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Author(s): David C. Thompson, CST-1
Clifford J. Hewitt, CST-6
Carl W. Wilson, CST-6

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A rapidly-tunable acousto-optic spectrometer for a space environment

David C. Thompson, Clifford J. Hewitt and Carl W. Wilson
Los Alamos National Laboratory, M/S E548, Los Alamos, NM 87545

ABSTRACT

As a complement to our work developing rapidly-tunable (~10-100 kHz) CO₂ lasers for differential absorption lidar (DIAL) applications,¹ we have developed a rapidly-tunable spectrometer. A rapid spectral diagnostic is critical for a high speed DIAL system, since analysis of the return signals depends on knowing the spectral purity of the transmitted beam. The spectrometer developed for our lidar system is based on a double-passed large- (75 mm) aperture acousto-optic deflector, a grating, and a fast single-element room temperature mercury-cadmium-telluride detector. The spectrometer has a resolution of ~0.5 cm⁻¹, a tuning range of 9.0-11.4 μm, a random-access tuning speed of greater than 80 kHz and a S/N ratio of greater than 100:1. We describe the design and performance of this device, as well as of future devices featuring improved resolution, higher speed and easier and more robust alignment. We will also briefly discuss the applications and limitations of the technique in a space environment.

Keywords: Acousto-optic, spectrometer, frequency-agile

1. INTRODUCTION

Lasers play a key role in many space-based applications. These include spectroscopy, metrology, and communications. In many of these applications, rapid and precise measurement and control of wavelength is of great importance. Lasers with narrow linewidths and broad tuning ranges are central to spectroscopic applications such as sensing of atmospheric constituents. Lidar measurements of various types, including differential absorption and Doppler measurements using heterodyne systems also rely on tunable laser oscillators. Wavelength agility is required to overcome changing conditions, such as atmospheric fluctuations, and for attaining high data rates. Therefore spectral diagnostics that can cover a wide spectral range with high resolution are critical.

We have developed a rapidly-tunable spectrometer as a complement to our work developing rapidly-tunable (~10-100 kHz) CO₂ lasers for differential absorption lidar (DIAL) applications. A rapid spectral diagnostic is critical for a high speed DIAL system, since analysis of the return signals depends on knowing the spectral purity of the transmitted beam. Our laser tuning technique uses a pair of AO intracavity modulators, essentially acting as a pair of tunable transmission gratings.¹

Figure 1 illustrates some of the basics of acousto-optic devices. The geometry of the acousto-optic interaction is shown in Figures 1a and 1b, and the AO device is shown schematically in Figure 1c. Momentum conservation between the sound and light waves requires that the incident and diffracted light waves (of vacuum wavelength λ) both be at an angle θ_B with respect to the sound wave (with frequency ν and velocity V_a) for efficient diffraction, with θ_B , the Bragg angle, given by

$$\frac{\lambda \nu}{2V_a} = \sin \theta_B \quad (1)$$

When the interaction length between light and sound is long enough (the Bragg regime), the theory of AO interactions^{2,3} predicts that the incident wave is diffracted into one (first order) diffracted wave with an efficiency that depends on the acoustic power and with essentially 100% efficiency at the correct acoustic power. While a number of effects can reduce this efficiency, these effects can usually be made quite small. The diffracted wave is

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also shifted in frequency relative to the incident wave by the acoustic frequency, with the sign of the shift depending on the relative orientation of the optical and acoustic waves. In isotropic media, this shift may be thought of as the Doppler shift of the optical wave in diffracting from the advancing or retreating acoustic wavefronts. A more generally applicable analysis in terms of conservation of energy gives an upshift when a phonon is absorbed, as in Fig. 1a, and a downshift when a phonon is emitted, as in Fig. 1b.

Figure 1. Acousto-optic modulators and deflectors. Efficient diffraction occurs when momentum is conserved between the incident (k_i) and diffracted (k_d) optical k-vectors and the acoustic k-vector (K). In (a), a phonon is absorbed from the upward-propagating acoustic wave, $k_d = k_i + K$, and the diffracted light is up-shifted in frequency. In (b), a phonon is emitted to the downward-propagating acoustic wave, $k_d = k_i - K$, and the diffracted light is down-shifted. An acousto-optic device is shown schematically in (c). A piezoelectric transducer generates an acoustic wave at the frequency of the RF source. Efficient diffraction occurs when both incident and diffracted beams are at the Bragg angle (θ_B) to the acoustic wavefronts.

Note however for a deflector, that as the deflection angle changes so does the Bragg angle. Maintaining high efficiency through the deflectors requires control of the direction of propagation of the acoustic waves. This is usually accomplished by using a phased transducer array.^{4,5}

The basic tuning configuration is shown in Figure 2. The two AO devices operate at the same radio-frequency (RF) frequency, with each efficiently diffracting the incident light. Since the diffracted light is also shifted in frequency (essentially the Doppler shift in scattering from the moving acoustic wave), the two devices are oriented so that the frequency shifts cancel, but the angular deflection of the light adds. In this configuration, the overall dispersion in a cavity round-trip is four times the dispersion from a single pass of one device. For a given acoustic frequency, only light of the selected wavelength is retro-reflected back into the gain medium. The tuning speed is limited only by the transit time of the acoustic beams across the optical beam. For typical beam sizes of a few millimeters, this gives tuning rates of up to ~ 1 MHz. In practice, gain recovery dynamics in the laser medium have limited our tuning rates to ~ 100 kHz.

Figure 2. Laser tuning using two AO modulators. The resonator is formed by a high-reflector (HR), a gain cell (GC), and an output coupler (OC). Only the selected wavelength is deflected by the two AO modulators (AOM1 and AOM2) so as to exactly retro-reflect. The selected wavelength is always at the Bragg angle.

For our application, we wish to be able to easily separate adjacent CO₂ laser transitions in the 9-11 μm wavelength range with a minimum spacing of $\sim 0.01 \mu\text{m}$. Therefore resolutions of ~ 2000 or more are required. The required combination of high speed, wide spectral range and high resolution presents a challenge. One approach might be a fixed spectrometer combined with a large array of detectors. However such arrays are either too slow, in the case of pyroelectric arrays, or too expensive, in the case of faster detectors such as Mercury-Cadmium-Telluride (MCT). Our approach has been to combine acousto-optic deflection to rapidly scan a spectrometer with a fast single-element detector.

Acousto-optic technology has many advantages for high speed diagnostic applications. While not as fast as electro-optic devices, acousto-optic deflectors, modulators and filters are far faster than mechanical methods and are a reliable and well-developed technology with no moving parts. They feature large angular ranges and high efficiencies and contrast ratios. Furthermore, voltages are generally low, important in field systems. Acousto-optic materials are available for wavelengths from UV to LWIR; in fact shorter wavelength devices are easier to build, with a better selection of materials and much lower acoustic power requirements.

2. PRESENT SPECTROMETER

The present spectrometer is shown schematically in Figure 3. The instrument is essentially an acousto-optically-scanned monochromator, with the beam waist of the focused input laser light and the detector forming the input and output slits, respectively. The input beam is expanded and collimated to fill the 75 mm (horizontal) aperture of the acousto-optic deflector (AOD) (Isomet Model LS600), while a cylindrical lens produces a narrow vertical focus at the grating. This enables all the light to pass through the 4 mm vertical aperture of the deflector. The 75 lines/mm grating operates in a Littrow configuration, with the angle of incidence varying with the AO deflection angle, depending on the wavelength and the acoustic frequency, according to Eq. 1. Light of the selected wavelength passes back through the deflector and is focused onto a small room-temperature MCT detector (Vigo System) by the collimator and a second cylindrical lens. Separation of the input and output paths is enabled by a small vertical tilt at the grating. Flat fold mirrors are used to reduce the overall size of the instrument, as well as to further separate the input and output optical paths.

The first-order design equations for this device are as follows. The net dispersion due to the two passes through the deflector and the Littrow grating is given by

$$d_{eff}^{-1} = \frac{N_g}{d_g \cos \theta_g} \pm N_a \frac{v_a}{V_a} \quad (2)$$

Figure 3. Schematic of AO spectrometer, with top (above) and side views. Light is focused onto the alignment pinhole and expands in the horizontal direction to the collimating mirror, while in the vertical direction it is collimated at a small size by the cylindrical lens. After passing through the AO deflector (twice) and being diffracted by the grating, which also introduces a small vertical angle to separate the input and output beams, the light is focused onto a small detector by the collimating mirror and a second cylindrical lens. Flat fold mirrors reduce the overall size of the instrument.

where d_g and θ_g are the grating line spacing and Littrow angle, respectively, and N_g , the number of grating diffractions is 1 here, and v_a and V_a are the acoustic center frequency and velocity, and N_a , the number of AOD passes, is 2 here. Then for a given center wavelength, λ_0 , and acoustic bandwidth $\Delta\nu$, the required net dispersion is determined by the required wavelength range $\Delta\lambda$, in turn determining d_g :

$$\Delta\lambda_{tune} = \frac{N_a \lambda_0 \Delta\nu / V_a}{d_{eff}^{-1}} \quad (3)$$

Then the wavelength resolution and the maximum tuning speed are both determined by the horizontal beam size, D :

$$\Delta\lambda_{res} = \frac{\lambda_0 / D \cos \theta_g}{d_{eff}^{-1}} \quad (4)$$

$$\nu_{tune} = \frac{V_a}{D} \quad (5)$$

Table 1 shows the design values, based on these equations, for a deflector bandwidth of 40 MHz about a center frequency of 70 MHz, an aperture, D, of 75 mm, and a 75 lines/mm grating. The acoustic velocity in Germanium is 5.5 mm/ μ s. Also shown is the measured performance. Figure 4 shows the laser output spectrum for nominal 10P22 (10.611 μ m) operation, with the laser slightly detuned to give some output at 10P20 (10.591 μ m) also. The spectrum is accumulated during repetitive pulse operation at 5 kHz, with the lasing on a different line each pulse. Each time the laser is nominally on the 10P22 line, the acoustic frequency is incremented to look at a different wavelength. Spectra for other laser lines can be accumulated in the meantime, when the laser is pulsed on those lines.

Parameter	Design Value	Measured Value
Tuning range	9.0 to 11.4 μ m	< 9.2 to > 11.2 μ m
Resolution (diffraction-limited)	0.27 cm^{-1}	---
Resolution (detector-limited)	0.40 cm^{-1}	0.5 cm^{-1}
Speed	73 kHz	73 kHz
Noise-equivalent laser power	0.12 mW	< 1.6 mW

Table 1. Design and measured values of various spectrometer performance parameters.

Figure 4. Spectrum of nominal 10P22 output from rapidly-tuned laser. Some 10P20 output is observed, due to laser de-tuning.

The control system for the spectrometer is shown in Figure 5. The laser's computer data acquisition and control system provides a digital frequency value at which to start the acoustic frequency scan, as well as a trigger when the laser is about to pulse on the line of interest. Together with manually-set digital values for the frequency increment and the number of points in the scan, these provide the inputs to a counter/adder circuit that outputs a sequence of digital frequency values. These are input to a rapidly-reprogrammable (~ 40 ns) digital frequency synthesizer.

(NEOS Technologies Inc. model N64010-200). The AO deflector uses a phased array to maintain approximate Bragg matching over the full bandwidth, so following amplification this radio-frequency (50-90 MHz) is split by a high power 4-way splitter and the signals to the 4 transducers are delayed by multiples of 14 ns. In our system, the signal from the detector is integrated, digitized, and stored by the computer data acquisition system. It may also be observed on an oscilloscope.

Figure 5. Control and data acquisition system for spectrometer. The computer data acquisition and control system for the rapidly-tuned laser also generates the initial frequency for the scan and synchronizes the spectrometer scan with the laser pulses.

Due to the relatively large aperture used and the long wavelength, the total peak RF power delivered to the deflector is ~ 100 W. Since AO power requirements scale as λ^2 , shorter wavelengths require substantially less power. Also, average powers may be substantially less, depending on repetition rates. For the full 75 mm aperture in a Germanium device, the RF pulse length must be at least $14\mu\text{s}$. Designs that reduce power requirements by using a smaller vertical aperture than the 4 mm used here are discussed in later sections.

This spectrometer has been in routine operation with our field lidar system for 2 years, and has proved invaluable in assuring single-line operation of the lidar transmitter.

3. IMPROVED SPECTROMETER DESIGN

While extremely useful, the spectrometer already described could be improved in a number of ways. We would like to increase the speed to 100 kHz or more. A higher spectral resolution would improve the sensitivity with which weak laser oscillation on neighboring lines could be detected. And the layout could be improved to make alignment easier. Therefore to address these issues, we have designed an improved spectrometer, which we are in the process of building.

The new design is shown in Figure 6. The most important change is that the entire spectrometer is double-passed. This doubles the spectral resolution for the same horizontal aperture (N_a and N_g are doubled in Eqs. (2) and (3)). Then by reducing the aperture to 55 mm, the speed can be increased to 100 kHz while also increasing the spectral resolution. The remaining changes in layout should facilitate alignment. Separation of the input and output beams occurs using a 50% beamsplitter, with the input and output collinear. This reduces the required vertical aperture of the AO deflector. While the signal is reduced by a factor of 4, this can be compensated for by using a more sensitive detector, an optically-immersed 1 mm^2 effective area TE-cooled MCT photoconductor (Vigo System #PCI-L-2TE). A slit of width of $\sim 100\text{ }\mu\text{m}$ located in front of the detector should match the spot size from the 500 mm focal length

collimator. Also, to facilitate alignment with a visible laser, all powered optics are reflective. An additional option to obtain higher data rates would be to use a small linear array in place of the single element detector. The acceptance angle for the deflector is determined by the divergence of the acoustic beam and is $\sim n_0 V_a / L v_a$ where L is the acoustic transducer length. So here with $L = 17$ mm, $v_a = 70$ MHz and $n_0 = 4.0$, an array with element width ~ 100 μ m and length small compared to 9 mm would be suitable.

Figure 6. Schematic diagram of improved spectrometer design. The number of passes of AOD and grating is doubled, allowing higher resolution with reduced aperture and higher speed. Separation of input and output light is with a beamsplitter, reducing AOD vertical aperture requirements and making alignment easier.

The expected performance of the new spectrometer is set out in Table 2.

Parameter	Design value
Tuning range	9.0 to 11.4 μ m
Resolution (diffraction-limited)	0.22 cm^{-1}
Resolution (slit-limited)	0.29 cm^{-1}
Speed	100 kHz
Noise-equivalent laser power	7.5 μ W

Table 2. Design values of various spectrometer performance parameters.

4. A NOVEL ACOUSTO-OPTIC SPECTROMETER

The combination of an AO deflector and a grating has the advantage of combining the rapid tunability of the AO device with the resolution of the grating. However, the requirement of Bragg matching makes it difficult to maintain high diffraction efficiency and spectrometer transmission over a wide range of deflection angles and wavelengths. The phased array approach can maintain approximate Bragg matching and provide high enough

diffraction efficiencies for geometries with a few passes. But for increased resolution, we are led to consider a geometry closer to that of the laser tuner in Fig. 2. With the elimination of the grating, Bragg matching is near-perfect, diffraction efficiencies can be very high ($\sim 97\%$ has been achieved¹), and resolution can be increased by using many passes of the device. If a pair of AO modulators like those in Fig. 2 were combined with a resonator structure to provide multiple passes, as depicted in Figure 7, a spectrometer with a number of interesting properties would result.

Figure 7. Combination of AO tuner with Fabry-Perot resonator structure. In the horizontal direction (top view), the light is collimated at a relatively large diameter, is deflected by the AO modulators AOM1 and AOM2, and bounces between partially-reflecting mirrors M1 and M2, which are planar along the horizontal direction. In the vertical direction, the light is focused into the AOM's, to minimize the vertical aperture requirements on the AOM's. Light exiting the resonator is focused onto a slit, to select one wavelength, similar to the laser tuner in Figure 2.

In Figure 7, we see that light bounces between partially-reflecting mirrors, with a pair of acousto-optic modulators between. The angle between the two mirrors sets up a condition for the wavelength that strikes the mirrors at normal incidence. This wavelength varies with the acoustic frequency applied to the two AOM's according to Eq. 1. As for the AO tuner, the acoustic wave propagation directions for the two AOM's are approximately counter-propagating, resulting in cancellation of the frequency and/or phase shifts introduced by the two AO devices. In order to maximize resolution but minimize the acoustic power required, it is best to use an asymmetric beam, with small vertical size and large horizontal size. This can be achieved as shown in Fig. 7, by focusing in the vertical direction while maintaining a collimated beam in the horizontal plane. The asymmetric input beam could be generated with an astigmatic afocal telescope, in the case of a laser, or with incoherent light by appropriately illuminating a slit and collimating the light from the slit. When light exiting the resonator is focused onto a slit or small detector, a single wavelength is selected.

There are two modes in which this configuration can be used. If the frequencies applied to the two AOM's are equal, then there is no net frequency shift. However, the pair of AOM's operate as an optical phase-shifter inside

the resonator. In this case, we have an acousto-optically-tuned Fabry-Perot resonator. Since the optical phase shift is cumulative on consecutive passes, the resonator is scanned over one free spectral range as the phase difference between modulators is varied between 0 and π . As with the other AO devices described earlier, the device speed is limited only by the transit time of the acoustic beam across the optical aperture, so this phase difference and the resonant wavelength can be changed very rapidly. However in addition to this, the lateral dispersion of the two AO modulators provides additional filtering, so it can be used as an order sorter and reduce or eliminate the ambiguity between multiple Fabry-Perot orders.

The wavelength resolution of the AOM's, from Eqs. 2 and 4 (with $N_g = \theta_g = 0$ since there is no grating), is

$$\Delta\lambda_{res} = \frac{\lambda V_a}{N_a D \nu} \quad (6)$$

and the Fabry-Perot free spectral range (FSR) is

$$\Delta\lambda_{FSR} = \frac{\lambda^2}{2n_0 L_{FP}} \quad (7)$$

where L_{FP} is the separation of the Fabry-Perot mirrors, in material of index n_0 . Equating these, we have sufficient resolution from the acousto-optic tuner to select a single order of the Fabry-Perot when

$$D = \frac{2n_0 L_{FP} V_a}{N_a \lambda \nu} \quad (8)$$

For example, if we have a pair of Germanium AOM's operating at $\lambda = 10 \mu\text{m}$ and $\nu = 200 \text{ MHz}$, a reasonable round trip efficiency of $\eta \sim 75\%$ and $N_a \sim 16$. For $L_{FP} = 20 \text{ mm}$, we have $D = 28 \text{ mm}$. The Fabry-Perot FSR is 0.063 cm^{-1} and the finesse, given by

$$F = \frac{2\pi\sqrt{\eta}}{1-\eta} \quad (9)$$

is ~ 22 . Then the overall resolution is 0.0029 cm^{-1} or $\lambda/\lambda_{res} = 350,000$.

The second mode is to operate the two AO modulators at different frequencies, or use only a single modulator, so that there is a net frequency shift $\Delta\nu$ on the light after each round trip. Then light from each round trip is incident on the detector with an incremented optical frequency. The beats between these different "orders" can be detected as a series of harmonics at frequency $\Delta\nu$, allowing independent measurement of the light from a given number of round trips. By appropriate filtering this allows electronic control of the effective number of round trips and thus the resolution of the spectrometer. The choice between one and two modulators depends on the tradeoff between the greater simplicity, lower losses and greater number of passes possible with a single device and the lower electronic bandwidth and higher resolution per round trip possible with two devices.

Assume Gaussian illumination with (horizontal) beam diameter D , two AOM's operating at frequencies ν_1 and ν_2 with $\Delta\nu = \nu_2 - \nu_1$, resonator mirror reflectivity R and transmissivity T , round trip efficiency η for the AOM's (including diffraction efficiency and absorption), and round trip phase delay of ψ (including the optical path difference and the optical phase shift from the AOM phase difference). Then the optical amplitude after n round trips, relative to the incident amplitude, at a small detector is given by

$$E_n = T\sqrt{\eta}(R\sqrt{\eta})^n \exp(-n^2 x^2 + 2\pi i n \Delta\nu t + i n \psi) \quad (10)$$

where

$$x = \frac{\pi D(\nu_1 + \nu_2) \delta \lambda}{V_a \lambda} \quad (11)$$

is a measure of wavelength detuning $\delta \lambda$.

Then the detector signal S_{det} is composed of beat signals at frequencies $n\Delta\nu$, given by

$$S_n = 2T^2 \sqrt{\eta} (R\sqrt{\eta})^n \exp(-n^2 x^2) \sum_{j=0}^{\infty} (R^2 \eta)^j \exp[-2j(4n+j)x^2] \quad (12)$$

for $n > 0$. A straightforward way to produce a spectrometer signal would be to high-pass filter the detector signal with a cut-off frequency corresponding to some number of round trips n_{min} . The results can be calculated numerically, and the full-width at half-maximum Δx is $\sim n_{min}^{-1}$. For a specific example, if we assume a round trip AO efficiency $\eta = 0.75$ and $R = 0.72$, which optimizes the signal for $n = 4$, and set $n_{min} = 4$, we find $\Delta x \sim 0.3$. Then if we have $\nu_1 + \nu_2 = 160$ MHz and $D = 10$ mm, we get $\Delta \lambda = 0.0033 \mu\text{m}$. The signal corresponds to 0.032 of the signal corresponding to the incident beam.

Another approach is to take the detector signal, multiply it by a reference signal at the fundamental frequency $\Delta\nu$ with suitable harmonic amplitudes, and integrate. In this way, we can recover the phase information. If the reference signal is given by

$$S_{ref} = \sum_{n=n_{min}}^{\infty} b_n \cos(2\pi n \Delta\nu t) \quad (13)$$

Then the integrated signal S is given by

$$S = \int_{-\infty}^{\infty} S_{det}(t') S_{ref}(t') dt' = \sum_{n=n_{min}}^{\infty} \cos(n\psi) S_n b_n \quad (14)$$

If, for example, $b_n = a^n$, then it can be shown that for $x = 0$,

$$S \propto \frac{1}{(1 - aR\sqrt{\eta})^2 + 4aR\sqrt{\eta} \sin^2\left(\frac{\psi}{2}\right)} \quad (15)$$

This is the usual Fabry-Perot response function, showing that we have recovered the necessary phase information. What is more, by manipulating the coefficients b_n in Eq. 13, the effective finesse can be changed. For example in Eq. 15, the effective finesse is

$$F = \frac{2\pi\sqrt{aR\sqrt{\eta}}}{1 - aR\sqrt{\eta}} \quad (16)$$

Since a can be greater than 1, it would appear that the finesse can be made infinitely large, independent of the values of R and η . This is due to the fact that increasing the coefficients b_n for larger n has the effect of emphasizing the larger round trip numbers. Of course as the light makes more and more round trips, the amplitude decreases, so eventually the resolution is limited by detector noise, the number of photons, or the dynamic range of the multiplier.

Electronic control of resolution, rapid control of phase, and variable spectral selectivity from the transverse dispersion provide much flexibility and a reconfigurable filter or spectrometer. In addition, the collinearity of the multiple passes (as opposed to the angular and spatial separation of the multiple passes in the devices discussed earlier), allows the use of acoustic transducers of minimum height, reducing acoustic power requirements.

5. ISSUES FOR ACOUSTO-OPTIC SPECTROMETERS IN SPACE

Up to now, we have primarily described devices built or designed for field systems, but not for space applications. Many of the useful characteristics of such instruments will also apply in a space environment. The lack of moving parts and the maturity, reliability and robustness of AO technology are important. The relatively low voltages are easier to handle than the much higher voltages required for electro-optic techniques – particularly in the infrared where electro-optic devices commonly require voltages of several kV. The large angular ranges possible from AO devices make compact instruments achievable.

However, some considerations for space environments need to be addressed. These include power requirements and environmental effects, such as temperature variations and radiation.

Acousto-optic devices can require a lot of power, particularly in the infrared due to the λ^2 dependence of the acoustic power required for high efficiency. Optimized geometries can reduce the power required. For the example discussed in Section 4, operating at 10 μm and 160 MHz with a single Germanium AO modulator of length 20 mm and corresponding minimum height of ~ 0.4 mm, the peak RF power required is about 9 W. With a beam diameter of 10 mm giving a required RF pulse length of 1.8 μs , the average power at a repetition rate of 100 kHz would be 1.6 W. There are other infrared materials with lower power requirements for high efficiency. For example Thallium Arsenic Selenide (TAS) requires about 20 times less power. However, like several other alternate materials, it has much poorer mechanical and thermal properties than Germanium, which is the most commonly used IR acousto-optic material. For AO devices in the visible or near IR, power considerations are much less important.

There have been a number of reviews of the effects of space environments on various optical components. See, for example, Refs. 6-8. The potentially susceptible components are the electronics, the optics, the AO devices and the detector(s).

Based on long use of both RF electronics for communications applications and many different kinds of optics for satellite remote sensing in all spectral bands, it is likely that the required electronics and optics can be made sufficiently immune to environmental influences. There have been a few studies of the influence of ionizing radiation on acousto-optic devices.⁹⁻¹² These have generally concluded that the dominant effect is thermal (rather than increased absorption due to defect formation), with the absorbed radiation giving rise to temperature non-uniformity that in turn result in index of refraction and acoustic velocity gradients that reduce efficiency and cause optical beam deflection and distortion. Absorbed radiation levels in orbits up to 3000 km altitude could be in the range of 10^3 to 10^5 rad (Si)/day or 10^{-7} to 10^{-5} W/g.⁶ Since similar, and usually larger, effects arise from the thermal effects of RF and acoustic power in AO devices, it is probable that any such radiation effects can be ameliorated by the same heat sinking and general thermal engineering techniques necessary for high performance AO devices. Should effects such as increases in absorption due to formation of color centers in bulk AO devices be significant, it appears that some materials are less susceptible. For example several III-V materials are reasonably efficient AO materials across a wide spectral range and seem to exhibit good resistance to radiation effects in various photonic devices.⁸

6. CONCLUSION

We have described a rapidly-tunable spectrometer developed for use with rapidly-tunable (~ 10 -100 kHz) CO_2 lasers. This spectrometer is based on a double-passed large-aperture acousto-optic deflector, a grating, and a fast single-element detector. We describe the design and performance of this device, as well as of a version featuring improved resolution, higher speed and easier and more robust alignment. We have also introduced a new device combining aspects of the acousto-optic laser tuner, a Fabry-Perot resonator and heterodyne detection. This newest concept

features the potential for very high, electronically-adjustable resolutions. We have also discussed the applications and limitations of these techniques in a space environment.

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Correspondence: Email: dcthomp@lanl.gov; Telephone: 505-667-5168; Fax 505-665-4026