Targeting *Cassini*'s Final Titan Flybys

Launched 15 October 1997, the *Cassini* robotic spacecraft has been in orbit about Saturn since 1 July 2004. During *Cassini*'s initial orbits, Saturn's north pole was deep in wintertime darkness. With the cycle of Saturn's seasons spanning more than 29 years, Figure 1 shows the planet's north pole illuminated by late spring sunlight as viewed from *Cassini* after nearly 12 years in orbit.

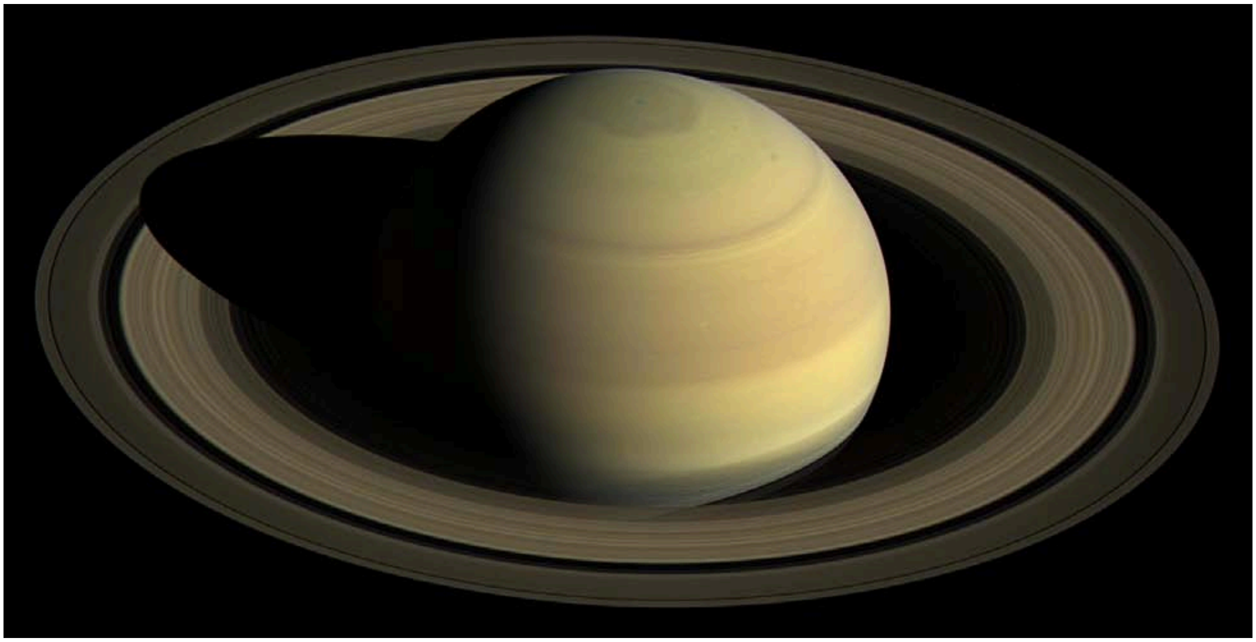

Figure 1. *Cassini*'s view of Saturn and its rings from 34° N Lat is captured with a true color mosaic of three images obtained on 25 April 2016, about 13 months before Saturn's next northern summer solstice. Note the dark hexagonal jet stream circumscribing Saturn's north rotational pole at about 77° N Lat. Each side of this hexagon is slightly larger than Earth's diameter. Image credit: NASA-JPL (reference PIA21046).

Figure 1's perspective cannot be achieved from Earth. Virtually none of Saturn's nightside is ever visible because of Earth's proximity to the Sun. Earlier in 2016, however, *Cassini*'s orbit inclination with respect to Saturn's equatorial plane was insufficient to achieve latitudes more than 1.4°, and the planet's rings were only viewed edge-on.[1] But by 25 April, inclination had been increased to nearly 29°.[2]

Although *Cassini*'s propulsive systems are essential to maintaining a precision trajectory according to plan, they are insufficient to appreciably change the spacecraft's Saturn orbit plane. In this context, the "heavy lifting" is done with accurately targeted flybys of Titan, Saturn's

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[1] All *Cassini* trajectory information in this report is obtained from JPL's *Horizons* ephemeris for the spacecraft last updated 9 September 2015. *Horizons* is available at http://ssd.jpl.nasa.gov/?horizons (accessed 24 November 2016). Because the real world *Cassini* trajectory is frequently corrected by its propulsive systems, the *Horizons* ephemeris remains highly accurate. On 16 November 2016, *Cassini* performed its 464th planned propulsive trajectory correction in Saturn orbit (some of these corrections were cancelled because they became too small in magnitude or inefficient based on final trajectory assessments).

[2] Despite being at i =28.8° on 25 April 2016, *Cassini*'s latitude on Saturn increased from 33.86° N to 34.01° N on this UT date. This curious geometry arises from Saturn's oblate cross-section along a meridian as quantified by the its 0.09796 flattening factor, the highest of any planet (Earth's is 0.00335).

largest moon, whose mass is 2.25% that of Earth's (or 1.83 times the Moon's mass). Titan orbits Saturn at a mean distance from Saturn's center of 1.22 million km and inclination of 0.28°. To retain Titan flyby capability, *Cassini* has therefore maintained a node on the Saturn equatorial plane near 1.22 million km. Each Titan flyby has a "T-NNN" designator, where "NNN" is a chronological sequence counter. *Cassini*'s inclination is plotted versus time as a series of "steps" in Figure 2, with each step corresponding to a Titan flyby.

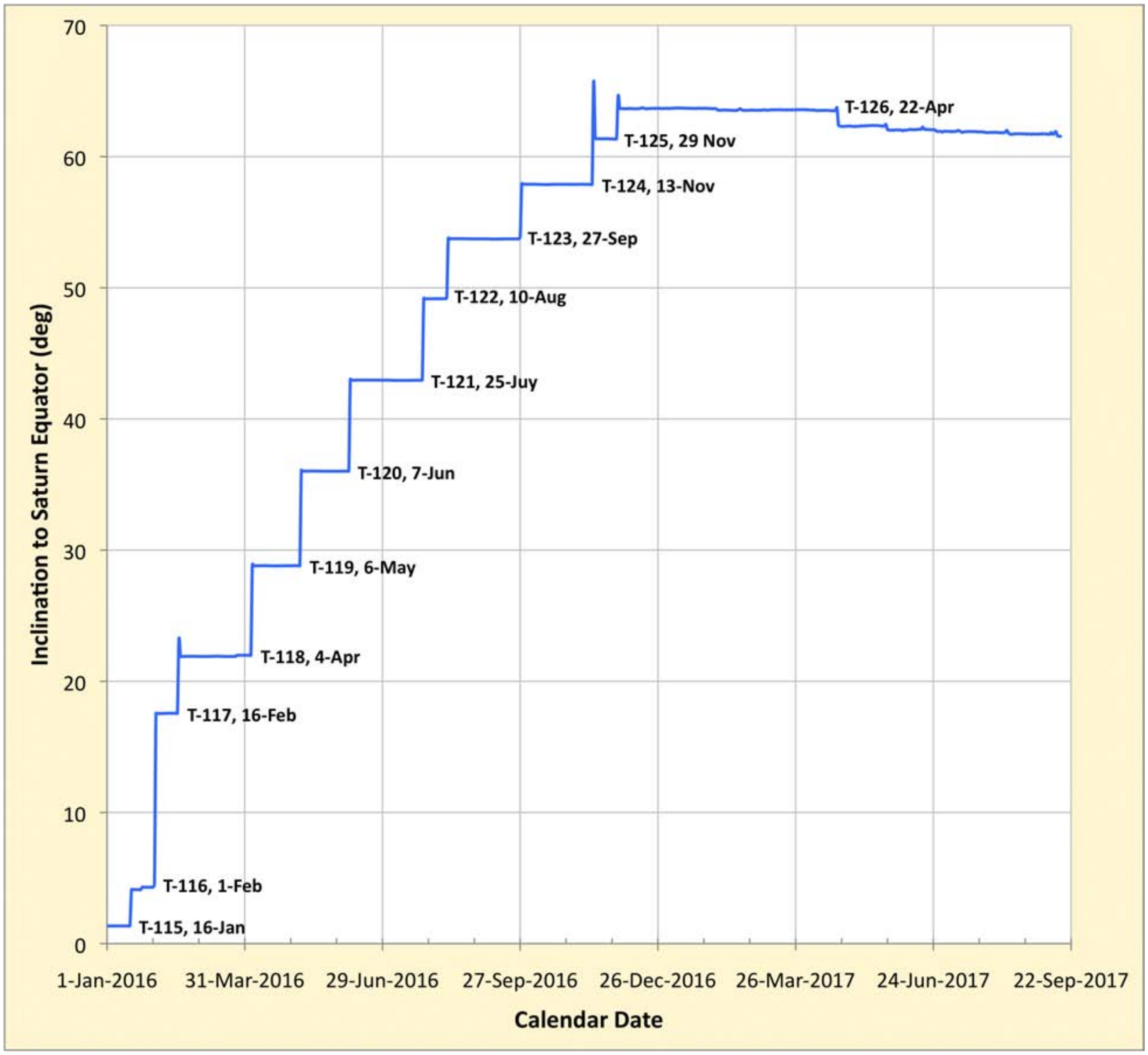

Figure 2. The history of *Cassini* inclination with respect to Saturn's equatorial plane is plotted during 2016 and 2017. Plotted data are computed at daily intervals, and inclination spikes arise when a Titan flyby, such as T-117's, is in progress at the computation epoch.

The Figure 2 plot ends on 15 September 2017, when *Cassini* is targeted to enter Saturn's atmosphere and incinerate. Spacecraft disposal is desirable at this time because *Cassini*'s propulsive consumables are nearing depletion after almost 20 years in space. Post-depletion, science-enabling trajectory and attitude control will no longer be possible. Furthermore, thanks to *Cassini* observations, Titan and Saturn's moon Enceladus are now known to have subsurface oceans, possible abodes for extraterrestrial life. Incinerating *Cassini* in Saturn's atmosphere is therefore deemed consistent with NASA's planetary protection policy.[3]

Figure 3 shows how Titan flybys in late 2016 and 2017 progressively lower the *Cassini* orbit's closest approach to Saturn's center, its perichrone, to achieve disposal. Note how perichrone evades potential collisions with particles in Saturn's G-Ring, F-Ring, and D-Ring during this process.[4]

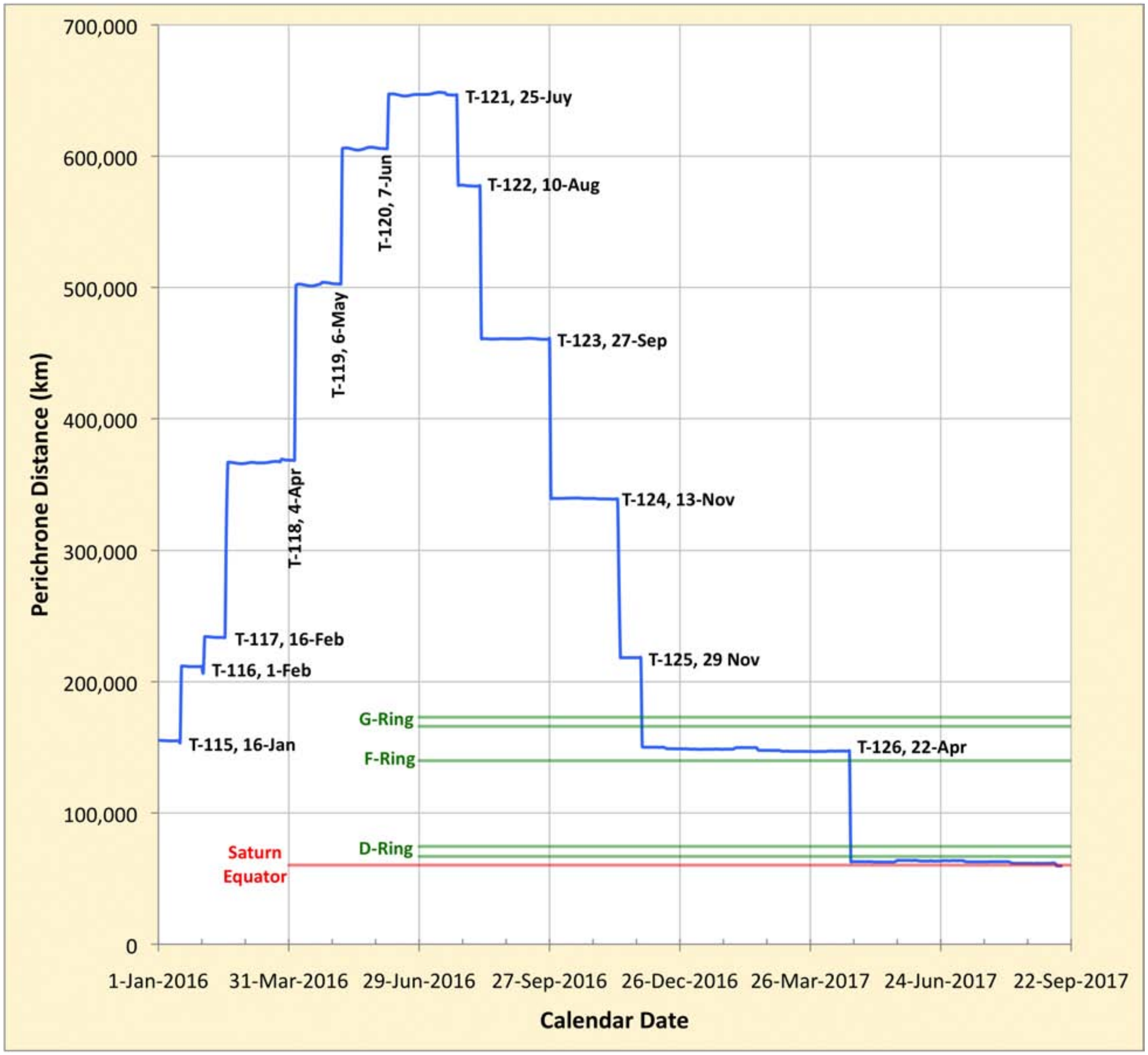

Figure 3. The history of *Cassini* perichrone is plotted during 2016 and 2017. Ring distances from Saturn's center are co-plotted in green, and Saturn's equatorial radius, where *Cassini* atmospheric incineration will occur, is co-plotted in red.

[3] Reference https://saturn.jpl.nasa.gov/mission/grand-finale/why-end-the-mission/ (accessed 24 November 2016).
[4] Ring distances from Saturn's center plotted in Figure 3 are obtained at http://nssdc.gsfc.nasa.gov/planetary/factsheet/satringfact.html (accessed 22 November 2016).

The interval between flybys T-125 and T-126 (29 November 2016 and 22 April 2017, respectively) is a series of 20 "ring-grazing" orbits with perichrone only 11,000 km outside Saturn's braided and dynamic F-Ring. Exposures in the Figure 1 mosaic are insufficient to image the F-Ring in its location immediately outside Saturn's visible rings, but details within an F-Ring segment are well resolved in Figure 4. Also visible in Figure 4 is the irregularly shaped moon Prometheus. *Cassini* will scrutinize ring features and irregular moons similar to those in Figure 4 during the 20 ring-grazing perichrone passages.

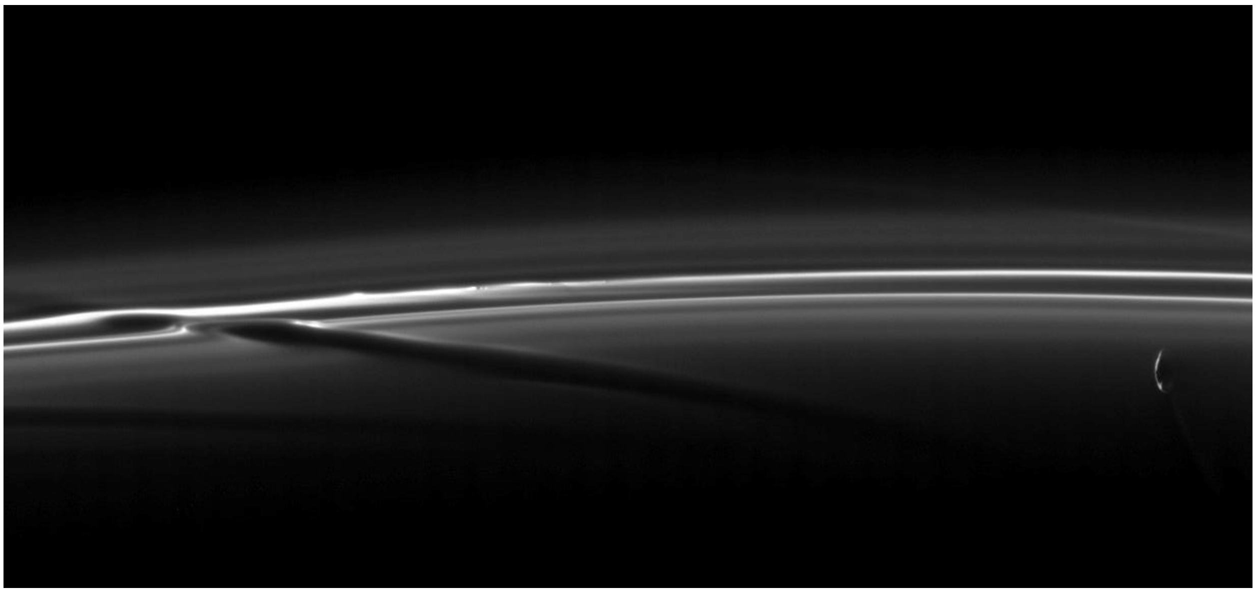

Figure 4. A portion of Saturn's F-Ring appears in this *Cassini* image obtained on 2 February 2009 from 24° S Lat. Disturbances in F-Ring particles at left are caused by recent passage of the shepherding moon Prometheus, seen in silhouette at right orbiting just inside the F-Ring. Diameter of Prometheus measured along its major axis is 148 km. Image credit: NASA-JPL (reference PIA11457).

As illustrated in Figure 3, *Cassini*'s final T-126 flyby lowers perichrone to a distance inside all the rings seen in Figure 1 and barely 2600 km above Saturn's atmosphere. This begins the "grand finalé" portion of the mission ending with *Cassini*'s incineration.

The sequence of Titan flybys chronicled in Figures 2 and 3 must be carefully timed to ensure Titan is in the same portion of its orbit as *Cassini*. Although the spacecraft's propulsive systems assist in refining this process, most of the fortuitous timing is provided by resonant orbit periods between Titan and *Cassini*. Titan's orbit period is fixed at 15.945421 days, so the desired resonance is conferred on *Cassini*'s orbit period primarily by the previous Titan flyby. As detailed in Figure 5, any orbit period for *Cassini* during 2016 and 2017 closely conforms to one of seven Titan resonances.

Figure 5 is annotated with each resonance using "N:M Titan" nomenclature. This notation conveys the number of complete *Cassini* orbits with "N" and the number of complete Titan orbits made in the same time interval with "M". For example, *Cassini* makes 20 orbits during the ring-grazing interval from T-125 to T-126 while Titan makes 9 orbits, leading to a 20:9 Titan period resonance.

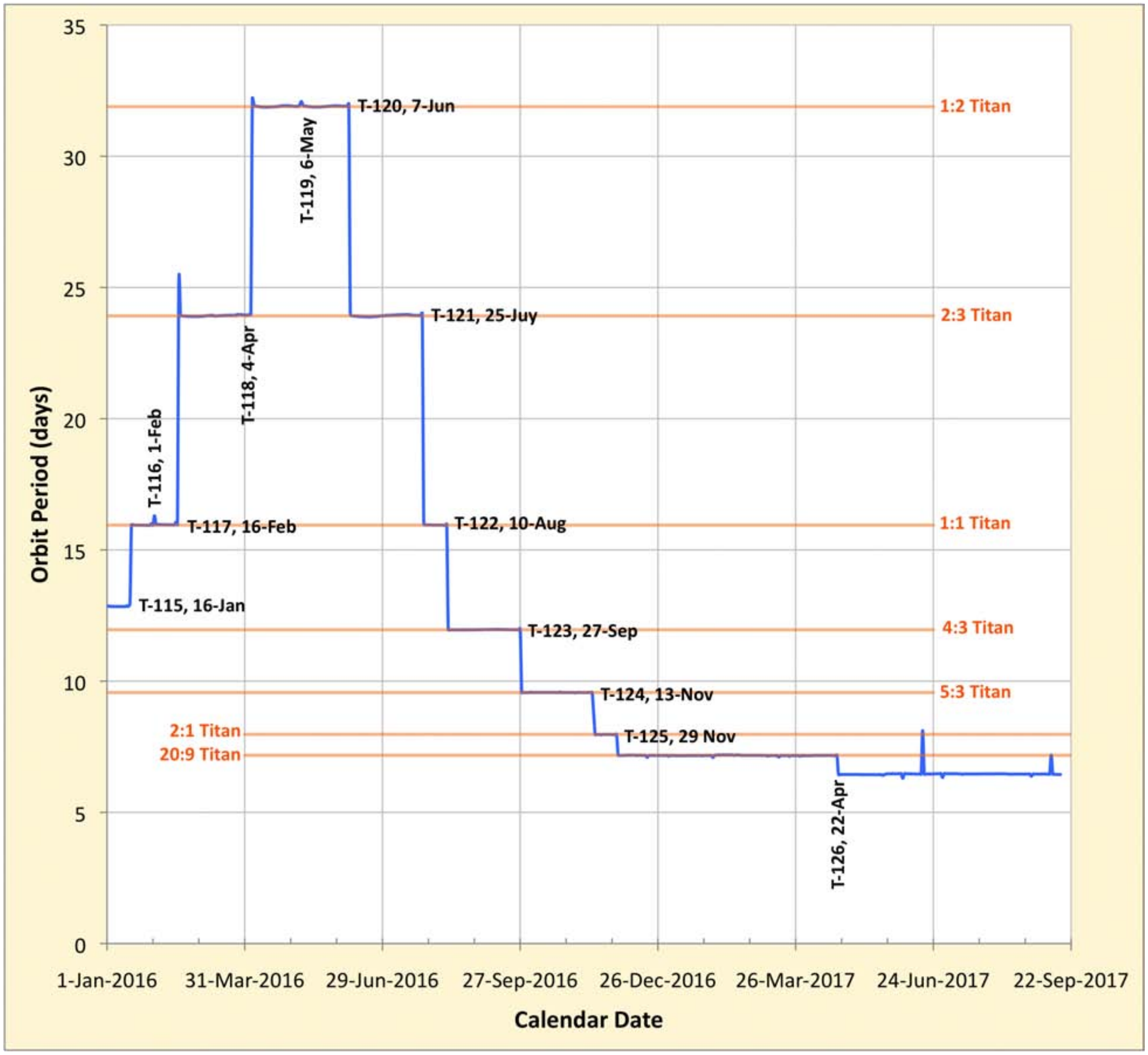

Figure 5. The history of *Cassini* orbit period about Saturn is plotted during 2016 and 2017. Orbit period resonances between *Cassini* and Titan, essential to providing properly timed Titan flybys, are annotated in orange.

Note how flybys T-116 and T-119 significantly alter inclination in Figure 2 while leaving *Cassini*'s orbit period virtually unchanged in Figure 5. From Kepler's third law, preserving Saturn-centered orbit period through a flyby requires *Cassini*'s Saturn-centered semi-major axis before and after the flyby also be preserved. The total energy or *vis viva* integral of conic motion relates semi-major axis to distance and speed. Because Saturn-centered distance is essentially constant during a Titan flyby, preserving *Cassini*'s Saturn-centered orbit period during such an event amounts to preserving Saturn-centered speed. Orbit period preservation through a flyby is a scalar requirement, but how does it relate to geometry as represented by inbound and outbound Saturn-centered *Cassini* velocities immediately before and after the flyby?

To visualize this constrained flyby geometry, consider the UVW coordinate system defined by Titan's Saturn-centered position $\boldsymbol{r}_T$ and velocity $\boldsymbol{v}_T$ at *Cassini* periapsis during a Titan flyby. The unit vector $\boldsymbol{U}$ points from Saturn along $\boldsymbol{r}_T$ toward Titan, $\boldsymbol{W}$ is directed normal to Titan's Saturn-centered orbit plane along the vector product $\boldsymbol{r}_T \times \boldsymbol{v}_T$, and $\boldsymbol{V} = \boldsymbol{W} \times \boldsymbol{U}$ in the right-handed convention. With $\boldsymbol{V}$ being the projection of $\boldsymbol{v}_T$ onto the plane whose normal is $\boldsymbol{U}$, Titan's nearly circular Saturn-centered orbit (eccentricity is 0.0288) supports visualizing $\boldsymbol{v}_T$ as well aligned with $\boldsymbol{V}$ at any time.

Geometry preserving *Cassini*'s Saturn-centered orbit period through a Titan flyby is driven by the angle θ between $\boldsymbol{V}$ and Saturn-centered *Cassini* velocity on the Titan flyby's inbound asymptote. Saturn-centered *Cassini* velocity on the Titan flyby's outbound asymptote must also deviate from the $\boldsymbol{V}$ direction by θ, or period will not be preserved. Thus, a period-preserving Saturn-centered Titan flyby outbound asymptotic velocity is constrained to lie on a cone whose axis is $\boldsymbol{V}$ and whose semi-apex angle is θ.

This precept has been assessed using multiple Titan flyby datasets from *Horizons*. Each dataset consists of the pertinent $\boldsymbol{r}_T$ and $\boldsymbol{v}_T$, together with *Cassini*'s Titan-centered position and velocity at flyby periapsis. The pertinent UVW coordinate system is defined by $\boldsymbol{r}_T$ and $\boldsymbol{v}_T$, while *Cassini* position and velocity at flyby periapsis define the Titan-centered hyperbolic flyby trajectory. This trajectory is sampled at a Titan distance of 20,000 km, roughly 46% of Titan's gravitational sphere of influence radius, to approximate flyby asymptotic velocities. The sampled velocities are incremented by $\boldsymbol{v}_T$ to produce Saturn-centered flyby approach and departure asymptotic velocities required to compute θ values. Results of these assessments are recorded in Table 1.

Table 1. *Cassini* Saturn-Centered orbit elements are sampled immediately before (inbound asymptote) and after (outbound asymptote) four Titan flybys. Note how preserving θ through flybys T-116 and T-119 also preserves orbit period even though orbit inclination is undergoing appreciable increases. When θ is not preserved through flybys T-124 and T-125, orbit period is appreciably changed in addition to inclination.

Flyby	Asymptote	*Cassini* Saturn-Centered		
		Inclination (deg)	Period (days)	θ (deg)
T-116	Inbound	4.3	15.94	56.536
	Outbound	17.5	15.97	56.598
T-119	Inbound	28.8	31.90	51.056
	Outbound	36.0	31.94	51.218
T-124	Inbound	57.9	9.56	63.760
	Outbound	61.3	7.97	67.154
T-125	Inbound	61.3	7.97	67.171
	Outbound	63.6	7.17	69.484

Figures 6 though 9 plot *Cassini* and Titan Saturn-centered inertial motion before, during, and after flybys T-124 and T-125. Each plot is viewed from a perspective very nearly normal to *Cassini*'s Saturn-centered orbit plane. Titan's motion therefore appears as an ellipse concentric with the planet's rings.

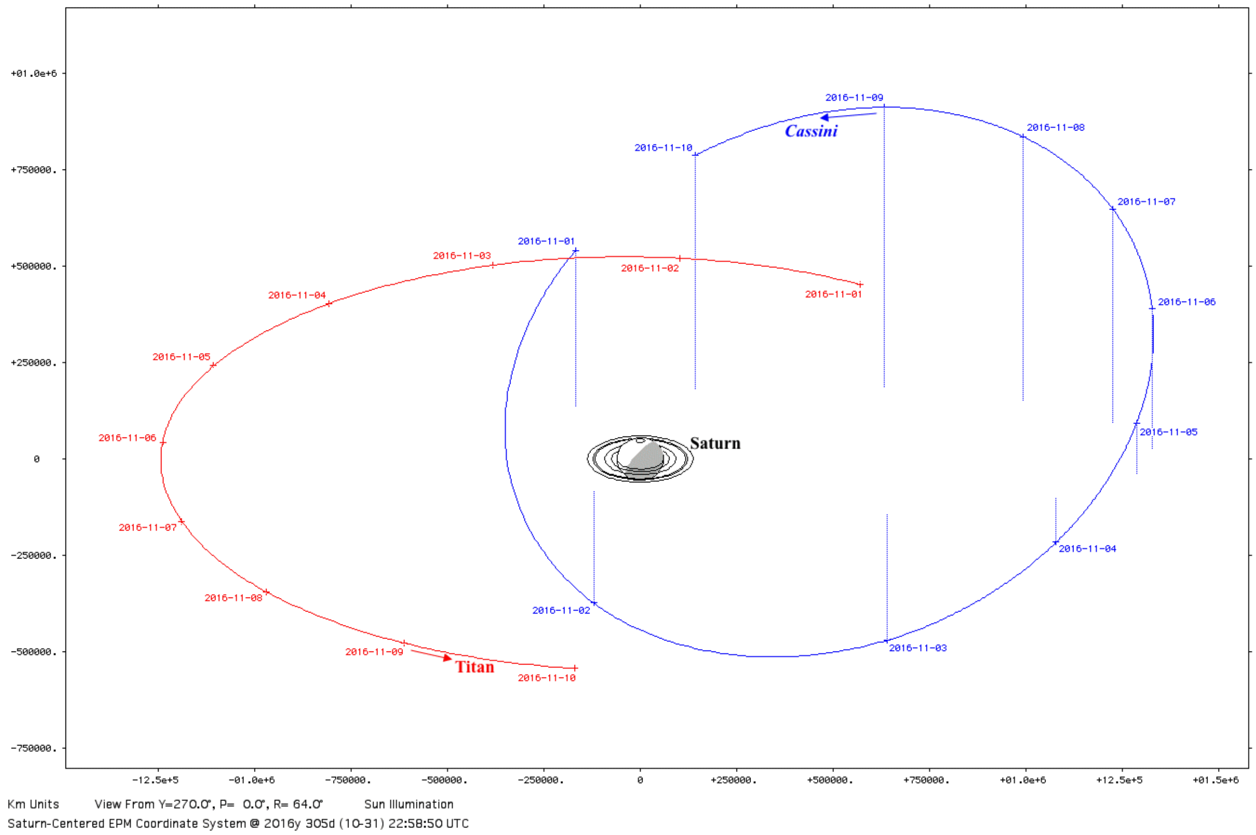

Figure 6. Saturn-centered inertial motion for *Cassini* (blue) and Titan (red) are plotted from 1 to 10 November 2016. Time ticks are at 00:00 UT on the annotated date in YYYY-MM-DD format. Dotted lines are projections onto Saturn's equatorial plane (nearly identical to that of Titan's orbit), and the shaded area is Saturn's nightside.

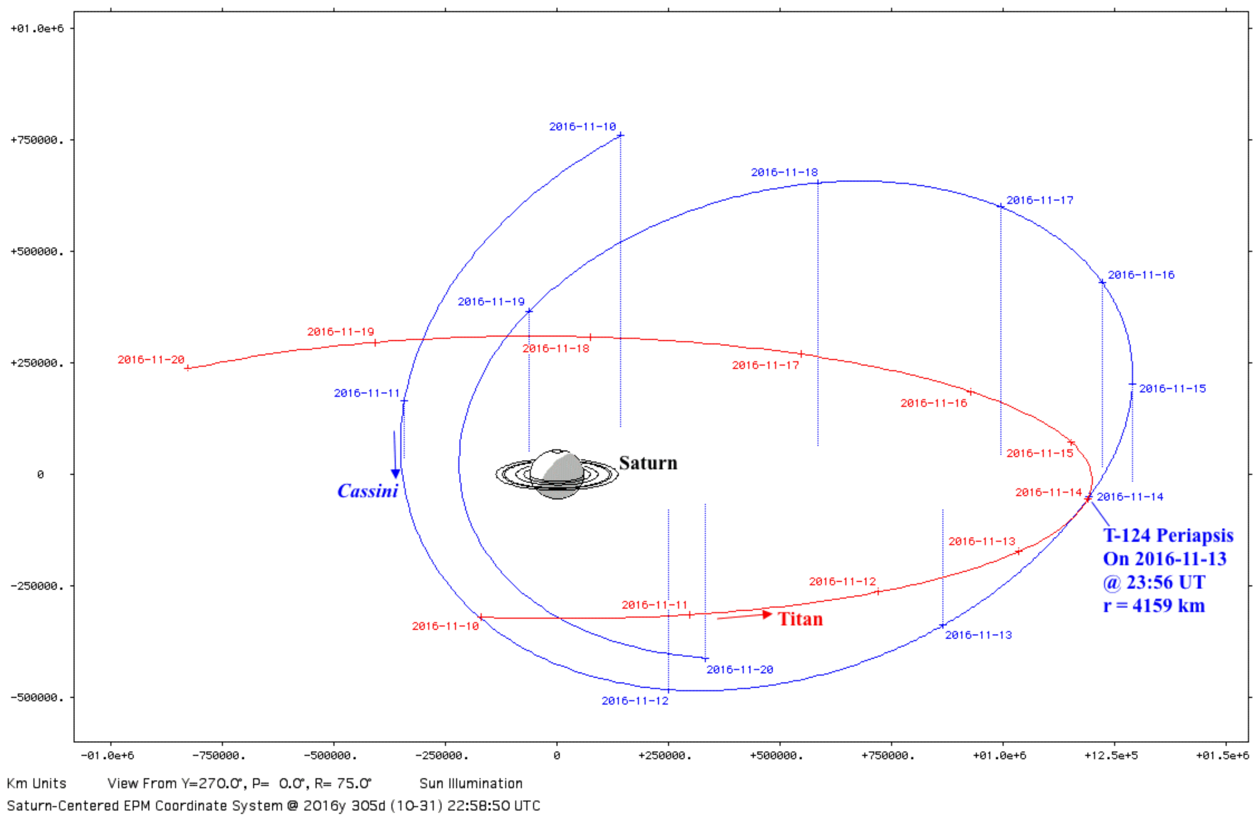

Figure 7. Saturn-centered inertial motion for *Cassini* (blue) and Titan (red) are plotted from 10 to 20 November 2016. Time ticks are at 00:00 UT on the annotated date in YYYY-MM-DD format. Dotted lines are projections onto Saturn's equatorial plane (nearly identical to that of Titan's orbit), and the shaded area is Saturn's nightside. Note how the T-124 flyby halves *Cassini*'s distance from Saturn's outermost illustrated ring[5] at perichrone. Note also how perichrone is placed very near *Cassini*'s descending node on Saturn's equatorial plane.

[5] The outermost ring annotated in Figures 6 through 9 is the A-Ring's outer limit at a distance near 136,800 km from Saturn's center. This is about 3000 km inside the F-Ring.

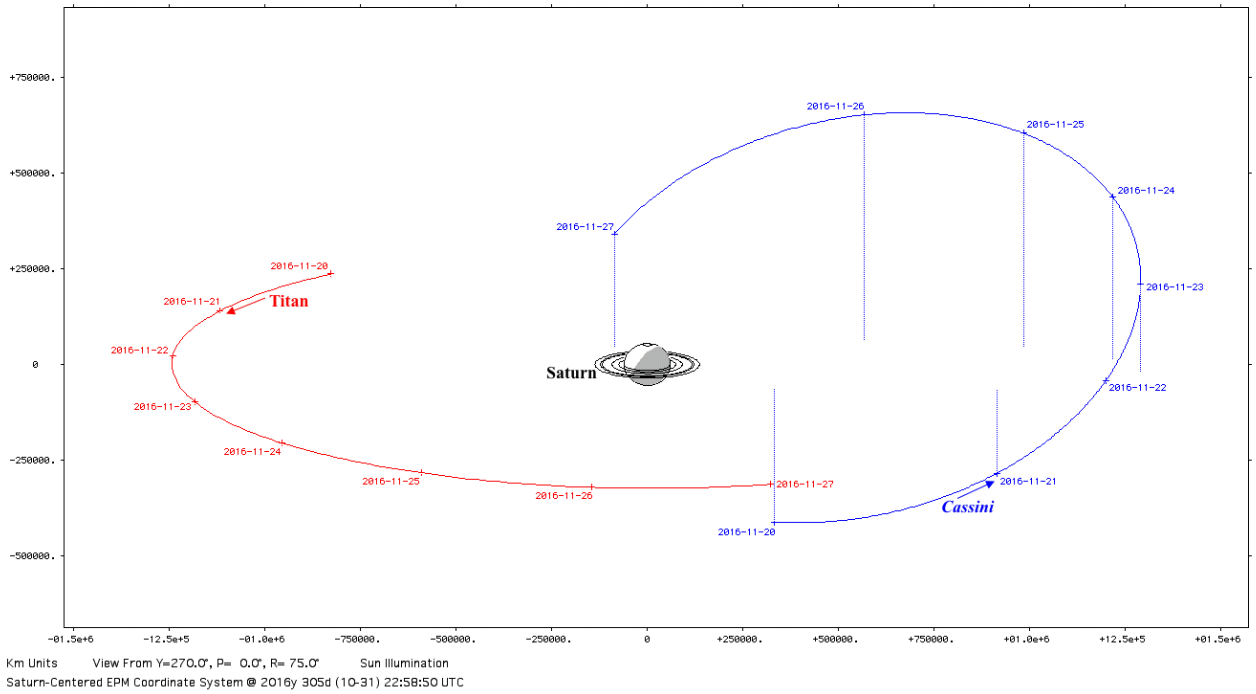

Figure 8. Saturn-centered inertial motion for *Cassini* (blue) and Titan (red) are plotted from 20 to 27 November 2016. Time ticks are at 00:00 UT on the annotated date in YYYY-MM-DD format. Dotted lines are projections onto Saturn's equatorial plane (nearly identical to that of Titan's orbit), and the shaded area is Saturn's nightside.

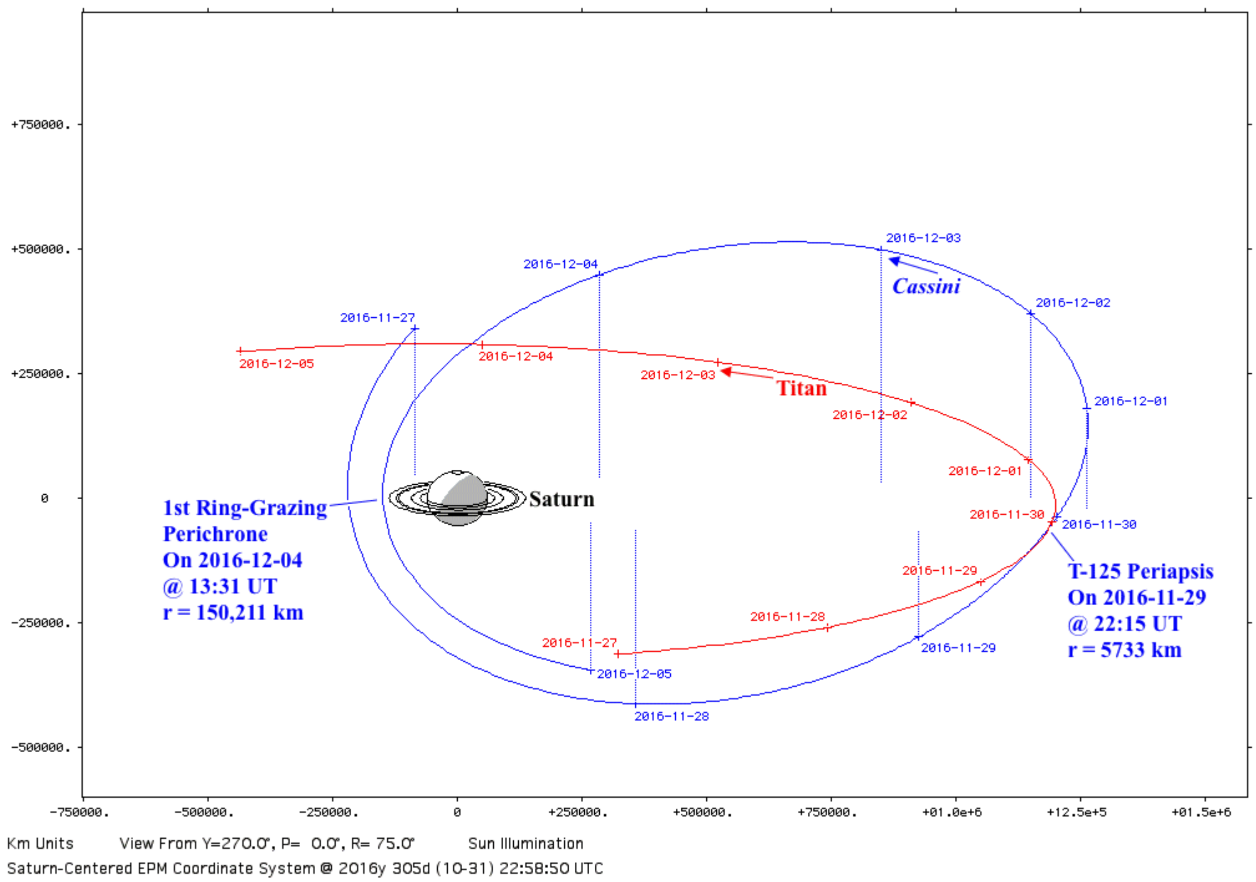

Figure 9. Saturn-centered inertial motion for *Cassini* (blue) and Titan (red) are plotted from 27 November to 5 December 2016. Time ticks are at 00:00 UT on the annotated date in YYYY-MM-DD format. Dotted lines are projections onto Saturn's equatorial plane (nearly identical to that of Titan's orbit), and the shaded area is Saturn's nightside. Note how the T-125 flyby sets up the first ring-grazing perichrone on 4 December 2016.