Lidar Technique for Measuring Ionospheric Barium Release Ion Density

J. Goree and J. S. Neff

INTRODUCTION

Sounding rocket experiments in the ionosphere are frequently carried out with an explosive canister of barium which detonates, producing a rapidly expanding cloud of metal atoms. To observe these ionospheric releases, we propose a remote sensing method, lidar.

Often, releases are carried out to study the Alfvén critical ionization velocity (CIV) effect [Haerendel, 1982; Wescott et al., 1986a]. As the barium cloud expands, it becomes ionized by solar ultraviolet radiation or, if electrons are heated by waves resulting from a velocity space plasma instability, by electron impact. This latter effect is the CIV phenomenon [Newell, 1985]. A threshold for this condition is that the neutral atom velocity must exceed , satisfying , where is an efficiency which depends on competing loss mechanisms [Newell and Torbert, 1985] and is the ionization potential of the neutrals. The CIV effect has been claimed to account for the results of laboratory experiments; however, in all but one [Haerendel, 1982] space experiment involving barium releases, the process was not observed.

A series of such tests in space, called the Condor project [Wescott et al., 1986a, b; Kelley et al., 1986; Torbert and Newell, 1986] relied partly upon observation of spontaneous optical fluorescence by cameras located on the ground to determine the ion concentration resulting from the explosion of a shaped charge of an alkaline Earth, such as barium. This method of ion detection has two shortcomings that are corrected with the observation technique proposed here.

The first difficulty is that the release must be performed in the presence of solar radiation, because optical stimulation in the visible is required to produce the fluorescence. If solar UV radiation is also present, it will ionize the barium. This ionization adds to the ionization due to the CIV effect; thus the method of measurement interferes with the experiment unless the UV component of the sunlight can be blocked. The Star of Lima experimenters attempted to block the UV by launching the barium just before sunrise to an altitude where the visible light would graze through the upper atmosphere but the UV would be absorbed by the ozone [Wescott et al., 1986a]. Although Haerendel [1982] was able to do this in the Porcupine experiment, in the Star of Lima test the rocket overperformed and detonated at too high an altitude, so that one could not positively say that UV photoionization did not account for the ion density that the experimenters observed.

The problem of attempting to observe the CIV process in presence of sunlight is quite serious due to the complication of momentum transfer, which Haerendel [1983] explained as follows. In addition to the energy balance that is usually taken into consideration in explaining CIV effect, one must also consider the momentum balance. Ionization of fast neutrals (by any mechanism) produces fast barium ions which lose momentum to the ambient plasma. This causes the rest frame of the ambient plasma to accelerate to a velocity nearer that of the fast barium neutrals. The free energy available to ionize the neutrals through the CIV effect is thus diminished. In the presence of a strong external source of ionization such as photolization, the CIV process may be entirely suppressed. Thus it is imperative to perform a CIV experiment under conditions where UV photoionization cannot take place. (We should note, however, that Goertz et al. [1985] also studied the momentum coupling process and found this problem to be less severe.)

The second difficulty of relying on passive fluorescence from the ions is that the optical signal represents a column average, along the line of sight, of the ion emissivity. The spatial resolution is thus somewhat limited if only one observation site is used. With several sites better results can be obtained, but only if the weather is fine at each of them and if all the remote cameras function correctly.

LIDAR PRINCIPLES

The two difficulties outlined above may be avoided by using an active remote sensing technique called lidar. A pulsed laser located on the ground is fired into the ionosphere, where the beam is partly absorbed by the ions. Fluorescence from the ions is then detected by a telescope located on the ground near the laser. The magnitude of the resulting signal yields the ion density and the delay in receiving it yields the range.

When it is used to observe ions in the laboratory, this method is referred to as laser-induced fluorescence (LIF). This laboratory technique is used routinely to monitor barium ions in Q machine plasmas [Hill et al., 1983]. A tunable dye laser is directed through the plasma, and a lens or small telescope collects the ion fluorescence and focuses it though an optical interference filter to a photomultiplier tube (PMT) detector. One thus measures the density of ions that are moving with the velocity that doppler shifts the laser light into resonance.
with the ion's atomic transition. By selecting a laser with a narrow frequency bandwidth and scanning the laser wavelength, the ion velocity distribution function can be measured. Alternatively, by selecting a laser with a large bandwidth so that all ions regardless of their velocity may absorb the laser light, the ion density can be measured.

The equipment and principles of lidar are essentially identical to those of LIF. The principal difference is the distance \( R \) between the plasma and the telescope. This difference is important in two ways. First, the larger value of \( R \) for lidar allows one to obtain ranging, i.e., spatial resolution. Second, the larger value of \( R \) causes the signal, which varies as \( 1/R^2 \), to be much smaller for the ionospheric measurement.

Atmospheric researchers use lidar to observe the Earth's natural sodium layer that is found between the altitudes of 80 and 100 km [Inaba, 1976; Gardner and Voelz, 1987]. The laser is generally pointed upward at the zenith. The laser light is partially absorbed by the sodium atoms, which have a density of typically \( 10^4 \) cm\(^{-3} \). The fluorescence is collected with a telescope onto a PMT.

A comparison of the sodium layer and a barium release is instructive. The optical transitions for Na and Ba\(^+\) are similar. The transition from the ground state of Na is \( 3S_{1/2} \rightarrow 3P_{1/2,3/2} \), with \( \lambda_0 = 589 \) nm and an oscillator strength \( f = 0.65 \). For Ba\(^+\), the best transition is \( 6S_{1/2} \rightarrow 6P_{3/2} \), with \( \lambda_0 = 455.4 \) nm and \( f = 0.7 \). For these two wavelengths, an excimer pumped dye laser has nearly the same efficiency.

The four chief differences in lidar for the sodium layer and a barium release are (1) the barium release is more localized transverse to the laser beam, (2) it has a shorter duration, (3) it has a different velocity distribution, and (4) it is at a higher altitude. Each of these differences will make lidar more difficult for the barium release. The more localized target of gas means that the laser and telescope must be pointed carefully, perhaps with the use of a tracking device to locate the sounding rocket if it is unguided. This means that the rocket would have to carry a beacon. The shorter duration will permit less signal averaging and will require that all the apparatus operate properly at the time of the release. The velocity distribution function of the ions must be estimated in advance to obtain a calibrated measurement of their density and to select a laser with an appropriate bandwidth. (This effect is manifested in the parameter \( \sigma_{\text{eff}} \), which is discussed later.) Due to its higher altitude, the barium release will result in less signal, according to the inverse square law. If one attempts to counteract the \( 1/R^2 \) effect by exploding the canister at a lower altitude, then the barium ions will collide with atmospheric oxygen atoms, and this will inhibit the CIV effect [Newell and Torbert, 1985].

Despite the four factors mentioned above that make lidar more difficult for the barium release than for the sodium layer, it is still a practical technique. The equipment involved would be virtually identical, except that a larger telescope might be needed. In fact, if one had an existing lidar setup that was designed to probe the sodium layer, the laser apparatus could be adapted inexpensively by changing the laser dye and interference filter and by adjusting the dye laser grating. The signal strength would be adequate for many barium experiments, as shown in the following calculation.

### Calculation of Signal Strength

To predict the optical power \( P_r \) of the signal that would be received, consider the lidar equation [Inaba, 1976]:

\[
P_r = P_0 A K^* T^2 n(R)\Delta R\sigma_{\text{eff}}/4\pi R^2
\]  

(1)

Here, \( P_0 \) is the laser power, \( A \) represents the telescope area, \( K^* \) is the optical transmission of the apparatus, \( T^2 \) is the two-way atmospheric transmission, \( n \) is the number density of the ions at a range \( R \), and \( \Delta R = c_t R/2 \). The duration of the laser pulse is \( t_p \), \( b \) is the branching ratio of fluorescence from \( 6P_{3/2} \rightarrow 6S_{1/2} \), and \( \sigma_{\text{eff}} \) is the effective absorption cross section. The result of (1) is used to find the total count rate

\[
N = \eta P_0 A \lambda_0 /hc
\]  

(2)

where \( \eta \) is the detector's quantum efficiency.

To estimate \( N \), consider the parameters that enter into (1) and (2). All of them except for \( \sigma_{\text{eff}} \) can be characterized straightforwardly. The lidar apparatus will be characterized typically by \( K^* = 0.2 \) and \( \eta = 0.15 \). If a dye laser with 14% efficiency is pumped by a 500-mJ excimer laser, with pulses \( t_p = 17 \) ns long, then \( P_0 = 4 \) MW. A low-quality 2.5 m diameter telescope would offer a collecting area of \( A_c = 5 \) m\(^2\). The atmospheric transmission is \( T = \exp (K X) \), where \( X = 1 \) at the zenith. The extinction of light due to aerosols and Rayleigh scattering is modeled by \( K = A + B X \), where the coefficients \( A \) and \( B \) vary according to geographic location, time of year, and most importantly, weather. Using values typical of Iowa City, \( A = -0.08 \) and \( B = -0.013 \mu \text{m}^{-4} \), we calculate that the transmission at \( \lambda = 455.4 \) nm is \( T = 0.68 \). The two-way transmission through the atmosphere is thus reduced to \( T^2 = 0.46 \).

The effective absorption cross section \( \sigma_{\text{eff}} \) depends not only on the atomic absorption cross section, but also on the optical bandwidth of the laser light \( \Delta \omega \) and on the ion velocity distribution function \( f(v) \).

The laser spectral intensity (power versus frequency) \( I(\omega) \) will depend on the construction of the dye laser that is used; typically, it will have a Gaussian dependence on \( \omega \). We will make the approximation that \( I(\omega) \) has a rectangular shape with a constant value \( I(\omega_0) \) for \( \omega_0 - \Delta \omega/2 < \omega < \omega_0 + \Delta \omega/2 \) and the value zero otherwise.

To compute an estimate of \( \sigma_{\text{eff}} \), consider the laser power absorbed per unit volume, \( dW/dt \). In terms of the cross section \( \sigma_{\text{eff}} \), \( dW/dt = h\omega n_p n_i \sigma_{\text{eff}} \), where \( n_p \) and \( n_i \) are the number densities of photons and ions, and \( c \) is the speed of light. The photon density is eliminated by considering that \( I(\omega_0)\Delta \omega = h\omega_n \). This yields

\[
dW/dt = I(\omega_0)\Delta \omega n_p n_i \sigma_{\text{eff}}
\]  

(3)

Here, the laser light power per unit area per unit frequency is \( I(\omega) \), and \( \omega_0 = 2\pi c/\lambda_0 \) is the atomic transition resonance frequency.

Now, from a semiclassical atomic physics model [Dementrader, 1982], the absorbed power density is also

\[
dW/dt = \int_{0}^{\infty} \alpha(\omega) I(\omega) d\omega
\]  

(4)

neglecting doppler broadening. The absorption coefficient \( \alpha \) is modeled by a Lorentzian,

\[
\alpha(\omega) = \frac{e^2}{2\hbar m_e \lambda_0} \sigma_{\text{eff}} \frac{f \gamma}{(\omega - \omega_0)^2 + (\gamma/2)^2}
\]  

(5)

where \( f \) is the oscillator strength.

To take into account doppler effects, \( \omega \) is replaced by \( \omega - kv \) on the right-hand side in (5), and (4) is generalized to

\[
dW/dt = \int_{-\infty}^{\infty} \alpha(\omega - kv) I(\omega) f(\omega) d\omega dv
\]  

(6)
The result expressed by (9) assumes that the experimenter has
comes
enter the specific parameters that apply to his or her experi-
especially the models chosen for $f(v)$ and $l(\omega)$, will make our

Combining (3) and (7) yields

$$dW/dt = \int f(\omega) n_f - \pi e^2 / 2 c e_p m_\nu$$

(7)

Combining (3) and (7) yields

$$\sigma_{eff} = \int f(\omega) n_f - \pi e^2 / 2 c e_p m_\nu \Delta\omega_i$$

(8)

Using the choice $\Delta\omega_i \approx \Delta\omega_\nu$ the estimate of $\sigma_{eff}$ in (8) becomes

$$\sigma_{eff} = \int f(\omega) n_f - \pi e^2 / 2 c e_p m_\nu \Delta\nu$$

(9)

The result expressed by (9) assumes that the experimenter has
tuned the laser light frequency to the resonant frequency of
the ion $\omega_\nu$, corrected by the doppler shift due to the velocity
of the rocket and the velocity of the gas from the exploding
shape. The approximations made in deriving (9), especially the models chosen for $f(\omega)$ and $l(\omega)$, will make our
result different from that of an actual specific experiment. The
experimenter can use the expressions presented above and
enter the specific parameters that apply to his or her experiment.
With this caveat in mind, let us assume $\Delta\nu = 6 \text{ km/s}$ in
a barium release. This yields an effective absorption cross
section of $\sigma_{eff} = 1.4 \times 10^{-16} \text{ m}^2$.

Using the above result in (1) and (2), with the parameters
that have been presented above and also in Table 1, the
photon count rate $\dot{n}_d$ will be $3.3 \times 10^5 \text{ s}^{-1}$. This is our signal.

**Signal-to-Noise Ratio**

To show that this signal is adequate, we must do two things.
First, we should compare it to the count rate for the noise
to find an estimate of the steady state signal-to-noise
ratio (SNR). Second, we must consider that the signal is inte-
grated over a limited duration of time; therefore only a finite
number of photons are thus counted. The PMT signal is
registered on a device called a range-gated photon counter.
In this instrument, photons are counted in several sequential
bins. The delay of the bin with respect to the time the laser
fires corresponds to the range. The width of the bin determines
the range resolution. For example, if the bin width is $10 \mu \text{s}$,
the range resolution will be $1.5 \text{ km}$. For the count rate $\dot{n}_d =
3.3 \times 10^5 \text{ s}^{-1}$ that was found above, an average of 3 photons
would be counted in each bin for a single laser pulse. The
single pulse SNR due to the photon statistics would thus be
approximately 2.

For comparison, consider the steady state SNR. It is deter-
mined by two sources of noise: skylight and detector shot
noise. The telescope must be adjusted to view only the area of
the sky illuminated by the laser, and not any more, in order to
minimize this effect. We will assume that the telescope receives
a solid angle corresponding to a 1-km diameter spot at range
of 200 km. Also, we assume the interference filter bandwidth is
0.5 nm, and the parameters listed in Table 1, including the
system transmission $K'$ and detector efficiency $\eta$. At zenith
at nighttime the skylight noise will then be $10^3 \text{ s}^{-1}$. The detector
shot noise will be only $10 \text{ s}^{-1}$ if the PMT is cooled. The
skylight noise is the greater of two. Using its value, we find
that the steady state SNR will be approximately 330, which is
greater than the steady state SNR found above. Photon statistics,
and not skylight or detector noise, will thus dominate the
noise entering into the overall SNR.

The statistics are improved by averaging over multiple laser
pulses. This is done at the expense of range and temporal
resolution. To weigh the benefits of signal averaging sensibly,
we must consider the resolution that would be required to
observe the barium release. Since the CIV process occurs on a
time scale of approximately 10 s, a temporal resolution of 0.5 s
would offer adequate observation of the development of the
release. An excimer-pumped dye laser can fire 100 pulses/s.
One would thus average over 50 pulses and count an average
of 165 photons per bin. The corresponding statistical noise of
$(165)^{1/2} \text{ photons}$ would yield an overall SNR of 13. In other
words, the error bars in the measurement of $n$ would be 8%.
This noise level should be acceptable for a CIV experiment.

In addition to the random errors analyzed above, system-
atic errors must be considered in fielding the lidar apparatus.
Two factors which could be dealt with successfully, exactly as
one does with sodium layer lidar, are the value of laser power
$P_0$, which can be measured accurately with a calorimeter, and
the detector system efficiency $\eta K'$, which can be calibrated
at the site by Rayleigh or Raman scattering on the atmosphere.
A greater problem may lie in the estimate of the ion velocity
distribution function, which enters into the calculation of $\sigma_{eff}$.
This must be known in advance of the experiment in order to
set the laser and to determine the absolute magnitude of the
ion density from the data. A distribution function can be
produced by numerical particle simulation if experimental
data is not available. Provided that this estimate can be made
accurately, then systematic errors may be less than the
random errors. In that case, the ion density measurement can
be made with an accuracy near the 8% level found above. If a
different set of parameters applies to an experiment, then the
criteria presented above can be used to compute the signal
strength and the size of the error bars.

**Experimental Configuration**

The most likely configuration that the experimenter would
choose would have both the laser and the telescope located on

### Table 1. Parameters Used in Calculating Photon Count Rate

<table>
<thead>
<tr>
<th>Parameter</th>
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<tbody>
<tr>
<td>$\lambda_0$</td>
<td>455.4 nm</td>
</tr>
<tr>
<td>$P_0$</td>
<td>4 MW</td>
</tr>
<tr>
<td>$A_0$</td>
<td>5 m²</td>
</tr>
<tr>
<td>$K_0$</td>
<td>0.2</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.15</td>
</tr>
<tr>
<td>$T_2$</td>
<td>0.46</td>
</tr>
<tr>
<td>$n_i$</td>
<td>$10^3 \text{ cm}^{-3}$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>17 ns</td>
</tr>
<tr>
<td>$b$</td>
<td>0.74</td>
</tr>
<tr>
<td>$R$</td>
<td>200 km</td>
</tr>
<tr>
<td>$\Delta v$</td>
<td>6 km/s</td>
</tr>
<tr>
<td>$N$</td>
<td>50 pulses</td>
</tr>
</tbody>
</table>

Assume now that the barium release results in an ion velocity
distribution function characterized by a width $\Delta\nu$, which
Corresponds to a doppler width $\Delta\nu = 2\pi\Delta\nu/\lambda_0$. For example,
if $\Delta\nu = 6 \text{ km/s}$, then $\Delta\nu = 8 \times 10^{15} \text{ rad/s}$. If the experimenter
knows in advance the value of $\Delta\nu$, then a laser grating can be
chosen so that $\Delta\nu \approx \Delta\nu$ to yield the largest possible lidar
signal. To model the distribution function, a rectangular shape
matching that of $l(\nu)$ can be used. Doing this, and approxi-
matings in this quantity must be considered. The latter effect

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the ground. The signal strength and noise levels presented in the last two sections were calculated for this arrangement. One might also consider using a smaller telescope and installing it in an instrumentation package that is flown on the same sounding rocket as the barium charge. The laser, however, must be located on the ground because the weight and electrical power consumption are both much too large for it to be put aboard a sounding rocket. (The only space vehicle likely to offer enough room and electrical power for an excimer-pumped dye laser would be NASA’s proposed space station.)

The experiment must be performed at high to mid-latitudes. This requirement is due to the importance of the Earth’s magnetic field. As explained above, the distribution function must be well-characterized to set up the laser and to interpret the data. This distribution function is the projection of the three-dimensional distribution function onto the direction of the laser beam. In a CIV experiment, the distribution function perpendicular to the Earth’s magnetic field will change during the course of the release, as can be seen in the phase-space plots of Machida and Goertz [1986]. In the direction parallel to the magnetic field, on the other hand, the distribution function will not vary as much and will be better characterized in advance of the experiment. The experimenter would choose therefore to point the laser beam parallel to the magnetic field. This would require that the experiment not be performed at low latitudes.

The CIV process will not occur readily unless the neutral atoms are injected with a nonzero velocity component perpendicular to the magnetic field. Therefore the shaped charge of barium should not be oriented to fire parallel to the laser beam, but rather obliquely to it.

The data produced by the lidar technique will be a plot of ion density versus range or altitude. This plot would be a snapshot of the density profile along the laser beam at a given time, with a new snapshot produced every half second. One could choose either to leave the direction of the laser beam the same during the entire release or to reposition it every half second to cover a raster in the sky. It might be desirable to do the latter if one expected an ionization front to sweep across the sky transverse to the laser beam and wished to observe this spatial effect.

**Conclusions**

We have shown that the lidar apparatus of the type already in use for studying the atmospheric sodium layer can be easily adapted to observe barium ions in a shaped charge release at nighttime. This would avoid the use of sunlight to see the ions in critical velocity experiments. Adequate signals can be attained if \( n_i = 10^9 \text{ cm}^{-3} \) and the range is 200 km. Using this method would produce plots of the ion density versus range, and these plots would be updated at intervals of 0.5 s. The parameters presented here result in 8% error bars in a measurement of ion density with range resolution of 1.5 km. We also present criteria useful for an experimenter to predict the signal and noise levels for experiments having other parameters.

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**References**


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