A 3 GHz instantaneous bandwidth Acousto-Optical spectrometer with 1 MHz resolution

M. Olbrich, V. Mittenzwei, O. Siebertz, F. Schmülling, and R. Schieder
KOSMA, I. Physikalisches Institut, Universität zu Köln

***Abstract*— The design and implementation of a new broadband acousto-optical spectrometer is discussed. The device has an instantaneous bandwidth of 3 GHz, and a resolution and fluctuation bandwidth of 1 MHz / 1.4 MHz respectively. The backend has no platforming errors and a power linearity in the order of 0.1% over a noise dynamic range of 13 dB. With an Allan minimum time of better than 300 seconds, it is ideally suited for a large number of applications, including measurements that have broad lines like extragalactic sources or planetary atmospheres, as well as line surveys. Also, sources which require a large dynamic range of the receiver are well accessible due to the excellent linearity of the backend. The system includes its own temperature stabilization and can easily be mounted into a standard 19" rack.**

I. Introduction

The exploration of the submm- and FIR frequency range for high resolution spectroscopy has produced large demand for wide band spectrometers, since the required bandwidth for the observation of Doppler-broadened atomic or molecular transitions scale with the frequency of the atomic or molecular lines. For example, extragalactic sources require sometimes about 600 km/sec velocity coverage, which corresponds to about 4 GHz bandwidth at frequencies near 2 THz. With new mixer technologies like Hot Electron Bolometers (HEB) it is now possible to achieve satisfying noise temperatures at these very high frequencies, and a new generation of observatories like SOFIA and Herschel will access this new spectral range in the near future. Similar, studies of pressure broadened lines of trace constituents in the Earth or other planetary atmospheres require large bandwidth as well in order to derive detailed abundance information in higher pressure regimes at lower altitudes. Particularly there the availability of very stable and reliable broadband spectrometers with high linearity is essential. In addition, line surveys will greatly benefit of high resolution large bandwidth backends.

When selecting a backend for a given instrument and observation one has to carefully balance the various advantages and disadvantages of different spectrometer technologies. Criteria should contain the resolution bandwidth, the fluctuation bandwidth (noise for a given resolution), power linearity, platforming effects of hybrid spectrometers, excess noise generated by the backend, and stability.

II. Large Bandwidth AOS design

According to the basics of the acousto-optical principle the required optical aperture Δx of a Bragg-cell for a given frequency resolution bandwidth $\delta\nu$ is defined by

$$\Delta x = V/\delta\nu$$

with V the velocity of the acoustic wave in the Bragg-crystal. The typical velocity of the acoustic shear wave in crystals like $LiNbO_3$ is about 3.5 mm/µsec. Consequently, the length of the illuminated acoustic field in the crystal has to be about 3.5 mm when considering a resolution near 1 MHz.

In order to provide sufficient acoustical power even at the end of the aperture, the acoustic attenuation should be sufficiently small. Since the damping constant of the acoustic field scales with $1/\nu^2$ (ν is the applied radio frequency), there is an upper limit for the maximum usable frequency for a given deflector material. For $LiNbO_3$ the damping constant is about $\delta = 3$ mm (1/e length) at a frequency of 2.1 GHz, which is the center frequency of a typical 1 GHz bandwidth AOS. Therefore, at a frequency of, say, 5 GHz, the resulting 1/e length would reduce to about 0.5 mm, corresponding to a maximum resolution of about 7 MHz. This estimate shows that it is not possible to achieve a satisfying resolution together with a bandwidth of several GHz using the well established $LiNbO_3$ Bragg Cells.

Additionally, an increased bandwidth requires a larger angular spread of the acoustic waves in the crystal. Consequently, the overall efficiency becomes drastically reduced at large bandwidth. Since the acousto-optical efficiency η depends strongly on the wavelength of the light source used in an AOS ($\eta \approx \lambda^{-2}$) one must also go to shorter laser wavelength for broadband AOS than the typically used laser diodes around 780 nm wavelength.

III. Broadband AOS components and setup

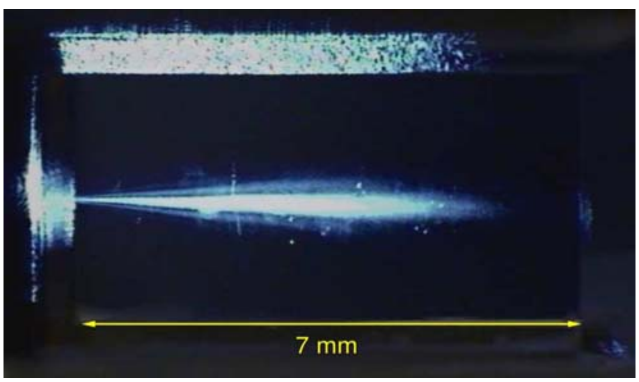
As a consequence from the above discussion it is obvious that a large bandwidth device requires a new Bragg-Cell material and a short wavelength laser light source.

A. Bragg Cell

In close collaboration with BAE Systems (UK) we developed a new Bragg-Cell where Rutile (TiO_2) is used for the first time as deflector material. Rutile has similar acoustical parameters like $LiNbO_3$ but it has a much lower acoustic attenuation. The most important acousto-optical properties are summarized and compared to the well established $LiNbO_3$ in the table below.

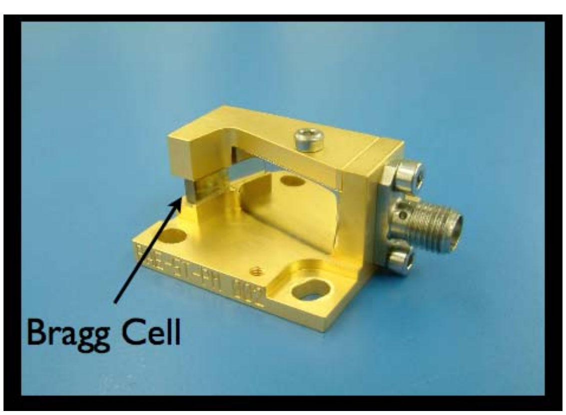
	Rutile (TiO_2)	$LiNbO_3$
Aperture time	1 µs	1 µs
Attenuation @ 2.1 GHz	0.8 dB/µs	4.9 dB/µs
3 dB bandwidth	3 GHz	1.4 GHz
Center Frequency	5.0 GHz	2.1 GHz
Diffraction efficiency	max 2.3 % / W	≥ 10 % / W

The table shows the basic acousto-optical properties of Rutile compared to LiNbO3. Rutile data are kindly provided by Dr. Lionel Kent, BAE Systems (UK)



Schlieren-image of the acoustic wave in the Bragg-Cell

From the acousto-optical properties for Rutile it follows, that the new deflector can provide a bandwidth of at least 3 GHz with a resolution up to 1 MHz. To fully take advantage of these properties, the laser and the CCD have to be selected accordingly.



Photograph of the mounted Bragg Cell. The Bragg-Cell itself has a size of about 7 mm x 3 mm. Picture kindly provided by Dr. Lionel Kent, BAE Systems (UK)

B. CCD

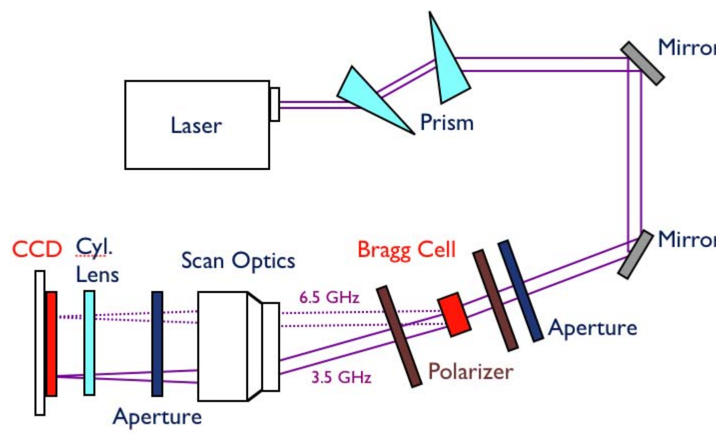
The deflected light from the Bragg-Cell should ideally be oversampled by a factor of two to allow efficient resampling in case the frequency axis of the backend has to be adapted or shifted for data analysis. The Fairchild CCD-191 has 6000 pixels, which exactly matches our requirements. Each pixel is 10x10µm square, the noise characteristics of the CCD allow a Noise Dynamic Range (NDR) of about 13 dB.

C. Laser

As laser we use a commercially available, optically pumped diode laser system (OPS) from Coherent Inc (Sapphire 488-200). It is operating single mode at a wavelength of 488 nm. Its high output power of more than 100 mW, the very clean TEM_{00} beam profile, and its high frequency and power stability make it a perfect light source for the BAOS.

D. Optical Setup

It is evident that the large number of pixels together with the relative low optical efficiency of Rutile requires a careful optical design, even with a rather high laser output power in excess of 100 mW. The schematic setup of the BAOS is shown in the figure below.



Schematic setup of the BAOS.

Two prisms expand the laser beam in horizontal direction to match the effective aperture of the Bragg-Cell. A polarizer in front of the bragg cell ensures the correct polarization angle for Rutile. Since the interaction with the shear wave in Rutile is anisotropic, the polarization of the diffracted light is changed with respect to the incident beam, a second polarizer behind the Bragg Cell is used to reduce the light scatter level. Additional apertures in the optical path further reduce the light scatter. To increase the optical throughput of the system, cylindrical lenses (focusing in vertical direction) are used in front of the deflector focusing the laser beam onto the sonic wave, and in front of the CCD.

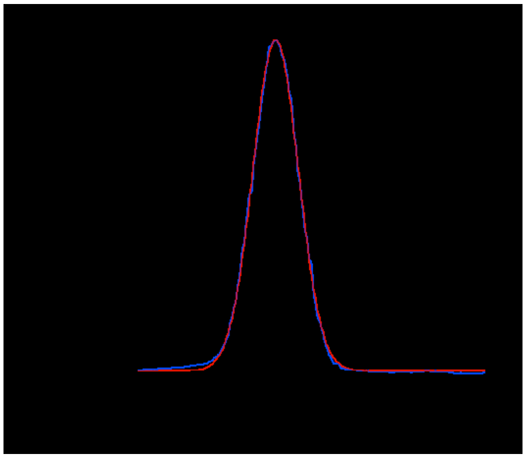
The optical setup of an AOS requires a high temperature stability. This is because the Bragg-angle itself is temperature dependent, as well as the laser speckles, and the optical alignment of the instrument. Usually we use a chiller with a temperature regulator, but this is not very practical for varying field applications. Therefor with the BAOS we use a Peltier regulator, which stabilizes the temperature of the complete optics to about 0.1 K. The Peltier cooler is directly mounted on the box of the optics unit.

IV. Test Results

The performance of the BAOS has been extensively measured and characterized in the laboratory and confirmed during a first run in the field. We present the most important test results that specify the resolution, linearity, and stability of the device.

A. *Frequency resolution*

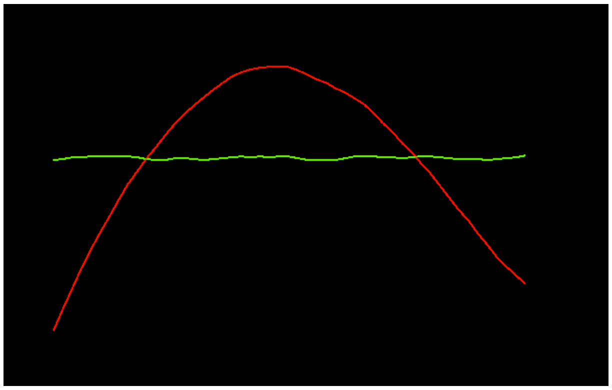
The resolution bandwidth of the BAOS is determined by the filter-curve. The measured value is about 1 MHz, the variation over the 3 GHz band is in the order of 10%. It is remarkable that the measured filtercurve is fully in agreement with numerical simulations that assume aberration-free optics. This proves that the quality of the laser beam, the optical components, and their alignment are „close to perfect“.



Sample filtercurve that has been recorded with a synthesizer step size of about 25 kHz. The blue line is the measured curve, the red line is a gaussian fit. The measured resolution bandwidth (δ_{res}) is 0.93 MHz, the fluctuation bandwidth (B_{fluc}) is 1.31 MHz.

B. *Frequency linearity*

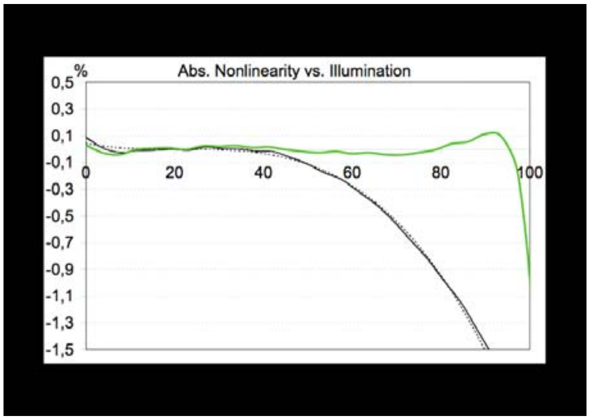
As is well known from the theory of acousto-optical spectrometers, their response is slightly different from linear in frequency. However, this can easily be corrected by a resampling procedure. For this calibration measurements with known frequencies (a „comb“ signal) are needed. After correction the frequency precision is in the order of ±50kHz over the 3 GHz band.



The deviation from a linear frequency scale (measured pixel positions - best linear fit, red curve) is in the order of ± 3MHz. The green curve shows the corrected data where the error has been reduced to about 50 kHz over the 3 GHz band.

C. *Power linearity*

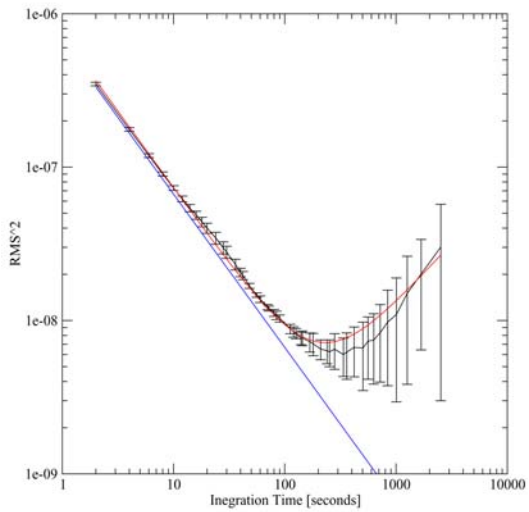
A common problem when using CCDs is their partly nonlinear response as function of the incident light. While deviations of a few percent are acceptable for many applications, AOSs need a linearity of better than 1% over the complete operating range. To ensure this we characterize the power linearity of our CCDs with a stabilized pulsed light source, which is used to illuminate the CCD for well defined periods of time. Once the non-linearity has been measured it can be corrected to a level near 0.1% during data analysis.



The figure shows the non-linearity of the Fairchild CCD-191. The black line is the measured non-linearity, the green curve is the corrected data. The corrected CCD has a non-linearity near 0.1% up to an illumination of about 95%.

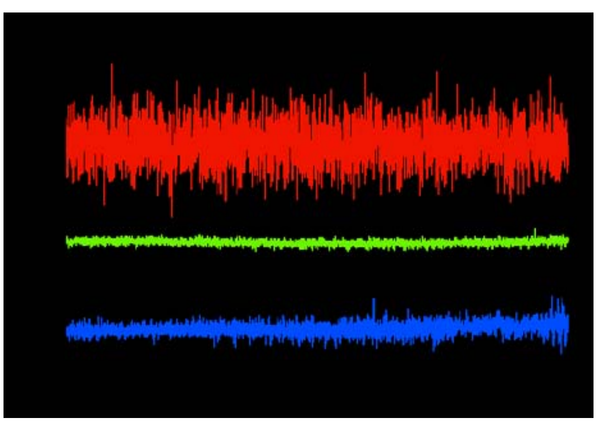
D. *Stability*

The stability of the instrument is determined by the Allan Variance. A typical Allan baseline plot is shown below. The straight line (blue) corresponds to the radiometric noise for a fluctuation bandwidth of 1.4 MHz. The reference value of 1.4 MHz is determined by the filter curve of the backend. The fact that for low integration times the variance of the baselines lies on to of the theoretical value shows that the BAOS does not contribute any noticeable noise to the measurement.



The Allan Baseline stability of the BAOS shows the variances of baselines for different integration times. The straight line (blue) is the radiometric noise for a fluctuation bandwidth of 1.4MHz.

Examples of the integrated baselines (sig-ref)/(ref-zero) are shown below. The top curve (red) corresponds to an integration time of two seconds and is pure radiometric noise without any noticeable instrument contribution. The lower curve (blue), which corresponds to a integration time of 2520 seconds, is completely dominated by the BAOS. From its shape it can be deduced that the excess noise is caused by laser speckles. The mid curve (green) is a typical baseline after 336 seconds integration time, which corresponds to the Allan minimum time in the above plot. Here the noise contains already some minor contributions from the laser speckles.



Sample baselines for various integration times. The upper curve (red) corresponds to a integration time of 2 seconds and is purely radiometric noise. The mid curve (green) corresponds to the Allan minimum time (here about 300 seconds) and has a RMS that is slightly higher than expected for radiometric noise. The bottom curve (blue) corresponds to 2520 seconds integration time and is completely dominated by laser speckles from the BAOS.

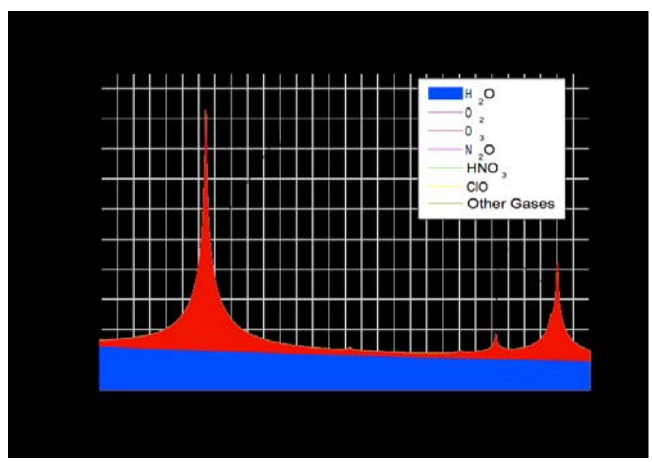
V. Conclusion

The performance of the backend is summarized in the table below.

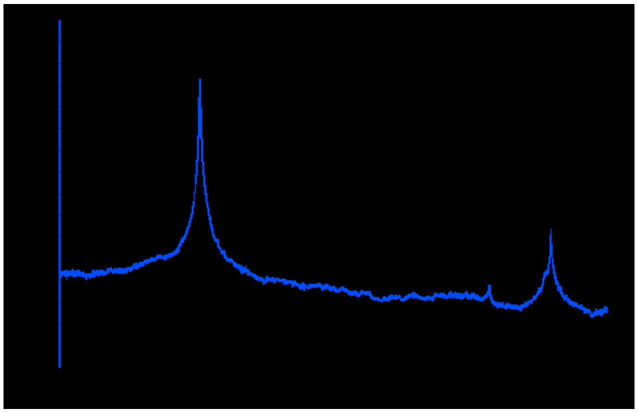
BAOS specifications

Total bandwidth	3 GHz
Number of valid frequency pixels	≈ 5300
Channel spacing	≈ 560 kHz
Resolution bandwidth	≈ 1.0 MHz
Fluctuation bandwidth	≈ 1.4 MHz
Allan variance minimum time	> 300 sec
Noise dynamic range	≈ 13 dB
Bandpass ripple	≈ 4 dB
Frequency linearity	better 50 kHz after resampling
Power linearity	non-linearity < 1 %

The spectrum below shows the „first light“ data taken in March 2007 with the KIRMA (Kiruna MW Radiometer) instrument in collaboration with U. Raffalski from the IRF, Kiruna, Sweden. It shows a 3 GHz spectrum of atmospheric Ozon lines around 210 GHz. The spectrum has been recorded with chop cycles of 5 seconds. The structure that is visible on the spectrum is caused by deficiencies of the frontend (compare the spectrum to the flat Allan baseline after 300 seconds), there is still some work to be done before the system can take full advantage of the BAOS.



Model prediction of the Earth atmosphere at around 210 GHz. The blue underground is from water vapor in the atmosphere, the red lines are the expected Ozone emission features.



Sample Ozone spectrum at 210GHz observed with KIRMA and the BAOS.

VI. ACKNOLEDGEMENTS

This work has been supported by the Deutsche Forschungsgemeinschaft (DFG) under special grant SFB 494.