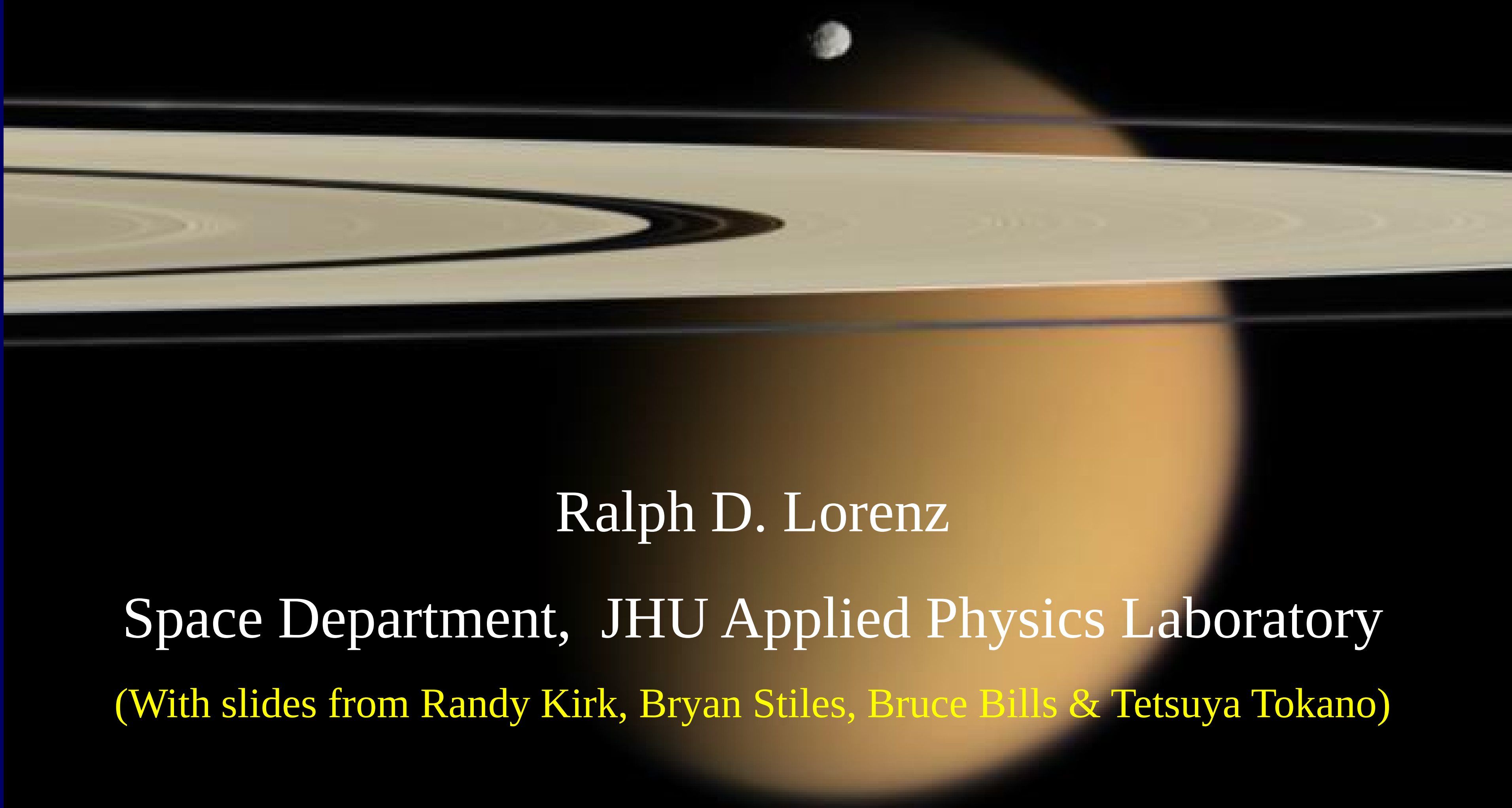
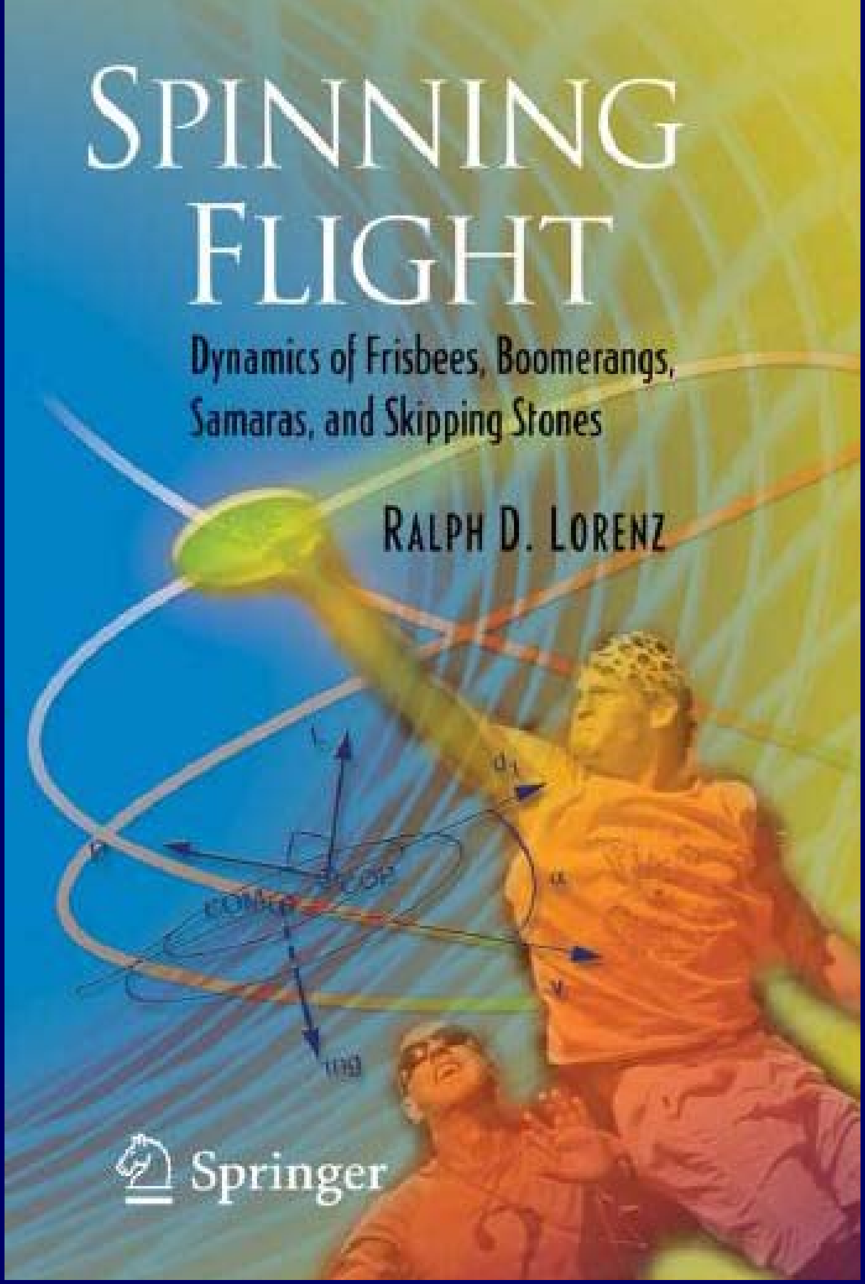
Titan's Spin



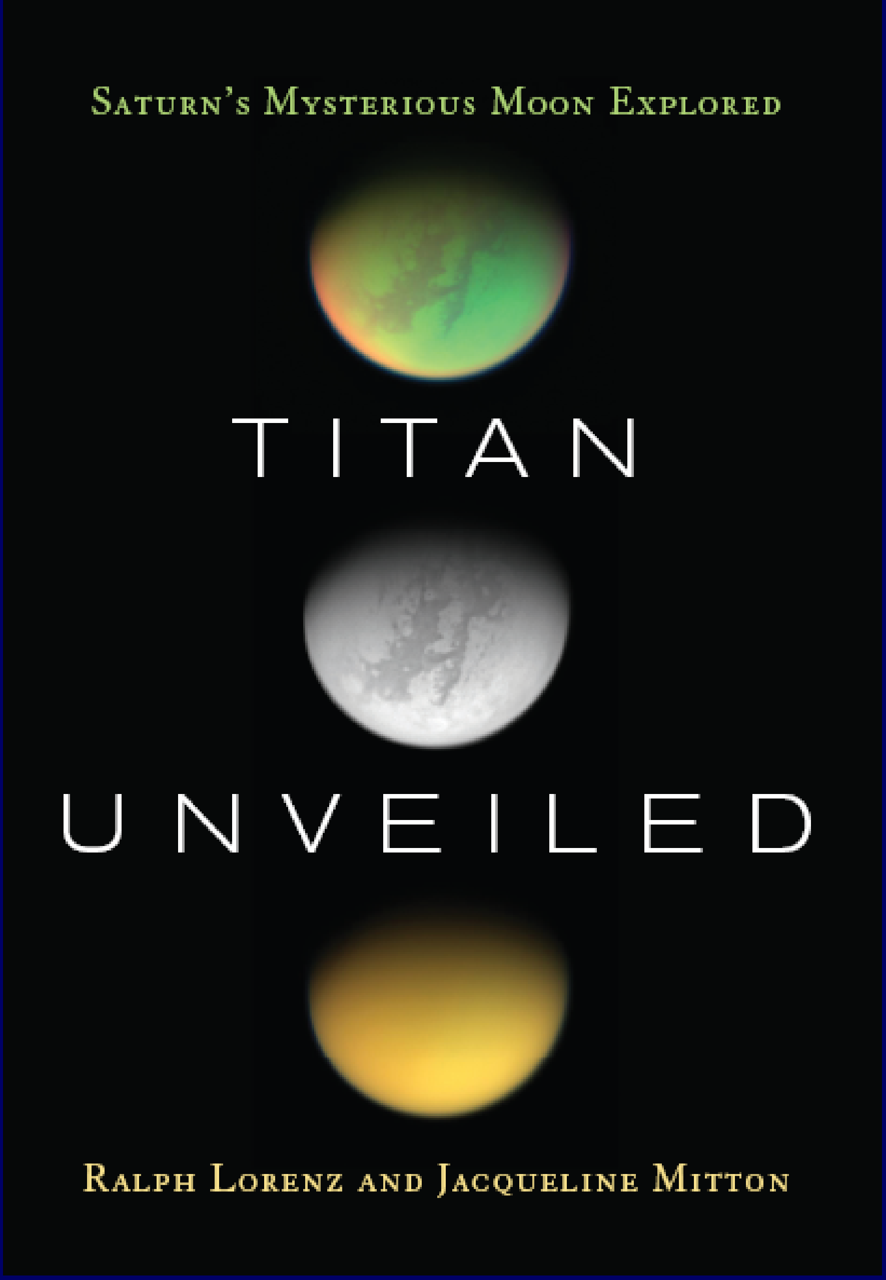
Ralph D. Lorenz

Space Department, JHU Applied Physics Laboratory

(With slides from Randy Kirk, Bryan Stiles, Bruce Bills & Tetsuya Tokano)



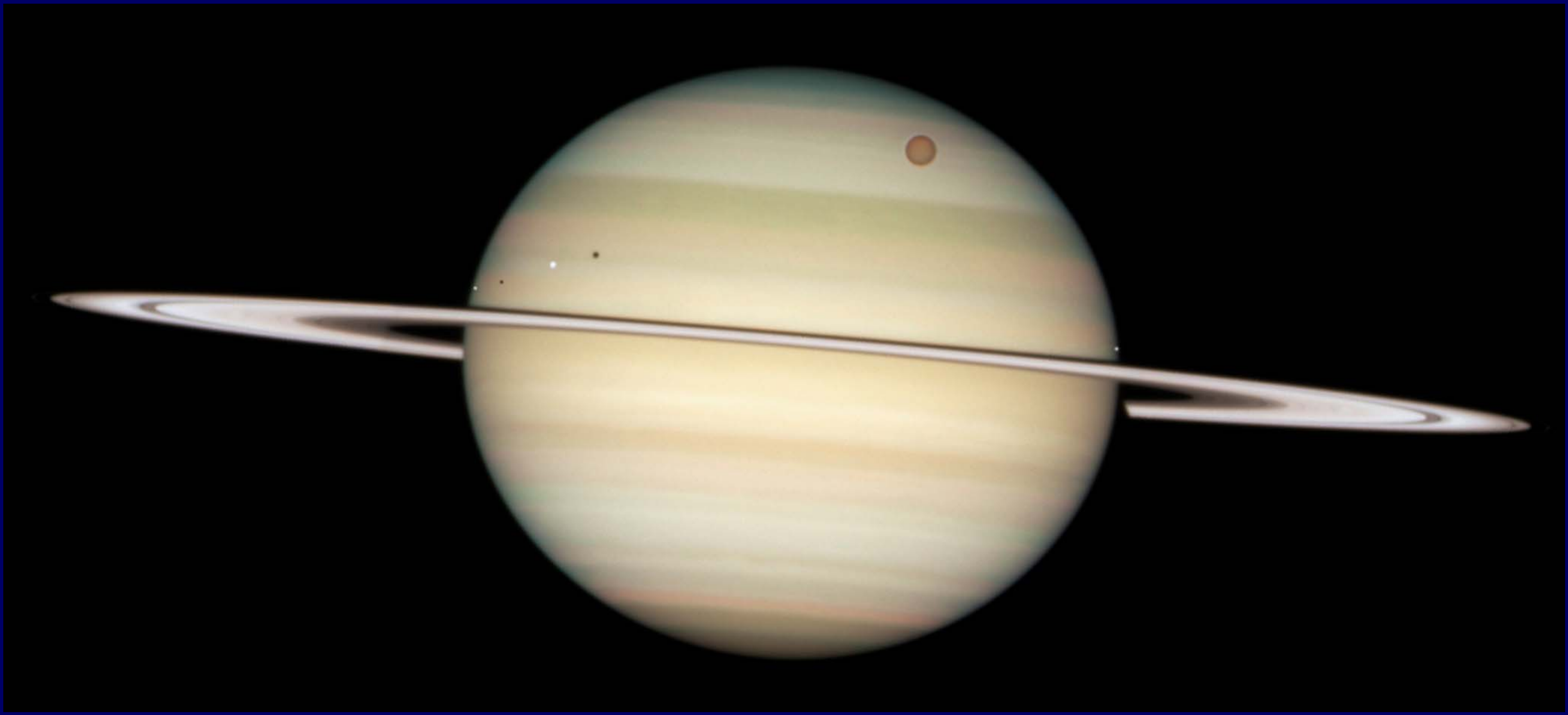
Springer 2006



PUP, 2008

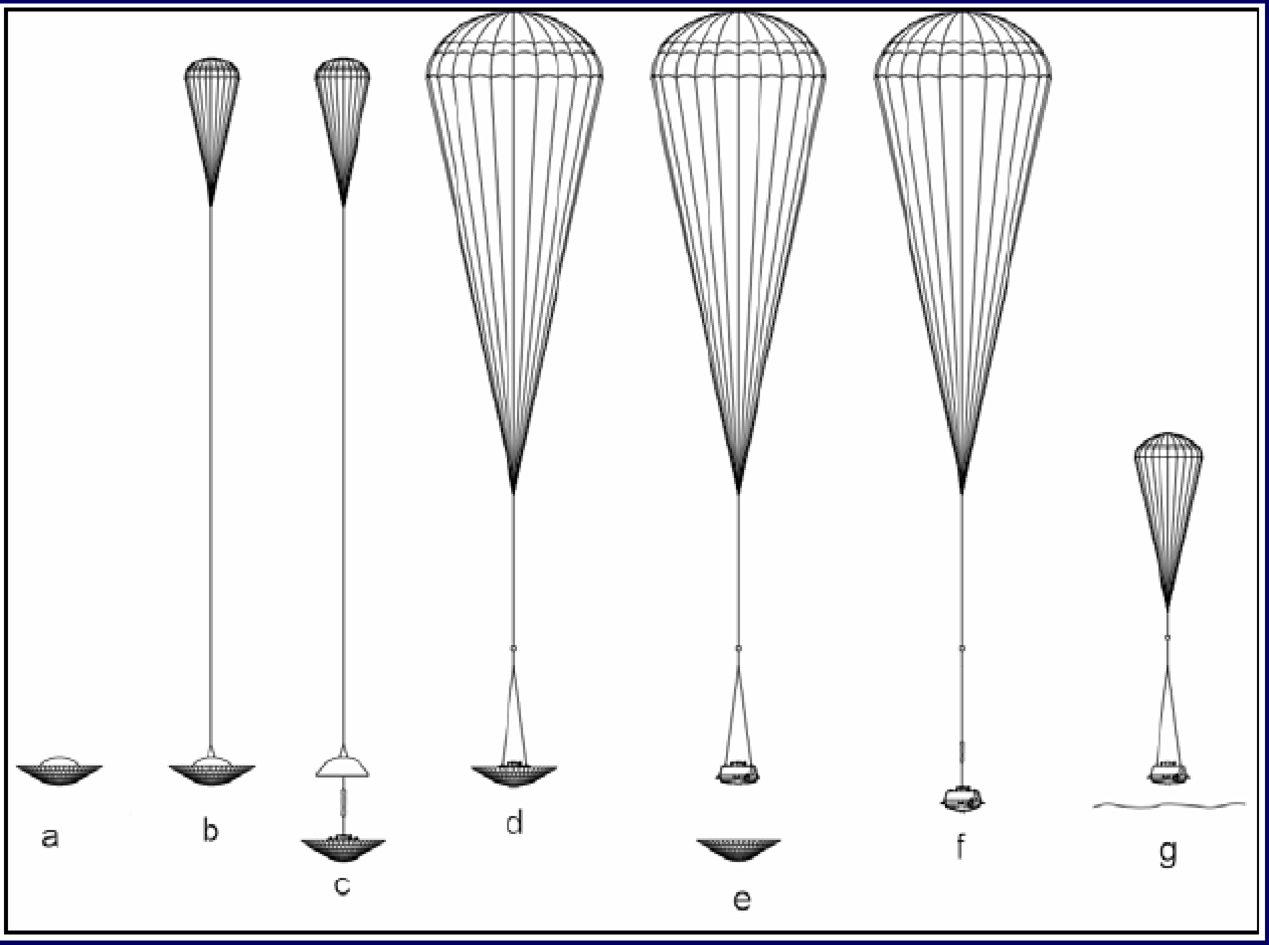
Saturn , February 2009

Hubble Space Telescope



Note that Saturn is visibly noncircular - it is rotationally flattened

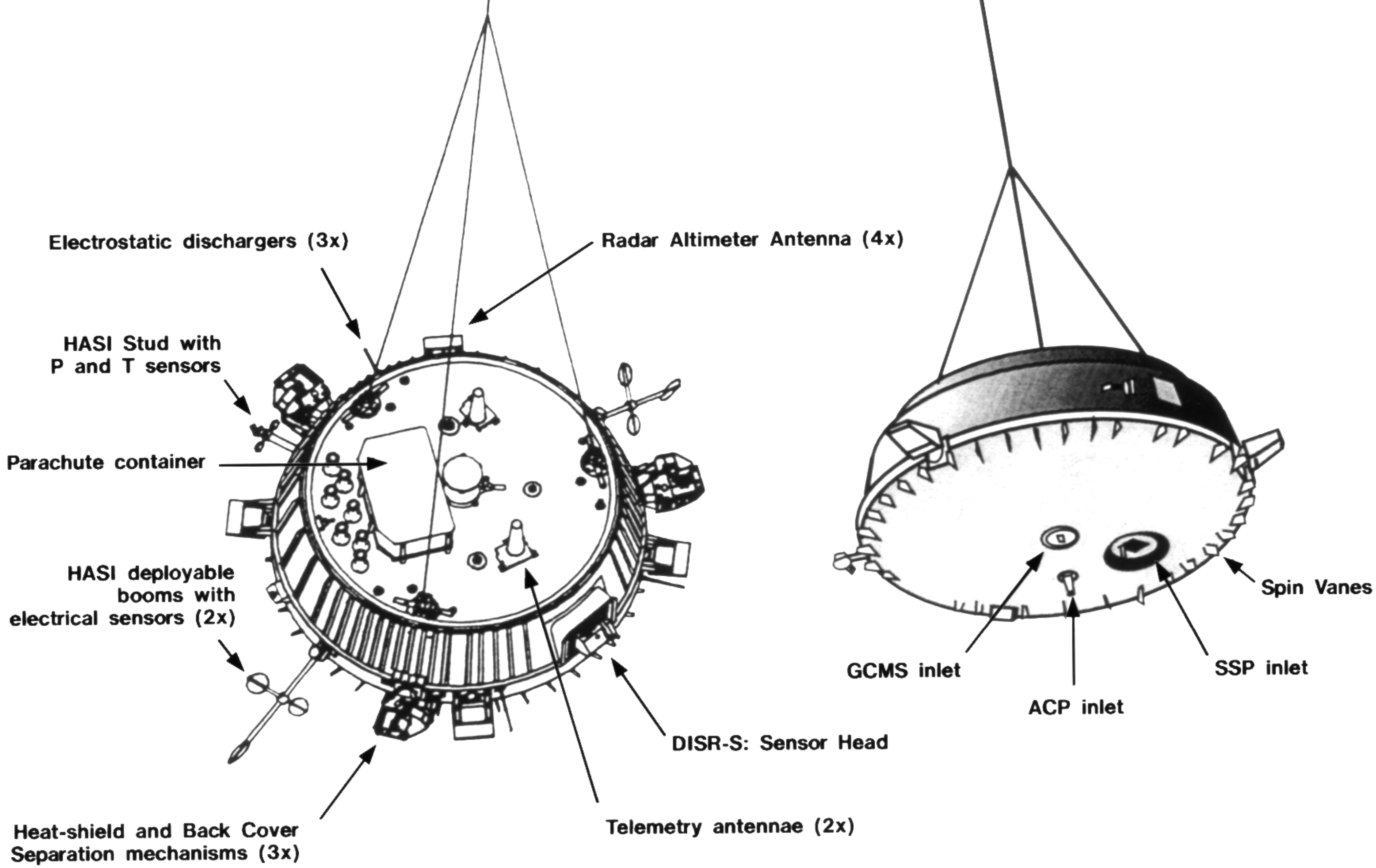
A spinful digression on The Huygens Probe



2.59m Pilot chute for transonic stability deployed by mortar through break-out patch.

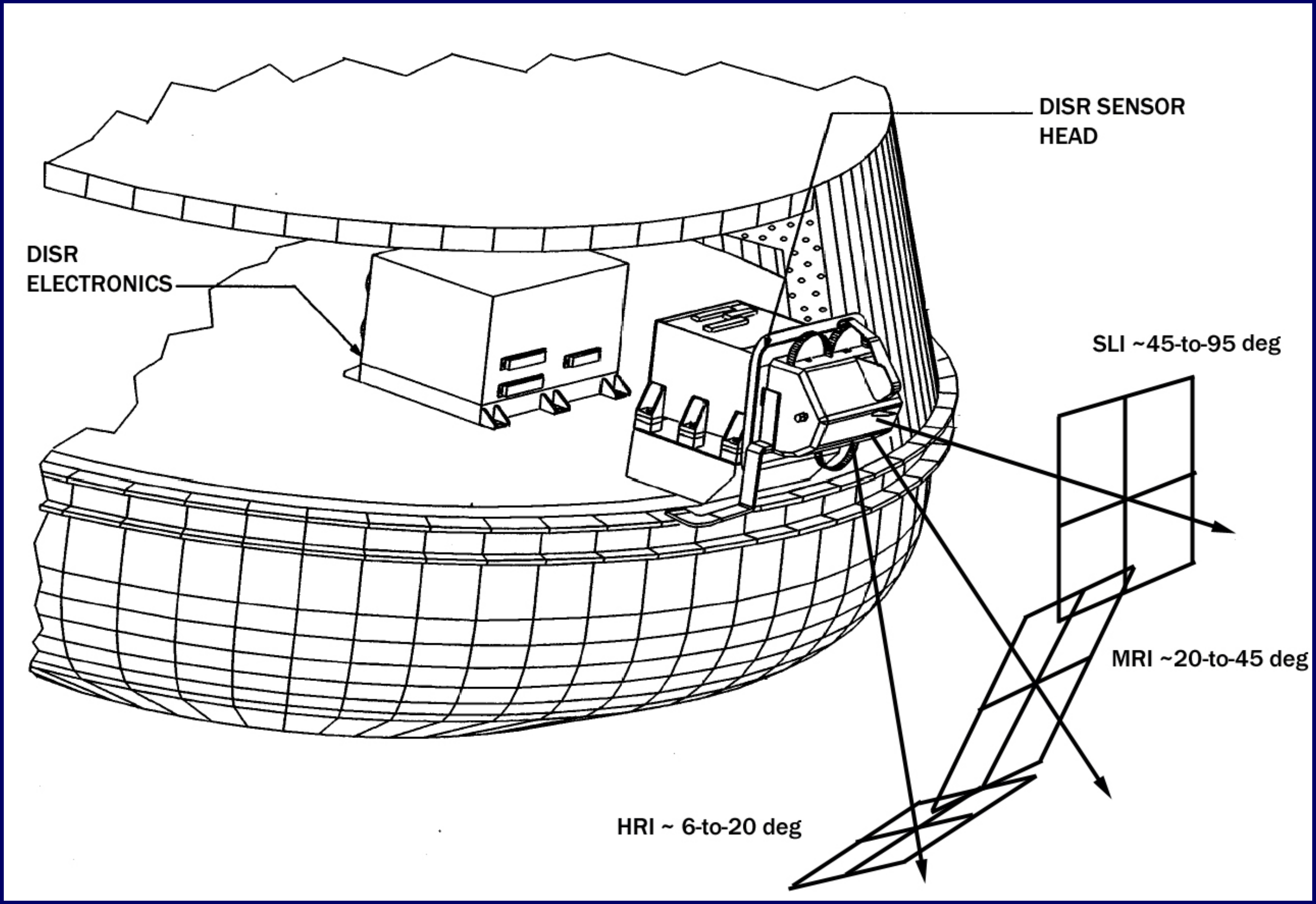
Pulls off back cover and deploys main chute via lanyard. 8.3m main chute needed for safe front shield separation.

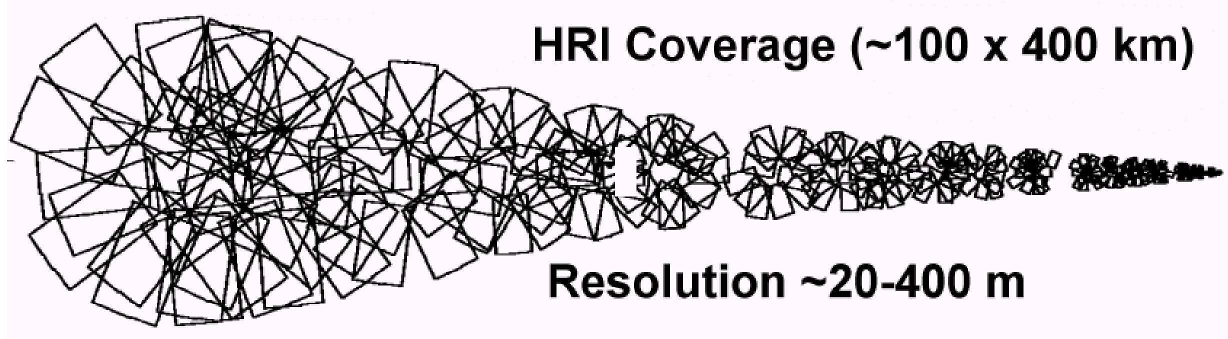
3.3m Stabilising drogue to achieve descent fast enough to reach surface within telecom & energy window.

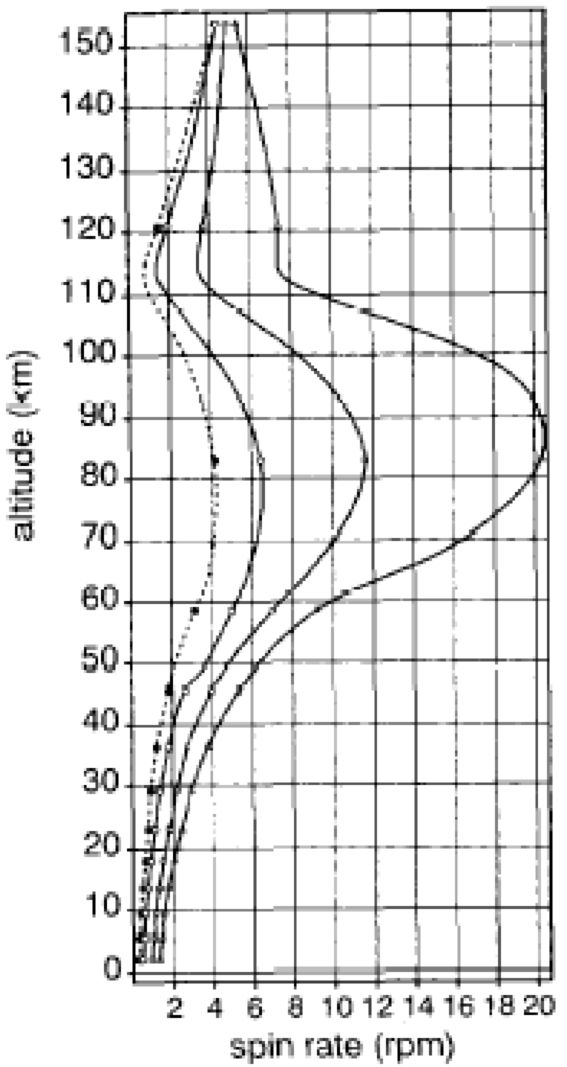


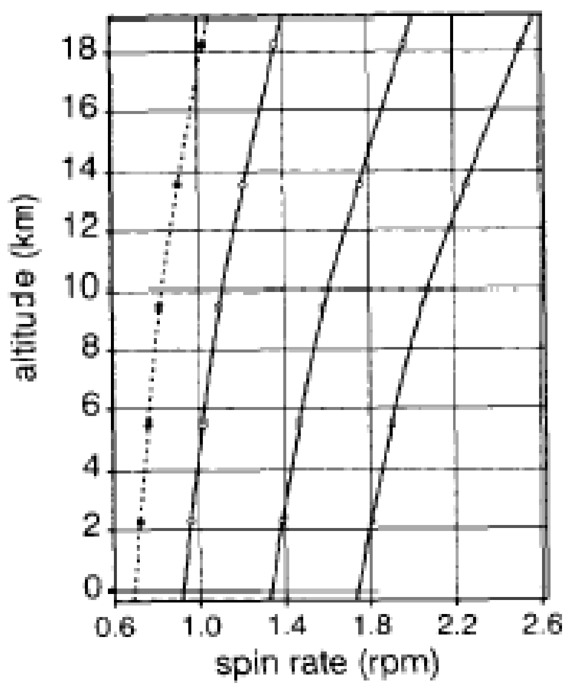
Huygens Descent Configuration. Spin Vanes (as for Galileo, Pioneer Venus) to cause slow rotation to pan DISR sensors. Spin vanes demand, subject to dynamics, an approximately constant 'corkscrew' rate revs/km.

DISR Imagers Approximate Fields-of-View



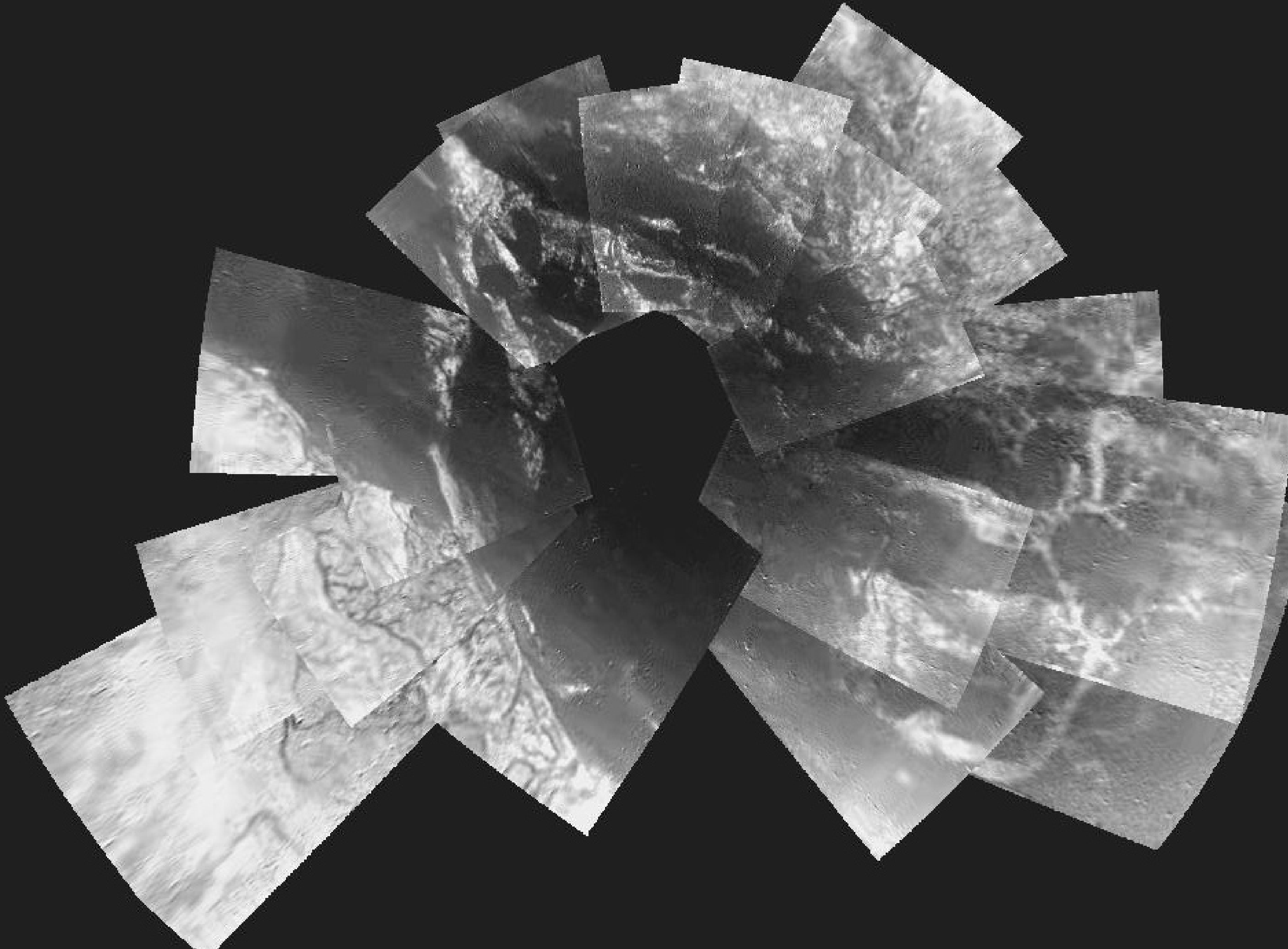


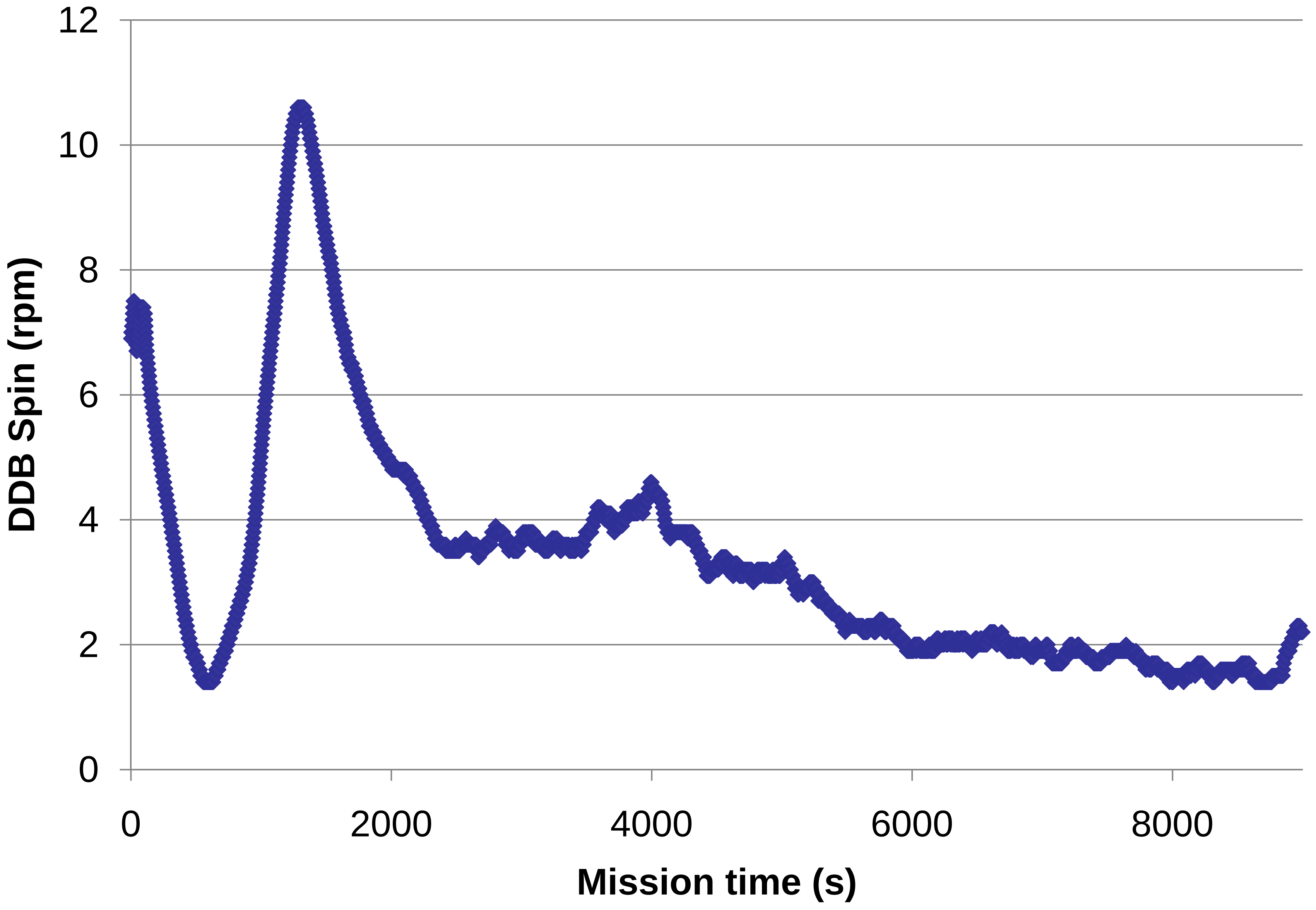




Spin requirement driven by DISR to measure solar radiation pattern (aureole etc.) and to pan imager.

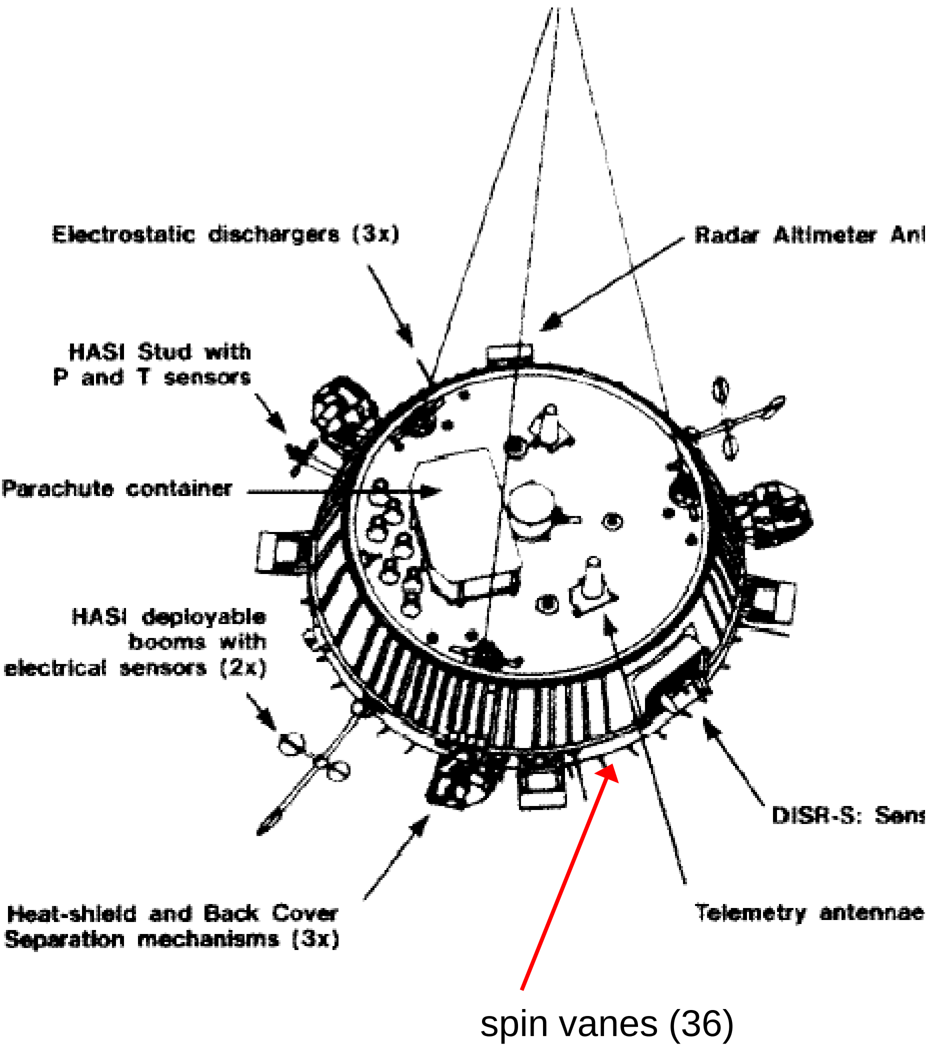
Expectation that spin at start of descent is near release rate, changes only slightly during low dynamic pressure main chute descent, then increases at parachute changeover to new profile that slowly declines.

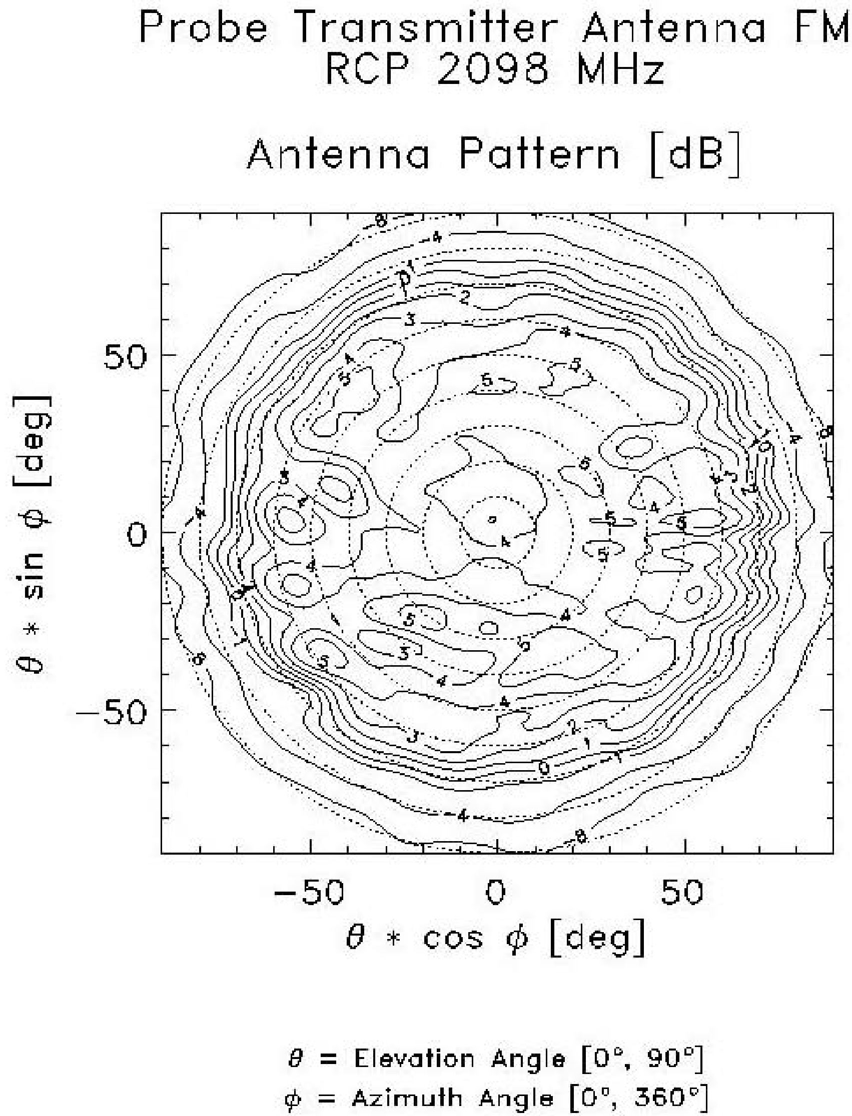




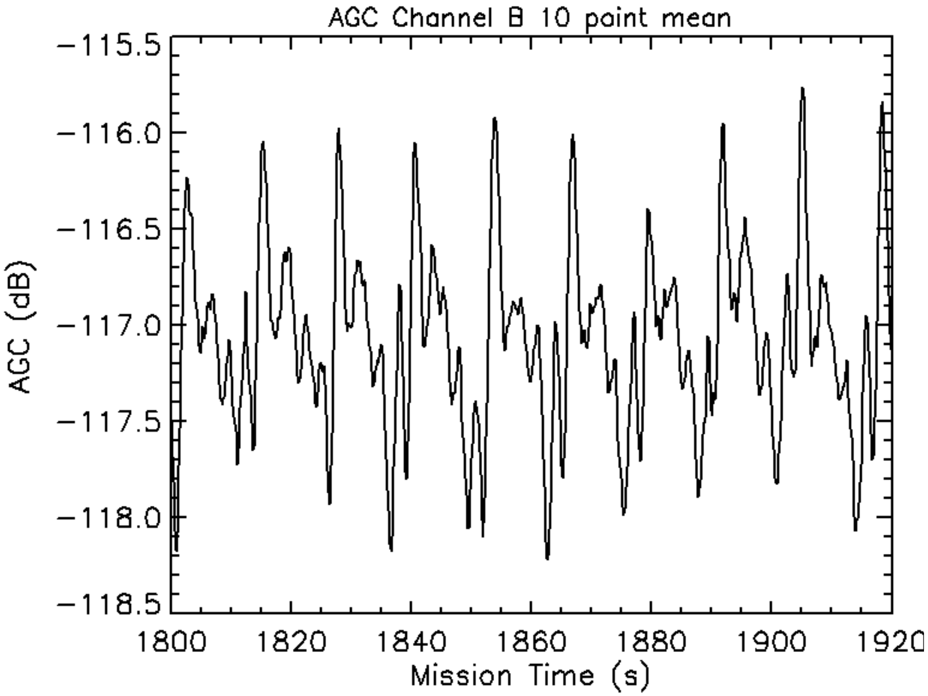
A puzzle - (unsigned) spin rate telemetry non-monotonic.

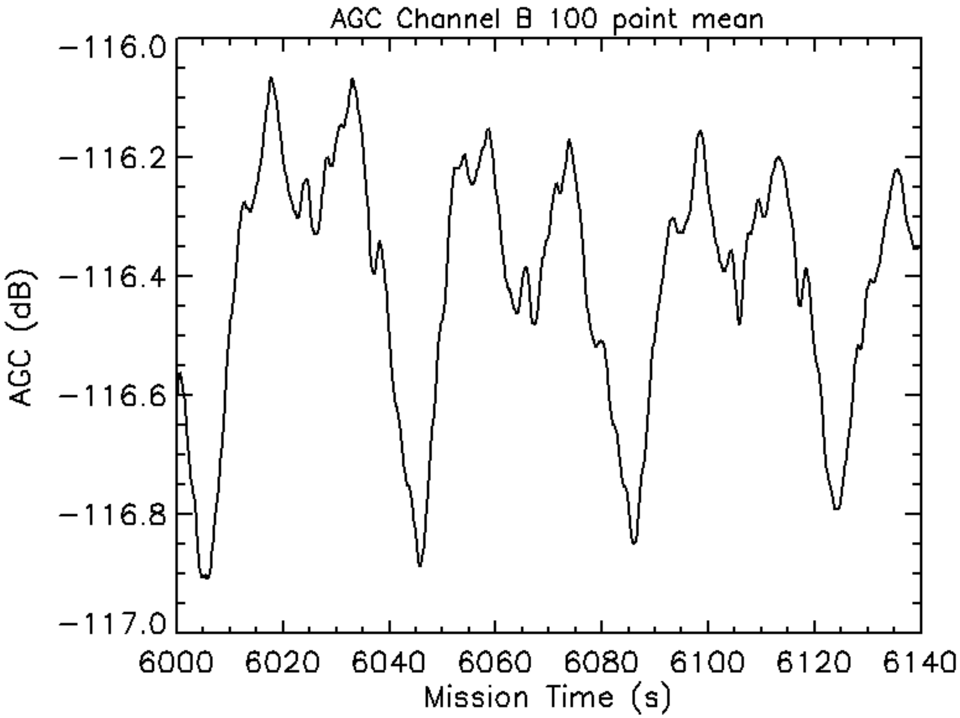
Probe Transmitter signal strength varies slightly with azimuth as well as elevation : some fluctuations expected due to probe spin



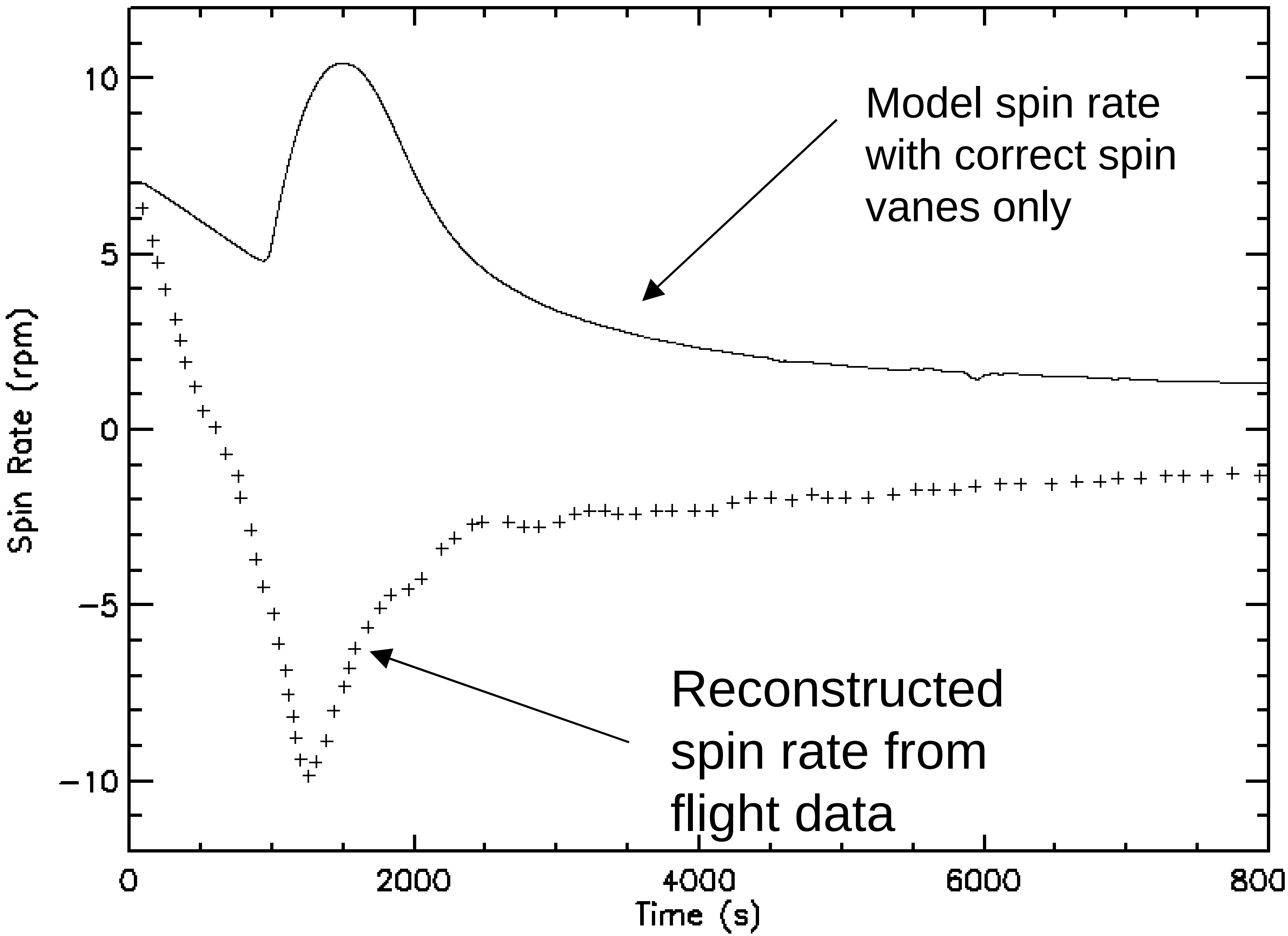


Periodic Spin modulation of AGC allows diagnosis of spin rate and direction

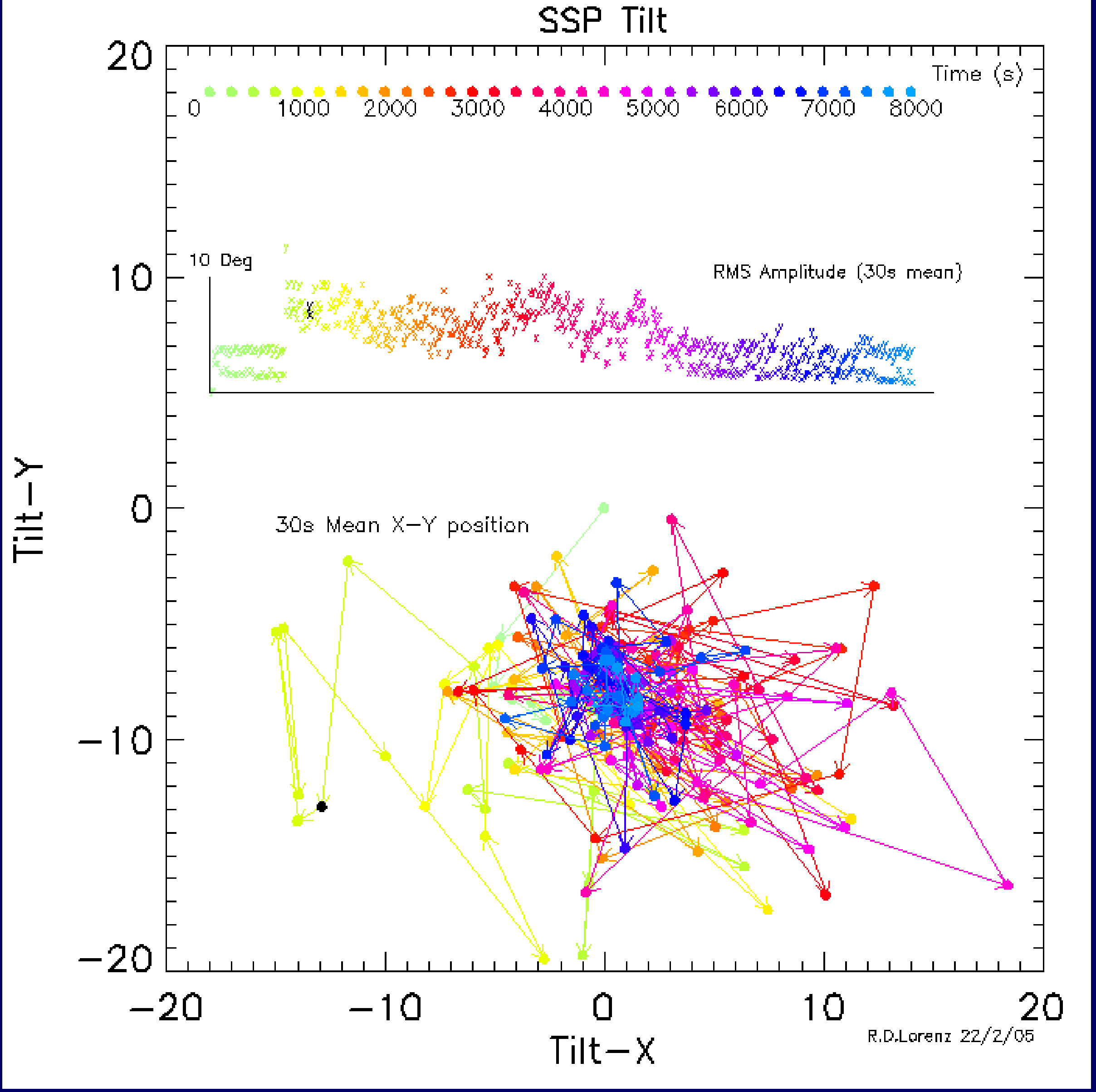




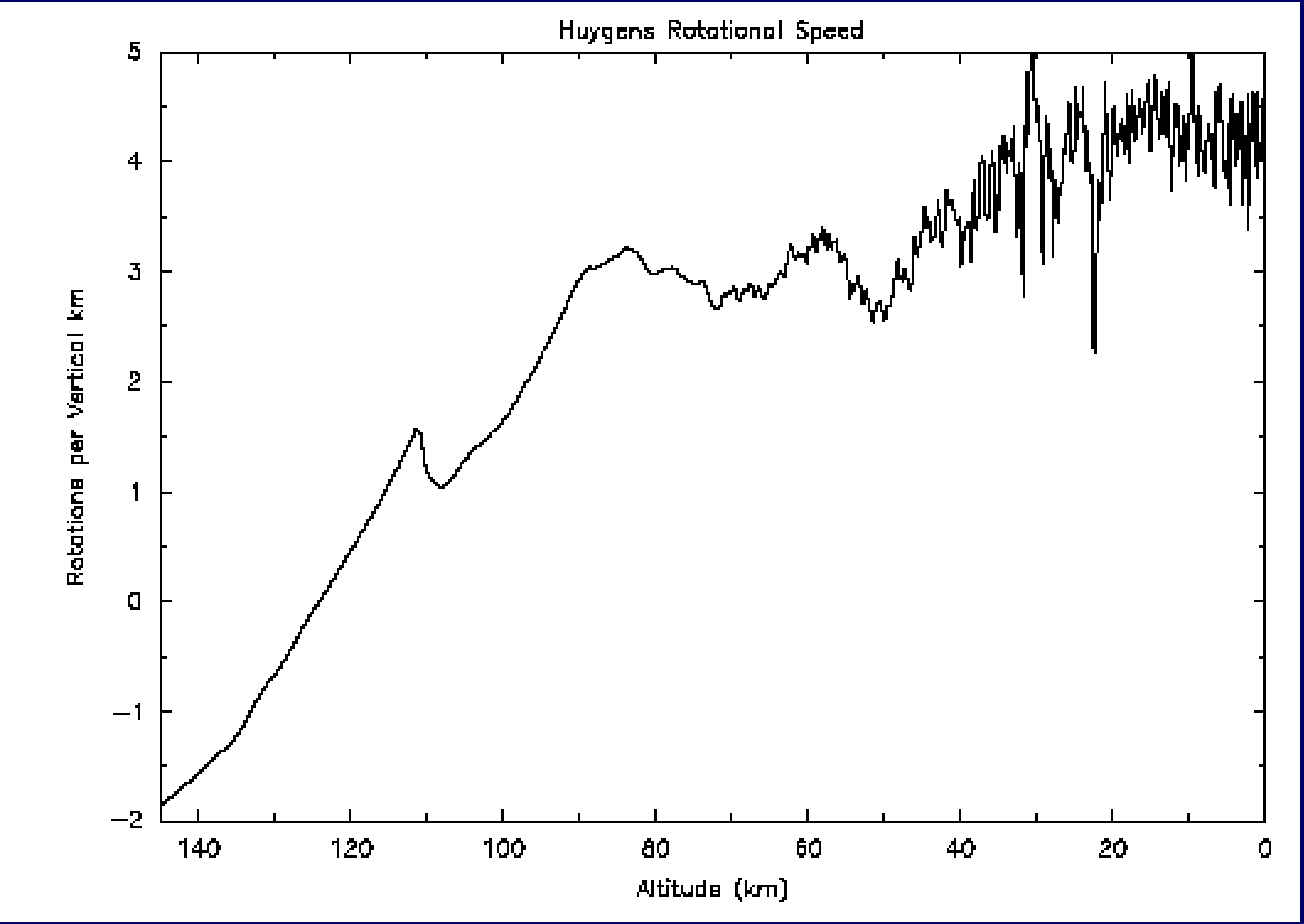
Mission did not follow expected profile



Overall spin reversal suspected to be torque from attachment fittings (unnoticed in 1996 balloon drop). Need wind tunnel test to verify.



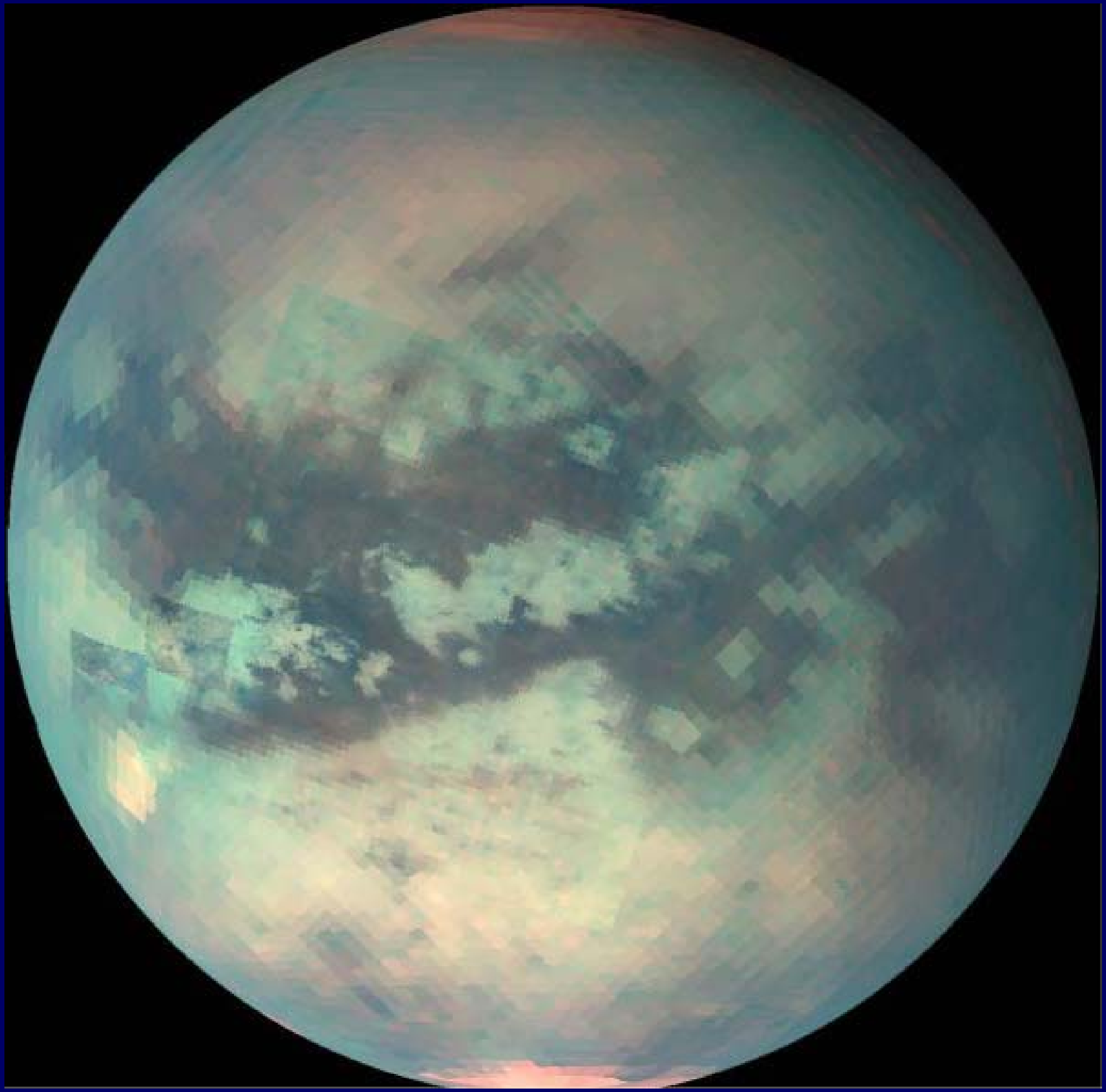
SSP X-tilt sensor mounted radially - should read +ve for both + and - spin. Shows scatter about zero, as expected, during most of descent. But suffers excursion at beginning of descent - boom not deployed ?



Some additional short-period accelerations in spin rate also point to a time-variable complication . Did HASI boom move?

Autorotation observed from parachute/probe interaction (wake?) in Mercury vertical wind tunnel tests

So, back to Titan…….

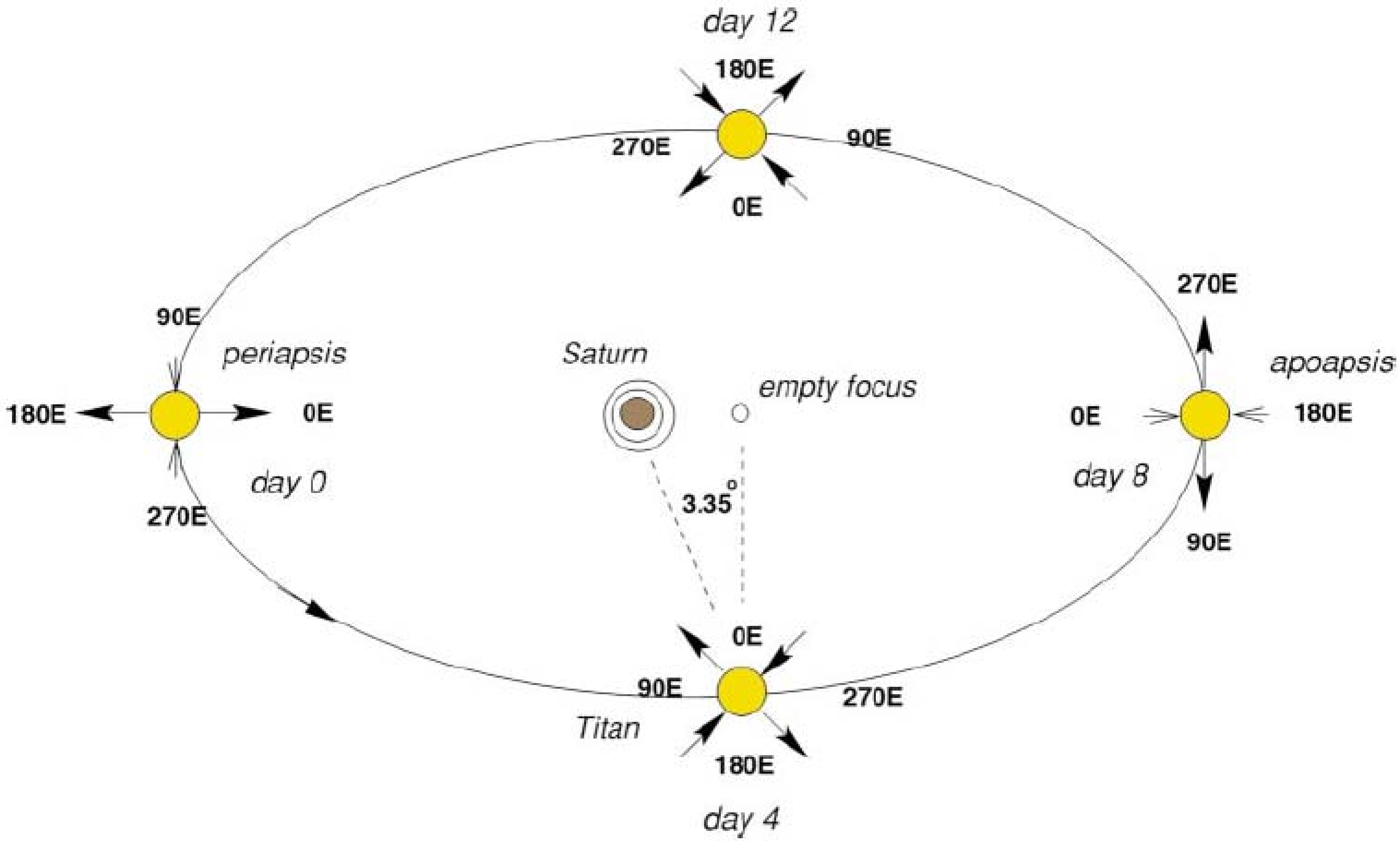


Large satellites near their primary will become tidally-locked - e.g. our Moon

Spin pole~orbit pole. Spin rate~orbit rate.

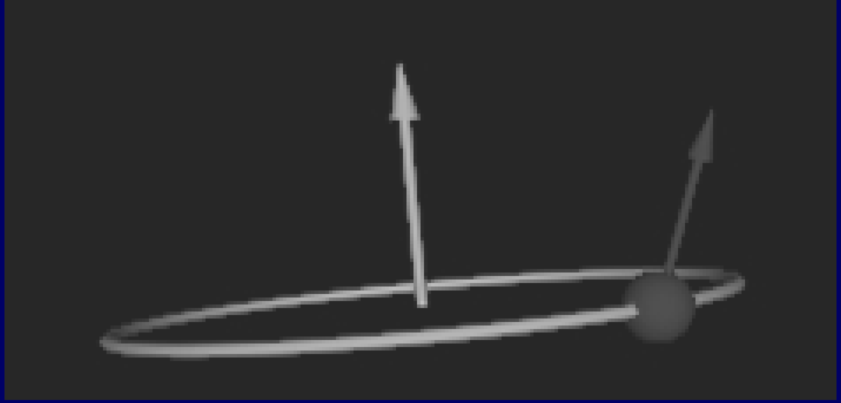
Always faces same side towards Earth

Situation is a little more complicated for an elliptical orbit : satellite rotates at constant rate, but angular rate around orbit varies (Kepler's 3rd law) so there is an apparent wobble or libration . Also tides….



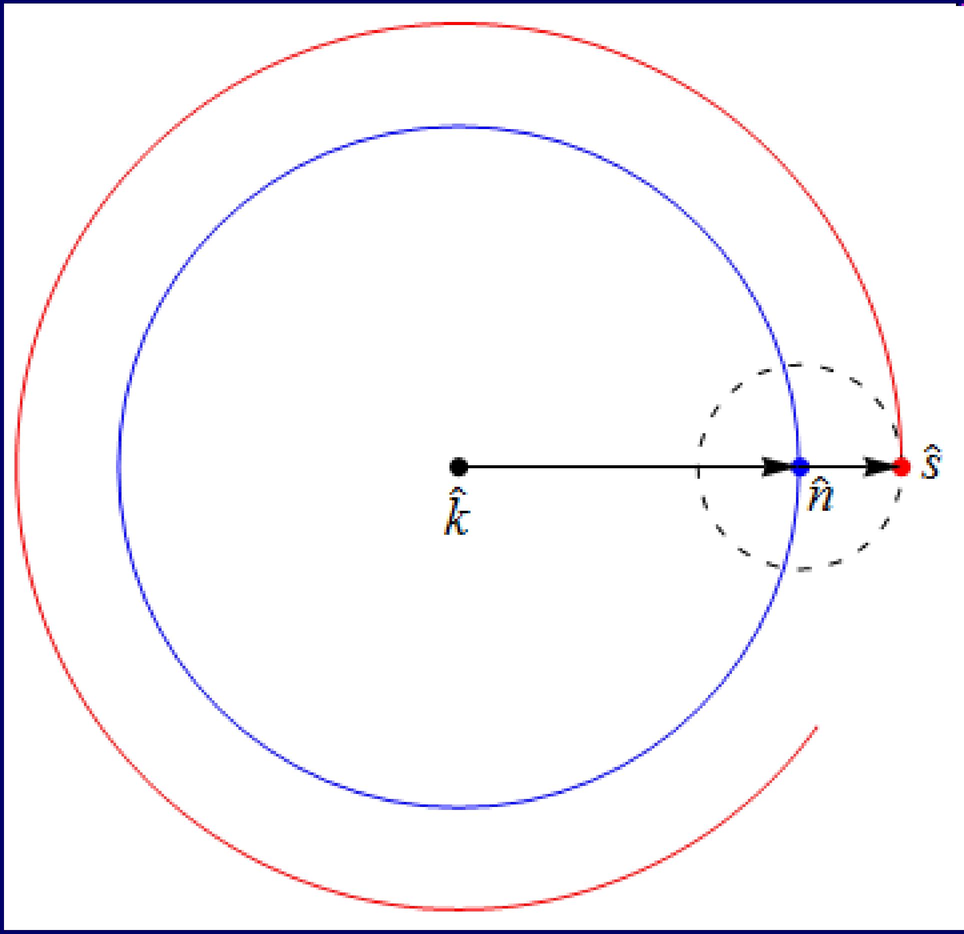
(Interesting but distracting story about tidal dissipation in oceans on Titan omitted - ask me about it later…)

Over the long term (centuries) Sun, Jupiter etc. slightly perturb Titan's orbit…. Precesses



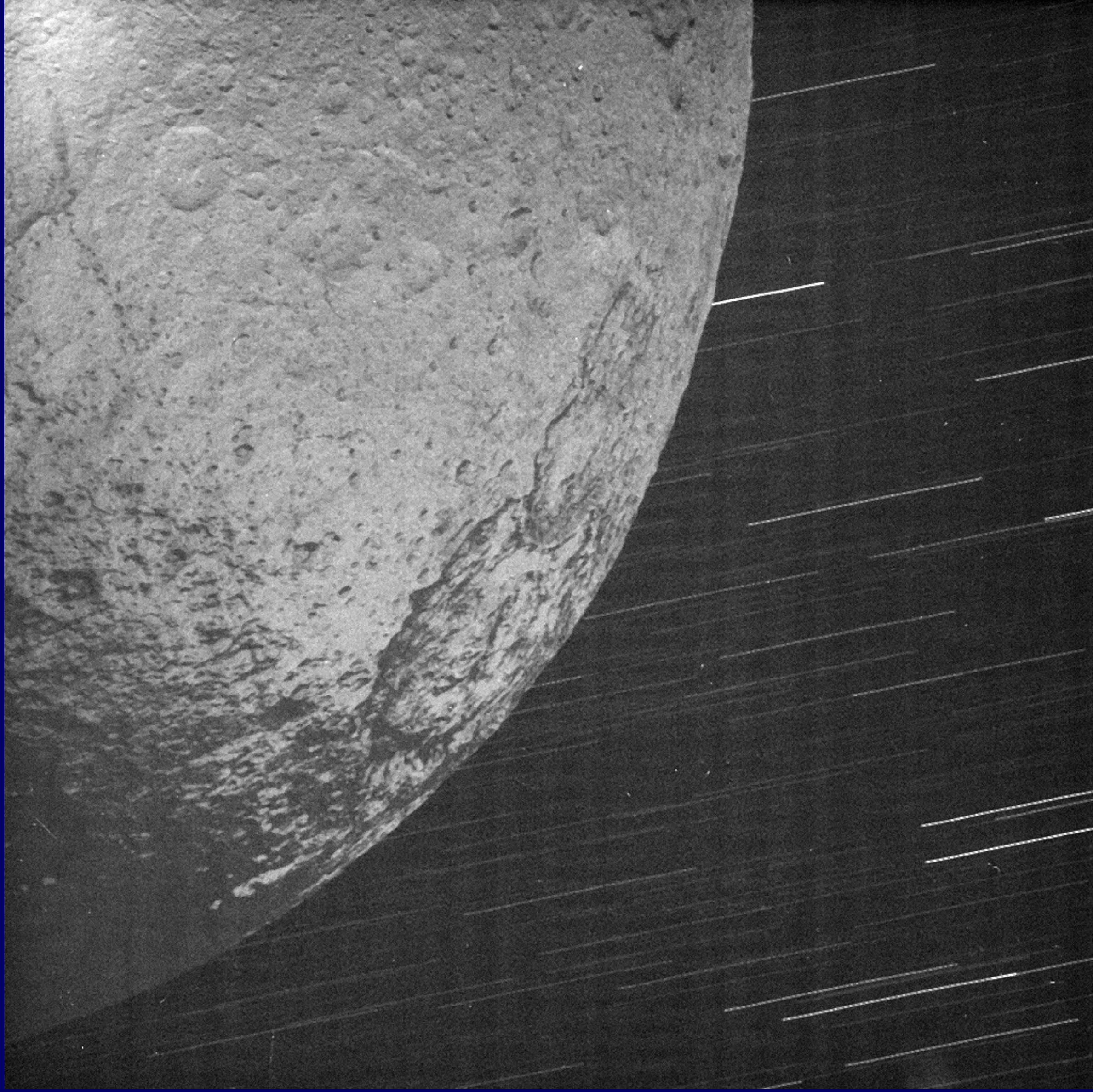
Cassini state - 1693

A relaxed system will have the satellite spin pole (s) precess around some fixed vector (k) at the same rate as the orbit pole (n). These three vectors will be collinear, and the obliquity (angle between spin pole and orbit pole) will depend on the moment of inertia (internal structure) of the satellite.



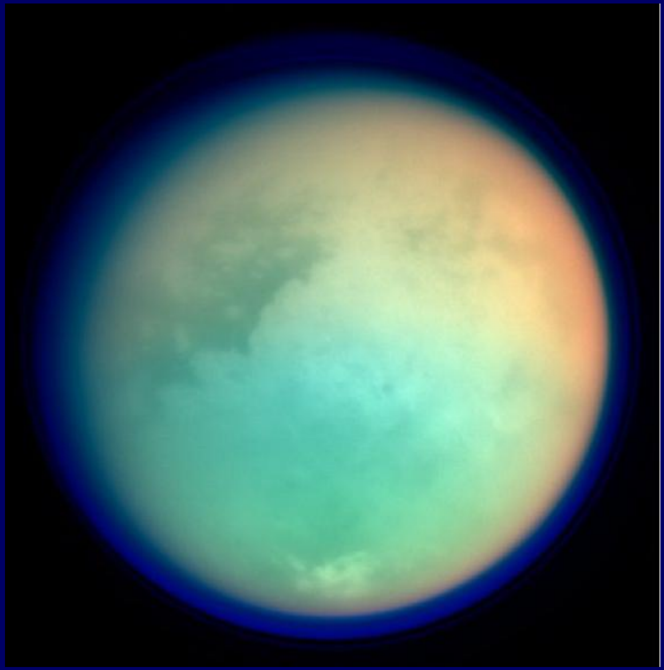
Precision measurements of satellite spin usually made with optical images - accuracy is enhanced substantially if fiducial markers (e.g. known stars) can be used for absolute angular position reference.

[Example saturnshine image of Iapetus]



Such images ('OPNAV's) are also used to refine orbit estimates of satellites and Cassini itself.

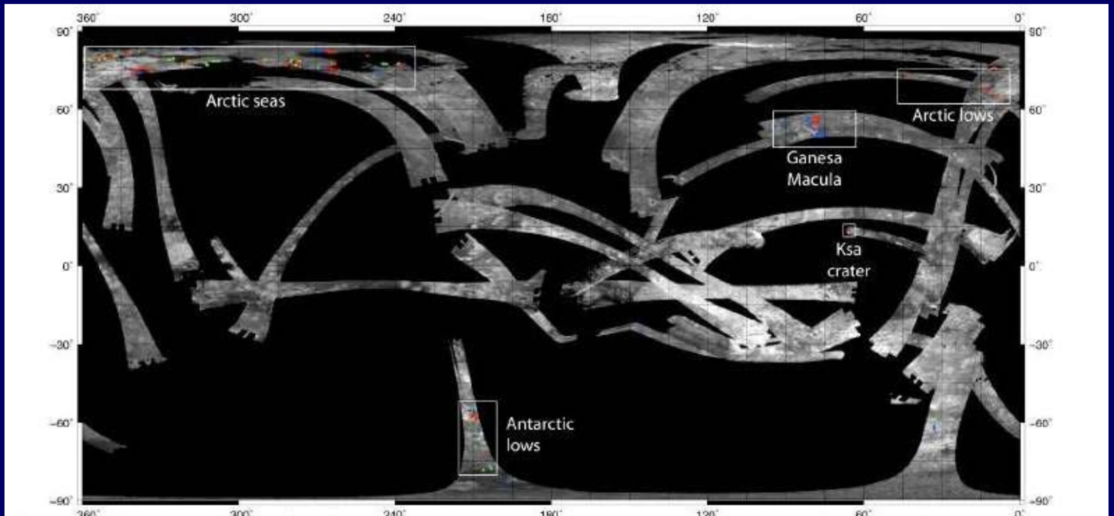
Planetary science trivia - the active volcanos on Io (powered by tidal dissipation) were discovered by a JPL engineer (Linda Morabito) looking at an OPNAV image. To get a precise position measurement of Io, she was fitting a circle to Io's limb, but the fit was poor - when the contrast was stretched she could see why - there was a volcanic plume making Io appear non-circular!



But Titan is a truly horrible object for optical navigation - nonuniform haze, atmospheric refraction & scattering.

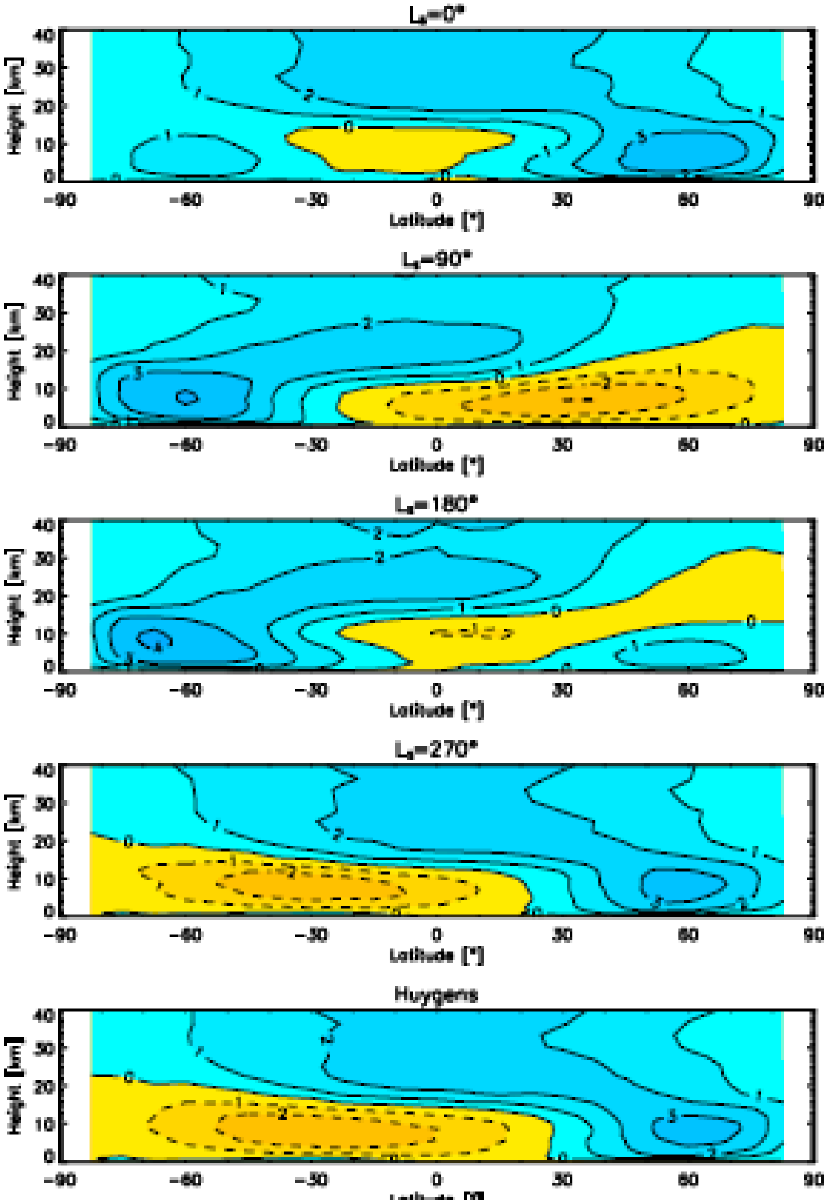
It was realized pre-arrival (e.g. Bruno Bertotti, Radio Science Team) that Radar measurements could determine spin pole and thereby infer moment of inertia independently of gravity measurements (which Radio Science team would perform). Requested that we get overlapping SAR swaths to correlate features and determine pole (probably to be ~0.5 degree off the orbit normal)

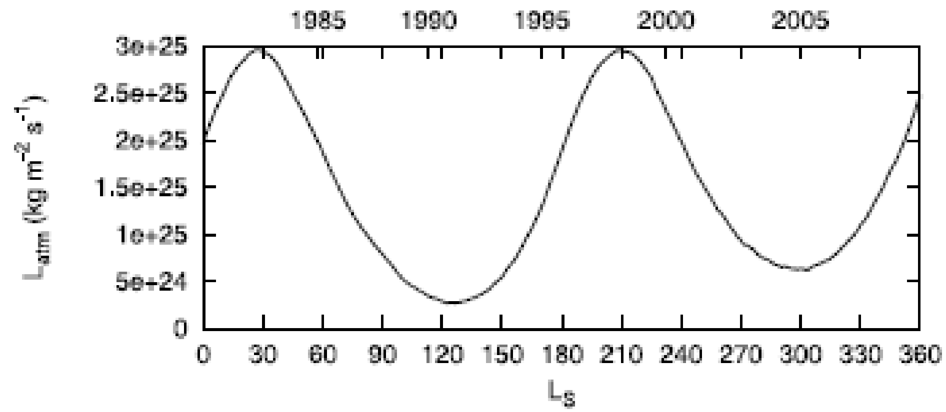
Radar team response 'We'll get lots of overlaps anyway - they're unavoidable (and good for stereo and other things)' Spin solution was on the 'to do' list, but only once a decent number of overlaps had built up (~T30).



Wind-induced seasonal angular momentum exchange at Titan's surface and its influence on Titan's length-of-day

Tetsuya Tokano and Fritz M. Neubauer

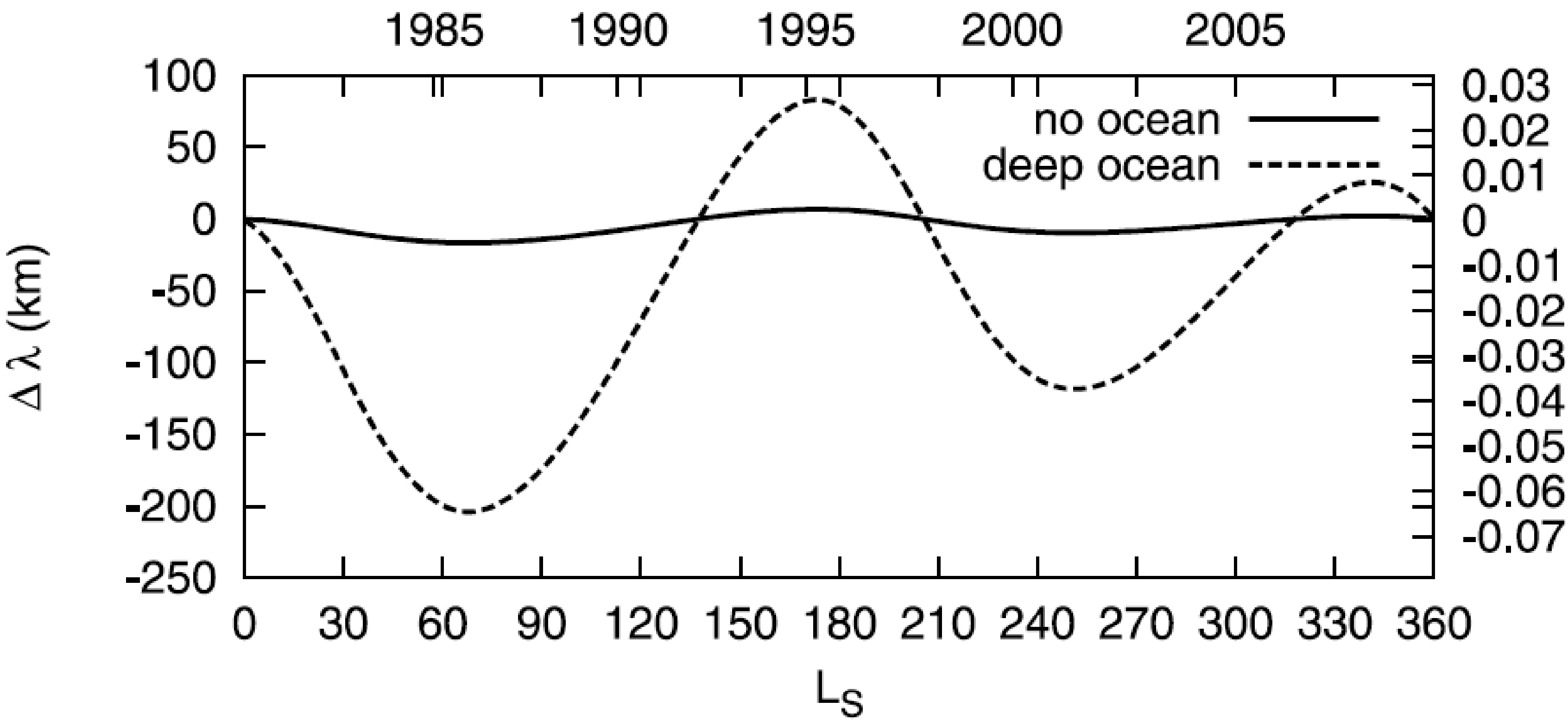




Tokano and Neubauer noted that winds change seasonally. Angular momentum is dominated by low-latitude, low-altitude winds. Seasonal reversal of these causes total angular momentum of the atmosphere to drop by about 80% of its mean value - transferred to surface…

GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L24203, doi:10.1029/2005GL024456, 2005

Exchange of angular momentum with surface will change rotation rate of crust, depending on moment of inertia (is crust decoupled from core by an internal ocean?)

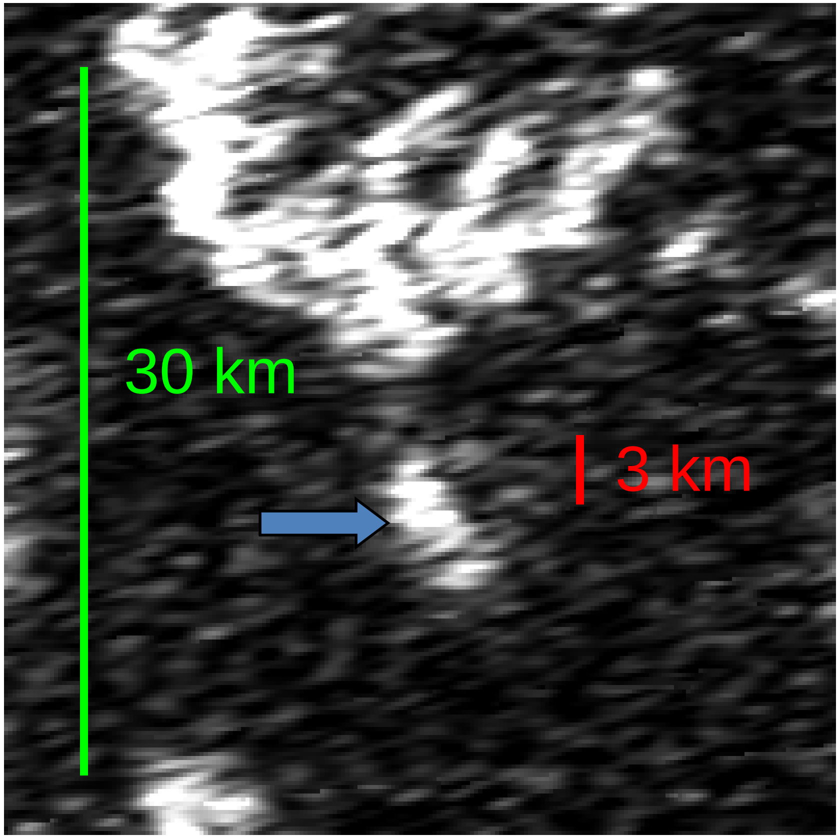


A striking prediction!

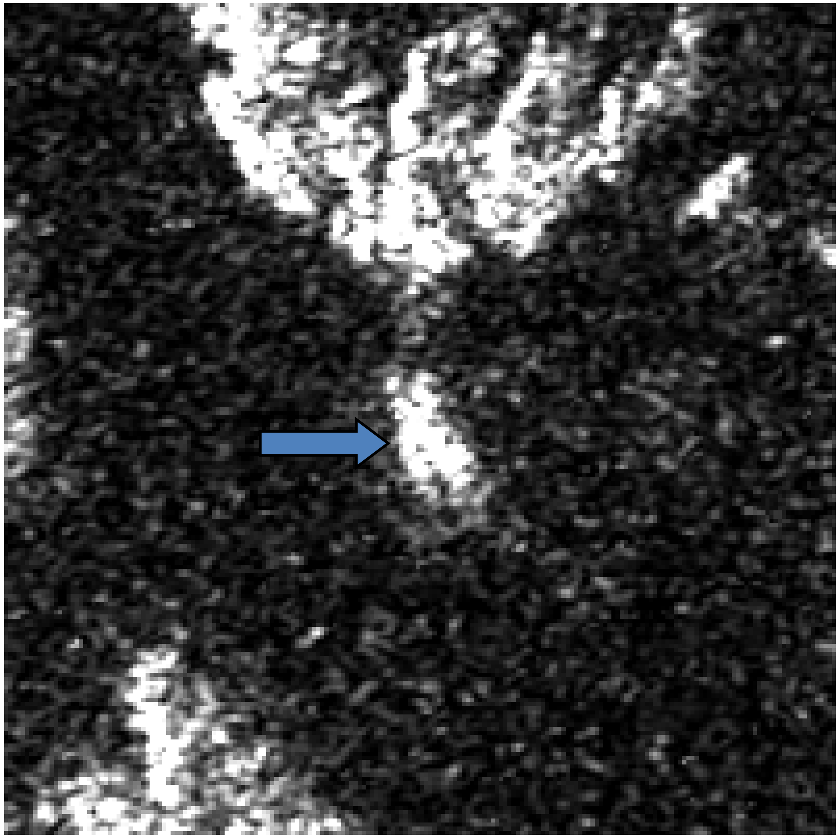
Radar Mapping

- 10-30 km observed feature mismatches due to pole location
- 2-3 km mismatches due spin rate and pole wobble

T25



T28



The Astronomical Journal, 135:1669–1680, 2008 May doi:10.1088/0004-6256/135/5/1669

DETERMINING TITAN'S SPIN STATE FROM *CASSINI* RADAR IMAGES*

Bryan W. Stiles[1], Randolph L. Kirk[2], Ralph D. Lorenz[3], Scott Hensley[1], Ella Lee[2], Steven J. Ostro[1], Michael D. Allison[4], Philip S. Callahan[1], Yonggyu Gim[1], Luciano Iess[5], Paolo Perci del Marmo[5], Gary Hamilton[1], William T. K. Johnson[1], Richard D. West[1], and the Cassini RADAR Team

[1] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr Pasadena CA 91109, USA
[2] United States Geological Survey, 2255 N. Gemini Dr. Flagstaff AZ 86001, USA
[3] Applied Physics Laboratory, Johns Hopkins University, 11100 Johns Hopkins Road, Laurel MD 20723, USA
[4] NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA
[5] University of Rome, Department of Aerospace Engineering and Astronautics, via Eudossiana 18, Rome, Italy
Received 2007 October 24; accepted 2008 February 12; published 2008 March 26

ABSTRACT

For some 19 areas of Titan's surface, the *Cassini* RADAR instrument has obtained synthetic aperture radar (SAR) images during two different flybys. The time interval between flybys varies from several weeks to two years. We have used the apparent misregistration (by 10–30 km) of features between separate flybys to construct a refined model of Titan's spin state, estimating six parameters: north pole right ascension and declination, spin rate, and these quantities' first time derivatives We determine a pole location with right ascension of 39.48 degrees and declination of 83.43 degrees corresponding to a 0.3 degree obliquity. We determine the spin rate to be 22.5781 deg day^{-1} or 0.001 deg day^{-1} faster than the synchronous spin rate. Our estimated corrections to the pole and spin rate exceed their corresponding standard errors by factors of 80 and 8, respectively. We also found that the rate of change in the pole right ascension is -30 deg century^{-1}, ten times faster than right ascension rate of change for the orbit normal. The spin rate is increasing at a rate of 0.05 deg day^{-1} per century. We observed no significant change in pole declination over the period for which we have data. Applying our pole correction reduces the feature misregistration from tens of km to 3 km. Applying the spin rate and derivative corrections further reduces the misregistration to 1.2 km.

Key words: celestial mechanics – methods: numerical – planets and satellites: individual (Titan) – techniques: image processing – techniques: radar astronomy

Inconstant Days

- Mars' Length-of-Day (LoD, measured by Pathfinder/Viking tracking) changes by about 1 ms over the Martian year – change of planetary moment of inertia by seasonal CO2 frost deposition at high latitude
- Earth's day (determined astronomically) changes in an annual cycle by ~0.8ms – change of zonal winds (hemispheric atmospheric angular momentum changes by almost 100%)
- Earth has a secular LoD increase ~2ms/century due to tidal despinning - Angular momentum exported to the moon.. (astronomy, plus lunar laser ranging, plus tidal rythmites in the geological record –e.g. 620 Myr ago LoD =21.9hrs)

Titan's Rotation Reveals an Internal Ocean and Changing Zonal Winds

Ralph D. Lorenz,[1]* Bryan W. Stiles,[2] Randolph L. Kirk,[3] Michael D. Allison,[4] Paolo Persi del Marmo,[5] Luciano Iess,[5] Jonathan I. Lunine,[6] Steven J. Ostro,[2] Scott Hensley[2]

Cassini radar observations of Saturn's moon Titan over several years show that its rotational period is changing and is different from its orbital period. The present-day rotation period difference from synchronous spin leads to a shift of ~0.36° per year in apparent longitude and is consistent with seasonal exchange of angular momentum between the surface and Titan's dense superrotating atmosphere, but only if Titan's crust is decoupled from the core by an internal water ocean like that on Europa.

Titan's massive atmosphere modifies its surface in many ways—notably by aeolian transport forming sand dunes and by fluvial erosion forming river channels—and it has been predicted (*1*) that angular momentum exchange between the surface and atmosphere might lead to seasonal variations in Titan's spin rate or length of day (LoD). Changes in wind patterns lead to a seasonal change (*2*, *3*) in Earth's LoD of ~1 ms, superimposed on longer-term variations in LoD due to gravitational tidal torque from the Moon. On Mars, a seasonal variation in LoD of ~1 ms measured by lander radio tracking (*4*) occurs as a result of the redistribution of mass in the CO_2 frost cycle. Also, a gravitational libration of Mercury revealing a liquid core was recently observed by planetary radar (*5*). These effects are quite subtle, but on Titan, a small body with a massive atmosphere, the changes can be substantial: Global Circulation Model (GCM) predictions of seasonal changes in LoD (*1*) are of some tens to hundreds of seconds (Titan's sidereal LoD is nominally equal to the orbit period of 1,377,684 s, or ~15.945 solar Earth days). This change leads to displacements of surface features from their expected positions by tens to hundreds of kilometers over time scales of a Titan season (about one-fourth of the 29.5-year Saturn orbital period), easily detectable by radar mapping.

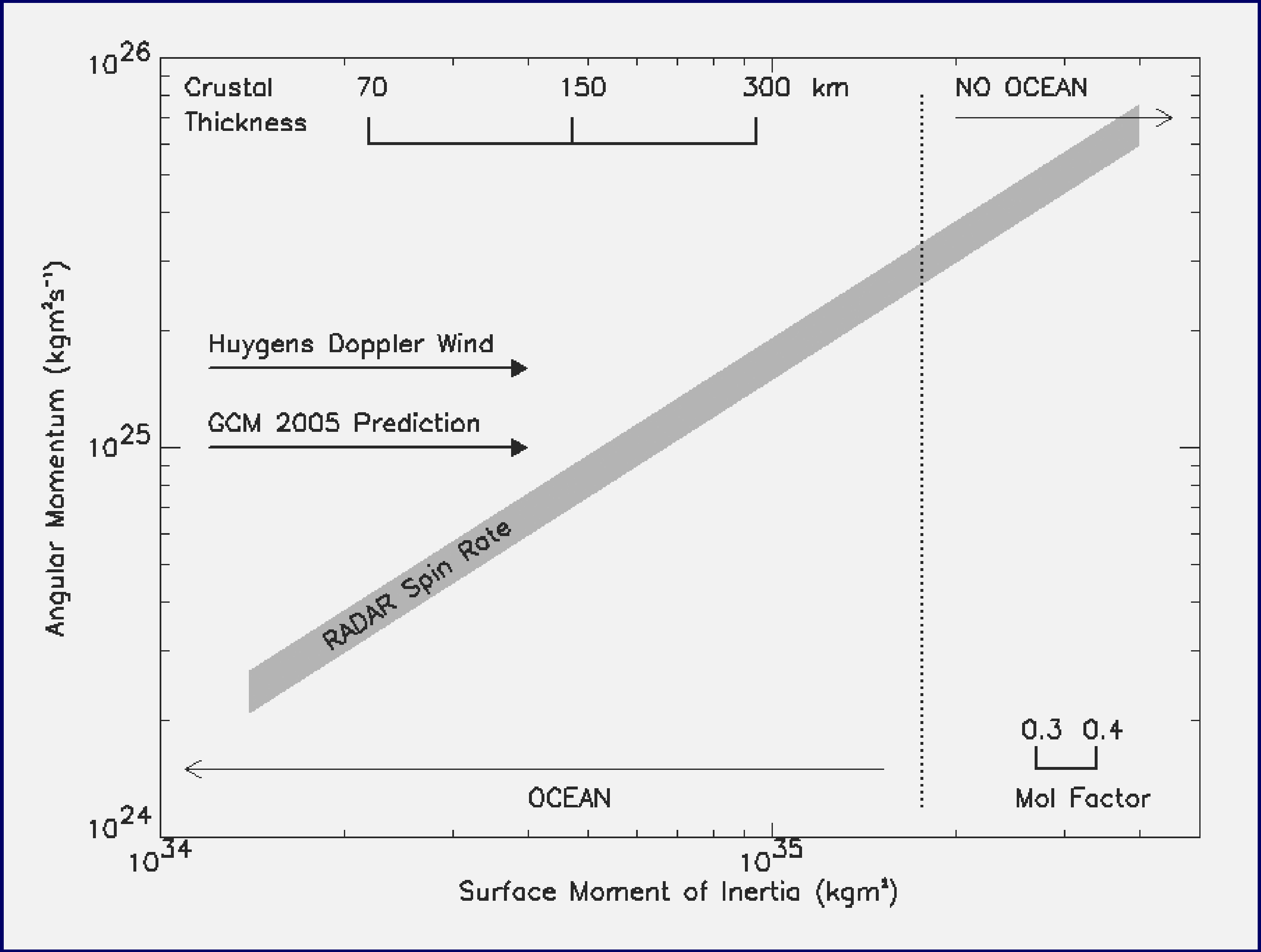
The high spatial resolution (<0.5 km) of images from the Cassini radar instrument, coupled with the geometric precision relative to an external reference frame afforded by radar imaging, has recently allowed Titan's spin state to be determined with great accuracy (*6*–*8*). In synthetic aperture radar (SAR) imaging acquired by Cassini between October 2004 and May 2007, there are 19 regions on Titan that are observed in more than one swath. Two independent analyses—one (*6*) using 150 manually determined landmark features, which are displaced by up to 30 km between swaths if the locations are computed with the previously assumed pole position and a synchronous rotation, and another (*7*) using numerical correlation of four overlapping images—both indicate a spin rate of 22.5781° per day, or 0.36° per year faster than synchronous spin. These analyses also determine the pole position, indicating an obliquity of Titan's pole from its orbital plane around Saturn of 0.3°. This is small enough to be meteorologically unimportant relative to the Saturn system obliquity that drives Titan's seasons (the ring plane, itself inclined by ~0.3° to Titan's orbital plane about Saturn, is inclined to Saturn's orbit around the Sun by some 26.7°, close to the present obliquities of Mars and Earth of 25.2° and 23.5°, respectively). Although the pole position (expected to precess on century-to-millennium time scales because of gravitational torques in the saturnian system) may provide constraints on Titan's internal structure, notably if Titan is in a dynamically relaxed spin-orbit equilibrium [a so-called "Cassini State," e.g., (*9*–*11*)], we focus here on the spin rate.

First, we note that Titan's spin-down time is short (<10^6 years) relative to the age of the solar system, so in the absence of external torques it should be in an asymptotic end state with synchronous rotation (*12*). Indeed, less accurate

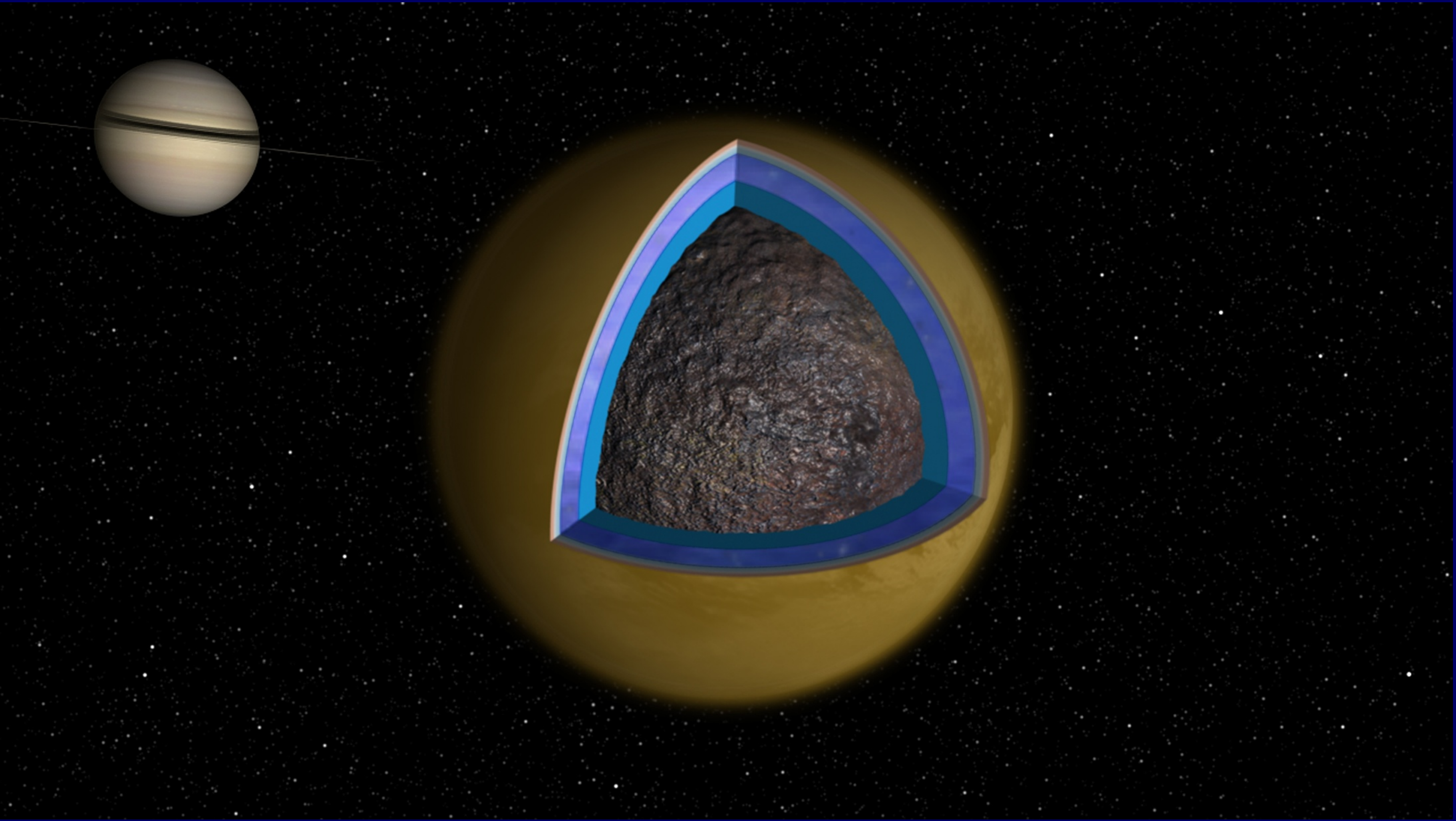
[1]Space Department, Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA. [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA. [3]U.S. Geological Survey, Flagstaff, AZ 86001, USA. [4]NASA Goddard Institute for Space Studies, New York, NY 10025, USA. [5]Università La Sapienza, 00184 Rome, Italy. [6]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA.

*To whom correspondence should be addressed. E-mail: ralph.lorenz@jhuapl.edu

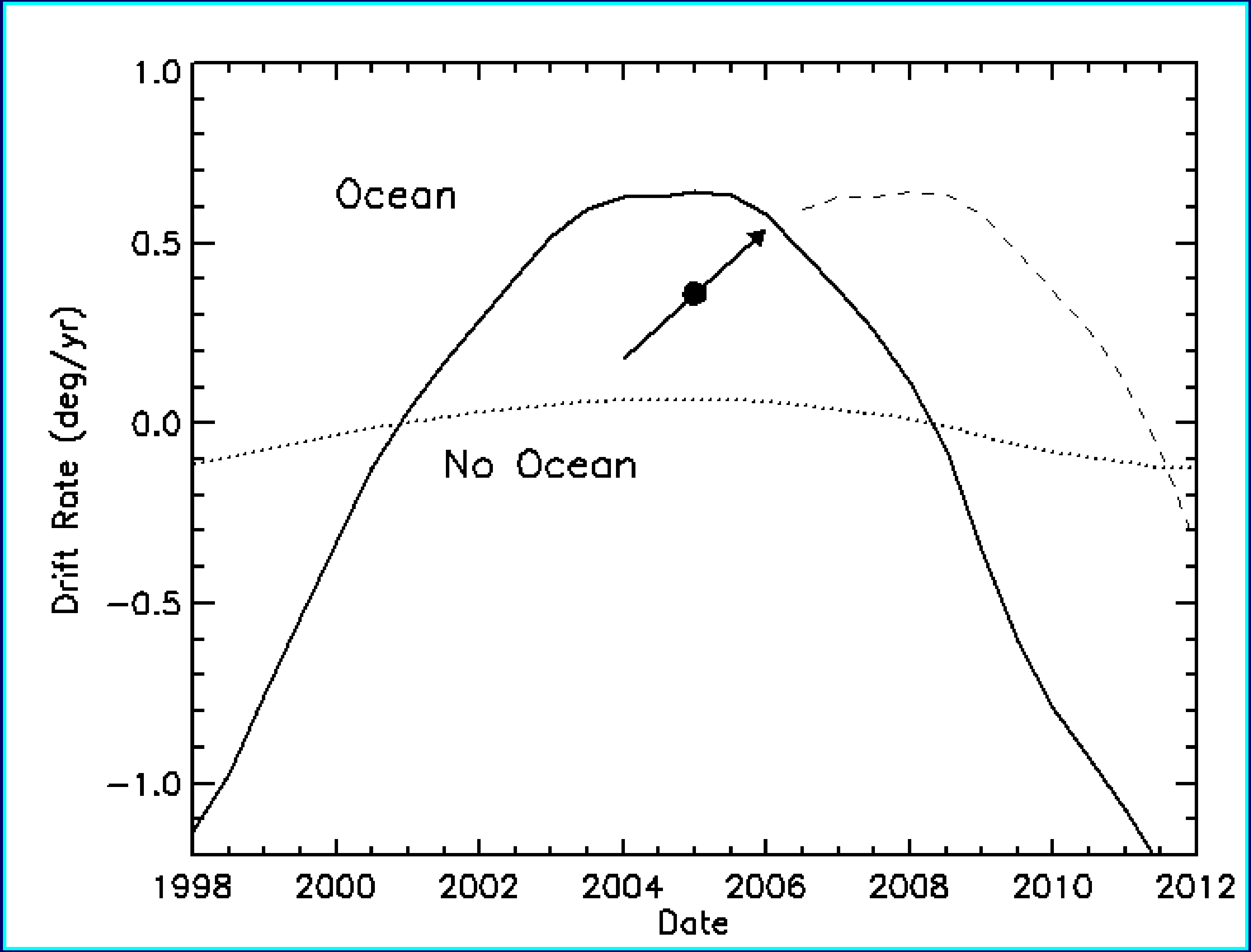
Nonsynchronous spin detected by RADAR difficult to reconcile with solid Titan. Requires extreme angular momentum change or an internal ocean overlain by crust (100-200km thick?).



The Ocean within…..



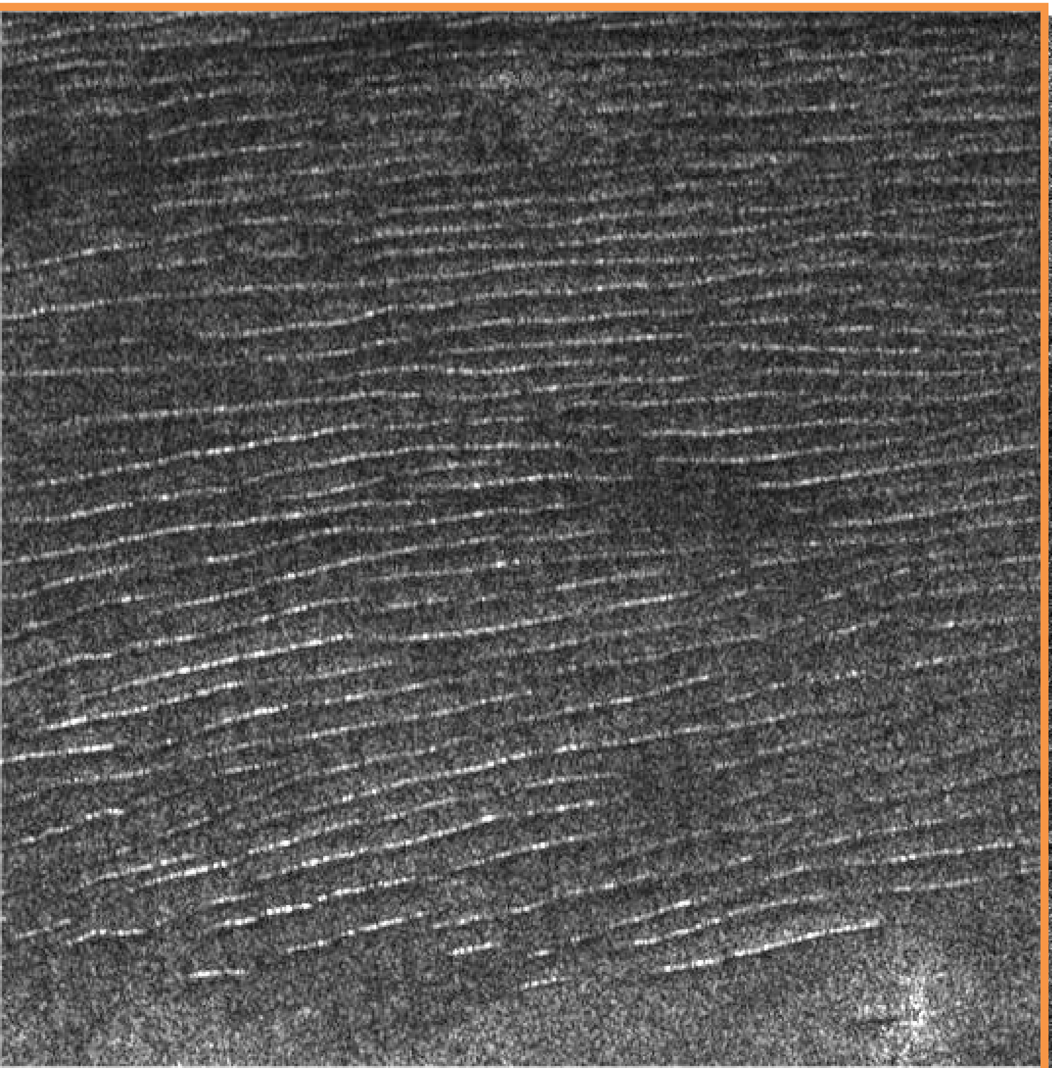
Spin rate variation in same range as predicted by Tokano model (but phase-lagged?)



That's ok - we know the GCMs are far from perfect

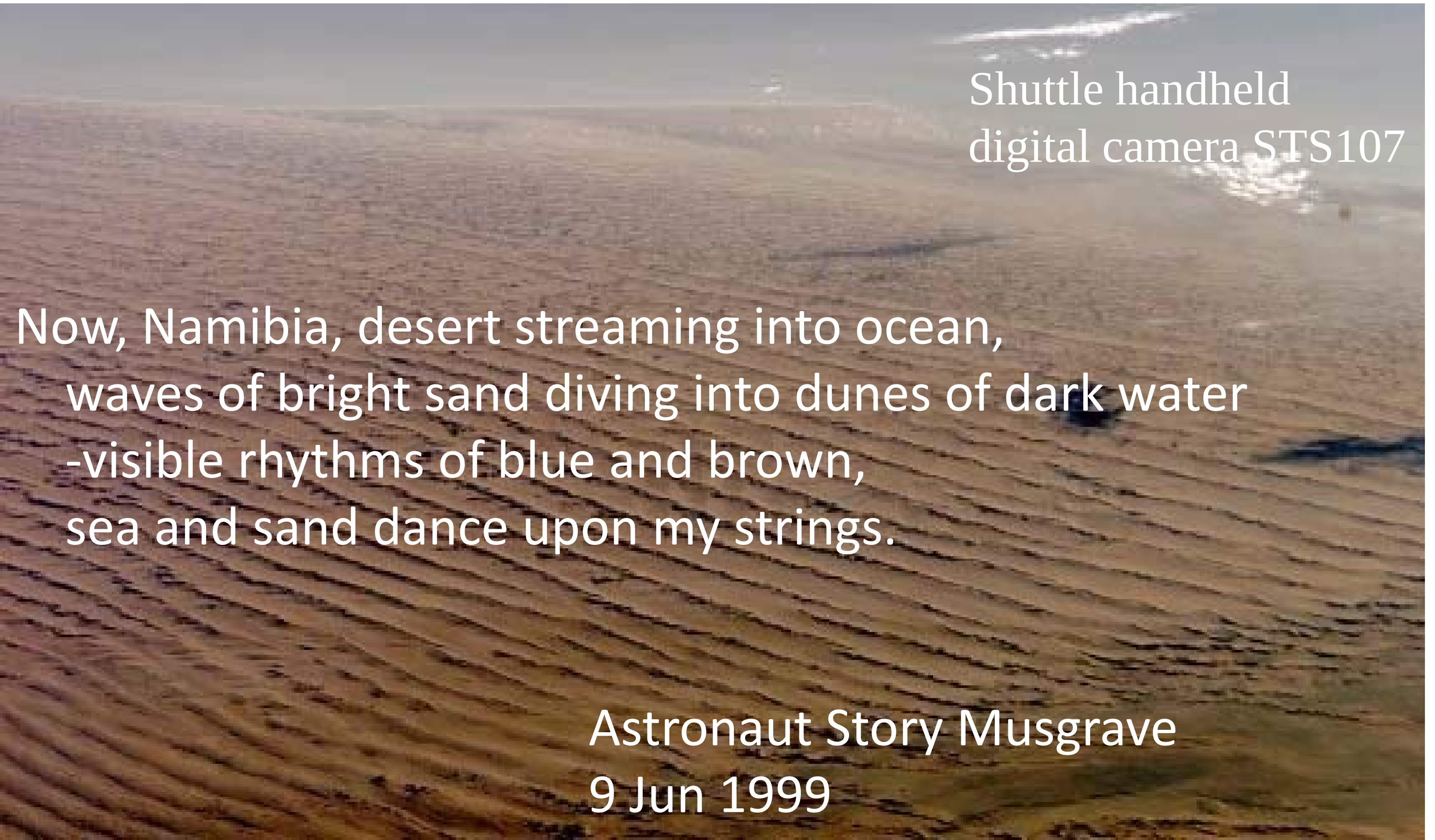
A surprise on Titan - Dunes !

Sometimes seen as positive ridges ~1-2km wide, 150m high. Sometimes only visible as dark streaks against brighter substrate

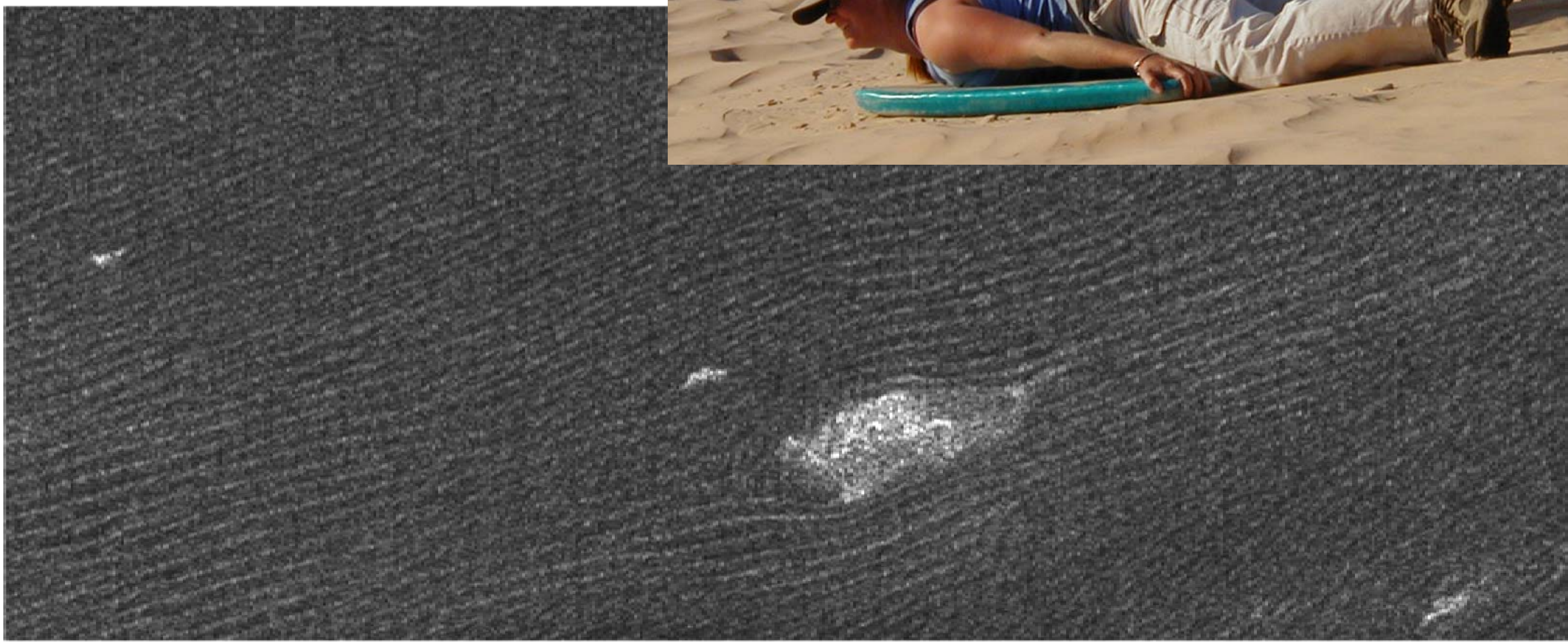


Linear dunes in the Namib Desert

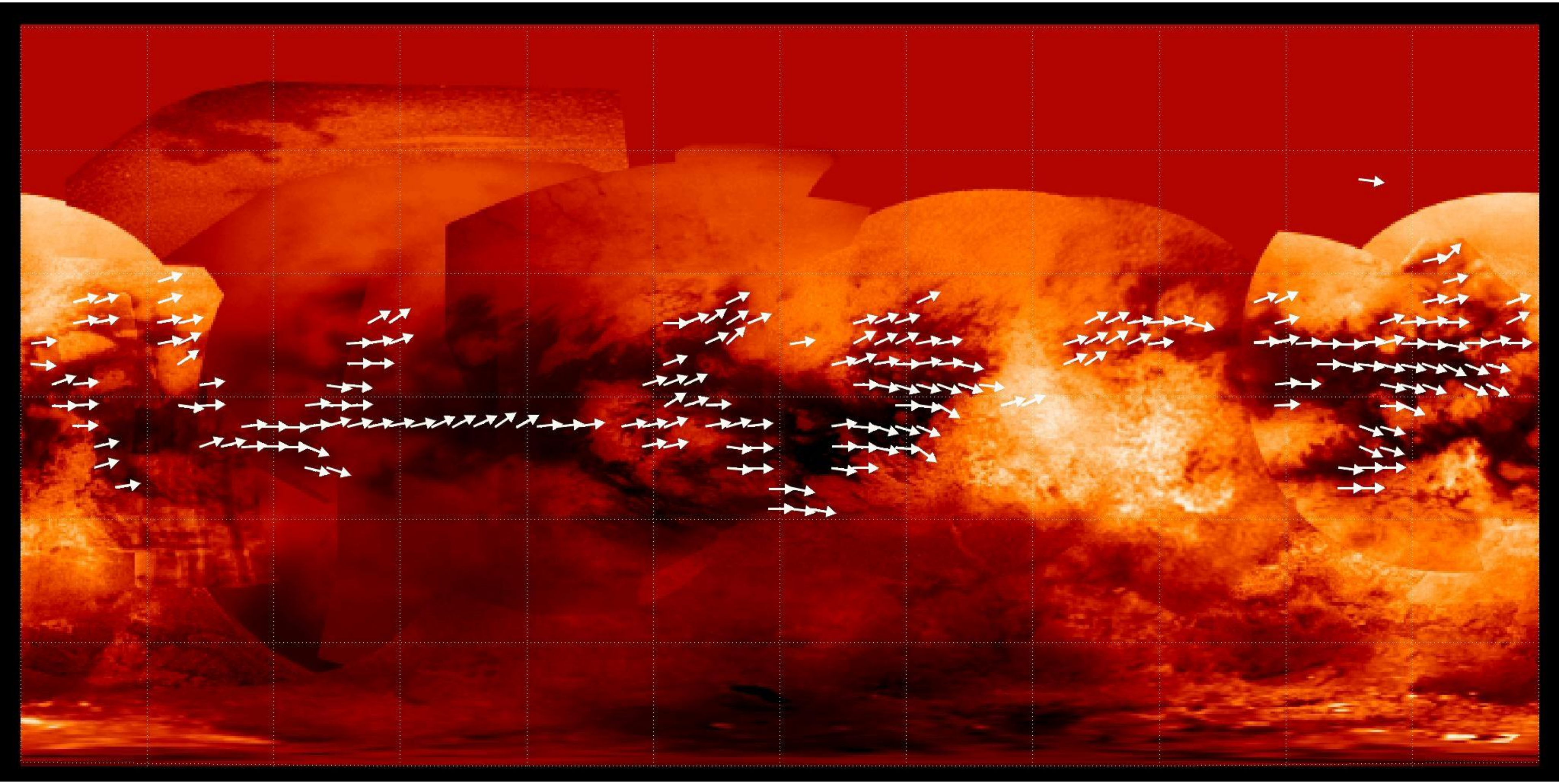
Longitudinal dunes form in alternating wind regime (line up along the vector mean of two dominant wind directions separated by ~120 deg)



Prof Jani Radebaugh of BYU demonstrates that the dune:wave analogy is not perfect…



Dunes ‘flow’ around hills allowing tracing of global wind patterns - 'teardrop' shapes allow resolution of 180 degree ambiguity. Jani has mapped out some 16,000 dune segments in radar data



Lorenz and Radebaugh,
GRL, 2009

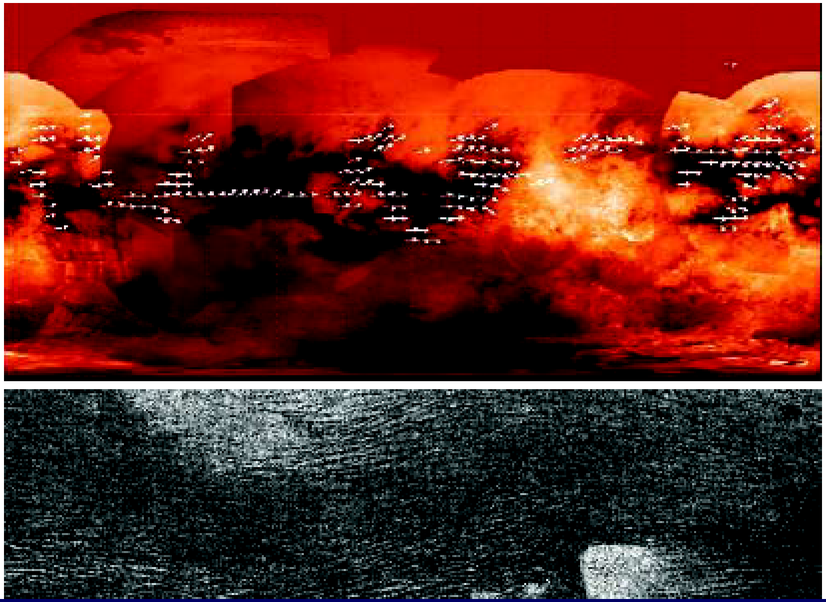
PLANETARY SCIENCE

In Dune Map, Titan's Winds Seem to Blow Backward

Christopher Columbus rode the trade winds from Europe to America. But on Saturn's moon Titan, a wind-driven westward voyage might not be possible. A new map of Titan's dunes reveals that near-surface winds at the equator blow the wrong way: from west to east. That's the opposite of the predictions made by models of Titan's atmosphere. Researchers say there's no clear path to reconciling those differences.

For the map, published in *Geophysical Research Letters* last month, planetary scientists Ralph Lorenz of Johns Hopkins University in Laurel, Maryland, and Jani Radebaugh of Brigham Young University in Provo, Utah, used images from the Synthetic Aperture Radar instrument on the Cassini spacecraft to map 16,000

Initially, the modelers questioned the results, says Claire Newman, a planetary scientist at the California Institute of Technology in Pasadena. "It's almost like you go, well, did



says. And although the dunes seem to be young, he says, they may be cemented in place, remnants of an atmospheric past.

The heights of Titan's topographic features are still not well mapped, so unknown hills and valleys could still be the culprits, says Sébastien Lebonnois, a planetary climatologist at the Laboratoire de Météorologie Dynamique (CNRS, University Paris 6) in Paris. Tetsuya Tokano, a planetary meteorologist at the University of Cologne in Germany, has added speculative topography to his model, to no avail. He now guesses that the dunes themselves could be diverting the winds, but the models don't have a fine enough resolution to study the dunes.

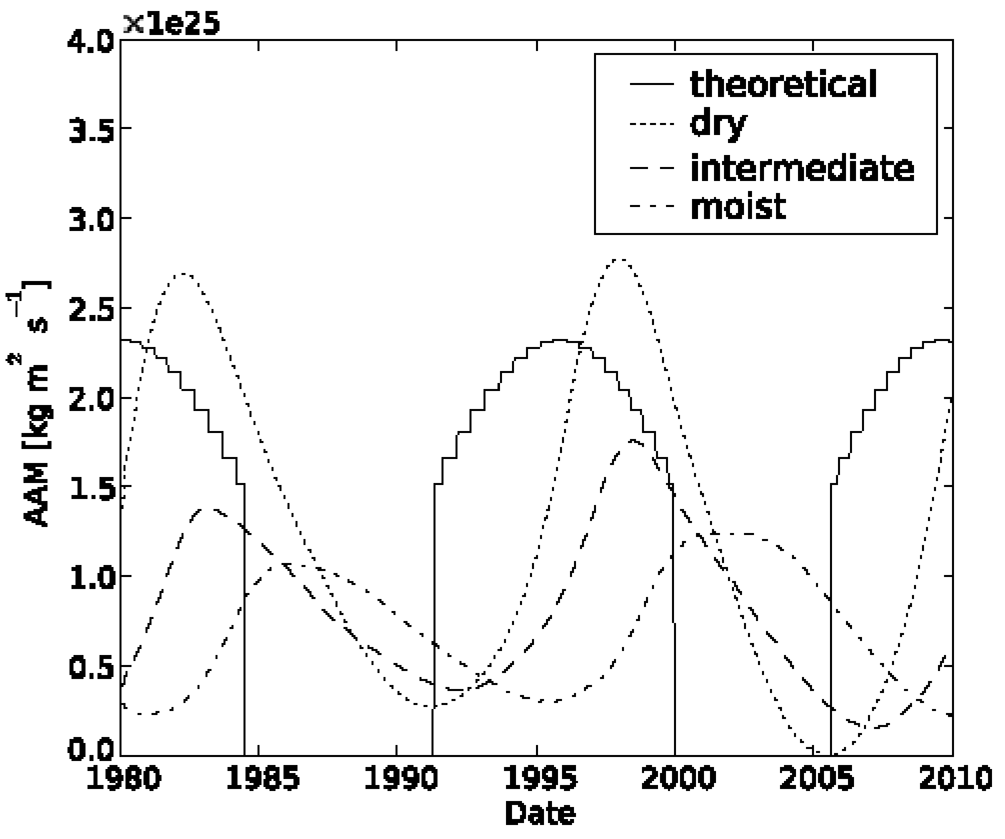
Mitchell plans to study the possible connection to Titan's atmos-

Theorem (1) : for any observation, a theorist can come up with an explanation to fit it…..

THE ASTROPHYSICAL JOURNAL, 692:168–173, 2009 February 10 doi:10.1088/0004-637X/692/1/168

COUPLING CONVECTIVELY DRIVEN ATMOSPHERIC CIRCULATION TO SURFACE ROTATION: EVIDENCE FOR ACTIVE METHANE WEATHER IN THE OBSERVED SPIN RATE DRIFT OF TITAN

JONATHAN L. MITCHELL
Institute for Advanced Study, Princeton, NJ 08540, USA; mitch@ias.edu
Received 2008 July 29; accepted 2008 October 28; published 2009 February 13



Theorem (2) : for any observation not fit by a theoretician, he or she will come up with an explanation why the observation must be wrong

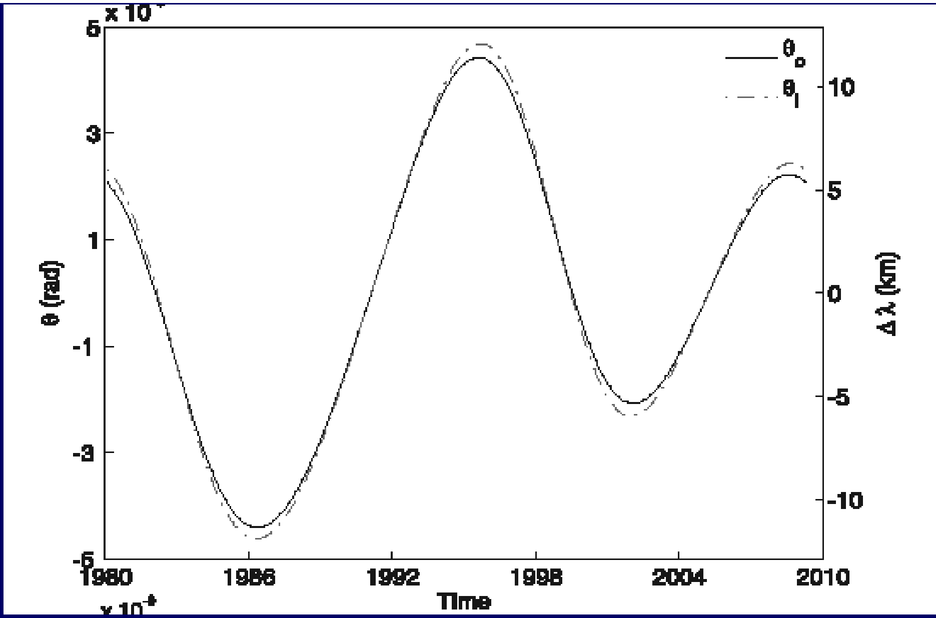
GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L16202, doi:10.1029/2008GL034744, 2008

Click Here for Full Article

Effect of internal gravitational coupling on Titan's non-synchronous rotation

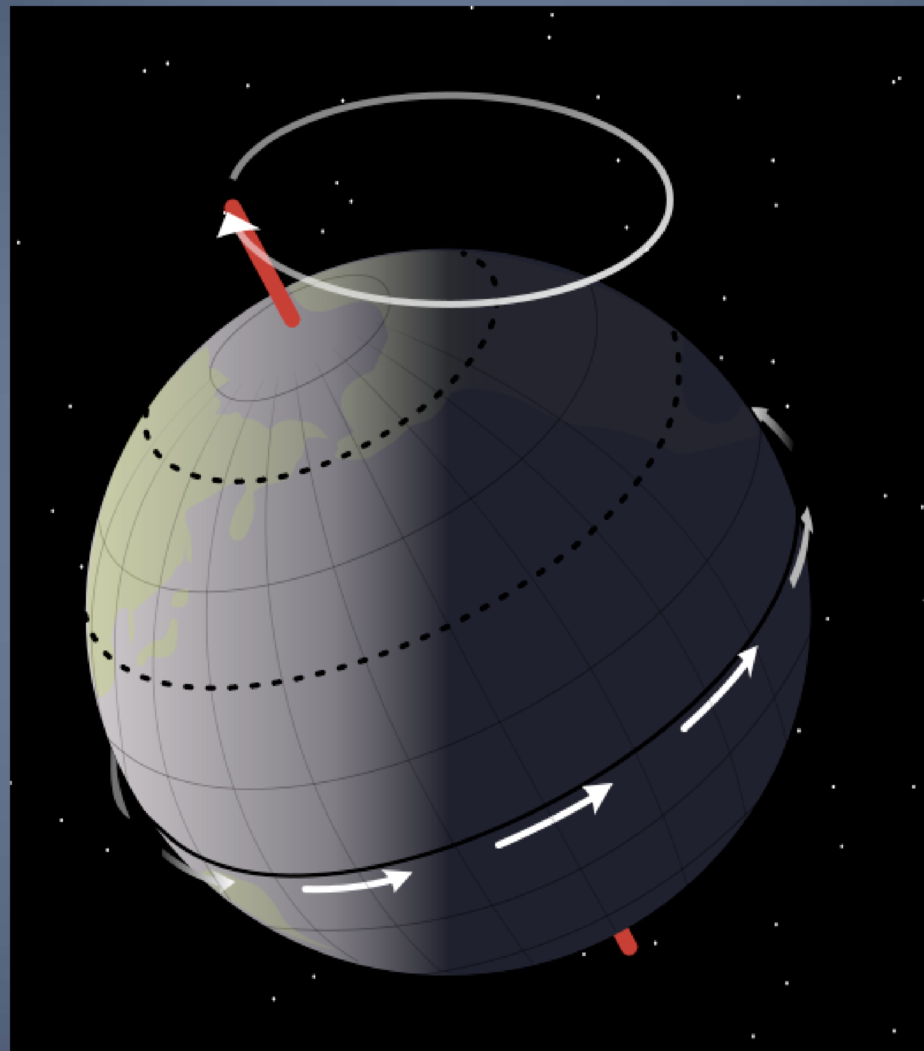
Ö. Karatekin,[1] T. Van Hoolst,[1] and T. Tokano[2]

Received 20 May 2008; revised 8 July 2008; accepted 16 July 2008; published 27 August 2008.

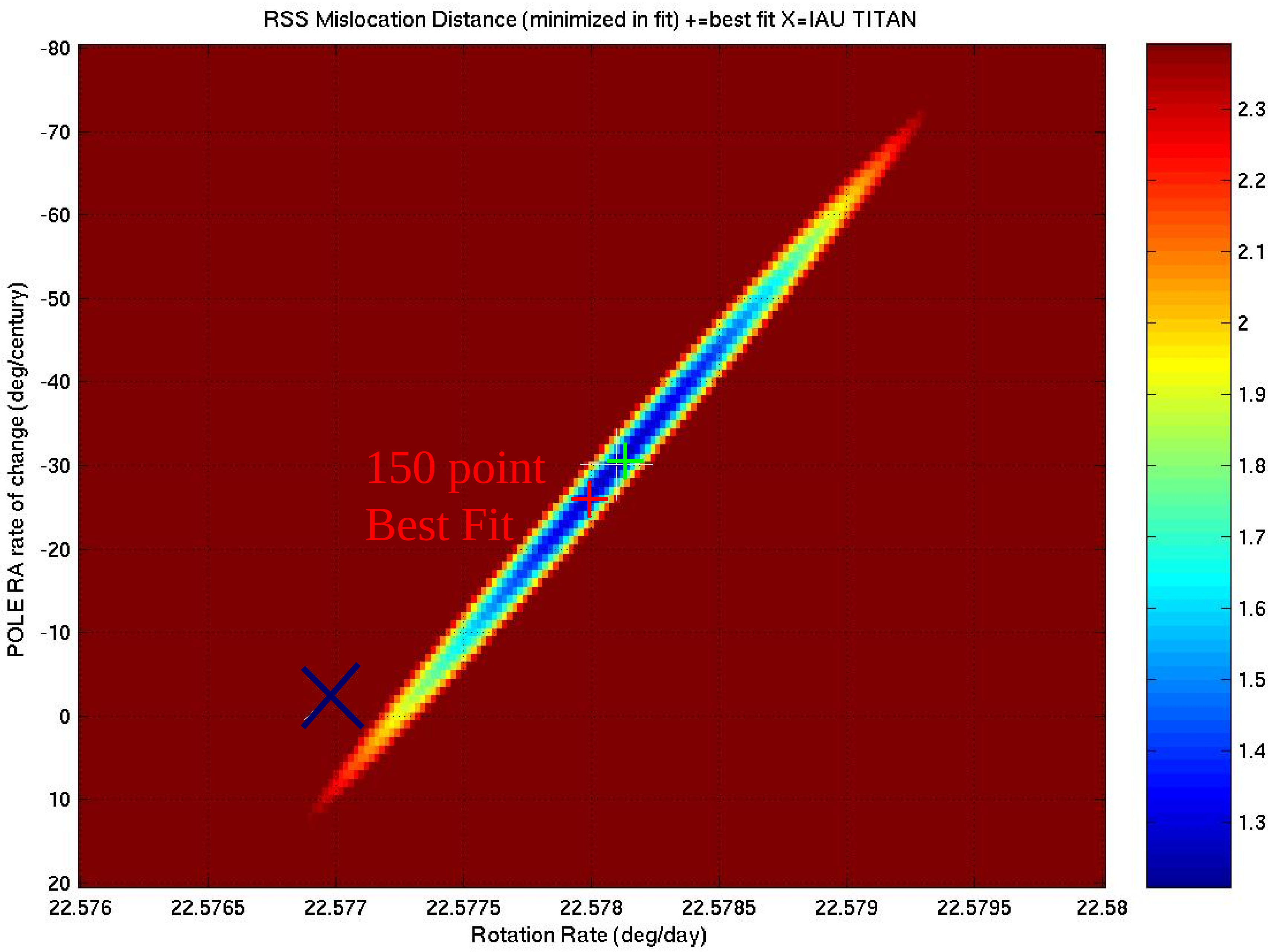


Nonspherical core, and nonspherical shell, would be gravitationally-coupled, so nonsynchronous rotation shouldn't happen….

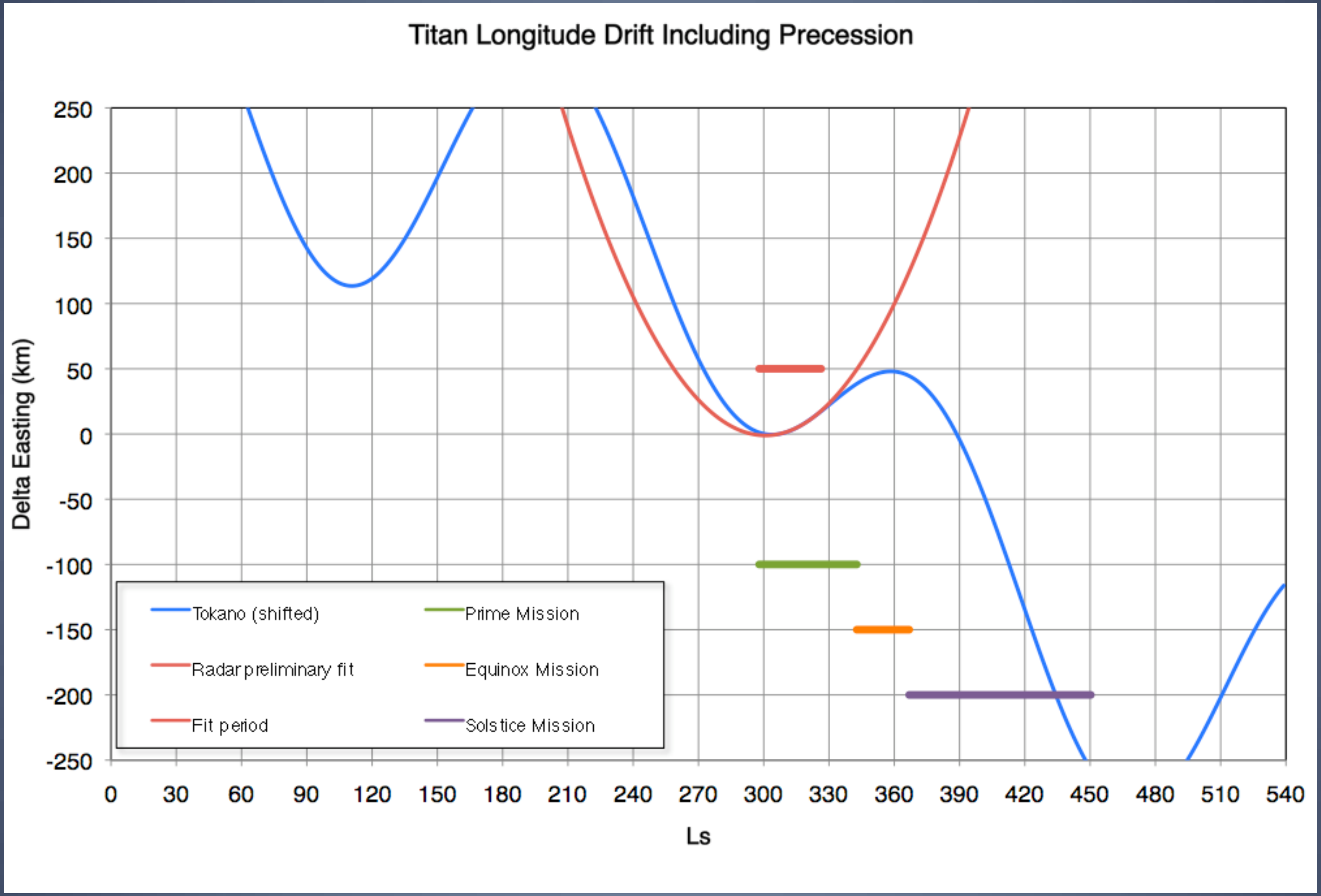
Spin Rate is Not the Whole Story



Pole is precessing backward at ¾ the
rate of apparent excess (nonsynchronous) spin


RSS Mislocation Distance (minimized in fit) +=best fit X=IAU TITAN
POLE RA rate of change (deg/century)
-80
-70
-60
-50
-40
-30
-20
-10
0
10
20
Rotation Rate (deg/day)
22.576
22.5765
22.577
22.5775
22.578
22.5785
22.579
22.5795
22.58
2.3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
150 point
Best Fit

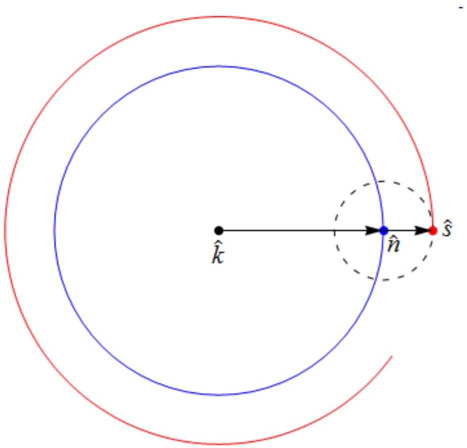
Net Effect of Spin & Precession

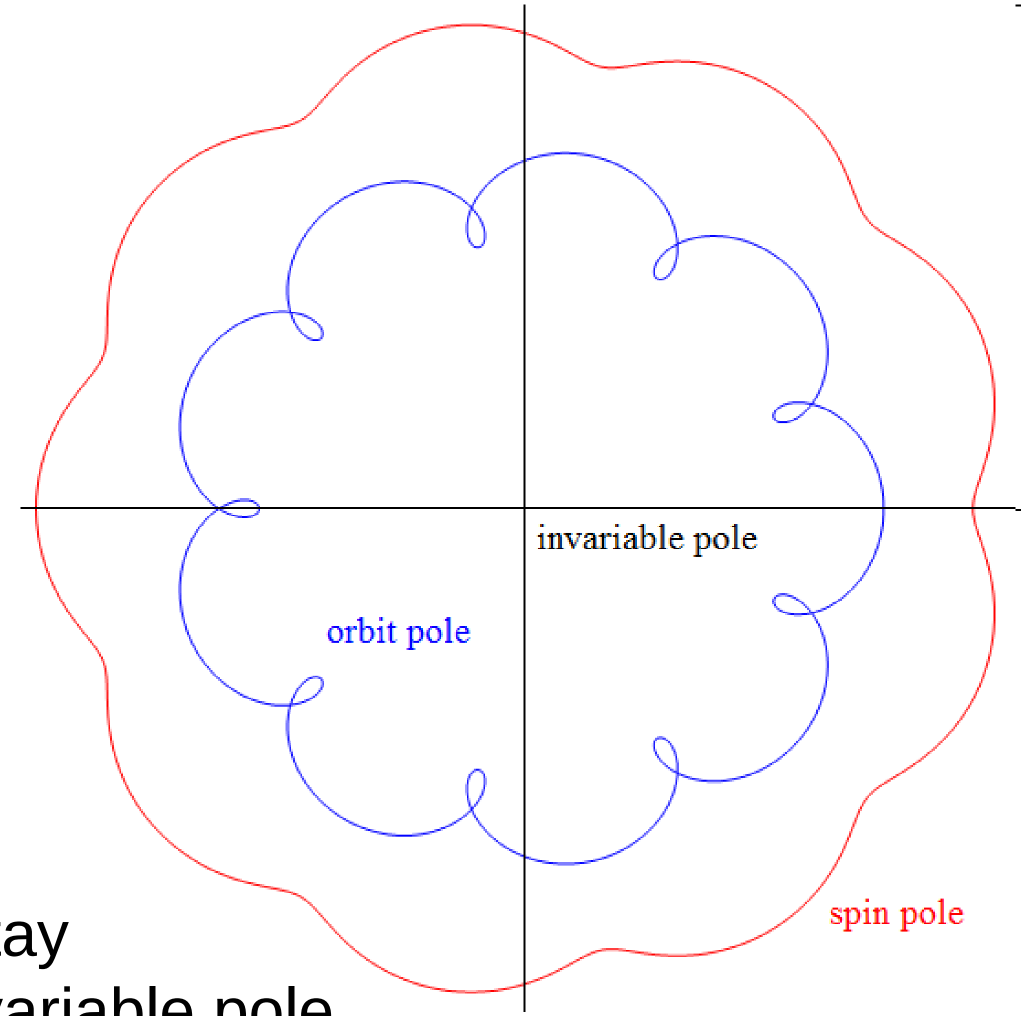


Cassini Solstice Mission (not yet approved) should see major divergence from present state

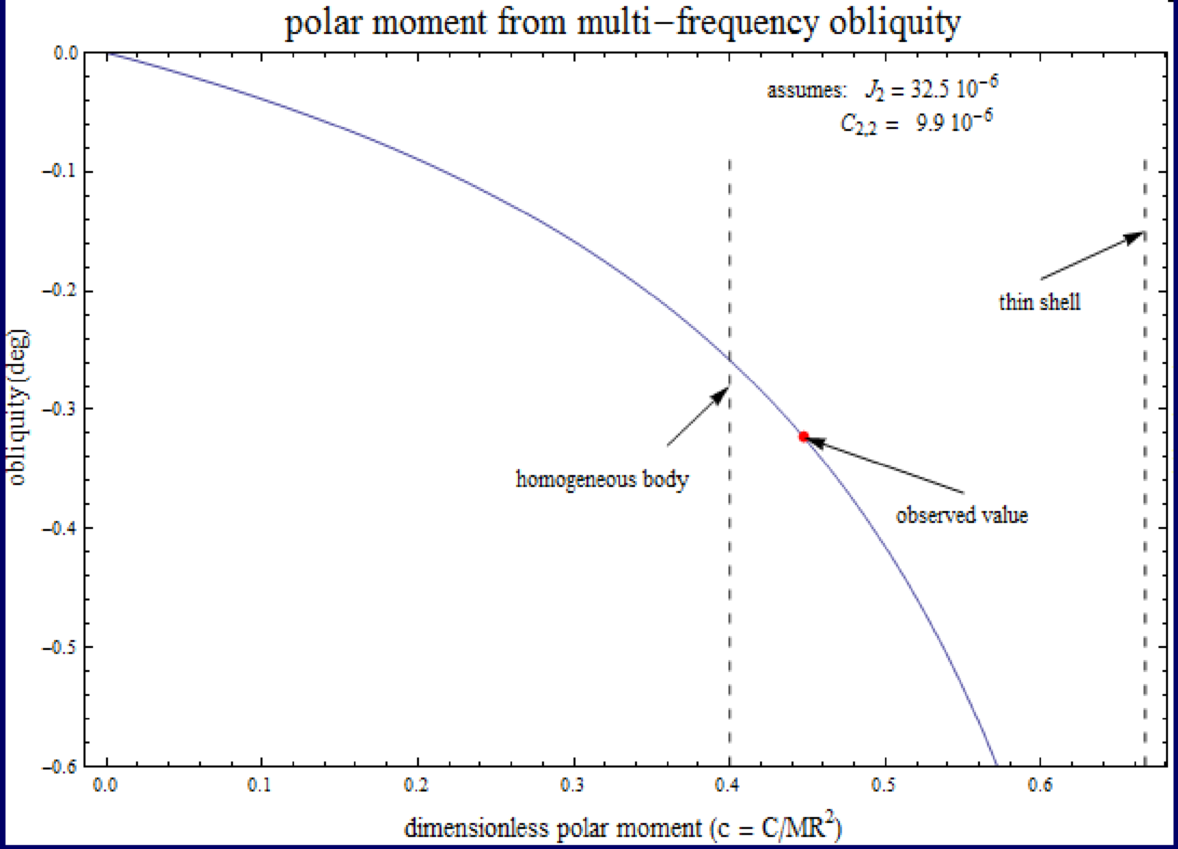
But Bills & Nimmo have pointed out (AGU08, LPSC09) that other terms vary in the Titan orbit - e.g. Titan's orbit not only precesses about Saturn's equator (~700 years) but Saturn's equator itself precesses with a period of ~1.7 million years

- multi-frequency Cassini state





damped spin pole does NOT stay coplanar with orbit pole and invariable pole



Polar moment of inertia from obliquity doesn't appear to be of same value as that inferred from the gravity field (not yet published). Rigid body theory not applicable?

Pretty universal agreement that rotation state is weird enough to require internal ocean (so my Science paper isnt yet wrong) but details really need to be worked out and more measurements obtained

Just to make things interesting, CIRS data suggests that atmosphere doesn't rotate around the geographical north pole…

Observation of a tilt of Titan's middle-atmospheric superrotation

Richard K. Achterberg[a,*], Barney J. Conrath[b], Peter J. Gierasch[b], F. Michael Flasar[c], Conor A. Nixon[a]

Icarus 197 (2008) 549–555

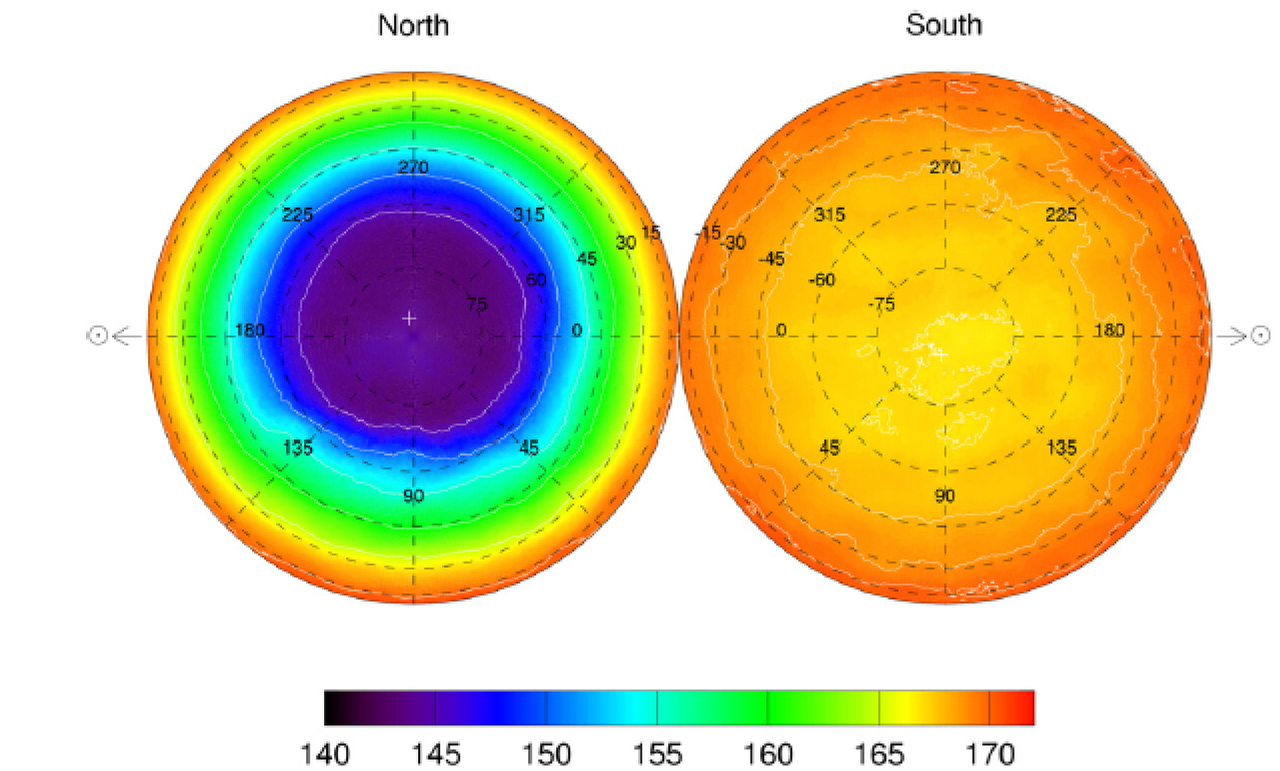
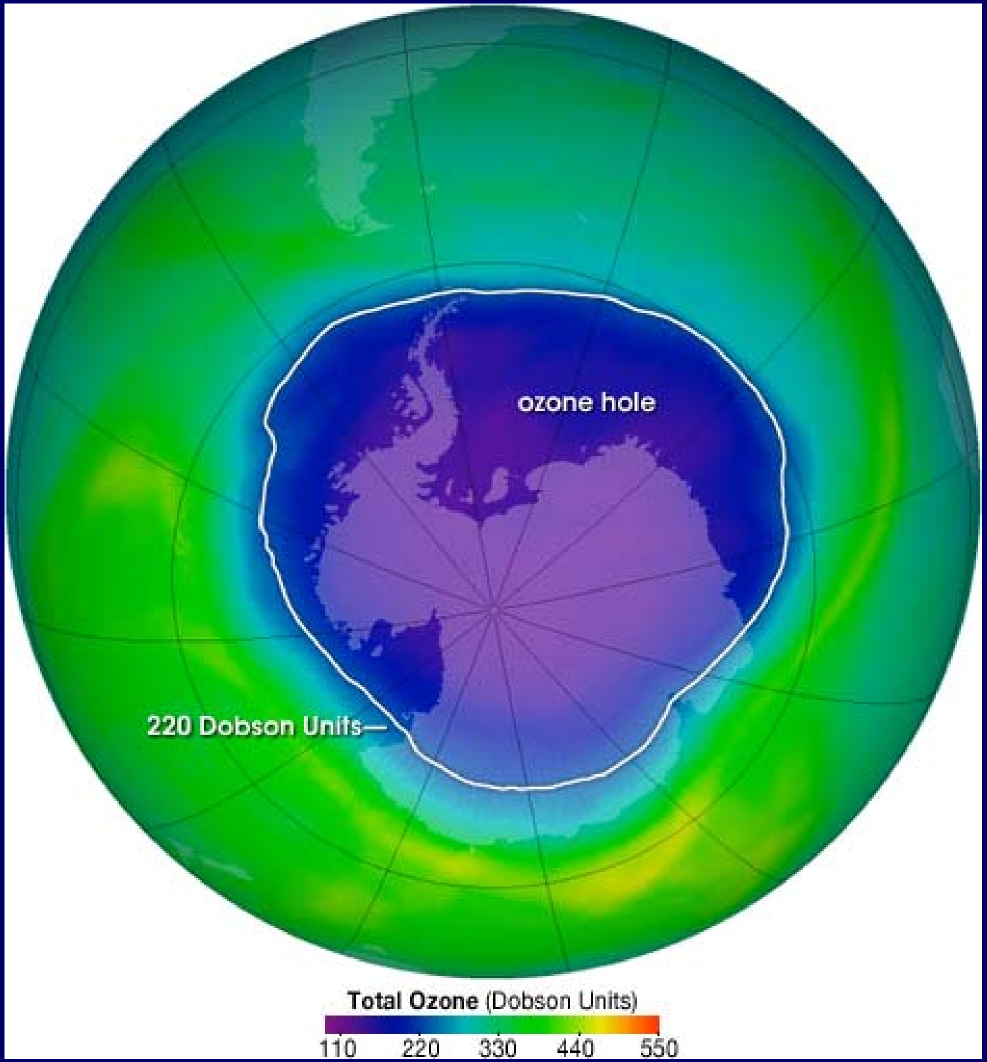
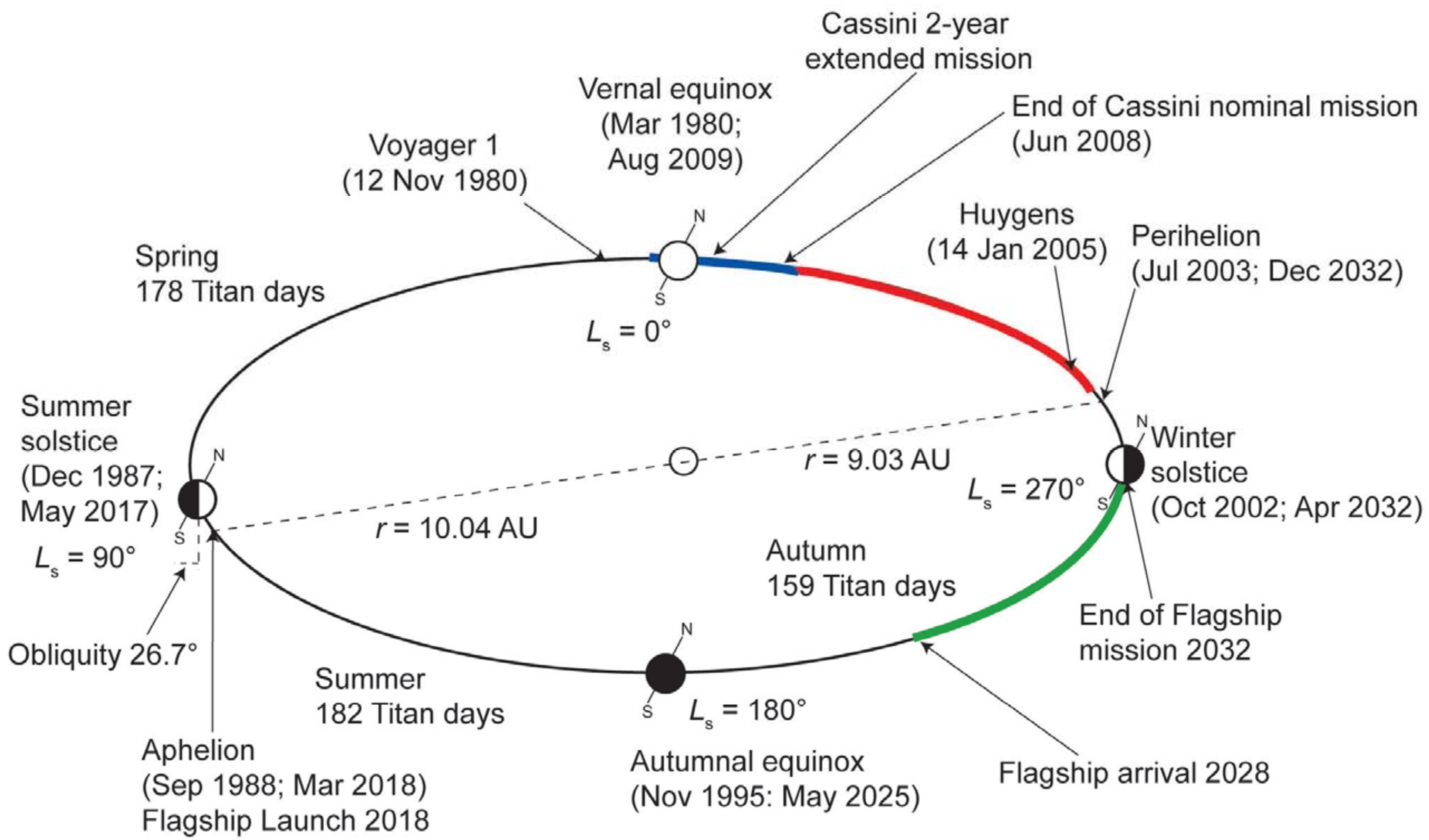


Fig. 3. Polar projection maps of retrieved temperatures at the 1 mbar level. The northern hemisphere is shown on the left and the southern hemisphere on the right. The color coded temperature scale in kelvins is shown at the bottom. The superposed grid represents latitude and west longitude in a Sun-fixed frame with the longitude of the sub-solar point at 180° W, such that the Sun direction is towards the left and right edges of the figure. Temperature contours are plotted at intervals of 5 K in the northern hemisphere, and 1 K in the southern hemisphere. The fitted axis of symmetry is indicated by a white cross (+).

But maybe that isnt so strange - terrestrial stratospheric features can be displaced too….
(note that there are some other similarities between Titan's polar hood and the Earth's ozone hole. Both are dynamically-confined areas of downwelling during polar winter, with distinct gas chemistry and aerosols (polar stratospheric clouds on Earth).

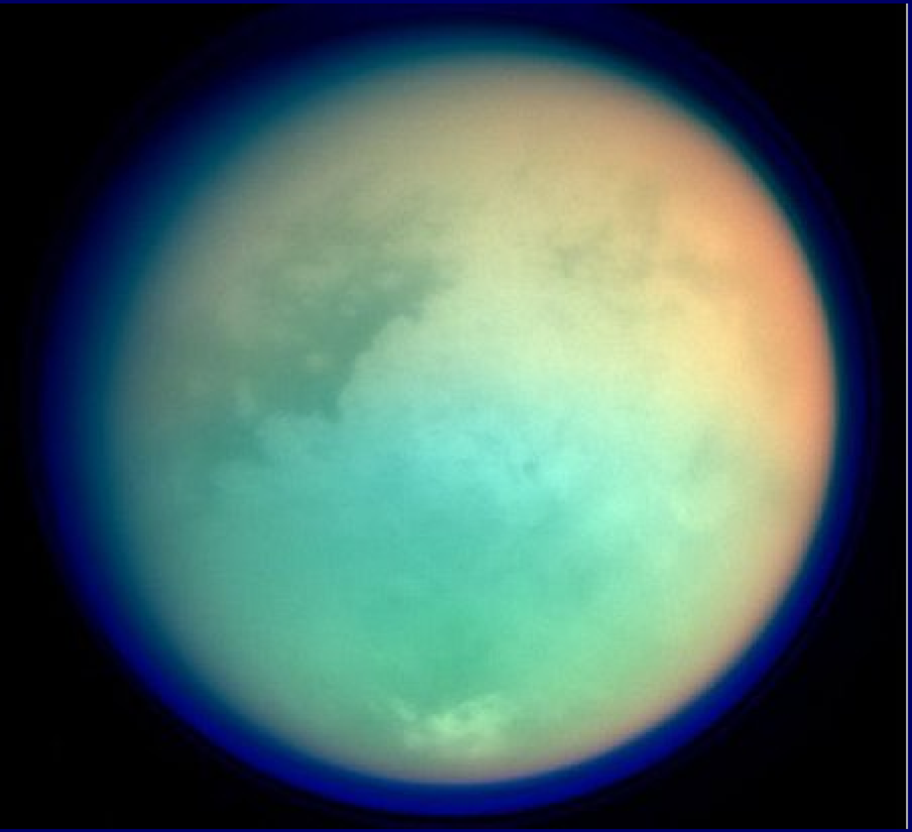


Croll-Milankovitch cycles on Titan ?



Orbital motion of Titan and Saturn around the Sun during one Saturn year. L_s denotes the Kronocentric (Saturnicentric) orbital longitude of the Sun that characterizes the season. 07-01121-04

At present, Southern summer is shorter and more intense than northern summer. But in tens of thousands of years that will change



Titan's north and south polar regions appear different - many more lakes and seas in the north than the south. Are we confronting a puzzle similar to that on Mars? What are the relative roles of topography and orbital/radiative forcing on the transport and accumulation of volatiles ?

If orbital/radiative forcing is dominant, will the lakes move to the south in 100,000 years?

A future Titan orbiter, or better yet a long-lived Titan Lander (as proposed in the 2007 APL/JPL Titan Explorer study for NASA) would provide unprecedented accuracy for measuring Titan's spin state (as was done for Mars Pathfinder…)

Conclusions

Nothing is ever simple!

Huygens probe spin suggests more than one unanticipated effect.

Titan spin is still a developing story - expect further theoretical and observational surprises. Spin bears on Titan's interior, its atmosphere and on mapping the surface.