Evidence of Temporal Variation of Titan Atmospheric Density in 2005-2013

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One major science objective of the Cassini mission is an investigation of Titan's atmosphere constituent abundances. Titan's atmospheric density is of interest not only to planetary scientists but also to mission design and mission control engineers. Knowledge of the dependency of Titan's atmospheric density with altitude is important because any unexpectedly high atmospheric density has the potential to tumble the spacecraft during a flyby. During low-altitude Titan flyby, thrusters are fired to counter the torque imparted on the spacecraft due to the Titan atmosphere. The denser the Titan's atmosphere is, the higher are the duty cycles of the thruster firings. Therefore thruster firing telemetry data could be used to estimate the atmospheric torque imparted on the spacecraft. Since the atmospheric torque imparted on the spacecraft is related to the Titan's atmospheric density, atmospheric densities are estimated accordingly. In 2005–2013, forty-three low-altitude Titan flybys were executed. The closest approach altitudes of these Titan flybys ranged from 878 to 1,074.8 km. Our density results are also compared with those reported by other investigation teams: Voyager-1 (in November 1980) and the Huygens Atmospheric Structure Instrument, HASI (in January 2005). From our results, we observe a temporal variation of the Titan atmospheric density in 2005–2013. The observed temporal variation is significant and it isn't due to the estimation uncertainty (5.8%, 1σ) of the density estimation methodology. Factors that contributed to this temporal variation have been conjectured but are largely unknown. The observed temporal variation will require synergetic analysis with measurements made by other Cassini science instruments and future years of laboratory and modeling efforts to solve. The estimated atmospheric density results are given in this paper help scientists to better understand and model the density structure of the Titan atmosphere.

Keywords*: *Cassini/Huygens spacecraft, Titan, Atmosphere, Density Structure, Huygens Atmospheric Structure Instrument (HASI), and Temporal Variation.

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Acronyms

AACS	Attitude and Articulation Control Subsystem
DSMC	Direct Simulation Monte Carlo
DSN	Deep Space Network (Tracking stations)
ESA	European Space Agency
FSW	Flight Software
HASI	Huygens Atmospheric Structure Instrument
INMS	Ion and Neutral Mass Spectrometer
JPL	Jet Propulsion Laboratory
LS	Least Squares
ORS	Optical Remote Sensing
RSS	Radio Science System
RWA	Reaction Wheel Assembly
S/C	Spacecraft
TCA	Titan Closest Approach
VIMS	Visible and Infrared Mapping Spectrometer

Nomenclature

$A_{Project}$	Projected area of the spacecraft [m^2]
C_D	Drag coefficient of free molecular flow of Titan atmospheric constituents [-]
h	Titan-relative altitude of Cassini [km]
h_0	Scale height of the Titan atmospheric density model [km]
H_{RWA}	Angular momentum vector of the reaction wheels [Nms]
H_{Total}	Total angular momentum vector of the spacecraft system [Nms]
I_{RWA}	Inertia tensor of the reaction wheels [kg-m^2]
I_{sc}	Inertia tensor of the spacecraft [kg-m^2]
R	Angular momentum accumulated on spacecraft due to Titan atmospheric torque [Nms]
r_{cm}	Displacement vector from the origin of spacecraft coordinate frame to center of mass [m]
r_{cp}	Displacement vector from the origin of spacecraft coordinate frame to center of pressure [m]
T_{Atm}	Titan atmospheric torque imparted on spacecraft [Nm]
$T_{Thruster}$	Reaction torque imparted on spacecraft due to thrusters' firing [Nm]
T_{RWA}	Reaction torque imparted on spacecraft due to the reaction wheel assemblies [Nm]
V	Titan-relative velocity of the spacecraft [m/s]
ρ_{Titan}	Density of Titan atmospheric constituents [kg/m^3]
ρ_0	Density of Titan atmospheric constituents on the surface of Titan [kg/m^3]
ω	Spacecraft angular rate vector [rad/s]
ε	Torque imparted on S/C due to secondary torque sources (e.g., solar radiation) [Nm]
σ	Standard deviation of estimation uncertainty

1. Cassini/Huygens Mission to Saturn and Titan

Launched on 15 October 1997, Cassini is the largest and most sophisticated interplanetary spacecraft ever built. After an interplanetary cruise that lasted almost seven years, on 30 June 2004, Cassini fired one of its two rocket engines for about 96 minutes in order to slow the spacecraft's velocity (by 626.17 m/s) to allow the spacecraft to be captured by the gravity field of Saturn.[1] After the completion of the Saturn Orbit Insertion, Cassini began a complicated suite of orbits around Saturn, designed to optimize science collection over not only Saturn, but also its icy satellites and moons. The Cassini-Huygens Mission studied Titan via 45 close flybys during its four-year tour of Saturn. In the first extended mission, named Cassini-Equinox mission (from July 2008 to September 2010), there were 26 Titan flybys. In the second extended mission, named Cassini-Solstice mission (from October 2010 to September 2017), there are 56 additional targeted flybys of Titan.

Titan is the second largest moon in the Solar System, second only to Jupiter's moon Ganymede. At 5,150 kilometers in diameter, Titan is larger than the planet Mercury. Titan is of great interest because it is the only known moon in the Solar system with a significant atmosphere. Titan's atmosphere is ten times thicker than Earth's. Except for some obstruction from clouds, Earth's surface is visible from space. But on Titan, a thick haze extending up to an altitude of 3,000 kilometers obscures the entire surface from optical observations. Through ongoing observations from Earth as well as data collected by the Pioneer 11 and the Voyagers 1 and 2 spacecraft, scientists now know that Titan's atmosphere is composed primarily of nitrogen. In fact, over 95% of its atmosphere is nitrogen, while the remaining 5% is composed of methane, argon, and other hydrocarbons.

Titan's atmospheric density is of interest not only to planetary scientists but also to mission design, navigation, attitude control, and thermal control engineers. Unexpectedly high atmospheric density has the potential to tumble the spacecraft during a flyby. Aerodynamic heating of science instruments and/or engineering equipment is of interest to spacecraft thermal control engineers. Mission design engineers and navigators are interested in the hydrazine "cost" of low-altitude Titan flybys as well as the impacts on navigation due to the thruster firing-induced ΔV imparted on the spacecraft.

The variation of Titan's atmospheric density with altitude is the focus of many past and present science investigations. One of the major science objectives of the Cassini mission is an investigation of Titan's atmosphere constituent abundances. To this end, the instrument named Ion and Neutral Mass Spectrometer (INMS) is playing an important role.[2] The INMS is determining the chemical, elemental, and isotopic composition of the gaseous and volatile components of the neutral particles and the low-energy ions in Titan's atmosphere and ionosphere. Additionally, the Huygens Atmospheric Structure Instrument (HASI), mounted on the Huygens probe, sampled and determined Titan's atmosphere density during the Probe's 2.5-hour descent through Titan's atmosphere on 14 January 2005. Results of HASI-based density estimates are given in Refs. 3 and 4.

2. Estimation of Titan Atmospheric Density Using Attitude Control Flight Data

During low-altitude Titan flybys, thrusters are fired to counter the tumbling torque imparted on the spacecraft due to the Titan atmosphere as well as to slew the spacecraft in order to meet the pointing needs of the science instruments such as INMS. Obviously, the denser Titan's atmosphere is, the more thruster firings will be needed. Therefore thruster firing telemetry data collected by the Attitude and Articulation Control System (AACS) could be used to estimate the three per-axis torques imparted on the spacecraft due to the Titan atmosphere. Since there is a known relationship between the atmospheric torque imparted on the spacecraft and Titan's atmospheric density, the estimated torque can be used to reconstruct the Titan atmospheric density.

To estimate Titan's atmospheric density, the per-axis torque imparted on the spacecraft due to Titan's atmosphere must first be determined. The rotational motion of the spacecraft during a Titan flyby is governed by the following Euler equation expressed in a body-fixed spacecraft coordinate frame:[1,5]

$$I_{SC}\dot{\vec{\omega}} + \vec{\omega} \times (I_{SC}\vec{\omega} + \vec{H}_{RWA}) = \vec{T}_{Thruster} + \vec{T}_{Atmo} + \vec{T}_{RWA} + \vec{\varepsilon} \qquad (1)$$

In Eq. (1), I_{SC} is the spacecraft's inertia tensor, $\vec{\omega}$ is the spacecraft's angular rate vector, and $\dot{\vec{\omega}}$ is the spacecraft's angular acceleration vector. The spacecraft's inertia tensor is estimated by ground software. This ground-based estimate of the inertia tensor has also been confirmed via in-flight calibration technique.[6] An onboard attitude estimator (the Kalman-Bucy filter) provides estimates of the spacecraft rate at 125-msec time intervals. The total angular momentum vector of the three reaction wheels, in the spacecraft body frame, is denoted by H_{RWA}. The torque imparted on the spacecraft by the reaction wheels is denoted by T_{RWA}. If the reaction wheels are all powered off during the Titan flyby, both H_{RWA} and T_{RWA} are zero in Eq. (1). Torque exerted on the spacecraft due to thruster firing, $T_{Thruster}$, is not available directly from the flight software. Instead, the onboard flight software object named Propulsion Manager estimates the force impulse due to all thruster firings (including effects due to thrusters' rise and tail-off dynamics). Using the estimated moment arms of all the thrusters, these force impulses are converted into the per-axis torque impulses. In effect, what the FSW has estimated is $\int \vec{T}_{Thruster}(t)dt$. Torque exerted on the spacecraft due to Titan's atmospheric density is denoted by T_{Atmo}. This is the unknown quantity that we wish to estimate. Environmental torque due to Titan's gravity gradient, solar radiation, magnetic field, etc. is captured in the "ε" term. These non-gravitational torques are very small (< 1.1 mNm) and are neglected to first order.[1]

The torque imparted on the spacecraft due to the Titan atmospheric density could be estimated as follow. Let us define the following angular momentum vector:

$$\vec{R}(t) = \int_0^t \{\vec{T}_{Atmo} + \vec{\varepsilon}\}d\tau = \int_0^t \{I_{SC}\dot{\vec{\omega}} + \vec{\omega} \times (I_{SC}\vec{\omega} + \vec{H}_{RWA}) - \vec{T}_{RWA} - \vec{T}_{Thruster}\}d\tau \qquad (2)$$

In this equation, R(t) denotes the angular momentum vector accumulated due to the Titan atmospheric torque imparted on the spacecraft. The time derivatives of the R(t) vector approximate the per-axis atmospheric torque imparted on the spacecraft. Details of this methodology were described in Refs. 1, 7, 8, and 9, and are not repeated here. The time derivatives of R(t) are determined numerically. One particularly efficient technique to estimate the derivatives was reported in Refs. 8 and 9.

The Titan atmospheric density is related to the torque imparted to the spacecraft by the following approximate equation:[1,7,8]

$$\vec{T}_{Atmo}(t) \approx \frac{1}{2} C_D \, \rho_{Titan}(t) \, V^2(t) \, A_{Projected}(t) \, \vec{u}_V(t) \times [\vec{r}_{CP}(t) - \vec{r}_{CM}] \qquad (3)$$

In Eq. (3), $\rho_{Titan}(t)$ is the time-varying Titan atmospheric density (kg/m^3). The spacecraft velocity relative to Titan is denoted by V (m/s). The unit vector of the spacecraft's velocity vector, in the S/C's coordinate frame, is denoted by $\vec{u}_v$. The symbol $A_{Projected}$ (m^2) denotes the projected area of the spacecraft on a surface that is perpendicular to the vector $\vec{u}_v$. The displacement vectors, from the origin of the spacecraft coordinate frame to the spacecraft's center of mass and center of pressure (m) are denoted by r_{CM} and r_{CP} respectively. For a given Titan flyby, r_{CM} is a constant vector while r_{CP} is a time varying vector. Both the projected area and the offset distance are estimated via ground software.[1,7–9]

The dimensionless quantity C_D is the drag coefficient associated with the hyper-thermal free-molecular flow of Titan atmospheric constituents passing by the body of the Cassini spacecraft. The drag coefficient C_D can be estimated using formulae given in Ref. 10. In our work, we assume C_D= 2.1±0.1. This is a reasonable drag coefficient value when compared with results determined using orbital data of Earth-orbiting satellites.[11] Density estimation methodologies similar to that used here have also been used to characterize the upper atmosphere of Venus;[12] to estimate Mars atmosphere density;[13] and to estimate Titan atmosphere density using HASI accelerometer data.[3–4, 14]

RCS thrusters firing in a vacuum or in the Titan atmosphere produce plumes that expand rapidly and can impinge on other parts of the spacecraft as well as interact with the flow around the spacecraft during Titan flybys. For the Mars Odyssey spacecraft,[15] these plumes produce effects on the aerodynamic control effectiveness of thrusters firing.[§] Placements of the Cassini RCS thrusters (see Ref. 1) are such that impingements of thruster plumes on other parts of the spacecraft are negligible. The interaction between thruster plumes and flow around the spacecraft could only be determined via flow simulations made using the Direct Simulation Monte Carlo (DSMC) method. Aerodynamic force and torque estimated for the Titan-70 flyby (with a TCA altitude of 878 km) using Eq. (3) compared well with those estimated using the DSMC method. For spacecraft flight directions involved in other Titan flybys, DSMC works were not done due to time constraint.

2.1 Uncertainty of the Density Estimation Methodology

Based on the expression given by Eq. (3), the uncertainty of the estimated Titan atmosphere density is given by:

$$[\frac{\sigma_\rho}{\rho}]^2 = [\frac{\sigma_{T_{Atmo}}}{T_{Atmo}}]^2 + [\frac{\sigma_{C_D}}{C_D}]^2 + 4 \times [\frac{\sigma_V}{V}]^2 + [\frac{\sigma_{A_{Projected}}}{A_{projected}} + \frac{\sigma_{r_{cpcm}}}{r_{cpcm}}]^2 \qquad (4)$$
$$= 4.9^2 + 1.6^2 + 4 \times 0.005^2 + [0.65 + 1.97]^2 \approx 5.8^2$$

In this expression, σ_S represents the one-sigma estimation uncertainty of the variable "S" (for example, the drag coefficient C_D). The estimation/measurements of quantities on the right-hand-side of Eq. (3) are assumed to be uncorrelated. Hence, the variances of the normalized quantities are added algebraically on the right-hand-side of Eq. (4) to produce the variance of the normalized Titan atmospheric density. But, we did assume that the estimation uncertainties of the spacecraft projected area and the r_{CP}–r_{CM} offset distance are fully correlated. Accordingly, the one-sigma estimation uncertainties of these two normalized quantities are first added before the sum is squared to produce a "combined" variance. The factor of "4" in front of the term $[\sigma_V/V]^2$ was introduced to account for the fact that $\partial\rho/\partial V$ = 2 in Eq. (3). Using the estimation

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[§]For the Mars Odyssey spacecraft, changes in the control effectiveness of the four attitude control thrusters depend on both the density of the Mars atmospheric density and the specific thruster involved. For the RCS-1 thruster of the Mars Odyssey spacecart, 2–6% changes were observed in DSMC analyses.

uncertainties given in Ref. 7, the one-sigma estimation uncertainty of the Titan atmospheric density is found to be 5.8%. As a comparison, the reported one-sigma estimation uncertainty of the HASI-based Titan density estimate is 2.6–3.3%.[3,14] HASI-based density estimate was made using accelerometer data. Hence, it is free of the estimation uncertainty of the r_{CP}–r_{CM} offset distance. Hence, the HASI-based density estimation uncertainty is smaller (better) than the 5.8% given in Eq. (4). But, there is only one set of HASI data (collected on 15 January 2005). The current torque-based density estimation methodology produced results for 43 low-altitude Titan flybys executed in the year 2005–2013.

3. Estimated Titan Atmospheric Density for Forty-three Titan Flybys

At the time when this paper is being prepared, forty-three low-altitude Titan flybys (with altitudes ≤1,200 km) have been executed. The estimated Titan atmospheric densities at the Titan Closest Approach (TCA) altitudes of these flybys are tabulated in Table 1. Note that the telemetry data of three flybys, T37, T46, and T64 were lost due to either outage of the Deep Space Network (DSN tracking stations) or spacecraft anomaly. As such, Titan atmospheric densities for these flybys could not be reconstructed. The TCA altitude of Titan-70, at 878 km, was the lowest of all flybys flown to date. Control authority of the spacecraft was maintained for this low altitude flyby by maintaining the spacecraft flyby attitude with a r_{CP}–r_{CM} offset vector that was almost co-aligned with the S/C's velocity vector.[9] As a result, the moment arm of the atmospheric force was small and the tumbling torque was well within the control authority of attitude control thrusters. For this flyby, as usual, the Titan atmospheric density was estimated using the thrusters' firing data. In addition, with the onboard accelerometer powered on for this flyby, the ΔV data measured by the accelerometer are also used to estimate the linear momentum imparted on the spacecraft. The Titan atmospheric density was estimated accordingly. Analyses of these flight data are still in progress. The preliminary T-70 density estimate given in Table 1 corresponds to that estimated using only the accelerometer data. Similarly, the preliminary T-87 density estimate given in Table 1 corresponds to that estimated using only the accelerometer data.

In Table 1, no density estimate is reported for the T-88 flyby. Typically, good density estimate could be made with estimated atmospheric torque sizes of 0.3–0.6 Nm (e.g., Titan-83, 85, and 86). The largest per-axis atmospheric torque estimated using T-88 thruster data was below 0.025 Nm. Hence, density estimation wasn't made for the Titan-88 flyby. On the other hand, two density estimates are reported for the Titan-87 flyby. Using data from the accelerometer (that was powered on only for selected Titan flybys including T-70 and T-87), the density estimate at TCA is 5.0×10^{-10} kg/m^3. The average value of the three per-axis density estimates made using thrusters' on-time is 6.6×10^{-10} kg/m^3. The best density estimate is likely to be in between these two values.

In Table 1, density estimates made using telemetry data of two high-altitude Titan flybys executed with the spacecraft attitude controlled by reaction wheels (instead of thrusters) are not included. Using an approach similar to that described above, the TCA densities of these flybys were estimated using RWA spin rate telemetry data instead of thrusters' on-time. Results are given in the following:

1. Titan-22, 2006-DOY362T10:05:22, 1,297 km, estimated TCA density is 1.57e-11 kg/m^3,
2. Titan-38, 2007-DOY339T00:07:37, 1,298 km, estimated TCA density is 1.45e-11 kg/m^3.

As expected, these density estimates are low at these higher TCA altitudes. Accordingly, one can expect the corresponding estimation uncertainty to be larger than that given in Eq. (4). For this reason, they are not included in Table 1, and are reported here just as a reference.

Table 1. Density Estimates of Low-altitude Titan Flybys (2005–2013)†

Flyby	Date/Time	TCA [km]	TCA Latitude [°]	TCA Velocity [km/s]	Prime Science	Peak Density [10^{-10} kg/m^3]
T5	2005-106T19:12	1027.4	74	6.1	INMS	6.36
T7	2005-250T08:12	1074.8	-67	6.1	RADAR	4.13
T16	2006-203T00:25	949.9	85	6.0	RADAR	23.3
T17	2006-250T20:17	999.5	23	6.0	INMS	7.62
T18	2006-266T18:59	959.8	71	6.0	INMS	16.78
T19	2006-282T17:30	979.7	61	6.0	RADAR	10.6
T20	2006-298T15:58	1029.5	8	6.0	ORS	6.7
T21	2006-346T11:42	1000.0	44	5.9	INMS	11.1
T23	2007-013T08:39	1000.3	31	6.0	RADAR	10.64
T25	2007-053T03:12	1000.4	31	6.2	RADAR	8.24
T26	2007-069T01:49	980.6	32	6.2	INMS	11.49
T27	2007-085T00:23	1009.9	41	6.2	RSS	8.51
T28	2007-100T22:58	990.9	51	6.2	RADAR	12.61
T29	2007-116T21:33	980.8	59	6.2	RADAR	16.34
T30	2007-132T20:10	959.2	69	6.2	RADAR	17.69
T32	2007-164T17:46	964.9	84	6.2	INMS	16.77
T36	2007-275T04:43	973.0	-60	6.3	INMS	10.59
T37	2007-323T00:52	999	-22	6.3	INMS	Data lost
T39	2007-354T22:58	969.5	-70	6.3	RADAR	13.67
T40	2008-005T21:30	1014.07	-12	6.3	INMS	8.09
T41	2008-053T17:32	999.7	-34	6.3	RADAR	10.44
T42	2008-085T14:28	999.4	-27	6.3	INMS	8.33
T43	2008-133T10:02	1001.4	17	6.3	RADAR	7.7
T46	2008-308T17:35	1105	-4	6.3	RSS	Data lost
T47	2008-324T15:56	1023.4	-22	6.3	ORS	3.07
T48	2008-340T14:26	960.6	-10	6.3	INMS	13.29
T49	2008-356T13:00	970.6	-44	6.3	RADAR	13.05
T50	2009-038T08:51	966.8	-34	6.3	INMS	14.15
T51	2009-086T04:44	962.6	-31	6.3	INMS	13.81
T55	2009-141T21:27	965.7	-22	6.0	RADAR	13.3
T56	2009-157T20:00	967.7	-32	6.0	RADAR	10.81
T57	2009-173T18:33	955.1	-42	6.0	INMS	20.46
T58	2009-189T17:04	965.8	-52	6.0	RADAR	11.9
T59	2009-205T15:34	956.2	-62	6.0	INMS	12.8
T61	2009-237T12:52	960.7	-19	6.0	RADAR	15.71
T64	2009-362T00:17	951.0	82	6.0	INMS	Data lost
T65	2010-012T23:11	1073.9	-82	5.9	INMS	1.52
T70	2010-172T01:27	878	84	6.0	MAG	39.8
T71	2010-188T00:23	1005	-56	5.9	INMS	7.66
T83	2012-143T01:10	953.5	73	5.9	INMS	10.97
T84	2012-159T00:07	959.6	39	5.9	RADAR	9.09
T85	2012-206T19:47	1012.0	62	5.9	VIMS	2.85
T86	2012-270T14:35	955.8	62	5.9	INMS	9.12
T87	2012-318T10:22	973.0	11	5.9	INMS	5.0††
T91	2013-143T17:33	970	46	5.9	RADAR	4.84

† Density estimates of two high-altitude Titan flybys, Titan-22 (1,297 km), and Titan-38 (1,298 km), are given in Section 3.

†† Density estimated using accelerometer data is 5.0×10^{-10} kg/m^3. Density estimated using thruster on-time data is 6.6×10^{-10} kg/m^3.

Fig. 1 is a semi-log plot depicting the estimated Titan atmospheric density as a function of the Titan-relative altitude. When the logarithm of the estimated density is plotted against the altitude, the data sets from these flybys produce straight lines with negative slopes. This suggests that the atmospheric density (ρ_{Titan}) is related to altitude (h) as follows:

$$\rho_{Titan}(h) = \rho_0 \exp(-h/h_0) \qquad (5)$$

Here, both ρ_{Titan} and ρ_0 have units of kg/m^3 and both h and h_0 have units of km. The least-square (LS) fits of the density estimates from forty-three low-altitude Titan flybys, [ρ_0, h_0], are given in Table 2. The mean modeling errors for each of the LS fits, given in Table 2, range from 0.42 to 6.82%. The average of all these modeling errors, for all 43 LS models, is 3.03%.

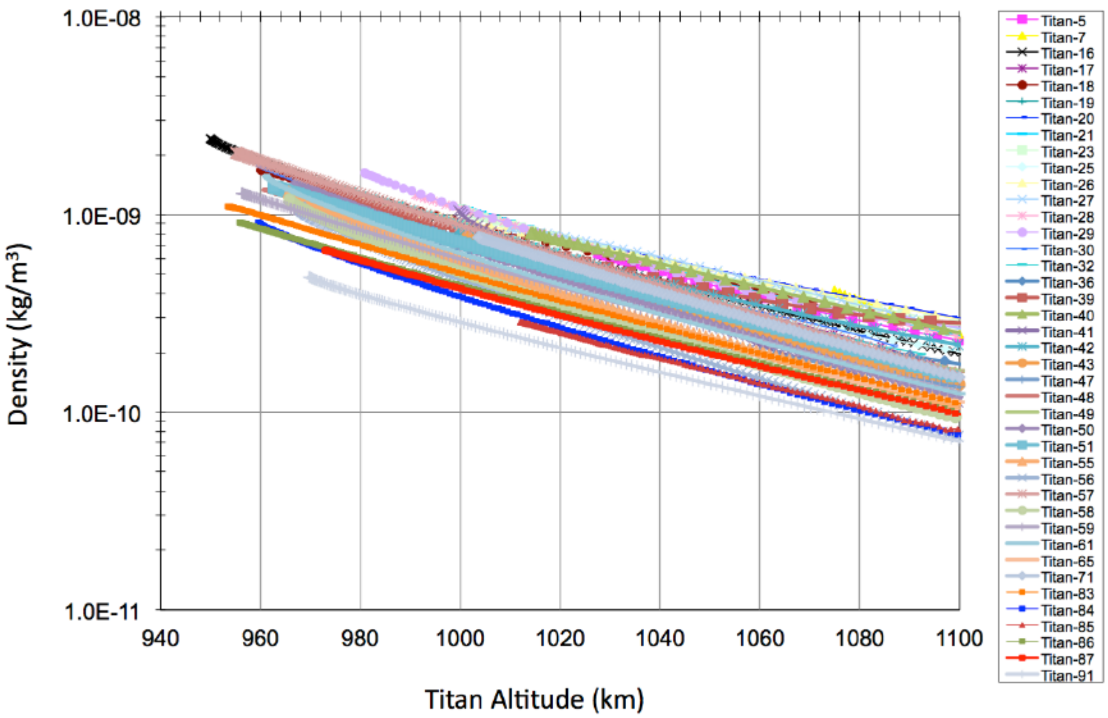

Figure 1. Titan Atmospheric Density Estimate As a Function of Titan-relative Altitude

Table 2. Model Parameters [ρ_0, h_0] of Titan Atmospheric Density[†]

Flyby	Date/Time	TCA [km]	Peak Density [e-10 kg/m^3]	Min. Altitude [km]	Max. Altitude [km]	Reference Density, ρ_0 [e-4 kg/m^3]	Scale Height, h_0 [km]	Mean Model Error [%]
T5	2005-106T19:12	1027.4	6.36	1028	1147	4.59	75.9	3.06
T7	2005-250T08:12	1074.8	4.13	1075	1195	766.8	56.3	2.27
T16	2006-203T00:25	949.9	23.3	950	1067	385.9	57.0	2.50
T17	2006-250T20:17	999.5	7.62	1000	1141	31.9	65.6	1.19
T18	2006-266T18:59	959.8	16.78	960	1076	11.3	71.4	1.37
T19	2006-282T17:30	979.7	10.6	980	1101	46.98	63.64	3.93
T20	2006-298T15:58	1029.5	6.696	1030	1144	0.63	89.9	0.99
T21	2006-346T11:42	1000.0	11.1	1000	1114	51.2	65.0	3.15
T23	2007-013T08:39	1000.3	10.64	1000	1115	6.74	74.6	2.22
T25	2007-053T03:12	1000.4	8.24	1000	1127	5.9	73.8	4.71
T26	2007-069T01:49	980.6	11.49	980	1107	0.83	87.7	0.58
T27	2007-085T00:23	1009.9	8.51	1010	1136	5.8	75.4	1.72
T28	2007-100T22:58	990.9	12.61	991	1117	43.7	65.6	3.25
T29	2007-116T21:33	980.8	16.34	981	1052	1312	53.78	1.86
T30	2007-132T20:10	959.2	17.69	959	1087	116.4	60.8	5.00
T32	2007-164T17:46	964.9	16.77	965	1092	302.7	57.8	0.84
T36	2007-275T04:43	973.0	10.59	973	1103	17.3	67.9	3.21
T39	2007-354T22:58	969.5	13.67	970	1101	3.84	76.8	5.20
T40	2008-005T21:30	1014.1	8.09	1014	1143	7.50	73.8	0.42
T41	2008-053T17:32	999.7	10.44	1000	1100	74,769	43.84	5.01
T42	2008-085T14:28	999.4	8.33	999	1130	3.57	76.8	3.04
T43	2008-133T10:02	1001.4	7.699	1001	1150	75.0	61.82	4.55
T47	2008-324T15:56	1023.4	3.07	1023	1160	0.15	94.7	1.01
T48	2008-340T14:26	960.6	13.29	961	1200	16.1	68.3	3.34
T49	2008-356T13:00	970.6	13.05	971	1150	36.27	64.98	4.67
T50	2009-038T08:51	966.8	14.15	967	1169	569.3	55.0	3.85
T51	2009-086T04:44	962.6	13.81	963	1165	64.1	62.6	1.77
T55	2009-141T21:27	965.7	13.3	966	1101	818.9	53.51	4.37
T56	2009-157T20:00	967.7	10.81	968	1100	3,406.5	49.17	5.08
T57	2009-173T18:33	955.1	20.46	955	1139	479	56.2	1.36
T58	2009-189T17:04	965.8	11.9	966	1070	2812.7	49.84	4.18
T59	2009-205T15:34	956.2	12.8	956	1140	53.2	62.6	2.37
T61	2009-237T12:52	960.7	15.71	961	1100	593.4	54.68	5.21
T65	2010-012T23:11	1073.9	1.52	1074	1249	0.58	83.7	1.26
T70	2010-172T01:27	878	39.8	878	1050	59.5	61.31	6.82
T71	2010-188T00:23	1005	7.66	1003	1182	149	59.74	1.06
T83	2012-143T01:10	953.5	10.97	953	1250	26.11	64.81	2.99
T84	2012-159T00:07	959.6	9.09	960	1101	228.03	56.04	4.40
T85	2012-206T19:47	1012.0	2.85	1012	1140	4.842	70.48	1.31
T86	2012-270T14:35	955.8	9.12	956	1250	18.73	65.62	2.91
T87	2012-318T10:22	973	5.0 (ACC)	973	1033	1.526	77.51	4.53
T87	2012-318T10:22	973	6.6 (Thrusters)	973	1250	7.23	69.7	3.10
T91	2013-143T17:33	970	4.84	970	1299	3.36	71.69	4.77

[†]Rows for T39, 46, and T64 have been removed from Table 1.

3.1 Titan Atmospheric Density Estimated By HASI, Navigation, and AACS Methodologies

Titan atmospheric density estimated using the methodology described in this paper is compared with that estimated by another science instrument carried onboard the Huygens probe: Huygens Atmospheric Structure Instrument (HASI). The Huygens probe was parachuted through the Titan atmosphere on 15 January 2005. It measured the temperature profile of the atmosphere, from an altitude of 1,400 km down to the surface. The density of the atmosphere was derived from the measured probe deceleration due to the aerodynamic drag force, using a similar method previously used for other planetary missions.[12,13] Over the altitude range of 840 to 1375 km, HASI-based density data could be approximated by either one of the following two expressions.

$$\ln(\rho) = -7.823542454 - 0.012774971 \times h \qquad (\pm 6.5\%) \quad (6)$$

$$\ln(\rho) = -4.975250007 - 0.018018761 \times h + 2.350855 \times 10^{-6} \times h^2 \qquad (\pm 3.7\%)$$

Over the same altitude range, density estimates made using Voyager-1 data collected on 12 November 1980, and reported in Refs. 3 and 16 could be approximated by either one of the following two expressions.

$$\ln(\rho) = -8.470679649 - 0.013156991 \times h \qquad (\pm 13.8\%) \quad (7)$$

$$\ln(\rho) = -3.075196277 - 0.023809097 \times h + 5.127491 \times 10^{-6} \times h^2 \qquad (\pm 6.01\%)$$

The HASI derived density profile, from 1,500 km down to 500 km, was found to be systematically higher than those obtained from Voyager-1 data.[3–4] The HASI (15 January 2005 at a latitude of -10.2°) and Voyager-1 (late 1980) results are cross-plotted in Fig. 2 with those results computed for Titan-5 (15 April 2005 at a latitude of +74°), Titan-7 (6 September 2005 at a latitude of –67°), and T-16 (21 July 2006 at a latitude of +85°). Data from these three Cassini Titan flybys are used because they were executed near the time of the HASI measurements (15 January 2005). With reference to Fig. 2, we observe that the HASI density estimates are systematically higher than their Voyager-1 counterparts. Densities estimated using the methodology reported in this paper (and Refs. 1, 7–9) fall in between their HASI and Voyager counterparts but are significantly closer to the HASI data than the Voyager-1 data.

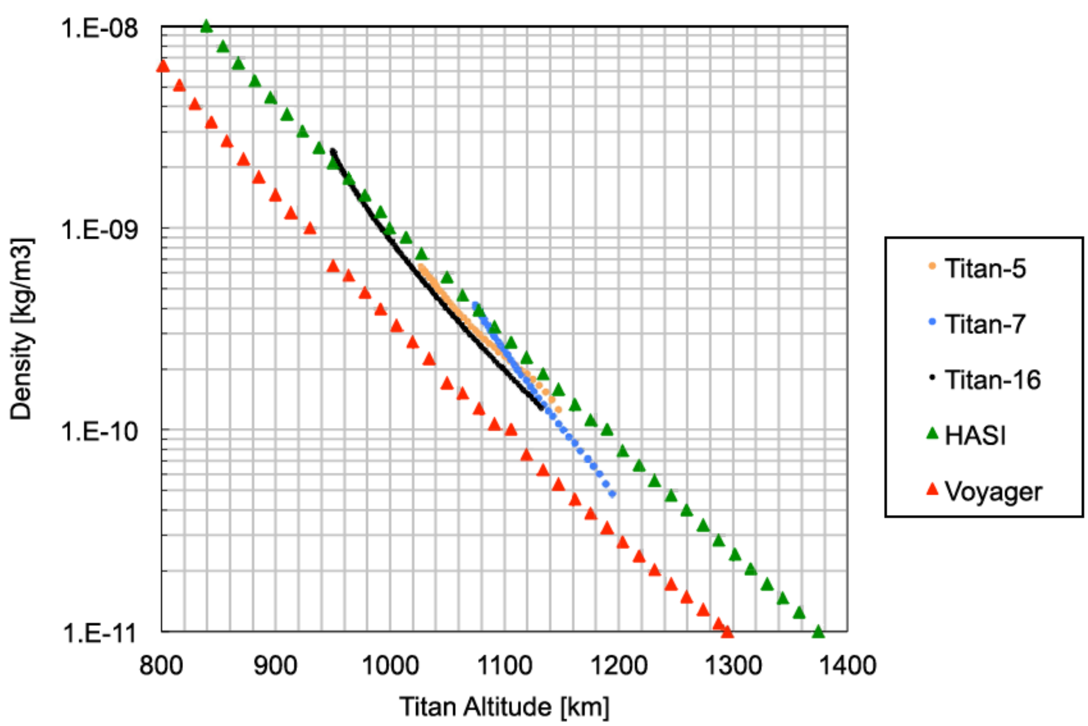

Figure 2. Titan Atmospheric Densities As Estimated by Voyager, HASI, and AACS

The spacecraft's inertial attitude for a limited number of Titan flybys (e.g., T-21) offered opportunity for the Cassini Navigation team to use Doppler data to estimate the ΔV imparted on the spacecraft due to the atmospheric force (instead of torque). For T-21 (11 December 2006), the navigation team reported a density estimate of 9.2×10^{-10} kg/m^3 at the TCA altitude of Titan-21 (1,000 km). This compared reasonably well with that estimated using the attitude control data: 11.1×10^{-10} kg/m^3. The HASI-based estimated Titan atmospheric density (at 1,000 km in 15 January 2005) is 10.0×10^{-10} kg/m^3.[3,4] The Voyager-based estimated Titan atmospheric density (at 1,000 km in late 1980), about 4.1×10^{-10} kg/m^3,[3,15] is significantly lower.

3.2 Observed Trends of Titan Atmospheric Density Data

There is an observed temporal variation of the Titan atmospheric density. For example, the Titan atmospheric density at a fixed altitude of 1,080 km for flybys conducted in 2005–2013 could be determined from Fig. 1. The variation of these 1080-km Titan atmospheric densities with time is tabulated in Table 3 and Fig. 3. Factors that contributed to this temporal variation have been conjectured but are largely unknown. A similar observation was made in Ref. 9. Beside the flyby altitude, what other factors might influence the Titan atmospheric density? Conjectures we considered include the following:

1. Latitude of flyby TCA,
2. Time of the flyby relative to the 11-year Solar cycle,
3. Execution of flyby TCA in the Sun side vs. shadow,
4. Interaction between the Titan atmosphere with the magnetosphere of Saturn,
5. Titan atmospheric activities (e.g., storms), and
6. Titan surface activities

Only conjecture #1, 2, and 3 are studied in greater depth. Preliminary findings are given in the following paragraphs.

<u>Impacts of TCA latitude</u>

The variation of Titan atmospheric density (at a constant altitude of 1080-km) with the TCA latitude is depicted in Fig. 4. As observed in that figure, there isn't any clear trend between the atmosphere density and the latitude. But the scattering might be a result of temporal variation of the atmosphere density. Hence, one must make comparisons between density estimates from flybys that were executed at nearly the same time. The following five (randomly selected) pairs of flyby density estimate data provide some indications of the dependency.

1. Near 2006-DOY-282 (two flybys that were executed within 16 days):
   a. Titan-19 (2006-DOY282, latitude = +61˚): Density at 1,080 km is 2.04e-10 kg/m^3
   b. Titan-20 (2006-DOY298, latitude = +8˚): Density at 1,080 km is 3.7e-10 kg/m^3

   Comment: There is a dependency between density and latitude. In the Northern hemisphere, density is higher near the equator.
2. Near 2007-DOY-053 (two flybys that were executed within 16 days):
   a. Titan-25 (2007-DOY053, latitude = +31˚): Density at 1,080 km is 2.46e-10 kg/m^3
   b. Titan-26 (2007-DOY069, latitude = +32˚): Density at 1,080 km is 3.66e-10 kg/m^3

   Comment: The altitude, latitude, and time these two density estimates were made are nearly identical. Yet, one density estimate is about 50% higher than the other one. There must be other factor(s), not yet uncovered, that caused this density difference.
3. Near 2008-DOY-340 (two flybys that were executed within 16 days):
   a. Titan-48 (2008-DOY340, latitude = -10˚): Density at 1,080 km is 2.12e-10 kg/m^3
   b. Titan-49 (2008-DOY356, latitude = -44˚): Density at 1,080 km is 2.12e-10 kg/m^3

   Comment: In the Southern hemisphere, density estimates for two flybys with latitudes that were separated by 34˚ are nearly identical. Hence, there is no dependency between density and latitude.
4. Near 2009-DOY-141 (two flybys that were executed within 16 days):
   a. Titan-55 (2009-DOY141, latitude = -22˚): Density at 1,080 km is 1.48e-10 kg/m^3
   b. Titan-56 (2009-DOY157, latitude = -32˚): Density at 1,080 km is 1.03e-10 kg/m^3

   Comment: At almost identical latitudes, one density estimate is nearly 50% higher than the other one. There must be other factor(s), not yet uncovered, that caused this density difference. See also Pair #2.
5. Near 2010-DOY-172 (two flybys that were executed within 16 days):
   a. Titan-70 (2010-DOY172, latitude = +84˚): Density at 1,080 km is 1.86e-10 kg/m^3
   b. Titan-71 (2010-DOY188, latitude = -56˚): Density at 1,080 km is 2.07e-10 kg/m^3

Comment: There is a large difference between the TCA latitudes, yet the density estimates are almost identical. Hence, one might conclude that there isn't a dependency between density and latitude.

Based on these data sets, one observes no clear and conclusive relation between the Titan atmospheric density and the TCA latitude.

Impacts of Solar cycle

Solar cycles 23 and 24 are depicted in Fig. 5. Solar minimum occurred during the months December 08 – June 09. This is about the same time the estimated Titan atmospheric density was at a local minimal (see Fig. 3). After the solar minimum, the Sun spot number increased significantly in 2010–13. But the atmospheric density did not track this increasing trend. Instead, the mean level of the Titan atmosphere density dispersion in 2013 is at a level that is comparable to its counterparts in 2009 and 2010. Solar cycle might have contributed to the temporal variation of Titan atmospheric density. But there might be other complications.

Impacts of Sun vs. shadow passage

Density data estimated using data from the Titan flybys 56 and 57 are used to investigate this factor. They are selected because they were executed at almost the same time, same latitude, and same altitude. Details of these flybys are given below. Why is there a factor of 2 between the density estimates?

- Titan-56: 2009-157T20:00, TCA was 967.7 km, TCA latitude was -32°, TCA density was 10.81e-10 kg/m^3, and
- Titan-57: 2009-173T18:33, TCA was 955.1 km, TCA latitude was -42°, TCA density was 20.46e-10 kg/m^3. This is about a factor of two larger than that of Titan-56.

As indicated in Fig. 6, for both flybys, the spacecraft flew by the dark side of Titan. Hence, the "Sun vs. shadow" factor could not be used to account for the "factor of 2" density difference.

Table 3. Temporal Variation of Titan Atmospheric Density (at 1080-km Altitude)

Flyby	Date/Time	Prime Science	Density at 1080-km [10^{-10} kg/m^3]
T5	2005-106T19:12	INMS	2.88
T7	2005-250T08:12	RADAR	3.68
T16	2006-203T00:25	RADAR	2.58
T17	2006-250T20:17	INMS	2.32
T18	2006-266T18:59	INMS	3.2
T19	2006-282T17:30	RADAR	2.04
T20	2006-298T15:58	ORS	3.76
T21	2006-346T11:42	INMS	3.09
T23	2007-013T08:39	RADAR	3.57
T25	2007-053T03:12	RADAR	2.46
T26	2007-069T01:49	INMS	3.66
T27	2007-085T00:23	RSS	3.44
T28	2007-100T22:58	RADAR	3.09
T29	2007-116T21:33	RADAR	3.13
T30	2007-132T20:10	RADAR	2.43
T32	2007-164T17:46	INMS	2.29
T36	2007-275T04:43	INMS	2.16
T39	2007-354T22:58	RADAR	3.11
T40	2008-005T21:30	INMS	3.30
T41	2008-053T17:32	RADAR	1.52
T42	2008-085T14:28	INMS	2.72
T43	2008-133T10:02	RADAR	1.86
T47	2008-324T15:56	ORS	1.63
T48	2008-340T14:26	INMS	2.12
T49	2008-356T13:00	RADAR	2.12
T50	2009-038T08:51	INMS	1.65
T51	2009-086T04:44	INMS	2.05
T55	2009-141T21:27	RADAR	1.48
T56	2009-157T20:00	RADAR	1.03
T57	2009-173T18:33	INMS	2.21
T58	2009-189T17:04	RADAR/UVIS	1.27
T59	2009-205T15:34	INMS	1.68
T61	2009-237T12:52	RADAR	1.66
T65	2010-012T23:11	INMS/RADAR	1.41
T70	2010-172T01:27	MAG	1.86
T71	2010-188T00:23	INMS	2.07
T83	2012-143T01:10	INMS/RADAR	1.48
T84	2012-159T00:07	RADAR	2.06
T85	2012-206T19:47	VIMS	1.08
T86	2012-270T14:35	INMS	1.33
T87	2012-318T10:22	INMS	1.05
T91	2103-143T17:33	RADAR	0.92

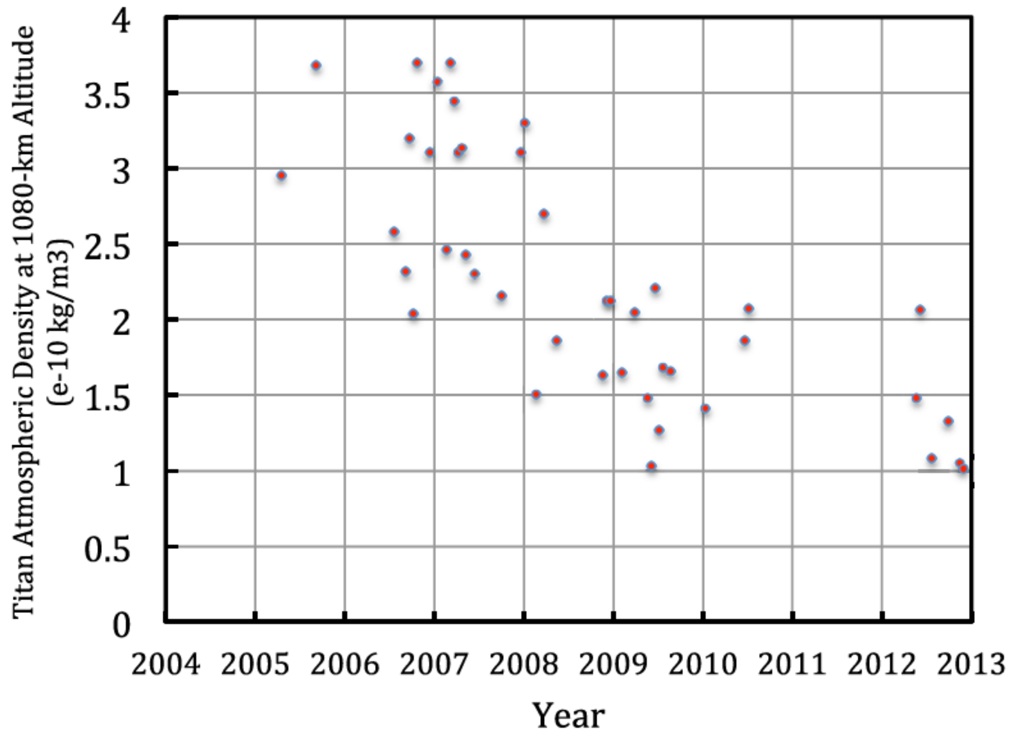

Figure 3. Density Estimates (at an Altitude of 1080 km) As A Function of Time (There wasn't any low-altitude Titan flyby in 2011)

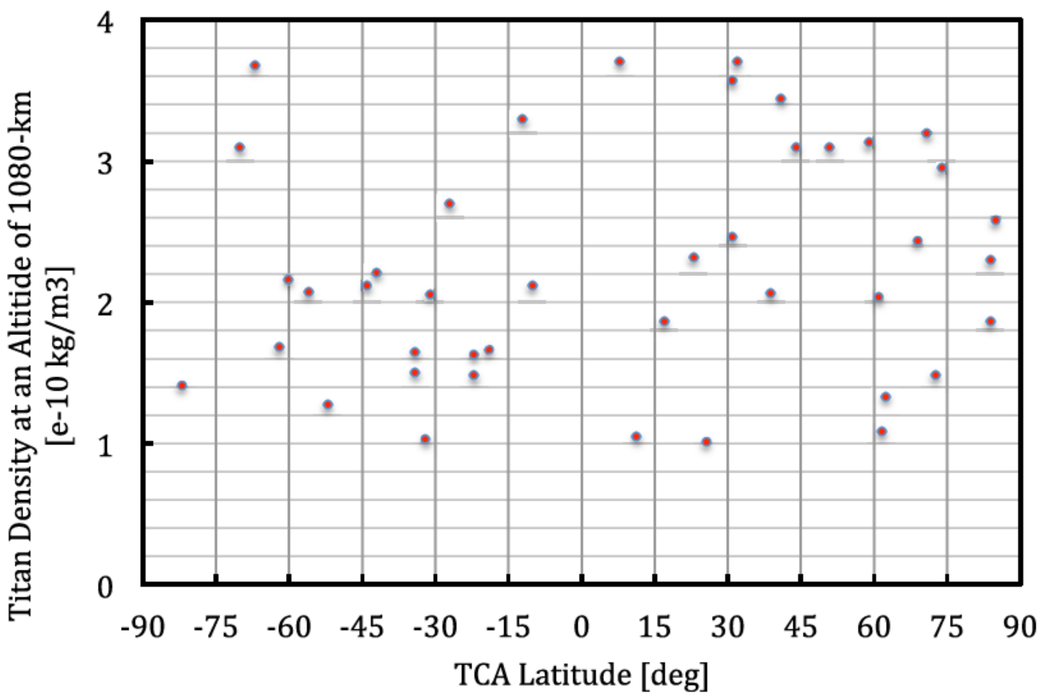

Figure 4. Variation of Titan Atmospheric Density Estimates (at an Altitude of 1080 km) With TCA Latitudes

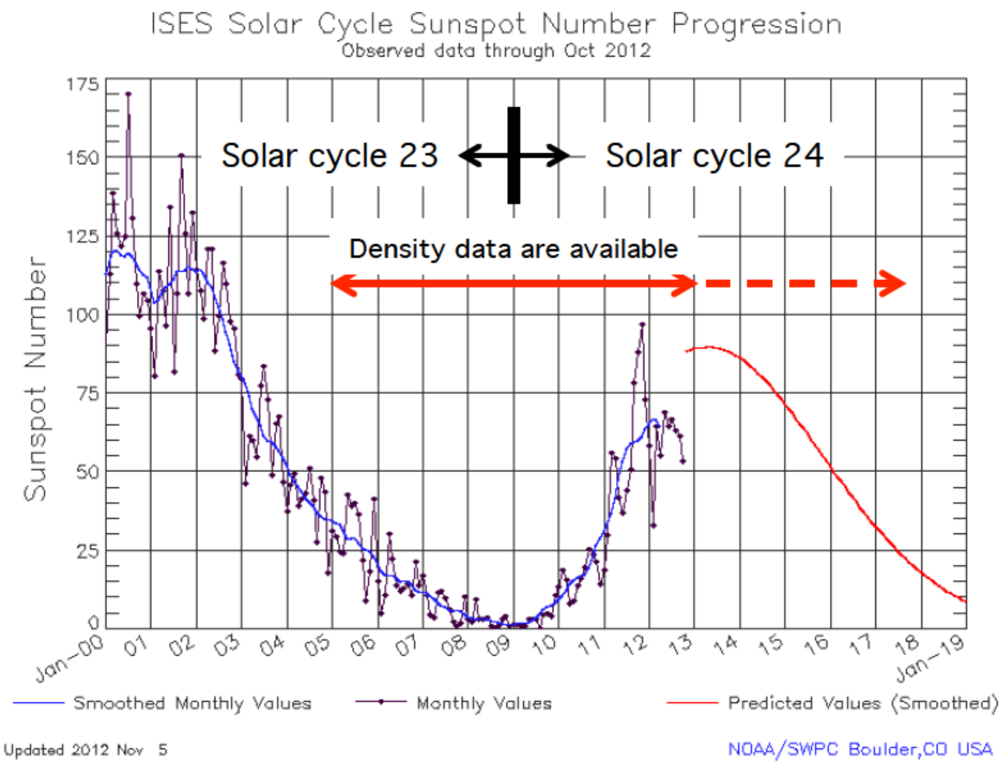

Figure 5. Solar cycles 23 and 24

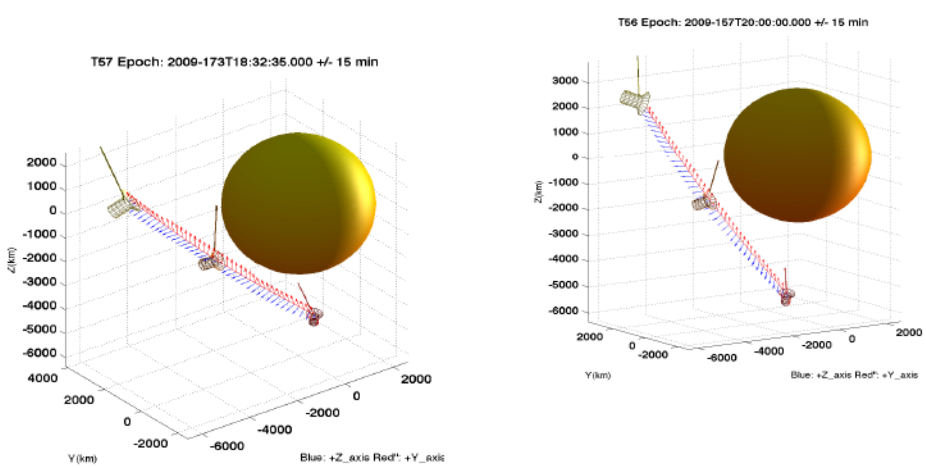

Figure 6. Flyby geometries of Titan-56 and 57 (TCA±15 min.)

4. Future Titan flybys

Density estimates from 19 future (in 2013 to 2017) low-altitude Titan flybys will help us better understand the temporal variation of Titan atmospheric density. Details of these flybys are tabulated in Table 4.

Table 4. Future Low-altitude Titan Flybys (2nd half of 2013 to 2017)

Flyby	TCA Year/Date	TCA [km]
T92	2013-Jul-10	964
T93	2013-Jul-26	1,017
T94	2013-Sep-12	1,017
T95	2013-Oct-14	961
T96	2013-Dec-01	1,018
T100	2014-Apr-07	963
T104	2014-Aug-21	964
T105	2014-Sep-22	1,021
T106	2014-Oct-24	1,013
T107	2014-Dec-10	980
T108	2015-Jan-11	970
T113	2015-Sep-28	1,036
T116	2016-Feb-01	1,027
T117	2016-Feb-16	1,018
T118	2016-Apr-04	990
T119	2016-May-06	971
T120	2016-Jun-07	975
T121	2016-Jul-25	976
T126	2017-Apr-22	979

5. Conclusions

Titan's atmospheric density is of interest not only to planetary scientists but also to the mission design and mission control engineers. Knowledge of the dependency of Titan's atmospheric density with altitude is important because any unexpectedly high atmospheric density has the potential to tumble the spacecraft during a flyby. In 2005–2013, 43 low-altitude Titan flybys were executed. The closest approach altitudes of these Titan flybys ranged from 878 to 1,027 km. Our density results are also compared with those reported by other investigation teams: Voyager-1 (in November 1980) and the Huygens Atmospheric Structure Instrument, HASI (in January 2005). From our density estimates, we observe a temporal variation of the Titan atmospheric density in 2005–2013. The observed temporal variation is significant and it isn't due to the estimation uncertainty (5.8%, 1σ) of the density estimation methodology. Factors that contributed to this temporal variation have been conjectured but are largely unknown. The observed temporal variation will require synergetic analyses with measurements made by other Cassini science instruments and future years of laboratory and modeling efforts to solve. The estimated atmospheric density data will help scientists to better understand the density structure and model of the Titan atmosphere. The same density estimation methodology will be used on data from 19 Titan flybys to be executed in 2013–2017.

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