Double-Edge Molecular Measurement of Lidar Wind Profiles at 355 nm

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ABSTRACT

We built a direct detection Doppler lidar based on the double-edge molecular technique and made the first molecular based wind measurements using the eyesafe 355 nm wavelenth. Three etalon bandpasses are obtained with step etalons on a single pair of etalon plates. Long-term frequency drift of the laser and the capacitively stabilized etalon is removed by locking the etalon to the laser frequency. We use a low angle design to avoid polarization effects. Wind measurements of 1 to 2 m/s accuracy are obtained to 10 km altitude with 5 mJ of laser energy, a 750s integration, and a 25 cm telescope. Good agreement is obtained between the lidar and rawinsonde measurements.

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Wind is one of the basic atmospheric state variables. It has long been recognized that global tropospheric wind measurements are required for understanding and predicting weather and climate on all time scales[1]. Despite its importance, there is no current global capability for measuring winds over the troposphere. We built a molecular based double edge system[2] at 355 nm as a follow on to our work on single edge aerosol systems[3,4]. The double edge system is compact, uses the eyesafe 355 nm wavelength, and is designed as a spaceborne representative system. The NASA Zephyr Shuttle based program selected to fly this system. We made the current atmospheric wind measurements in March 1998 to provide an experimental demonstration of the feasibility of the technique for the Zephyr program.

Direct detection lidar techniques can use use either aerosol[3-8] or molecular[2,3,9-11] backscatter for measuring the atmospheric wind field. Aerosol-based wind measurements can use high spectral resolution since the aerosol backscattered spectrum is narrow with respect to the laser width and as a result has the same spectral width as the outgoing laser. Thus, they offer the possibility of high sensitivity measurements in areas of high aerosol backscatter. However, large regions of the Southern hemisphere as well as mid-oceanic regions have low aerosol concentrations in the free troposphere. As a result, current aerosol systems can only provide a partial measurement capability. On the other hand, the molecular backscattered spectrum is broad which limits the sensitivity of the measurements. However, molecular scattering provides a dependable and reasonably uniform source of scattering on a global basis. This is particularly important for satellite-based wind measurements.

We utilize a double edge lidar technique for measuring the wind using the molecular signal backscattered from the atmosphere as shown in Figure 1. The molecular signal is spectrally broadened by Doppler shifts due to the random thermal motion of molecules and by Brillouin scattering[1,2]. The method is similar to the single edge molecular method for determining the wind[3]. With the single edge we measure the Doppler shift of this Rayleigh-Brillouin (R-B) spectrum by locating it on a moderately sharp edge of a high spectral resolution filter. Relatively large changes in signal are observed for small frequency shifts due to the steep slope of the edge. A small portion of the outgoing beam is sampled to determine the frequency of the outgoing laser signal by measuring its location on the edge of the filter. Likewise, the frequency of the laser energy backscattered from the atmosphere is measured for each range element. The Doppler shift, and thus the wind, is determined from a differential measurement of the frequency of the outgoing laser pulse and the frequency of the laser return backscattered from the atmosphere. This makes the measurement insensitive to laser and filter frequency jitter and drift. A detailed description of the theory for the single edge method is given in Ref. (3).

We recently described double-edge lidar techniques for measuring the wind using the signal backscattered from either molecules[2] or aerosols[8] in the atmosphere. With these techniques, we use a second edge measurement for signal normalization instead of an energy monitor measurement as is used in the single edge method. This doubles the signal change per unit Doppler shift, the sensitivity of the measurement, and leads to almost a factor of two improvement in the measurement accuracy.

The edge filter measurement generally depends upon the magnitude of the atmospheric backscattered molecular, R-B, and aerosol signals. Thus, in general the molecular and aerosol signals have to be spectrally separated, measured separately and treated independently in the analysis. We can, however, greatly simplify the measurement by locating the edge filter measurement in a crossover region where the fractional change in the measured molecular and aerosol signals are equal for a given frequency shift. That is[2],

$$\frac{1}{R_i(\nu_i,\nu_l)}\frac{d}{d\nu}R_i(\nu_i,\nu_l) = \frac{1}{T_i(\nu_l-\nu_i)}\frac{d}{d\nu}T_i(\nu_l-\nu_i) \tag{1}$$

for each edge filter where

$$R_i(\nu_i,\nu_l+\Delta\nu) = \int_{-\infty}^{\infty} T_i(\nu-\nu_i)I_R(\nu-\nu_l-\Delta\nu)d\nu \tag{2}$$

In the above equations T_i is the transmission of the ith edge filter for the laser, I_R is the backscattered Rayleigh-Brillouin spectrum, ν_l is the laser frequency, and $\Delta\nu$ is the Doppler shift. Thus, the measurement sensitivities are equal for the molecular and aerosol portions of the signal. In this case, the aerosol signal acts in an identical manner to the molecular signal and the measurement is desensitized to the effects of aerosol scattering[2].

The detector package layout is shown in Figure 2. A single longitudinal mode Nd:Yag laser is frequency tripled to provide the required 355 nm output. The laser energy is 80 mJ per pulse at 355 nm with a 30Hz repetition rate. The laser has an angular output of 0.5 mrad. A small portion of the outgoing laser signal is picked off, sent to the telescope and from there travels through the optical system to the etalon to allow the outgoing laser frequency to be measured as described below.

The major portion of the laser energy is sent to the atmosphere. A portion of this energy is backscattered from each range element of the atmosphere. The signal is collected by a 25 cm diameter telescope. It is focused into a multimode fiber optic cable which sets the field of view of the telescope at 0.125 mrad. The signal from the fiber is collimated and directed into the Fabry-Perot etalon which serves as the double-edge filter. The laser energy of 80 mJ per pulse is too large for tropospheric measurements even for our relatively small 25 cm diameter telescope. As a result, we utilize the mismatch between the 0.125 mrad field of view of the telescope and the 0.5 mrad divergence of the laser to reduce the laser energy to 5 mJ/pulse. We note that even for this reduced laser energy, saturation effects still occur for altitudes less than 2km.

The high resolution etalon is capacitively stabilized. It is composed of three bandpasses. One bandpass uses a circular region on the two basic etalon plates while the two other bandpasses use coatings with a thickness of a fraction of $\lambda/2$ on circular regions of one plate. These cotaings form step etalons which shift the frequency of the basic bandpass by a fraction of a free spectral range. Two of these bandpasses are used as the double edge etalons for the atmospheric measurement as shown in Figure 1. The third bandpass is used as a locking etalon. It is located with one half-width point, HWHM, centered between the two edge etalons. We use a servo control system to lock the half-width point of the locking etalon to the pulsed Nd:YAG laser frequency to remove laser and etalon frequency drift. The outgoing laser wavelength can then be measured with high precision since the half width is the point of maximum sensitivity. A low angle design with a 5° incidence angle is used for splitting the signal between the two edge channels, the locking channel, and the energy monitor channel to eliminate polarization effects. The etalons have a spectral bandwidth of 1.55 GHz, full width at half maximum.

The double edge etalons are located about the laser frequency with a separation of ±2.60 GHz. This corresponds to the crossover point where the sensitivity, the percent change in signal per m/s, is the same for the molecular and aerosol signals. These parameters also allow us to obtain the minimum measurement error while simultaneously achieving aerosol desensitization[2].

High speed phtomultiplier detectors with a quantum efficiency of 28% are used in a photon counting mode for both the edge and energy monitor detectors. The photon counting signals are collected in a multichannel scalar and integrated over a variable number of shots. We typically used integration times of 10s which corresponds to 300 shots at 30Hz. The system records the signal for each of the two atmospheric edge etalon channels averaged over n shots as a function of altitude. To measure the wind speed profile along the line of sight in a given direction, we perform one measurement in the chosen direction and another along the vertical as a calibration. We first subtract the background for each measurement. We then calculate the ratio between the detected photons in each edge channel for a given altitude. The wind profile is found as

$$V = \frac{1}{\theta}\left(\frac{R - R_\upsilon}{R_\upsilon}\right)$$

where R and R_υ represent the ratio of the two edges for each altitude in the chosen or vertical direction, respectively, and θ is the sensitivity of the system calculated theoretically[2], $\theta = 0.0072$. We find the standard deviation for each altitude using measurements over several data sets at each altitude.

Figures 3a and 3b show a comparison of our lidar wind profile measurements made at the University of Geneva at 11.00 PM on 3/27/98 and at 7:00 PM on 3/29/98, respectively, with rawinsonde profile wind measurements made by the Swiss Meteorological Service at Payerne, Switzerland at a distance of 50 km. In Figure 3, the rawindsonde wind profiles are projected onto the line of sight of the lidar measurements. We made the lidar measurements at an azimuth angle of 53.7° and at zenith angles of 30° and 0°. We did not make measurements in a second orthogonal direction since there were nearby buildings. For Figure 3a(3b), the standard deviation was calculated using an average over 750 (320)s, 225000 (10000) shots, with an effective laser energy of 5 mJ per shot. This is equivalent to an average over 47 (20)s and 1400 (624) shots with the full laser energy of 80 mJ per shot. The standard deviation of the lidar measurement is shown by the horizontal bar at each altitude and varies from 1 to 2 m/s in Fig. 3a. As shown, the lidar wind measurements are in good agreement with the rawinsonde data.

We built a direct detection Doppler lidar based on the double-edge molecular technique and made what we believe are the first molecular based wind measurements using the eyesafe 355 nm wavelength. The differential frequency method and the use of a locking channel produce a feasible robust system. Wind measurements are obtained to greater than 10 km altitude with a small system using 5 mJ of laser energy. We recently successfully participated in a field campaign using a portable version of this system and will report on this shortly.

Figure Captions

Figure 1: Double edge measurement of Doppler shifts $\Delta\nu$ of the R-B profile with the laser at frequency ν_l and the two edge filters at frequencies ν_1 and ν_2.

Figure 2: Optical layout of detector package where EM is the energy monitor, PMT is a photomultiplier detector, and BS is a beamsplitter.

Figure 3: Comparison of double edge lidar wind measurements with 5 mJ laser energy, with standard deviation shown by bar, and rawinsondes for (a) 3/27/98 with 225000 shots and for (b) 3/29/98 with 10000 shots.

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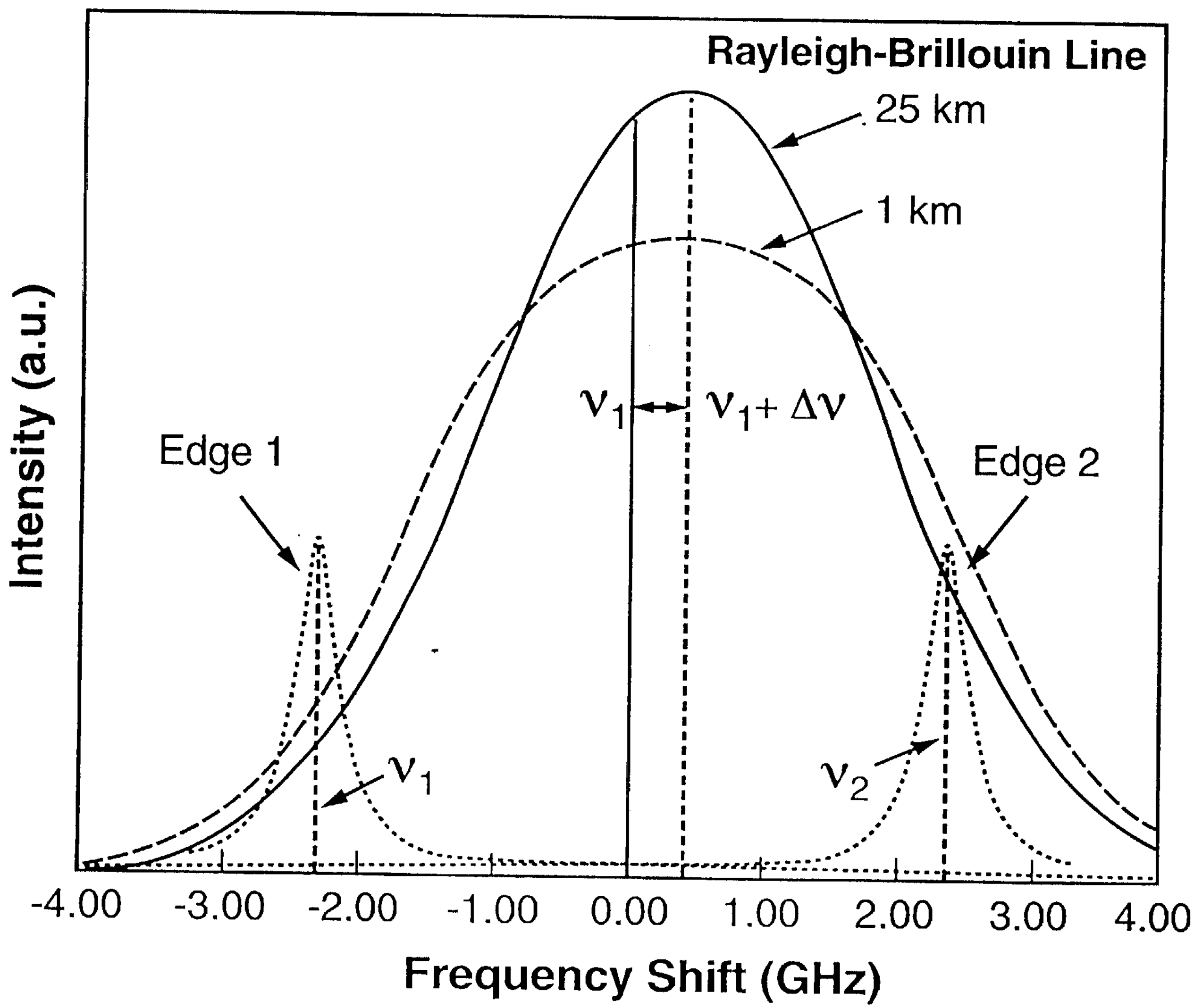
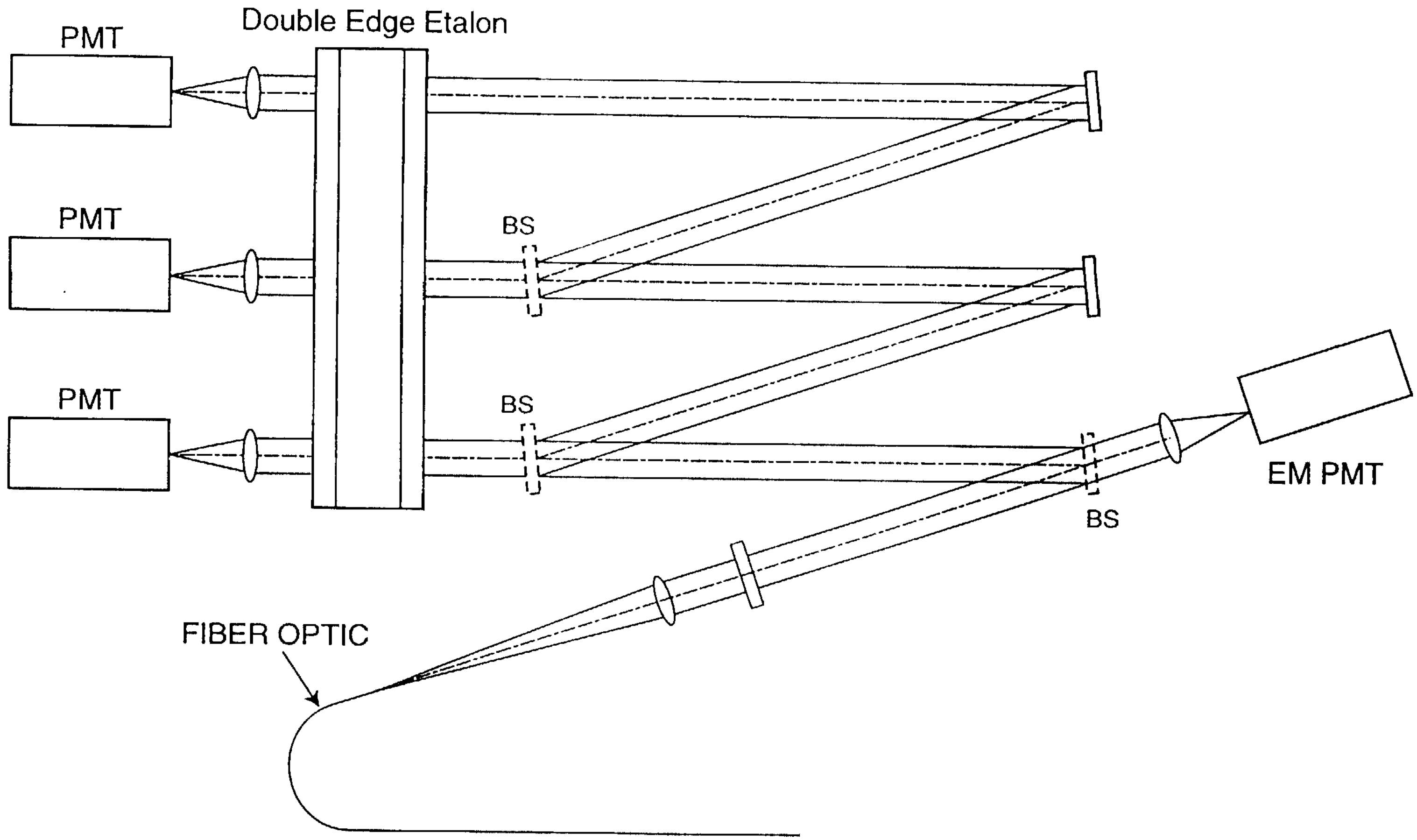

Rayleigh-Brillouin Line
25 km
1 km
ν_1
$\nu_1 + \Delta\nu$
Edge 1
Edge 2
ν_1
ν_2
Intensity (a.u.)
-4.00
-3.00
-2.00
-1.00
0.00
1.00
2.00
3.00
4.00
Frequency Shift (GHz)

L70.008



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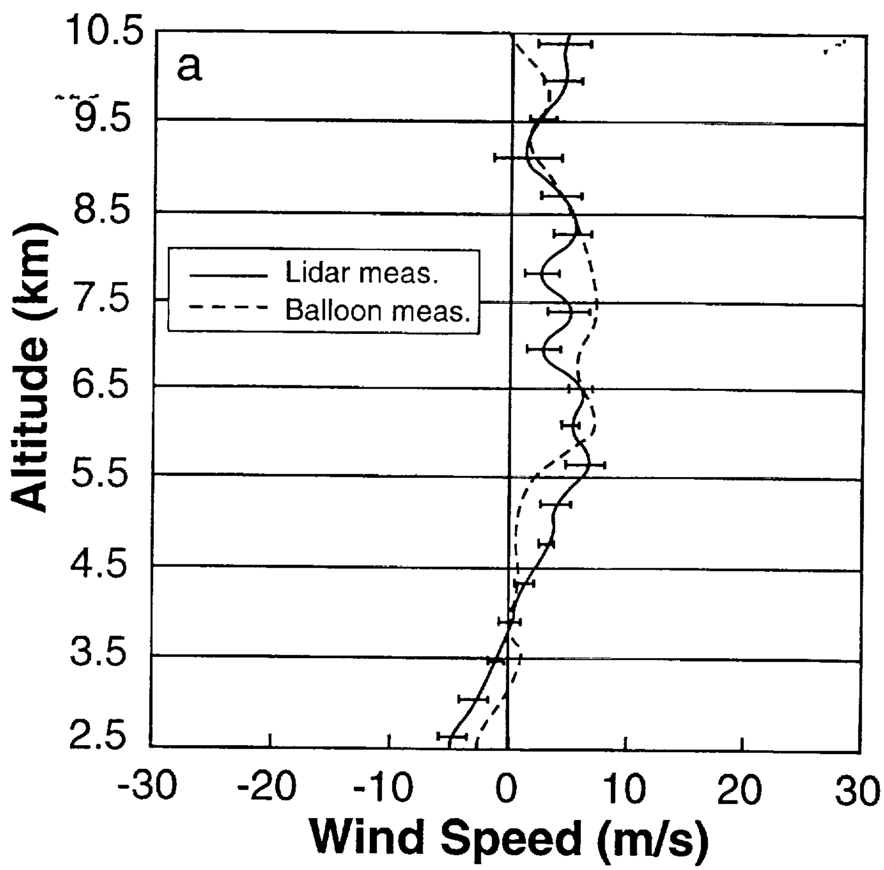
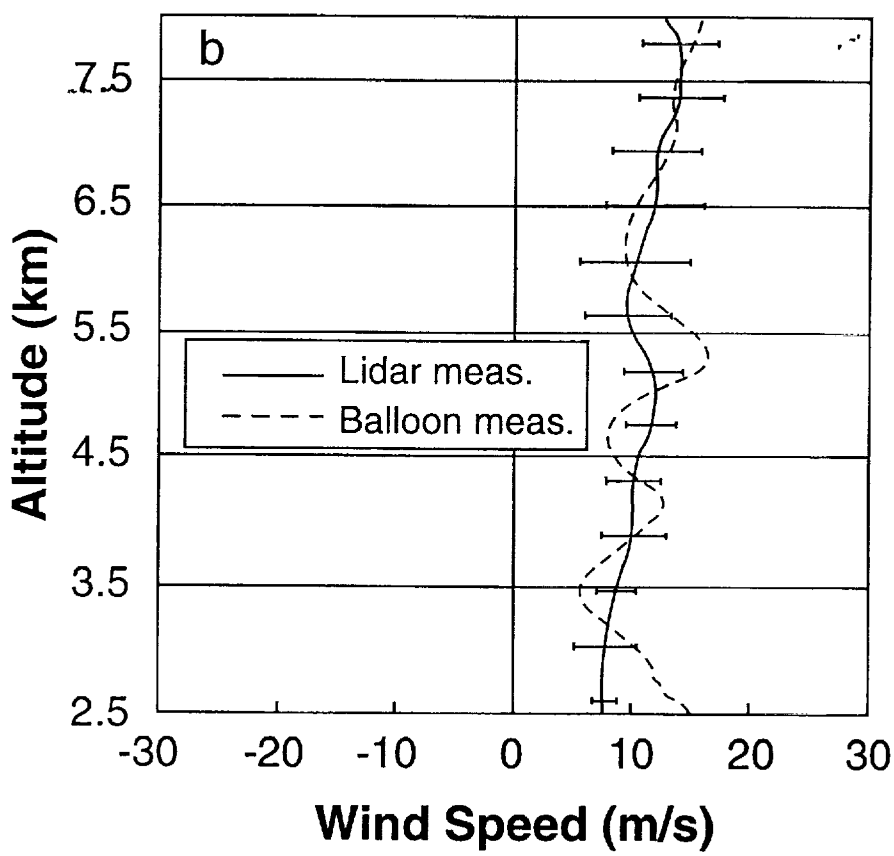

a
Lidar meas.
Balloon meas.
Altitude (km)
10.5
9.5
8.5
7.5
6.5
5.5
4.5
3.5
2.5
-30
-20
-10
0
10
20
30
Wind Speed (m/s)

L70.007


b
7.5
6.5
5.5
4.5
3.5
2.5
Altitude (km)
Lidar meas.
Balloon meas.
-30
-20
-10
0
10
20
30
Wind Speed (m/s)

L70.003