Presentation

DESCENT TRAJECTORY AND ATTITUDE RECONSTRUCTION OF HUYGENS PROBE USING DESCENT IMAGER / SPECTRAL RADIOMETER (DISR) DATA

B. Rizk[(1)], M.W. Bushroe[(2)], E. Karkoschka[(3)], E.A. McFarlane[(4)], C. See[(5)], M. G. Tomasko[(6)] and the DISR Team

Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ1629 E. University Blvd., University of Arizona, Tucson AZ, 85721-0092, USA.

1. bashar@LPL.arizona.edu
2. mbushroe@LPL.arizona.edu
3. erich@LPL.arizona.edu
4. lmcfar@LPL.arizona.edu
5. csee@LPL.arizona.edu
6. mtomasko@LPL.arizona.edu

ABSTRACT

Data from the Descent Imager / Spectral Radiometer (DISR) imagers are used to reconstruct probe trajectory and attitude during the latter part of the descent phase. The fortuitous overlap between the coverage provided by the three near-IR imagers and that of the Sun Sensor (SS) allowed each image's position, already referenced to the emplacement of other images, to be referenced at high altitude to the position of the Sun. While not complete, the process of image mosaic creation has derived preliminary models of ground-track, wind profile and tip-tilt between 2200 and 8700 sec mission time and allowed a reasonable extrapolation to the surface.

1. INTRODUCTION

The basis of the DISR descent-trajectory recovery is a natural outcome of choices made during DISR and the Huygens probe's design as well as the Titan radiative environment encountered during the mission's duration. During probe design, no sensor whose primary function is attitude-determination was included in the mission manifest, with the exception of the DISR Sun Sensor. On an instrument bristling with light-gathering subsystems of every variety, on a probe destined to experience the entry heat of aerobraking friction, whose parachute-payload system was expected to spin steadily, but sway hardly at all, and which was expected to survive a surface impact intact, such a function was deemed an unreachable luxury. The azimuth and part of the spin axis orientation was to be measured by the Sun Sensor and, if the need arose, the data provided by the various DISR sub-systems could themselves be used as attitude sensors to supplement the Sun Sensor.

Unfortunately, the DISR Sun Sensor did not perform as needed. While in lock, it was designed to record the apparent azimuth and zenith angle of the Sun on every rotation, information capable of providing the azimuth history of the probe throughout the descent, as well as measuring the pitch of the probe in the direction of the Sun. To get into lock and thus be recorded as valid sun pulses, its triplet of signals had to pass a series of stringent criteria, one of which concerned the difference of time between the first and second pulses and the second and third pulses. These two time differences could not differ from each other by more than a specific preset factor which, throughout the first half of the mission (before 4000 sec after T_0), was violated on nearly 80% of the rotations.

During the last half of the mission (after 4000 sec), the Sun Sensor simply lost sensitivity and stopped generating pulses altogether. The combination of a filter which was somewhat out of the main methane window and unexpectedly cold temperatures near the front of the Sensor Head housing reduced its responsivity to well below that needed to create a valid signal. Of the approximately 325 valid pulses expected from the Sun Sensor during the descent, it produced 45, none of which were located in the last half of the descent, when most of the images in which the surface of Titan was visible were recorded. Thus, due to a combination of factors, the need did arise for the various DISR sub-systems, in addition to their primary functions, to be used as attitude sensors.

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Employing the imagers as their own attitude sensors had been practiced repeatedly during the cruise phase using field images acquired from a helicopter platform. Panoramic reconstructions of image frames as controlled by camera station location, altitude and attitude (defined here as azimuth, roll and pitch) were used to determine all of these variables for each instance of image acquisition. Successfully sizing, shaping and placing adjacent images with respect to each other, as controlled by identifying overlapping features, determines position and attitude. Several aspects of the Huygens descent have acted to make this process more interesting than it would otherwise have been, including a thicker and more pervasive haze than expected, the loss of half the images reducing coverage and converting the vast majority of image triplets to doublets and singlets, and an unexpected spin direction.

The series of algorithms in place at the descent's commencement have been somewhat altered to accommodate these realities. The existence of not just one, but two, high-fidelity altitude histories of the probe reduce the number of variables that needed solution by one per image. Assuming a spin axis aligned with the local vertical reduce the number of variables by another two per image. Derivation of initial trajectories and azimuths from the images provides location and orientation baselines for other data streams, which are then incorporated to refine and extend the image-based models. Ultimately, a best-fit ground track is used to constrain the azimuth and horizontal location, allowing the spin axis orientation (in terms of either roll & pitch or spin axis tilt & tilt azimuth) to be solved by a process of reconciliation with the ground track.

2. DATA

The data used to derive the results in this work consist of: 1) some 137 partial image triplets, mostly medium-resolution imager (MRI) and high-resolution imager (HRI) images, emplaced within the context of 5 separate panoramic mosaics, between 55.1 km and 400 m, a change of scale of 135, from mission times 2195 to 8782 sec, 2) a total of 45 sun pulses which cover the region between 136.2 to 30.8 km, from mission times 266-3994 sec, a period that included some 201 probe rotations; below 30.8 km, a region of about 119 probe rotations, no Sun Sensor information was recorded and 3) a total of 19 useful ULIS spectra acquired just before touchdown, between 3 km and 10 m, between mission times 8232 and 8864 sec, as well as several acquired after touchdown.

3. METHOD AND RESULTS

Fixing the six variables of location and orientation (X,Y,Z, α, β, γ) for the probe currently begins by setting the altitude, Z, to that determined by the HASI pressure sensor, assuming the roll and pitch, α and β, to be zero, and deriving the values of azimuth, sub-probe longitude and latitude, X,Y and γ starting with the approach outlined in [1], but with some modifications based on the lack of any clear space due to aerosol rainout and the loss of half the images.

Originally, the visibility of the horizon was to allow roll and pitch to be determined from mercator projections of Side-Looking Imager (SLI) data near the horizon. Because of the presence of haze all the way to the surface, the horizon is effectively shielded in the wavelength region of the DISR near-IR imagers above an altitude of about 3 km. In addition, due to the random loss of half of the images, MRI's and HRI's are often present without an accompanying SLI, or vice versa. The roll and pitch are thus not immediately available except near the surface hence they are initially assumed to be small and set to zero.

Finding the azimuth, sub-probe longitude and latitude by correlating the placement of gnomonic projections of HRI and MRI images proceeds much as planned. Aided by the significant overlap between 15 valid Sun Sensor pulses with 21 high-altitude partial triplets between 30 and 55 km altitude (2195 to 3994 sec) as well as a dozen ULIS measurements near the surface, an absolute azimuth scale has been established and transferred to the image-triplet-generated mosaics. No glory or sun shadows have yet been observed in any of the MRI's which could perform the same function and none are anticipated. The act of assuming zero pitch and roll amounts to assuming the derived azimuth to be equal to the ground azimuth, even though it is actually the azimuth within the Huygens spin plane.

As image frames are displaced, rotated and reprojected to new shapes by the mosaic-creation software, each of their azimuths and their sub-probe longitudes and latitudes are automatically altered. Beginning from the highest to lowest altitudes (opposite to the direction originally intended, because Sun Sensor overlap exists only at high altitudes) the images for which sufficient feature correlation can be found are fit into the overall mosaic. Correlation is difficult near the surface where the rapid change of scale and incomplete coverage, especially of MRI's, is particularly felt.

DISR data was gathered in cycles approximately 2-3 minutes long. Each image cycle recorded a dozen images equally spaced in azimuth so as to maximize coverage of the view of the hemisphere below the probe. Because of the assumption that roll and pitch would average to zero on timescales of less than a minute, averaging the sub-probe longitudes and latitudes in each cycle is a valid operation and contributes toward improving the signal to noise. Two difficulties with this procedure occur at the beginning and end of the image data. At the beginning, at high altitude, near 2200 sec, the first two cycles have only 2 members and 1 member, respectively, because of the degraded quality of the images from those heights. At the end, before touchdown, the longer period of time needed to complete the low near-surface cycle requires breaking up the last cycle into two separate cycles. In the end the history of average sub-probe longitude and latitude vs. time are fit separately with polynomials to derive a ground-track. The fitted longitude history reproduces the data very well, the latitude history somewhat less so. The relative errors in both are similar, about 0.05° of longitude or latitude at high altitude decreasing to about 0.0002° of longitude/latitude near the surface (1-2 km).

The polynomial fits for the history of each image cycle's sub-probe longitude and latitude are shown in Figs. 1 and 2.

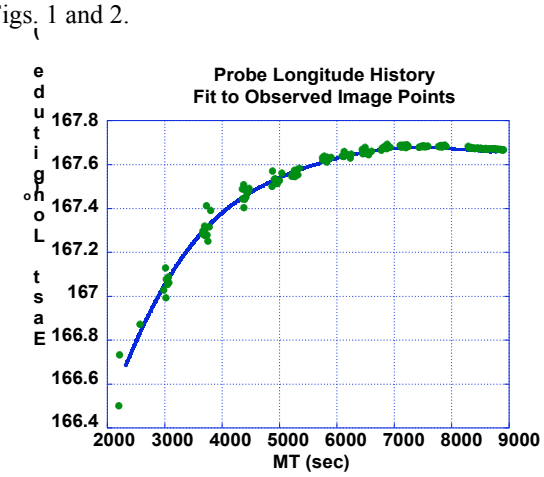

Fig. 1 Sub-probe east longitude vs. mission time (MT), or time after T_0, a time corresponding to UTC/SCET of 14 Jan 2005 09:10:21 and a probe altitude of about 150 km. The dots mark the 137 measurements of sub-probe longitude between mission times 2196 and 8782 sec, or altitudes from 55.1 km to 408 m [2], from DISR image triplet location relative to one of 5 gnomonic panoramic mosaics, adjusted by an offset to give a sub-probe east longitude of 166.6120° at a mission time of 2200 sec, as derived by the Doppler Wind Experiment (DWE) team [3]. The profile is also routinely adjusted by an offset to give a sub-probe longitude of 166.5991° at 2200 sec, as derived by the Descent Trajectory Working Group (DTWG-3) [4]. The measured longitudes for each of the 15 cycles into which the data were divided, were fit by an 8th-order polynomial recorded by the line.

The latitude fit is not very well constrained between 2000 and 2500 sec because of the sparseness of data but otherwise the two fits compare well with the data. The longitude history is adjusted by the results of the DWE and DTWG profiles at high altitude (near 2200 sec after T_0) to have the same values there. The average of the DISR-derived sub-probe latitudes for the ground-track is set to the DWE or DTWG-assumed latitude for the whole descent for the purposes of comparison.

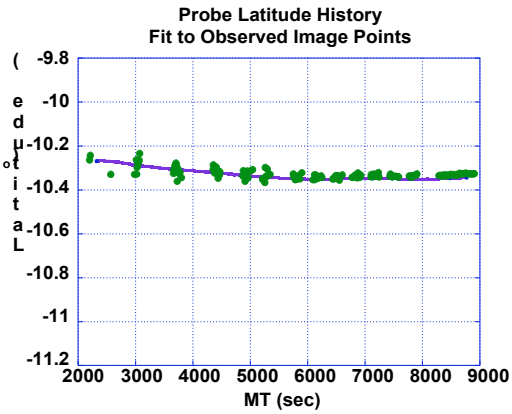

Fig. 2 Sub-probe latitude vs. mission time. The dots mark the 137 measurements of sub-probe latitude from DISR image triplet location relative to a gnomonic panoramic mosaic, adjusted by an offset such that the average of the latitude measurements between 2196 and 8782 sec give a sub-probe latitude of -10.3284° (DWE) [3]. The profile is also routinely adjusted by an offset which equates the average to -10.34°, as derived by the Descent Trajectory Working Group (DTWG-3) [4]. The measured latitudes for each of the 15 cycles into which the data were divided, were fit by an 8th-order polynomial recorded by the line. See the caption of Fig. 1 for further information.

When combined into a ground track, shown in Fig. 3, the results indicate that the probe's steadily increasing eastward drift caused by Titan's pro-grade winds slows, then halts altogether near 7 km altitude, producing first a west-southwest-, then a west northwestward-trending ground track that travels westward for about 1 km horizontally and descends 7 km vertically, during the

last 15 minutes of the descent. This can be seen in Fig. 3, where both the altitude and latitude are plotted as a function of longitude. A degree of longitude is equal to 44 km at this latitude on Titan, so the major horizontal divisions of Fig. 3 correspond to less than 1 km. When one considers that the major vertical divisions equal 5 km, one can see that during the last part of the descent the probe descended at a very steep angle, some 8° off vertical.

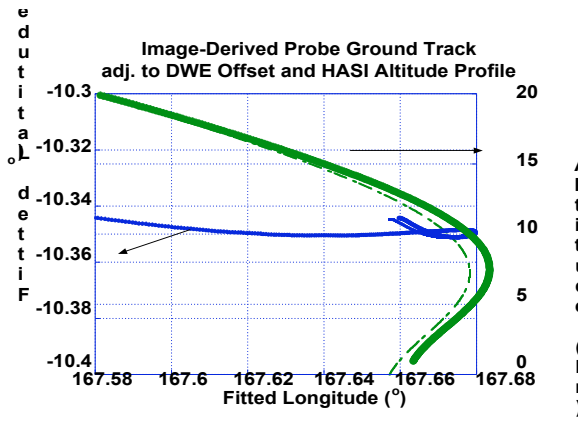

Fig. 3 Probe ground track, displayed as a thinner line, compared to probe altitude, displayed as a thicker line. Arrows point to the appropriate axis. The altitude axis should be expanded by a factor of almost 6 to recover a one-to-one correspondence in linear scale. Using DWE high-altitude references, the touchdown point is extrapolated to be east longitude 167.657°, latitude -10.345°. Using DTWG-3 high-altitude references, the touchdown point is extrapolated to be east longitude 167.644 °, latitude -10.356°.

The longitude and latitude fits are then differentiated to derive rates of change of sub-probe longitude and latitude which can be converted to zonal and meridional wind histories, based on the assumption that the rate of change of position of the sub-probe point reflects the horizontal wind velocity, shown in Fig. 4. The eastward wind slows from near 30 to 10 ms^{-1}, between 50 to 30 km altitude, and from 10 to 4 ms^{-1}, between 30 to 20 km altitude. The eastward winds die completely at 7 km. The generally pro-grade nature of the winds between 50 and 10 km agrees with models of Titan's zonal winds available before Cassini/Huygens' arrival [5], although the intensity of the flow is somewhat reduced from the average predicted before entry. When extrapolated to the ground, the wind velocities implied by the imager ground-track die to less than 0.5 ms^{-1}.

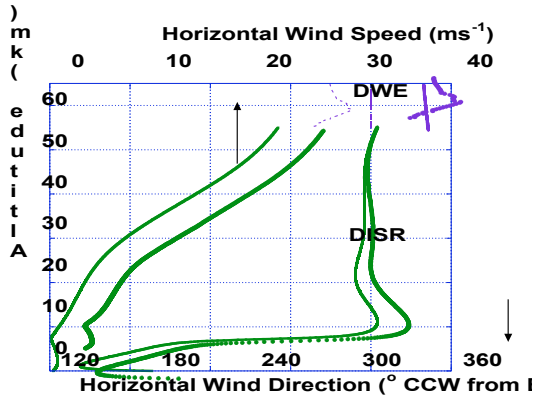

Fig. 4 Horizontal wind speed and direction as a function of altitude compared to the DWE results [3]. The DISR data was computed by differentiating the longitude and latitude fit polynomials displayed in Figs. 1 and 2. Titan's pro-grade winds slow from near 30 to 10 ms^{-1} within the region from 50 to 30 km altitude and from 10 to 4 ms^{-1} from 30 to 20 km altitude. They drop to zero and reverse at around 7 km, near the expected top of the planetary boundary layer and increase in speed to about 1 ms^{-1} near 2-3 km before dropping to 0.3 ms^{-1} again by the time the probe reaches the surface. The direction begins as due east, and then turns through South to the West-Northwest between 5-7 km, the turn beginning between 7-9 km. The winds are extrapolated to be retrograde at the surface, but the error bars (not shown) of 1 ms^{-1} at the surface would include surface prograde winds. The error bars at high altitudes (4 ms^{-1}) would include the last DWE point.

The signature of the planetary boundary layer (PBL), calculated to have a thickness of between 4 and 8 km, based on scaling the Earth's near-equatorial PBL thickness of 1-2 km by the inverse square-rooted ratio of the planetary rotation rates, may be seen in the minimum reached by the horizontal wind speed at 7 km, which can be an indication of entry into this layer [6].

In comparing each actual measured sub-probe longitude and latitude location with the fitted ground-track, if one assumes that the total difference in position between fit and measured points can be explained by the tip and tilt of the probe's spin axis, then one can derive, for the relatively accurately measured azimuth of each instance of successfully-placed image triplet, the roll and pitch of the probe needed to return the measured point to the fitted ground track. These rolls and pitches are shown in Figs. 5 and 6. If one converts them into actual spin axis tilt and spin axis tilt azimuth histories, one gets the curves shown in Figs. 7 and 8.

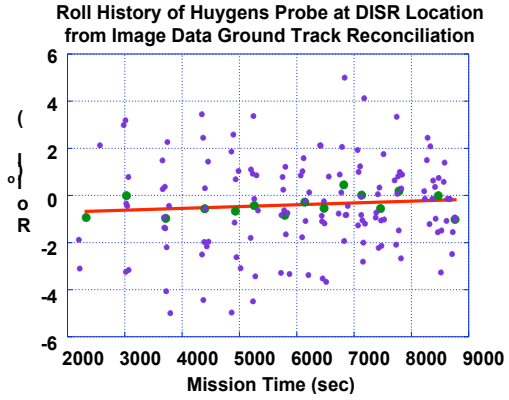

Fig. 5 Roll history of probe at DISR's location on the experiment platform for each of the 137 points contributing to the DISR image-derived ground track, plotted as the smaller dots, compared to the average rolls for each of the 15 cycles and a line fit through the average points. The average rolls should tend to zero, the more closely a cycle acquires all of the images which were scheduled, a trend which is observed to within the errors (not shown), but which are probably about +- 0.6-1°. The rolls in total average to -0.32^{o}. Roll is defined as a motion of the DISR corresponding to a rotation around the Huygens +Z axis, which is aligned with the nose of the DISR and points outward along the plane of the experiment platform and radially away from its center. The rolls after 8000 sec mission time were measured by direct observations of the horizon in the DISR SLI.

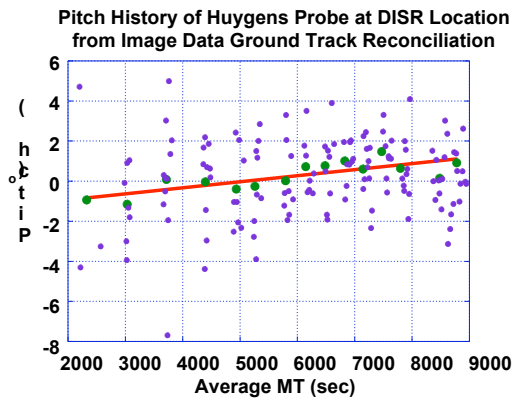

Fig. 6 Pitch history of probe at DISR's location on the experiment platform for each of the 137 points contributing to the DISR image-derived ground track, plotted as the smaller dots, compared to the average rolls for each of the 15 cycles and a line fit through the average points. The average pitches should tend to zero, the more closely a cycle acquires all of the images which were scheduled, a trend which is not quite observed to within the errors (not shown), but which are probably about +- 0.6-1°. The pitches in total average to 0.29^{o}. A linear trend is seen in the data, which is probably random in nature. Pitch is defined as a motion of the DISR corresponding to a rotation around the Huygens -Y axis, which is along the plane of the experiment platform, but perpendicular to a line extending outward from the center of the platform through the nose of the DISR. The pitches after 8000 sec mission time were measured by direct observations of the horizon in the DISR SLI.

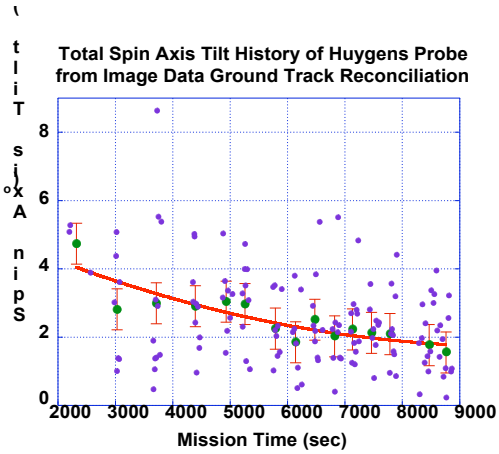

Fig. 7 Spin axis tilt history of Huygens probe derived from DISR image data, computed from the rolls and pitches in Figs. 5 and 6 and plotted as the smaller dots, compared to the average tilts, the larger dots and a line fit through the average tilts. The tilt is seen to decrease as the probe descends through the atmosphere, a result that agrees with the expected decrease in wind shear by a factor of 2 predicted in [7] if one assumes that the tilt is excited by atmospheric turbulence generated by the average wind shear. Note that cluster of tilts after 8000 sec match the trend set by the tilts before 8000 sec even though the two sets are measured by different techniques.

In Fig. 7, a history of the magnitude of the probe's tilt, it is seen that the mean tilt during the last 50 km of the descent averages to 2.4^o and decreases in a fairly monotonic fashion the lower one descends in the atmosphere, as indicated by the simple parabola that it drawn through the green points, which represent the average tilt for each image cycle. The decrease in the tilt by a factor of 2 as the probe descends lower, agrees with the expected decrease in wind shear predicted in [7], a reasonable result if the tilt is excited by atmospheric turbulence generated by the average wind shear.

In Fig. 8, all spin axis azimuth points are plotted on a histogram bins 30° wide in centered on 0°, which is due east. A maximum is observed offset to the North by some 30 and 60° from East and a smaller one offset by a similar amount toward the South from West. This northeast-southwest line is close, but perhaps not close enough to the zonal wind direction to be believable. It may be that the spin-axis azimuths are just random, a product of random wind shear rather than any specific parachute-probe mode and the variation in the histogram merely represent noise.

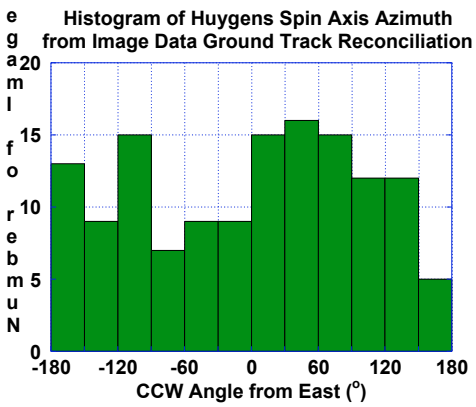

Fig. 8 A histogram of Huygens spin axis azimuth binned by 30°. A subtle trend toward east-northeast-west-southwest oscillations may be seen, but is difficult to interpret, not directly parallel with the zonal wind direction.

5. CONCLUSION

Data from the DISR Imagers have been used to derive the history of the Huygens Probe's sub-probe location and spin-axis orientation below 55 km for its January 2005 descent to the surface of Titan. As a by-product, the imagers and several other DISR instruments have also produced a history of the probe's azimuth, which was not discussed in this paper, but was relied on greatly to produce the results shown here. The ground-track confirms the generally eastward trend expected for the Huygens Probe given prograde zonal winds, except in the last 7-8 km, a region almost certainly corresponding to Titan's planetary boundary layer, where the zonal winds apparently turn retrograde. The meridional component of the wind is a fraction of the zonal component, of order 1-2 ms^{-1}, with comparable error bars, which reflect the 10° absolute uncertainty associated with the current azimuth model.

Rolls and pitches below 3 km, after 8000 sec past T_0, were derived by aligning the observed horizon line in a mercator projection of the SLI to be horizontal and at the proper nadir angle. Rolls and pitches above 3 km were derived by computing the motions needed to reconcile the sub-probe longitude and latitude observed for a particular image set with the fitted ground track. The rolls and pitches, converted into total spin axis tilt and profiled by mission time, decrease by the factor expected if proportional to the vigor of turbulence generated by the wind shear profile predicted before entry. The spin axis azimuth history appears to indicate a mostly random excitation source.

7. REFERENCES

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