THE ARECIBO POTASSIUM LIDAR DAYLIGHT RECEIVER

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ABSTRACT

We are building a receiver system that will permit high-resolution Doppler-resonance temperature lidar observations of the mesospheric potassium layer under daylight conditions at the Arecibo Observatory, Puerto Rico (18.35°N, 66.75°W). This receiver combines a very narrow field of view with a magneto-optical spectral filter that together reduce the sky background signal by about 40 dB, while having only a minor effect on the signal level. The signal strength is then enhanced by a photon counting avalanche photodiode, which replaces the photomultiplier tube detector.

1. INTRODUCTION

Measurements of the nocturnal thermal structure of the mesopause region have revealed a complex and dynamic environment. Night-only observations show that tidal modulations of the thermal structure require daylight data to fully characterize (see, e.g., Friedman and Chu, Tropical/sub-tropical mesopause thermal structure from Arecibo, PR (18.35°N, 66.75°W) and Maui, HI (20.7°N, 156.3°W) in this volume). For this reason, we are developing daylight capability for the potassium Doppler resonance temperature lidar at the Arecibo Observatory.

The development of the Arecibo K lidar daylight capability follows closely that of *Fricke-Begemann et al.* [1, 2]. As in that work, we have used a three step approach to enabling daylight observations of the terrestrial potassium layer, and through those, measurements of temperatures in the mesopause region. First, we have narrowed the observing field-of-view in order to reduce the volume of sky from which scattered sunlight enters the detector, while still receiving all of the signal photons. Second, we have built a special magneto-optical filter, called a Faraday Anomalous Dispersion Optical Filter, also known as Faraday Filter or FADOF, in order to reduce the solar background light through spectral filtering. Finally, we have implemented a Geiger-mode avalanche photodiode (APD) to greatly enhance photon detection efficiency, and hence the signal strength.

The use of the FADOF as a narrow-band filter for upper atmospheric lidar was first demonstrated by *Chen et al.* [3]. They have now made measurements with this filter for a decade, and other Na FADOFs are in use throughout the world. Due to its high density in the mesopause region, sodium signal is strong, and single-channel versions of these polarization-sensitive devices are generally used, accepting the loss of half of the signal.

Potassium lidars do not enjoy the benefits of large atomic abundance—the K abundance is only about 1% that of Na. For this reason, a two-polarization K FADOF was developed for lidar, with a total throughput of 75% at the resonance wavelength [1]. The reduced K signal as compared with Na is compensated for in two other ways, one is that available laser technology permits much larger laser pulse energy to be applied to the K layer, and the other is that an APD detector replaces the photomultiplier tube, resulting in four-times better photon detection efficiency.

This paper describes the development we have undertaken in three sections. First, we describe field-of-view narrowing and the issues involved. Second, we discuss the implementation of the FADOF. Third, we present the use of the APD detector and how it is implemented. Finally, we show anticipated performance of the receiver in daylight conditions.

2. FIELD OF VIEW REDUCTION

There are a number of parameters to consider when narrowing the field-of-view of a resonance lidar. Due to the fact that fluorescence is subject to saturation effects, there are hard limits to the laser intensity that can be applied to the metal layer [4]. The two systematic factors that affect this are the laser power and the beam cross-section. The first factor is substantially mitigated in K lidars versus Na lidars because the pulse peak power is almost two orders of magnitude lower, as the laser energy is distributed in a much longer pulse (> 200 ns) from alexandrite lasers than it is from Nd:YAG lasers (< 10 ns). The second factor is the major issue in field-of-view reduction.

Solar background reduction for daytime lidar gains most by reducing the field-of-view of the receiver. Limitations include telescope numerical aperture (NA) and the NA of the receiver train—which is in this case an optical fiber. The telescope is a 80-cm f/15 cassegrain. At a distance of 23 cm from the focus a 50-mm focal length condensing lens is inserted, resulting in a system NA of 0.19. This light is coupled into an optical fiber. For nocturnal observing, a fiber with 1.5 mm core diameter and NA=0.39 is normally used. Projected on the sky through the telescope, this fiber results in a field-of-view on the sky of 0.7 mrad. The

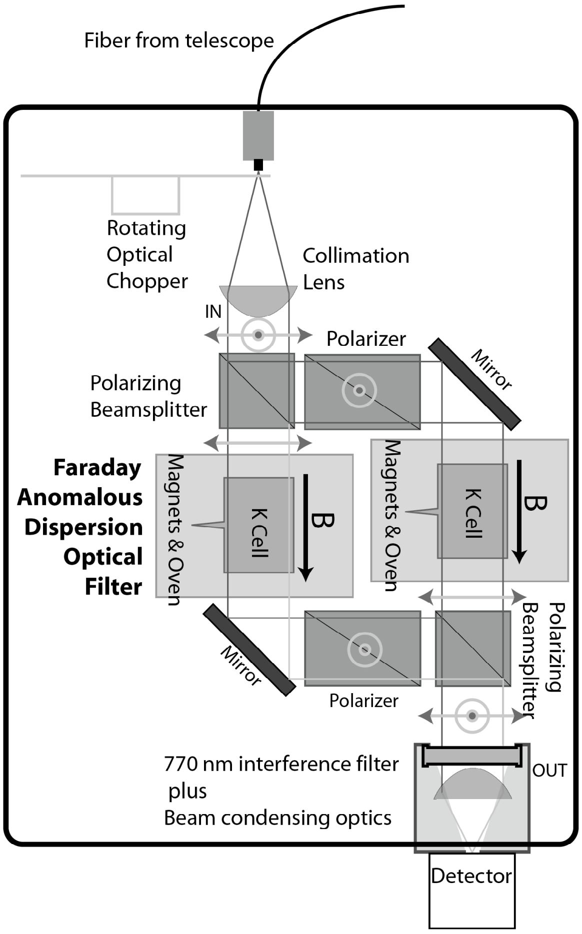

Fig. 1. K lidar daytime receiver layout from optical fiber to detector.

aperture étendue is 0.59 mm, while the telescope étendue, at 0.7 mrad full angle, is 0.28. For daytime observing this is replaced by a fiber of core diameter 0.55 mm and NA of 0.22. The field of view (full angle) is then reduced from 700 to 250 μrad, and the result is a background light reduction by a factor of 7.4. The reduction in fiber NA from 0.39 to 0.22 gives additional background light reduction. Daytime étendues are 0.10 and 0.12 mm for the telescope and fiber, respectively.

With such a tight field-of-view, maintaining alignment between the transmitter and receiver is not trivial. Thermal changes in the lab or around the telescope can cause enough mechanical shifting to misalign the system. For this reason, we will add active alignment maintenance. This will be done by modulating and adjusting the pointing of the transmitter beam while optimizing the return signal from Rayleigh scattered light from the stratosphere.

3. FARADAY FILTER IMPLEMENTATION

The Faraday filter depends on polarization rotation and Zeeman Effect line splitting of photons in resonance with the atomic transition of an atomic or molecular vapor. Because the filter is polarizing, half of the signal photons do not make it through, but are rejected by the first polarizer. These are sent through a second filter, which is oriented orthogonally to the first. The FADOF bandwidth is tailored to the application, which for K lidar is around 3–3.5 GHz, or 6–7 pm. This is under 1% of the bandwidth of the interference filter, which is used for both night and daytime operation. Background light is further reduced by the fact that the solar background within the filter band is reduced by 80% due to the narrow solar Fraunhofer line [5, 6]. Together the filter and low solar intensity reduce the background by about 30 dB. The remaining ~10 dB background reduction comes from the narrower field-of-view.

The FADOF is mounted on an optical bench with the layout as shown in Fig. 1. The complete unit, including the input fiber and the condensing lens are enclosed inside a light-tight box. The fiber and condensing lens are mounted to the optical bench with special flanged holders in order to prevent stray light from entering the filter. The detector lies outside the filter and is baffled to block stray light. A rotating wheel chopper/shutter is used to block light from low altitudes entering the detector. Its rate is phase-locked to a multiple of the laser repetition frequency.

4. AVALANCHE PHOTODIODE

The Avalanche Photodiode (APD) is shown in Fig. 1 as “Detector”. An APD is not a simple replacement for a

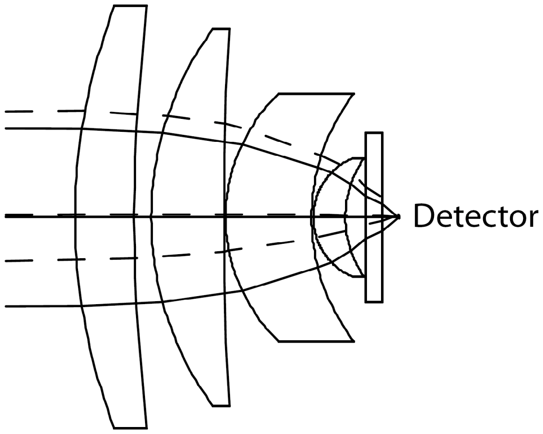

Fig. 2. Optical layout of the APD condenser lens system for the Arecibo K lidar detector. The first three lenses are off-the-shelf and have focal lengths of 100, 40 and 36.5 mm, while the fourth is a custom meniscus designed to provide both the final focal step and minimize spherical aberrations. The combination provides the required demagnification power with minimal spherical aberration. The flat is the detector window. The solid lines are the paraxial rays, while the dashed represent the field subtended by the finite fiber size.

photomultiplier tube (PMT). Although there is a great benefit to the increased photon detection efficiency, 68% as compared with 15% for a GaAs PMT at 770 nm, the APD has less dynamic range than a PMT, and it must be protected carefully from saturation. Implementation of the APD is a complication. The photocathode is only 0.17 mm diameter, which is ~0.3× the diameter of the fiber. Further complicating the situation is the fact that the fiber NA is 0.22, so we have to demagnify the fiber tip with an NA of 0.71 to image it completely on the APD. A special lens combination has been designed for this purpose, which is shown in Fig. 2.

In Fig. 2, there are two sets of rays. These represent the finite size of the fiber tip as projected through the optical system of Fig. 1. The solid lines are the axial rays, while the dashed lines represent the off-axis rays.

5. SYSTEM PERFORMANCE

The present and expected system performance parameters are shown in Table 1. The present performance parameters are based on nighttime operations with a PMT detector. Expected parameters following the daytime upgrade are calculated for both night and day observing. Note that the nighttime performance is expected to improve by about a factor of two even though the FADOF remains in the receiver, while the daytime performance should be almost identical to the present nighttime performance.

Fig. 3 shows the transmission curve for a prototype filter we have constructed. The plot also shows fringes from a confocal etalon with a free-spectral-range (FSR) of 2.0 GHz (long dashes) and the K Doppler-free fluorescence spectrum (short dashes), which were recorded simultaneously with the filter curve and are used to give a frequency scale. This filter closely matches the theoretical curve for a vapor temperature of 110 C and axial magnetic field of 1400 Ga.

The emission spectrum from the K D_1 resonance consists of 12 lines, representing all possible transitions in the combined absorption emission process in the Doppler-broadened distribution of atoms. The FADOF filters this emission spectrum, and when exciting the fluorescence in the spectral wing the highest frequency emission lines lie on the edges of the filter transmission curve. Increasing the magnetic field, with a resulting

Table 1. Present and expected Temperature Error for the Arecibo K Lidar at T = 200 K, 10 minute integrations and 3 km average. Daylight values are based on background levels for a 45° solar zenith angle [1].

	ΔT at peak	ΔT at RMS
Present	4.1 K	6.8 K
After Upgrade – night	2.3 K	3.8 K
After Upgrade – day	4.2 K	6.9 K

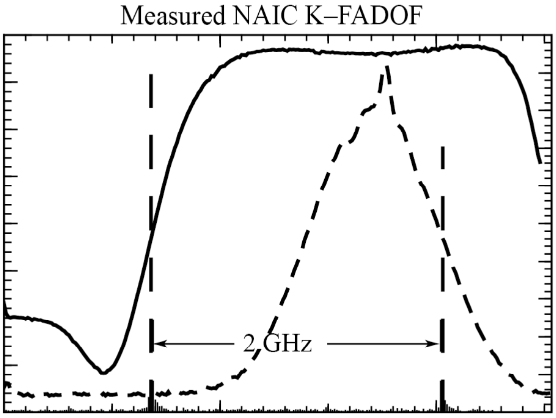

Fig. 3. Measured transmission curve for the Arecibo prototype FADOF. Below the transmission curve are the Doppler-free fluorescence spectrum from our K cell (short dashes) and the peaks from a 2.0 GHz free-spectral-range confocal etalon (long dashes). Both are used to compute a frequency scale. This filter closely matches a model curve for a vapor temperature of 110 C and magnetic field of 1400 Ga.

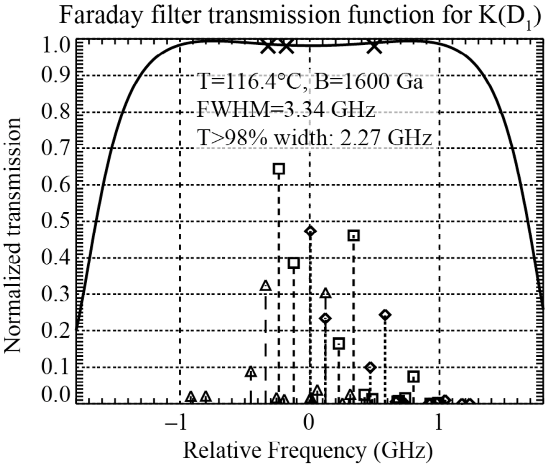

Fig. 4. Theoretical transmission function for a K FADOF with vapor temperature of 116.4 C and axial magnetic field of 1600 Ga. In the transmission curves the laser frequencies for exciting the mesospheric K are shown by the '×' symbols. Under the transmission curve are the 12 emission lines for each excitation frequency. The long-dashed lines with triangles are for the red-shifted excitation (left ×), the medium dashes with squares are for the center excitation (center ×), and the short-dashed lines with diamonds are for the blue-shifted excitation (right ×).

increase required in K atom density in the filter cell, broadens the filter width. One can then choose between accounting for the filter shape in computing temperatures from the mesospheric potassium on the one hand, or using a broader filter width and allowing somewhat more background light through on the other.

A filter with a spectral width of about 3.5 GHz provides excellent background reduction and has little effect on the emission spectrum. We have calculated its effect on the temperature computation, and it comes to under 0.5 K at an atmospheric temperature of 200 K. Thus, we have specified to the filter manufacturer a magnetic field of 1600 Ga and cell oven temperature of 116.4°C. The theoretical transmission curve for this filter is shown as the solid line in Fig. 4. Under the curve are plotted emission spectra for each of the three excitation laser frequencies. The long-dash/triangle emissions correspond to laser excitation at –241 MHz from the center wavelength. The short-dash/square emissions correspond to the center laser excitation, which is –180 MHz from the spectral center of mass. And the short-dash/diamond emissions correspond to those from excitation at +678 MHz from the center wavelength. Only the two weakest emissions from the blue-shifted excitation lie outside the flat-top part of the filter (>98% transmission).

The effect of the filter on atmospheric Rayleigh scattering is a more important consideration because its spectral width is twice that of the resonance spectrum. Scattered light from 35–45 km is used to calibrate the signal and make accurate density measurements. The Faraday Filter bandpass must be deconvolved from the Rayleigh spectrum, and this depends on what part of the spectrum the laser is tuned to and the mean temperature in the 35–45 km altitude range. The filter function will be closely monitored for this purpose, while we will use an atmospheric model such as MSIS to provide the stratospheric temperatures in order to achieve precise measurements of mesospheric potassium density and temperature.

It is not known at this time how close to local noon the daytime lidar can operate. The Na lidar at CSU [3] operates in midsummer with a solar zenith angle under 20°, but it is likely that there are fewer aerosol particulates above Fort Collins than Arecibo. This is one of a number of parameters that will be determined when the daytime lidar is operational.

CONCLUSIONS

We are in the process of upgrading the Arecibo Observatory K Doppler-resonance temperature lidar for daylight capabilities. This process includes three elements: narrowing of the field-of-view, installing a Faraday filter for spectral filtering, and increasing the photon detection efficiency with a photon-counting APD. These coupled with the solar Fraunhofer line will reduce background light by about 40 dB, thus allowing operation in full daylight. We have built a prototype of the FADOF, which has been thoroughly tested, and the results of these tests were used to specify a filter that will transmit both polarizations with a minimal effect on the temperature measurements while providing excellent out-of-band attenuation and high center transmission. Tests of the daylight capability and initial daylight measurements are planned for late-2006.

ACKNOWLEDGMENTS

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