Titan Wind Analysis using Lagrangian Coherent Structures

Ronald Kam Fai Fung
Mentors: Professor Jerrold Marsden, Dr Claire Newman, Dr Philip du Toit, Sarah Sherman

California Institute of Technology, September 1, 2009

Abstract

Since 2004, the Cassini-Huygens mission has been providing pictures of Titan's striking landscape of sand dunes and hydrocarbon lakes. Subsequently there have been plans for a return mission involving a Montgolfière balloon or aerobot to be deployed in Titan's thick atmosphere. Lagrangian Coherent Structures are transport barriers separating regions of different dynamical flow, and through their calculation on a wind model for Titan it is possible to identify regions which should be avoided for deployment as well as those which will maximize surface coverage. It is demonstrated that prominent Lagrangian Coherent Structures exist around the North Pole at the anticipated mission arrival time, suggesting that a Montgolfière balloon without horizontal actuation would be trapped if deployed in that region. Secondly, few Lagrangian Coherent Structures exist close to the surface indicating that an aerobot with limited horizontal actuation should descend to low levels to minimize the control effort expended in changing its course.

Introduction

In 2004, the Cassini-Huygens mission provided the first glimpses of Titan's striking and geologically diverse landscape, characterized by equatorial sand dunes, polar hydrocarbon lakes and cryovolcanoes. In fact, scientists have compared Titan to a primordial Earth, citing its atmosphere rich in organic compounds and the presence of stable bodies of surface liquid as features analogous to our own planet. It is in the context of this over-arching and extraordinary interest in exploring Titan that recent efforts have been taken to study Titan's atmospheric patterns.

NASA is currently considering plans to send a return mission to Titan within the next few decades. At present, it is estimated that the mission will take place around the year 2030, which would be during the season of northern winter on Titan. Initial plans involve sending a lighter-than-air vehicle that is able to drift in Titan's dense nitrogen-rich atmosphere, capable of making both remote and in situ measurements, for example imaging, spectrometry and surface-sampling. The benefits of such a form of spacecraft include minimization of power usage and flight mass, and the ability to penetrate Titan's dense smog of organic photochemicals which would otherwise hide the moon's surface from view by visual sensors. [1] One option is the Montgolfière hot air balloon which only has control in the vertical direction and drifts passively in the horizontal direction as dictated by Titan's wind field. Movement in the vertical direction is allowed by controlling the escape of heated air from the balloon. Another option is the aerobot, which has both horizontal and vertical actuation. The obvious advantage of the aerobot is that it is not as dependent on favorable winds to carry it to the desired destination and it would also take less time to reach a particular site on Titan's surface. However, the horizontal control is not unlimited due to fuel constraints.

This paper investigates the optimal location in Titan's atmosphere where a Montgolfière balloon or an aerobot should be released in order to maximize the total area covered and to pass through particular regions of interest. Previous research papers including that of Lorenz have suggested that the trajectory of a passive balloon would be confined to a narrow latitude band, based on the assumption that the zonal (east-west) winds are dominant [2]. However, recent findings by Tokano et al. have indicated that a larger proportion of Titan's surface may be accessible to a passive balloon at low altitudes [3]. Han, a SURF student in 2008, found that deploying a balloon near one of the poles would allow the near surface winds to take the balloon towards the equator while being super-rotated around Titan, and this would enable one hemisphere to be explored [4]. These possibilities are explored in this paper.

From a scientific point of view, the key landmarks on Titan's surface include the hydrocarbon lakes containing pools of liquid methane which are located near Titan's poles. This is an important target for exploration because the lakes are the first stable bodies of surface liquid found in our solar system outside of Earth. Other important landmarks include the large sand dunes located near the equator, sculpted by the strong zonal winds on Titan, as well as drainage channels and Xanadu, a highly reflective plateau, located in the low latitudes mostly in the southern hemisphere. As such, an important goal for the future mission to Titan is finding an optimal point of deployment for the Montgolfière balloon to reach as many of these landmarks as possible.

Background: Lagrangian Coherent Structures

In order to determine the optimal location at which to deploy the balloon, the technique of finding the Lagrangian Coherent Structures in Titan's atmosphere is employed. Lagrangian Coherent Structures are time- and space-dependent transport barriers which separate regions of different dynamical flow,as shown in Figure 1. The black line delineates a Lagrangian Coherent Structure, on either side of which the neighboring particles diverge. The Lagrangian Coherent Structures in Titan's atmosphere are like walls which prevent particles from passively crossing over from one side to the other.

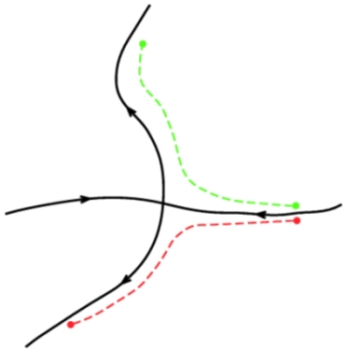


Figure 1. Lagrangian Coherent Structures separate regions of different dynamical behavior

Quantitatively, the Lagrangian Coherent Structures are found by taking the input data of Titan's wind field, provided by the TitanWRF general circulation model, and calculating the finite-time Lyapunov exponents for each point in the time-varying flow field. The finite-time Lyapunov exponent (FTLE) is a scalar value which characterizes the amount of stretching about the trajectory of a point in the domain, or in other words, how fast neighboring particles diverge from that point as time evolves [5]. The Lagrangian Coherent Structures can then be identified as the ridges (local maxima) of the FTLE field, where there is maximum divergence of neighboring particles. Identifying the Lagrangian Coherent Structures in Titan's atmosphere is useful because they demarcate the regions within which a passively drifting Montgolfière balloon would be confined, depending on the location of deployment.

Background: Titan's wind field

According to the TitanWRF general circulation model, Titan's wind field is highly variable depending on the season, latitude, longitude and height. The wind in Titan's atmosphere is almost purely zonal up to a height of 50km above the surface. Of particular significance are the reversals between easterlies and westerlies which occur at different latitudes and heights depending on the season. There are also meridional (north-south) winds, characterized by Hadley cells where the air rises in the warmer regions of the atmosphere and descends in the cooler regions. In addition, there are meridional tidal winds caused by the gravitational field of Saturn which are rapidly time-varying and have a period of 1 Titan day [6].

Figures 2-5 show wind profiles for different seasons on Titan, with Ls referring to the planetocentric solar longitude which gives the position of a planetary body in its orbit around the Sun. Ls 0 corresponds to northern spring equinox, Ls 90 to northern summer solstice, Ls 180 to northern autumn equinox and Ls 270 to northern winter solstice.

Figure 2 is a plot for northern winter solstice (Ls 270) showing the zonal wind profile averaged across all longitudes. Figure 2 shows that for heights above 18km, there are westerlies at all latitudes. However, easterlies occur below 18km around the equator and in the southern (summer) low latitudes. Below this, there are weak westerlies near the surface with an average speed of 1m/s. Figure 3 is a plot showing all three wind components- zonal winds, meridional winds and vertical winds. During northern winter, there is a single Hadley cell, rising in the south and falling in the north.

The wind profile for northern summer is almost the mirror image of northern winter, with easterlies occurring in the northern low latitudes and a single Hadley cell rising in the north and falling in the south.

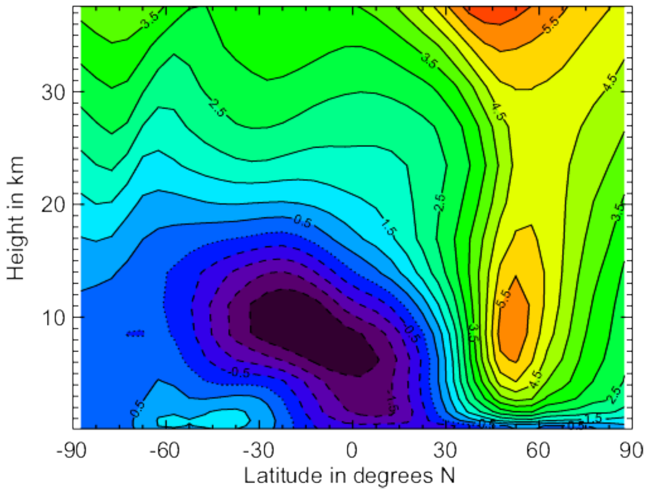


Figure 2. Plot of zonally averaged zonal winds at Ls 270. Solid lines indicate westerlies, dotted lines indicate easterlies.

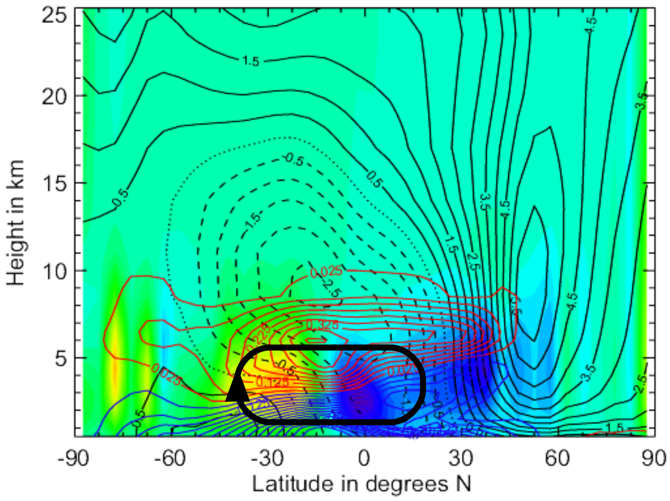


Figure 3. Plot of zonal, meridional and vertical winds at Ls 270. Black lines are zonal winds, with solid and dotted lines for positive and negative direction respectively. Red lines are positive meridional winds and blue lines are negative meridional winds. Red/yellow shading is positive vertical winds and blue shading is negative vertical winds. The circulation is shown schematically by the thick black line and arrow, as characterized by the single Hadley cell.

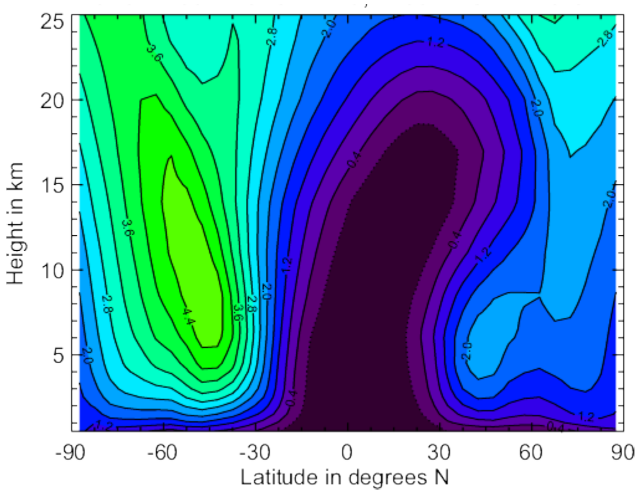


Figure 4. Plot of zonally averaged zonal winds at Ls 90. Legend is the same as for figure 2.

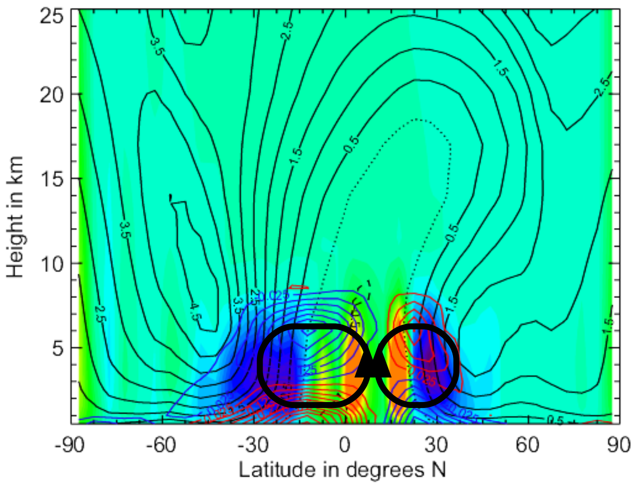


Figure 5. Plot of zonal, meridional and vertical winds at Ls 90. There are two Hadley cells co-existing at this season. Legend is the same as for figure 6.

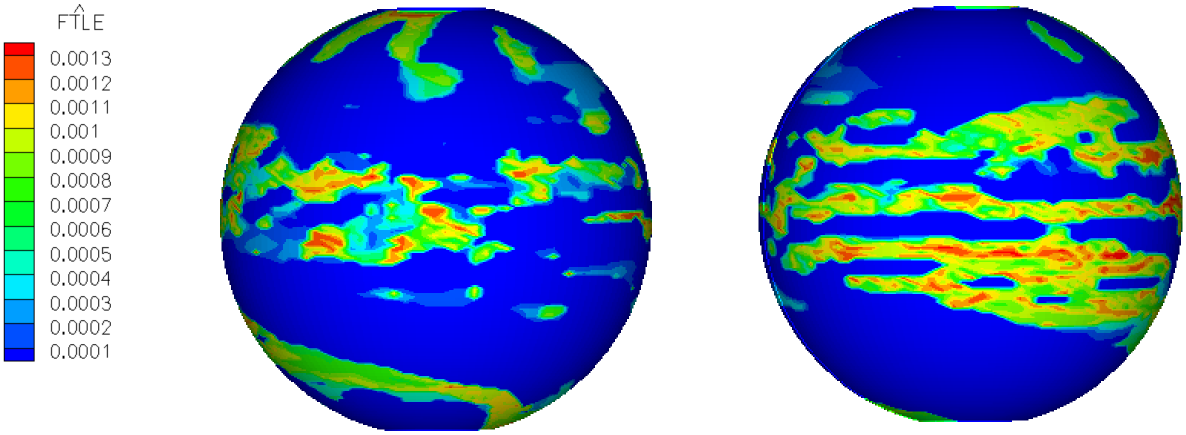
Figure 4 is a plot for northern fall equinox (Ls 90) showing the zonal winds averaged across all longitudes, while figure 5 shows the zonal, meridional and vertical winds for this season. Figures 4 and 5 show that there are westerlies for all latitudes at all heights, with only very weak easterlies near the surface. Furthermore, during northern fall there is a reversal of the global Hadley circulation, when two large Hadley cells rising from the equator and extending to the south and north poles temporarily coexist.

Results

The NEWMAN code software was used to calculate the finite time Lyapunov exponents which are needed to identify the Lagrangian Coherent Structures in Titan's atmosphere. The NEWMAN code is a Linux based program written by Dr Philip du Toit which inputs the wind velocity raw data provided by TitanWRF, and outputs the FTLE values for each data point. The data visualization program Tecplot was used to display the FTLE values as a 2D or 3D plot of Titan's atmosphere. The NEWMAN code was also used to produce drifter plots which are useful in visualizing particle trajectories.

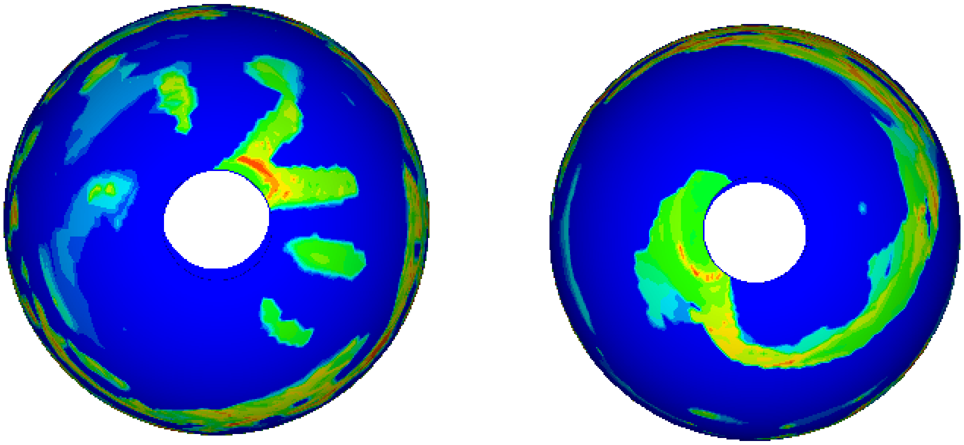
Most of the FTLE plots produced are for the northern winter season as this is the season for the projected mission to Titan. Figures 6, 7 and 8 are the FTLE plots for different heights within Titan's lower troposphere. Heights of 1km, 5km and 10km were chosen because this will be the most likely range of heights that the Montgolfière balloon will remain within. According to the NASA Jet Propulsion Laboratory, 15km is the maximum operating altitude of the balloon as methane icing poses a danger above this altitude. Also, although the mountain range just south of Titan's equator reaches heights of up to 2km [7], Titan has a relatively flat topography and the average height of its mountain peaks is 440m [8]. As such, it will be feasible for the balloon to descend close to the surface in certain regions and travel at altitudes as low as 1km.

In Figures 6, 7 and 8, the Lagrangian Coherent Structures can be identified as the red bands which are local maxima in the FTLE field. The same scale is used for all three sets of FTLE plots to allow for a valid comparison between the different height levels.



-180° to 0°

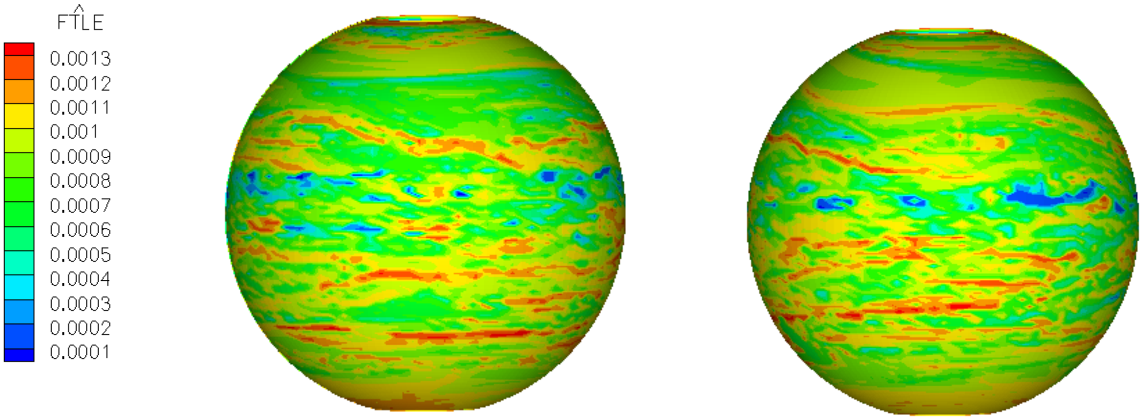
0° to 180°



North Pole

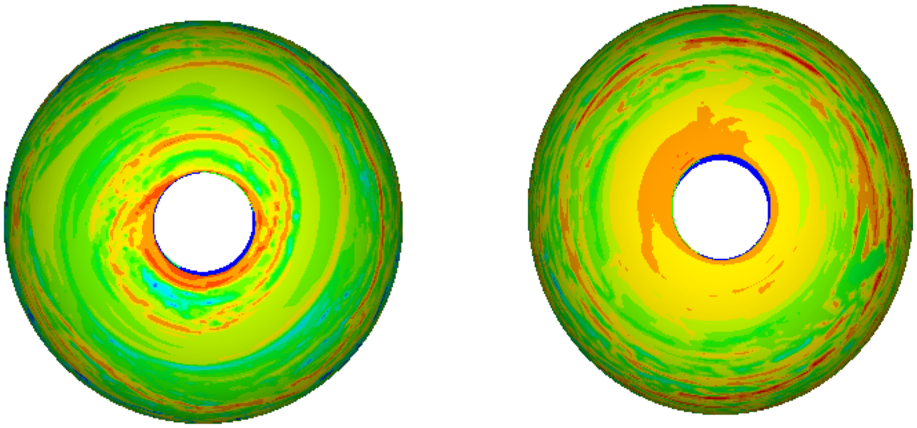
South Pole

Figure 6: FTLE Plots for 10km altitude at Ls 270



-180° to 0°

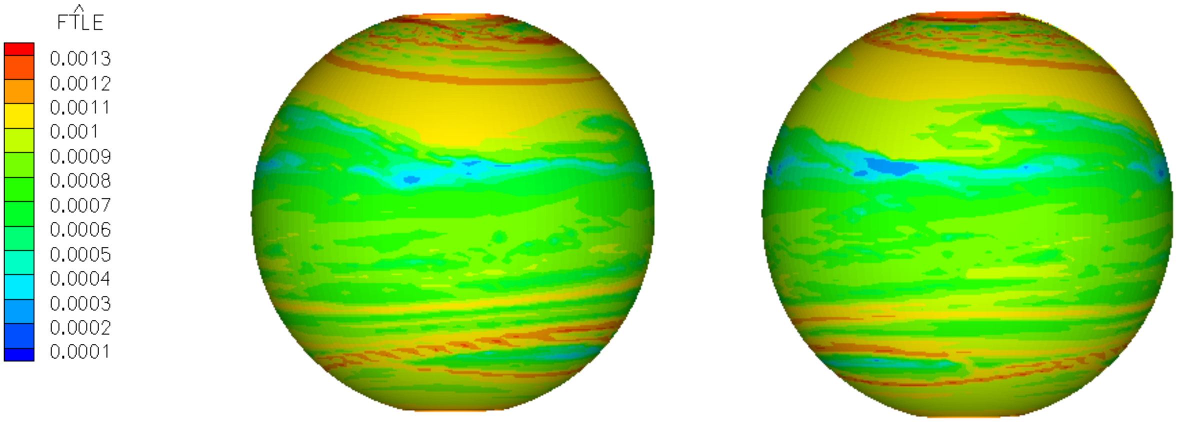
0° to 180°



North Pole

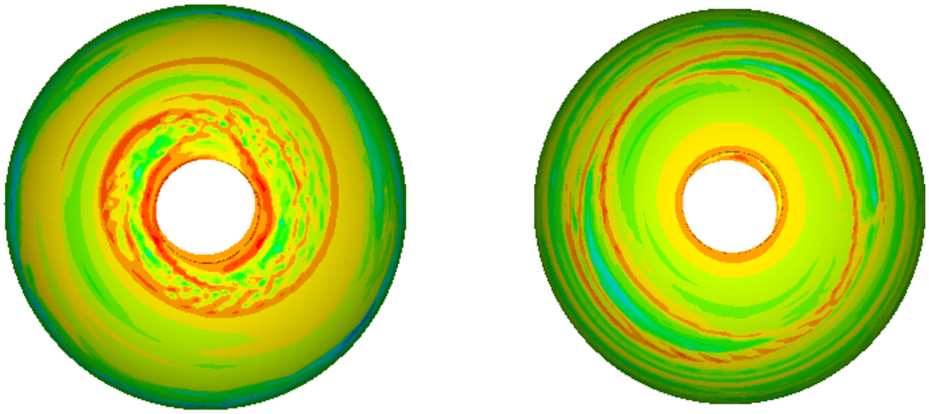
South Pole

Figure 7: FTLE Plots for 5km altitude at Ls 270



-180° to 0°

0° to 180°



North Pole

South Pole

Figure 8: FTLE Plots for 1km altitude at Ls 270

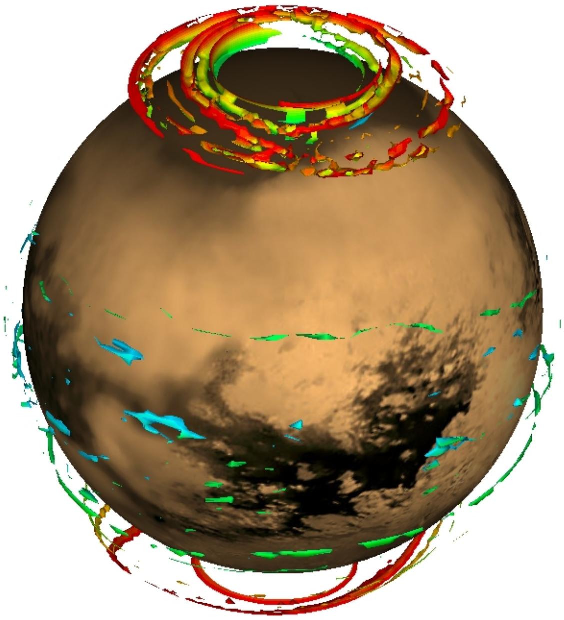


Figure 9. FTLE isosurface for regions with FTLE value ≥ 0.0012 at Ls 270. The isosurface is color coded by altitude, with red depicting an altitude of 10km and blue depicting the lowest altitudes near Titan's surface.

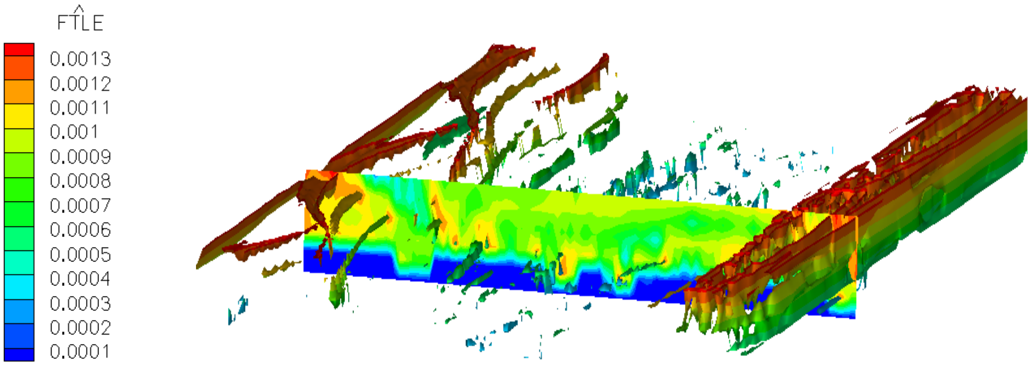


Figure 10: FTLE isosurface for regions with FTLE value ≥ 0.0012, projected onto the FTLE plot for Ls 270. South Pole is on the left, North Pole is on the right, with the different longitudes projecting into and out of the page. The isosurface is color coded with red depicting an altitude of 10km and blue depicting the lowest altitudes near Titan's surface. The FTLE plot in the plane of the page is a cross section taken at 0° longitude, showing latitude versus height. The color legend the FTLE plot is shown on the left.

Figure 9 shows a FTLE isosurface only displaying the regions where the FTLE value is 0.0012 or higher. This figure is useful because it provides a 3D view of where the strongest transport barriers are located, namely near the North and South Poles. Figure 10 is a plot of the same FTLE isosurface, viewed on a rectangular coordinate system and projected onto the regular FTLE plot.

One prominent Lagrangian Coherent Structure that can be identified from figures 6-8 is the band stretching across the latitude range 65°N to 80°N and surrounding the North Pole. Figure 9 shows that this Lagrangian Coherent Structure consists of several rings completely encircling the North Pole. However, this transport barrier is primarily restricted to altitudes of 4 to 10km as shown in Figure 10 where the FTLE isosurface only extends from about half way up the vertical column to the top near the North Pole. Even so, it would clearly be advisable to avoid this region when deploying the Montgolfière balloon as, without horizontal actuation, it would likely remain trapped near the North Pole and be unable to cross the strong transport barrier as it attempts to migrate southwards.

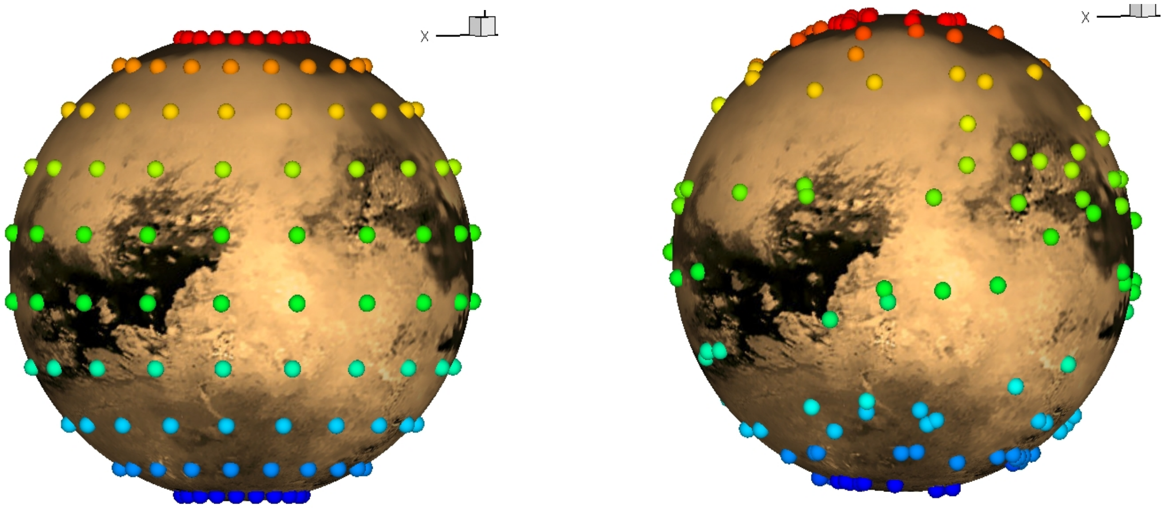
This conclusion is supported by the drifter plots in Figure 11 which clearly show a divergence in the flow of the drifters at around 65°N. The drifters are color coded by the latitude of their starting position. As time evolves, the drifters starting at latitudes north of 65°N, color coded in red, orange and yellow, remain trapped near the north pole, with very few of the green drifters starting just south of 65°N being able to cross over into this region. By frame 200, it is possible to see a gap developing between the higher and lower latitudes in both hemispheres, which is consistent with the Lagrangian Coherent Structure identified above.

As such, the optimal location to deploy the Montgolfière balloon would be south of 65°N, in the mid latitudes in the northern hemisphere. This would allow the balloon to drift southwards towards the equator and into the southern hemisphere as it is moved across all longitudes by the strong super-rotating zonal winds on Titan. The balloon would thus be able to maximize its coverage of the surface of Titan, while visiting the key landmarks such as Xanadu, the sand dunes, cryovolcanoes and drainage channels which are located near Titan's equator and in the low latitudes of the northern and southern hemispheres. Figure 6-8 show that there is a virtual absence of strong transport barriers near the equator and in the low latitudes, except for scattered “spot Lagrangian Coherent Structures” which can easily be avoided through use of vertical control. Hence it would be relatively easy for the Montgolfière balloon to drift southwards towards the equator. Furthermore, the surface winds blowing from north to south in the lower branch of the Hadley cell (Figure 3) would assist the balloon in steadily migrating southwards.

While this plan would mean that the Montgolfière would not be able to reach the hydrocarbon lakes at the North Pole, which are an important target for exploration, this will not be a problem as NASA has plans to deploy a separate probe at the North Pole to conduct surface sampling of the lakes, along with the Montgolfière which would be able to focus on the equatorial and mid latitude regions.

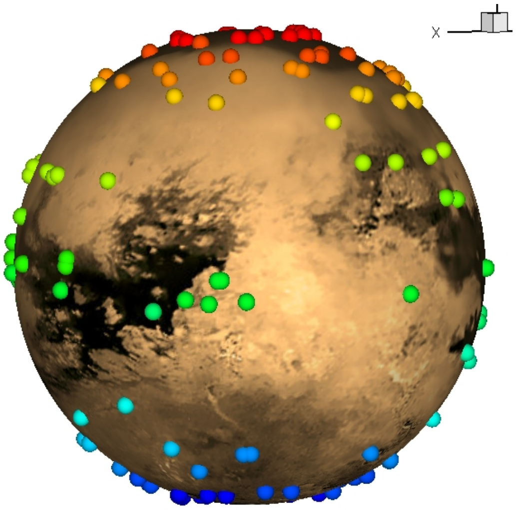
While Figure 6 suggests that there is an analogous Lagrangian Coherent Structure encircling the South Pole, the transport barrier there is much more porous than the one around the North Pole. Figure 10 shows that the Lagrangian Coherent Structure at the South Pole exists only in a narrow altitude range, between 8km and 10km. As such, a Montgolfière balloon would easily be able to use vertical control and descend to lower altitudes in order to maneuver around the transport barrier. Hence, the aforementioned plan to deploy the Montgolfière balloon in the mid latitudes in the northern hemisphere and allow it to drift southwards would not preclude the possibility of the balloon reaching as far south as the South Pole. This would enable a large proportion of Titan's surface to be explored.

Another important conclusion to be drawn from the FTLE plots is that smaller transport barriers exist at the lower altitudes near Titan's surface. Figure 6 and 7 show prominent Lagrangian Coherent Structures at altitudes between 5 and 10km, whose FTLE plots consist of many bands of red. In contrast, the FTLE plot at 1km is primarily blue which indicates very low FTLE values, and minimal transport barriers at this altitude level. This observation is supported by Figure 9 where even the Lagrangian Coherent Structure around the North Pole does not extend all the way down to Titan's surface. This suggests that an aerobot should use vertical control to descend to low altitudes to minimize the energy expended in horizontal actuation in the event that it needs to cross a transport barrier. Even where there are transport barriers at low altitudes, these barriers are much weaker and able to be crossed with minimal control effort. In fact, Figure 8 shows a virtual absence of even spot Lagrangian Coherent Structures across most latitudes.



Frame 1, t=0

Frame 100, t=8 Titan days or 128 Earth days



Frame 200, t=16 Titan days or 256 Earth days

Figure 11. Drifter plot for 10km altitude at Ls 270

The robustness of Lagrangian Coherent Structures to random noise was also briefly investigated in the final stages of the project. The approach was to add a 4D vector of random values (with components in time and in the x,y and z directions) to the input wind data from the TitanWRF model. Subsequently, the modified wind data was input into the NEWMAN code to compute the FTLEs and produce the FTLE plots as before. This was done for the following cases: 0% noise, 1% noise, 2% noise and 5% noise, as shown in Figures 12-15.

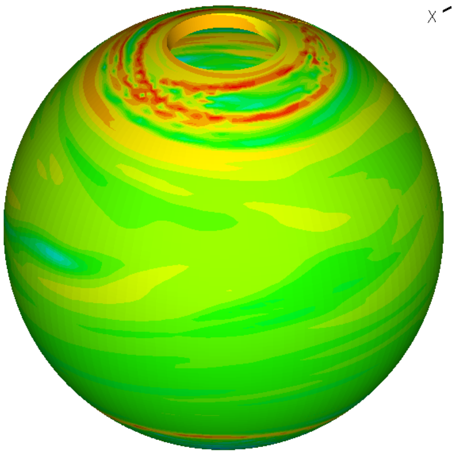


Figure 12. FTLE plot for 10km altitude at Ls 270 with 0% noise.

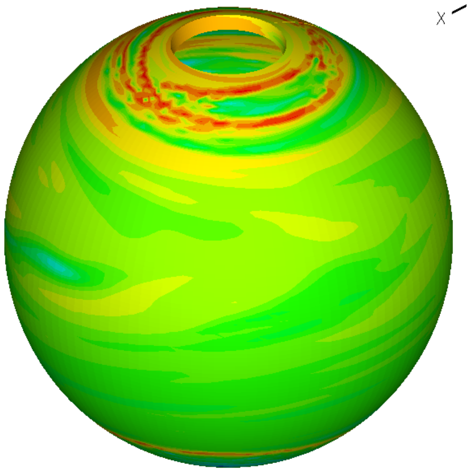


Figure 13. FTLE plot for 10km altitude at Ls 270 with 1% noise.

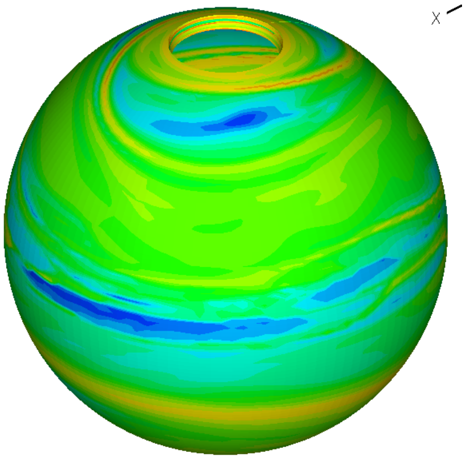


Figure 14. FTLE plot for 10km altitude at Ls 270 with 2% noise.

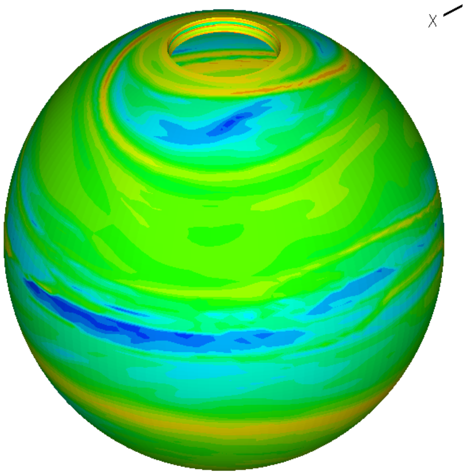


Figure 15. FTLE plot for 10km altitude at Ls 270 with 5% noise.

It is clear that the Lagrangian Coherent Structures are robust to 1% random noise, as the FTLE plots in Figures 12 and 13 are virtually identical. However, with the addition of just 2% noise in Figure 14, the large scale structures are completely different. For example, there is no prominent Lagrangian Coherent Structure surrounding the North Pole in Figure 14 as there is in Figure 12. From this, it is clear that Lagrangian Coherent Structures are not very robust to random noise and and disappear with just 2% noise.

However, this is not altogether surprising as the noise that was added in our tests is completely random, whereas the noise which is encountered in reality would be less random, with more correlations between adjacent gridpoints. For example, if a zonal wind jet peaks at a slightly higher latitude in the real atmosphere than predicted in the model, the wind for each latitude involved would be expected to change similarly at all longitudes. In another instance, if the wind velocities encountered in the real atmosphere are higher than those predicted in the model, one would expect them to be consistently so across all grid points.

Hence, it would be worthwhile to conduct further tests using more systematic ways to add less random noise, for example adding noise which only alters the magnitude but not the direction of the wind vectors. These tests would enable a fairer assessment of the robustness of Lagrangian Coherent Structures to noise. This is an important area of future research as it determines the amount of credence and weight that can be accorded to the Lagrangian Coherent Structures technique to make decisions such as the optimal location of deployment for a Montgolfière balloon in Titan's atmosphere.

Conclusions

This project has explored the global patterns of wind flow in Titan's atmosphere and deduced the large-scale transport barriers which play a crucial role in determining the trajectory that a Montgolfière balloon may follow if deployed at various locations. Based on a mission time during the season of northern winter on Titan, the Montgolfière balloon should be deployed south of 65°N, in the northern mid latitudes, in order to maximize surface coverage and reach the landmarks of interest. Secondly, a useful strategy for an aerobot would be to descend to low altitudes in order to minimize the horizontal control expended when it is necessary to cross a Lagrangian Coherent Structure.

However, there is much future work that can be done in this area to enhance our understanding of Titan's atmospheric patterns and its implications for a return mission to Titan. In this project, the finite-time Lyapunov exponents were integrated forward in time to calculate the Lagrangian Coherent Structures which represent regions of maximum divergence of neighboring particles, or in other words, transport barriers. An idea for a future project is integrating the finite-time Lyapunov exponents backwards in time to produce plots which show the regions of maximum convergence, known as the “transport highways” in an atmospheric flow. This could help to determine the regions which are easily accessible and can be arrived at from a range of starting locations, or regions which are conducive to a Montgolfière balloon hovering in roughly the same place, perhaps to conduct surface sampling, with minimal control effort.

Secondly, the Lagrangian Coherent Structures for different seasons apart from northern winter can be investigated. This would be beneficial because the proposed return mission to Titan may be postponed and end up occurring in another season. Furthermore, this work would enhance our understanding of the effect of seasonality on Titan's atmospheric patterns.

Furthermore, it would be worthwhile to investigate the impact of intrinsic atmospheric variability associated with atmospheric models. By comparing the results obtained from TitanWRF data taken from the same season but over several different years, it would be possible to note the extent to which the wind flow can vary even with all other factors such as the strength of the solar forcing being identical. Structures such as planetary scale waves can introduce a significant degree of intrinsic variability in localized regions.

The final area of improvement would be working on the TitanWRF model to make it as accurate as possible in matching the actual wind fields on Titan. This is all the more important given that Lagrangian Coherent Structures are shown to be relatively sensitive to noise, and discrepancies between the wind model and the actual wind field could have a dramatic impact on whether the transport barriers as identified in the FTLE plots actually exist. While the current TitanWRF model shows very good agreement with the data obtained during the Huygens probe descent in 2005, certain inconsistencies such as the zonal direction of wind flow at the equatorial surface still need to be resolved [9]. Once these inconsistencies are resolved, the TitanWRF model will serve as a extremely valuable tool in planning the return mission to Titan.

Acknowledgments

I would like to acknowledge the invaluable help and advice I received from Professor Jerrold E. Marsden, Dr Claire Newman, Dr Philip du Toit and Ms Sarah Sherman which have enabled the conception and fruitful completion of my project. I am also grateful to Alberto Elfes and his team for sharing with me their research work at JPL.

References:

[1] Pankine, A.A., Aaron, K.M., Heun, M.K., Nock, K.T., Schlaifer , R.S., Wyszkowski, C.J., Ingersoll, A.P., Lorenz, R.D. (2004) Directed aerial robot explorers for planetary exploration. *Advances in Space Research*, 33, 1825–1830

[2] Lorenz, R.D. (2000) Post-Cassini exploration of Titan: science rationale and mission concepts. *J. Brit. Interplanet*. Soc., 53, 218–234.

[3] Tokano, T., Lorenz, R.D. (2006) GCM simulation of balloon trajectories on Titan. *Planetary and Space Science*, 54, 685–694

[4] Han, B.M. (2008) Titan Wind Analysis using Lagrangian Coherent Structures. SURF technical report.

[5] Shadden, S.C. (2005) Lagrangian Coherent Structures: Analysis of time-dependent dynamical systems using finite-time Lyapunov exponents. Online tutorial.

[6] Tokano, T., Neubauer, F.M. (2007) Tidal Winds on Titan caused by Saturn. *Icarus,* 158(2):499-515

[7] Battersby, S. (2006) Titan's ice mountains revealed by long shadows. *New Scientist*, 13 September 2006.

[8] Radebaugh, J., Lorenz, R.D., Kirk, R.L., Lunine, J.I, Stofan, E.R., Lopez, R.M.C, Wall, S.D. (2007) Mountains on Titan observed by Cassini Radar. *ICARUS,* 192(1):77-91

[9] Newman, C.E., Richardson, M.I., Toigo, A.D., Lee, C. (2008) Comparing TitanWRF and Cassini results at the end of the Cassini Prime Mission. Powerpoint Presentation.