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# Technological Needs for European Space Agency's Microwave Limb Sounders

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**Abstract** – Since they present good capabilities for the detection of important trace species for atmospheric chemistry, the European Space Agency (ESA) has, in recent years, investigated a number of limb sounding instrument principles. These feasibility studies have provided baseline concepts which have helped to grasp the main features of these instruments and to identify their critical aspects. A number of scientific and technical activities have then followed, dedicated to specific topics, from retrieval simulations to developments of antennas, calibration loads, mixers, support to campaigns, etc. To make observations in the upper troposphere and lower stratosphere (UTLS), where they are the most urgently needed, the ESA limb sounder concept is called MASTER (Millimetre-wave Acquisitions for Stratosphere/Troposphere Exchange Research), which counts five broad detection bands, hence five receivers, from 200 to 500 GHz. The main channels of MASTER for UTLS sounding, which detect in priority ozone, water vapour and carbon monoxide, are centered near 300, 325 and 345 GHz.

## I. INTRODUCTION

ESA's strategy concerning earth observation is now spearheaded by its Earth Observation Envelope Programme (EOEP). The programme is managed and executed within the Directorate of Applications. Within EOEP, work related to the definition of future earth observation missions takes place mainly at the European Space Research and Technology Centre (ESTEC, The Netherlands), and is performed by the Future Programmes Department.

A candidate for a new mission can be classified either as a Core Earth Explorer, an Opportunity Earth Explorer, or an Earth Watch. An Earth Explorer is defined as a scientific or demonstration mission, deemed to be financed primarily by ESA, possibly aided by other space agencies, while an Earth Watch has a commercial or operational potential and assumes a large financial contribution from an interested partner, such as the private sector or the European Union. A proposed scientific mission which would require substantial funding, such as many instruments aboard a large platform, would be proposed as a Core Explorer. A small scientific mission, requiring technology deemed readily available, would be presented as an Opportunity Explorer. The selection process for the implementation of Explorers involves and depends mainly upon the European and Canadian scientific community. The scientists themselves identify which missions they want to see implemented, while ESA acts as a facilitator and

provides technical expertise and recommendations concerning programmatic aspects.

At the time of writing of this paper, a Call for Ideas for Core Earth Explorers has been initiated by ESA. It is expected that a proposal will be made by the atmospheric chemistry community for a new mission which could include a millimetre-wave limb sounder, and possibly also submillimetre-wave and far infrared (or THz) limb sounders. The time frame for the launch of such a next Core Explorer is not earlier than 2008.

Table 1: Instrument Requirements

MASTER			
Band	Spectral Range (GHz)	Noise Temp. (K)*	Vertical Resolution (km)**
A	200.5-209	4000	4.5
B	294-305.5	6000	3
C	316.5-325.5	6000	3
D	342.25-348.75	6000	3
E	497-506	6000	2

Spectral resolution: 50 MHz nominal  
3 MHz in specific intervals  
\*: SSB detection, with ca 30 dB image attenuation  
\*\*: Interval, at the limb, containing 85% power

SOPRANO			
Band	Spectral Range (GHz)	Noise Temp. (K)*	Vertical Resolution (km)**
A	497.5-504.75	5000	4
B	624.6-629	6000	4
D	952-955	10000	4

Spectral resolution: 3 MHz nominal  
0.3 MHz in specific intervals  
\*: SSB detection, with ca 20 dB image attenuation  
\*\*: Interval, at the limb, containing 85% power

PIRAMHYD		
Targeted OH Line	Spectral Range (GHz)	Noise Temperature (K)*
@ 2.5 THz	2508.5-2511.5	20000
	2512.8-2515.8	20000
or @ 3.5 THz	3532-3535	30000
	3540-3545	30000
	3549-3552	30000

Vertical resolution: 2 km (FWHH at the limb)  
Spectral resolution: 1 MHz  
\*: SSB detection, with ca 20 dB image attenuation

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## II. INSTRUMENT CONCEPTS

During the last decade, ESA has conducted a considerable number of activities concerned with microwave limb sounding for atmospheric chemistry: Scientific studies, instrument studies, technology breadboarding, support to airborne measurement campaigns. Many activities are currently on-going and others are planned in the near future. This interest is justified by the capability of microwave limb sounding to provide concentration profiles of important species with high vertical resolution, and that down to relatively low altitudes.

ESA has defined three microwave limb sounder concepts: MASTER (Millimetre-wave Acquisitions for Stratosphere/Troposphere Exchange Research), SOPRANO (Submillimetre-wave Observations of PProcesses in the Atmosphere Noteworthy for Ozone), and PIRAMHYD (Passive Infra-Red Atmospheric Measurements of HYdroxyl). These are passive instruments, ie they simply detect the radiation emitted

relying on the use of frequencies at the upper end of the millimetre-wave range, the high vertical resolution required for the retrieval of species in the upper troposphere translates into an antenna with a large diameter. Figure 2 shows an artist's impression of MASTER. The large 2.2 m diameter of the antenna is oriented along the vertical. MASTER is a big instrument, weighing about 300 kg, and consuming about 350 W of power. It operates at room temperature.

Stratospheric depletion of ozone is the main topic addressed by SOPRANO measurements. Ozone, chlorine monoxide, hydrogen chloride and nitric oxide are the main target species. SOPRANO is shown on figure 3, and its main requirements are also listed in table 1. The higher frequencies and the more relaxed vertical resolution requirements allow for a much smaller antenna, with a vertical diameter of only 1 m. The instrument is still big, weighing about 150 kg, and consuming about 300 W. At the time of the last SOPRANO study, it was still deemed necessary to

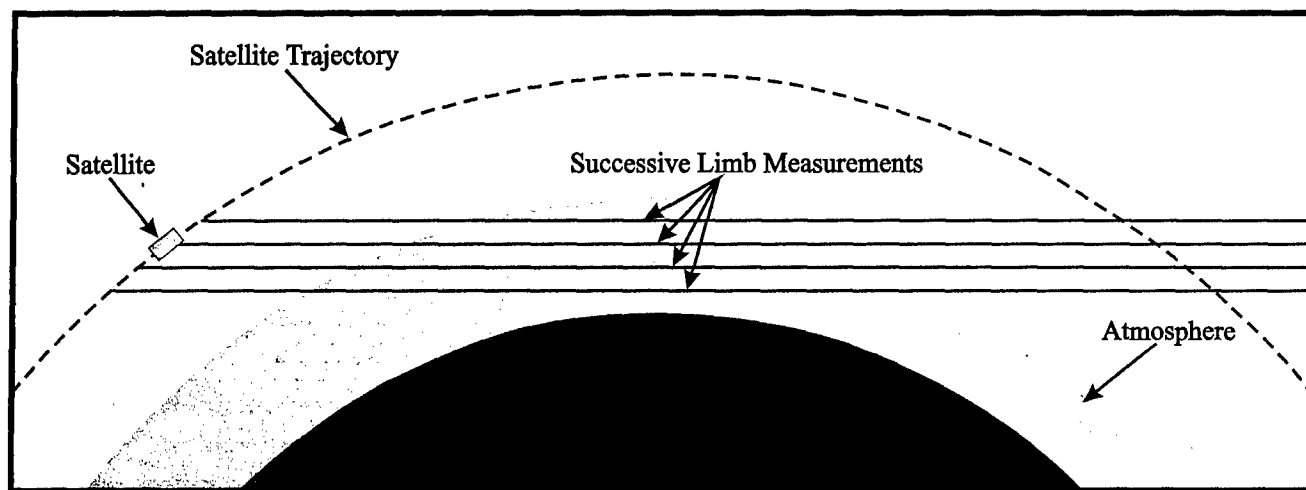


Figure 1: Limb Sounding Geometry

by the atmosphere itself. The geometry of limb sounding is shown on figure 1. The instruments observe the atmosphere tangentially, against the deep space background. MASTER, SOPRANO and PIRAMHYD have a single instantaneous viewing direction, so that successive measurements have to be taken to gather sufficient information from all desired altitudes. A single measurement gives mostly information on the lowest height region viewed by the line of sight (LOS). Figure 1 shows a special case where the timing of the scan is such that successive measurements have parallel LOS, which yields a vertical locus of tangent points. Generally, limb sounders may adopt different scan patterns, so that tangent points of a given elevation scan may not at all rest close to a vertical line.

MASTER targets mainly the detection of water vapour, carbon monoxide and ozone in the UTLS. High resolution maps of these species are needed for appropriate modelling of atmospheric effects related to global changes, such as radiative forcing, exchanges between the stratosphere and the troposphere, and upper tropospheric chemistry. MASTER is shown on figure 2, and its main requirements are listed in table 1. Although

actively cool its D receiver to 80 K to achieve the required sensitivity. Note that band A of SOPRANO is covered by band E of MASTER. Should both instruments be destined to fly on the same platform, some simplifications could be envisaged.

ESA investigations have been relatively modest on the subject of hydroxyl detection. This radical is a main player in many chemical reactions, and considerable insight into atmospheric processes would be gained by providing measurements of hydroxyl in the UTLS. Unfortunately, measurements below 20 km are very difficult, since, as one goes to lower altitudes, water vapour renders the atmosphere increasingly opaque, and since the hydroxyl concentration itself diminishes.

Three quite different instrument principles can be considered for PIRAMHYD. One could attempt to detect hydroxyl either using a Fabry-Perot interferometer, a microwave receiver, or a Fourier transform spectrometer. Each technique has, as always, its advantages and disadvantages. In the case of the microwave receiver, heterodyne detection offers good performance even at 300 K operating temperature, with high spectral

resolution and relatively good spectral coverage. However, the local oscillator is quite complex. Table 1 also contains the requirements for the microwave receiver version of PIRAMHYD. Still, a choice has to be made between detection of hydroxyl either at 2.5 THz or 3.5 THz. For spectroscopic reasons the 3.5 THz version is preferred, if technology allows [ref.1].

The priority having been given to MASTER and SOPRANO in the last years, the microwave version of the PIRAMHYD instrument has not yet been the subject of comprehensive ESA activities with the space industry.

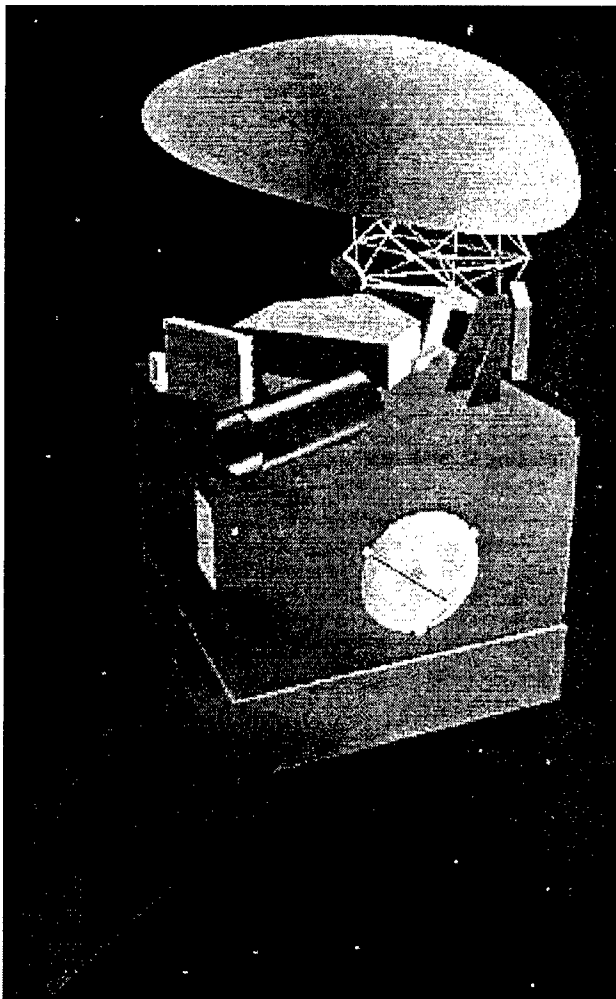


Figure 2: MASTER on a Small Satellite [ref.6]

ESA involvement in this domain has been limited to scientific studies and to the development of a 2.5 THz mixer [ref.3]. Hence, the rest of the discussion will be limited to sub-THz, ie MASTER and SOPRANO. These two instruments are quite similar. Putting aside the more common subsystems such as pointing mechanism, computer, coolers, and power supply, MASTER and SOPRANO have three main parts: Antenna, receivers, spectrometers.

### III. ANTENNA

The work on the antenna subsystem is typical of the way ESA has conducted its investigations on these limb sounders. Eight years ago, the first instrument studies started on sets of specifications which were based on various assumptions, many of them concerning the

sensitivity of retrieved profile accuracies to instrumental parameters and instrumental errors. These industrial activities were then followed by scientific investigations involving retrieval simulations, the latter using as inputs many results of the industrial studies, which then yielded refined sets of specifications for the instruments. This process was iterated once more, ie other industrial studies [ref.5-8] followed by other scientific studies [ref.9-12].

It was assumed, at the beginning of this process, that the surface accuracy of the main reflectors of the antennas had to be quite high, and that only very low side-lobes could be tolerated. The measurement of the antenna pattern was deemed important but not critical. It turned out, however, that the accuracy of the manufactured surface and the level of the side-lobes can be relaxed, as long as the antenna pattern is precisely measured and that the antenna shape, of course, does not change afterwards. This relaxed requirement on side-lobes offers the degree of freedom of weakening the illumination taper, with the goal of either reducing the antenna size or reducing the beamwidth, the latter of which would improve the precision of the retrieved profiles. The emphasis in the development of this subsystem has thus shifted from a difficult manufacturing tolerance to a serious stability requirement, and from a highly efficient beam to a highly accurate measurement of the antenna pattern.

The stability requirement for the antennas is on the order of 10 microns peak to peak. This means, basically, that the shape of the reflectors, once in orbit and taking measurements, shall not differ by more than 10 microns from the shape that the reflectors had when the antenna patterns were being measured in the test facility on earth. This is deemed feasible with a reflector made of CFRP (carbon fibre reinforced polymer). A study [ref.5] concluded surprisingly that partial shielding might be preferable to complete shielding of the reflectors from sun illumination, since the former could translate into low temperatures which would distort the reflector more than thermal gradients caused by the latter.

Retrieval simulations [ref.9-12] were done to assess the required accuracy of the measurement of the antenna patterns. It turns out that an accuracy of -50 dB is needed, relative to the boresight. This requirement assumes that any noise rectification occurring at the -50dB level is properly taken out. If not, the accuracy requirement is then -65 dB. This is difficult but possible. Currently, no facility exists in Europe to perform these measurements on 2 m diameter antennas.

### IV. RECEIVERS

As shown on the MASTER and SOPRANO requirements in table 1, the wide bandwidths of these instruments constitute a predominant feature. Another one is single side-band detection (SSB). This mode has been preferred over double side-band detection (DSB) to avoid the problems of characterization and stability of the relative response. Although the requirements of table 1 do not seem outrageously demanding, their simultaneous achievement remains to be demonstrated. Using room temperature receivers, except for receiver D of SOPRANO (at 80 K), it is difficult to reach the desired

sensitivity and image rejection over such wide bandwidths.

The receiver subsystems can be broken down into mixer (including feedhorn), quasi-optics (QO), local oscillator (LO), and intermediate frequency (IF) amplifier. Here follows a summary of the main conclusions of the various tradeoff studies. *Mixer*: Schottky diodes are chosen for

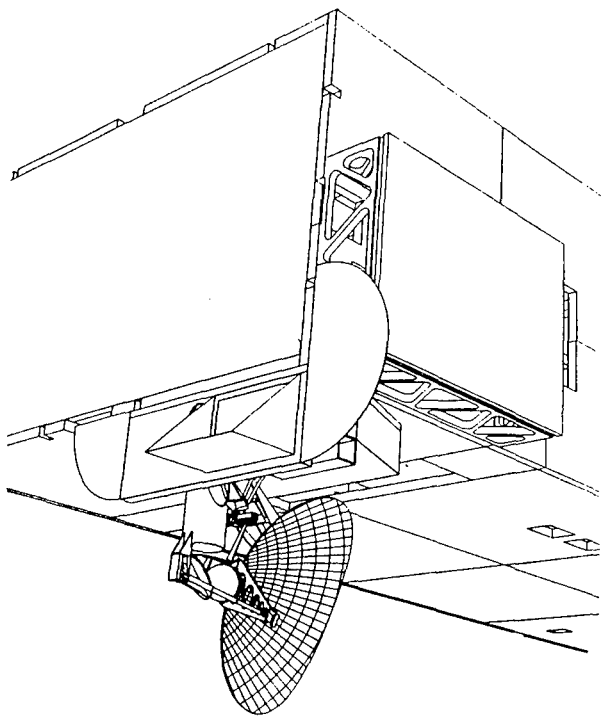


Fig.3: SOPRANO on ENVISAT-Type Platform [ref.7]

operation at room temperature. For reliability, reproducibility, and quality control, whisker contacted diodes are avoided where possible. Planar technology is preferred. Waveguide mixers using corrugated feedhorns are still preferred over open structure mixers. The configuration of the receiver is mainly determined by the type of mixer, ie either fundamentally-pumped (FP) or sub-harmonically pumped (SHP). At the time of completion of the instrument studies, however, an SHP configuration was deemed premature for receiver D of SOPRANO (950 GHz). If FP still keeps a performance edge over SHP, the latter is now preferred, since, among others, it simplifies the LO and its injection. *QO*: To perform frequency separation, single side-band rejection, and LO injection (for FP), polarizers and various kinds of dichroic plates can be used. For SOPRANO, where bandwidths are not as wide, and where image rejection requirements are less stringent, Martin-Puplett interferometers can also be considered. Whatever the solution, the combination of the requirements of low loss and high image band rejection results in a high IF. *LO*: Solid state oscillators are possible over this frequency range, and so consist of a Gunn diode source and multipliers (eg based on heterostructure barrier varactors). Phase locked loops are used. *IF amplifier*: Because of the high frequency range, 15 to 35 GHz, and of the poor conversion efficiency of the mixer, even low noise amplifiers (eg based on high electron mobility

transistors) contribute significantly to the overall system noise temperature.

A note concerning the calibration of the instrument: A high radiometric accuracy is required, ie about 0.5 K in absolute brightness temperature. To achieve this, a two-point characterization method is required, where deep space and an internal calibration blackbody constitute respectively the cold and hot loads. A switching mirror allows to take characterization measurements in three ways: Deep space viewed through the whole antenna, deep space viewed through the switching mirror, blackbody viewed through the switching mirror. The combination of antenna reflector temperature readings and characterization measurements yield the calibration information. The current design of the blackbody relies on the principle of a cone-shaped cavity and specular reflection [ref.3].

## V. SPECTROMETERS

The spectral requirements included in table 1 are achieved in a straightforward manner with acousto-optical spectrometers (AOS)[ref.3], except for the high resolution channels of SOPRANO, which can be taken care of by either digital auto-correlation spectrometers [ref.4] or chirp-transform spectrometers [ref.2]. However, if an AOS offers excellent performance, its 2.2 GHz bandwidth limitation necessitates a large number of units and considerable IF circuitry. Development of a spectrometer which would analyse simultaneously a 12 GHz bandwidth could greatly simplify the instruments and reduce mass and power consumption.

## VI. CURRENT AND PLANNED ACTIVITIES

ESA is currently pursuing several activities related to needed technologies for microwave limb sounders. KASIMIR aims at achieving a competitive 650 GHz mixer performance with planar diodes and an open structure architecture. Related to KASIMIR are activities related to improving quality and process control in diode fabrication. ADMIRALS aims at fabricating and testing a MASTER flight representative antenna, both mechanically and electromagnetically representative, and upgrading an existing antenna test facility to allow its use up to 500 GHz. In MARSCHALS, an airborne simulator of MASTER will be fabricated, with the aim of performing measurement campaigns from either a stratospheric balloon or the russian Geophysika aircraft. These measurements would demonstrate the capability of MASTER to retrieve concentration profiles with the desired accuracy and vertical resolution in the UTLS. A technology breadboarding activity has been started to demonstrate the feasibility of the MASTER receiver B requirements.

In the near future, ESA will initiate activities on wide-band (12 GHz) spectrometers and on the development of mixer diodes. The latter counts in its objectives a contribution towards a competitive european capability. Upon reception of proposals for the Call for Ideas for Core Earth Explorers, it is possible that further activities related to microwave limb sounding for a future atmospheric chemistry mission will be defined.

## VII. CONCLUSION

The context and the main conclusions of the ESA activities related to microwave limb sounding have been presented. Emphasis has been put on sub-THz investigations, ie for MASTER and SOPRANO. The main technological challenges still remaining concern the accurate measurement of the antenna pattern, the stability of the antenna structure, and the simultaneous achievement of receiver requirements: Sensitivity, bandwidth and image rejection. These challenges and the demonstration of limb sounding capabilities are being addressed by ESA.

### Acknowledgement

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