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## Stratospheric global winds on Titan at the time of Huygens descent

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[1] Measurements of stratospheric zonal winds on Titan were made in preparation for and during the time of the descent of the Huygens Probe into Titan's atmosphere on 14 January 2005. Fully resolved emission lines from ethane near 11.7  $\mu\text{m}$  were measured on the east, center, and west positions on Titan using the NASA/GSFC Heterodyne Instrument for Planetary Wind And Composition, HIPWAC, mounted on the National Astronomical Observatory of Japan 8.2 m Subaru Telescope on Mauna Kea, Hawaii. Analysis of the Doppler shifts of the emission line shapes yielded mean prograde gas velocity  $\sim 60 \pm 65$  m/s at altitudes below  $\sim 120$  km ( $\sim 5$  mbar). This result is consistent with retrievals from the Huygens Doppler Wind Experiment and from other observations near this altitude range. Current spectral line shapes, however, differed significantly from those obtained in similar measurements on Subaru in 2004 and on the NASA IRTF in 1993–1996, which retrieved prograde zonal winds  $190 \pm 90$  m/s at 230 km ( $\sim 0.4$  mbar). The cores of the emission lines, which probe the high-altitude region, could not be fitted as before to retrieve wind directly using the accepted atmospheric model for Titan. They imply an approximately tenfold increase in ethane mole fraction ( $1.2 \times 10^{-4}$ ) with strong wind shear above the stratopause, providing a potential probe of the lower mesosphere and possible evidence of temporal and spatial variability. Results contribute to coordinated measurements of winds by various techniques providing information on the altitude distribution of wind velocity in Titan's atmosphere from near the surface to the lower mesosphere.

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### 1. Introduction

[2] The dynamics of Titan's atmosphere are of great interest for the study of atmospheres of slowly rotating bodies and for comparative studies of atmospheres in our solar system, in particular that of the Earth. The atmosphere of Titan is similar to that of the Earth in that it is composed mainly of nitrogen with a surface pressure of  $\sim 1.5$  atmospheres. However, its principal minor atmospheric constituents ( $\text{CH}_4$ ,  $\text{H}_2$ ,  $\text{C}_2\text{H}_6$ ), its slow rotation period ( $\sim 16$  days),

its distance from the Sun, and its local environment are quite different. These facts make it a unique laboratory for the study of physics, chemistry, and dynamics of Earth-like atmospheres at orbital distances of the outer planets. Titan is a major target for study with the NASA/ESA Cassini-Huygens mission. The Huygens Probe [Lebreton and Matson, 1997] and its complement of instruments provided a wealth of information on all aspects of Titan's atmosphere and surface during its successful descent and landing 14 January 2005 UT [Lebreton et al., 2005]. Ground-based observations before, during and after the descent provide additional altitude and global information and long-term context complementary to the in situ measurements by Huygens. Here we describe direct measurements of global stratospheric zonal winds on Titan during the descent epoch and compare the results to measurements taken at periods well before 2005 and to contemporaneous measurement of winds made by other observers (Table 1; Figure 1).

[3] Atmospheric circulation in the cyclostrophic regime has been studied extensively theoretically [Leovy and Pollack, 1973; Allison et al., 1994; del Genio and Zhou, 1996; Gierasch et al., 1997; Hourdin et al., 1995, 2004; Luz et al., 2003; Rannou et al., 2004] and observationally [Flasar et al., 1981; Hubbard et al., 1993; Goldstein et al., 1991; Kostiuk et al., 2001, 2005; Bouchez, 2004; Luz et al.,

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**Table 1.** Wind Retrieval Results

Date/Telescope/Method (Reference)	Wind Direction	Horizontal Wind Speed	Altitude
1993–1996 IRHS/IRTF [ <i>Kostiuk et al.</i> , 2001]	prograde >94% probability	210 ± 150 m/s (60N–60S)	120–300 km <sup>a</sup> peak: 210 km <sup>a</sup>
February–March 2003 and February 2004, IRAM Submillimeter [ <i>Moreno et al.</i> , 2005]	prograde	60 ± 20 m/s 160 ± 60 m/s	450 ± 100 km 300 ± 150 km
18 December 2003 HIPWAC/Subaru [ <i>Kostiuk et al.</i> , 2005]	prograde >98% probability	190 ± 90 m/s (15N–50S)	130–320 km <sup>b</sup> peak: 230 km <sup>b</sup>
July–October 2004 Cassini/CIRS [ <i>Flasar et al.</i> , 2005]	?	100 m/s <sup>c</sup> 40 m/s <sup>c</sup>	~180 km ~110 km
15 January 2005 HIPWAC/Subaru (this work)	prograde	low, <60 m/s (15N–50S)	below ~120 km
7, 12, 14, 15 January 2005 UVES/VLT [ <i>Luz et al.</i> , 2005, 2006]	prograde	lower limits 46.3 ± 7.5 m/s 53.3 ± 10.7 m/s	110–280 km peak: 170 km peak: 200 km
14 January 2005/DWE/Huygens [ <i>Bird et al.</i> , 2005]	prograde	100 m/s <60 m/s	120 km below 100 km

<sup>a</sup>Values derived using thermal profile of *Yelle et al.* [1997].

<sup>b</sup>Values derived using CIRS thermal profile [*Flasar et al.*, 2005].

<sup>c</sup>Note that quoted CIRS values are as published, which assumes zero wind velocity at 10 mbar, inconsistent with DWE. No quoted uncertainty estimates are given.

2005; B. Sicardy et al., The two Titan stellar occultations of 14 November 2003, submitted to *Journal of Geophysical Research*, 2006 (hereinafter referred to as Sicardy et al., submitted manuscript, 2006)]. The only two slowly rotating bodies available in our solar system for these studies are Venus (243 day rotation period) and Titan. Unlike Venus, where cloud structure can be used to track wind velocity, the direction and magnitude of zonal winds on Titan are more difficult to measure by cloud imaging, since no distinct stratospheric cloud feature that can be used to trace global winds was observed from the ground [*Griffith et al.*, 1998; *Roe et al.*, 2002]. Recently Cassini ISS measurements were able to deduce a low wind speed from cloud structure near Titan's surface (near ~20 km altitude [*Porco et al.*, 2005]). Indirect methods from Voyager IRIS and Cassini CIRS thermal maps [*Flasar et al.*, 1981, 2005] and stellar occultation [*Hubbard et al.*, 1993; *Bouchez*, 2004; Sicardy et al., submitted manuscript, 2006] have been used to estimate wind speed from 60–230 m/s, but not its direction. High-resolution infrared heterodyne spectroscopy [*Kostiuk*, 1994] enabled direct measurements of Doppler shifts of spectral lines of ethane on Titan and thus for the first time direct retrieval of stratospheric zonal wind speed and direction in the 120–320 km altitude region, peaking above 210 km [*Kostiuk et al.*, 2001, 2005]. Millimeter-wave heterodyne spectroscopy enabled direct measurements of Doppler shifts of emission lines from nitrile constituents on Titan, probing altitudes above 300 km, into the mesosphere [*Moreno et al.*, 2005]. *Luz et al.* [2005] measured Doppler shifts of the visible solar Fraunhofer spectrum reflected from Titan's atmospheric haze to deduce winds in the 115–280 km region, peaking near 170–200 km. All Doppler shift results yield a mean prograde atmospheric circulation (winds in the direction of the orbital angular momentum). Wind speeds retrieved by these methods vary, suggesting not inconsistency but an altitude distribution of upper atmospheric zonal wind (Figure 1).

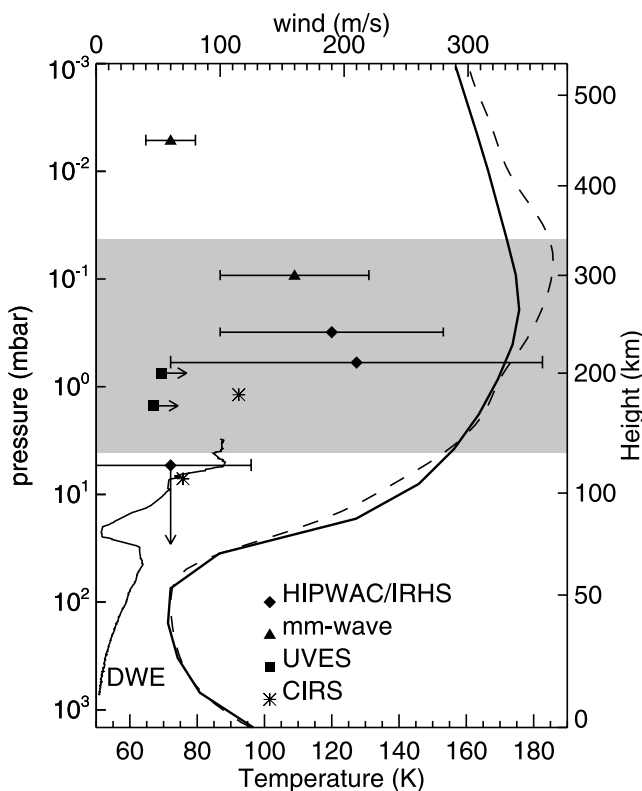
[4] The Huygens Doppler Wind Experiment [*Bird et al.*, 2002] measured Titan's wind during the Huygens descent,

probing altitudes below 140 km [*Bird et al.*, 2005]. The wind velocity retrievals and the atmospheric regions covered are shown in Figure 1. As can be seen from the thermal structures [*Yelle et al.*, 1997; *Flasar et al.*, 2005] and wind speed profile there is quite a high degree of variability in the wind speed from the troposphere through the mesosphere. Previous infrared heterodyne spectroscopy was found to be sensitive to the upper stratospheric/stratopause region (130–320 km), peaking near 230 km while the UVES measurements of reflected solar lines [*Luz et al.*, 2005] were sensitive from ~115 to 280 km, peaking near 170 km and 200 km, according to two visible channels measured by them. These two techniques provide good coupling between the lower altitudes probed by the Doppler Wind Experiment and the upper stratosphere, in which the maximum wind velocity values have been retrieved.

## 2. Observations

[5] We report here on infrared heterodyne measurements of Titan's zonal wind field in coordination with measurements by *Luz et al.* [2006] using the UVES instrument mounted on the ESO VLT Kueyen-UT2 telescope around the Huygens probe descent period. Infrared heterodyne spectroscopy measurements were made with the Goddard Space Flight Center (GSFC) Heterodyne Instrument for Planetary Wind And Composition (HIPWAC) mounted at the Nasmyth focus of the National Astronomical Observatory of Japan 8.2 m Subaru telescope on Mauna Kea, Hawaii. Observations were scheduled for 13–15 January 2005 UT, straddling the descent period of the Huygens probe into Titan's atmosphere; all dates reported here are UT. Poor weather on Mauna Kea prevented observations on 13 January and severely limited measurements on 14 January. Good spectra were obtained on 15 January despite poor seeing.

[6] The high spectral resolution possible with infrared heterodyne spectroscopy,  $\lambda/\Delta\lambda > 10^6$  [*Kostiuk*, 1994;



**Figure 1.** Direct velocity retrievals in the stratosphere: HIPWAC/IRHS [Kostiuk *et al.*, 2001, 2005, this work]; UVES [Luz *et al.*, 2005, 2006]; DWE [Bird *et al.*, 2005]; millimeter-wave [Moreno *et al.*, 2005]; and CIRS [Flasar *et al.*, 2005]. Different altitudes are probed by the different techniques. Results indicate large wind variation with height and possibly with time. The shaded region indicates the region probed by HIPWAC/IRHS before Huygens. The temperature profiles used for analyzing HIPWAC/IRHS data are shown, pre-Cassini [Yelle *et al.*, 1997] (solid line) and Cassini CIRS at  $\sim 15^\circ\text{S}$  [Flasar *et al.*, 2005] (dashed line). Although the CIRS results are indirect, they are contemporaneous and are included for comparison. CIRS values are adjusted for a wind velocity of 55 m/s at 10 mbar, as measured by the DWE. Flasar *et al.* [2005] assumed a boundary condition of zero velocity at 10 mbar in their analysis. No quoted uncertainty estimates are given.

Kostiuk and Mumma, 1983], measures the true shapes of spectral lines in the mid-infrared region from which information on species abundance and local temperature can be constrained [Kostiuk *et al.*, 1997, 2005; Livengood *et al.*, 2002]. Absolute frequency of the measured line can be determined to 1 part in  $10^8$ , since measurements are made relative to  $\text{CO}_2$  laser transitions, whose frequencies are known to  $1:10^{12}$  [Freed *et al.*, 1980]. With good signal-to-noise ratio on the measured lines, gas velocities (Doppler shifts) to an accuracy of 2 m/s can be retrieved remotely [Goldstein *et al.*, 1991].

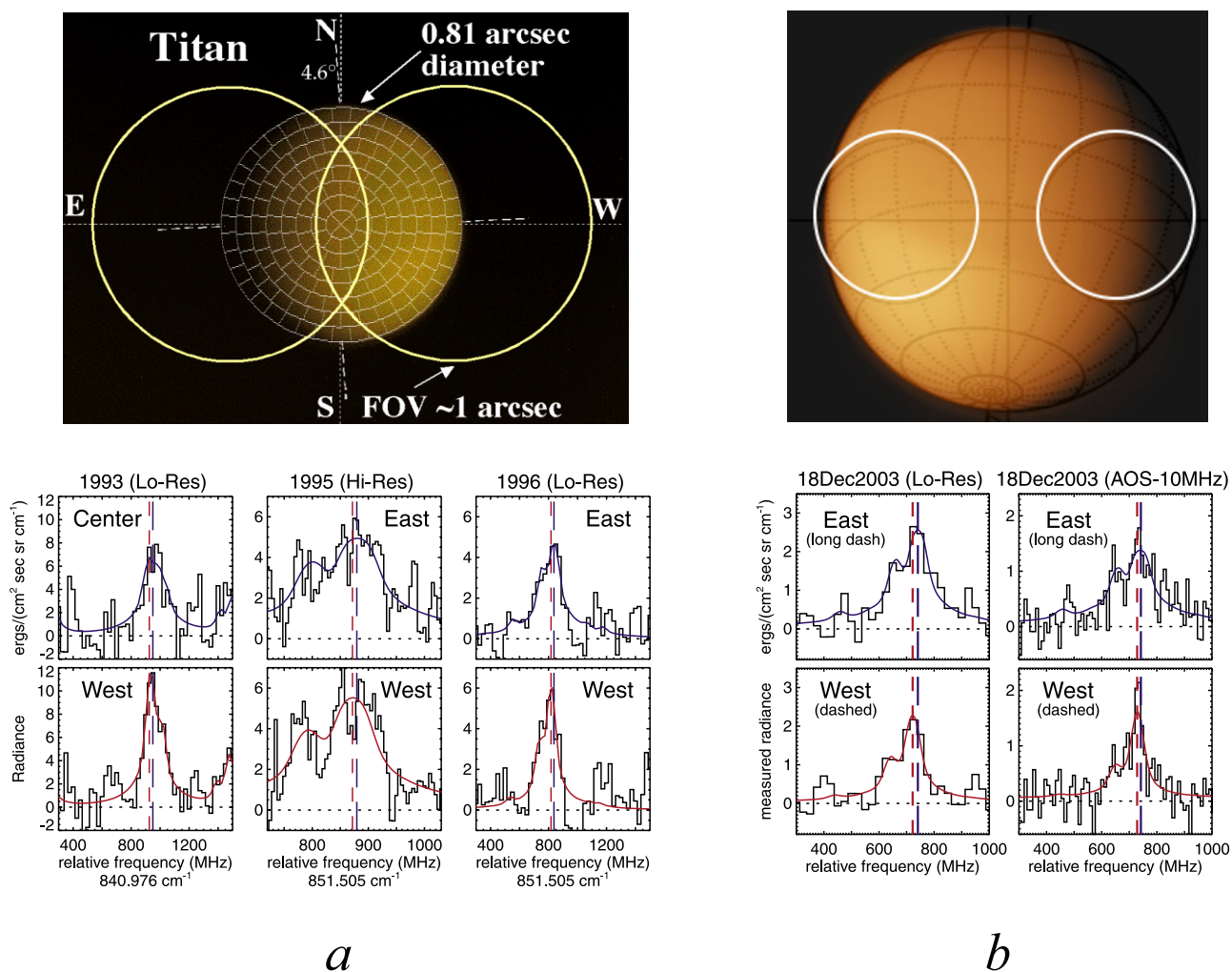
## 2.1. Previous Measurements

[7] Using this technique and the GSFC Infrared Heterodyne Spectrometer (IRHS) on the NASA 3-m Infrared Telescope Facility (IRTF) on Mauna Kea, Hawaii in 1993–1996, we measured fully resolved emission lines of

ethane ( $\text{C}_2\text{H}_6$ ) near  $11.7\ \mu\text{m}$  from the east and west hemispheres and retrieved a prograde zonal wind direction and a mean speed of  $210 \pm 150\ \text{m/s}$  (Figure 2a) from the relative Doppler shift between the east-west spectra. Measurements with HIPWAC were taken on Subaru on 18 December 2003 with a much-improved observing geometry (Figure 2b). The wind velocity retrieved was consistent with the IRHS/IRTF measurements,  $190 \pm 90\ \text{m/s}$ , peaking near 220 km altitude [Kostiuk *et al.*, 2005]. Both sets of measurements revealed similar line shapes of the distinctive ethane doublet, composed of a strong and a weak line. Measurements with IRHS were made at 25 MHz ( $0.00083\ \text{cm}^{-1}$ ) and 5 MHz ( $0.00017\ \text{cm}^{-1}$ ) resolution using an RF filter bank to analyze the spectra. In 2003 we used an additional back-end spectrum analyzer, an acousto-optic spectrometer (AOS), which provides 1 MHz resolution [Tolls *et al.*, 2004]. AOS data binned to 10 MHz are shown alongside the 25 MHz filter bank data in Figure 2b. In all measurements the shapes of the lines in the doublet were consistent with a constant-with-height ethane mole fraction of  $\sim 1 \times 10^{-5}$  for a pre-Cassini thermal profile [Yelle *et al.*, 1997], as fitted with our beam-integrated radiative transfer code [Hewagama *et al.*, 1998; Kostiuk *et al.*, 2001, 2005]. Some difference between east and west line shapes exists, but can be explained by differences in the altitude distributions of either the  $\text{C}_2\text{H}_6$  abundance or temperature [Kostiuk *et al.*, 2005]. A refit of the data using the Cassini CIRS retrieved thermal profile (Figure 1) changed the wind and uniform  $\text{C}_2\text{H}_6$  mole fraction values by less than 10%, well within the previously derived uncertainties. The warmer upper CIRS thermal profile raised the amount of contribution from higher altitudes to the line emission, thus slightly raising the height of peak contribution to 230 km and the region of significant contribution to 320 km.

## 2.2. The 2005 Measurements

[8] HIPWAC was used on Subaru for the measurements in January 2005. Frequencies were measured relative to the P18 transition ( $851.4895\ \text{cm}^{-1}$ ) of a  $^{14}\text{C}^{16}\text{O}_2$  laser local oscillator stabilized to drift  $\leq 1\ \text{MHz/hr}$  ( $\sim 10\ \text{m/s/hr}$ ). The geometry for measurements is given in Figure 3. On 14 January, during the descent of the Huygens Probe, observations were limited by high winds and by seeing of  $\sim 1.8\ \text{arcsec}$  in the visible and  $\sim 1\ \text{arcsec}$  at  $11.7\ \mu\text{m}$  [Rodder, 1981; Boyd, 1978]. On 15 January the visible seeing was still poor,  $\sim 1\ \text{arcsec}$  ( $\sim 0.53\ \text{arcsec}$  at  $11.7\ \mu\text{m}$ ), but winds were lower, improving tracking of the effective instrumental field-of-view, FOV, of 0.61 arcsec. Measurements on each position were taken in 4-minute periods and the resultant spectra are averages of the total integration time ( $\sim 1\ \text{hour}$  each). The fitted spectra (solid curves in figures) were obtained using the beam-integrated radiative transfer code [Hewagama *et al.*, 1998], using an input atmospheric model, and taking into account the contribution to the total measured spectrum by the emission from different viewing angles on Titan, illustrated by segments on Titan in Figure 2a. The characteristics of the input atmospheric model include the profile of temperature versus pressure, a profile for ethane mole fraction, the mean molecular mass, and gravitational acceleration at the surface of Titan, from which model spectra, contribution functions, and the scale of pressure versus altitude are computed. The

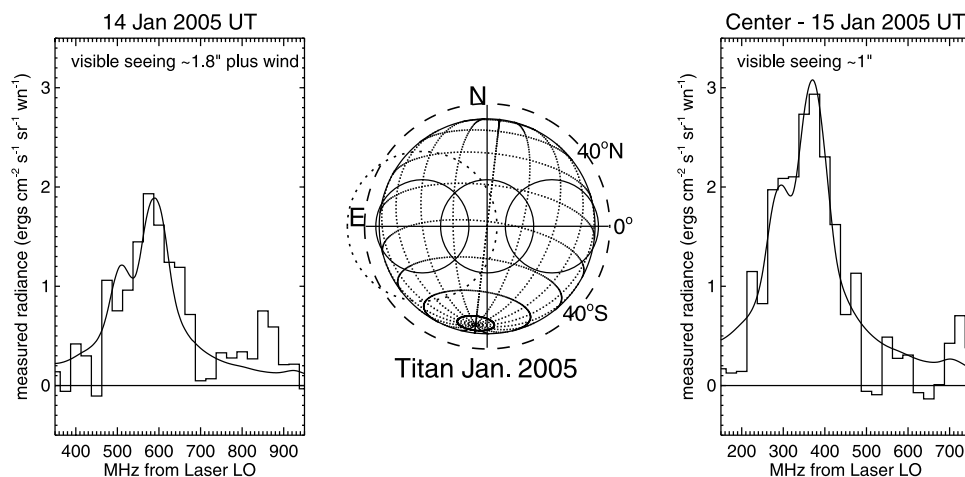


**Figure 2.** (a) Observing geometry and results using IRHS and 3-m IRTF, 1993–1996. Coordinates are shown as viewed on the sky. Retrieved mean prograde velocity is  $210 \pm 150$  m/s. Filter bank spectra at 25 MHz resolution are shown for 1993 and 1996. High-resolution (5 MHz) spectra are shown for 1995. The Doppler shift direction is indicated by the color and the vertical lines (blue, long dash line at higher frequency), consistent with gas approaching on the east and receding on the west. From *Kostiuk et al.* [2001]. (b) Observing geometry and results using HIPWAC and 8.2 m Subaru, 18 December 2003. Retrieved prograde velocity is  $190 \pm 90$  m/s. Filter bank 25 MHz spectra and AOS 10 MHz (binned) spectra are shown. All spectra and fits (solid lines) in Figure 2 are consistent with the measured line shape of the ethane doublet. From *Kostiuk et al.* [2005]. Note the much smaller 0.4 arcsec FOV on the 0.89 arcsec Titan.

atmospheric model is uniform across Titan, which is treated as a rigid rotator. Details of the measurement technique, instrumental and observational considerations, and data analysis are given by *Kostiuk et al.* [2001, 2005]. Results of measurements and fits to line spectra from Titan’s disk center are given in Figure 3. The line spectra are qualitatively similar to past measurements and fits to the disk center data were consistent with ethane mole fractions and thermal profiles determined from HIPWAC/Subaru in 2003 and from prior IRHS/IRTF data. Note the intensity difference between the two measurements, indicating the signal degradation due to seeing and tracking on 14 January.

[9] On 15 January, measurements were taken on the east, center and west regions of Titan with the goal to compare the ethane emission line frequencies and measure the Doppler shifts due to zonal wind velocities in the strato-

spheric region where the lines are formed, as was done in the past. The measured line shapes from the east and west (Figures 4 and 5) appear different from those measured in previous years (Figure 2). The measured intensities of the strong and the weak lines in the  $C_2H_6$  doublet are more equal, as seen in both filter bank and in the AOS 10 MHz spectra (Figure 4). These east and west spectra cannot be fitted with the accepted thermal profiles and the previously retrieved uniform-with-height ethane mole fraction distribution [*Kostiuk et al.*, 1997; *Livengood et al.*, 2002], including the Cassini CIRS derived value of  $\sim 2 \times 10^{-5}$  [*Flasar et al.*, 2005]. The modeled line profiles in Figures 4 and 5, using previously derived parameters, illustrate this. To retrieve any information on wind velocity and ethane abundance the line profiles must be accurately modeled. This will require significant changes to the currently ac-



**Figure 3.** Observing geometry on Titan (0.88 arcsec diameter) on 14 and 15 January 2005 with HIPWAC on Subaru and the disk center measurements on each day. Note the difference in measured intensity of the ethane line and the corresponding visible seeing. The diffraction-limited FOV at  $11.7 \mu\text{m}$  is shown (solid circles) along with the infrared instrumental FOV on the days observed: 1 arcsec diameter on 14 January (dashed circle), centered on Titan, and 0.61 arcsec diameter on 15 January (dotted circle). The latter example is shown offset toward the limb as for the wind measurements primarily reported here. The actual position for the 15 January spectrum shown on the right was centered on the disk. Coordinates are shown as viewed on the sky.

cepted atmospheric models for Titan. Two problems arise: Why are the limb spectra different from the disk center spectrum? And what would cause such a drastic temporal (or spatial) variability in Titan's atmosphere when compared to previous measurements?

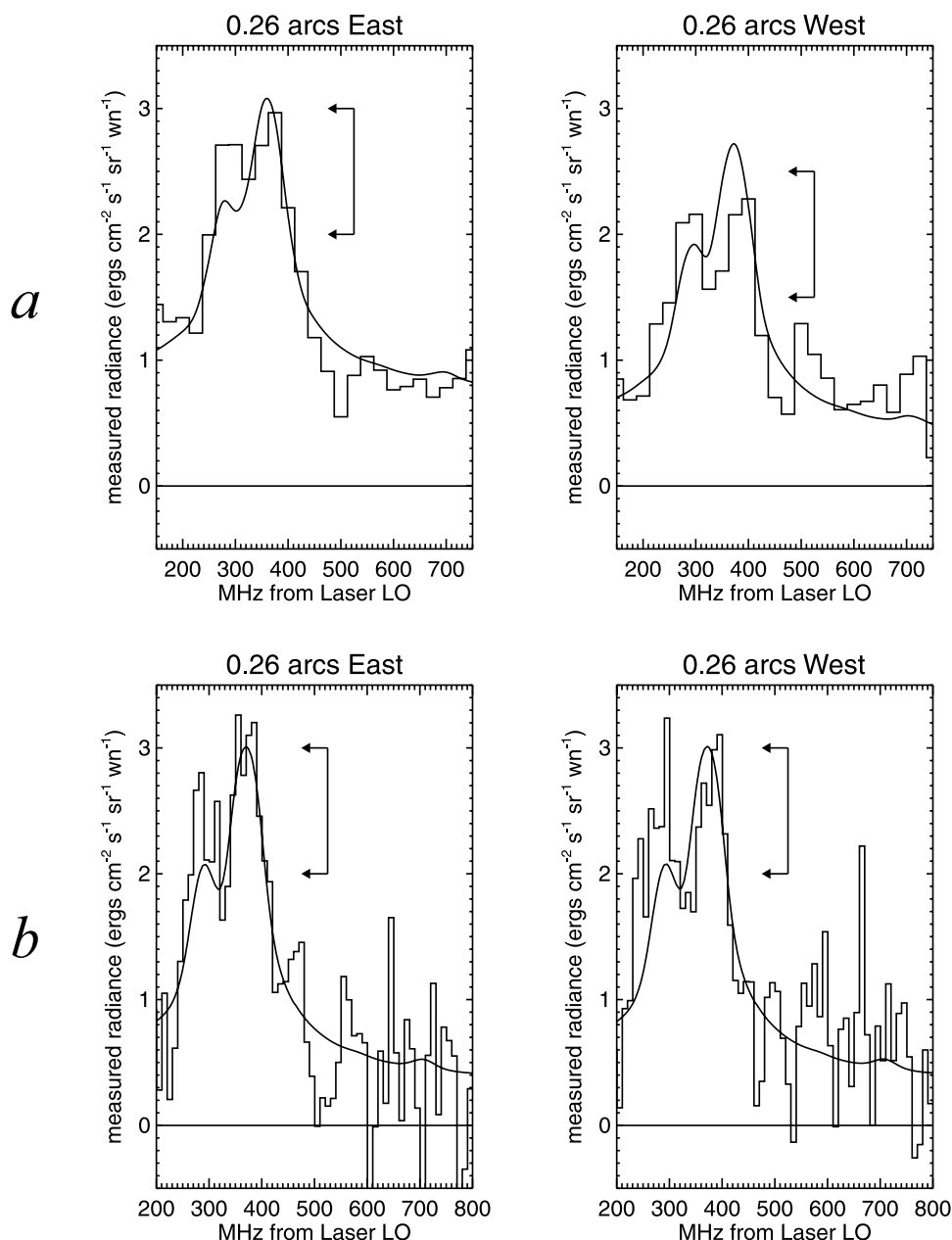
[10] Transient and instrumental effects are unlikely to modify the  $\text{C}_2\text{H}_6$  line shapes. Data were taken in 4 minute periods, alternating between the east, center, and west positions. The individual scans are averaged over  $\sim 1$  hour total integration on each position, spread over nearly the same  $\sim 4$  hour period on Titan. Any temporal changes longer than 4 minutes would then be displayed equally in data from each position on Titan. Instrumental effects due to the RF spectral analyzers are unlikely, since the line shapes are identical (within the resolving power) between the RF filter bank and AOS (Figures 4a and 4b). Transient instrumental effects would appear in all three data sets, not just on the off center measurements.

[11] Navigation errors are also unlikely to generate the observed east-west line shapes. Telescope tracking and pointing errors are estimated to be  $< 0.1$  arcsec using the HIPWAC visible guide system. Differential refraction between the visible and infrared image was accounted for in the guiding by use of appropriate filters and guide image offsets (0.09 arcsec maximum) determined from differential refractivity measured by *Livengood et al.* [1999] and verified with stellar measurements. In theory, the relative ethane line intensities of the strong and weak lines in the doublet can change with observing geometry on the limbs, e.g., a misalignment of the beam. The stronger line will approach saturation before the weaker line when viewed near the limb through large atmospheric paths, thereby changing the line intensity ratio. However, due to the relatively large beam (Figure 1), which contains contributions from a range of viewing angles on Titan, this limb contribution is relatively small and the "air mass" effect is

minimal in modifying the line shapes for over 0.2 arcsec misalignment toward the limb, after which the low beam filling reduces the line intensity to levels comparable to the noise. A major effect of misalignment is a reduction in the absolute measured intensities, not their relative intensities. Such a misalignment would also have to be in the opposite directions on each limb to be consistent with the data, as the measured intensities at each limb are approximately equal.

### 3. Results and Discussion

[12] The resolved spectral line shape is formed through a range of altitude/pressures in Titan's atmosphere. The contribution functions derived from the radiative transfer fitted lines are a measure of the degree to which an altitude region with particular values of temperature, pressure, abundance and velocity contributes to the detected emission at a fixed frequency along the line shape. Figure 5 illustrates the altitude regions probed by a spectral line fitted to the disk center spectrum measured on 15 January and how the line modeled on the west position, using the same retrieved parameters, compares to the measured west line shape. The relevant contribution functions are shown. Note that the altitude region of maximum contribution and the region where maximum wind was observed in previous measurements (Figure 1) falls near the line center, where the measured limb spectra are poorly fit by the model. Independent fits to the east and west spectra using the previously accepted and the Cassini CIRS atmospheric models can only fit the high frequency wing reasonably well, but not the highest signal-to-noise data near the line center (Figures 4 and 5). From Figure 5 it can be seen that velocity retrieval above  $\sim 120$  km altitude is not possible. Limited information on the wind may be obtained from the line wings alone, on altitudes below  $\sim 120$  km (frequencies  $> 50$  MHz from line center).

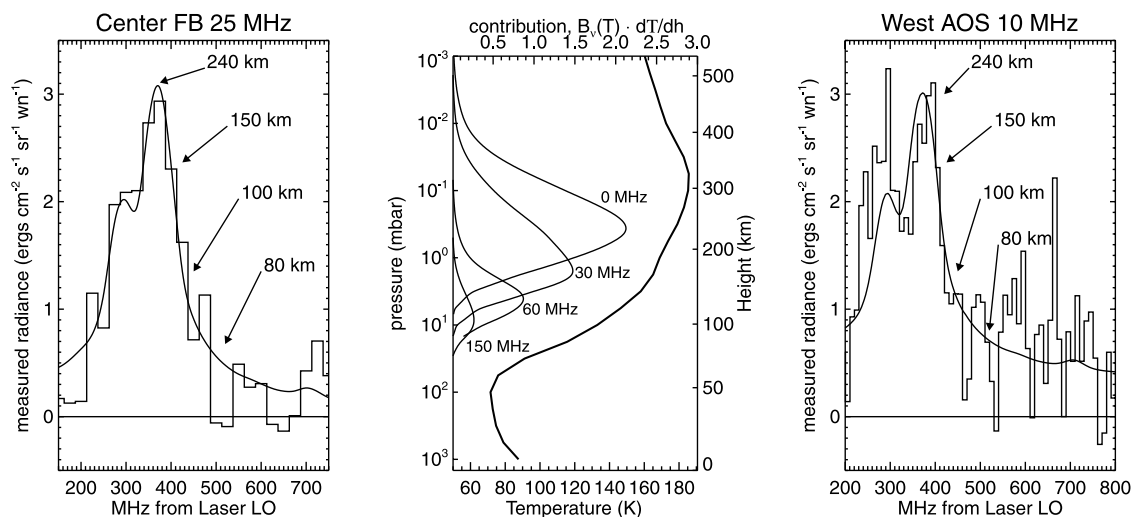


**Figure 4.** Spectra measured (histograms) on 15 January 2005 on the east and west positions on Titan. (a) Filter bank data at 25 MHz resolution. (b) AOS data, measured at 1 MHz resolution, binned to 10 MHz. Both data sets, taken simultaneously, reveal unexpected line shapes on the east and west. The solid line spectra are modeled for the east and west position geometry based on retrievals from fits to the disk center, which are consistent with all previous retrievals. Note the disagreement with the measured limb spectra near line center (arrow bars), particularly with the weaker secondary line.

[13] A fit of the line wings only, probing only the lower stratosphere ( $\sim 70$ – $120$  km), does lead to a 60 m/s mean horizontal prograde wind, but with an uncertainty of equivalent magnitude (Table 1). This result of low statistical confidence is not inconsistent with retrievals from the Doppler Wind Experiment and from the UVES measurements [Luz *et al.*, 2006] during the same general time period (see Figure 1).

[14] If the frequency region near line center on the east and west data can be properly modeled, better retrieval of velocity information may be possible. Since limb “air mass” line saturation effect alone is not likely the cause

of the measured line shape and line intensity ratio of the C<sub>2</sub>H<sub>6</sub> doublet, as discussed above, another possible effect is the preferential reabsorption of the strong line relative to the weak one in the mesospheric region, where the temperature decreases with altitude. The current ethane abundance and thermal profile do not indicate much relative contribution to the line emission above the stratopause,  $\sim 310$  km (see Figure 5, contribution functions). The reabsorption effect is negligible in the modeled spectra (Figure 4). However, if the ethane mole fraction distribution were increased sufficiently at the high altitudes, then the reabsorption effect becomes more important. The observed spectra demonstrate



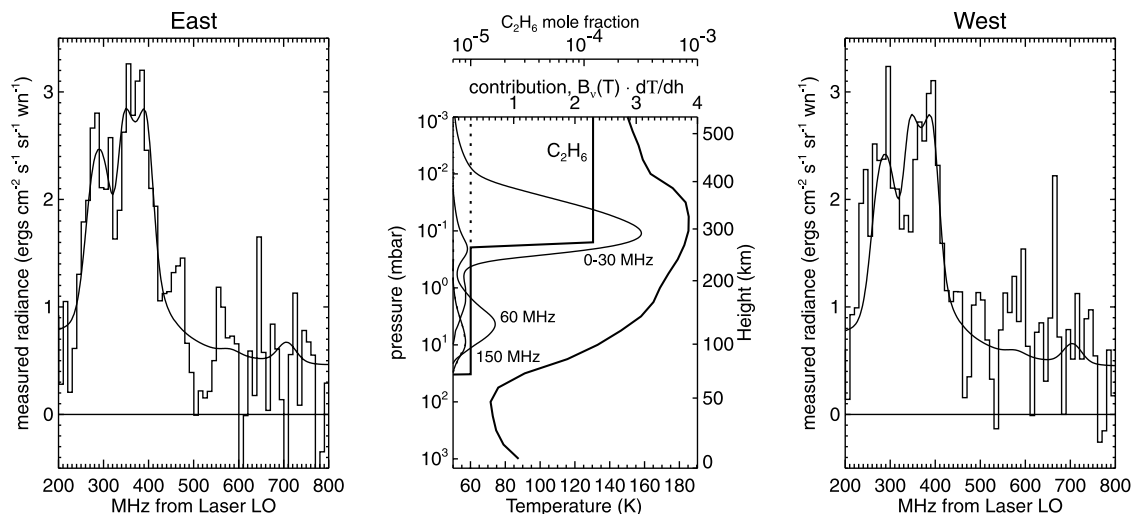
**Figure 5.** Titan atmospheric model and altitudes probed by emission at frequencies along the ethane line shape indicated by the contribution functions (“0” MHz is at line center, probing  $\sim 240$  km). On the west, only the wing of the strong line can be fit well. This limits any velocity retrieval in the region above  $\sim 120$  km.

greater maximum brightness temperature at disc center than in the limb measurements, consistent with reabsorption by ethane gas in a region of negative temperature gradient with altitude above the peak of the contribution functions, i.e., a mesosphere with a significant concentration of ethane.

[15] T. A. Livengood et al. (High-resolution infrared spectroscopy of ethane in Titan’s atmosphere in the Huygens epoch, submitted to *Journal of Geophysical Research*, 2006; hereinafter referred to as Livengood et al., submitted manuscript, 2006) tested various distributions of ethane in Titan’s stratosphere in an attempt to fit the disc center spectrum using the CIRS derived thermal profile at  $15^\circ\text{S}$  latitude [Flasar et al., 2005].

[16] For the purpose of investigating possible velocity retrieval we found a coarsely modified altitude distribution

of  $\text{C}_2\text{H}_6$  mole fraction, constant with height above 35 mbar and increasing approximately tenfold in the upper stratosphere/mesosphere, comes closest to addressing the line shapes measured. Figure 6 illustrates the resultant simplified ethane distribution/atmospheric model and the resultant modeled ethane spectra from the east and west positions. The  $\text{C}_2\text{H}_6$  mole fraction in the lower stratosphere remains at  $1.3 \times 10^{-5}$  as previously derived. Above the 0.13 mbar level the mole fraction increases to  $1.2 \times 10^{-4}$ . This  $\text{C}_2\text{H}_6$  distribution changes the altitude regions probed by the line shape as illustrated by the contribution functions (Figure 6). The true distribution clearly must be more gradual than the “step” assumed here, but the mean effect illustrates the possible modification to the ethane emission line profiles. A comparably large ethane mole fraction ( $1.21 \times 10^{-4}$ ) was



**Figure 6.** Modified  $\text{C}_2\text{H}_6$  mole fraction distribution and modeled emission line spectra. The increased abundance in the mesosphere leads to significant reabsorption of the emission and to spectra closer to those measured on Titan. The altitudes probed are also altered as indicated by the contribution functions. The thermal profile is from Cassini CIRS [Flasar et al., 2005].



also measured near  $\sim 1200$  km by the Ion Neutral Mass Spectrometer, INMS, on Cassini [Waite *et al.*, 2005]; therefore an increase in fractional ethane with altitude above the stratopause is not unreasonable. This increase in mole fraction at high altitudes does not affect the total  $C_2H_6$  column significantly and thus would not be easily observable by lower spectral resolution instruments; the increase in the integrated ethane column mole fraction is only  $\sim 10\%$  (see further discussion by Livengood *et al.* (submitted manuscript, 2006)).

[17] This simplified ethane distribution still does not provide fully satisfactory fits to the measured data. It does provide qualitative support for modifying the ethane distribution at the higher altitudes.

[18] The shapes of the modeled lines cannot be adjusted by abundance alone to adequately fit the measured lines, especially those of the west limb. Figure 1 indicates a significant variability of zonal winds with altitude. The winds measured by various techniques (Figure 1) drop by more than 100 m/s from the middle stratosphere to the mesosphere. Our modified abundance profile increases the contribution from the mesosphere; thus the reabsorption must occur in regions of lower wind speed (Doppler shift), and thus the absorption component is shifted in frequency relative to the emission component, further altering the line shapes. This effect will be different on the east and west hemispheres, where the line-of-sight component of the prograde zonal wind is in different directions (approaching in the east, receding in the west). At disk center both wind components will be “zero” since there is no mean line-of-sight velocity component. This, and a more accurate distribution and thermal profile, could explain the remaining discrepancies between the measured and currently modeled lines. To investigate this further our beam-integrated radiative transfer program needs to be modified to include the effect of wind velocity distribution with altitude. Additional measurements on Titan must also be made with HIPWAC to improve the signal-to-noise on the data and investigate further spatial and temporal variability that appears to be the norm on Titan.

#### 4. Conclusions

[19] Stratospheric zonal wind speed and direction on Titan were retrieved from Doppler shifted  $C_2H_6$  spectral lines near equinox, 1993–1996, and in December 2003, following southern summer solstice, about one year prior to Huygens insertion into Titan’s atmosphere on 14 January 2005. These measurements yielded a mean prograde wind of  $\sim 190 \pm 90$  m/s near  $\sim 0.4$  mbar ( $\sim 230$  km altitude). Within two years of Huygens insertion wind measurements were also taken using Doppler shifts of visible solar Fraunhofer lines by Luz *et al.* [2005] retrieving lower limits to wind speed of 50 and 62 m/s at altitudes near 170 and 200 km, and by Moreno *et al.* [2005] with millimeter-wave interferometry, retrieving  $160 \pm 60$  m/s winds at 300 km, decreasing to  $60 \pm 20$  m/s at 450 km. These direct results point to a significant variability of wind with altitude and are supported by results from stellar occultation measurements over similar periods probing an overlapping range of altitudes [Bouchez, 2004; Sicardy *et al.*, submitted manuscript, 2006].

[20] Coordinated measurements were made with HIPWAC and with UVES near the time of Huygens descent in January 2005 in an attempt to provide altitude information on zonal wind to complement and compare to measurements from the Huygens Doppler Wind Experiment and retrievals from Cassini CIRS thermal maps. Results of measurements of zonal winds on Titan are presented in Figure 1, forming a more complete measured altitude profile of Titan’s global circulation, which can be used to constrain dynamical and global circulation models of Titan’s atmosphere.

[21] Wind velocity retrievals from measurements by HIPWAC at Subaru 15 January 2005 are limited by the ethane line shapes formed in Titan’s stratosphere. The measured line shapes and intensity ratios of the same ethane emission spectra (doublet) are different from those measured in previous periods (Figures 2 and 3) and cannot be modeled by the accepted stratospheric ethane abundance and thermal profiles. This inability to fit the spectra near the line cores limits retrieval of any velocity information to altitudes below  $\sim 120$  km. Fitting the wings of the lines yields  $60 \pm 65$  m/s prograde zonal wind, a result which is not statistically significant. The value at the altitudes probed is, however, consistent with the UVES-retrieved lower limit at  $\sim 170$  km of  $\sim 50$  m/s and very consistent with the Doppler Wind Experiment retrievals of  $<60$  m/s below  $\sim 100$  km [Bird *et al.*, 2005]. Figure 1 and Table 1 summarize our wind field measurements and compare them to those taken by Doppler methods by others during and near the period of Huygens descent, providing times and altitudes probed by the different techniques.

[22] Instrumental effects and pointing uncertainties cannot explain the observed line shapes measured on the east and west hemispheres. The unexpected line shapes may provide information on the atmosphere in the altitude regions where the line emission forms. A tenfold increase in ethane abundance near and above the stratopause permits modeled emission spectra to better fit the data, but not ideally (Figure 6).

[23] The pressure/altitudes where the cores of the  $C_2H_6$  lines are formed are also the regions where highest zonal wind velocities are measured,  $\sim 200$ – $300$  km. Above those altitudes the wind velocity is seen to drop in the mesosphere by at least 100–130 m/s ( $\sim 11$  MHz). This wind shear effect would further alter the emission line shapes, since it would shift the mesospheric reabsorption in frequency relative to the high velocity emission core. Since the effect is due to line-of-sight velocity, the west would be altered differently from the east and the center measurement would be nearly unaffected since there the zonal velocities are perpendicular to the line of sight.

[24] This possible line shape retrieval is sensitive to Titan’s stratopause/mesosphere, which can be compared to current [Flasar *et al.*, 2005] and future Cassini retrievals, and can be used as a probe of physical and chemical conditions in the lower mesosphere, including wind shear. Temporal and spatial variability in the global circulation also are suggested when comparing measurements from different epochs and positions on Titan.

[25] Results need to be investigated further by including wind distribution with altitude in our beam-integrated radiative transfer code, as well as testing modified ethane abundance and thermal profiles and their effect on Titan’s

emission spectra. Additional measurements are needed to test the models presented here and to measure the seasonal and spatial changes in the atmosphere of this unique satellite of Saturn.

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