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14. Abstract/Notes

The development of the lidar technique in the early sixties, and the subsequent introduction of tunable lasers, made accurate measurements of the vertical distribution of the alkali metals in the atmosphere possible for the first time. Over the last decade a great deal of information has been obtained on the spatial and temporal variations of sodium, and rather less information has been obtained about potassium and lithium. The possibility of making continuous observations of the vertical distribution of sodium, coupled with temperature measurements via the determination of the Doppler spectrum of the returned lidar signal, offers a potentially useful technique for studying the dynamics of the 80 to 100 km region of the atmosphere.

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LIDAR STUDIES OF THE ALKALI METALS

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Abstract. The development of the lidar technique in the early sixties, and the subsequent introduction of tunable lasers, made accurate measurements of the vertical distribution of the alkali metals in the atmosphere possible for the first time. Over the last decade a great deal of information has been obtained on the spatial and temporal variations of sodium, and rather less information has been obtained about potassium and lithium. The possibility of making continuous observations of the vertical distribution of sodium, coupled with temperature measurements via the determination of the Doppler spectrum of the returned lidar signal, offers a potentially useful technique for studying the dynamics of the 80 to 100 km region of the atmosphere.

Introduction

Efforts to probe the atmosphere by active optical techniques started before the 2nd World War. Synge (1930) first suggested that scattering of light from a searchlight beam could be used to determine atmospheric densities, and Hulburt (1937) appears to have been the first to successfully apply the technique. Subsequent improvements were made by Johnson et al. (1939), who introduced the use of photoelectric detectors, and Elterman (1954) who much refined the technique and made measurements at heights up to 65 km.

The main limitation of the searchlight technique was that the light source was continuous, so that height resolution could be achieved only by separating the searchlight and the receiver by many kilometres, and defining a scattering volume by the intersection of the searchlight beam and the cone of sensitivity of the receiver. Early attempts to use a pulsed light source, employing discharge tubes (Friedland et al., 1956), suffered from the limitations of the sources available. The development of the first pulsed laser by Maiman (1960) solved this problem, providing a source which in many ways is ideal for an optical radar. By allowing the use of narrow bandwidth filters and a narrow beam divergence, the narrow bandwidth and coherence of the laser made it possible to reduce the receiver background noise by many orders of magnitude.

The first measurements of atmospheric parameters using laser radar, or lidar, were made by Fiocco and Smullin (1963), followed by Collis and Ligda (1966), McCormick et al. (1966), Bain and Sandford (1966) and Clemesha et al (1966). These early measurements all used ruby lasers and were concerned with measuring either Rayleigh scattering from the major molecular constituents of the atmosphere, with the aim of determining atmospheric density, or Mie scattering from aerosols. The development of the pulsed dye laser, tunable over a range of wavelengths, opened up the possibility of measuring the vertical distributions of selected minor constituents for which convenient resonant transitions exist. This technique was first applied by Bowman et al. (1969), who used it to measure the vertical distribution of atmospheric sodium.

The basic lidar technique

All the lidars which have been used for studies of the alkali metals have been monostatic, i.e. with the transmitter and receiver effectively coincident, and there appear to be no advantages to be gained by using a bistatic system. For this reason only the monostatic system will be discussed here. The laser is assumed to transmit a pulse whose duration is short in relation to the required height resolution. It is easy to show (Kent et al., 1967) that the signal return, S(z), from a height, z, for such a lidar is

$$S(z) = \frac{\sigma(z)}{z^2} \; A \, \Delta z \, N_0 \, Q \, T(z)^2 \qquad (1)$$

where $S(z)$ is the signal received from the range interval $z - \Delta z/2$ to $z + \Delta z/2$,
$\sigma(z)=n(z)\rho$ is the volume backscattering coefficient at range z,
$n(z)$ is the number density of scatterers of backscattering coefficient ρ at range z,
A is the area of the lidar receiver,
N_0 is the energy contained in the transmitted pulse,
Q is the overall efficiency of the lidar receiver,
$T(z)$ is the atmospheric transmission between the lidar and range z.

In the case of lidars designed to measure resonant scattering from the alkali metal layers, the received signal is invariably so weak that photon counting techniques must be used to measure it. In this case it is convenient to express S(z) and N_0 in terms of numbers of photons.

In practice it is virtually impossible to relate the received signal to the number density of the scatterers in an absolute sense because T(z), and even Q, are not accurately known. This problem is conveniently overcome, in the case of resonant scattering from the alkali metal layers, by comparing the resonant scattering with Rayleigh scattering from the main atmospheric constituents at much lower heights, where the atmospheric density is accurately known. In this way we can eliminate Q and N_0 from equation 1. If we take the case of sodium, for example, the backscattering coefficient per molecule for a typical laser bandwidth of 10 pm is about 1.4×10^{-17} m^2 SR^{-1}, and the density at the peak of the layer around 90 km is of the order of 3×10^9 m^{-3}, giving a volume backscattering coefficient of about 4×10^{-8} m^{-1}, SR^{-1}. A similar volume backscattering coefficient for Rayleigh scattering from the principal atmospheric constituents is obtained at about 23 km, where the number density is about 10^{24} m^{-3}, and the effective backscattering coefficient per molecule is 3.93×10^{-32} m^{-2}, SR^{-1}. The signal from this height would be about 15 times the sodium signal because of the $1/z^2$ factor in the lidar equation. In practice a somewhat greater height would normally be used in order to avoid scattering from stratospheric aerosols.

Under normal conditions atmospheric extinction for visible wavelengths is negligible above 20 km (neglecting, for the moment, extinction by the resonant scatterers themselves), allowing us to eliminate T(z) from equation 1, as well as Q and N. We can then write

$$\frac{S_1}{S_2} = \frac{z_2^2}{z_1^2}\frac{\sigma_1}{\sigma_2}\frac{\Delta z_1}{\Delta z_2}$$

where the subscript 1 refers to the alkali metal layer, and 2 refers to the stratospheric reference signal. Thus we get the alkali metal density, n_1, at height z_1 in terms of the atmospheric number density, n_2, at some reference height, z_2:

$$n_1 = \frac{S_1}{S_2}\frac{z_1^2}{z_2^2}\frac{\Delta z_2}{\Delta z_1}\frac{\rho_2}{\rho_1} n_2 \qquad (2)$$

In equation 2, ρ_2, the average backscattering coefficient per air molecule, is accurately known. The determination of ρ_1, the effective backscattering coefficient per alkali metal atom, is more difficult because it depends on the laser emission spectrum. The parameter ρ_1 is given by

$$\rho_1 = \int_0^\infty I(\lambda)\rho(\lambda)d\lambda \Big/ \int_0^\infty I(\lambda)d\lambda \qquad (3)$$

where $I(\lambda)$ is the laser energy and $\rho(\lambda)$ is the alkali atom backscattering coefficient, both as functions of wavelength, λ. $\rho(\lambda)$ can be calculated from a knowledge of the hyperfine structure of the resonance involved, the oscillator strengths and the temperature of the atoms. Since a reasonable estimate of the temperature can be made, there is no difficulty in determining $\rho(\lambda)$. An accurate determination of $I(\lambda)$, on the other hand, is not easy, and the laser spectrum will tend to change as a function of several laser parameters such as input energy, dye lifetime and flashtube wear. Most workers have made a spectroscopic determination of the laser bandwidth, and have calculated ρ_1 on the assumption of a Gaussian line shape. An alternative approach is to measure ρ_1 directly by sweeping the laser through the resonance line, and measuring the scattering of its output by the appropriate alkali atoms in a scattering cell. This method gives good results, but requires a laser whose output wavelength can be shifted in small, accurately known steps.

Practical details

The major difficulty with any lidar for upper atmospheric studies is one of obtaining signal returns strong enough for an accurate determination of the required parameter to be made. At least in the case of nighttime operation, external noise due to extraneous light sources is generally less important than the shot noise in the signal being measured. Thermal noise in the receiver can usually be reduced to negligible levels by cooling the detector. On the assumption that the detected photon pulses follow a Poisson distribution, the fractional precision in the measurement is simply $1/\sqrt{S}$, where S is the total number of photons detected from a given range interval; or, more precisely, 63% of samples will fall within the range $\bar{S} \pm \sqrt{S}$ where $\bar{S}$ is the true mean value of S. If external noise is not negligible then the precision becomes $\sqrt{S}/(S-N)$, where N is the external noise.

As can be seen from equation 1, S can be increased by increasing N_0, the number of photons transmitted, proportional to the pulse energy of the laser, A, the receiver area, or Q, the receiver efficiency. The last of these parameters depends on the quantum efficiency of the photomultiplier detector used, but has a maximum value of about 20% for the sodium wavelength, and is less at the wavelengths appropriate for lithium and potassium.

Since we can accumulate the signal from pulse to pulse, N_0 is simply the total number of photons transmitted during a measurement. This means that the mean power of the laser, rather than the pulse energy, is the important parameter in this respect. On the other hand, N_0 should be large enough for the condition $S >> N$ to hold. The pulse energy and mean power of the laser and the receiver area are major items in the cost of the lidar, and their relative values must be chosen on the basis of an incremental cost analysis. Typical values in use are 50 mJ, 50 mW and 0.5 m^2, although much larger values can be achieved, particularly for the laser parameters, and have been used by some workers.

A further factor which must be taken into account in optimising the lidar characteristics is the laser bandwidth. For atmospheric sodium measurements a full bandwidth of about 0.07 Å has generally been used. This is appreciably larger than the Doppler width of the line at mesopause temperatures, which is about 0.03 Å. A reduction in the laser linewidth would consequently increase the effective scattering cross-section and the received signal. On the other hand, a reduction in the laser bandwidth generally involves a reduction in output energy, and a bandwidth of 0.07 Å probably represents close to the best compromise between bandwidth and energy. It should also be remembered that narrower bandwidths mandate better laser stability, and greater difficulty in determining the effective resonant scattering cross-section.

So far we have been discussing nighttime observations of sodium, where it is comparatively easy to achieve a signal much stronger than the combined sky noise and p.m.t. dark current. In the case of the other alkali metals, whose concentrations are much less than that of sodium, and in the case of daytime measurements, this is not always so. In this case it is necessary to use higher pulse energies and to minimize extraneous noise sources. For daytime measurements the limiting factor is sky noise, and this is minimized by the use of a narrow angular beamwidth and narrow receiver bandwidth. Beamwidths used for daytime observations are of the order of 0.2 mR, placing limitations on the sort of optics used. As an economical way of achieving large receiver areas, some lidar groups have used plastic Fresnel lenses or searchlight mirrors, but such systems cannot produce the narrow beamwidths required for daytime measurements. Narrow receiver bandwidth is achieved by inserting a Fabry-Perot interferometer in the optical path, giving a bandwidth of the order of 0.2 Å. In the case of sodium, decreasing the receiver bandwidth results in a disproportionately large decrease in noise because of the existance of a strong solar Fraunhoffer line. It should be noted that a narrow angular beamwidth is necessary, not only to reduce the area of sky viewed by the receiver, but also in order to make it possible to use the narrow bandwidth Fabry Perot interferometer.

Extinction and Saturation Effects

In the analysis presented above it has been assumed that virtually all the alkali atoms to be detected are in the ground state, and that these atoms cause negligible extinction of the lidar beam. Neither of these assumptions is entirely valid, and, under certain circumstances, saturation and extinction must be allowed for.

Extinction is appreciable only in the case of sodium; for the other alkali metals the concentration is too small for the effect to be important. Even in the case of sodium the effect is significant only for exceptionally high abundances. In correcting for extinction it must be remembered that the spectrum of the lidar pulse changes as it propagates through the layer, and that the spectrum of the returned signal can be quite different from that of the transmitted one. An inadequate appreciation of these points appears to have led to a certain amount of confusion in the literature. A correct analysis of the effects of extinction has been published by Simonich and Clemesha (1983), who have shown that the magnitude of the effect depends on the bandwidth of the laser emission, and that it is greatest for a bandwidth much less than that of the sodium line. For a typical lidar, with a transmitted bandwidth much greater than that of the atmospheric sodium, the effect of extinction is about 3% for the return from the peak of a typical layer with 5×10^{13} m^{-2} abundance. This would increase to about 5% for a narrow band laser. In practice, an iterative technique can be used to correct for this extinction.

Apart from the minor influence of the laser bandwidth, resonant extinction depends only on the scattering cross-section and number density of the alkali atoms involved. Saturation effects, in contrast, are independent of the number density of scattering atoms, but depend on the power density in the transmitted beam and the lifetime of the excited state. The saturation problem has been investigated in some detail by Megie et al (1978), who showed that the importance of the effect depends on the ratio of the excitation rate, proportional to the product of the power density incident on the scattering atoms and their effective scattering cross-section, to the transition probability for spontaneous emission (the Einstein A coefficient). Megie and his coworkers used a dye laser pumped by a Q-switched ruby laser to measure atmospheric potassium. The short (30 nS) pulse duration of their laser combined with a fairly narrow transmitted beamwidth (0.5 mR) resulted in a power density of about 1 MW m^{-2} at the height of the layer, causing about 10% of the potassium atoms to be in the excited state, with a consequent 10% decrease in the expected signal. Megie et al. point out that this effect could become important in the case of future measurements using higher powers and narrower beamwidths. On the other hand, it seems that this difficulty, should it arise, could be overcome by using a laser with a longer pulse duration and consequently lower peak power.

The INPE Lidar

As an example of a lidar system in use for studying atmospheric sodium, the following is a description of the INPE lidar. This system is used to provide both sodium and stratospheric aerosol measurements simultaneously. Figure 1 is a block diagram of the system, and Figure 2 shows the optical system. More detailed views of the transmitting and receiving systems are shown in Figures 3 and 4 respectively. The transmitter uses a flashlamp pumped dye laser to give a maximum output of about 70 mJ in a 2 μS pulse. Three Fabry-Perot etalons are used to tune the output to 5890 Å and reduce the bandwidth to about 0.07 Å. One of these etalons is piezo-electrically tuned and forms part of a servo loop to keep the laser tuned to the D_2 line emitted by a sodium lamp (Clemesha et al, 1975). Referring to Figure 3, the laser output beam is collimated by L_1, L_2 and M_1 to give a final angular beamwidth of about 0.1 mR. A small fraction of the laser output is sampled by a partially reflecting mirror, M_2, and is focussed onto a small opening in an integrating sphere. A photodiode, illuminated by the light which escapes from a second small hole in the integrating sphere, provides a signal proportional to the total laser energy, and a third opening allows a small fraction of the light to enter a sodium vapour cell maintained at 106°C. The light scattered by the sodium vapour, measured by a photomultiplier, provides a measure of the laser energy within the D_2 line width. Both the total energy and the sodium vapour scattered signal are recorded along with the lidar signal, making it possible to correct for changes in the laser output spectrum which occur during observations. It should be mentioned that such changes, resulting from aging of the dye and flashlamp, and accidental miss-alignments, are by no means negligible. A helium-Neon laser, the beam from which can be introduced into the system by means of a movable mirror (not shown in the figures) is used for alignment purposes. This monitoring system, together with the ability to tune the laser via the piezo-electrically controlled etalon, also makes it possible to determine the effective sodium scattering cross-section experimentally, as described in the section headed "Basic lidar technique".

The receiving optics use a 76 cm diameter spherical mirror of 17 m focal length. This mirror was used because it happened to be available, and a much shorter focal length would normally be employed. Nevertheless, there are advantages to using such a long focal length. Apart from cost considerations, the long focal length makes it possible to use the mirror off axis without introducing excessive aberrations. After passing through an adjustable diaphragm, which defines the receiver angular beamwidth, the light is collimated in a 13 mm diameter beam which is filtered by a 7 Å bandwidth interference filter before being focussed onto the input end of a light-guide. A beam splitting device in the light-guide directs 95% of the light to the high sensitivity photomultiplier, and the remaining 5% to the low sensitivity tube. Multiple reflection on the photocathode of the p.m.t. is used to increase its quantum efficiency. The use of 2 photomultipliers in this way increases the dynamic range of the system, making it possible to record the scattering from as low as 10 km, simultaneously with the signal from the sodium layer.

Just in front of the entrance to the light guide is a rotating shutter which prevents the strong signal scattered in the lower atmosphere from reaching the p.m.t. For daytime observations, the receiver bandwidth is reduced by inserting a Fabry-Perot interferometer between the collimator and the interference filter.

As shown in Figure 2, the transmitting and receiving optics, which are almost coaxial, point horizontally at a 120 cm diameter plane mirror mounted on a surplus 60 inch searchlight base. In this way a limited degree of beam steering is possible, a feature which has been exploited to make spaced observations of both sodium and stratospheric aerosols (Clemesha et al, 1980, 1981a).

Referring to Figure 1, the pulse outputs from the photomultipliers, after amplification and threshold discrimination, are fed to a 100 channel high speed scaler, 25 channels of which are dedicated to the low sensitivity p.m.t., and 71 to the high sensitivity tube. The remaining 4 channels are used to record the laser energy, sodium vapour cell output, number of shots fired and time. The opening and closing of each channel is programmed in sequence, and is normally set to cover the height ranges of interest in intervals of 1 km. An accurate determination of the ratio between the sensitivities of the two photomultipliers is assured by a 16 channel overlap. The signals for time intervals corresponding to ranges from which no appreciable scattering should be detected are recorded to give values of the noise level to be subtracted from the measured photon counts. This system is somewhat antiquated (it was designed in 1968), and it will by replaced by a more flexible microprocessor-based system in the near future.

The photon counts, typically accumulated for 50 laser shots, are transferred to a small desk top computer which carries out a partial analysis of the data in order to monitor the system performance and the behaviour of the sodium layer. The data is also recorded on digital data cassettes for subsequent transmission to INPE's mainframe computer. Laser firing and readout of the multichannel scaler is controlled by a programmer, and suitable arrangements are made to ensure that the laser firing is synchronised to the receiver shutter.

Specifications for the INPE lidar are given in Table 1.

TABLE 1. Specifications for the INPE Lidar

	Nighttime Value	Daytime Value
Transmitted energy	30 mJ	60 mJ
Pulse duration	2 μs	2 μs
Repetition rate	0.4 s^{-1}	0.4 s^{-1}
Wavelength	5890 Å	5890 Å
Total transmitted bandwidth	0.08 Å	0.08 Å
Receiver area	0.39 m^2	0.39 m^2
Receiver bandwidth	7 Å	0.3 Å
Transmitter beamwidth	0.15 mR	0.15 mR
Receiver beamwidth	0.4 mR	0.2 mR
Receiver efficiency	2.4 %	1 %
Height interval	1 km	1 km

Published Results

It is not the purpose of this article to review the results of lidar studies of the alkali metal layers, but some representative results are outlined here in order to give examples of the sort of information obtainable.

Results of extensive observations of the sodium layer have been published by Gibson and Sandford (1971), Megie and Blamont (1977) and Simonich et al (1979). Apart from a single measurement of the total abundance of potassium, published by Felix et al. (1973), the only results of observations of potassium and lithium have been presented by Megie et al. (1978) and Jegou et al. (1980) respectively. More recently the french workers have also measured calcium and ionized calcium (Chanin, personal communication, 1983) but the results of these observations have not yet been published. The theory of the alkali metals in the atmosphere will not be discussed here. The interested reader is referred to Kirchhoff (1983), Kirchhoff and Clemesha (1983) and Kirchhoff et al (1981), and the references therein.

The following brief survey of results is divided into Vertical Distribution, Diurnal Variations, Seasonal Variations, Dynamical Effects and Temperature Measurements.

Vertical Distribution

In Figure 5 we show average distributions for sodium, potassium and lithium. The curve labelled "Na Winkfield" is an annual average derived from measurements made by Gibson and Sandford (1971) at a latitude of 51°N, and "Na S.J. dos Campos", for 23°S, is from Simonich et al. (1979). The curves for potassium and lithium, derived from data published by Megie et al. (1978) and Jegou et al. (1980) respectively, are both for a latitude of 44°N. The sodium distributions shown in Figure 3 are based on a fairly large number of individual profiles taken over a complete year, and provide a good estimate of the true average vertical distribution. Considerably less data are available for potassium and lithium, and, particularly in the case of lithium, the profiles shown must be considered representative rather than truly average. As can be seen from the figure, the peak of the sodium layer is about 3 km higher at 23°S than at 51°N, and the mid-latitude profile shows significantly more sodium on the bottomside as compared with the low latitude one. This increased bottomside sodium results mainly from the large winter increase observed at mid latitudes. It is difficult to base any conclusions on the relative distributions of potassium and sodium, but, according to Megie et al. (1978), the peak of the potassium layer is generally about 1 km lower than that of the sodium layer.

Diurnal variations

Although the first daytime lidar measurements of atmospheric sodium were made by Gibson and Sandford (1972), studies of the 24 hour variations have been published only by Clemesha et al. (1982) and Granier and Megie (1982). The french workers state that they observed "no regular variation of the characteristic parameters of the sodium layer .... during the diurnal cycle", although they do not give any indication of the extent of the data set on which they base this conclusion. The brazilian group, in contrast, observed strong diurnal and semi-diurnal oscillations in the layer which they observe at 23°S (Figure 6). The oscillations appear to be mainly the result of tidally induced vertical motions in the atmosphere, and their study would appear to provide a useful technique for investigating atmospheric tides in this height region. A distinctive feature of such observations is that they provide information on the vertical tidal motions of a neutral species, unobtainable by other techniques.

One important result of the daytime measurements is that they have shown that there is no large variation between the daytime and nighttime abundances of sodium. Earlier dayglow measurements by Blamont and Donahue (1964) had suggested the existance of a large increase in sodium during the day, but the more recent observation of the lack of any such enhancement has made it possible to eliminate a number of models which had been suggested for the sodium layer (Kirchhoff and Clemesha, 1983, Clemesha et al., 1981b).

No daytime observations of the other alkali metals have been reported as yet.

Seasonal variations

The available data on seasonal variations is summarised in Figure 7. Sodium shows a winter maximum at all latitudes, and the main variation is clearly seasonal rather than annual. The details of the variation are not the same at different latitudes, the mid-latitude data showing a sharp increase in October, November and December, with comparatively little variation during the rest of the year, while the southern hemisphere low latitude results show a broad winter maximum, with minimum abundances in December and January. A further difference is that the winter maximum at mid-latitudes seems to be mainly the result of increased sodium on the bottomside of the layer, while at low latitudes there is no systematic annual variation in the vertical distribution.

The rather sparse lidar data available for potassium (Megie et al., 1977) shows no regular seasonal variation, in agreement with earlier twilight photometry results (Hunten, 1967). According to Jegou et al. (1980), lithium shows an annual variation similar to that of sodium, but, in view of the paucity of the lithium data, this conclusion must be viewed with some caution.

As yet there is no satisfactory explanation for the seasonal variations. Megie et al. (1978) have suggested that the sharp winter peak in sodium might be caused by vertical transport of sodium compounds from the surface, and a number of workers have suggested that photochemical effects might be involved. Unfortunately, neither our knowledge of vertical transport in the atmosphere, nor our understanding of the photochemistry of sodium are sufficient for us to adequately test these ideas. Other possibilities, such as changes in the rate of sublimation of sodium from mesospheric aerosols (Fiocco and Visconti, 1973) or meridional transport (Fujiwara and Hirono, 1973) are similarly difficult to test.

Dynamical effects

A number of workers have pointed to the existence of perturbations in the sodium layer which appear to be caused by dynamical effects in the main atmospheric constituents. As has already been mentioned, Clemesha et al. (1982) have demonstrated the existence of strong diurnal and semidiurnal oscillations in the layer, attributable to tidal perturbations. Shorter period oscillations, apparently caused by gravity waves propagating through the layer, have been studied by Richter et al (1981). Thomas et al. (1977) and Clemesha et al. (1981c) have made spaced observations with a steerable lidar in order to investigate horizontal gradients, and the latter workers have used such measurements to derive horizontal wind velocities in the 80 to 100 km region.

Temperature measurements

The ground state alkali metal atoms detected by laser radar are in thermal equilibrium with the ambient air molecules, so a measurement of their velocity distribution is equivalent to a determination of the ambient temperature. If, as is usually the case, the laser bandwidth is considerably greater than the width of the thermal Doppler spectrum (about 0.03 Å for sodium), then it would be possible, in principle, to determine the temperature by measuring the spectrum of the returned signal. In practice,a direct determination of this sort would be very difficult because of the very low light levels involved and the high spectral resolution necessary. Blamont et al. (1972) overcame this problem by measuring the attenuation produced in the returned signal by a sodium vapour cell maintained at a known temperature. Since the extinction depends on the linewidth of the signal returned from the sodium layer, its measurement can be used to derive the temperature of the sodium atoms. This technique was first used in sodium twilight measurements by Bricard and Kastler (1944).

The absorption cell technique used by Blamont and his coworkers suffers from the disadvantage that the extinction produced by the cell is a rather slowly varying function of the temperature of the scattering atoms responsible for the lidar signal, with the result that the latter must be integrated over long time periods in order to give the required precision of measurement. An alternative technique, which has been demonstrated by Thomas and Bhattacharyya (1980), is to use a very narrow bandwidth laser to actually measure the thermal velocity distribution by measuring the signal return at a number of discrete wavelengths. This technique, requiring as it does, very precise control of the laser wavelength, involves certain experimental difficulties, but offers the potential for accurate determination of temperature in the 80 to 100 km height range with good resolution in both height and time.

Future Work

As a result of lidar observations, it is probably true to say that we now know more about the morphology of atmospheric sodium than any other minor constituent of the earth's upper atmosphere. On the other hand, this knowledge has not led to a greatly increased understanding of the origin of atmospheric sodium, nor of the way in which it interacts with other species. The main difficulties in the way of solving these problems are a lack of accurate knowledge of the variations in space and time of other minor constituents, and of the appropriate rate coefficients for reactions between sodium and these species, combined with our ignorance of both vertical and horizontal transport effects. In view of this situation it seems that an improved understanding of the alkali metals in the atmosphere will come about not so much from better measurements of their variations in space and time, but rather from improved measurements of the other species with which they might react, better laboratory determinations of the appropriate rate coefficients, and an improved understanding of transport effects. This should not be taken to imply that more observations are unnecessary, particularly in the case of the alkali metals other than sodium, for which few measurements have been made. Improved geographical coverage would be helpful, all the observations so far having been made at middle to high latitudes in the northern hemisphere, or low latitude in the southern. The possible existence of an assymmetry in the seasonal variation between northern and southern hemispheres (Simonich et al., 1979) could be checked if several years observations were made at middle latitudes in the southern hemisphere.

The proposed Shuttle Lidar (NASA, 1979) could make a major contribution to our understanding of the alkali metals in the atmosphere. Not only would the improved geographical coverage be important, but the proposed measurement of other minor species such as O_3 and OH might greatly improve our understanding of this region of the atmosphere.

Apart from the potential of the Shuttle Lidar, it is the opinion of the author that the most important future contribution of lidar observations of the alkali metals lies in the use of these species, principally sodium, as tracers for atmospheric dynamics and temperature measurements. In the height region between 80 and 100 km, an adequately designed and located lidar could provide continuous measurements of temperature with a time resolution of a few minutes and a height resolution of about 1 km, along with estimates of horizontal and vertical velocity components. Such a system would be a most powerful tool for the study of atmospheric dynamics in the mesopause region.

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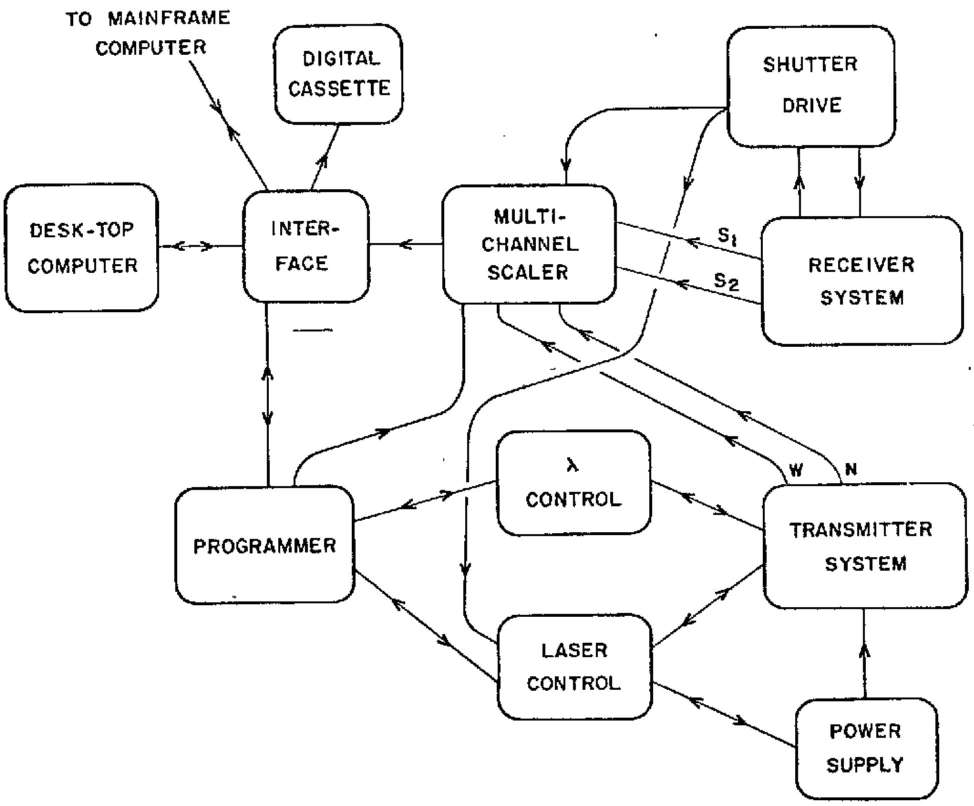

Fig. 1 - Block diagram of the INPE lidar.

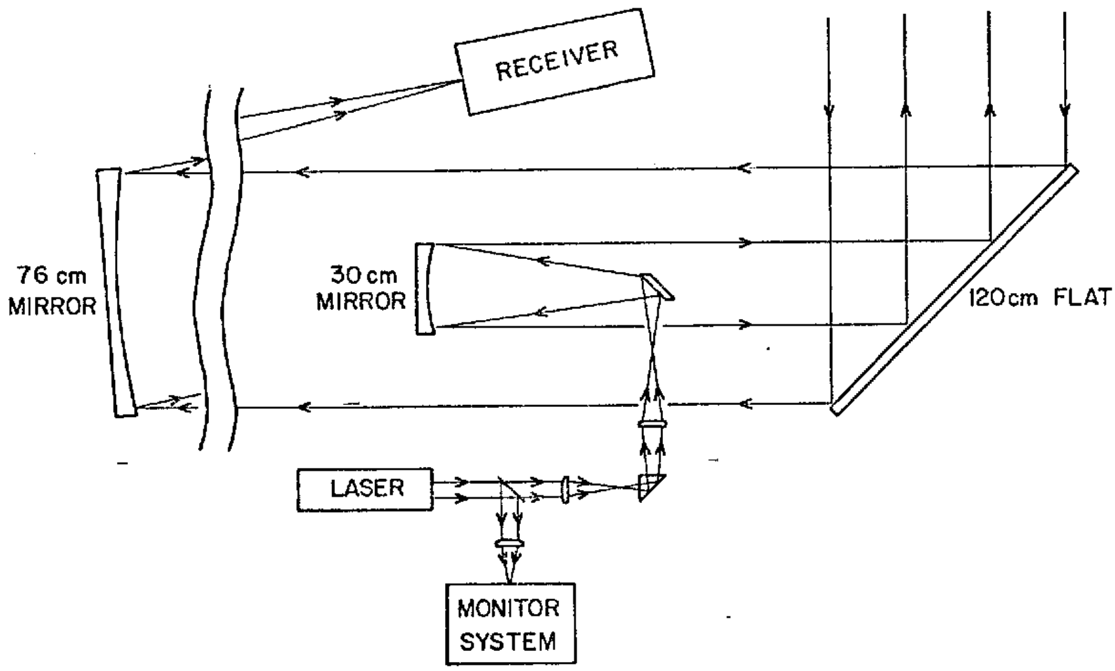

Fig. 2 - Basic optical system of the INPE lidar.

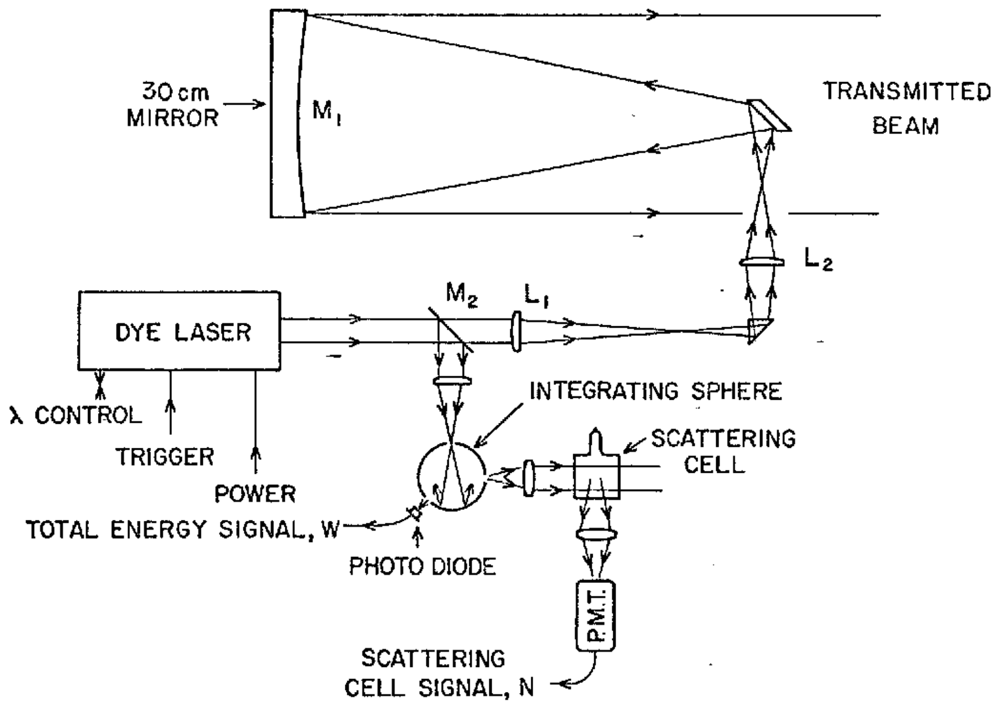

Fig. 3 - Lidar transmitter.

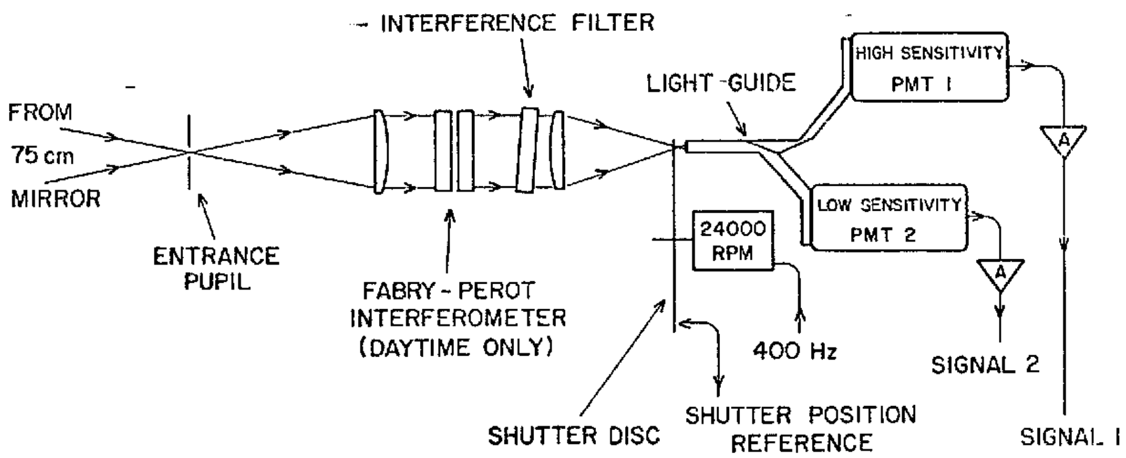

Fig. 4 - Receiver optics.

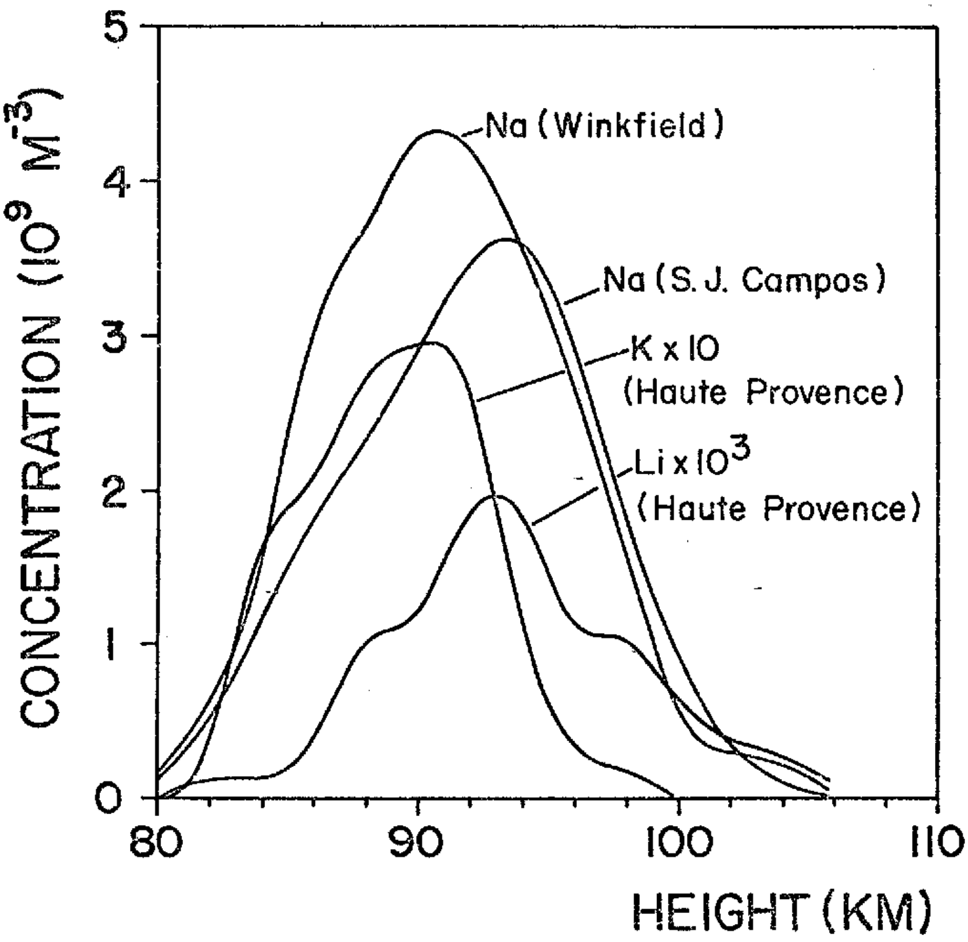

Fig. 5 - Average vertical distributions of sodium, potassium and lithium.

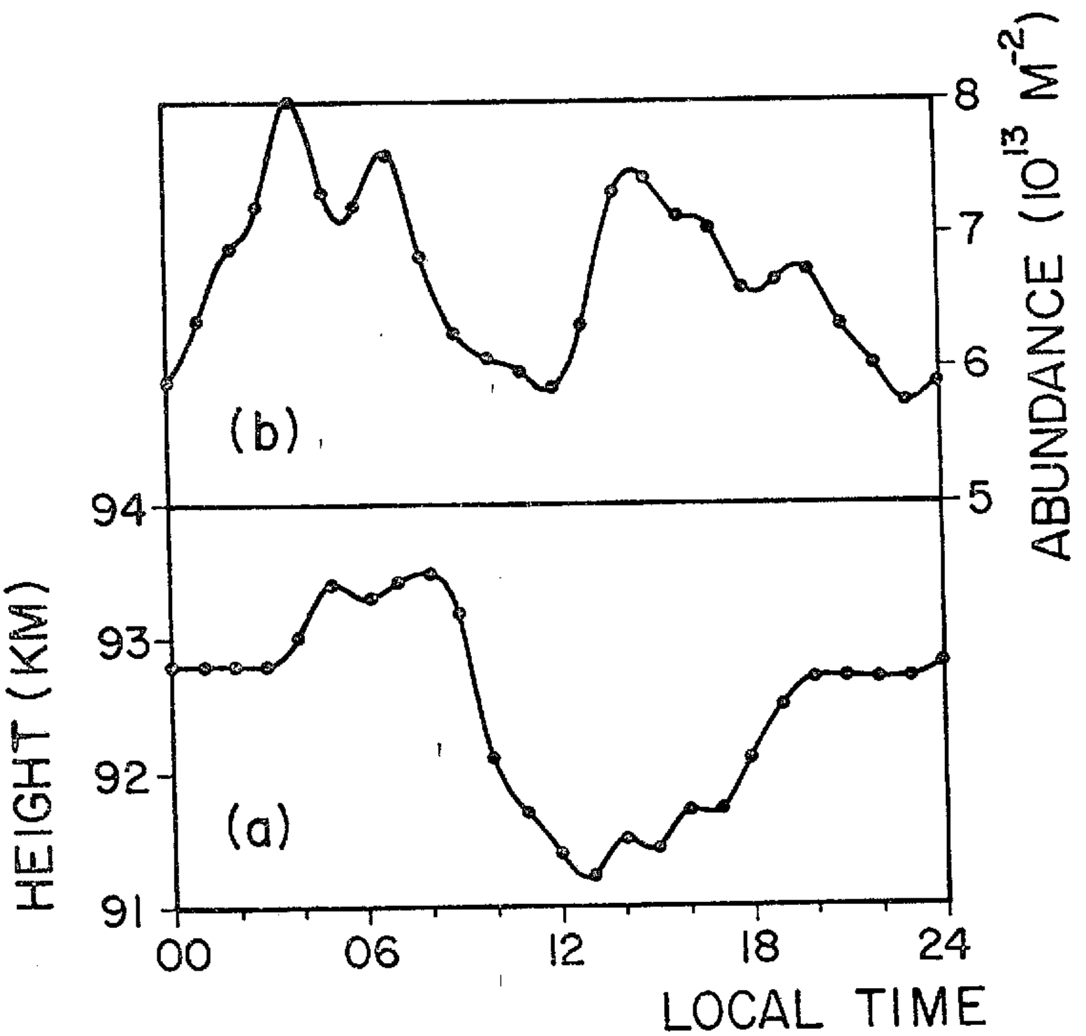

Fig. 6 - Diurnal variations of sodium measured at São José dos Campos.

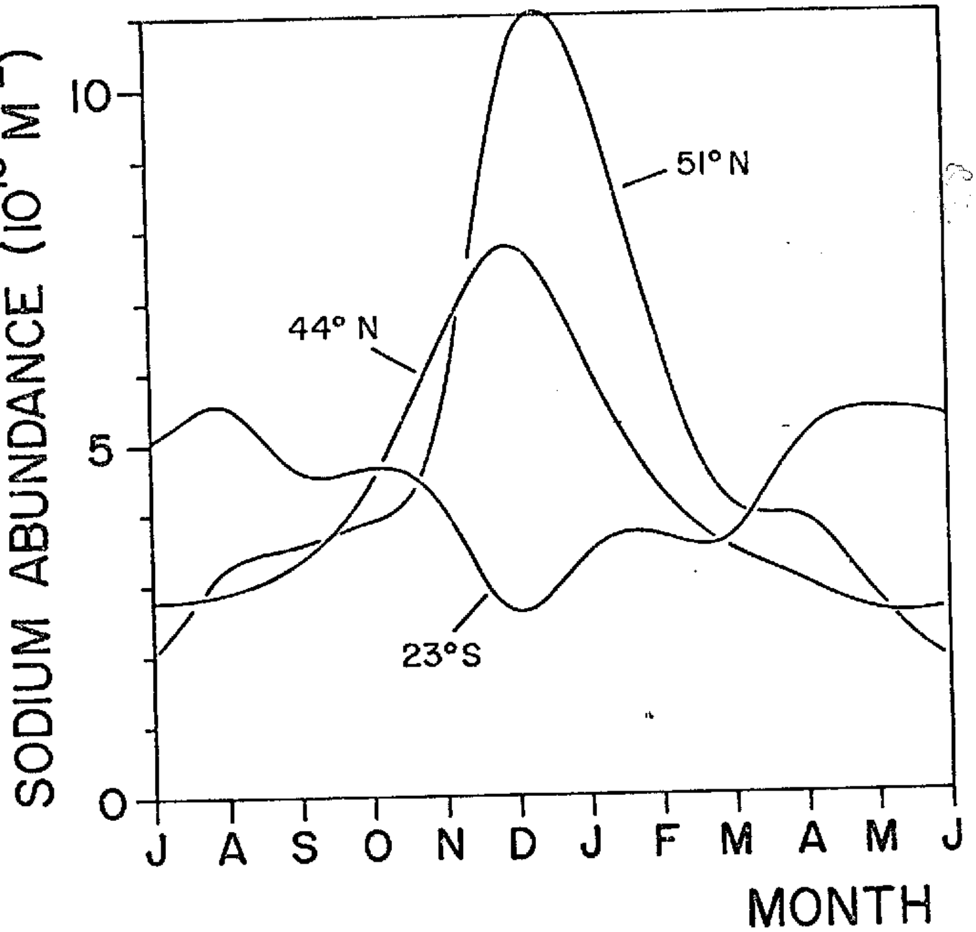

Fig. 7 - Seasonal variations of sodium for three latitudes.