Centre for EO Instrumentation

Technology Market Case Study No. 12 (Draft 1)

HYMS – Hyperspectral Microwave Sounder for Spaceborne Earth Observation

The Challenge

With average global temperatures rising, the frequency and severity of extreme weather-related phenomena, such as heat waves and violent storms, are predicted to grow. These weather events result in, for instance, extensive periods of drought or flash / prolonged flooding that generate significant societal impact worldwide and cause a fiscal loss amounting to approximately 5% of global gross domestic product. Accurate weather prediction is therefore crucial in not only providing a greater understanding of climate change, but also in enabling the rapid deployment of mitigation measures that minimise loss of life and global resource and infrastructure damage.

Whilst most weather phenomena occur on a typical timescale of hours, severe weather events are an exception. With respect to predicting the latter, the spatial and temporal distribution of meteorological parameters that strongly influence weather formation, such as humidity and temperature, can change very rapidly. It is not unusual, for instance, for variations to occur across a few tens of kilometres and on a timescale of minutes. Moreover, these weather forming regions are often shrouded by cloud structures that impede measurements throughout the stratified layers of the atmosphere at infra-red and optical wavelengths.

Fortunately, the dielectric penetration capability of longer wavelengths, i.e., microwaves, and the presence of related molecular spectral signatures together allow vertical humidity and temperature profiles to be measured largely unimpeded from an instrument platform placed in low Earth orbit. Microwave remote sounding has, therefore, long been recognised as offering a considerable observational advantage in gathering weather related atmospheric data when compared with shorter wavelength detection systems. Consequently, microwave observation of the atmosphere is an important measurement method that delivers key meteorological parameter information to computational weather modelling systems.

However, microwave instrumentation tends to be physically very large. Necessary space platforms have historically been extensive in size to ensure the provision of sufficient in-orbit accommodation and electrical power. Moreover, it is not unusual for microwave payloads to be combined with sensors operating at different wavelengths that together provide a comprehensive high-precision Earth observation measurement capability that services metrological centre needs.

Large spaceborne observation systems therefore perform a very necessary meteorological data gathering service that underpins weather forecasting. However, the systems are costly and lengthy to develop, and their scale limits deployment numbers to single or at best a few in-orbit platforms. As a result, global measurement is a relatively lengthy procedure that relies upon spacecraft orbit progression. This, in turn, restricts the delivery of full spatial data sets to a timescale of many hours and the ability to gather information related to rapidly forming severe weather events is therefore compromised.

To address the above limitation, a new method of globally measuring weather influencing parameters, e.g. humidity and temperature, on a more rapid timescale is necessary. This capability will fill a gap in the meteorological armoury provided by larger space-based Earth observation systems. The challenge presented is, then, one of developing a meteorological sensing approach that augments existing and planned large-scale meteorological sounders through the delivery of precision global weather forecasting information on a near instantaneous (nowcasting) timescale.

The Solution

Retrieving atmospheric data in support of numerical weather prediction is a complex process. Measurement of primary meteorological parameters of humidity and temperature is accomplished in the microwave domain by the detection and characterisation of the spectral emission signatures of molecular water vapour (H_2O) and oxygen (O_2) respectively. This not only requires use of sensitive microwave detection systems capable of sensing extremely low signal power levels, but also a simultaneous ability to resolve the molecular spectral shape from which meteorological vertical distribution data are gleaned. Moreover, and for rapid delivery, the necessary instrumentation needs to be configured with a compact architecture that allows its incorporation within small satellite platform structures that can be cost effectively reproduced to form a low Earth orbit constellation observational system.

To achieve the above, the RAL Space, part of the Science and Technology Facilities Council, has developed a new and highly compact hyperspectral microwave sounder (HYMS) that specifically targets O_2 and H_2O molecular emissions occurring at frequencies of 60 GHz and 183 GHz respectively. The new instrument comprises a miniaturised microwave front-end heterodyne detection system combined with high-speed digital backend sampling technology. Together, these key technology advancements deliver a sensitive microwave spectrometer with MHz scale resolution that complements current Earth observation sounders. Furthermore, the compact form allows integration with a small satellite platform and relatively low-cost reproduction that is compliant with the mass production and rapid deployment need of constellation satellite formation. Used in a constellation format, the HYMS system supports high precision atmospheric data acquisition on a rapid timescale for extreme weather event modelling and prediction.

Realising the above system has posed several technical challenges. The most notable is the need to sample the spectral intensity within a narrow bandwidth and which, in turn, demands an enhancement in detection sensitivity to maintain the same degree of data accuracy, i.e. radiometric precision. The latter is fundamentally limited by the electrical noise present within the detection system, and this needs to be minimised to allow the spectral signature to be observed. To achieve this, low electrical noise[1] microwave amplifier and frequency mixer technology has been combined and configured in an innovative package form to produce a state-of-the-art heterodyne (frequency down-convertor) microwave receiver.

The output of the receiver is coupled to a new compact digital sampler developed by STAR-Dundee Ltd., UK. This unit transforms the down-converted molecular signal directly into a power spectrum to allow interrogation and analysis of the spectral shape.

HYMS Development and Demonstration

The HYMS concept has been tested within a laboratory environment and important technical project milestone steps achieved include:

- All critical front-end components developed and demonstrated.
- A single sideband receiver system noise equivalent temperature of <200 K has been measured across the oxygen bands, 50 to 58 GHz and 63.3 to 68 GHz, and a double sideband receiver noise equivalent temperature <690 K, from 175 to 192 GHz has been measured across the water vapour band.
- Oxygen channel noise equivalent radiometric precisions of ~0.25 K and ~0.45 K have been measured in 10 MHz and 3 MHz spectral bandwidths respectively for a 300 ms integration time.[2]

[1] In microwave radiometry, input signal noise power is often presented as a noise equivalent temperature in units of Kelvin. Operating within this framework, a receiver system noise equivalent temperature provides a measure of the instrument sensitivity, with lower noise temperatures indicating a superior performance.

[2] Radiometric precision is the ability of a radiometer system to distinguish differences in source (brightness) temperature. It represents an overall indication of the system sensitivity.

- A suitable wide band, 9.6 GHz, high-speed digital sampling spectrometer has been demonstrated with 1 MHz spectral resolution.

As a further demonstration of the HYMS concept, the system has been engineered into the form of a full radiometer (SERMON) and deployed on the BAE 146 Facility for Airborne Atmospheric Measurements (FAAM) airborne observatory operated by Cranfield University (www.faam.ac.uk). During August 2021, a successful airborne engineering trial took place that proved the instrument flight worthiness.

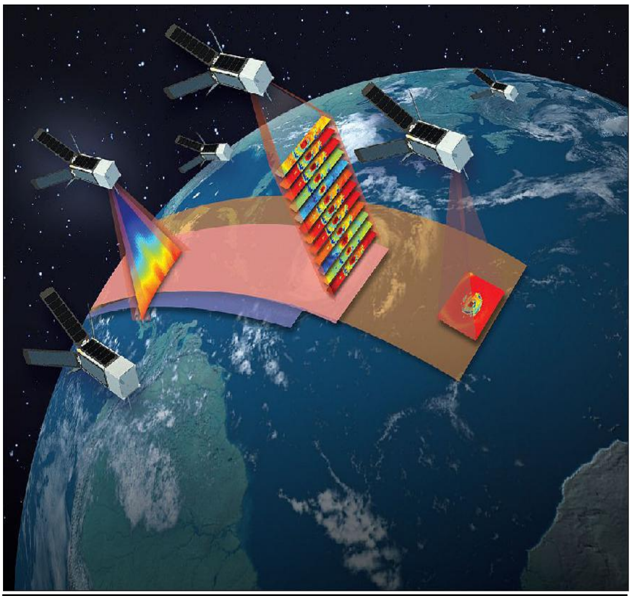
Future airborne HYMS measurement campaigns are planned to acquire atmospheric data. These data will be compared with output from complementary microwave instruments (ISMAR and MARSS) flown simultaneously. Although these instruments possess inferior spectral resolution, they will support verification of the HYMS measurements and confirm the advantages of hyperspectral measurements in terms of delivering improved retrieval accuracies.

The HYMS demonstrator instrument (SERMON) ready for airborne deployment is shown on the left. It is mounted on the FAAM aircraft (middle) for atmospheric sounding proof-of-concept. The FAAM BAE 146 aircraft used for airborne deployment is shown on the right. (Image credit: RAL Space, STFC)

Next Steps of Wider Deployment

The technical advancement achieved with HYMS places the UK in position of advantage with respect to international competitors. This substantially enhances the prospects of gaining involvement in, and leadership of, future space related missions involving the development and application of microwave hyperspectral sounding.

A commercial exploitation plan for the instrument is in preparation. This has the objective of preparing the technology for a first phase of space flight demonstration, followed by a series of small satellite launches to form an observation constellation. Global weather nowcasting will then be provided for a range of customers including energy, agriculture, government, and finance.



A constellation of identical 3U CubeSats providing atmospheric sounding. The CubeSat at the left has a temperature profile of a simulated tropical cyclone from a numerical weather prediction model. (image credit: MIT/LL, NASA)

Support from CEOI

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CEOI

The Centre for Earth Observation Instrumentation (CEOI) works with UK academia and industry. Its objective is to develop a world leading, internationally competitive, UK Earth Observation (EO) instrument and technology research and development capability, enhanced through teaming of scientists and industrialists. The CEOI is funded by the UK Space Agency with parallel technology investment sourced from the commercial sector.

Further information regarding this project and other technology developments funded by CEOI can be found at ceoi.ac.uk. Alternatively, please contact:

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