Operational Performance of the TIMED Doppler Interferometer (TIDI)

Wilbert R. Skinner*[1], Rick J. Niciejewski[1], Timothy L. Killeen[2], Stanley C. Solomon[2],
Daniel Gablehouse[2], Qian Wu[2], David Ortland[3], David A. Gell[1], Alan R. Marshall[1],
Edwin Wolfe Jr[1]., Marie Cooper[1], and Julie F. Kafkalidis[1]

[1]Department of Atmospheric, Oceanic, and Space Sciences
The University of Michigan, Ann Arbor, Mi. 48109-2143
[2]High Altitude Observatory, National Center for Atmospheric Research, Boulder, Co. 80307-3000
[3]Northwest Research Associates, Bellevue, Wa. 98009-3027

ABSTRACT

The TIMED Doppler Interferometer (TIDI) is a Fabry-Perot interferometer designed to measure winds in the mesosphere and thermosphere (60-180 km) as part of the TIMED mission. TIDI is a limb viewer and observes emissions from OI 557.7 nm and rotational lines in the O_2(0-0) Atmospheric band. Wind measurement accuracies approach 3 ms^{-1} in the mesosphere and 15 ms^{-1} in the thermosphere. The TIDI instrument's performance during the first year and a half of operation is discussed in this paper. Many subsystems are working as designed. The thermal control system is holding the instrument temperatures at their desired set-points. The CCD detector is working as expected with no changes observed in the gain, bias or read noise. The instrument suffers from a light leak that causes the background to be elevated and increases the uncertainty in the wind measurement. Nothing can be done to eliminate this problem but modeling of the background has eliminated any systematic effect. Water outgassing from the spacecraft or instrument has deposited as ice on some part of the optics and reduced the instrument's sensitivity. This problem has been reduced by two spacecraft rolls which pointed the TIDI radiator to view more of the earth causing the optics to warm up and sublimate much of the ice.

Keywords: Fabry-Perot interferometers, remote sensing, wind measurements

1. INTRODUCTION

The Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED) Doppler Interferometer (TIDI) is a Fabry-Perot interferometer designed to investigate the dynamics of the earth's mesosphere and lower thermosphere-ionosphere (MLTI) from an altitude of 60 to 180 km as part of the TIMED mission.[1] The TIDI interferometer (or Profiler) measures the horizontal vector wind field with a vertical resolution of ~2 km at the lower altitudes and with accuracies that approach ~3 m/s under optimum viewing conditions. The TIDI design allows for 100% duty cycle instrument operation during daytime, nighttime, and in auroral conditions. The design is discussed in detail by Killeen et al. (1999)[2]. TIDI is a limb viewer and observes emissions from OI at 557.7 nm and rotational lines in the O_2(0-0) Atmospheric band at 762 nm to determine the Doppler shift and hence the wind. Some of the key TIDI parameters are shown in Table 1. TIDI is a direct descendent of other spaceflight Fabry-Perot interferometers built at the Space Physics Research Laboratory of the University of Michigan. The first instrument was the Dynamics Explorer Fabry-Perot Interferometer (DE-FPI) which was a single-etalon instrument designed for observations of emissions from the thermosphere.[3] The High Resolution Doppler Imager flying on the Upper Atmosphere Research Satellite (HRDI/UARS) is a triple-etalon Fabry-Perot system designed for observations of the stratosphere, mesosphere, and lower thermosphere (10-120 km).[4,5] The TIDI instrument uses designs and concepts developed in these programs while incorporating new ideas and technologies.

TIMED was launched 7 December 2001 into a 74° inclination 625 km circular orbit. TIDI was initially activated 11 December 2001 and instrument checkout continued until late January 2002 when scientific measurements began. Table 2 shows the dates of some of the more significant events.

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Table 1. TIDI parameters

Spacecraft altitude	625 km
Orbital inclination	74.1^o
Time to precess through 24 hours of local time	120 days
Instrument mass	41.8 kg
Electrical Power	19.32 watts (orbit average)
Heater Power	11.0 watts
Data Rate	2494 bits/s
Telescope field of view	0.05^o (vertical) x 2.5^o (horizontal)
Altitude Resolution	2 km
Etalon gap	2.2 cm
Overall finesse	6-8
Spectral Range	550 – 900 nm
Detector	SiTE ST-005A CCD
Lifetime	>2 years
Operational temperature	20±5°C for profiler -83°C for detector -50 to -60 for detector housing -20°C to 40°C for telescopes
Retrieved quantities	vector wind field from 60 to 180 km

Table 2. Significant TIDI events

Event	**Date**
7 December 2001	TIMED launch
11 December 2001	Initial TIDI turn-on
14 December 2001	First optical functional test
31 December 2001	TIDI telescope covers opened
2 January 2002	First test of science mode
8-16 January 2002	TIDI powered off
13 February 2002	Changed CCD binning from equal wavelength to equal area
13 February 2002	Decreased CCD set-point temperature from -80^oC to -83^oC
25 May 2002	Flight software version 32 uploaded. Corrects small pointing error when spacecraft is flying backwards
22 July 2002	Turned detector window heater on full rather than controlling the window to -60^oC
28-30 September 2002	Turned CCD heater on full
5 October – 10 November 2002	Turned CCD heater on full
18-19 November 2002	TIDI put in safe configuration due to Leonids meteor shower
28-29 January 2003	First TIMED roll maneuver
1-6 April 2003	Second TIMED roll maneuver
12 June 2003	TIMED inertial reference unit #1 turned off and #2 turned on

During activation two significant anomalies were observed. The first one noted was an increased detector background that was ultimately traced to a small light leak in the optical system. The second was a decrease in the apparent sensitivity of the system. The cause of this problem was identified as water outgassing from the instrument or spacecraft that deposited as ice on some optical component. The two problems and means to minimize their impact on the mission are discussed in later sections. In addition, this paper will discuss some aspects of the operational performance of the TIDI interferometer during the first year and a half of the mission.

2. THERMAL PERFORMANCE

The thermal performace of the TIDI instrument is critical to the overall ability to accurately measure winds. For example, the Fabry-Perot etalon can drift with temperature and this drift is indistinguishable from a Doppler shift. The drift for the TIDI etalon is on the order of 10 $m\ s^{-1}\ {}^{o}C^{-1}$ which requires the etalon temperature be known and controlled to better than 0.1 ^{o}C. The thermal control system consists of a radiator that always points to the anti-sun (cold) side of the spacecraft. The radiator partially views the earth so the overall radiator efficiency varies somewhat as a function of solar beta angle as the amount of backscattered solar radiation varies. Figure 1 shows the temperature of the detector housing, the etalon, and the CCD during the first 18 months of operation. The detector housing (window) temperature (Figure 1a) was initially held at –60^{o}C. Once it was determined that ice had deposited on the optics, the heater duty

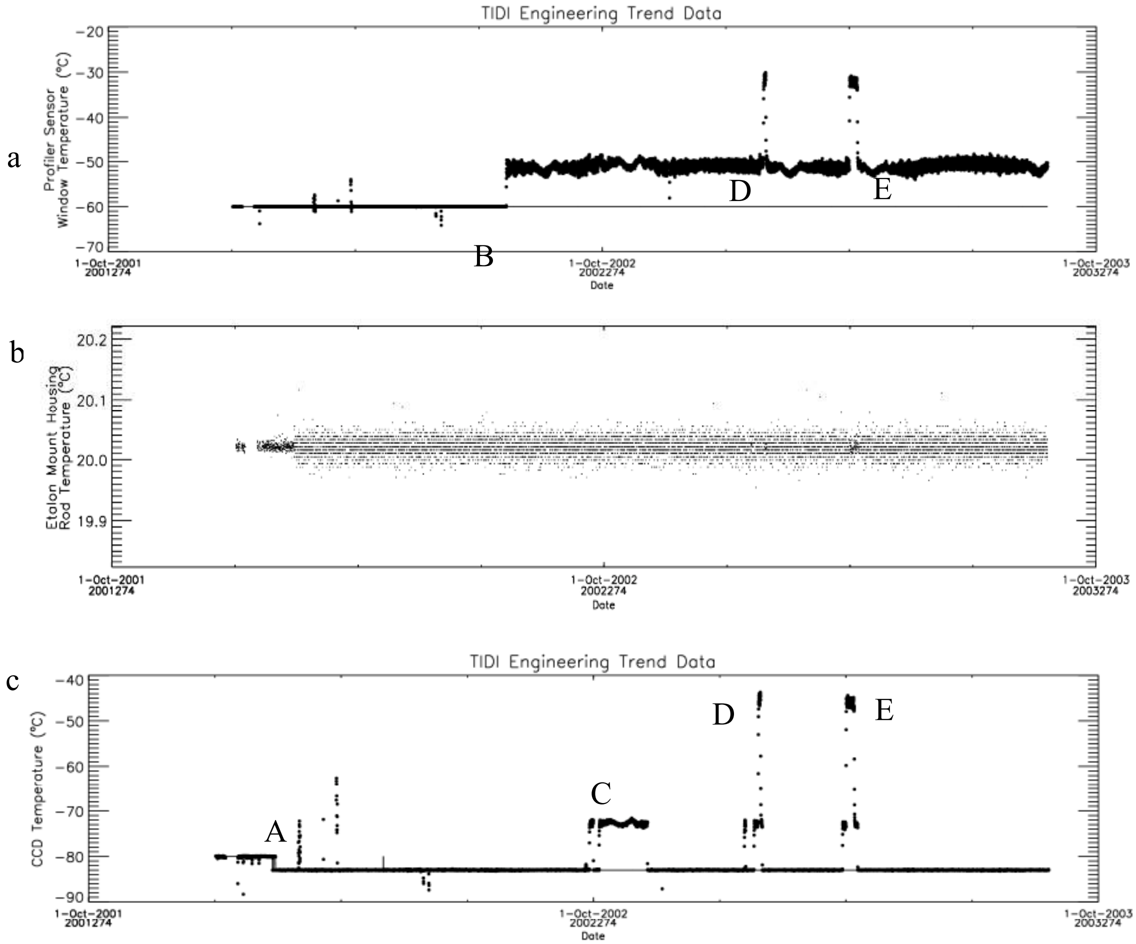

Figure 1. Temperatures of various TIDI components. a = Detector window housing, b = etalon, c = CCD. A = CCD temperature setpoint changed to –83^{o}C from –80^{o}C, B = window housing heater turned on full time, C = CCD heater test, D = spacecraft roll 1, E = spacecraft roll 2.

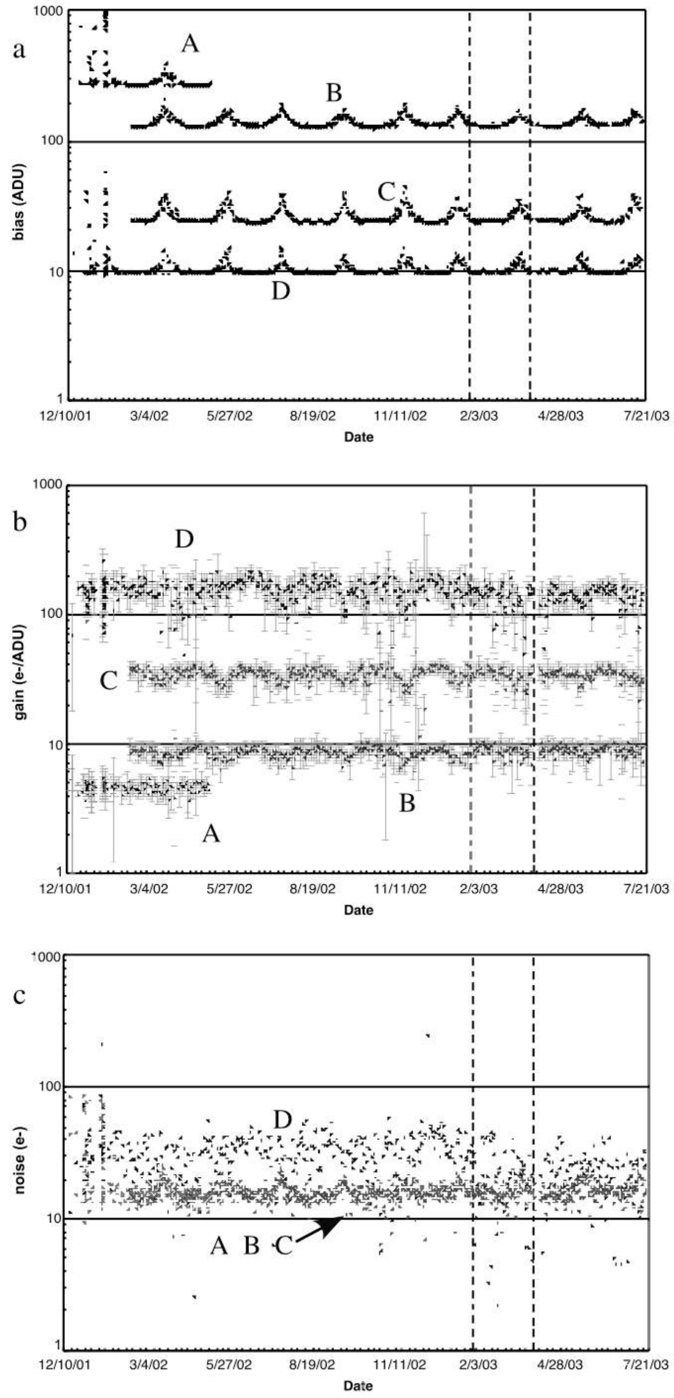

Figure 2. TIDI CCD parameters from December 2001 until July 2003 as determined by daily photon transfer calibrations. a = bias, b = gain, c = read noise. A = nominal gain = 5 e-/count, , B = nominal gain = 10 e$^-$/count, C = nominal gain = 40 e$^-$/count, D = nominal hgain = 160 e$^-$/count. The two vertical dashed lines indicate the times of the spacecraft rolls.

cycle was increased to 100% in an attempt to remove any deposition from the window. This was not successful but is was decided to leave the heater on full time in hopes of preventing additional deposition. The two temperature spikes are the result of the spacecraft rolls, which will be discussed later. The etalon temperature (Figure 1b) has remained remarkably constant through the mission and this implies an etalon thermal drift is not a problem for this instrument. The CCD temperature (Figure 1c) was initially held at –80°C. Because the CCD heater dury cycle could sometimes reach 100% it was decided to lower the temperaure to –83°C to allow the control system to have positive control at all times.

3. CCD PERFORMANCE

Key properties of the CCD detector, including gain, bias, and read noise are monitored in flight by performing a "photon transfer" calibration[6] as part of the daily calibration sequence. The CCD can be operated with one of 4 different gain settings. The highest gain setting is 5 electrons/count and was chosen to have a gain approximately equal to the expected read noise. The second setting is 10 electrons/count and was picked to have twice the dynamic range. The third setting is 40 electrons/count and was selected to allow measurments of the brightest expected signals. The final setting is 160 electrons/count and was included so a pixel near full well capacity could be read without overflowing the counter. The counter is a 12 bit A-D which permits a maximum signal of 4095 counts. The CCD that was flown has a read noise of approximately 15 electrons, so the 5 electrons/count gain setting is not used. The gain of 10 electrons/count is used for all nighttime measurements and the weaker daytime signals, and the gain of 40 electrons/count is used for observations of the bright daytime O_2 lines. The gain of 160 electrons/count is not used for any science measurements, but is used for most of the calibrations. Figure 2 shows the bias, gain, and read noise for the four gain settings. All have remained constant through time. The bias and gain show periodic peaks and valleys which occur at high solar beta angles. These are believed to be a result of light contamination which occurs during the calibration. All TIDI calibrations are performed as the spacecraft goes from day to night, starting when the solar zenith angle reaches 90° at the satellite. At high beta angles the spacecraft is flying along the terminator and will remain illuminated by the sun much longer than at lower beta angles.

3. LIGHT LEAK

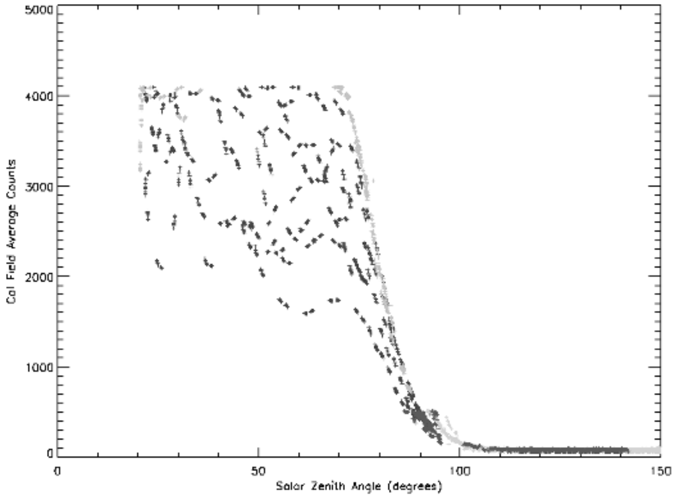

Figure 3. Plot of average counts in calibration field on 7 January 2002 as a function of solar zenith angle. Note the 12 bit counter overflows at 4095 counts.

The TIDI detector background is significantly higher than expected during satellite daytime. This is believed to be the result of stray light entering the profiler, probably through the back (anti-sun) side of the instrument around labyrinth seals meant to provide thermal isolation of various components. The net result is an increased error in the derived winds. Immediately after commencing science investigations early in January 2002, it became apparent that the detector background was much higher than expected. Investigation revealed it had the following characteristics:

- The background levels are significantly above the values expected from thermal noise.
- The background follows a Poisson distribution, i.e., the variance of the background in electrons is equal to the mean.
- The background shows a marked day/night variation (see Figure 3) and showed strong variations between orbits.
- The background varies strongly with beta angle condition (see Figure 4).

The source of the background was initially a subject of much speculation but when the background was plotted as a function of satellite geographic position (figure 5) it became clear there was a strong correlation between location and geography and cloud cover. This reasonably eliminated all possibilities except for a light leak. The correlation with geography is due to the variation in albedo from place to place. Locations with high albedo, such as the Sahara desert reflect more sunlight, some of which impinges on the radiator and enters the profiler. The largest backgrounds occur over Antarctica during austral summer.

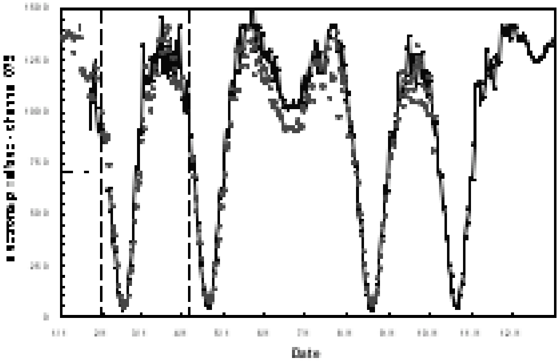

Figure 4. Plot of the detector background for 2002 (solid line) and 2003 (dots). The minima occur when the solar beta angle is near 90 degrees (i.e. spacecraft flying along the terminator). The TIMED orbit was chosen so that the beta angle one year apart is the same.

The most likely source of the light is

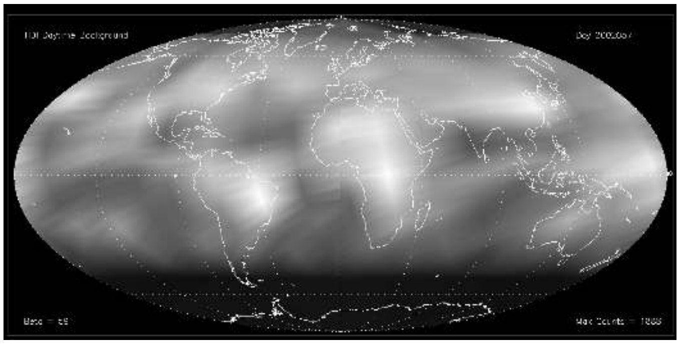

Figure 5. Background signal as a function of geography for March 8, 2003.

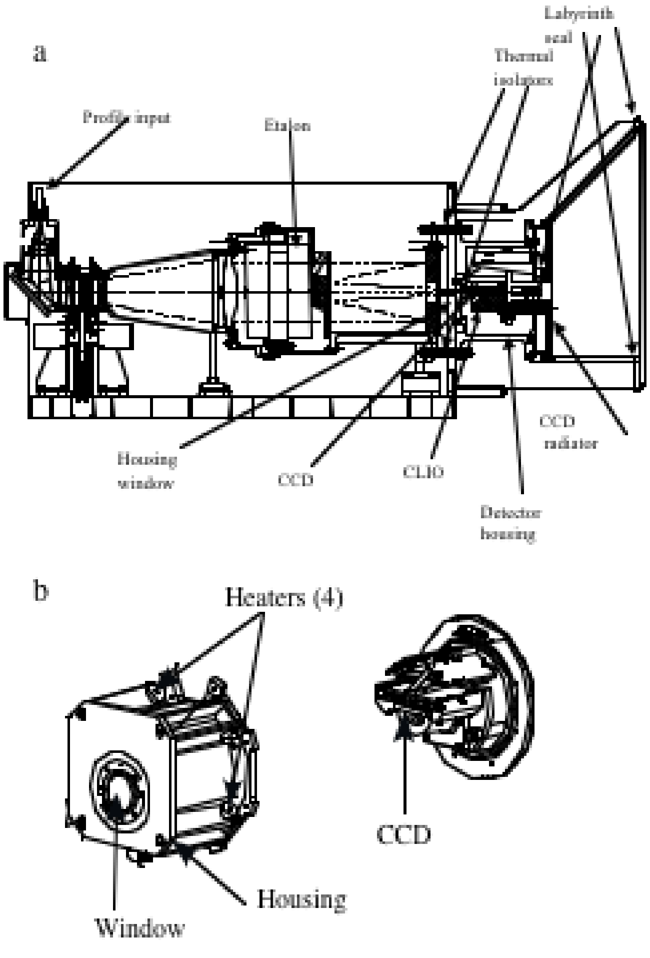

Figure 6. a) Key components of the TIDI interferometer, b) exploded view of detector section.

through labyrinth seals that are located on the back (anti-sun) side of the instrument (figure 6). These seals were designed to provide thermal isolation between the CCD radiator, earth shade and profiler housing. The problem is probably a design flaw. It has been suggested that perhaps there was a launch shift that caused some part of the labyrinth seal to move. This seems very unlikely since any movement would probably interfere with the operation of the thermal control system, which is behaving perfectly. The labyrinth seals are coated with gold for thermal reasons, but gold has a high reflectance in the visible and it is possible that with as few as 3 bounces light could enter the profiler.

4. ICE DEPOSITION ON OPTICS

Information derived from the TIMED/TIDI instrument flight data indicate that water ice has deposited on some optical component(s) of the instrument. This ice has lowered the throughput of the instrument and caused a significant amount of scattered light. The net result is an increased error in the derived winds. The long-term response to a white light lamp illuminating the calibration field section of the detector is shown in Figure 7. For this test, a white light calibration lamp illuminates the calibration scene of the CCD through the 732 nm interference filter for a short period of time once a day at satellite dusk. There was an initial rapid decrease in the recorded signal that leveled by mid-2002. The data in figure 7 show the effects of 2 spacecraft rolls that are described below.

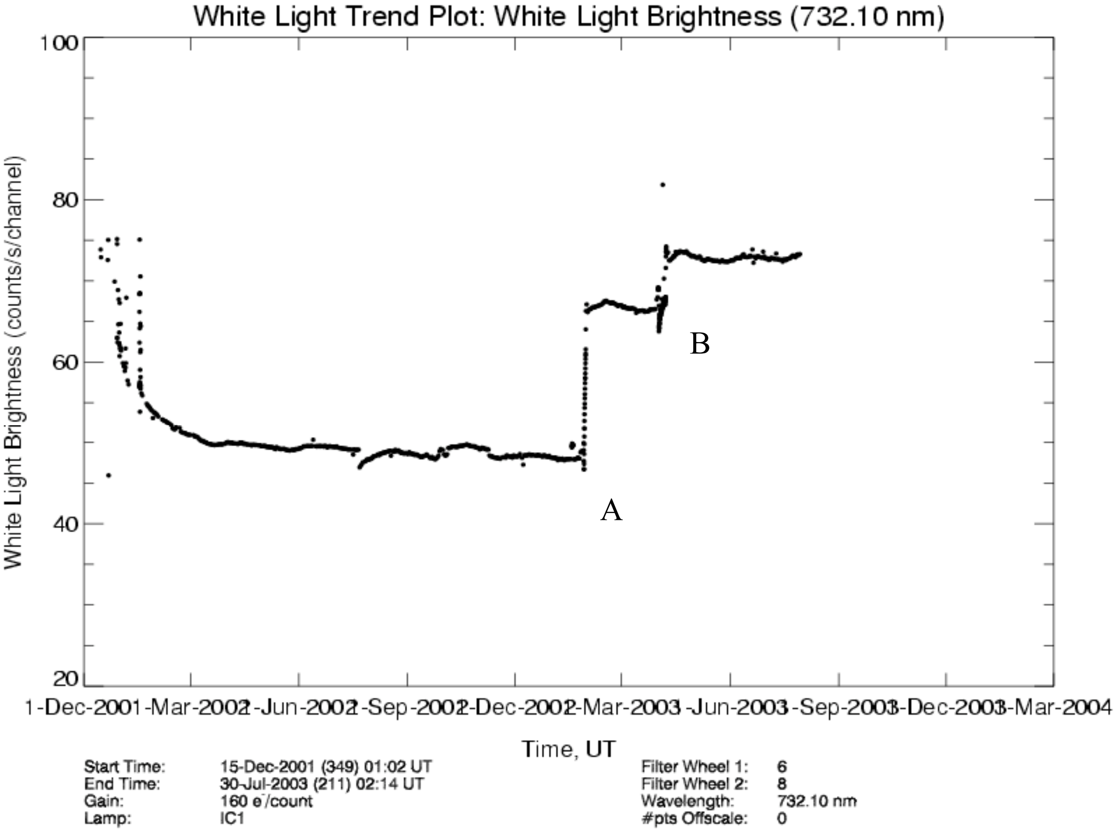

Figure 7. The trend in signal level as observed by TIDI against a white light calibration lamp viewed through the 732 nm filter. Note the fast decrease in signal near the start of the mission and the leveling in the latter half of 2002. The two spacecraft rolls occurred at A and B.

In figure 8, two calibration images using the neon spectral lamp are compared. A clear difference is seen between calibration images taken shortly after launch and images several months later. There is clear broadening of the spectral features, the peak signal is reduced, and scattered light is evident in the later image. This is consistent with the apparent reduction in sensitivity as measured by the white light calibrations shown in figure 7. However, the integral across the image is essentially unchanged between the two images, demonstrating that rather than a change in response or an absorptive process, we are dealing with a predominantly forward-scattered contamination process, as if looking at headlights through a windshield with frost on it.

A way to examine the time trend of this behavior is to perform column integrals of selected calibration images taken throughout the mission. In figure 9, integrals along a column that should not be illuminated during the white light image test are shown. This gives an indication of the time-dependence of the scattering function, and mirrors the corresponding decrease in apparent sensitivity shown in figure 7. Taken together, figures 7 and 9 show that nearly all of the scattering increase occurred during the first four months of the mission.

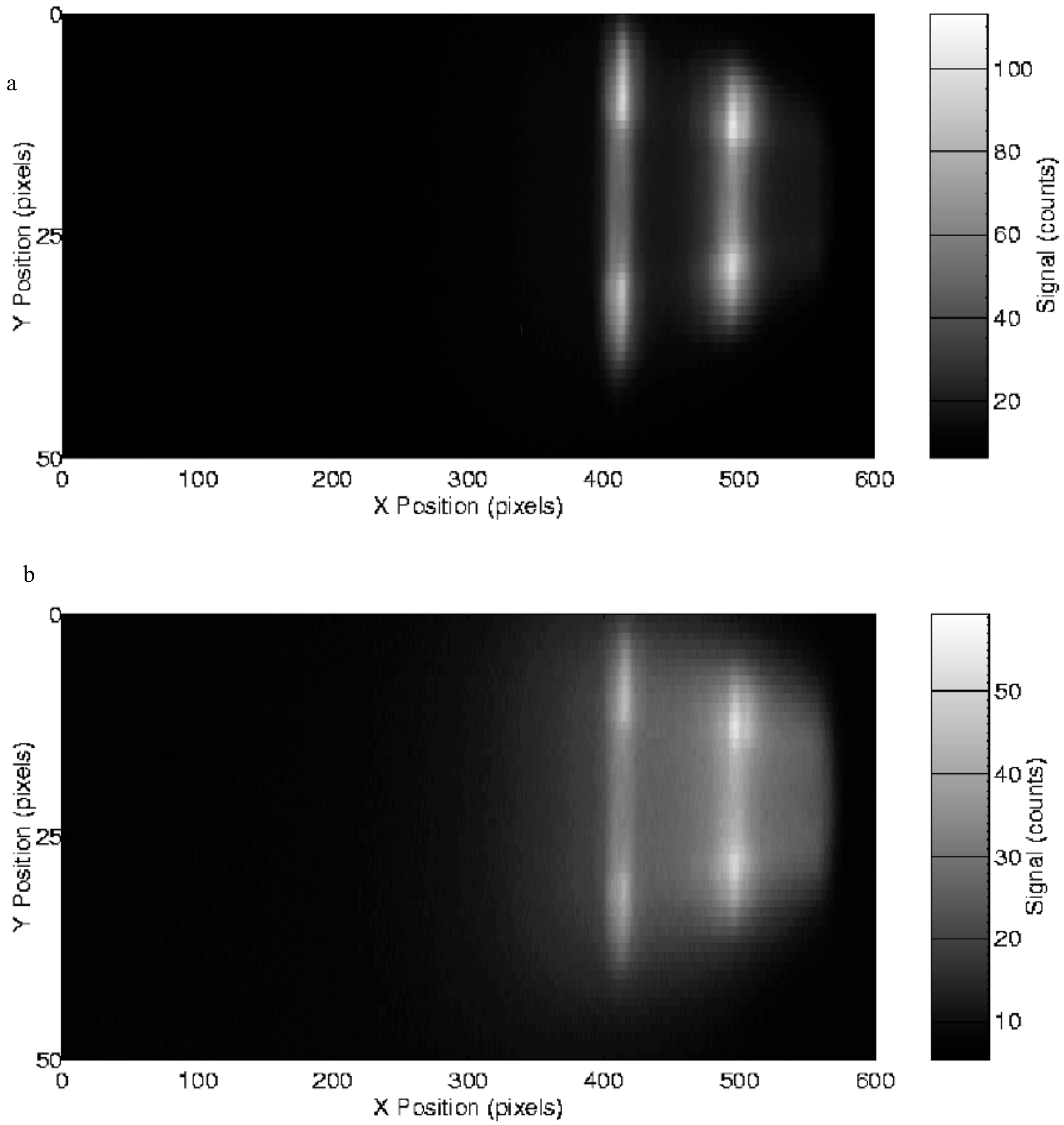

Figure 8. White-light calibration image obtained on 14 December 2001 using the neon lamp and the 630 nm filter. Bottom: White-light calibration image obtained on 21 July 2002 using the same lamp and filter. Note the change in scales.

The most probable cause of the symptoms described above is scattering by water ice that has deposited on some component(s) of the optics. Water is the leading candidate because there are no other strong candidates (e.g. the amount of epoxy in the instrument is too small to contribute much outgassing) and results from the SABER[7] instrument that is also on TIMED, also see sensitivity changes. SABER is an infrared radiometer and observations of its on-board calibration lamps reveals an absorption curve that matches water.

There are three possible candidate locations for the ice buildup: the detector housing window, the circle to line interferometer optic (CLIO)[8], and the CCD detector. There are three temperature regimes in the TIDI profiler. Drawings of the profiler and detector region are shown in figure 6. The volume inside the profiler

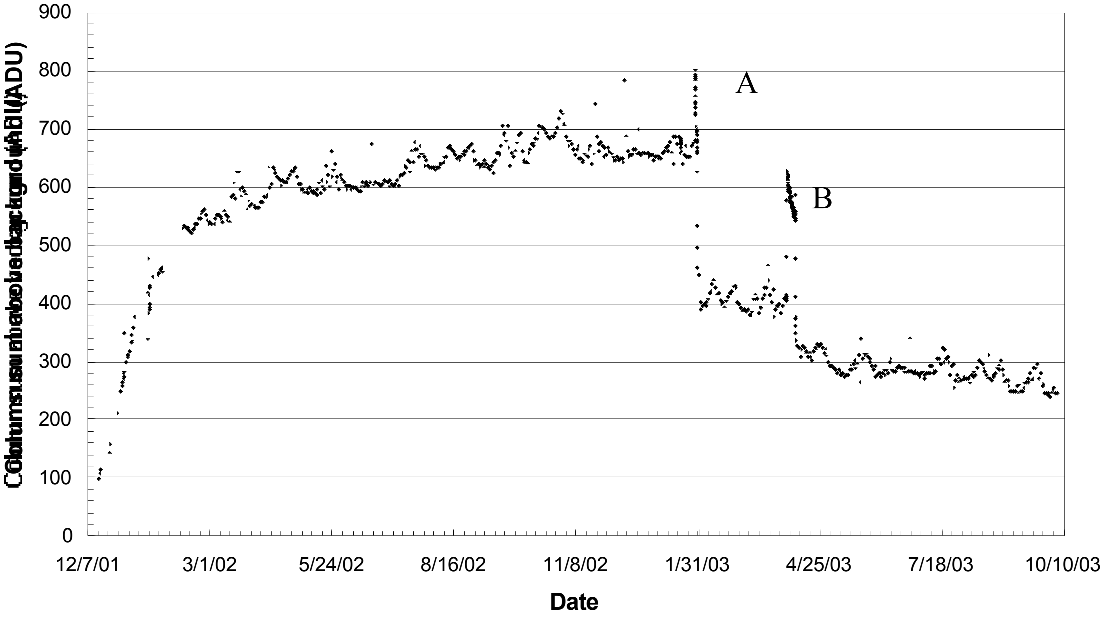

Figure 9. The trend in the column sum of column #350 for calibration images obtained with the 866 nm interference filter. This is off the directly illuminated area and is a metric of the amount of scattered light. A beta cycle dark count enhancement appears every two months. A = spacecraft roll 1, B = spacecraft roll 2.

is physically separated from the interior of the detector chamber, but both volumes are open to space through the labyrinth seals. Most of the instrument, including the optics, Fabry-Perot etalon, and the filters reside at near room temperature (20°C). Examination of temperature data since launch shows this temperature to be very stable (see figure 1). The second regime is the detector housing that is held at a nominal temperature of -60°C. The only optical component held at this temperature is the housing window. The final regime is the detector and CLIO, which is held at a nominal temperature of -83°C. The window, CLIO, and detector are possible locations for the sublimated water.

There are small heaters on the detector housing (3W) and on the CCD (0.75W). Tests have been run with these heaters on full in an attempt to remove the ice. These raised the temperature of housing and CCD about 10^{o}C above nominal. This temperature increase was too small to remove any significant amount of ice. The only remaining means to increase the optics temperature was to raise the heat load on the radiator and keep the heaters on full. This could be accomplished by rolling the spacecraft so the TIDI radiators look more at the earth. Spacecraft safety considerations limited the roll to 30^{o} from the nominal orientation. Two rolls have been performed. The first was in late January 2003 for 2 days and the second in early April for 6 days. The effect on the thermal state is seen in Figure 1. Both the detector and housing temperatures increased significantly. The detector housing temperature rose from -50^{o}C to nearly -30^{o}C, while the CCD increased from -80^{o}C to about -50^{o}C. This increase in temperature was sufficient to remove a significant amount of ice, resulting in an increase in the instrument throughput as seen in Figure 7 and decrease in the amount of scattered light as shown in Figure 8.

TIDI has no controlled means on orbit to investigate and trend behavior through the telescopic views in a fashion similar to that used in the calibration field. TIDI is designed to investigate and study the dynamics of the upper atmosphere by diagnosing airglow spectra, which are naturally variable in brightness. It is possible to investigate the relative sensitivity of adjacent spectral channels in the telescopic scenes by exposing the detector to scattered sunlight from the lower atmosphere. This has a similar affect to exposing the calibration field to a white light source, but it is not possible to trend the telescopic channels as there is

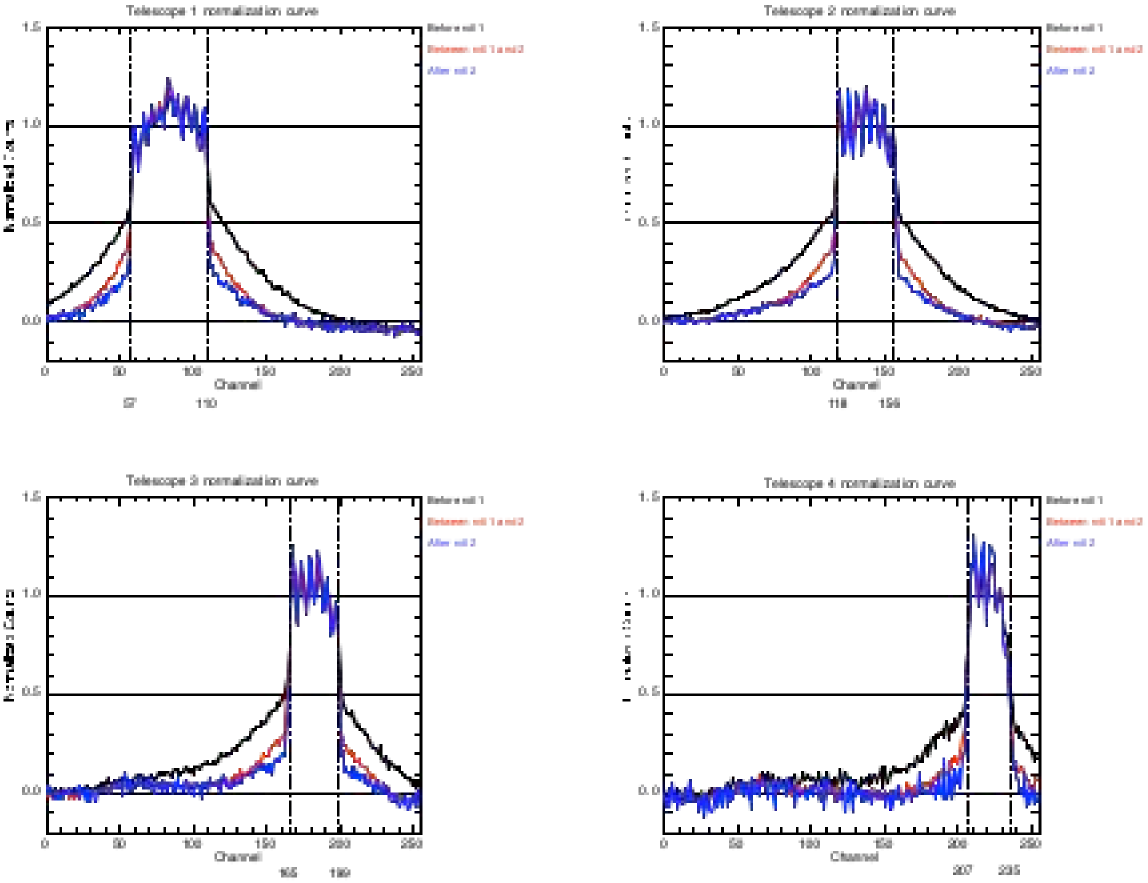

Figure 10. Normalized instrument response (NORCAL) to atmospheric white light for each of the four telescopes. To obtain the curve for telescope 1, the shutters for the other three telescopes were closed and telescope 1 was pointed to a tangent altitude of 40 and 45 km. The normalized difference is plotted. The procedure is repeated for the other telescopes. The dashed vertical lines indicate the position on the detector where the telescope field would fall if there were no scattering. Any signal outside these lines is a consequence of contamination. Results from running the procedure on three different days are presented.

no control on the strength of the solar backscattering. Nevertheless, these normalization-calibration (NORCAL) tests, which are performed once a week, allow a quantification of any instrument scattering effects.

Figure 10 displays examples of normalized white light spectra obtained during a NORCAL run before the first roll, between the two rolls and after the second roll. The procedure is to expose the detector to scattered sunlight at 40 and 45 km tangent altitude and to view the backscattering through the three interference filters currently used for airglow measurements. The justification for the calibration is to characterize the channel-to-channel sensitivity of TIDI and to normalize the airglow spectra against the inherent fiber optic structure. Ideally, there should be no cross talk between adjacent spectral channels or adjacent scenes (fields of view), and so the intensity pattern viewed with all four telescope shutters open should overlap that viewed with any one telescope shutter open for that particular scene. Figure 10 indicates that this is definitely not the case and suggests that a significant amount of white light scattering is occurring. The data also support the assertion that any scene’s light can be scattered up to two scenes away.

These data clearly indicate that the roll maneuvers have been successful in removing much of the ice. Some still remains, but given the rate of removal on the second roll, which was much slower than the first, and the fact that calculation show the improvement in the wind error that might result from additional heating is small, it was decided not to perform any additional special spacecraft maneuvers.

6. SUMMARY

The TIDI instrument has been operational for more than 18 months. The instrument has proven to be very stable and reliable. There were two significant anomalies that have challenged the TIDI team. The most significant issue is the system light leak. There was no way to correct this problem, but modifications to the instrument modes of operation by adjusting integration times to avoid occasional detector overflows and collecting frequent background measurements to allow an accurate modeling of the background characteristics have minimized the impact. This modeling effort has greatly reduced systematic effects of the undesired background, but it cannot, of course, reduce the random errors resulting from the larger signal level. The second major issue was condensation of some material, most likely water, on some surface in the optical path. This decreased the transmittance of the instrument and resulted in a significant amount of scattered light. Because of the design of TIDI which images all four telescopes side by side on a single CCD, this results in a large amount of cross talk between telescope fields. Again, this has been carefully modeled and the systematic effects can be minimized. Unlike the light leak, some corrective measures could be taken. By warming the optics, the ice could be driven off the optics. The TIDI internal heaters proved to be too small to raise the temperature, but a roll of the spacecraft that pointed the TIDI radiator more at the earth and increased the loading on the radiator significantly raised the temperature and most of the condensation has been removed. No further rolls are anticipated to remove the rest of the material. With these problems now well understood, the necessary mode changes made, upgrades to the data processing software in place, wind fields from TIDI will soon be available.

ACKNOWLEDGEMENTS

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*wskinner@umich.edu; Telephone: 734 647 3960; Fax: 734 763 7130