

Analysis of Flight Test Results of the Optical Ice Detector

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ABSTRACT

Cloud phase discrimination, coupled with measurements of liquid water content (LWC) and ice water content (IWC) as well as the detection and discrimination of supercooled large droplets (SLD), are of primary importance in aviation safety due to several high-profile incidents over the past two decades. The UTC Aerospace Systems Optical Ice Detector (OID) is a prototype laser sensor intended to discriminate cloud phase, to quantify LWC and IWC, and to detect SLD and differentiate SLD conditions from those of Appendix C. Phase discrimination is achieved through depolarization scattering measurements of a circularly polarized laser beam transmitted into the cloud. Optical extinction measurements indicate the liquid and ice water contents, while the differential backscatter from two distinct probe laser wavelengths implies an effective droplet size.

The OID is designed to be flush-mounted with the aircraft skin and to sample the air stream beyond the boundary layer of the aircraft. The volume of the sampled airstream is several orders of magnitude greater than that of traditional airborne cloud probes, such as the Forward Scattering Spectrometer Probe (FSSP). The OID has flown on the University of North Dakota (UND) Cessna Citation-II research aircraft in a wide variety of atmospheric conditions, which cloud probes on the aircraft have verified to corroborate the OID data. In this paper, we compare UND cloud probe measurements with those from the UTC Aerospace Systems OID to demonstrate the possibility of using the OID to meet the need for measurements of various icing parameters.

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INTRODUCTION

Increased awareness of the flight hazards posed by supercooled large droplets and airborne ice crystals has prompted civil aviation authorities to issue new industry standards to cover atmospheric conditions beyond those in 14 CFR 25, Appendix C. The new Appendix O includes freezing drizzle and freezing rain. [1] Numerous cases of engine power loss and even flameouts have been attributed to ice crystal ingestion, focusing additional attention on the need to detect high concentrations of airborne ice crystals. Airframe manufacturers must demonstrate the capability of an aircraft to comply with these new standards. One means of compliance is to sense the presence of hazardous conditions with sufficient rapidity for the crew to take appropriate action, whether that should be activating icing protection systems, increasing engine thrust, or simply exiting the hazardous region. We present the results of recent flight tests of a prototype Optical Ice Detector (OID) intended to meet the need for cognizance of hazardous flight conditions beyond those specified in Appendix C.

Previous flight tests of a prototype OID demonstrated the capability of distinguishing liquid water clouds from ice clouds. [2, 3, 4] Estimates of liquid water content (LWC) were also made with the effective droplet diameter derived from the other traditional particle sizing probes on the test aircraft. For these latest flight tests, the OID uses a two-color differential absorption technique to estimate the

effective droplet diameter of the cloud, obviating the need for data from other cloud droplet-sizing probes. The cloud data in this paper are derived solely from the OID, with those from the other optical probes included only for reference and comparison.

SENSOR DESCRIPTION

The OID is an airborne, micro-pulse polarimetric lidar with a footprint comparable to that of current ice detectors. Unlike traditional optical cloud probes, the OID simultaneously samples *all* of the particles illuminated by the laser beam rather than individual droplets or crystals that pass a few at a time through a thin sample volume. The received light is a composite of the scattering from all particles (both water droplets and ice crystals) illuminated by the laser. Likewise, the polarization state of the received light is a composite of the polarization generated by all of the illuminated particles. Simultaneously sampling a large number of particles ensures that data collected are representative of the entire cloud.

With the use of pulsed near-infrared lasers, the OID is capable of correlating the temporal delay of the received light signal with distance from the sensor. Range resolution allows the exclusion of scattering generated by particles within the boundary layer of the aircraft, where the droplet and crystal distribution is likely to be

dissimilar to that impinging on other parts of the aircraft. This reduces the need for aerodynamic analysis in selecting the optimal location of the detector on the particular airframe.

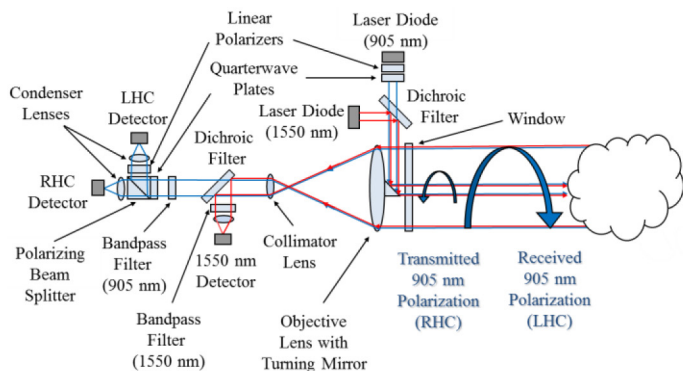


Figure 1. Optical Ice Detector (OID) Schematic. The OID is a short-range, micro-pulse lidar with two overlapping probe laser beams, one at 1550 nm and the other circularly polarized at 905 nm. The 905 nm beam performs cloud phase discrimination. The ratio of the total backscatter at 905 nm to that at 1550 nm correlates with the effective droplet or crystal diameter.

Cloud Sampling Volume

Appendix O regulations include typical cumulative droplet distributions for freezing rain and drizzle, with MVD greater than and less than 40 μm . The largest droplet diameters, which contribute heavily to the LWC and pose the greatest icing hazard, are also the least numerous. It is vital for an optical icing sensor to sample a sufficient volume of space to ensure that these sparse, large droplets are at least illuminated by the probe laser beams.

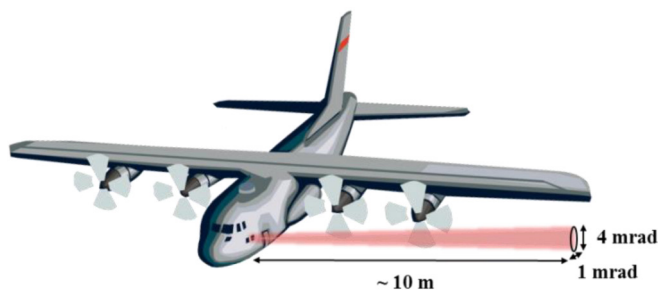


Figure 2. Illumination volume for a single laser pulse from the OID. The typical detection range is 10 m. The forward motion of the aircraft causes the beams to sweep out a volume proportional to the airspeed.

For the OID, two detection volumes must be considered. The first is the volume sampled by a single laser pulse. Each laser beam forms an oblate, conical sampling volume with the short axis of the cone base parallel to the flight vector. The sampling volume extends laterally into the airstream as far as the degradation of the signal-to-noise ratio permits. Depending on the cloud attenuation, the maximum detection range is ten to twenty meters. The beam divergence of the lasers is $\sim 4 \text{ mrad} \times 1 \text{ mrad}$, with a beam waist of 12 mm diameter at the window. Light traverses the distance from the OID to particles at the maximum detectable range and back to the sensor in only 150 ns. Even at 500 knots (250 m/s) airspeed, the forward translation of the aircraft during the elapsed sampling time is less than 0.1 mm. The OID laser acts like a strobe lamp, rendering the sampled air stream

virtually stationary during the sampling period. When the maximum detection range is ten meters, the sampled volume of cloud for a single laser pulse is 4.5 liters.

The other detection volume is the one created by the forward motion of the aircraft. The laser pulse repetition rate is 20 kHz. At 500 knots (250 m/s) airspeed, the aircraft moves 12 mm between consecutive laser pulses, a distance equal to the laser beam waist at the OID window. Contiguous laser pulses generate sampling volumes which almost completely overlap one another, as if the lasers were operating in a continuous-wave mode; the composite volume is the lateral cross-section of the diverging beams multiplied by the distance through which the aircraft motion sweeps the beams through the cloud. The volume is $(300 \cdot v_{\text{aircraft}})$ liters/s, where v_{aircraft} is the forward velocity of the aircraft in m/s.

This is a large sampling volume, even over a short detection time. Optical atmospheric research probes such as the Forward Scattering Spectrometer Probe (FSSP) sample at most 40 to 50 ml/s. [5] Table 1 lists the total number of drizzle droplets larger than 100 μm diameter and rain drops greater than 500 μm that are sampled by the OID both in one laser pulse and in one second. The figures assume an aircraft traveling at 250 knots (125 m/s) through each of the four drizzle/rain conditions outlined in Appendix O, when the LWC is 0.18 g/m³, which is the upper limit LWC for the case of freezing drizzle with MVD > 40 μm at -25°C over 17.4 nautical miles horizontal extent. (The upper limits of LWC for drizzle with MVD < 40 μm and rain all lie above 0.18 g/m³.) Every laser pulse illuminates at least one large droplet that is characteristic of drizzle or rain. The influence of these large droplets on the composite lidar signal generated by the entire distribution is considered later in this paper. However, their presence in the thousands to more than one million during one second of sampling suggests the efficacy of the OID for sensing icing conditions beyond those of Appendix C.

Table 1. Sampled large droplet counts for Appendix O freezing drizzle and freezing rain droplet size distributions (with MVD < 40 μm and MVD > 40 μm). The upper figure is for a single laser pulse, while the lower is for one second of signal integration. The aircraft speed is 125 m/s, and the liquid water content is 0.18 g/m³.

	Freezing Drizzle (MVD < 40 μm)	Freezing Drizzle (MVD > 40 μm)	Freezing Rain (MVD < 40 μm)	Freezing Rain (MVD > 40 μm)
$\sum_{d=100\mu\text{m}}^{D_{\text{max}}} N(d)$	72	162	Single laser pulse	
	6.0×10^5	1.3×10^6	One second integration	
$\sum_{d=500\mu\text{m}}^{D_{\text{max}}} N(d)$	Single laser pulse		1	2
	One second integration		8.0×10^3	1.7×10^4

Detection Modes

With the introduction of a second laser wavelength, the Optical Ice Detector combines into one sensor three cloud lidar detection methods used by researchers for both Earthbound and airborne

instruments. The methods are: cloud optical extinction and backscatter measurements, differential absorption lidar for the determination of LWC and SLD conditions, and circular polarimetry for cloud phase discrimination. These three techniques provide complementary data that together form a more complete description of the icing conditions than would be possible with only a single measurement mode.

Extinction and Backscatter Lidar

Like other cloud lidars, the Optical Ice Detector directly measures the optical extinction and backscatter of the cloud that it probes. The cloud particles create a single composite echo $P(r)$, where r is the distance that the leading edge of the laser pulse has penetrated into the cloud. (The range r is proportional to the elapsed time T after the emission of the laser pulse from the OID.)

$$P(r) = \beta G(r) e^{-2\alpha r} \quad (1)$$

β is the backscatter coefficient (in units of $\text{m}^{-1} \text{ster}^{-1}$), and α is the extinction coefficient (in units of m^{-1}). It is assumed that the cloud is homogenous over the short working range of the OID so that α and β are constants. The function $G(r)$ is a light collection efficiency function that depends on the intensity, divergence, and temporal shape of the laser pulses, as well as the configuration and efficiency of the receiver optics. This function is determined empirically by measuring the laser echoes from a hard target of known reflectance placed at various distances from the OID over its entire working range.

A simple inversion of the lidar signal $P(r)$ yields the backscatter and extinction. When the range-resolved echo intensity is normalized by $G(r)$ and plotted against r on a semi-log plot, the slope is -2α and the y-intercept is $\ln(\beta)$.

$$\ln\left(\frac{P(r)}{G(r)}\right) = \ln(\beta) - 2\alpha r \quad (2)$$

Both α and β depend on the density of water droplets and ice crystals as well as their size distributions. The ratio of α to β (known as the *lidar ratio*) is an indication of the typical droplet or crystal size. Clouds with small droplet sizes generate lidar ratios ~ 19 sr; smaller droplet sizes are associated with larger lidar ratios, and vice versa.

Calculation of LWC requires an additional parameter, the effective droplet diameter D_{eff} :

$$D_{eff} = \frac{\langle D^3 \rangle}{\langle D^2 \rangle}, \quad (3)$$

which is the ratio of the third moment of the droplet diameter distribution to its second moment. The liquid water content is then

$$LWC = \frac{1}{3} \rho \alpha D_{eff}, \quad (4)$$

where ρ is the density of water.

The correlation of lidar ratio with droplet size can provide an estimate of the effective droplet diameter. [6] However, measuring the backscatter β requires calibration of the OID response to a cloud of known backscatter. This can be difficult to perform in the lab. (The OID is not sensitive enough to measure molecular scattering that is commonly used to calibrate cloud lidar.) Furthermore, if the flush-mounted window of the OID becomes soiled or crazed during operation, the calibration is compromised. The calculation of α requires only knowledge of the rate at which the signal is sampled and a measurement of the relative signal decay over time. The sampling rate is easily controlled and maintained, and the decay rate is independent of changes in the transmission of the window. As much as possible, the OID relies on relative measurements to avoid sensor calibrations that are difficult to perform and to maintain over the life of the sensor.

Two-Color Lidar

An alternative method of measuring an effective droplet diameter is to incorporate an additional wavelength, or “color”, into the Optical Ice Detector. This differential absorptive two-color technique is described by Westbrook *et al.* [7] for the estimation of drizzle droplet sizes from a ground level cloud lidar. Two beams of laser light, each with a distinct near-infrared wavelength, probe the cloud. The wavelength of one beam is 905 nm, for which there is little absorption of the light by either water droplets or ice crystals. The wavelength of the additional laser beam is 1550 nm, which lies near a peak in the absorption spectra of water and ice. For droplets with diameters greater than ~ 20 μm , the scattering efficiency is virtually identical at both wavelengths, but the backscatter is lower at the absorbing wavelength than at the non-absorbing wavelength. The log of the ratio of the backscatter at 905 nm to that at 1550 nm is defined as the two-color ratio (TCR):

$$TCR = 10 \cdot \log_{10} \left(\frac{\beta_{905}}{\beta_{1550}} \right). \quad (5)$$

Like the determination of the extinction coefficient, the two-color ratio is a relative measurement. Provided that the output of each laser is monitored and the sensitivity of each photodetector is maintained, only the relative magnitudes of β are necessary. No absolute calibration of the OID sensor with regard to β is required.

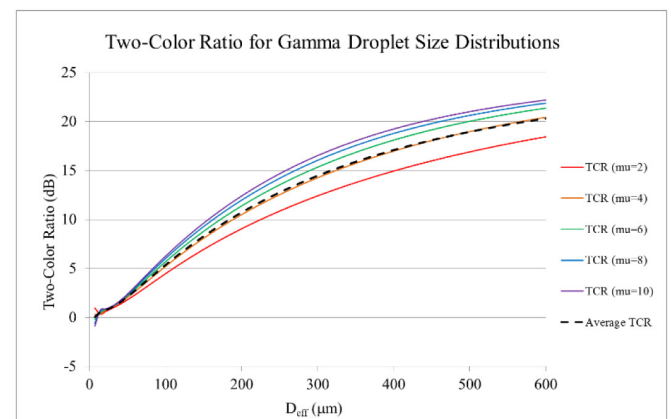


Figure 3. Two-color ratio as a function of effective droplet diameter D_{eff} for gamma droplet size distributions with various shape parameters μ . The dashed line is an average of the curves with $\mu = 2$ and $\mu = 10$. The lowest effective droplet diameter plotted is 4 μm .