The NCAR Airborne Infrared Lidar System (NAILS)
Design and Operation

Ronald L. Schwiesow
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PREFACE

This Technical Note outlines the current status of the NCAR airborne infrared lidar system (NAILS). The system is being developed with NCAR support to provide new remote sensing capabilities for the university atmospheric science research community.

Ed Eloranta (University of Wisconsin), Carl Frihe (University of California, Irvine) and Ken Sassen (University of Utah) have cooperated by making suggestions during the formative phases of the project, and I encourage continuing cooperative involvement in the refinement of the system. Al Cooper (Atmospheric Technology Division [ATD]), Don Lenschow (Atmospheric Analysis and Prediction Division [AAP]), and Jack Warner (Cloud Systems Division [CSD]) have helped define the needs for such a lidar and what its capabilities must be to be useful. Research needs have been a controlling factor in design choices. Constructive questions on the technical aspects of the lidar design by Jeff Keeler (ATD) and Bob Serafin (ATD) have improved the lidar system.

This document is a progress report on an ongoing project. Later Technical Notes will describe refined versions of the lidar.

Ronald L. Schweisow
1 March 1987
ACKNOWLEDGMENTS

The initial impetus and encouragement for NAILS came from Byron Phillips. Paul Lightsey, who was a faculty visitor from the University of Northern Colorado in 1986, helped refine the optical layout and performance calculations for the system. Norm Zrubek did the mechanical and aerodynamic design for the lidar, and Kim Weaver developed the signal processing component. Numerous other RAF staff helped in construction, installation, and elimination of noise pickup problems.
ABSTRACT

The goal of the lidar development program discussed in this Tech Note is to add remote, clear-air wind sensing capability to the instrumentation available on Research Aviation Facility (RAF) aircraft. A fairly simple lidar to measure atmospheric backscatter profiles and backscatter depolarization ratios, as a first step toward a Doppler lidar system, has a number of applications in boundary-layer and cloud physics research. Operation at a wavelength of 10.6 μm in the middle infrared allows for growth to a Doppler wind-measuring lidar and assures eye safety. Performance calculations for NAILS indicate a useful range to at least 1 km for a backscatter coefficient of $5 \times 10^{-9} \text{m}^{-1} \text{sr}^{-1}$ with a resolution of ±10 m in both vertical and flight-track directions, and to greater range with more averaging or in more strongly scattering environments. The system fits on the King Air above the down-looking camera port together with standard instrumentation. We have designed a compact, direct-detection optical system that allows easy conversion between aerosol-profiling and depolarization-profiling modes and that can be modified for heterodyne (coherent) detection and Doppler wind measurements. The signal-processing electronics includes provision for real-time, height vs time display of backscatter or depolarization along the flight track.
I. PURPOSE AND BACKGROUND

The Research Aviation Facility of the Atmospheric Technology Division of NCAR is developing an airborne infrared Doppler lidar system for a variety of applications in atmospheric science research. At its present stage of development, the lidar does not yet operate in a heterodyne mode, but it is useful for making measurements of the vertical profile of the backscattering coefficient from an aircraft. Such profiles are useful for sensing the top of the mixed layer, for mapping the top or bottom of cloud decks, and for differentiating between ice and liquid cloud particles by means of the depolarization ratio, for example.

This Tech Note describes the present lidar system in more detail than is appropriate for a journal article. It is intended to serve as an operations manual to help potential users understand the lidar system and the data it produces. By presenting detail on the design, we hope to stimulate thinking about how lidar can contribute to future observational programs and about how the system can be improved or modified to increase its usefulness for research.

Range-resolved measurements of backscatter profiles and Doppler velocities have been made from aircraft (e.g., Bilbro et al., 1984 and 1986). NAILS is intended to be an easily accessible system that can be flown on aircraft like the King Air and Gulfstream G-I. It is part of the RAF development effort in airborne remote
sensing, which is designed to support observational atmospheric science, particularly programs sponsored by NSF at universities and at NCAR.

II. RATIONALE

A. DOPPLER CAPABILITY

Lidar measurement of the atmospheric wind field by Doppler techniques is the primary goal of the RAF lidar effort. A pulsed laser transmitter is required for range resolution. Of available pulsed lasers, only the CO$_2$ laser has demonstrated a sufficiently narrow linewidth to be useful for Doppler wind measurement. Although work on Nd:YAG lasers (Kane et al., 1984) and excimer lasers (Pacala et al., 1984) for Doppler measurements is underway, such lidars have not yet been successfully demonstrated. Menzies (1986) reviews various Doppler lidar possibilities with more detail than considered here and concludes that a pulsed CO$_2$ laser provides the best performance for a satellite-based application.

We have chosen to base NAILS on a pulsed CO$_2$ laser to allow eventual development of the system into a Doppler lidar that uses proven technology. The product of range and velocity resolution for a Doppler lidar is limited by the laser wavelength (Schwiesow, 1986; Keeler et al., 1987) so the choice of operating at a wavelength of 10.6 $\mu$m has implications for wind measurement. With an infrared Doppler lidar we expect to achieve a range resolution of $\pm 50$ m and a velocity accuracy of $\pm 0.5$ m/s (by averaging a spectrum with a width of $\pm 4$ m/s) for signal-
to-noise ratios of 10 dB and greater.

B. EYE SAFETY

The safe pulse energy density for laser wavelengths of 1.4 μm and shorter is 5 μJ/cm² (Sliney, 1986) because the eye is transparent to these wavelengths. At 10.6 μm the exposure limit is an average power density of 100 mW/cm², which corresponds in practice to a pulse energy density of 100 mJ/cm² (Sliney and Freasier, 1973). This difference between visible and infrared of more than $10^4$ in exposure limits is a strong argument for the use of an infrared lidar.

For NAILS, the laser operates at 300 mJ per pulse at approximately 50 pulses per second. Assuming a uniform beam density for simplicity, the transmitted beam is eye safe at a diameter of 2 cm for a single pulse and at a diameter of 15 cm for continuous exposure. This means the beam is safe at the exit of the beam expander (5 cm) for a single pulse and at the exit of the telescope (30 cm) for average power. For an observer on the ground, limits for a single pulse are appropriate. Because the safety factor is more than 200 for a single pulse at the telescope output, we neglect scintillation focusing of the beam.

An eye safe lidar is considerably easier to use in field projects than one that is not eye safe. For example, FAA approval requires only a statement that the lidar is eye safe by American National Standards Institute standard ANSI Z-136.1-1986. No special aircraft separation is required in experiments using multiple aircraft. Operation over land is as easy as operation over the ocean.
C. APPLICATIONS

The basic data from a simple backscatter lidar are profiles of backscatter vs altitude as shown schematically in Fig. 1. From these data, one can infer the height of the mixed layer and its variation with distance along the flight track to compare with measurements of other variables (e.g., Kunkel et al., 1977; Uthe et al., 1980; Boers et al., 1984; Melfi et al., 1985; and Atlas et al., 1986).

Fig. 1. Idealized lidar backscatter return with the top of the mixed layer at approximately 2.1 km. Additional layering is evident 0.8 km.

To infer the height of the mixed layer and perhaps elevated scattering layers, some objective definition of the top of the layer, such as the height of the maximum
negative gradient of signal return, must be adopted. When aerosol particles are trapped beneath an inversion and collect moisture, sometimes there is an elevated relative maximum of backscatter signal. Because the relative humidity is a maximum at the top of the mixed layer, soluble particles in the air form solution droplets of maximum size there. The relationship between backscatter profile and profiles of temperature, humidity, and other variables requires further study (Kaimal et al., 1982).

Measurements of the thickness of the mixed layer are especially useful when they are made remotely from an aircraft because the data can be correlated with in situ data on three-dimensional wind, state parameters, gas concentrations, or fluxes made at the same time. Determining in situ boundary-layer data and thickness values from the same aircraft requires an upward-pointing lidar. Flight-track plots of backscatter profiles provide insight into boundary-layer structure. Intrusions of upper air, local breakup of inversions, subsidence of scattering layers, and similar phenomena can be revealed by lidar data. Useful information on the mixed layer is available even if backscatter measurements are only qualitative. Wave structures in any region where a vertical gradient of backscatter exists are visible on a time series of lidar profiles from an aircraft.

In cloudy regions, the lidar gives flight-track data on the top (if flying above) or bottom (if flying beneath) structure of the cloud, from which spatial scales can be determined. If an ice cloud is optically thin, liquid droplets show up as regions
of enhanced scattering and are also detected as regions of reduced depolarization ratio. Such data are useful for icing and other studies. Additional microphysical applications of NAILS data on backscatter and depolarization include ice habits, ice/water discrimination, and droplet size variations (via Mie theory) when a constant number density of a reasonably monodisperse particle-size distribution can be assumed, as in a lee-wave lenticular. For depolarization measurements from clouds, a lidar must have a well-defined output polarization, which is fairly easy to achieve with any reasonable laser wavelength, and two orthogonally polarized receiver channels. Because backscatter resulting from clouds is much stronger than that from aerosols, lidar sensitivity is not critical for cloud detection, but a more sensitive lidar can penetrate farther into cloud than a less sensitive one.

The surveying capability of the lidar as a clear-air remote sensor is useful for locating the center of tenuous source plumes, which allows an aircraft to carry chemical instruments into the highest-concentration regions of the plume without flying a raster-scan pattern.

D. PRACTICAL ASPECTS

Of commonly available laser systems, CO₂ lasers have the highest efficiency for converting electrical energy to optical energy. For example, some transverse-excitation-discharge laser heads can operate with either CO₂ or excimer gases. With the same power supply, the pulse energy of the CO₂ system is 3 to 10 times that of
the excimer. For a given laser pulse energy, a lidar based on a CO\textsubscript{2} discharge will have a smaller power supply and will be easier to cool.

**III. PERFORMANCE CALCULATIONS**

A. SIGNAL-TO-NOISE RATIO

The signal-to-noise ratio (SNR) of a lidar system depends on system parameters and the atmospheric backscatter coefficient. For a lidar, the definition of SNR is based on photon statistics, where the desired signal is a correct estimate of the ensemble average of the photon arrival rate from some source (under specified experimental conditions) and where noise is anything that contributes to the uncertainty in the estimated average photon flux. Since photons obey Poisson statistics, the uncertainty in a single realization of a photon-counting experiment where \( S/\hbar \nu \) photons are counted is \( (S/\hbar \nu)^{1/2} \), and the best estimate for the ensemble average is \( S/\hbar \nu \). \( S \) is the detected signal energy and \( \hbar \nu \) is the energy of a single photon. In an ideal case, where the SNR is determined by only the shot noise on the photon arrival rate (often called signal noise limited), the SNR is simply \( (S/\hbar \nu)^{1/2} \). Increasing the counting time or the number of experiments increases the SNR by the square root of the number of time periods or experiments.

The importance of considering the received number of photons is that the achieved SNR in any lidar can be no better than the limit imposed by Poisson statistics on the photon arrival rate.
Other contributions to the photon count rate, such as background radiation or counts generated in the detector, contribute noise to the extent that the value of these extraneous contributions cannot be subtracted from the detected count rate. That is, only fluctuations in the background or detector count rate constitute lidar noise; the ensemble average, which can be determined for approximately continuous noise sources by measuring in the interpulse period, is not noise. Poisson statistics are again applicable to evaluate fluctuations, so that, for example, detector-noise power depends on the square root of the bandwidth of the measurement.

One element in the analysis of SNR is the atmospheric-backscatter coefficient $b$. Although much research on the climatology of aerosol-backscatter coefficient profiles remains to be done, Post (1984) presents the best available statistics on aerosol-backscatter profiles near Boulder, Colorado. The backscatter coefficients tend to follow a lognormal distribution, on a cumulative probability plot, for any particular season and altitude. For example, the backscatter coefficient for Spring, 1983, had a 50% probability of being at least $4 \times 10^{-9} \text{ m}^{-1} \text{ sr}^{-1}$ at 4 km ASL, and it is generally greater at lower altitude. Geometrically-averaged-backscatter coefficients at 4 km ASL range from approximately $7 \times 10^{-10} \text{ m}^{-1} \text{ sr}^{-1}$ in winter to $7 \times 10^{-9} \text{ m}^{-1} \text{ sr}^{-1}$ in the summer, so a typical value is near $b=5 \times 10^{-9} \text{ m}^{-1} \text{ sr}^{-1}$ at the 50% probability level for an altitude of 4 km ASL for spring/summer cumulus research. The standard deviation is a factor of five in backscatter coefficient at 4 km ASL, and it is generally less at higher altitude and is somewhat more lower in
the atmosphere.

Other reports support these backscatter values. A more limited data set from Schwiesow et al. (1981a) indicates a slightly smaller average backscatter value of $1 \times 10^{-9} \text{ m}^{-1} \text{ sr}^{-1}$ at 4 km ASL in early spring, a value also reported by Menzies et al. (1984) for summer in California. Rothermel and Jones (1985) found values similar to Post's in Huntsville, Alabama. The backscatter value probably would be larger in a marine boundary layer and closer to the surface.

To calculate an SNR, consider practical system parameters from Table 1, applicable to NAILS.

### Table 1. Aerosol Profile Lidar System Characteristics

<table>
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<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Laser pulse energy $E$</td>
<td>0.3 J</td>
</tr>
<tr>
<td>Telescope area $A$</td>
<td>0.071 m$^2$</td>
</tr>
<tr>
<td>Detector quantum efficiency $e$</td>
<td>0.5</td>
</tr>
<tr>
<td>Optical transmission $t$</td>
<td>0.5</td>
</tr>
<tr>
<td>Length of scattering region $l$</td>
<td>20 m</td>
</tr>
<tr>
<td>Range $r$</td>
<td>2 km</td>
</tr>
<tr>
<td>Operating wavelength</td>
<td>10.6 $\mu$m</td>
</tr>
<tr>
<td>Detector noise power $N$</td>
<td>$0.84 \times 10^{-12} (\text{W Hz}^{-1/2})$</td>
</tr>
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From a simple lidar equation (e.g., Schwiesow, 1986) in the form

$$S(r) = E \times b(r) \times l \times A \times e \times t \times \exp(-2 \times a \times r)/r^2,$$
we can calculate that the signal in the detector is approximately $1.0 \times 10^4$ photons/pulse for a backscatter coefficient of $5 \times 10^{-9}$ m$^{-1}$ sr$^{-1}$ at a range of 2 km if we neglect attenuation ($a=0$) over this short range. In a direct-detection lidar, the dominating noise is detector noise. A receiver bandwidth of 20 MHz is adequate for a range resolution of 20 m, so the number of photons corresponding to the noise equivalent power of the detector is $2.7 \times 10^4$ photons/pulse for a range gate of 20 m.

A direct-detection lidar will have an SNR of less than one on a single-pulse basis (no averaging) at a range of 2 km, with the sample volume at an altitude of 4 km ASL under average summer continental aerosol conditions. At the repetition rate planned, 50 pulses per second, we can average over eight pulses and still achieve a resolution better than 20 m along the flight track at a flight speed of 100 m/s. Averaging eight pulses increases the SNR by $8^{1/2}$, which is a factor of almost three, so the SNR for averaged data is one at the limiting conditions considered. Better SNR is available for applications involving shorter range, more averaging, or targets such as the boundary layer that scatter more strongly than the assumed target.

A limited range is one of the most severe limitations of the current version of NAILS. For this reason, we intend to proceed as directly as possible to coherent (heterodyne) detection, which is limited by statistical noise on the photon arrival rate rather than on detector noise. Although a complete analysis of heterodyne SNR is out of place in this Tech Note, we expect an increase in maximum range by a factor of ten, but signal averaging will still be required to reduce the noise.
associated with fluctuations in the signal from the sum of random phases associated with coherent detection of scattering from a distributed target. This averaging may make it desirable to operate the NAILS laser at its maximum repetition rate of 150 Hz. Plans for eventual coherent detection suggested a high repetition rate capability for the NAILS laser.

B. CLOUD PENETRATION

For clouds with droplet diameters of 24 μm and smaller, there is a linear relation between attenuation at a wavelength of 10.6 μm and the liquid water content (Gertler and Steele, 1980; Bruce et al., 1980; Chimelis, 1982). The attenuation is \( \approx 60 \text{ dB/km} \) at a water content of 0.1 g/m\(^3\). The backscatter coefficient from a small cumulus cloud might be \( \sim 30 \text{ dB} \) more on the average than that of typical clear air (i.e., \( 5 \times 10^{-6} \text{ m}^{-1} \text{ sr}^{-1} \)) because cirrus is approximately 20 dB more (Post et al., 1982). On the other hand, laboratory work by Jennings (1986) suggests a backscatter coefficient of \( 4 \times 10^{-5} \text{ m}^{-1} \text{ sr}^{-1} \) (almost 40 dB more than our clear air assumption) for a droplet cloud having an attenuation of 60 dB/km. In any event, the optical parameters of parts of a cloud vary over wide ranges, and any estimate of penetration can be only a rough estimate.

The penetration of a lidar probe into a cloud depends on range to the cloud, among other factors, but it is possible to extrapolate the previous clear-air SNR calculation to a lidar operating in a cloud with a liquid water content of 0.2 g/m\(^3\). If we assume a penetration depth of 200 m, the two-way attenuation in the cloud
is 48 dB. In the equation for received signal energy, this factor is countered by a range-squared correction of 20 dB (for a range reduction from 2 km to 200 m) and by an increased backscatter coefficient conservatively estimated as 30 dB. A penetration depth of 200 m for a liquid water content of 0.2 g/m³ is a consistent estimate for the performance of NAILS.

These very tentative estimates need to be tested by lidar field measurements. Multiple scattering in cloud leads to range aliasing. A diffraction-limited heterodyne lidar is much less sensitive to multiple scattering effects than is a direct-detection lidar with a larger field of view.

C. COMPARISON TO OTHER LIDARS

Most airborne lidars for applications similar to those planned for NAILS use laser transmitters of wavelength 1.06 μm or shorter. Examples of these instruments include Browell et al. (1983), Melfi et al. (1985), and Uthe et al. (1980 and 1982). Some of the differences between short- and long-wavelength lidars in the areas of frequency stability, power efficiency, and eye safety have been discussed under the rationale for NAILS, earlier in this Tech Note. This section mentions other differences related to applications.

Compared to lidars at wavelengths of 1.06 μm and shorter, a system operating at 10.6 μm will respond to larger particles in the size distribution. For profiling the mixed layer, the aerosol backscatter is important, but the molecular return masks the differences between regions of differing particle concentration. The
aerosol/molecular contrast is higher for longer lidar wavelengths because the molecular backscattering coefficient varies as wavelength to the -4 power whereas aerosol scattering varies as wavelength to the -0 to -3 power, depending on the particle size distribution. Applications involving measurements of the mixed layer suggest an infrared lidar. Post (1978) finds that a lidar at 10.6 μm is most sensitive to particles in the 1- to 3-μm radius range for typical aerosols because for smaller particles the scattering is too weak and for larger particles the number density is too low.

Even though the aerosol backscatter coefficient at a 10.6-μm wavelength compared to that at 0.694-μm is calculated to be 20 to 100 times weaker (Fitzgerald, 1984) or measured to be 400 to 1,100 times weaker (Schwiesow et al., 1981a) under various conditions, the fact that the number of photons per joule is larger in the infrared (IR) means that good signal statistics are possible with a lidar operating at 10.6 μm. Lading et al. (1980) calculate for a Junge particle size distribution the number of received photons per incident joule as a function of lidar wavelength. This number peaks at a wavelength of approximately 10 μm, even for distributions with power law coefficients as large as -3.5 (assuming an index of refraction of m = 1.7 - 0.01 i). Recall from the discussion of signal-to-noise ratios that the best possible SNR depends on the received number of photons.

When compared to received photon-statistical noise, detectors in the infrared are much noisier than are detectors in the visible. This means that an IR lidar uses cryogenically cooled photovoltaic or photoconductive detector elements of minimum
area, which in turn places a much higher premium on minimum beam divergence and good beam alignment than is the case with a visible-wavelength lidar. To reduce the influence of detector noise, IR lidars often use heterodyne detection, which is very rare in visible lidars. Since heterodyne detection is sensitive to the sum of the scattered signal electric fields, rather than to the sum of intensities (power) as in direct (light-bucket) detection, noise from phase fluctuations on the return can be significant and can require multipulse averaging.

Because scattering from aerosols depends on the optical wavelength, comparing simultaneous measurements from short-and long-wavelength lidars may give additional insight into mixed-layer structure; inferences of the top of the mixed layer may be different with different wavelengths even when using the same definition of mixed layer top based on the backscatter profile. In addition, the ratio of short- to long-wavelength backscatter coefficient gives information on the size of the scattering particles.

Existing pulsed CO$_2$ lidars give evidence that NAILS builds on demonstrated technology. Bilbro et al. (1984 and 1986) have flown a heterodyne Doppler lidar for a number of years on the NASA Convair 990. This system used a master oscillator and power amplifier laser approach with a pulse energy of approximately 14 mJ. Steinvall et al. (1983) have successfully measured aerosol profiles with a ground-based, direct-detection lidar operating at 10.6 $\mu$m with a detector cooled to liquid nitrogen temperature. This system is close to the existing development stage of
NAILS. These authors show useful profiles to 2 km or the top of the mixed layer, depending on elevation angle, using integration over 25 laser pulses. Uthe (1986) has flown a direct-detection CO$_2$ lidar for tracer gas concentration measurements.

IV. DESIGN DETAILS

A. LASER

For a number of reasons mentioned before, NAILS is based on a pulsed CO$_2$ laser. To maximize the SNR, we need the largest pulse energy practical under the constraints of cost and the aircraft platform. High average output power is important to allow signal averaging. The scale of cost and time for our development project restricts the laser choice to commercially available units because we can afford neither the cost nor the risk of a custom laser development. This means that the performance and design of NAILS is adapted to existing units.

The standard approach to pulsed CO$_2$ lasers with high pulse energy is a transverse-excitation, atmospheric-pressure (TEA) discharge. Low pressure discharge technology (Pulse Systems, Inc.) would be very attractive except that pulse lengths are too long (>5 μs) without an expensive Q-switch that has not yet been demonstrated on this laser. Q-switched lasers with CW excitation have good average power but low pulse energy. Candidate TEA lasers include those by Lumonics Inc., Laser Applications Ltd., and Laser Science Inc. (LSI).

A separable laser head and power supply is essential if the lidar system
is to be mounted as an external pod on the aircraft, as originally planned for NAILS, and is valuable for flexibility in mounting the system in the cabin. Minimum overall weight is important because NAILS will be used in conjunction with other instrumentation on the aircraft. The LSI laser is the only candidate with a separable head, and it is the lightest and most compact. The cost of this practicality is reduced pulse energy, although the average powers of all three systems are similar. Our judgment is to weight practicality over maximum pulse energy, because the loss of SNR in the signal beam is only the square root of the ratio of pulse energies for the same average power. Lower pulse energy should allow longer life for the optical components, which are a weakness of high-energy TEA lasers. The simplest LSI laser, which is incorporated into NAILS, can be upgraded with other optical resonator configurations, already developed, for increased coherence.

The specifications of the LSI model 150G in NAILS include: pulse energy, multimode, 440 mJ at 50-Hz maximum, 300 mJ nominal; repetition rate, 0 to 150 Hz; average power, 35 W maximum; pulse length, 130 ns nominal (plus tail); and gas regenerator for sealed-off operation.

B. OPTICAL SYSTEM

Heterodyne lidars operate with a single spatial mode (i.e., a diffraction-limited focal volume), so transmit and receive telescope apertures must be the same size and the two beams must be aligned to closer than 10 μrad for efficient heterodyning. The most compact and economical way to do this is to use a transceiver,
which means the same telescope for both beams. Even for direct-detection lidars, use of the same aperture size for transmit and receive beams offers the advantages of minimum detector size for a given laser beam divergence and therefore maximum sensitivity in cases where the SNR is dominated by detector noise. Because a transceiver is best for Doppler lidar and is helpful for a simple direct-detection system like this stage of NAILS, we have chosen such a configuration.

With a transceiver, transmit and receive beams are separated at a beam splitter. This is most efficiently done with a polarization beam splitter and a quarter-wave phase retarder in the beam so that the lidar propagates circularly polarized radiation, and the transmit and receive beams are orthogonally polarized on the laser/detector side of the phase retarder. To reduce the amount of transmitted energy directly entering the detector (i.e., parasitic light, which can be a problem with a transceiver configuration), the quarter-wave plate should be as close to the telescope aperture as possible.

The optical layout for the NAILS transceiver is shown in Fig. 2. The design attempts to minimize the number of optical surfaces, consistent with geometric constraints. The transmit and receive beams are congruent and self-aligning from the polarization beam splitter (PBS) forward. The PBS serves as the transmit-receive switch in the system, which is fairly standard for CW CO₂ laser Doppler anemometers. The reflective phase retarder (PR) serves as a quarter-wave plate, but, being developed for industrial use, is much less expensive than a transmission
element. The afocal beam expander (BE) magnifies the laser beam diameter by five, serves the first stage of the telescope, and reduces the energy density on element PR. Parasitic scattering and reflection from BE is not significantly reflected from the PBS into the detector because the radiation is horizontally polarized. Laser

Fig. 2. Optical layout for NAILS using direct detection of the backscattered radiation. Mirror M1 folds the laser beam from below to pass the polarization beam splitter (PBS) with little loss. Mirror M2 directs the transmitted beam through the 5X beam expander (BE) to the quarter-wave reflective phase retarder (PR) and to the telescope via mirror M3. The circularly polarized return is changed to vertical polarization in passing PR so that it is reflected at PBS to the detector D1 through lens L1.
light reflected from PBS (resulting from imperfect polarization in the high-gain laser) exits to a lucite beam dump. Mirror M1 allows the laser to be mounted compactly with its axis parallel to the telescope axis and changes the polarization of the laser beam from vertical (to its base) to horizontal (to the optical base plate) for efficient use of the PBS and mounting of the detector D1. The optical path from PR to mirror M3 is at 45° to the baseplate because PR requires the incident polarization vector to be at 45° to its plane of incidence. Mirror M3 folds the beam vertically downward into the telescope.

All optical mounts are designed and machined to close enough tolerances that the only adjustment in the entire system is a three-axis positioner on the detector lens (L1). This is the only critical adjustment because the self-aligning nature of the optical design means that other alignments need to be good enough only to avoid gross vignetting (i.e., loss of energy from the edges of the optical beam caused by striking apertures in the optical train). Positioning L1 places the return signal on the detector chip, which is only 0.2 mm in diameter to reduce detector noise. In effect, positioning L1 aligns laser and detector axes. All optical elements except L1 are ZnSe, which transmits red light for alignment, or are reflective so that a HeNe alignment laser can be used to check for vignetting.

For cloud depolarization measurements, a second detector is used as shown in Fig. 3. In this configuration, mirror M2 is replaced by a beam splitter (BS), which serves as the transmit-receive switch, and the function of PBS is changed
to analyze the return signal into two orthogonally polarized components. PR can be replaced by a mirror for simplest analysis of the return, or circularly polarized light may be transmitted. The required use of a 50% beam splitter to separate transmit and receive beams with a transceiver used for depolarization studies results in an overall optical loss of almost 6 dB. Because cloud returns are much stronger

Fig. 3. Optical layout for NAILS used to measure the depolarization ratio of the return. The transmitted beam is directed via mirrors M4, M5, and M6 to the 50% beam splitter (BS), which serves as a transmit-receive switch. In contrast to Fig. 2, the PBS in this mode directs vertically polarized return to D1 and directs horizontally polarized return to D2 via mirror M7.
than aerosol signals, this loss is not critical to the success of cloud research. The alternative of multiple telescopes in an aircraft environment or of an optical system with less commonality with the backscatter-profile (and eventual Doppler) lidar is less attractive than the 50% beam splitter. The shift from backscatter-profile to depolarization mode requires only a few changes on the optics plate and does not compromise the performance for profiling at all.

We have chosen a Dall-Kirkham telescope for the transceiver because the optical elements are comparatively easy to manufacture to diffraction-limited accuracy and because the coaxial input is easier to adapt to an aircraft port than a Newtonian telescope, which has the input near the secondary mirror. A Dall-Kirkham is both significantly less expensive and more compact than an off-axis design. The NAILS telescope has a 30-cm usable aperture, which is about as large as is useful for an infrared heterodyne system in the boundary layer (Schwiesow and Calfee, 1979), and a primary focal length of 92.3 cm. A central absorber on the telescope secondary eliminates reflections of the parasitic on-axis rays, which could otherwise overload the detector from the transmitter pulse. The effective focal length of the system is 1.27 m, which gives with the detector sensitive area a full-angle field of view of 0.16 mrad. This field is almost twice the diffraction-limited field of view of the system (one spatial mode) of 0.086 mrad so that NAILS will not suffer signal loss when the laser operates in higher-order transverse modes or with minor optical imperfections.
Figure 4 shows the outline of the transceiver and its relationship to the other elements in the optical system. A vertical axis for the laser allows the proper polarization for the layout of Fig. 2 and lowers the center of gravity of the optics head. The telescope tube is designed as a pressure vessel so that the aircraft can be pressurized without the need for a large infrared window at the aperture of the

Fig. 4. The optics head assembly, which includes the laser (L), optics package (O) (Figs. 2 and 3), and Dall-Kirkham telescope (T). The head is rigidly attached to seat rails on the floor (F) by more struts than shown. The telescope housing is a pressure vessel open to ambient pressure, while the cabin is pressurized. A small window at the top of the telescope is the optical pressure window. The telescope is an afocal system with a magnification of approximately 6.67.
telescope. The optical pressure window is a ZnSe plate of diameter 50.8 cm behind the telescope primary, just beneath the optics package in Fig. 4. When mounted in the King Air with a 35-cm hole at the camera port, a boundary-layer control fence around the leading edge of the hole reduces aerodynamic oscillations.

C. SIGNAL PROCESSING

Figure 5 shows how the various elements of the signal processing system work together. For depolarization measurements, an additional channel from detector to digitizer is installed.

Fig. 5. Schematic diagram of the signal processing electronics. All digital components except the digitizer (digital oscilloscope) and the tape deck are mounted in the VME rack. The color monitor presents a real-time display of backscatter or depolarization on a time-height display. The output of the detector preamplifier PA is compressed by the logarithmic amplifier LA, which has a balanced output. The balanced output lines, used to reduce electromagnetic interference from the laser current pulse, are driven by line drivers (LD) and combined to an unbalanced line at the input to the digitizer by line receiver (LR).
The detectors (Judson J19D series) use HgCdTe photovoltaic (rather than photoconductive) elements of 0.2-mm diameter, which are cooled to the temperature of liquid nitrogen (77 K) to reduce noise (detectivity $D^*$ is $2.6e8 \text{ m Hz}^{1/2} \text{ W}^{-1}$); the Dewar hold time is over 10 hours. To reduce noise further, a cold shield with 30° field of view is installed. Photovoltaic optical detectors are current sources because a photon creates an electron-hole pair in the solid-state detector element; the preamplifier input impedance must be correctly chosen for adequate voltage output with desired frequency response. A frequency response of at least 15 MHz at the -3 dB point assures that the range resolution of the lidar is limited by laser pulse length rather than by detector bandwidth, because a Fourier series representation of a laser pulse of 130 ns full width at half maximum (FWHM) has a bandwidth of approximately 8 MHz (FWHM). A 15-MHz bandwidth allows a comfortable margin and later expansion to Doppler signal detection. Matched preamplifiers with a gain of 34 dB, noise figure less than 2 dB, and output impedance of 50 ohms are closely coupled to each detector to complete the detector modules.

To reduce the dynamic range of the signal, NAILS can incorporate two logarithmic amplifiers (Analog Modules LA-90-DC) with 90 dB dynamic range and 1 dB linearity, specially matched to a total gain difference of 0.5 dB to provide accurate depolarization signals. The output is balanced differential to reduce noise pickup on the lines to the digitizer; the logamps are mounted close to the detector preamps in a shielded housing. A buffer amplifier at the digitizer completes the
analog portion of the signal processing when logamps are used.

Reduction of noise pickup requires careful shielding of the signal circuit. The detectors and preamps are electrically isolated from other conductors, such as the optics plate, and are grounded through the signal coaxial lead to the oscilloscope input shield. A battery power supply for the detector preamplifier is mounted in an isolated, shielded enclosure with the preamp.

Signals are digitized by a compact digital oscilloscope (Tektronix 2430), which also provides an A-scope display of the lidar return. The maximum sampling rate is 100 Msamples/s on two simultaneous channels with 8-bit resolution and 1024 points per channel. The manufacturer gives a guideline of 6.9 bits effective accuracy, which includes noise on internal amplifiers. An HP-85 terminal emulator allows selection of digitizing rate and of trigger delay (and thereby range limits) as well as signal amplification. Terminal input also controls trace averaging in the digitizer (usually 8 traces for typical NAILS applications at a laser pulse repetition frequency of 64 Hz) to reduce the bit rate that must be transferred via GPIB lines to the display and recording processor. The maximum data transfer rate planned is 32 kbytes/s. Components of the signal processing system that are mounted in a VME card cage include a microcomputer (MVMC 110), which is based on a 68000 microprocessor, an IEEE-488 bus interface (MVME 300), a global memory board (MVME 201), a nonvolatile memory board (MM 6600), a Pertec-compatible magnetic tape interface (MCT 6020), and a color graphics controller.
A real-time display on the aircraft allows NAILS data to be immediately useful in guiding an experiment and checking lidar operation. The display is height vs time on the vertical and horizontal axes with either backscatter return (corrected for range-squared and logarithmic compression) or depolarization ratio selectable for display as 4-bit color information. Display parameters (time, height limits, and number of digitized profiles averaged for each display trace) are selected from the HP-85 terminal emulator. The display is continuously updated with a moving cursor bar that marks the position of the aircraft and the leading edge of the new data. Typical scales are 0 to 3.8 km from the aircraft (downward) for the vertical and 6 min (36 km along the flight track) in the horizontal. The video display (Electrohome ECM 1301 monitor) has a resolution of 512 x 512 pixels.

Post-flight data analysis routines are still under development. They include correction for range, geometry, and a provision for an attenuation correction supplied by the user. Typical graphical products are time-height plots over user-selected scales and ranges of backscatter or depolarization as color displays, greyscale displays, or contour plots. Research development support system (RDSS) software, now used to display radar data, can be used and adapted for graphical display of the lidar data.

Time-series plots of the height of the mixed layer, or cloud base or top, using a backscatter profile gradient algorithm are one way of reducing the amount of
data inherently available from a remote-sensing instrument. Data on the aircraft position, already available in the airborne data system (ADS) on all NCAR aircraft, are necessary to convert the range scale from the lidar to a ground-referenced coordinate system. The position data also allow time-series mixed-layer or cloud variables from NAILS to be presented on x-y coordinates.

D. MOUNTING

NAILS is designed to fit on the starboard side of the King Air between the wing spar and camera port as indicated in Fig. 6. The laser power supply, which

![Diagram of NAILS installation](image)

Fig. 6. Position of NAILS (plan view) in the King Air. From the operator's position (OP), the system is controlled at the data/display rack (DR) mounted behind the wing spar (WS) and over the inertial navigation unit. Power supply (PS) drives the laser head (L). The optical beam handling package (O), which is shown in Figs. 2 and 3, feeds telescope (T), which views downward through the open camera port.
uses standard 19-in rack-mount components, projects into the aisle so that the port side of the aft cabin must be left clear for exit. The data rack fits over the inertial navigation unit and contains the terminal, display, and signal processing electronics, as well as the power inverter and laser cooler. A simple water-to-air heat exchanger is adequate to cool the laser, although some power loss occurs when the coolant temperature is above 25° C.

All components are mounted rigidly to the seat rails. We have no electronic or optical problems that have been attributed to the rigid mount. The telescope is centered over the camera port on the King Air and attached to an adapter plate in the port, so the optics head has an overconstrained mount. NAILS performed satisfactorily to an altitude of 12,700 ft with a 2.7-psi cabin pressure differential in airframe compatibility tests. The pulsed laser had no detectable electromagnetic interference effects on any aircraft system (including avionics) nor on the standard ADS and computer.

E. SPECIFICATIONS SUMMARY

This section lists the parameters of the lidar that are of direct interest to users, omitting instrument design variables, in Table 2. Some values are design estimates that may be modified with further tests.
Table 2. NAILS Lidar, Stage 1 (Direct Detection)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating wavelength</td>
<td>10.6 μm</td>
</tr>
<tr>
<td>Height resolution</td>
<td>±10.0 m</td>
</tr>
<tr>
<td>Track resolution (variable)</td>
<td>±10.0 m</td>
</tr>
<tr>
<td>Design backscatter coefficient</td>
<td>5e-9 (m⁻¹sr⁻¹)</td>
</tr>
<tr>
<td>Maximum range, from aerosols</td>
<td>2 km</td>
</tr>
<tr>
<td>Maximum range, from clouds</td>
<td>5 km</td>
</tr>
<tr>
<td>Minimum range (dead zone)</td>
<td>100 m</td>
</tr>
<tr>
<td>Eye safety factor at telescope aperture</td>
<td>200</td>
</tr>
<tr>
<td>Signal channels</td>
<td>2</td>
</tr>
</tbody>
</table>

V. FUTURE DEVELOPMENT

A. OTHER PLATFORMS

Although the King Air is useful for NAILS development and downlooking applications, it is not easy to adapt the platform for upward viewing with the large telescope required for adequate signal. NAILS is being modified to mount the telescope with a horizontal axis and to incorporate an elliptical steering mirror so that the beam can be directed anywhere in a plane perpendicular to the telescope axis. This modification will allow NAILS to use a cabin window port in a larger aircraft and to make ground-based tests and application of the system easier.
We intend to install NAILS in the NCAR Electra with a fairing around the turning mirror, which will project from an aft cabin window on the port side of the cabin. With the mirror, the system can be used looking up to measure the distance to the top of the mixed layer while the Electra is making measurements with in situ instruments in the layer. Aircraft larger than the King Air, such as the Electra or Gulfstream G-I, permit carrying a number of special instruments in addition to NAILS and the standard meteorological instrumentation.

It is unlikely that the size and weight of NAILS will be significantly reduced in the near future. Backscatter coefficients are unchanging, given the operating wavelength of CO₂ lasers, so the telescope aperture must stay large enough to collect adequate signal. CO₂ laser efficiency is controlled by molecular parameters, so electrical power input is unlikely to be reduced. Minor reductions in the size and weight of the laser power supply are possible, but we expect no major changes because the laser systems have been refined for more than 10 years. The much smaller lidars that exist either operate near the visible, where the backscatter coefficient is larger but the possibility of Doppler measurements is very low, or detect only very strong scatterers such as clouds or solid targets. CW CO₂ laser Doppler velocimeters are generally much more compact than NAILS but operate at short range (up to 500 m) with very poor range resolution.

B. HETERODYNE DETECTION

The first stage of NAILS, which uses direct detection, is limited in range by
detector noise. Heterodyne detection, where the signal is mixed with an optical local oscillator, raises the power of the beat frequency sufficiently above detector noise that the noise level in the system is sensitive to Poisson statistics on the photon arrival rate and to speckle noise, which results from the fact that signals from each scattering particle may add in or out of phase. The photon-statistical SNR as defined in Section III A. is the square root of the number of photons detected in any observing period. For a heterodyne lidar, this ratio is often called the carrier-to-noise ratio (CNR) to allow for the contribution of speckle noise on the signal. Based on the SNR calculations for a direct-detection lidar, a heterodyne version of NAILS would have a CNR of approximately 100 per pulse or 300 under the conditions giving an SNR of one for direct detection (an average over 8 pulses). All other things being equal, a heterodyne NAILS would have a range limit approximately 10 times that of a direct-detection system. Keeler et al., (1987) give a more complete discussion of heterodyne SNR.

Speckle noise is independent of range and dominates the SNR of a heterodyne lidar when the CNR is greater than one. It is reduced by averaging over a number of profiles and/or range cells. For a single measurement on an array of scatterers, the standard deviation of the estimate of the backscatter coefficient is equal to the mean, so the speckle SNR is equal to the square root of the number of independent measurements that are averaged. In practice this means that the laser should be operated at the maximum pulse repetition frequency, which means reduced pulse
energy, and that the increase in range and sensitivity from heterodyning comes at a cost of decreased spatial resolution. For example, at a pulse-repetition frequency of 150 Hz, backscatter coefficients for ranges up to 5 km averaged for 1 s would yield a vertical resolution of ±10 m, an SNR of 11 dB, and a horizontal resolution of ±50 m at a flight speed of 100 m/s. Other combinations of resolution and SNR could be chosen.

Conversion of NAILS to heterodyne operation (H-NAILS) requires stabilization of the mode structure and output frequency of the laser. A number of techniques can be used, including injection locking with a CW laser and a hybrid TEA discharge with a low-pressure gain cell in the optical cavity. The laser manufacturer has developed a more stable version of our unit that is comparatively expensive, but the stabilization for heterodyne backscatter estimates does not have to be as good as that for Doppler measurements. In addition to a stable transmitter, heterodyne operation requires a CW local oscillator laser, to mix with the return, and slight changes to the optical layout. Major elements of NAILS, such as telescope, beam expander, polarization coding, and detectors are applicable to H-NAILS.

C. DOPPLER MEASUREMENTS

The Doppler upgrade to the lidar, D-NAILS, allows measurement of the radial velocity component of scatterers, which gives components of the wind (depending on scan geometry) with respect to the aircraft platform. Wind measurements can be made with better spatial resolution along the flight path than can hetero-
dyne backscatter estimates, because fluctuations in the heterodyne signal level affect velocity estimates differently than they affect backscatter coefficient estimates. Spatial resolution along the beam is less for D-NAILS than for NAILS, because the laser pulse must be made longer to achieve sufficient laser frequency stability for adequate velocity accuracy.

Velocity accuracy and range resolution can be exchanged, but a representative estimate for D-NAILS is a range resolution of ±50 m and a velocity accuracy of ±0.5 m/s for conditions with good SNR. The velocity resolution (ability to detect two regions in the spatial resolution cell with different velocities) is approximately ±4 m/s. For special applications that require greater velocity accuracy or resolution but can sacrifice range and/or range resolution, D-NAILS can be operated in a CW mode (e.g., Schwiesow et al., 1981b).

Conversion of H-NAILS to D-NAILS requires further refinement of the transmitter frequency stability, including reduction of frequency chirp during a pulse. Two CW lasers stabilized to a constant difference frequency are required, one to serve as the transmitter reference and one at a different frequency as a local oscillator. Doppler operation requires a major change in the signal processing electronics to extract the Doppler information. A Doppler processor could be installed immediately after the logamp.
REFERENCES


