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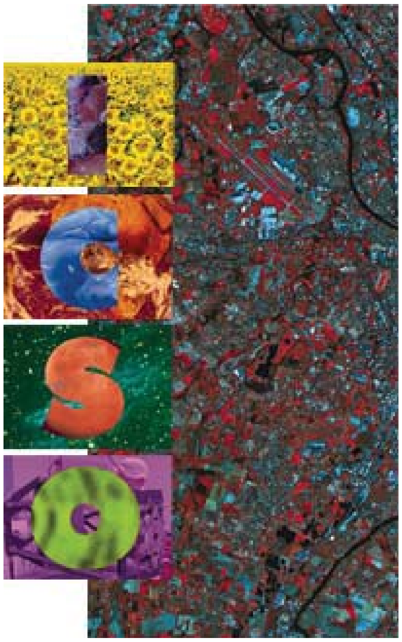

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SMILES/AOS: ACOUSTO-OPTICAL SPECTROMETER FOR HIGH RESOLUTION SUBMILLIMETER-WAVE SPECTROSCOPY

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RESUME – SMILES / AOS est un projet de spectromètre acousto-optique en phase de développement destiné à la caractérisation des ondes sub-millimétriques émises par l'atmosphère. Le spectromètre est développé par ASTRIUM pour l'agence spatiale japonaise NASDA. Il sera implanté sur le module japonais (JEM) de la station internationale (ISS). Un concept de spectromètre acousto-optique permet d'obtenir une résolution élevée nécessaire à la détection des espèces chimiques tout en couvrant une large bande spectrale, ce que ne pourraient réaliser des techniques à base d'auto-corrélateurs avec des encombrements et consommations compatibles d'une utilisation spatiale. Il est proposé de présenter le concept de spectromètre acousto-optique et les choix retenus par ASTRIUM pour conduire à un instrument qualifié spatial aux performances optimisées.

ABSTRACT *- An acousto-optical spectrometer (AOS) is employed in order to meet scientific mission objectives of submillimeter-wave limb-emission sounder (SMILES) to be aboard the Japanese Experiment Module (JEM) of International space station (ISS). AOS is developed by ASTRIUM for the Japanese space agency (NASDA). The capability of multi channel detection with AOS is suitable for observing multi-chemical species in a wide frequency region. Low noise of the AOS enables us to obtain the spectra with a very high sensitivity. Several technical concerns relating to important instrumental characteristics of AOS are discussed and expected performance of the design are overviewed.*

1. INTRODUCTION

Superconducting submillimeter-wave limb emission sounder (SMILES) is a mission to obtain global mappings of stratospheric trace gases such as ClO, HCl, HO_2, HNO_3, BrO and O_3 by observing them at the frequency band of 624.32 - 626.32 GHz and 649.12 - 650.32 GHz. It is scheduled to be launched in 2005 and operated on the Japanese Experimental Module (JEM) at the International Space Station (ISS). For achieving high-sensitive and multi-species observation of atmospheric emission aimed in the mission, NASDA use low noise (near quantum noise-limit) receivers based on a super-conducting technology as well as multi-channel spectrometers capable of wide instantaneous observation band. In the JEM/SMILES, the use of Superconductor-Insulator-Superconductor (SIS) mixer operated at 4 K cooled by mechanical cooler fulfills the principal mission requirements. Selection of the radio-spectrometer, however, is also essential and should pay attention to utilize high performance of the SIS mixer as much as possible.

Among spectrometers so far proposed and used for the backend of the radiometer, filterbank (FB), autocorrelator (AC), and acousto-optical spectrometer (AOS) are three representatives. FB was widely used in the astronomical observation, but due to the complexity in increasing the number of detection channels, some FBs have been replaced by other spectrometers up to present. Instrumental performance of AC is now developing in accordance with a recent innovation of digital technologies, but quantization noise of the state-of-the-art AC still cannot be selected due to a small number of resolution bit. Large power consumption is another concerns in wide band AC. On the contrary, AOS has a capability of multi-channel, and wide-band detection without additional noise. Power consumption and instrumental volume per single spectroscopic channel are small when compared to other spectrometers. So NASDA have concluded to adopt two AOS for spectrometers of JEM/SMILES because of their advantageous points in resource consumption, available bandwidth, and noise performance.

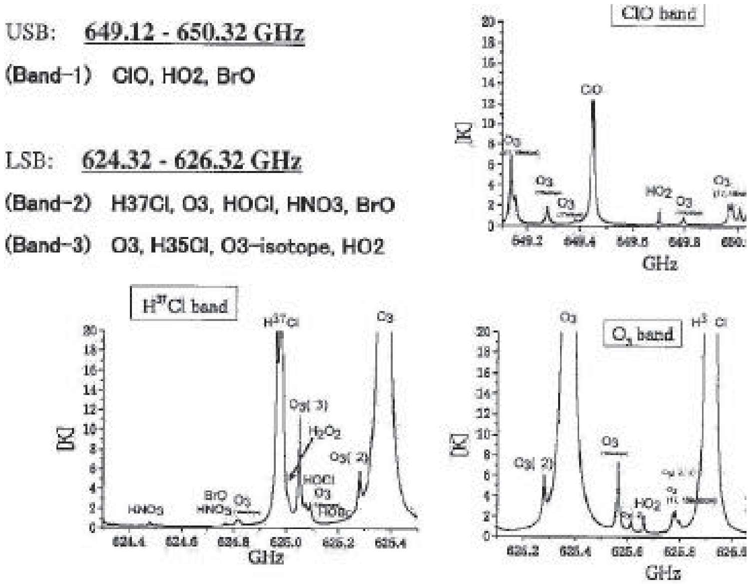

Figure 1: Simulation of species detection by AOS

Development and sophistication of AOS have been lead over several years by the University of Köln in Germany and by the Observatoire de Paris, CNRS, ARPEGES with the financial support of CNES and ESA. They applied their spectrometers not only for radio-astronomy, but also for another field such as atmospheric science. From instrumental point of view, state-of-the-art AOS has been passed space qualification and its capability has been demonstrated in the sub millimeter-wave observation satellites.

AOS/SMILES in-orbit operating conditions call for a specific spaceborne design. So the industrial activity led by ASTRIUM starting from the concept published by C. Rosolen, A. Lecacheux et al. from the Observatoire de Paris is probably the best organisation to solve the technical challenges of the study as it benefits from the large experience of each group in the relevant technical fields in

Space programs (SILEX, ATLID, SEVIRI, SPOT,…) and in the development of ground Acousto-Optic Spectrometers.

In the present paper, the technical concerns in designing AOS instrumental characteristics are discussed, and expected spectroscopic performance of AOS to be used in JEM/SMILES is overviewed.

2. TECHNICAL CONCERNS IN DESIGNING AOS INSTRUMENTAL PERFORMANCE

2-1. Working principle of AOS

The application of AOS and its usefulness was first demonstrated in the field of radio astronomy in 1970s. Since then it has been recognized as one of the suitable spectrometers for analyzing a wide band and faint signal embedded in radiometric noise. The key component of AOS is the Bragg cell that is responsible for converting microwave signal to corresponding acoustic wave propagating in the crystal. If the monochromatic light is irradiated to the crystal, propagating acoustic wave generates a diffracted beam by Bragg diffraction. The diffraction angle of the impinged light is inversely proportional to the wavelength of acoustic wave, consequently the frequency domain spectra of input microwave signal appears at a focal plane of the deflected light. The detection will be achieved by putting one-dimensional CCD detector at the position of the focal plane.

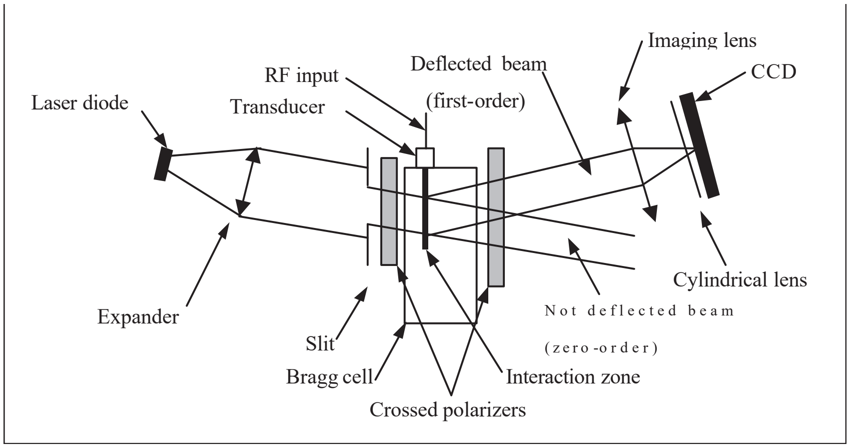

Figure 2: Schematic diagram of AOS

In case that AOS is applied to atmospheric observation, we have to consider two properties in addition to normal instrumental specifications of an optical spectrometer such as resolution, bandwidth and signal-to-noise ratio. Those are noise dynamic range and Allan Variance. These are important because a signal level of reference spectrum is different from observed spectrum in typical atmospheric observation. The details are discussed in the following sections.

2-2. Noise dynamic range (NDR)

The concept of 'Noise dynamic range (NDR)' is different from usual 'dynamic range' used in ordinary spectrometer, and is very important in the treatise of the signals embedded in the noise. The noise characteristics of RF signal that comes from IF amplification unit is basically determined by noise characteristics of the front end system of the radiometer. This will be optically converted to measure its frequency spectrum in the AOS. The process is accomplished by 'reading out' the number of the collected charges against the channel of charge coupled device (CCD). Ideally the 'read out' values should reflect on the input RF noise characteristics, but it is little bit modified by various factors of the spectrometer in reality. The variance of the original RF noise at CCD is expressed by the following modified radiometric equation;

$$N_{RF}^{2} = \frac{Q^{2}}{Bt}$$

where Q, B, and t correspond to the number of collected charge at CCD, noise bandwidth, and integration time for collecting charge, respectively. The contributors of modification of the noise characteristics can be photon shot noise, CCD dark noise, quantization noise of analog to digital converter, and detection circuit noise, namely;

$$\begin{aligned} N_{add}^2 &= N_{photon}^2 + N_{CCD}^2 + N_{AD}^2 + N_{Detection-circuit}^2 \\ &= \left(\sqrt{Q}\right)^2 + \left(q_0\right)^2 + \left(Q_{sat} \Big/ \sqrt{2^{2n} \cdot 12}\right)^2 + \left(q_{eff}\right)^2 \end{aligned}$$

where, q_0, Q_{sat}, n, and q_{eff} are dark current noise, the amount of saturation charge, quantization bit of the A/D converter to be used and equivalent amount of charge of detection circuit noise, respectively. The read out noise is not the same as the input RF noise any more;

$$N_{read-out}^2 = N_{RF}^2 + N_{add}^2 ,$$

The modification of the noise characteristics means an increase of effective system noise temperature. In the case of AOS, the higher in signal level, the smaller in relative contribution of additional noise to the RF noise. So if the criterion is settled so that the noise variance ratio $N_{read-out}^2 / N_{RF}^2$ to be less than 1.21, then we can define usable signal range of the spectrometer with less than 10 % increase of effective system noise temperature. We call this 'noise dynamic range'. As far as the observed spectrum lies within the noise dynamic range, the increase of the effective system noise due to the spectrometer can be negligible. Alternatively, we can calculate an increase of noise at a given signal level. Its coefficient is a function of the signal level, and expressed as $f(D)$, where $D = Q_{sat} \big/ Q$, and $T_{sys}^{eff} = T_{sys}^{org} \cdot f(D)$. $f(D)$ is expressed as the following;

$$f(D) = \sqrt{1 + \frac{B \cdot t}{Q_{sat}} \cdot D + B \cdot t \left(\frac{q_0^2 + q_{eff}^2}{Q_{sat}^2} + \frac{1}{2^{2n} \cdot 12} \right) \cdot D^2} \qquad (1)$$

It is essential for obtaining a wide dynamic range to minimize coefficients of a series of D in equation (1). This result tells the following suggestions in designing AOS. Given the noise bandwidth,

- Integration time should be shortened to increase RF noise.
- Selection of the CCD having large saturation charge and low dark noise is important.
- State-of-the-art detection circuit is necessary to minimize q_{eff}.
- The number of bit of the A/D converter must be large enough for quantization noise to be negligible.

2-3. Allan Variance

The end-to-end restitution performance of the AOS depends on its temporal stability, mainly dictated by the thermal stability of the spectrometer. Such stability can be expressed as Allan Variance that is defined as follows:

$$v_a(\tau) = \frac{1}{B\tau} + \frac{1}{2}\left(\Delta T \frac{\Delta G}{G}\right)^2 \tau^2$$

where B, τ, ΔT, ΔG, G correspond to the noise bandwidth, integration time, thermal stability, gain stability of the spectrometer, gain of the spectrometer.

The first term is the radiometric noise, decreasing with the increasing number of acquisitions. The second term represents the drift of the AOS with a gain sensitivity of $\Delta G/G$ for a thermal drift of ΔT. ΔT is time dependent. The Allan variance is minimum when the following equation is fulfilled:

$$\tau^3 \max B\left(\frac{\Delta G}{G}\right)^2 \Delta T^2 = 1$$

An Allan variance of 60 seconds requires that the laser diode and the RF amplifiers achieve a thermal stability better than 0.01°C over the considered period. This stability can be easily achieved in well-controlled laboratory conditions. This stability is challenging in-orbit where the temperature of the environment of AOS evolves 100 times quicker.

3. AOS OF JEM/SMILES

3.1. General characteristics of AOS

AOS of SMILES consist of three parts, acousto-optical unit (AOU), RF amplifier unit (RFU) and control and video unit (CVU). The AOU includes two spectrometers each of which has 1200 MHz frequency coverage with 1500 spectral channels. The 'resolution bandwidth' of the spectrometer is 1.8 MHz. The unit exposure time of CCD is set to 4.9 ms and the collected charges are read-out at the rate of 800 kHz. Each output spectrum is obtained every 500 ms by accumulating the 96 unit spectra.

Figure 3: The architecture of the AOS (preliminary design)

Analyser Unit (AOU & RFU). All the optical and RF components requiring thermal or mechanical stability are grouped on this two sides bench. A temperature stability of better than 0.01°C will be achieved over one minute thanks to the use of a double stage thermal control: the first stage is actively controlled thanks to heaters and thermo-couples when the second stage take profit of its thermal capacitance to achieve the requirement by thermal inertia. The bench also acts like a shield to ensure high electrical field isolation between the video elements, and the RF ones that are put on the opposite side of the bench. The Bragg cells that are located on the acousto-optical unit side are connected to the RF amplifier unit via a RF harness passing through the bench.

Control and Video Unit (CVU). The CVU includes all the electrical functions such as power supply, thermal control, telecommands, and video signal transfer.

3.2. From design to industrial definition

Industrial definition of AOS takes benefit from the large experience of ASTRIUM in the relevant technical fields in space programs. AOS is so based on the re-use of pieces of equipment that have been developed and validated on previous programs and that have also been space qualified. Thanks to this approach, risk of development is minimized:

- The electrical architecture is based on low noise ODIN star sensor and on SPOT5 SSD sun sensor used on all ASTRIUM observation platforms.
- The optical elements that need to be ultra-stable use the technologies developed on SILEX optical link where end-of-life pointing stability is few microradians.
- The CCD focal plane takes profit of the developments on sensors optical heads
- The RF unit packaging is based on MHS and on telecom payloads to provide a highest EMC screening

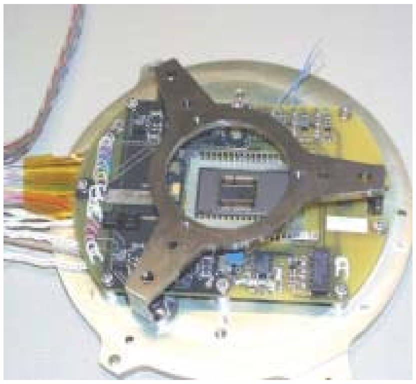

Figure 4: View of micro-sensor optical head

Figure 5: View of ODIN sun sensor board

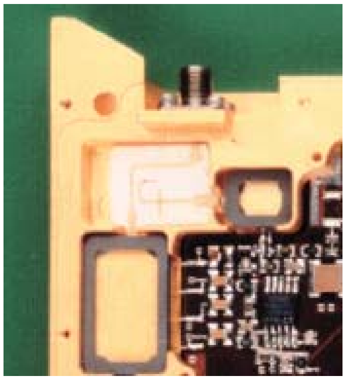

Figure 6: View of RF payload

3.3. Performance of AOS

The system noise temperature of JEM/SMILES will be 500 K thanks to adopting SIS mixer operated at 4K. This is one of the distinguished features of SMILES mission when compared to other atmospheric observation program from the space. Therefore it is important not to deteriorate this performance by AOS. To achieve this purpose, AOS will have noise dynamic range as wide as possible. Figure 7 shows the plot of $f(D)$. It can be found that at the illumination level of 9dB down from the saturation, the additional noise contribution is still less than 10%.

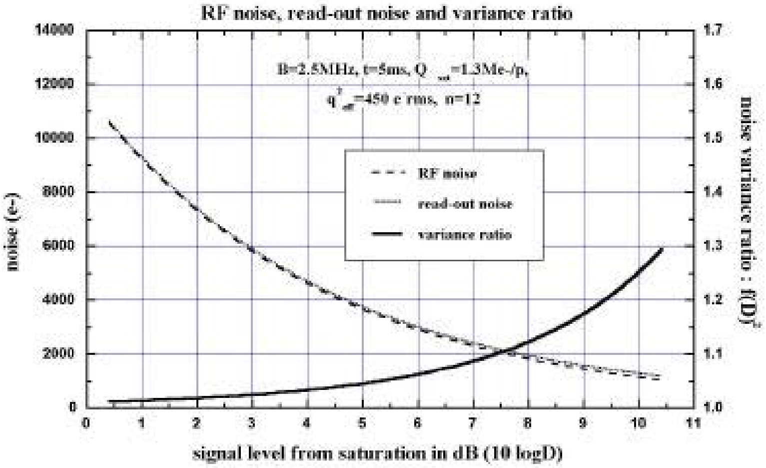

Figure 7: Plot noise variance ratio

4. CONCLUSION

With the consequence of the trade off in terms of spectrometer performance and resource consumption, AOS has been adopted by NASDA as the radio spectrometer of SMILES. AOS has a capability of wideband, multi-species spectrometry, which design meets the science mission objectives.

AOS expected main performances	
Input frequency range	1.55 – 2.75 GHz
Frequency resolution (–3dB)	1500 channels / 1.2 GHz
Frequency deviation from best fitted curve / Frequency drift	< 30 kHz / < 170 kHz
Noise dynamic range (noise variance ratio)	1.1 @ 7.5 dB
Power consumption without thermal control / Mass / Volume	37 W / 13.6 Kg / 27 litres

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