Rapid optical method for logging dust concentration versus depth in glacial ice

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We describe the design and simulated response of a dust logger consisting of a downward-pointing phototube, ~2 m below side-directed light-emitting diodes (LEDs), attached to a cable that can lower the device down a 3-in. (7.5-cm) borehole filled with butyl acetate. LED photons that enter the ice are scattered or absorbed by dust grains, and those that reach the phototube provide a measure of dust or volcanic ash concentration at a given depth. An increased dust concentration associated with an ancient colder climate will usually result in an increase in collected light, but may decrease collected light if air bubbles are present. Centimeter-thick volcanic ash bands can also be detected. The concept is based on six years of experience with pulsed light sources used to measure optical properties of deep Antarctic ice. © 2001 Optical Society of America

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1. Introduction

The dust logger described in this paper exploits some features of two modern optical techniques—the ocean transmissometer1 and the Antarctic muon and neutrino detecting array (AMANDA) collaboration’s method for mapping optical properties of deep glacial ice.2–5

To study depth dependence of the mass concentration of particles (usually mainly microorganisms) in the ocean, oceanographers use a transmissometer, consisting of a 660-nm light-emitting diode (LED) viewed by a detector with an acceptance of ~1 deg at a distance of 25 cm on the axis of a cylinder through which water can freely flow. The transmission is corrected to standard conditions when salinity, temperature, and density are recorded simultaneously. The contribution of yellowish dissolved organic matter is negligible at a wavelength of 660 nm. Beam attenuation that is due to pure seawater is taken to be constant and is calibrated at the factory. Thus the concentration of small particles, mostly microbial, is determined by subtraction of the contribution of pure seawater to the attenuation by particles.6

The AMANDA collaboration recently completed a large observatory, buried in deep glacial ice, for tracking high-energy neutrinos from astronomical sources.7,8 They used an optical method to determine at what depths the ice near the South Pole is sufficiently transparent to enable them to use the Cherenkov light from charged particles to determine the direction of the particles. Using a hot-water drilling technique, they melted cylindrical holes down to depths of ~2000 m in which were submerged strings of photomultiplier tubes (PMTs) and pulsed light sources, around which the water was allowed to refreeze. The PMTs served both to measure ice clarity as a function of depth and to record arrival times of Cherenkov light from relativistic charged particles. The light sources consisted of nitrogen lasers (337 nm) and LEDs (370 and 470 nm) at various depths in the ice and of light pulses transmitted from the surface down optical fibers to diffuser balls at various depths. Distances in solid ice between emitters and receivers were 10–120 m. From analyses of the distribution of arrival times of photons traveling between the emitters and the receivers, they were able to determine the wavelength dependence and depth dependence of both the scattering coefficient and the absorption coefficient for light as a function of depth in ice.

The AMANDA collaboration found that air bubbles dominated the light scattering at shallow depths, but that this contribution decreased with depth because of compression of the bubbles and because of their transformation into nearly invisible air–hydrate crystals. At ~1400 m the transformation was com-
Below 1400 m the propagation of light was constrained only by the presence of dust particles deposited onto the snow by aerosols and later compacted into ice. The dust concentration inferred from the timing distributions and from application of Mie theory varied with the depth of the ice. Between 1400 and 2200 m near the South Pole the depth dependence matched the pattern measured in the Vostok ice core at depths from ~400 to ~930 m when properly scaled for differences in snow accumulation rate. The scaling was used to calibrate the age versus the depth at the South Pole by use of the age versus the depth that had been determined by chemical and physical studies of the dust as a function of depth in the Vostok core.

In this paper we show that AMANDA’s optical method of measuring dust concentration in glacial ice can be adapted to fit into a vertical cylinder slender enough to be lowered into a 3-in. (7.5-cm) access hole filled with butyl acetate, a standard drilling fluid. From simulations of the response of this device, we conclude that one can rapidly read out the dust concentration at depths down to bedrock, measure scattering by air bubbles, measure dust in the presence of air bubbles, and detect volcanic ash layers with a typical thickness of ~1 cm. Advantages of this dust logger include speed, economy, and the ability to measure both insoluble and soluble dust in situ at ambient pressure. In contrast to the ocean transmissometer, which measures a sample of ocean water that passes inside the instrument, our dust logger samples the optical properties of a large volume of ice several meters in radius, which avoids contamination that might be introduced into the hole during drilling.

2. Motivation for Dust Logging

Dust serves as a proxy for climate: It correlates well with δ18O in glacial ice and in planktonic foraminifera in sea sediments reflects the amount of the Earth’s water frozen in ice. It is thus a measure of long-term variations of Earth’s temperature and of great interest to paleoclimatologists. In sea sediments the δ18O has traced a rough sawtooth curve with a periodicity of close to 100,000 years for eight cycles, showing that major ice ages recur every 100,000 years. For still earlier times the periodicity was approximately 41,000 years. In both cases the periodicity is sufficiently precise that it must be controlled by astronomical phenomena. Some researchers believe in Milankovitch’s explanation of the 105-year cycle in terms of changes in the eccentricity of the Earth’s orbit, whereas others argue that the gradual change in the Earth’s orbital inclination, which also has a period of 100,000 years, somehow causes the major ice ages. The cause of the rather abrupt change from 41,000 to 100,000 years is unknown and is a subject of interest and speculation.

The paleoclimatic record in ice cores is not as extensive as in sea sediments. The analysis of the dust and δ18O in the oldest known ice core—at Vostok Station—shows that the deepest ice, at ~3500 m, has an age of ~420,000 years and that four cycles of ice ages are preserved, in accordance with the corresponding record in sea sediments. To make further progress in understanding the causes of ice ages, it would be highly desirable to have a portable dust logger that could search for major peaks in dust concentration as a function of depth in regions of Antarctica suspected of having ice much older than 420,000 years at its base.

A second motivation for a dust logger is in glaciology, especially in the study of the flow of cold ice. For a complete understanding of how ice flows, one needs to measure not only the stress and strain as a function of depth and position for ice flowing down an incline, but at the same time to determine the temperature, crystal fabric, chemical composition of impurities, and dust distribution in the same ice whose flow is being studied.

A third motivation is in volcanology and the possible role of volcanic ash in triggering worldwide cooling.

3. Design of a Compact Dust Logger

Figure 1 shows the design of a logger whose performance we simulated. A high-speed mechanical access drill would be used to drill a 3-in.
diameter hole, to be filled with butyl acetate drilling fluid, extending from the surface down to bedrock. After removal of the drill, the logger would be lowered on a cable kept taut by means of a weight, and readings would be taken either continuously or at predetermined depth increments. The cable (a standard four-connector logging cable) would provide power for the LEDs and for a 1-in. (2.54-cm) downward-facing PMT and would return signals from the PMT to the surface.

We carried out simulations for LEDs (Nichia Corporation) with peak emission at 370 ± 10 nm; LEDs that emit at 470 nm would work just as well. (The absorption coefficient measured in situ in the highly pure South Pole ice is less than 10⁻² m⁻¹ at both wavelengths.) An isotropic distribution of emitted photons was tracked from the light source into ice containing dust, bubbles, and volcanic ash, within which a small fraction of the photons scattered enough to impinge in an upward direction on a thin cylindrical disk of ice representing the PMT window. PMT and other electronic efficiencies were not simulated because we only wanted to find out relative changes in the PMT signal as a function of dust or bubble concentration in a local region of the ice. The effective scattering coefficient b_e and the absorption coefficient a were recalculated each time a photon passed into an ice layer (assumed to be horizontal) with a different dust or bubble concentration. To speed up the simulation, instead of a photon being absorbed, it was given a weight from 0 to 1, depending on the path traveled and the type of ice traversed. At the detection volume, these weights were summed up as a probability of a given photon reaching that location in an upward direction. Because of the cylindrical symmetry of the problem, we summed over all azimuth directions for photon emission and detection. Results were compared for photons emitted in three equal solid-angle bins, from 60° to 90° (relative to upward direction), from 90° to 120°, and from 120° to 180°, simulating different LED emission configurations.

Because of the similarity of refractive index of butyl acetate (n = 1.390) to that of ice (n = 1.322), we ignored refraction at the wall of the hole and treated butyl acetate as being equivalent to ice. Owing to the small volume of butyl acetate relative to the volume of ice sampled by each photon, the resulting error is small. Measurements with a laboratory spectrophotometer showed that butyl acetate is quite transparent to light throughout the visible and UV down to a wavelength of approximately 260 nm.

The 1–3-m spacing between the emitters and the detectors and the downward orientation of the PMT were chosen to prevent photons from scattering from the wall of the hole or from the drill fluid and from entering the PMT without sampling the bulk ice.

4. Dust Modeling

Based on measurements by the AMANDA collaboration, an optical model of high-purity glacial ice containing traces of dust was developed. Absorption is treated by a three-component model³ that combines laboratory measurements of absorption of infrared and UV light with in situ measurements in South Pole glacial ice in the 310–650-nm range. At wavelengths λ < 210 nm and λ > 500 nm, absorption is dominated by the properties of ice itself, whereas in the intermediate range absorption is dominated by impurities. A simple but accurate expression of the dependence of absorption on wavelength is given by

$$a(\lambda) = A \exp(-0.48175\lambda) + B \exp(-6700/\lambda) + C M_{dust}^{-\kappa},$$

(1)

where λ is in nanometers and M_dust is the experimentally determined mass concentration of impurities contributing to light absorption. The first exponential term is the Urbach tail, which dominates at λ < 210 nm; the second exponential describes the rise of absorption in the red and infrared; and the third term, proportional to dust concentration, dominates in the range 210 < λ < 500 nm. The values M_dust and k are determined from fits to AMANDA data in South Pole ice. The best-fit proportionality constants are given by³ A = 8 × 10⁻⁸ and B = 8100, whereas C is absorbed into M_dust during fitting of experimental data. The best fit² to the exponent k yields 1.1. Because it is difficult to make an accurate measurement of the angular distribution of scattered light in the deep glacial ice, the AMANDA collaboration used the approximation in which the effective scattering coefficient b_e is given by b_e(λ) = b_e(λ)[1 - g(λ)], where b_e(λ) is the depth-dependent mean coefficient for geometric scattering, g(λ) = (cos θ), and θ is the scattering angle. The value (cos θ) = 0.8 ± 0.1 was found to be a good estimate for all ice depths.²

The best-studied wavelength in the AMANDA data set is 532 nm (green light of frequency-doubled YAG laser) and is our reference point. From the relation²

$$b_e(\lambda) = (\lambda/532)^{-\alpha} b_e(532),$$

(2)

we can calculate b_e for any given wavelength. By use of the Mie-scattering theory, with concentrations of four dust components (mineral dust, acid droplets, salt grains, and soot) determined from measurements in ice cores and with size distributions taken from Table 4.2 of Ref. 20, α is calculated to be 0.84 for the deep South Pole ice (1.4–2.3 km).² Finally, C M_dust is an empirically determined value related to the impurity concentration and can be well approximated by C M_dust = 158 b_e(532) − 0.634.¹⁸ In our simulations, we used b_e(532) = 0.026 m⁻¹ as a baseline, which corresponds to the cleanest South Pole ice found at depths below 2.1 km.

The model described here applies to dust in South Pole ice at all depths. However, because the dust composition in glacial ice at other locations (e.g., near the coast or near volcanic regions) may be somewhat different, we simulated the response of the dust logger to ice containing dust with a wide range of values of the ratio of effective scattering to absorption at 370...
nm, $D = b_4(370)/a(370)$. For deep South Pole ice, our model yields $D = 5.87$.

5. Results of Simulations

A. Dust Bands without Air Bubbles

Inside a disklike band of enhanced dust concentration, the simulated PMT signal as a function of time in response to a pulse of light from the LEDs showed a rapid rise to a peak value, typically occurring at a time $\sim 5$ ns after a hypothetical direct trajectory, followed by an approximately exponential decrease in time. The peak value of returned light, the integrated value for 1–22.5 ns, the integrated value for 1–50 ns, and the integrated value for 1–100 ns track the shape of the excess dust in the band, and all of them scale faster than linearly with dust concentration.

Figures 2–4 show examples of dust logger response characteristics and spatial resolution in bubble-free ice for various vertical profiles, with dust concentration rising to a maximum of a factor of 6 above background. The factor of 6 increase is conservative in that dust concentration increases as much as a factor of 30 above background at glacial maxima, for example, from the Holocene to the Last Glacial Maximum.\textsuperscript{21} In Fig. 2 the thick solid curve shows a triangular dust profile, with the background value normalized to unity. The three broken curves show the simulated PMT response integrated for 22.5, 50, and 100 ns for photons emitted at 60–90° zenith angles. For each of the three integration times the signal sharply tracks the dust concentration, with a depth resolution of $\sim 1$ m. The ratio of response in and out of the dusty region is 7.5 times as high as the ratio of dust concentration for an integration time of 22.5 ns and five times as high for 50- and 100-ns integration times.

With the integration time fixed at 50 ns, Fig. 3 compares the responses to a 4-m-deep region of enhanced dust concentration as a function of zenith angle of emission of the LEDs. For downward-directed light (open squares), the pattern of detected signal peaks $\sim 3$ m above the dust layer. For light emitted at 60–90° (crosses), the signal peaks $\sim 1$ m...
above the dust layer. The full width at half-maximum for the response of the logger is of the order of the thickness of the dust band.

Figure 4 shows that the logger easily resolves two 2-m-thick dust bands with a vertical separation of 10 m. Shortening the LED to PMT separation improves the ability to separate the two dust bands.

In their optical study of dust at depths of 1200–2300 m in South Pole ice, the AMANDA collaboration detected bands of enhanced dust concentration typically at least 100 m thick and a factor of 2–4 above minimum dust levels. Our simulations show that, because of its compact size, our dust logger should be able to detect a factor of 2 increase in dust concentration in a band only a few meters thick.

Figure 5 shows the effect of variations in the optical properties of dusty ice from \( D = 0.1 \) (strongly absorbing, e.g., hematite) to 10 (highly transparent, e.g., quartz). For \( D = 0.1 \) the presence of dust leads to a strong decrease in signal; for \( D = 10 \) the dust is transparent and much more strongly scattering than the pure ice, and thus leads to a strong increase in signal. (Instead of a single-scattering albedo, we used \( a \) and \( b_{\text{a}} \), which provide more physical insight when representing multiple scattering of light through dusty ice.)

**B. Detectability of Dust Bands in Regions of High Bubble Concentration**

At a site where the accumulation rate is large, the record of the Holocene (the warm period from the present back to the end of the last ice age, \( \sim 17,000 \) years ago) extends well below 1000 m, and the record of the Last Glacial Maximum (\( \sim 22,000 \) years ago) peaks at a still greater depth, where all bubbles have undergone a phase transformation into solid air-hydrate crystals. However, at a site such as Vostok or Dome C, the snow accumulation rate is so low that the Last Glacial Maximum record is at a depth of only a few hundred meters. At such a shallow depth, air bubbles contribute far more to light scattering than does dust, but they contribute nothing to absorption. We now show that the dust logger can detect increases in dust concentration even at depths where bubbles dominate light scattering. In regions of strong scattering, a photon undergoes a random walk from the emitter to the receiver, and an analytic approximation is valid:

\[
\begin{align*}
    u(d, t) &= \left[3b_{\text{a}}(z)/4\pi v_g t\right]^{3/2} \exp[-3d^2b_{\text{a}}(z)/4v_gt] \\
    &\quad - a(z)v_g t, \tag{3}
\end{align*}
\]

Here \( u(d, t) \) is the density of photons at a distance \( d \) from the source at time \( t \) (normalized to unity at \( t = 0)\); \( b_{\text{a}} = b_{\text{bub}} + b_{\text{dust}} \) is the sum of scattering coefficients for bubbles and dust; \( v_g = c/1.322 \) is the group velocity of 370-nm photons in ice; \( d \) is the distance from the emitter to the receiver; and \( a(z) \) is the absorption coefficient of light (with dust but not bubbles contributing) at depth \( z \). Equation (3), which is valid in the limit of many scatters (\( d \gg b_{\text{a}}^{-1} \)), is much quicker to evaluate than running numerical simulations. The effective scattering coefficient for bubbles is given by

\[
b_{\text{bub}} = (1 - (\cos \theta))n_{\text{bub}} \pi r_{\text{bub}}^2, \tag{4}
\]

where the first factor, with \( (\cos \theta) \approx 0.8 \), takes into account the forward peaking in the scattering. For typical bubble concentrations and radii at depths of a few hundred meters (\( n_{\text{bub}} \approx 500 \text{ cm}^{-3} \) and \( r_{\text{bub}} \approx 100 \mu\text{m} \), \( b_{\text{bub}} \approx 3 \text{ m}^{-1} \). For an \( \sim 2\text{-}m \) dust logger, the inequality \( d \gg b_{\text{a}}^{-1} \) is thus satisfied, even though \( b_{\text{dust}} \ll b_{\text{bub}} \).

Figure 6 shows the results of an application of Eq. (3) to air bubbles plus dust at a site with a low accumulation rate. For \( b_{\text{bub}} \) we used Eq. (4) with \( n_{\text{bub}} \) and \( r_{\text{bub}} \) taken from microscopic measurements of Vostok ice core samples, with values shown as solid circles. For \( b_{\text{dust}} \) representative of a warm period we chose a constant value of 0.025 m\(^{-1}\), and for dust representative of a cold period we chose a trapezoidal shape, ramping up linearly at depths from 300 to 400 m to a plateau value of 0.325 m\(^{-1}\) and decreasing back to 0.025 m\(^{-1}\) at depths from 475 to 500 m. The values used in our calculations are shown as solid triangles. To illustrate the effect of the presence of bubbles on the dust signal, it does not matter that we ignored the subpeaks and valleys in the measured dust concentration in a cold period.

The solid curves show the calculated signals in the dust logger for a 250-ns integration time for three different dust types (\( D = 1, 4, \) and 8). Note that, by virtue of their large scattering coefficient, the bubbles cause an amplified negative image of the dust band. In the absence of dust (dashed curve), the signal that is due to the bubbles would track the decline of \( b_{\text{bub}} \) with depth; in the absence of bubbles, the signal that

Fig. 5. Responses to dust bands with values of \( D (=b_{\text{a}}/a) \) from 0.1 (highly absorbing) to 10 (highly scattering) in 20 m of bubble-free ice. Note the semilogarithmic scale.

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is due to the dust would increase, tracking the trapezoidal dust concentration (see Figs. 2–4 for triangular and square-wave patterns). When both bubbles and dust are present, the bubbles confine most of the photons to the dusty region until they are absorbed, thus leading to the negative image of the dust (solid curves).

C. Volcanic Ash

We modeled a volcanic ash band 1 cm thick and with a concentration and size distribution of ash chosen to mimic a typical ash band reported by Gow and Williamson.\(^{15}\) \(D\) was taken to be 5.87, the same as that of the dust modeled in Figs. 2–4. The increased signal that is due to the ash band was easily detectable. Although the resolution in depth would depend on the logging speed and details of the electronics, a resolution of \(\sim 1\) m would appear feasible. If the ash consisted of dark, highly absorbing grains, the amount of light reaching the phototube would decrease instead of increase (as could be concluded from Fig. 5), thus providing a crude measure of composition.

D. Volume of Ice Sampled

One way of seeing the effect of bubbles is to compare the radius of the volume of ice outside the hole that is sampled when bubbles are absent or present. To estimate volume, we used Eq. (3). For integration times of 22.5, 50, and 100 ns, 90% of the photons scattered back into the PMT from bubble-free ice \((b_{\text{dust}} = 0.035\ \text{m}^{-1})\) come from radial distances as far out as 3.5, 4.7, and 6.3 m, respectively, compared with much smaller radial distances for bubbly ice with \(b_{\text{bub}} = 2.5\ \text{m}^{-1}:\) 0.41, 0.55, and 0.74 m, respectively.

In each case the presence of bubbles reduces the volume sampled by a factor of approximately 600.

6. Conclusions

The principle on which the dust logger is based has been demonstrated thoroughly by the AMANDA collaboration, who used pulsed light emitters and phototube receivers separated by distances from 10 to 120 m to map the vertical distribution of bubbles and dust. The same simulation techniques and diffusion equation used by AMANDA apply to our logger, which we plan to test in a 1-km-deep butyl-filled hole at Siple Dome, Antarctica.

The logger can detect both thin and thick dust bands in bubble-free ice. For dust with the ratio \(b_d/a \geq 0.5,\) typical of most glacial ice, the PMT signal in the dust band is greater than background; for a hypothetical dust band with \(b_d/a < 0.25,\) the signal is depressed below background. The logger can also locate regions of large dust concentration even in the presence of a strongly scattering bubble concentration, but as a negative image, i.e., a decrease in signal superimposed on a high-background signal that is due to bubbles alone. Volcanic ash bands \(\sim 1\) cm thick can be detected, with a depth resolution of the order of \(1\) m.

Because the refractive indices of the ice and of the butyl acetate are similar, the results are insensitive to the scale of roughness of the hole. The logger is economical to build, and readout is continuous and straightforward. It has several other advantages over methods such as laser light scattering and microscopic or chemical analysis, which require that thousands of sections of a several-kilometer-long core be removed from the ice and transported to an ice-core laboratory for analysis: it can quickly read out data for \textit{in situ} ice at ambient pressure; it provides a continuous record, unaffected by possible fracture and loss of portions of a core; and it averages over a volume several meters in radius in the ice surrounding the hole, rather than a volume of a few centimeters in radius inside the hole.

In the absence of bubbles, dust concentrations typical for glacial maxima produce large signals, narrow dust bands only a few meters apart can clearly be resolved, and the signal tracks both triangular and square-wave dust distributions to within \(\sim 1\) m.

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References

1. For example, see WET Labs transmissometer at http://www.wetlabs.com/Products/index.html.


