Observations of Typhoon Melissa during the Lidar In-Space Technology Experiment (LITE)

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ABSTRACT

The Lidar In-Space Technology Experiment (LITE) provided the first high-resolution (15 m) vertical profiling of clouds and aerosols from space. The LITE instrument flew aboard the space shuttle as its prime payload during Space Transportation System (STS)-64 from 9 to 20 September 1994. The lidar obtained vertical profiles of backscatter data at 1.064-, 0.532-, and 0.355-µm wavelengths through a cross section of Typhoon Melissa on 15 and 17 September 1994 during the strengthening and weakening phases of the cyclone. These data provide a unique high-resolution view of aerosols, clouds, and precipitation within the eye, eyewall, and cirrus shield of a tropical cyclone. The data show precipitation cascading from the eyewall into a 27-km-wide eye at the surface, with a clear column of air adjacent to the eyewall and surrounding the boundary layer clouds within the eye. During the weakening phase, the convection is found to be unorganized and weak near the center of circulation. By this time, Typhoon Melissa produced a layer of cirrus approximately 5 km thick that extended 4000 km between the center of circulation and the equator.

1. Introduction

The ability to predict the intensity and movement of tropical cyclones depends on understanding their structure. Current techniques employed by forecasters include using information on horizontal cloud structure to predict intensity changes in tropical cyclones (Dvorak 1975; Kidder et al. 2000). Information on tropical cyclone structure is provided by Doppler radar, aircraft in situ measurements, drop sondes, and satellite passive remote sensing images and soundings. However, these instruments do not allow the vertical cloud structure of tropical cyclones to be studied. Lidars could provide this new information, but ground- or aircraft-based lidar would be impractical. Now, data from a space-based lidar are available to provide a new technique to study tropical cyclone structure and are the topic of this paper.

The description of the structure of tropical cyclones begins with the most distinguishing feature of a mature tropical cyclone—the eye. Using drop sondes and visual inspection during flights in Typhoon Marge (1951), Simpson (1952) observed that tropical cyclones have an exceptionally warm eye with a strong pressure gradient, domed stratocumulus clouds capping the boundary layer, and a sloped eyewall. Malkus (1958) explained that the warm eye is caused by adiabatic compression, mitigated by evaporating precipitation in the subsidence of the eye. Emanuel (1983) explained that the sloped eyewall is caused by moist convection that follows lines of constant angular momentum that slope away from the center with height because of decreasing tangential winds.

Using 12 yr of instrumented aircraft observations, Shea and Gray (1973) and Gray and Shea (1973) found that the eye air is continually replenished by new sinking and warming air, based on measured divergence rates in the eye. On the contrary, Willoughby (1998) used soundings in the eye to suggest that the dry air above the inversion has a long lifetime inside the eye, mixes weakly with the moist air from the eyewall, and experiences only a few kilometers of subsidence. This subsidence can be forced convectively (Shapiro and Willoughby 1982), but turbulent fluxes of angular momentum from the eyewall mechanically causing the eye to spin up are thought to help to warm the eye to temperatures beyond what convectively forced subsidence can do alone (Emanuel 1997).

Jordan and Schatzle (1961) used aircraft radar to observe the “double eye” of Hurricane Donna, which had a clear area in its center and a separate clear area between two rings of precipitation. Hose and Colón (1970) used ground-based radar to show a full cycle of the formation of a double eye, which includes the shrinking of the radius of the two eyes until the inner eye dissipates. This cycle causes the deepening of a tropical cyclone because the condensational heating in...
the ring of convection in a tropical cyclone results in pressure decreases inside the ring that cause the eye to contract and to intensify (Shapiro and Willoughby 1982; Willoughby et al. 1982). If present, a secondary eyewall will often destroy an inner eyewall because of the lower-tropospheric outflow and negative wind tendencies that eyewalls force in their centers (Willoughby et al. 1982).

The eyewall contains the most intense horizontal and vertical winds and is where most condensational heating takes place, which, along with adiabatic compression, warms the eye. Doppler radars provide direct observational evidence of upper-level outflow and lower-level convective downdrafts under the eyewall rain maximum and outward from the main updrafts. They reveal that the eyewall is made up of a primary azimuthal circulation that is outward with height and a secondary circulation that slopes inward at low levels, outward at the tropopause, and upward inside the eyewall. They also show the asymmetric structure of the cyclone, including a stronger updraft and a higher outflow in front (ahead of the cyclone along its track) of the cyclone and to the left of the shear vector. Modeling studies by Shapiro (1983) show higher updrafts caused by greater frictional convergence in front of moving hurricanes. Furthermore, modeling and observational studies by Frank and Ritchie (1999, 2001) and Black et al. (2002) show stronger updrafts to the left of the environmental shear vector. Marks et al. (1992) extended the findings by Doppler analysis to show a large area of downdraft immediately inside the eyewall. They also showed that a broad radar reflectivity maximum, an updraft maximum at low levels, and outflow at all levels are characteristics of weakening tropical cyclones.

Outflow at the top of tropical cyclones is necessary to sustain the deep updrafts in the eyewall and leads to a cirrus cloud shield that spirals anticyclonically from the eyewall. Emanuel (1988a,b) relates the secondary circulation to the Carnot engine in producing the energy in a tropical cyclone. In this theory, energy is transferred from the ocean to the air in the boundary layer and is removed radiatively in the colder outflow. The difference between the sea surface temperature and the outflow temperature is proportional to the efficiency of the tropical system in converting heat energy to mechanical energy. High ice concentrations such as were found at the top of Tropical Cyclone Jason during the Stratosphere–Troposphere Exchange Project may assist in radiatively cooling the outflow layer. Knollenberg et al. (1993) suggest that the source of this high ice concentration is the nucleation on sulfuric acid aerosols from the upper troposphere or lower stratosphere. The energy produced in the secondary circulation balances the frictional dissipation of the primary azimuthal circulation. Emanuel (1988a) uses this balance to calculate a maximum potential intensity for tropical cyclones. Of course, environmental factors, such as vertical wind shear, often prevent tropical cyclones from reaching this intensity.

Tropical cyclones produce a large amount of optically thick cirrus in their outflows. Fett (1964) observed bandlike convection exterior to the cirrus cloud shield and noted that tropical cyclones progressing to higher latitudes tend to have trailing convective cloudiness directed toward the equator. Merrill’s (1988) 7-yr study of composite upper-troposphere wind data reveals that the principal outflow jet in most tropical cyclones occurs east of the cyclone in the Northern Hemisphere and is dominated by strong equatorward flow to the intertropical convergence zone (ITCZ).

All of these studies have been limited to observing precipitation-size particles (radar), horizontal structure (aircraft and satellites), or isolated vertical profiles of thermodynamic data (dropsondes). Spaceborne lidar observations can give a high-resolution vertical cross section of cloud particles and optical properties through much of a tropical cyclone’s upper layers, thereby providing new information on tropical cyclone structure.

The purpose of this paper is to present and to describe the vertical tropical cyclone cloud structure from data gathered by an active remote sensor, namely, the Lidar In-Space Technology Experiment (LITE; McCormick et al. 1993). Depending on atmospheric optical thickness, lidars provide information on vertical cloud and aerosol structure. The LITE lidar gathered data over the center of circulation of Typhoon Melissa twice in its 11-day 1994 shuttle mission. The description of the LITE measurements will be largely qualitative, as is usually the case for a new application of a technology and, in particular, for a measurement without validation.

Section 2 gives a description of remote sensing techniques used to study features of tropical cyclones pertinent to this paper. Section 3 discusses LITE and gives a brief description of the instruments on LITE, and section 4 describes how the data are analyzed. Section 5 describes the observations made by LITE, and section 6 describes the plans for a long-duration spaceborne lidar similar to LITE.

2. Instrument

The LITE payload was mounted in the shuttle cargo bay during Space Transportation System (STS)-64 from 9 to 20 September 1994 and is the first lidar to be flown in Earth orbit to study our atmosphere. The purpose of the experiment was primarily to test the ability of a spaceborne lidar to observe the optical properties of aerosols and clouds in the Earth atmosphere (McCormick et al. 1993). These observations afford scientists the ability to observe aerosols and clouds globally for studies of climate forcing and feedback. However, because of the high resolution of the measurements, a variety of atmospheric processes on a much smaller scale may also be studied.

The lidar on LITE is described fully elsewhere (Couch et al. 1991; McCormick et al. 1993; Winker et al. 1996) and briefly herein. The lidar pointed 5° off
TABLE 1. Comparison of several characteristics of the Doppler radar, Geostationary Operational Environmental Satellite (GOES) imager and sounder, Advanced Microwave Sounding Unit (AMSU), and the LITE lidar pertaining to remotely sensed weather systems.

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Active (radio wave backscatter)</th>
<th>Passive (upwelling radiance)</th>
<th>Passive (upwelling radiance)</th>
<th>Active (laser backscatter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelengths</td>
<td>30 mm</td>
<td>24 channels (0.55–14.71 μm)</td>
<td>20 channels (1.6–12.6 mm)</td>
<td>0.355, 0.532, and 1.064 μm</td>
</tr>
<tr>
<td>Primary measurements</td>
<td>Wind, precipitation</td>
<td>Clouds, water vapor, temperature, ozone</td>
<td>Water vapor, temperature</td>
<td>Clouds, aerosols</td>
</tr>
<tr>
<td>Horizontal resolution (km)</td>
<td>1</td>
<td>1–4</td>
<td>48</td>
<td>0.74</td>
</tr>
<tr>
<td>Vertical resolution</td>
<td>Typically &gt; 300 m</td>
<td>17 levels, &gt; 1 km</td>
<td>40 levels, &gt; 300 m</td>
<td>15 m</td>
</tr>
<tr>
<td>Orbit/measurement platform</td>
<td>Airborne or ground only</td>
<td>Geostationary orbit</td>
<td>Sun synchronous orbit</td>
<td>Inclined orbit</td>
</tr>
</tbody>
</table>

LITE can vertically resolve the precipitation-free cirrus shield and stratocumulus clouds capping the boundary layer within the eye. However, the use of a spaceborne lidar with a single nadir-directed beam would be impractical from an operational weather-forecasting perspective because of the lack of continuous global coverage. Also, lasers cannot penetrate optically thick clouds. Nevertheless, the high-resolution horizontal and vertical data from a spaceborne lidar when it intersects a tropical cyclone should be invaluable from a research perspective. Doppler radar can observe the dense overcast region while lidar can vertically resolve the dynamically important rain-free eye and cirrus outflow. In the future, it may be possible to increase greatly the per-orbit coverage of a spaceborne lidar by increasing the number of laser beams that are simultaneously emitted and detected in a fan-beam or scanning system.

3. Data analysis

Figure 1 shows four panels of backscatter signal profiles taken during LITE. Platt (1979) gives a good explanation of the difference between the measured attenuated backscatter and the true cloud or aerosol backscatter. The mathematical relation between the two is

$$b'(z) = \beta(z) \exp \left[ -2 \int_{z_0}^{z} \sigma(z) \ dz \right],$$

(1)

where $\beta'(z)$ is the attenuated backscatter, $\beta(z)$ is the true backscatter; and $\sigma(z)$ is the volume extinction coefficient, which is integrated from lidar height $z_{o+}$ to cloud height $z$, and back to $z_{o-}$. True backscatter is retrieved with algorithms employing retrieval methods such as those given by Klett (1981) or Fernald (1984). These retrievals account for the attenuation of the transmitted lidar beam and the received backscattered beam due to extinction. This paper analyzes the attenuated backscatter. Therefore, the backscatter signal strength from higher clouds is observed from a less attenuated incident lidar beam than is that from lower clouds.

LITE data were obtained from the NASA Langley Research Center Atmospheric Science Data Center and at the time of writing could be publicly accessed from...
Fig. 1. Examples of LITE profiles of uncalibrated backscatter counts per second at 0.532 μm in and near Typhoon Melissa during (a) the night of 17 Sep 1994 outside the cirrus shield of Typhoon Melissa, (b) the night of 17 Sep 1994 near the center of its circulation, (c) the day of 15 Sep 1994 in Melissa’s eye, and (d) the day of 15 Sep 1994 in its eyewall.

The data analyzed in this paper do not use the provided calibration constant and, therefore, are uncalibrated. Within the images analyzed in this paper, the calibration constants are similar, but no relation should be inferred between separate images, especially between those obtained during the day and those obtained at night.

Figures 1a, b were taken at night on 17 September 1994 during orbit 123, when the LITE ground track passed within 30 km of the center of circulation of Typhoon Melissa. The first profile, Fig. 1a, was taken outside the cirrus shield of Typhoon Melissa and represents approximately a clear-air profile at night. The backscatter signal increases exponentially toward the ground because of the exponential increase in density and, therefore, molecular backscatter. At the bottom of the profile in Fig. 1a, and in the two cloud layers centered at 5.4 and 15.2 km near the center of circulation in Fig. 1b, the backscatter saturates the digitizers. The digitizers on LITE often saturated at night because of higher gain settings used for measuring stratospheric aerosols. Backscatter from clouds, boundary layer aerosol, and the ground resulted in saturation at these gains. Figure 1b shows how cloud layers attenuate the lidar beam. Above and below each cloud, any backscatter would be molecular, but the signal is lower in Fig. 1b below each cloud than the molecular backscatter of Fig. 1a. This reduction in signal is especially noticeable below the lower cloud in Fig. 1b, which has attenuated the beam to a point at which no molecular or ground signal is observed beneath it.

Figures 1c, d were taken during the day on 15 September 1994 from orbit 85 when the LITE ground track passed directly over the eye of Typhoon Melissa. As described earlier, daytime-mode operation of the lidar uses filters, apertures, and reduced gain settings at the detector to compensate for the increased background light. Furthermore, this background signal is measured and subtracted electronically on board of LITE before the signal reaches the counters to prevent saturating the digitizers. Figure 1c shows a mostly clear profile in the eye with a thin layer of particles near the top of the eye. The ground return is clearly seen at the bottom of the profile, suggesting that the upper layer of particles does not completely attenuate the signal. Note, however, that the exponentially decaying molecular profile is nearly absent. The molecular signal is masked by the reduced detector gain setting and the large background signal that was removed. Figure 1d shows a completely attenuating cloud in the eyewall of Typhoon Melissa. Notice the absence of a ground spike.
4. Applying LITE data to study tropical cyclones

The synoptic history of Typhoon Melissa is described fully in Etro and Bassi (1994) and briefly here. Typhoon Melissa was first characterized as a tropical depression moving west at 0600 UTC 11 September 1994, forming over the warm sea surface waters inside a monsoon cloud band. Melissa slowly strengthened and curved to the north in the next couple of days under the influence of a deep southwesterly monsoon flow (Fig. 2). On 13 September 1994, Melissa attained typhoon intensity and developed a small eye. From 0600 UTC 14 September 1994 to 0600 UTC 15 September 1994, Typhoon Melissa rapidly strengthened, with maximum sustained winds increasing from 150 to 240 km h\(^{-1}\) (42–67 m s\(^{-1}\)). Its central pressure fell 49 hPa, and its eye diameter decreased. At 0357 UTC 15 September 1994, near the end of this period, LITE first crossed the center of the circulation of Typhoon Melissa. Peak intensity was reached 8 h later with maximum sustained winds of 250 km h\(^{-1}\) (69 m s\(^{-1}\)) and a central pressure of 904 hPa. Melissa subsequently began to become more influenced by a strong ridge to the northeast, which accelerated the typhoon’s movement from 18 to 30 km h\(^{-1}\) (5.0–8.3 m s\(^{-1}\)) by 18 September 1994, when it weakened to tropical storm intensity. LITE crossed near the center of the circulation a second time at 1303 UTC 17 September 1994 while Melissa was still at typhoon strength with winds sustained at 125 km h\(^{-1}\) (35 m s\(^{-1}\)).

Figure 3 shows a Geostationary Meteorological Satellite (GMS) image at 0425 UTC 15 September 1994, revealing the two-dimensional large-scale structure of Typhoon Melissa, including the eye, the central dense overcast of the cirrus shield, spiral cloud bands emanating from the center, and a clear but apparently unstable environment marked by scattered cumulus clouds. A distinct eye is seen from the shadow cast by the eyewall onto the boundary layer cloud within the eye. Most tropical cyclones have some clouds at the top of the boundary layer within the eye region, but the difference in height from the cirrus shield causes a distinct eye to be seen in the geostationary satellite’s visible and infrared (IR) images.

Figure 4a is a LITE lidar profile of backscatter counts obtained between 0355 and 0400 UTC 15 September 1994 over the western Pacific when the center of Typhoon Melissa was at 18.6°N, 159.7°E. At this time, Melissa was near its peak strength. The typhoon was moving approximately due north at 20 km h\(^{-1}\) (5.6 m s\(^{-1}\)) and the LITE satellite was moving northeast so that the image is a cross section from the southwest on the left (near the rear of the typhoon) to the northeast on the right (near the front of the typhoon; see Fig. 3). Vertical profiles of backscatter counts are displayed as altitude versus distance from the center of Typhoon Melissa’s circulation, where positive values indicate distances toward the front of the typhoon. Figure 4b shows the nadir-looking LITE camera image. Figures 4a,b have a similar horizontal scale and are displayed together for easy comparison.

The lidar data show that the width of Typhoon Melissa’s eye at 1 km above the ocean is 27 ± 2 km and increases to 72 ± 2 km at 16 km above the ocean. The cirrus cloud top, or top of the typhoon’s outflow, can be observed more accurately by lidar than by radar because of the lack of radar wavelength scatterers in this region (Dodge et al. 1999). On the eyewall at the front of the typhoon, the highest cirrus cloud backscatter signal occurs at 18.00 ± 0.05 km. On the eyewall at the rear of the typhoon, the highest cirrus cloud backscatter signal is observed at 17.50 ± 0.05 km. This 0.5-km-higher outflow in front of the typhoon is smaller than
Fig. 4. (a) LITE 0.532-μm lidar data of Typhoon Melissa on 15 Sep 1994. A grayscale is used so that larger aerosol and cloud backscatter appears gradually whiter. Pure white represents a backscatter signal that saturated the digitizers and is usually associated with optically thick clouds. The bottom of the eyewall has been magnified in the circular inset. (b) Nadir-looking LITE camera image taken nearly simultaneously to the lidar image. The image is aligned so that it approximately matches the horizontal scale in (a) and the LITE orbit path is approximately through the center from the left (southwest) to the right (northeast).

the 1.5–2.0-km height asymmetry observed using radar in Hurricane Alicia (1983) (Marks and Houze 1987). However, Hurricane Alicia was in a more sheared environment at the time of observation by Marks and Houze (1987) than Typhoon Melissa was during the LITE observation. Therefore, the difference in the eyewall height asymmetry between Hurricane Alicia and Typhoon Melissa may be caused by less shear-induced vertical motion in Typhoon Melissa. Frictional convergence in the front of Typhoon Melissa may have contributed to the eyewall height asymmetry.

Outside of approximately 125 km at the front of Typhoon Melissa, the cloud-top height becomes lower and reaches a minimum value of 5.80 ± 0.05 km before
rung to about 15 km at approximately 200 km in front of Melissa’s eye. The lowering of the cloud-top height corresponds to the clear area seen in the LITE camera image. Whether this is a developing secondary eye wall (Jordan and Schatzle 1961; Hoose and Colón 1970; Shapiro and Willoughby 1982; Willoughby et al. 1982) or a spiral rainband is not clear from the data. The cirrus shield outside the clear area is lower by approximately 2 km and has a lower optical depth (larger laser pulse penetration depth) than the primary cirrus shield.

The slope of the eyewall can be observed and accurately measured from the lidar backscatter data in Fig. 4a. Both the front and the back eyewall made a 47° slope with the ocean surface in the lowest 6 km, similar to that seen by radar in other tropical cyclones (Jorgenson 1984a). Above this height, the front eyewall was not visible because of the attenuation caused by the cirrus shield above. The rear eyewall continued the 47° slope up to about 10 km at which point the slope angle began to decrease, similar to other tropical cyclones (Dodge et al. 1999).

The boundary layer height at the base of the eye is observed with the lidar by the presence of a stratocumulus cloud layer, and its altitude and structure are accurately determined. These boundary layer clouds in the eye can also be observed in the LITE camera image in Fig. 4b. The boundary layer height in the eye changes as a tropical cyclone varies in intensity (Willoughby 1998). The highest cloud top in the stratocumulus layer is measured by the lidar to be 1.50 ± 0.05 km and is found toward the front of the typhoon. The inset of Fig. 4a shows that the stratocumulus cloud layer is surrounded by a clear ring of air adjacent to the eyewall. This clear ring was seen in other tropical cyclones and suggests strong subsidence (Jorgenson 1984a,b; Liu et al. 1999).

An area of enhanced backscatter occurs near the top of the eye. This backscatter, difficult to see in the camera image (Fig. 4b), appears to be significant blow-off of cirrus outflow from the eyewall that is cascading into the eye. This blow-off may be a source of moisture and evaporative cooling or frictional drag inside the eye. However, the calculated optical depth of approximately 0.1 suggests that there are not enough particles entering the eye to affect the thermodynamics or to produce subsidence. Yet, subsidence appears to extend all of the way to the ocean surface along the eyewall, causing the clear ring in the stratocumulus. Willoughby (1998) used the saturation pressure difference, \( P - P_{sat} \), to give an estimate of the total subsidence in the eye. However, they state the amount of subsidence in the eye would be underestimated if virga fell and evaporated within the eye. Heymsfield et al. (2001) found a mesoscale subsiding current of air within the eye of Hurricane Bonnie from the ER-2 Doppler Radar (EDOP) adjacent to an intense convective cell within the eyewall. However, Hurricane Bonnie was in a more sheared environment that may have accentuated the subsiding current.

Blow-off from Typhoon Melissa appears to be associated with and connected to convective cells within the eyewall. This blow-off may be evidence of a significant amount of outflow converging into the eye, carrying with it angular momentum that forces subsidence convectively (Shapiro and Willoughby 1982) or mechanically (Emanuel 1997) within the eye during various stages of cyclone development.

Because of the optical thickness of the cirrus shield and because of the lower signal-to-noise ratio of daytime LITE measurements, the lidar signal is attenuated before it reaches the bottom of the cirrus shield. Nonetheless, we can glean a few useful optical properties of the cirrus shield. Figure 5 shows the pulse penetration depth versus distance from the center of circulation. The pulse penetration depth is a measure of the distance that the lidar beam travels into a cloud layer. It is measured from the top of the cloud layer to the lowest point that still has a backscatter signal. The pulse penetration depth within the first 100–120 km of the center of circulation is approximately 2 km and then increases to 3.5 km outside this radius, indicating a reduction in backscatter. High concentrations of small particles consistent with regular pristine crystals of solid hexagonal columns at the top of the outflow were used to explain the high values of integrated attenuated backscatter near the center of Typhoon Melissa (Platt et al. 1999). These particles are found at the very top of the typhoon outflow (>17 km altitude) and at very cold temperatures (<−60°C). Large backscattering coefficients at the top of a tropical cyclone can lead to radiative cooling of the outflow layer and an increased difference between storm top and bottom temperatures that may lead to storm intensification (Emanuel 1988a).

Figure 6 is an IR GMS image taken at 1234 UTC 17 September 1994. The ground track of the LITE orbit 123, which occurred about 30 min after the satellite image was taken, is plotted on top of this image. Typhoon Melissa at this time was weakening as it moved
into a less favorable environment. No eye is apparent, but the characteristic spiral-shaped cirrus shield is still present. A long tail of cirrus spirals out to the east of the typhoon and south to the equator. LITE observed a path from northwest to southeast through the center of the typhoon, out of the cirrus shield to the southeast and into the tail of cirrus at the equator.

The LITE data for orbit 123 that correspond to the IR image of Fig. 6 are shown in Fig. 7. The data were obtained between 1300 and 1307 UTC 17 September 1994 when the center of Typhoon Melissa was at 31.9°N, 152.2°E, still over the western Pacific. This figure provides a good vertical cross section of a typhoon during its weakening phase. The backscatter profile data came within 30 km of the center of circulation. No eye was apparent at this time, though there was a break in the cirrus shield 250 km to the northwest of the center of rotation apparent on both the lidar data (at ~250 km in Fig. 7) and the IR image. Because of the improved signal-to-noise ratio at night, it is possible to observe the cloud structure through much higher optical depths.

The cirrus shield extends over 4000 km, with approximately 80% of it in the downwind direction. This

![Image](image1.png)

**Fig. 6.** An infrared satellite image from GMS obtained at 1234 UTC 17 Sep 1994. Overlying this image is the ground track of LITE orbit 123, which occurred about 30 min after the satellite image. The latitude lines are plotted at 20° intervals. The 40°N latitude line near the top of the figure is labeled. LITE is moving to the southeast.

![Image](image2.png)

**Fig. 7.** LITE 0.532-μm lidar data of Typhoon Melissa on 17 Sep 1994. The color shading is similar to Fig. 4a, but the horizontal scale indicating distance from the center of circulation is much larger. Positive distances from the center of circulation represent distances to the southeast as shown on orbit 123 in Fig. 6.
scale agrees with the length scale of hurricane outflow found in a composite of hurricanes in the Atlantic basin (Merrill 1988). Three distinct areas of deep convection exist. One is located within 300 km of the center of rotation and consists of the area that contains the center of circulation. This convection no longer fills the depth of the troposphere, as it did during the strengthening phase, and is detached from the cirrus shield outflow by approximately 5 km. The convection appears to be disorganized and weak, though most of the clouds completely attenuate the lidar signal. These characteristics are qualitatively consistent with the wind and radar reflectivity structure described by Marks et al. (1992) during the weakening phase of Hurricane Norbert. The cirrus shield above this convection is optically thicker than the cirrus downstream of it.

Upstream (negative distance) of the central convection is a thick cirrus shield detached from the cirrus over the center; this upstream shield completely attenuates the lidar signal. This cirrus is approximately 3 km lower than the cirrus over the center of the typhoon and its trailing cirrus. The optical thickness of this cirrus shield suggests that strong convection probably produced it and is probably a spiral rainband.

The third area of convection is located at the ITCZ and begins about 2000 km downstream (positive distance) of the center of the typhoon. The trailing cirrus connects this convection to the typhoon center. The entire cirrus shield is between 4 and 5 km in geometric thickness for nearly the entire 4000 km that it spans. The height of the cirrus tops throughout most of this span is nearly as high as the highest cirrus tops in the daytime image on 15 September 1994. This pattern of cirrus spanning from the tropical cyclone center to the ITCZ on the eastern side of the storm is qualitatively similar to the typical composite Northern Hemisphere tropical cyclone described by Merrill (1988) and modeled by Guinn and Schubert (1993). This is the first observation of the thickness of this trailing cirrus to the authors’ knowledge.

5. Summary and future studies

LITE’s lidar backscatter data through a cross section of Typhoon Melissa during its strengthening and weakening phases provide the first high-resolution vertical cross section of clouds through the center of a tropical cyclone. Precise high-resolution measurements of the cirrus shield cloud height and thickness, inversion height, eyewall slope and width, convection distribution, and eye structure were described. To our knowledge, no other remote sensor has provided all of these measurements through a cross section of a tropical cyclone.

The paper has shown that, near the peak of the typhoon’s development, precipitation from the eyewall cascades into the eye and a clear column of air separates the eyewall from the stratocumulus boundary layer clouds within the eye. This clear area suggests subsiding air within the eye and may be caused by outflow intrusions into the eye. The eyewall slopes outward with height and reaches higher altitudes in the front of the typhoon. Optically thick cirrus clouds exist in the eyewall and in the outer rainbands. The radiative effects of this cirrus may contribute to changes in intensity of the tropical cyclone. Outside of the eyewall, the cirrus shield decreases in altitude, with a few areas of increased vertical development that coincide with higher optical depths.

During the weakening phase of the typhoon, the convection is unorganized, with convective tops varying in altitude over relatively short horizontal distances. The tops of the convection are also vertically separated from the cirrus shield by a clear area of generally more than 5 km. The cirrus shield survives long after the convection weakens.

In the future, a long-duration satellite called the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO; Winker et al. 2002), with instruments similar to LITE, will orbit Earth in a polar orbit, providing lidar data with global coverage over a design lifetime of 3 yr. Table 2 compares the instrument parameters between LITE and CALIPSO. Unlike LITE, CALIPSO will measure two planes of polarization at 0.532 μm, providing information on particle shape and phase. Particles with irregular shapes, such as ice, will depolarize the backscatter signal, allowing retrieval of particle phase (Sassen 1991). CALIPSO will use digitizers that allow a much greater dynamic range of measurements than that observed with LITE. Color

| Table 2. Comparison of some instrument parameters of LITE and CALIPSO, a future Earth-orbiting satellite mission that will fly an instrument similar to LITE. |
|---------------------------------|---------------------------|
| CALIPSO                        | LITE                      |
| Duration of data               | Parts of 10 days          |
| Wavelengths                    | 0.355, 0.532, 1.064 μm     |
| Polarization                   | None                      |
| Altitude (km)                  | 240–260                   |
| Horizontal resolution (m)      | Variable, 333–5000        |
| Vertical resolution (m)        | 740                       |
| Digitizers                     | Variable, 30–300          |
|                               | 15                        |
|                               | Dual digitizers providing 22 bits |

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ratios of the 1.064- and 0.532-μm backscatter signals will provide information on relative particle radii for radii < 1 μm (Winker et al. 1996). CALIPSO will also fly a three-channel imaging infrared radiometer that will measure the effective cirrus cloud particle size (Prabhakara et al. 1988). Like LITE, CALIPSO will fly a nadir-looking LITE camera. The long-duration measurements of CALIPSO will provide many opportunities for routine characterization of tropical cyclones. At the time of writing, more information on the CALIPSO mission was available online at http://www-calipso.larc.nasa.gov/.

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