1–3
- Given the estimated torque, the Titan atmospheric density could be computed accordingly
- Similar estimation methodologies had been used by others
  - Magellan used RWA rate data to characteristic the upper atmosphere of Venus. See Ref. 5
  - Mars Pathfinder used accelerometer data to estimate Mars atmosphere density. See Ref. 6
  - Cassini HASI also used accelerometer data to estimate Titan atmosphere density. See Refs. 13–15

Torque due to Titan's Atmospheric Drag

$$\vec{T}_{Atmosphere}(t) = C_d \frac{1}{2}\rho(t) \times V^2(t) \times A_{Project}(t) \times [\vec{cp}(t) - \vec{cm}] \times \{-\vec{u}_V(t)\}$$

- Nomenclatures:

$T_{atm}(t)$	= Torque vector imparted on S/C	[Nm]
C_d	= Drag coefficient ≈ 2.1±0.1	[-]
V(t)	= S/C Titan-relative flyby velocity	[m/s]
$A_{project}(t)$	= Projected S/C area	[m^2]
ρ(t)	= Density of the Titan atmosphere	[kg/m^3]
cp(t)-cm	= Offset between S/C's c.m. and c.p. vectors	[m]
$u_V(t)$	= S/C's velocity unit vector (in spacecraft coordinate frame)	[-]



Ground Software for Density Estimation

- A ground software is developed to compute the angular momentum vector imparted on the S/C due to the atmospheric torque:

$$\int_0^t \vec{\mathrm{T}}_{\mathrm{Atmosphere}}\, d\tau = \int_0^t \left\{ \mathrm{I}\dot{\vec{\omega}} + \vec{\omega} \times (\mathrm{I}\vec{\omega} + \cancelto{0}{\vec{\mathrm{H}}_{\mathrm{RWA}}}) - \vec{\mathrm{T}}_{\mathrm{Thruster}} - \cancelto{0}{\vec{\mathrm{T}}_{\mathrm{RWA}}} \right\} d\tau$$

$$= \mathrm{I}[\vec{\omega}(t) - \vec{\omega}(0)] + \int_0^t \vec{\omega} \times \mathrm{I}\vec{\omega}\;\; d\tau \; - \int_0^t \vec{\mathrm{T}}_{\mathrm{Thruster}}\;\; d\tau$$

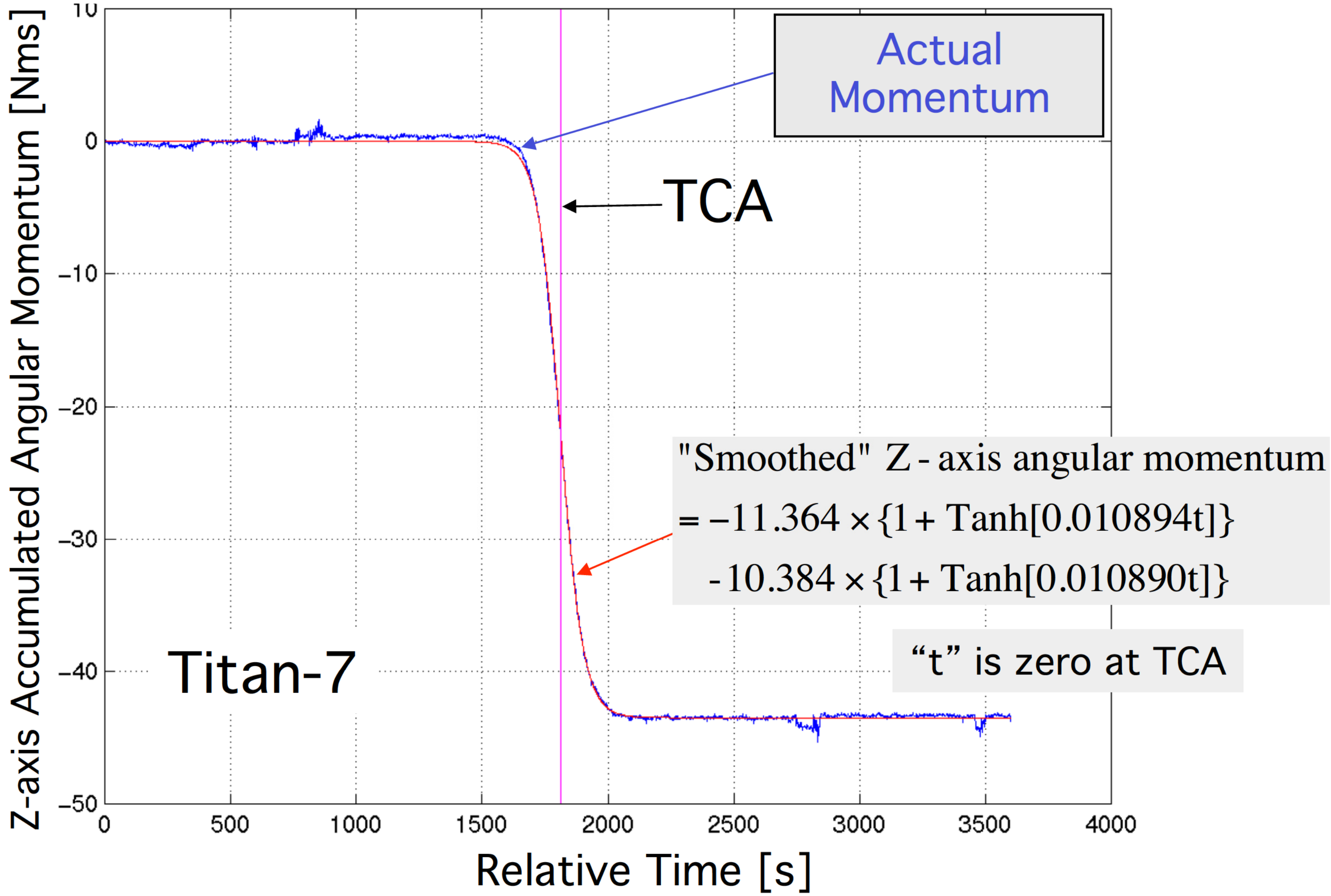
- All quantities on the right-hand-side of this equation are available from either telemetry or ground estimated values of S/C parameters:
  - Telemetry:
    - $\omega(t)$ are available from the on-board attitude estimator (Kalman-Bucy filter)
    - Eight thrusters' on-time are available from the FSW. They are used to estimate the per-axis thruster-based angular momenta imparted on the S/C using:
      - The thrusters' moment arms (are known from pre-launch measurements)
      - Thruster magnitude are predicted via GSW and inflight estimation. See Refs. 9
      - Thrusters' tail-off impulse are inflight estimated. See Ref. 10
  - Parameters:
    - Inertia tensor (I) and S/C's center of mass, etc. are estimated via ground software tools. See also flight experience documented in Refs. 8–9

Ground Software for Density Reconstruction (Continued)

- The accumulated per-axis angular momentum is differentiated with respect to time to yield the per-axis atmospheric torque on S/C as a function of time
  - But the data is too “noisy” to be differentiated directly
  - In order to differentiate the accumulated per-axis angular momenta accurately, the data is first fit by the sum of two hyperbolic tangent functions†
    - The per-axis torque is determined accordingly
  - See next page for an example

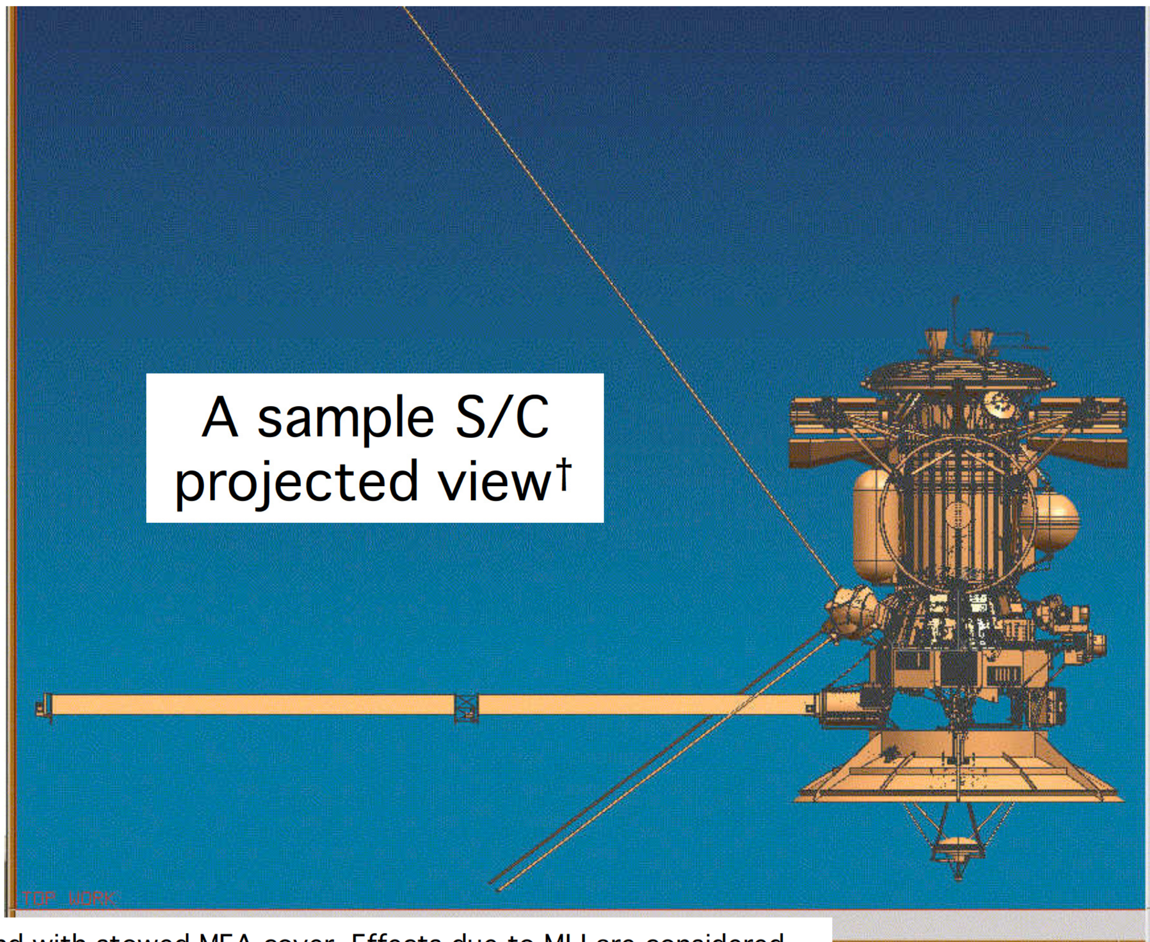
†Obviously, this is not the only “smoothing” methodology.

Reconstructed Z-Axis Accumulated Momentum



Estimation of Projected Area and C.P. Location

- A total of 144 projected views of the spacecraft were used to estimate the projected area and c.p. location as functions of azimuth and elevation angles (12×12=144)



†Without the Probe and with stowed MEA cover. Effects due to MLI are considered

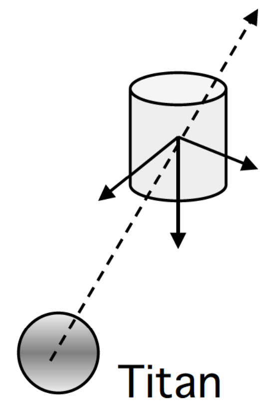
Titan Gravity Gradient (GG) Torque

- Titan gravity gradient torque is a function of both the distance between the c.m. of the S/C and Titan, and the S/C's attitude relative to the S/C-to-Titan vector
- With the worst-case S/C's orientation, and when the S/C is at TCA, the G.G. torque is:

$$T_{GG\text{-}MAX} = \frac{3}{2}\mu_{Titan}\frac{(I_{max} - I_{min})}{d^3}$$

where:

μ_{Titan}	$= GM_{Titan} \approx 8.9782 \times 10^3$ km^3/sec^2 (see Ref. 7)
d	= distance between Titan's c.m. and S/C's c.m.
	= 950+2575 km (at closest approach, representative)
I_{max}	$= I_{XX} \approx 7200$ kg-m^2 (representative)
I_{min}	$= I_{ZZ} \approx 3700$ kg-m^2 (representative)
$T_{GG\text{-}MAX}$	≈ 0.001076 Nm (very small)



Magnetic, Solar Radiation, and RTG Torque

- Magnetic disturbance torque results from the interaction between the S/C's residual magnetic field and the magnetic field of Saturn

$$T_{magnetic} = M_{Moment\text{-}arm} \times \frac{B_{Saturn}}{R_{ps}^{3}}$$

where:

$M_{Moment\text{-}arm}$ = S/C magnetic moment arm = 1.4 Amp-m^2 (see Ref. 1)

B_{Saturn} = Magnetic flux density on the surface of Saturn

= 8.3e-5 kg-s^{-2}-Amp^{-1} (Ref. 1)

R_{ps} = distance between Saturn and S/C in planet radii

= 20.3 (at Titan)

$T_{Magnetic}$ ≈ ***1.38e-8 Nm*** (very small)

- Combined solar radiation torque and RTG torque ≈ ***2e-6 Nm*** (very small) (Ref. 1)

Estimation Uncertainties of Components in Torque–Density Equation (see Refs. 3, 11–12)

- Assumptions:
  - Various terms in equation are uncorrelated except
    - The projected area and the cp-cm moment arm are fully correlated
  - The equation has a squared velocity term. Hence the factor "4" in the error expression

$$\vec{T}_{Atmosphere} = C_d \frac{1}{2} \rho V^2 A_{Project} (\vec{cp} - \vec{cm}) \times (-\vec{u}_V)$$

$$\left[\frac{\sigma_\rho}{\rho}\right]^2 = \left[\frac{\sigma_T}{T}\right]^2 + \left[\frac{\sigma_{C_D}}{C_D}\right]^2 + 4 \times \left[\frac{\sigma_V}{V}\right]^2 + \left[\frac{\sigma_{A_P}}{A_P} + \frac{\sigma_{|cp\text{-}cm|}}{|cp\text{-}cm|}\right]^2$$

Uncertainties	Estimation Uncertainty 1σ [%]
Projected area (σ_{Ap}/A_p)[a]	0.65
Moment arm ($\sigma_{cp\text{-}cm}/\|cp\text{-}cm\|$)[b]	1.97
Drag coefficient (σ_{CD}/C_D)[c]	1.6
Flyby velocity uncertainty (σ_V/V)[d]	0.005
Estimated atmospheric torque (σ_T/T)[e]	4.9
Density Uncertainty (σ_ρ/ρ)	5.6

[a]Estimated error of projected area is ±0.35 m^2. Nominal value is >18 m^2. That is, 3σ is <1.95%.

[b]The 3σ of c.m. location knowledge requirement is 5 cm. Estimated error of c.p. is ±3.2 cm. Nominal value of |cp-cm| is >100 cm. Hence, the 3σ error of |c.p.-c.m.| is RSS(5,3.2)/100 = 5.9%.

[c]Experimental results are bounded by 2.1±0.1. That is, 3σ is 4.8%. NASA Langley's independent estimate (via DSMC) is 2.02.

[d]Nav. team has estimated that 1σ velocity error is 0.3 m/s. Nominal flyby velocity is 6000 m/s. Hence, 1σ = 0.005%.

[e]See next page.

Estimation Uncertainty of Torque Imparted on Spacecraft (see Refs. 3, 8–10)

- The spacecraft attitude at the TCA of most Titan flybys was quiescent

$$\int_0^t \vec{T}_{Atmosphere} d\tau = \int_0^t \left\{ I\dot{\vec{\omega}} + \vec{\omega} \times I\vec{\omega} - \vec{T}_{Thruster} \right\} d\tau = -\int_0^t \vec{T}_{Thruster}\, d\tau = -\sum_{i=1}^{8} F^i_{thruster}(t) \times \text{On-time}^i_{thruster}(t) \times L^i_{thruster}$$

$$\text{Momentum imparted on S/C due to Drag} = -\text{Momentum imparted on S/C due to thrusters' firing}$$

$$\text{Momentum imparted on S/C due to drag} \approx \sum_{j=1}^{2} K_j \{(1 + \tanh(k_j t)\}$$

$$\vec{T}_{Atmosphere}(t) = +\sum_{j=1}^{2} k_j K_j \operatorname{sech}^2(k_j t)$$

Uncertainties	Estimation Uncertainty 1σ [%]
Thruster magnitude[a]	1.7
Thruster's tailoff impulse[b]	0.85
Predicted location of thrusters[c]	0.03
Thrusters' on-time telemetry (@ 1-sec interval)[d]	3.3
Curve fitting error[e]	3
Neglected GG, RTG, solar torque[f]	0.02
Estimated torque imparted on the S/C	4.9

[a]The 3 σ estimation requirement of thruster magnitude is better than 5%.

[b]The 3 σ estimation requirement of thruster impulse is better than 2.5%. See also Ref. 10.

[c]The thruster locations are known to better than 1 mm. Smallest moment arm is 123.4 cm. That is, 3 σ is 0.08%.

[d]Telemetry resolution is 1 msec·. Representative smallest thruster firing time is 10 msec in one RTI. Hence, 3 σ is 10%.

[e]Representative curve fitting error.

[f]Estimated magnitude of Titan GG torque is 1.1×10^{-3} Nm (worst S/C attitude and 950-km flyby). It represents about 0.06% of the Z-axis control torque authority.

Comparison of Titan Atmospheric Density Estimation Uncertainties

System	Estimation Uncertainties 3σ [%]	References	Year
HASI	5.7–7.8	13	2003
HASI	10	15	2005
SCO AACS	16.8	1–3, 11–12	2005-07

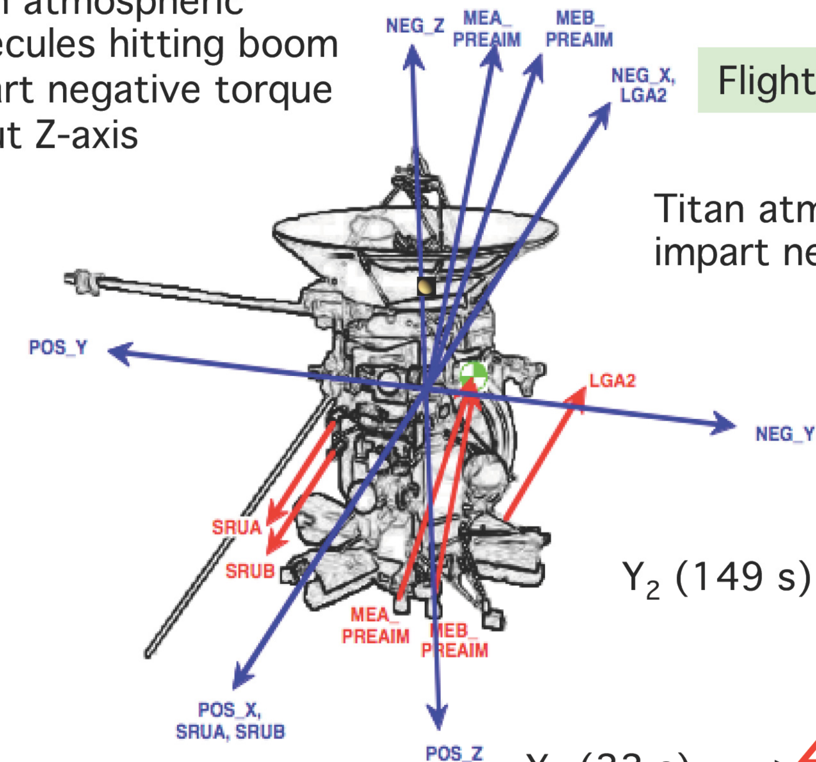
Titan-16 Flyby: Summary

- Titan-16 flyby configurations:
  - Titan Closest Approach (TCA) is 2006-DOY-203T00:25:26
  - TCA Altitude (km): 950 km
  - Thruster control: From TCA-51.4 min. to TCA+59.2 min.
    - Dead-band = [2, 2, 20] mrads for about 79 min.
    - Dead-band = [2, 2, 2] mrads for the last 32 min.
  - Base attitude pair at TCA:
    - Primary: -Z to Titan
    - Secondary: -X to Titan RADAR IVD
  - MEA cover was open
- Peak thruster duty cycle = 62% (Y2/Y4)
- Reconstructed Titan atmosphere density at TCA (950 km)
  - Density = 2.42×10^{-9} kg/m^3

Titan-16 Flyby Orientation

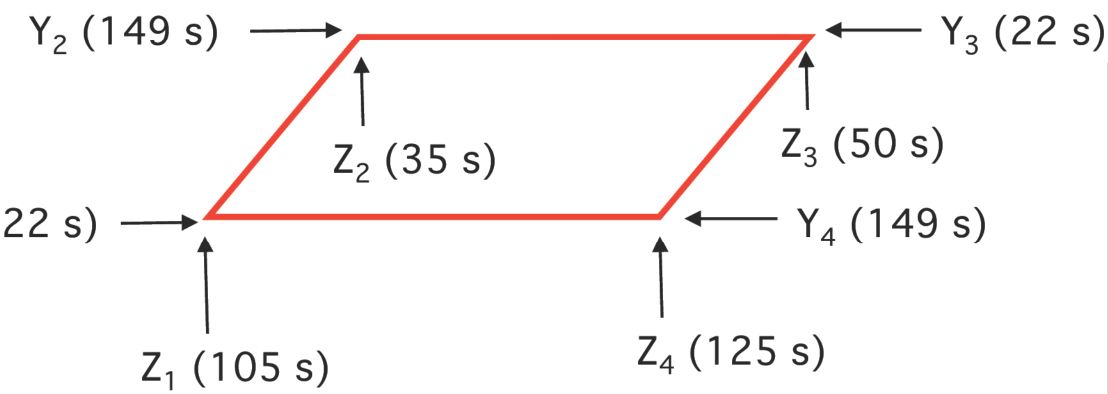
Neg Z to Titan

Titan atmospheric molecules hitting boom impart negative torque about Z-axis

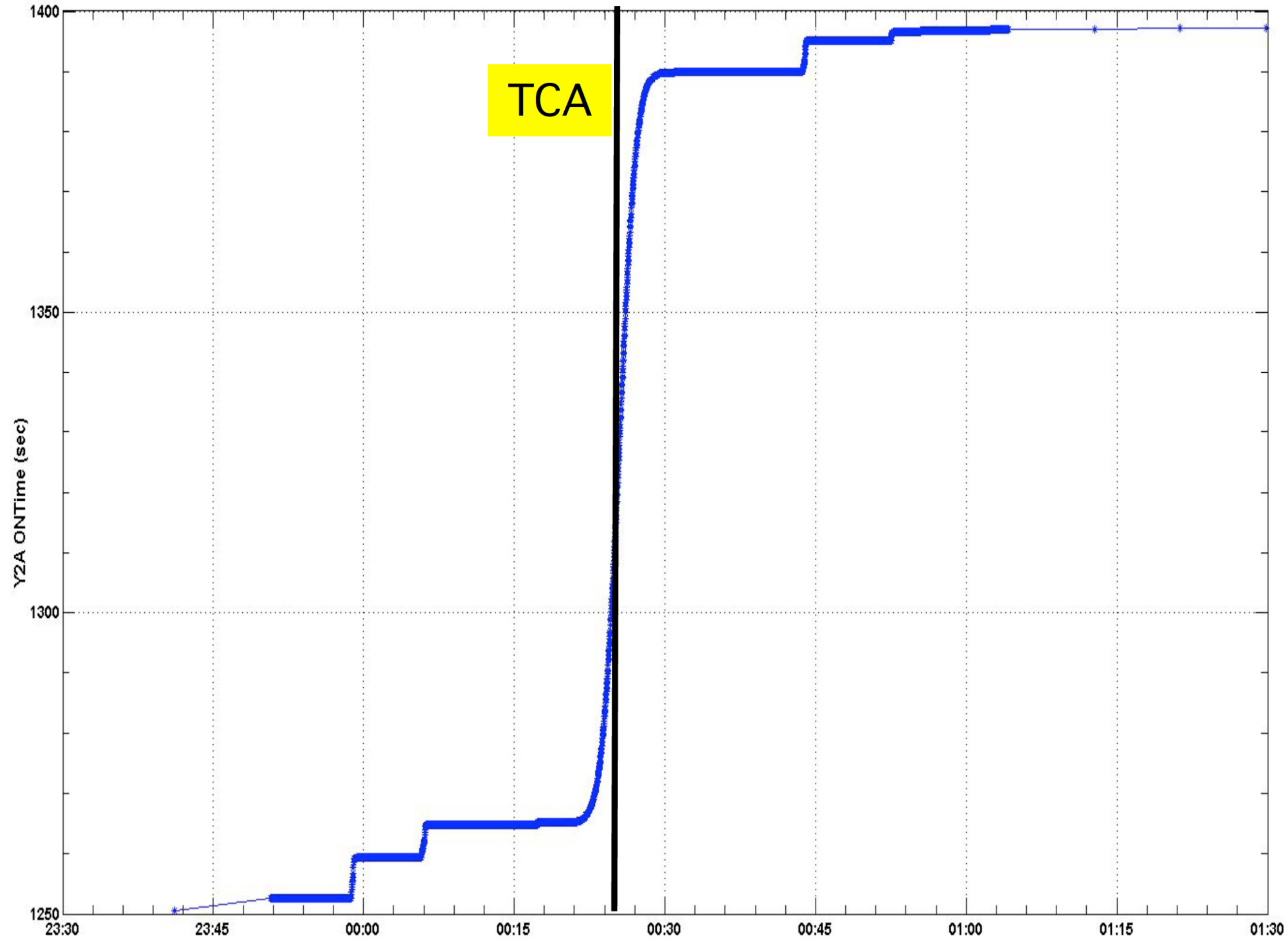


Flight Path Direction (-X-axis)

Titan atmospheric molecules hitting HGA impart negative torque about Y-axis

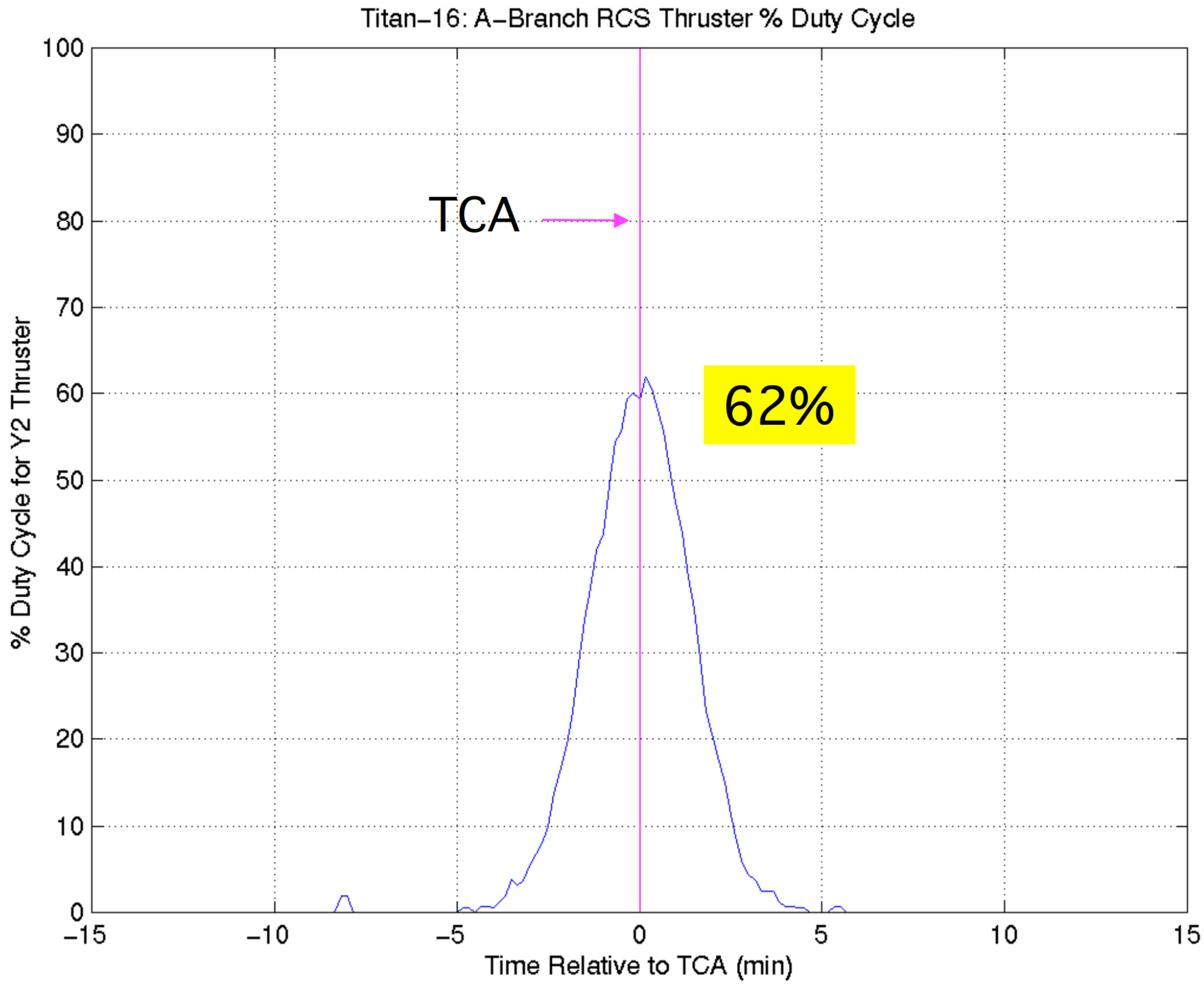


Y2A Thruster On-time



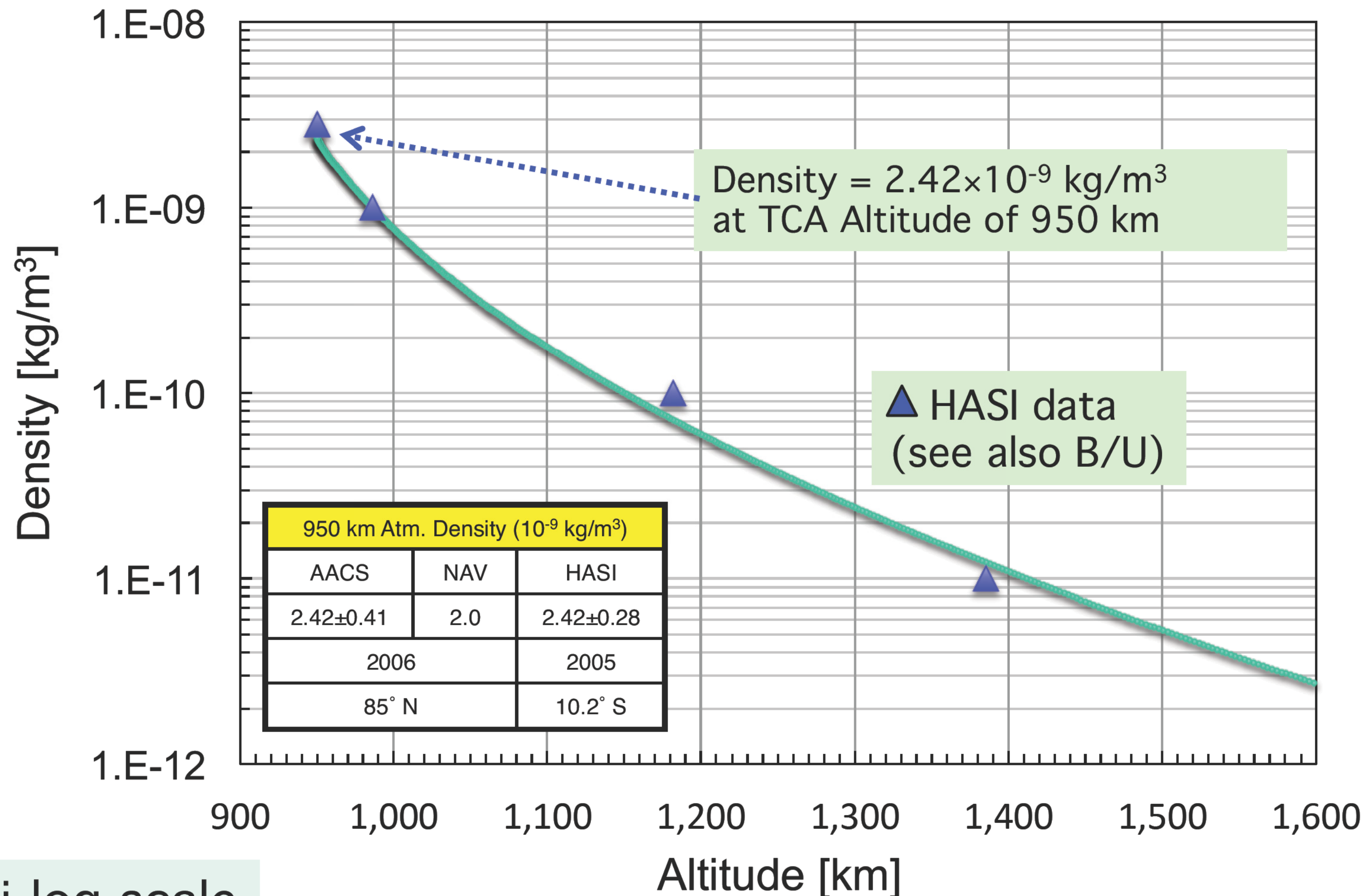
TCA is at 2006-DOY-203T00:25:26

Y2-Y4 Thruster Pair Duty Cycle



Titan 16 Reconstructed Density

- TCA was at 2006-DOY-203T00:25:26 at an altitude of 950 km with a latitude of 85° North



950 km Atm. Density (10^{-9} kg/m³)		
AACS	NAV	HASI
2.42±0.41	2.0	2.42±0.28
2006		2005
85° N		10.2° S

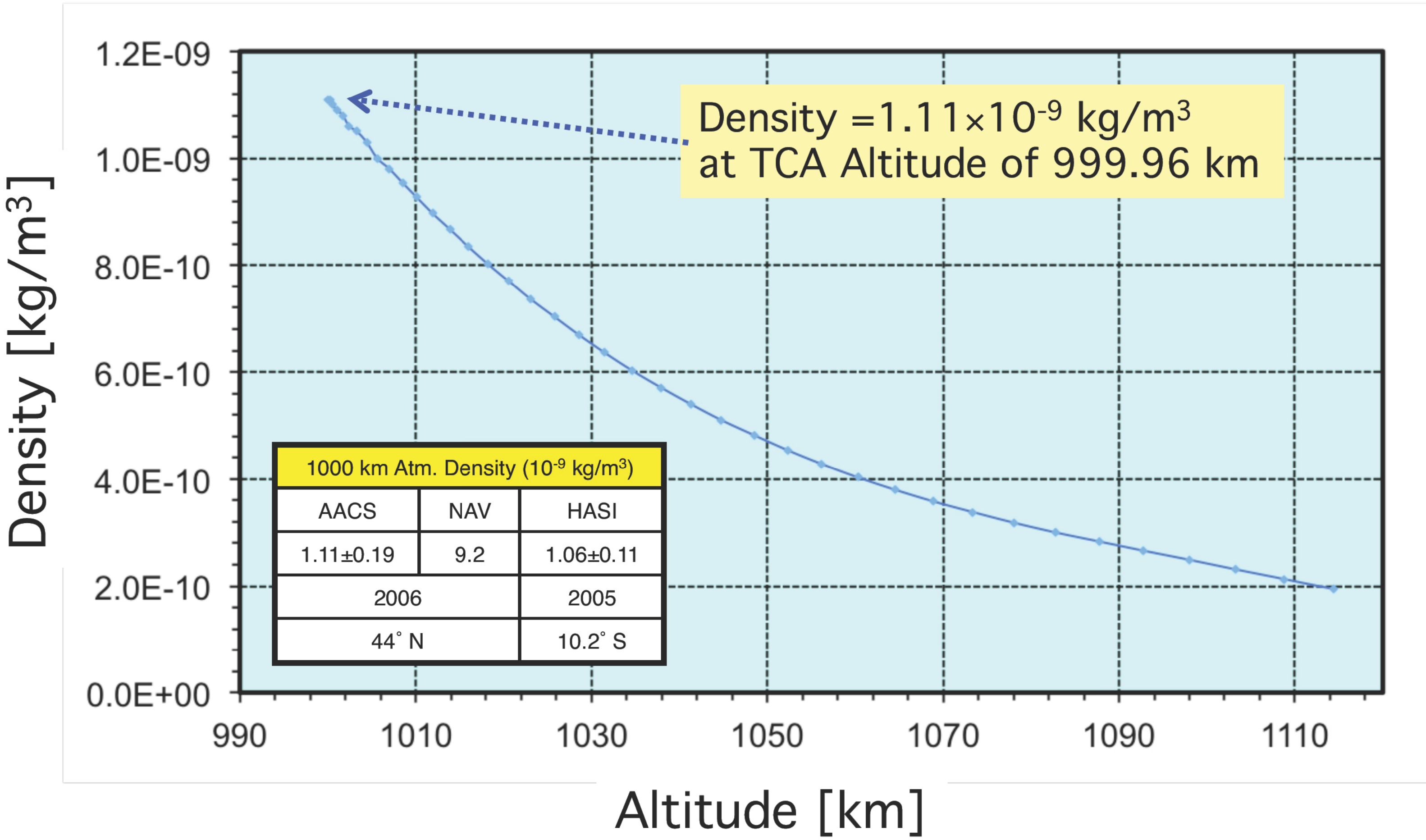
Semi-log scale

Titan-21 Flyby: Summary

- Titan-21 flyby configurations:
  - Titan Closest Approach (TCA) is 2006-DOY-346T11:41:30.8
  - TCA Altitude (km): 1000 km
  - Thruster control:
    - Dead-band = [2, 2, 20] mrads
  - Base attitude pair at TCA:
    - Primary: -Z-axis to Titan Radar –Z (IVD)
    - Secondary: +X to Titan Radar +X (IVD)
  - MEA cover was open
  - INMS was prime science
- Peak thruster duty cycle = 31% (Y2/Y4)
- Reconstructed Titan atmosphere density at TCA (999.96 km)
  - Density = 1.11×10^{-9} kg/m^3

Titan 21 Reconstructed Density

- TCA was at 2006-DOY-346T11:41:30.8 UTC SCET at an altitude of 999.96 km with a latitude of 44° North



1000 km Atm. Density (10^{-9} kg/m^3)		
AACS	NAV	HASI
1.11±0.19	9.2	1.06±0.11
2006		2005
44° N		10.2° S

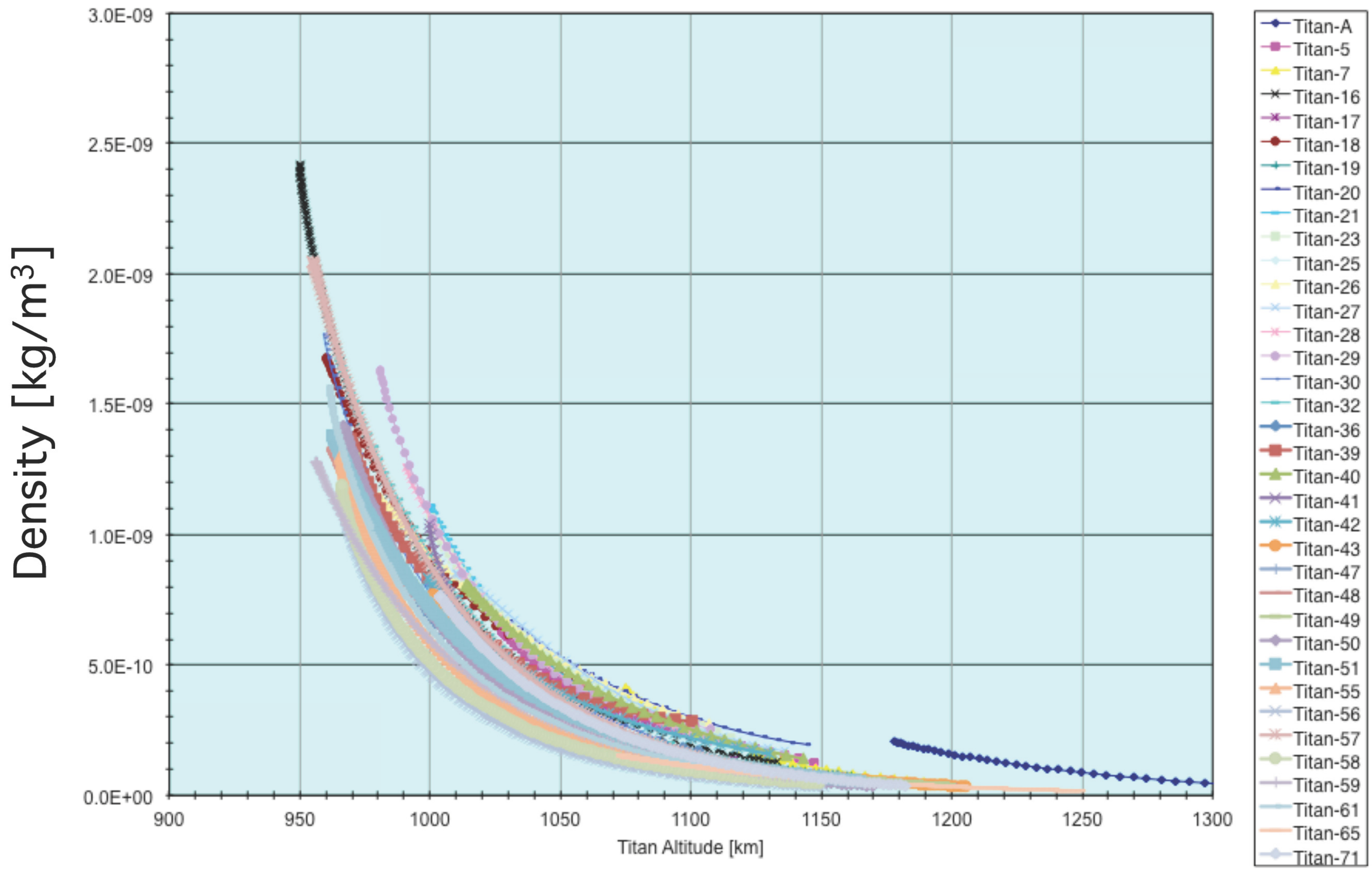
Low-altitude† Titan Flybys (2004–2010)

Flyby	Date/Time	Sequence	TCA [km]	TCA Latitude [°]	Velocity [km/s]	Prime Science	Peak Density [10^-10 kg/m^3]
TA	2004-300T15:30	S05	1174	39	6.1	INMS	2.04
T5	2005-106T19:12	S10	1027.4	74	6.1	INMS	6.36
T7	2005-250T08:12	S14	1074.8	-67	6.1	RADAR	4.13
T16	2006-203T00:25	S22	949.9	85	6	RADAR	24.2
T17	2006-250T20:17	S23	999.5	23	6	INMS	7.62
T18	2006-266T18:59	S24	959.8	71	6	INMS	16.78
T19	2006-282T17:30	S24	979.7	61	6	RADAR	10.6
T20	2006-298T15:58	S25	1029.5	8	6	ORS	6.7
T21	2006-346T11:42	S26	1000	44	5.9	INMS	11.1
T23	2007-013T08:39	S27	1000.3	31	6	RADAR	10.64
T25	2007-053T03:12	S28	1000.4	31	6.2	RADAR	8.24
T26	2007-069T01:49	S28	980.6	32	6.2	INMS	11.49
T27	2007-085T00:23	S28	1009.9	41	6.2	RSS	8.51
T28	2007-100T22:58	S29	990.9	51	6.2	RADAR	12.61
T29	2007-116T21:33	S29	980.8	59	6.2	RADAR	16.34
T30	2007-132T20:10	S30	959.2	69	6.2	RADAR	17.69
T32	2007-164T17:46	S31	964.9	84	6.2	INMS	16.77
T36	2007-275T04:43	S34	973	-60	6.3	INMS	10.59
T39	2007-354T22:58	S36	969.5	-70	6.3	RADAR	13.67
T40	2008-005T21:30	S36	1014	-12	6.3	INMS	8.09
T41	2008-053T17:32	S38	999.7	-34	6.3	RADAR	10.44
T42	2008-085T14:28	S39	999.4	-27	6.3	INMS	8.33
T43	2008-133T10:02	S40	1001.4	17	6.3	RADAR	7.7
T47	2008-324T15:56	S45	1023.4	-22	6.3	ORS	3.07
T48	2008-340T14:26	S46	960.6	-10	6.3	INMS	13.29
T49	2008-356T13:00	S46	970.6	-44	6.3	RADAR	13.05
T50	2009-038T08:51	S47	966.8	-34	6.3	INMS	14.15
T51	2009-086T04:44	S49	962.6	-31	6.3	INMS	13.81
T55	2009-141T21:27	S50	965.7	-22	6	RADAR	13.3
T56	2009-157T20:00	S50	967.7	-32	6	RADAR	10.81
T57	2009-173T18:33	S51	955.1	-42	6	INMS	20.46
T58	2009-189T17:04	S51	965.8	-52	6	RADAR/UVIS	11.9
T59	2009-205T15:34	S52	956.2	-62	6	INMS	12.8
T61	2009-237T12:52	S53	970	-19	6	RADAR	15.71
T65	2010-012T23:11	S56	1072.8	-82	5.9	INMS/RADAR	1.52
T71	2010-188T00:23	S61	1005	-56	5.9	INMS	7.66

† Altitude ≤1290 km * INMS flybys are highlighted in light blue.

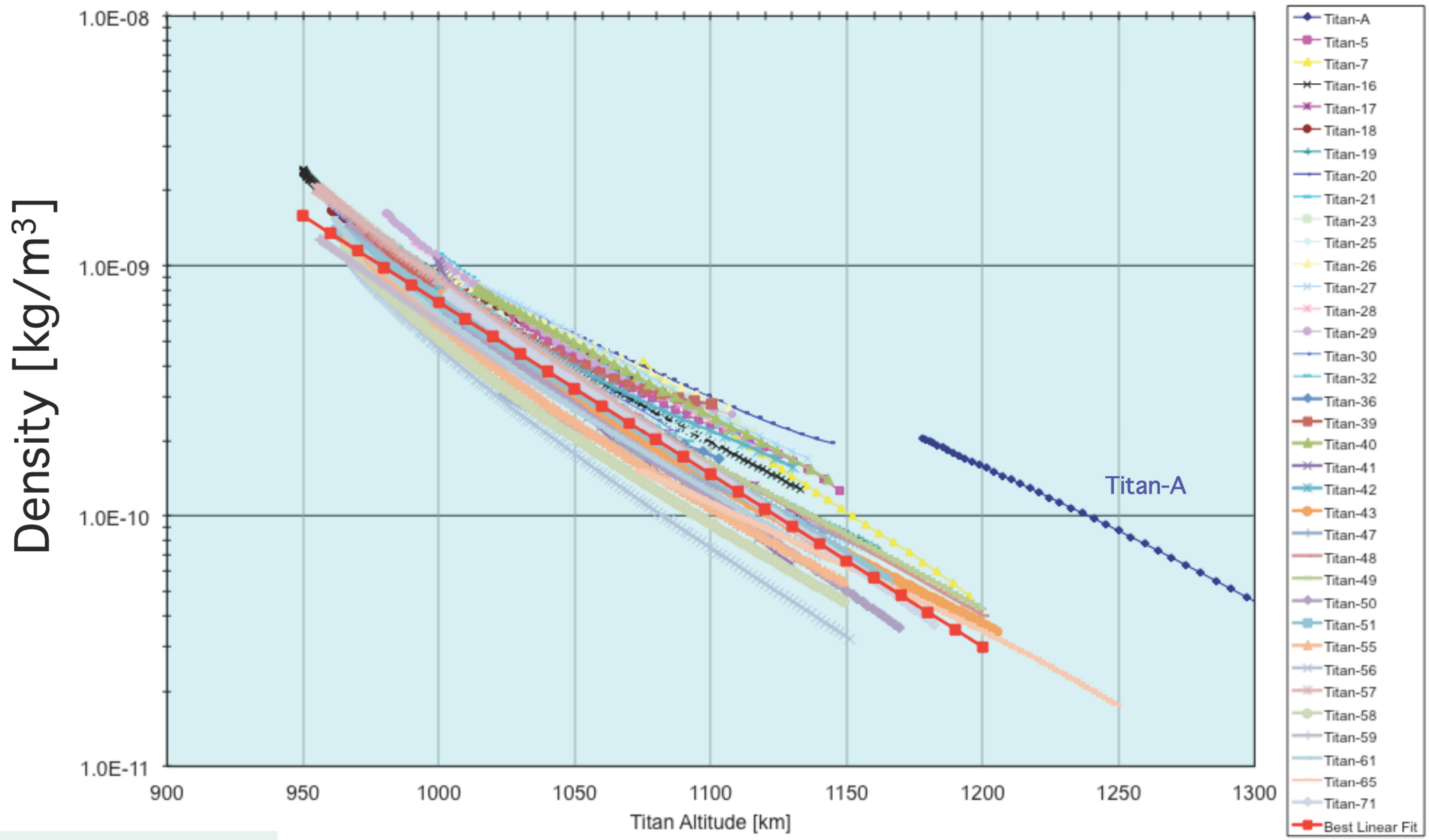
⋄ Data from the T37 and T64 flybys are not available for analysis. Analyses of T70 data by JPL and NASA Langley are in progress.

Reconstructed density vs Altitude for All Low-altitude† Titan Flybys (2004–2010)



†Altitude ≤1290 km

Reconstructed density vs Altitude in log scale for All Low-altitude† Titan Flybys (2004–2010)



Semi-log scale

$$\ln(\rho) = -0.01587h - 5.186$$

$$\rho = 0.005594e^{-\frac{h}{63.0120}}$$

$$(R^2 = 0.9329,\ R = 0.9657)$$

ρ = Titan Atmospheric Density (kg/m^3)

h = Titan Relative Altitude (km)

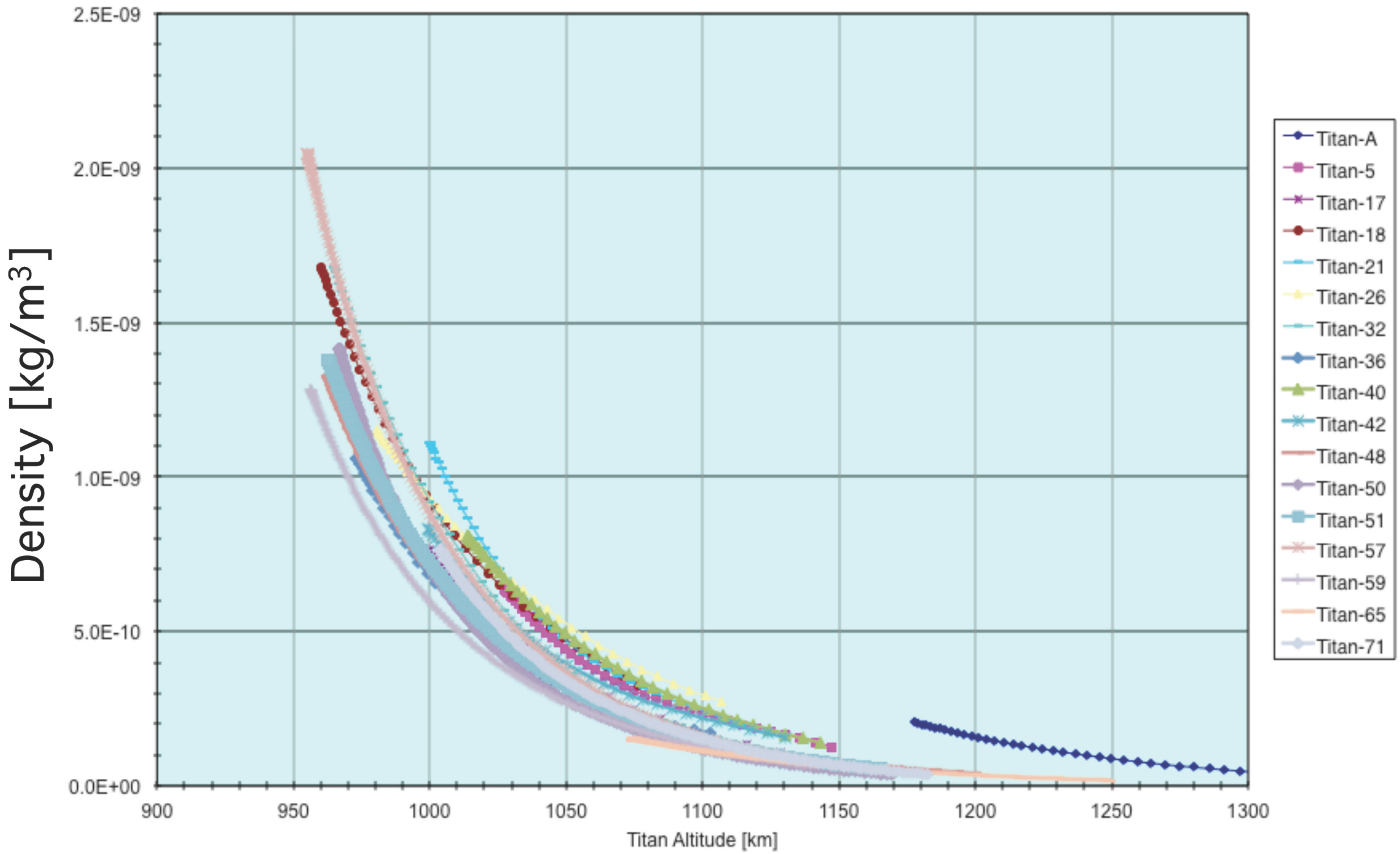
R^2 = Coefficient of Determination

R = Correlation Coefficient

† Altitude ≤1290 km

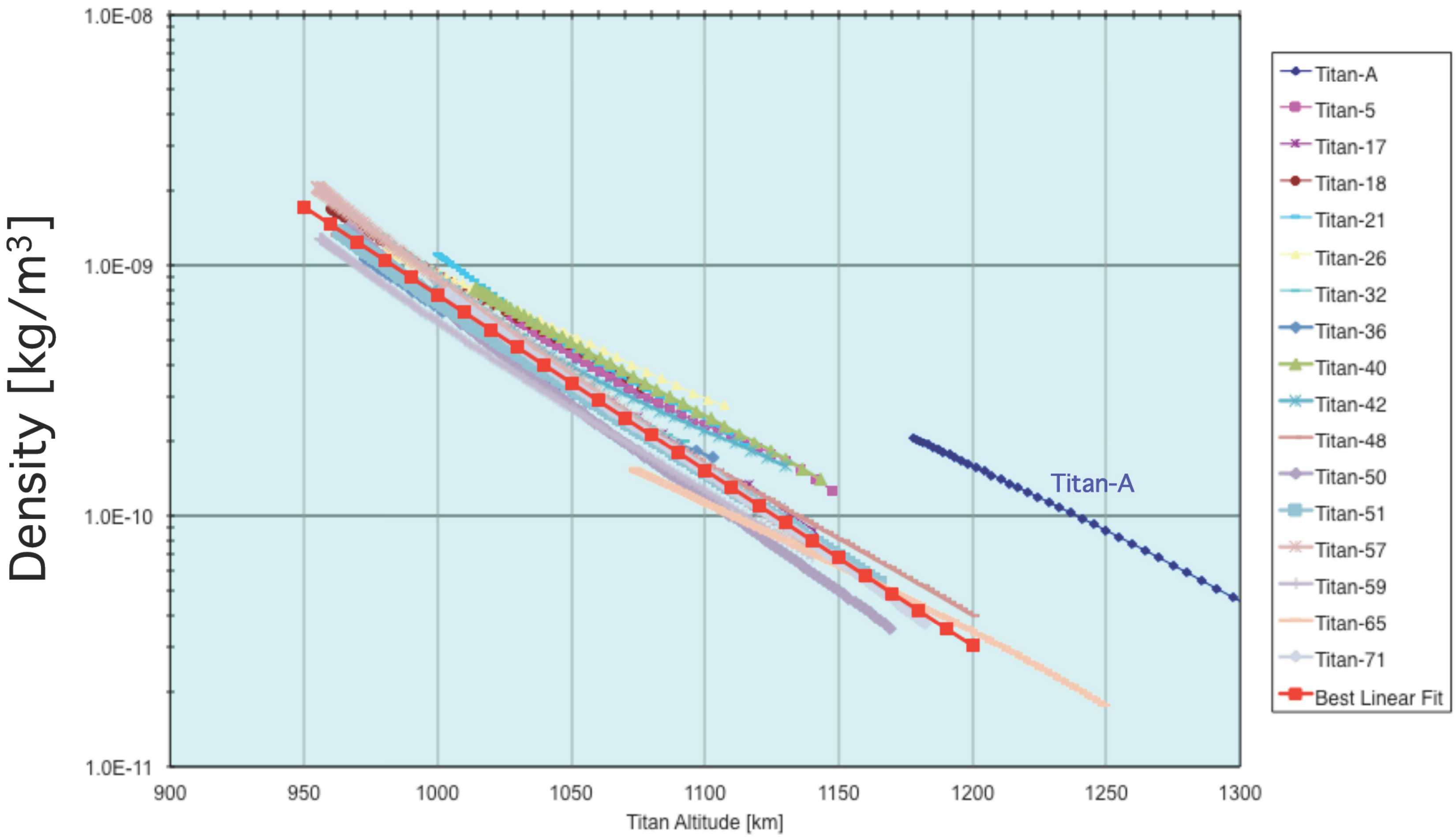
* Titan-A data was excluded when least square linear fit was performed.

Reconstructed density vs Altitude for All Low-altitude† INMS-centric Titan Flybys (2004–2010)



†Altitude ≤1290 km

Reconstructed density vs Altitude in log scale for All Low-altitude† INMS-centric Titan Flybys (2004–2010)



Semi-log scale

$$\ln(\rho) = -0.01614h - 4.853$$

$$\rho = 0.007804e^{-\frac{h}{61.9579}}$$

$$(R^2 = 0.9667,\ R = 0.9832)$$

ρ = Titan Atmospheric Density (kg/m^3)

h = Titan Relative Altitude (km)

R^2 = Coefficient of Determination

R = Correlation Coefficient

† Altitude ≤1290 km

* Titan-A data was excluded when least square linear fit was performed.

Summary and Conclusion

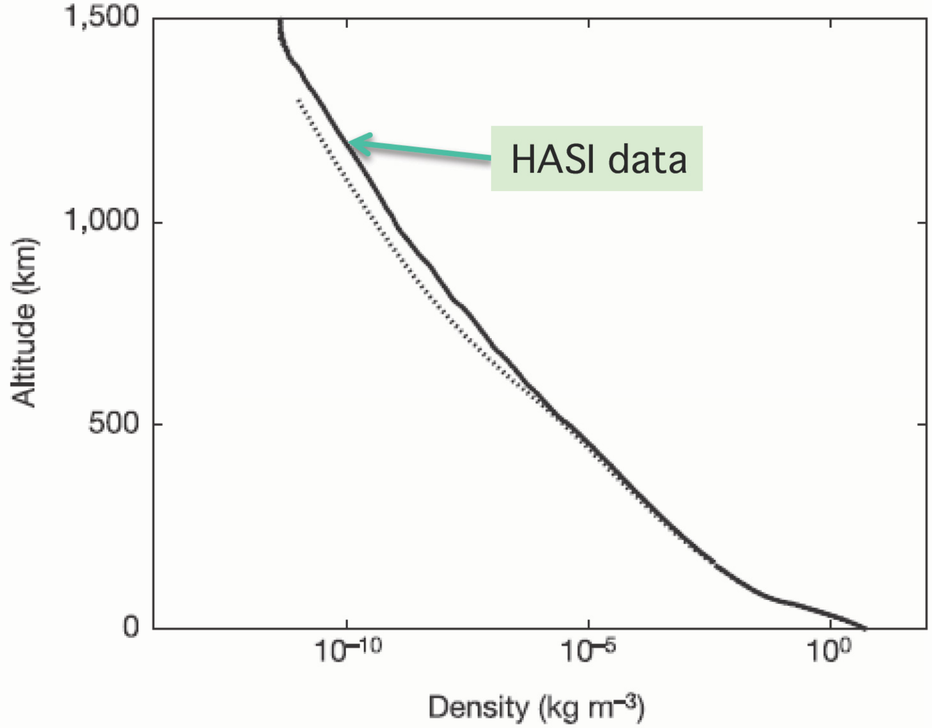
- Safe flybys of Titan at low altitude are of critical important to the Cassini mission. Well before the prime mission, SCO AACS has developed methodology to confirm the adequacy of spacecraft control authority during these flybys
- The same methodology could be used to estimate the Titan atmosphere density, as a function of Titan-relative altitude
  - Data used:
    - Thrusters' on-time telemetry data, magnitude, and tail-off impulse
    - Spacecraft's c.m. and c.p. locations, projected area, inertia matrix, estimated S/C per-axis rate, Titan-relative velocity, others
  - Estimation uncertainty of the AACS methodology is 5.6% (1σ)
- Estimates of Titan atmospheric density for 36 low-altitude Titan flybys executed in 2004–2010 (INMS was prime science for 17 of these flybys) are given in this report
- Similar methodologies were used to estimate the Enceladus plume density (E3, E5, E7, and E9). See Refs. 11–12

Backup Charts

Source:

HASI DATA

Paper Title: “In situ measurements of the physical characteristics of Titan’s environment”
Authors: M. Fulchignoni, et al
Vol 438|8 December 2005|doi:10.1038/nature04314



Ref. 15 (2005)

Figure 1 - The atmospheric density profile of Titan as measured by HASI

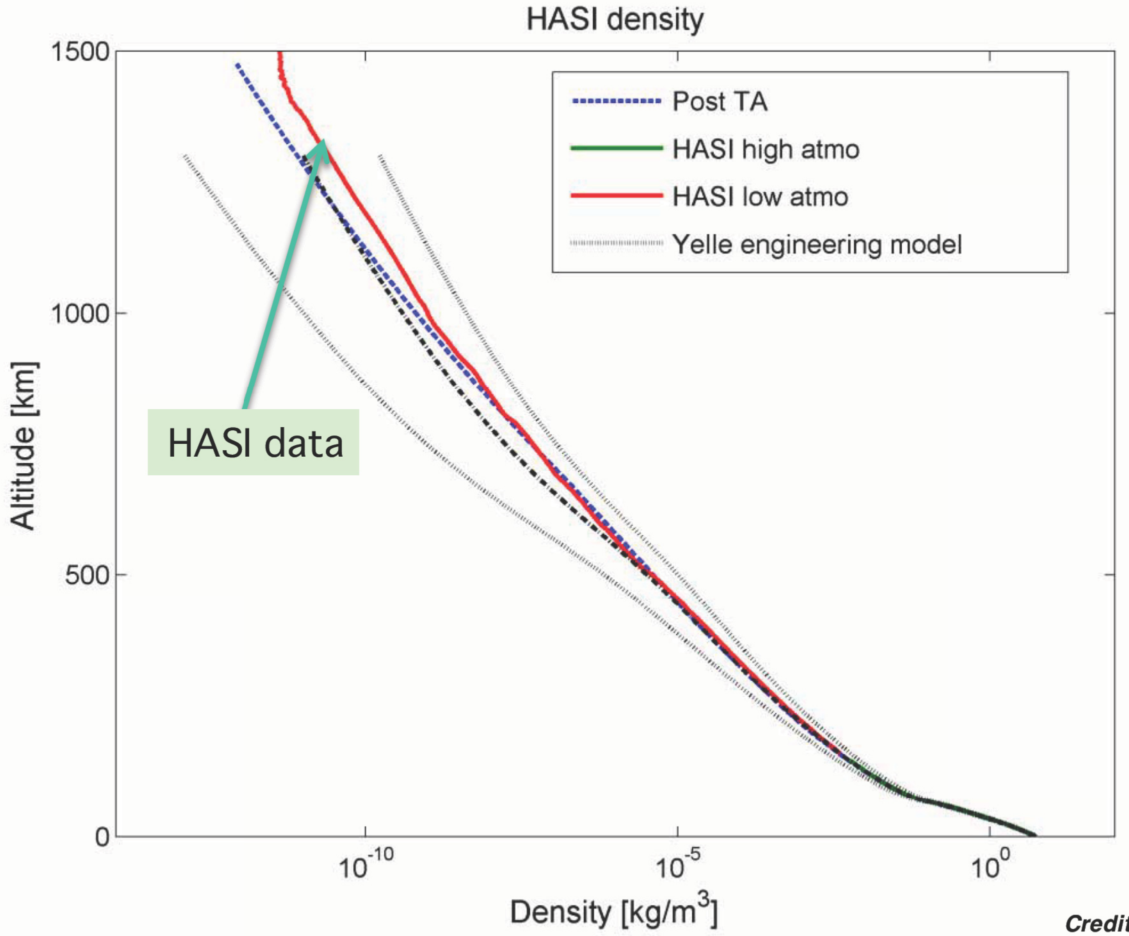
Note: *The density profile as derived from HASI measurements (solid line) is shown in comparison with the engineering model of Titan’s atmosphere13 derived from Voyager 1 data (dashed line). Density in the upper part of the atmosphere is derived from the ACC accelerometer data. The threshold density was 5 × 10^{-12} kgm^{-3}.* ***The uncertainty on the density Determination is of the order of 10%,*** *mainly due to the uncertainty on the aerodynamic drag coefficient and on the probe velocity.*

Ref. 14 (2007)

Results on Titan's Atmosphere Structure by the Huygens Atmospheric Structure Instrument (HASI)

M. Fulchignoni[1,2]
[1]LESIA Obs. Paris-Meudon, [2]Université Paris Diderot – Paris 7

HASI density profile



Ref. 14 (2007)

Credit: ESA / ASI / UPD/ OU /

Titan-A Workshop

Reconstruction of Titan Atmospheric Density Using Spacecraft AACS Flight Data

Two charts presented at the Titan-A workshop

Attitude and Articulation Control Subsystem (AACS)

Cassini Spacecraft Operations Office (SCO)

November 15, 2004

Agenda

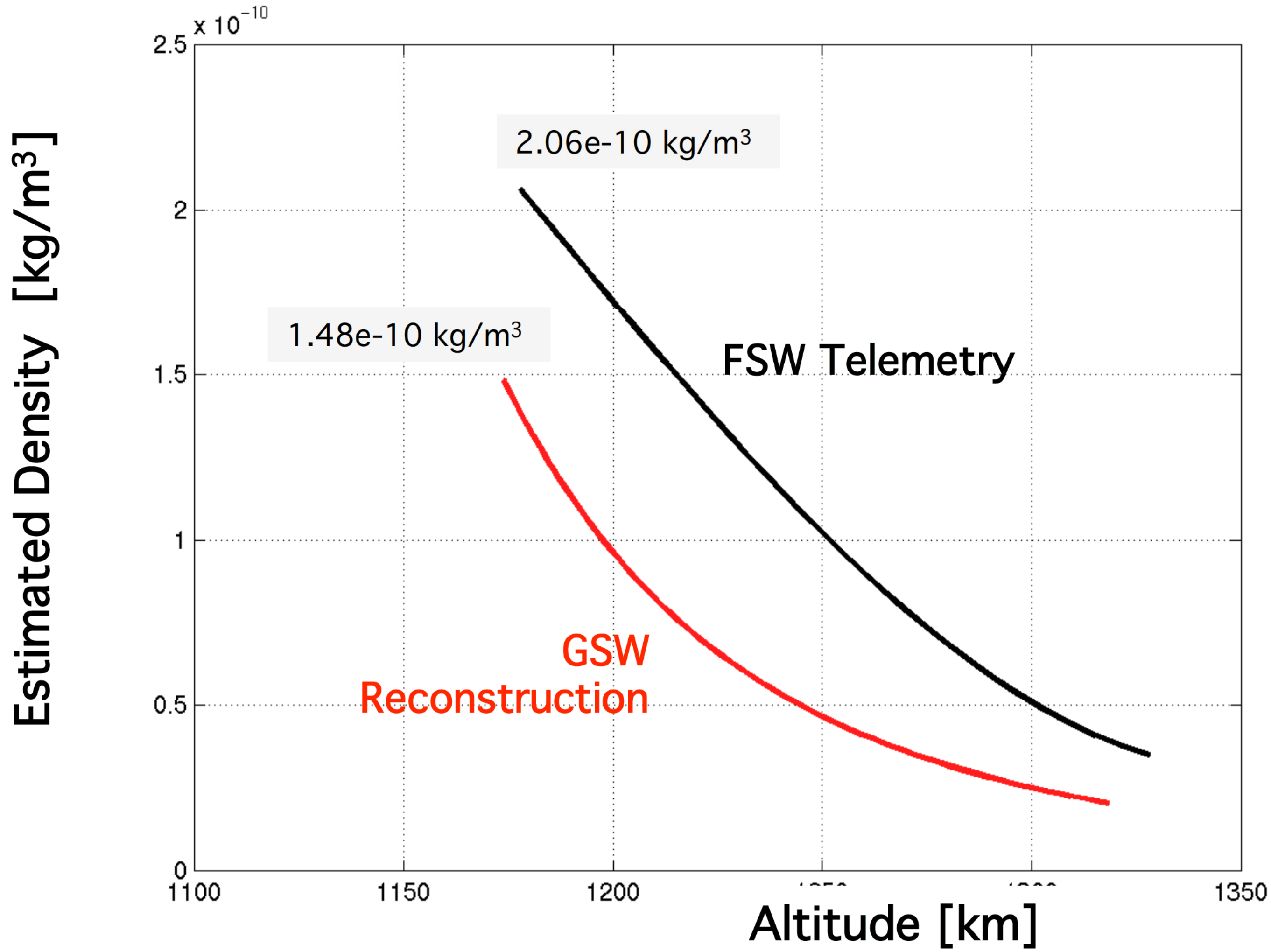
- Introduction - Allan Lee
- Results of Density Reconstruction:
  - First AACS Approach - Toni Feldman
  - Second AACS Approach - Sam Sarani
- Summary and Conclusion - Allan Lee
  - Implication for future 950-km flybys

Acknowledgements

- With significant contributions from Cassini AACS Flight Software team lead, Jay Brown, as well as Dave Myers and Leticia Montanez. Thermal team lead, Jerry Millard, and Stuart Clark also made contributions.

Result Comparison

- The reconstructed density as a function of Titan-relative altitude of two approaches:



NASA Langley Research Center Study of Cassini S/C Model

Mission Planning Forum

26 July 2005

Purpose

- To understand the differences in Titan atmospheric drag estimates between INMS and AACS data sets

What

- Using JPL supplied CAD models of Cassini, estimate spacecraft Cd, center of pressure, and moment arms
    - JPL CAD model took months to prepare since original s/c files were done by different s/w which is now obsolete
        - Files had to be converted to usable software
    - File generated by Div 35 was very detailed but over 1 Gb when finished
    - Ingestion of CAD file by Langley took months to prepare because of size of input file

Process

- High fidelity surface grid defined by Langley
  - MLI surface added by hand from s/c drawings
- Simulate Ta flyby conditions
  - Velocity, surface area, temperature
- Perform Monte Carlo simulation to calculate forces, and moments by summing up the contribution of each individual surface element

Results

- For both Direct Simulation and Free Molecular flow
  - Cd ~ 2.2 for 17.8 m^2 surface area exposure for Ta

- Torques and moment arms similar to AACS

- Results consistent with AACS calculations

Future Work

- Make some adjustments to DSMC calculations
- Define flow field near INMS instrument
    - Refine grid and look at number density near instrument
- Vary s/c surface temperature
    - AACS suggests that assumed numbers may be too high
- Consider thruster plume interactions
- Repeat simulation for T5