Building space-qualified detector chips

■ Artist's impression of Sentinel-5P and the **TROPOspheric** Monitoring **Instrument** (Tropomi), which maps a multitude of trace gases such as nitrogen dioxide, ozone, formaldehyde, sulphur dioxide, methane, carbon monoxide and aerosols - all of which affect our health and our climate.

The role of space-based instruments in observing the Earth is well-known, but the key technologies behind the instruments are less well understood. Philippe Chorier describes the development of detector chips for high priority environmental and meteorological missions, in particular the importance of mercury cadmium telluride (MCT).

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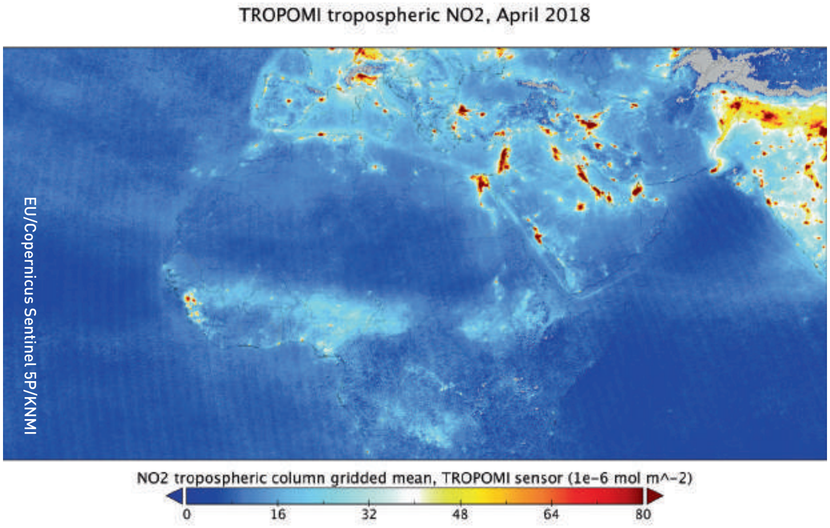
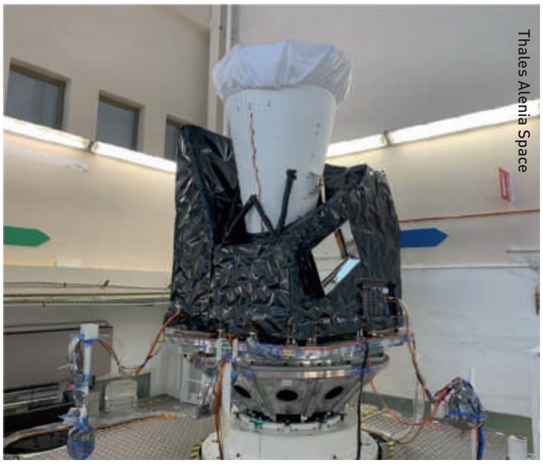
Our Earth is in a fragile state and severe weather is wreaking havoc. Just consider the horrendous storms that ripped through towns and villages in central Europe this summer, or the intense heat in North America that has contributed to numerous and devastating forest fires.

Against this backdrop, the biggest concern has to be the rapid rise in carbon dioxide emissions, which is driving changes to weather patterns and threatening to make the homelands of some of the world's poorest inhospitable. Also important, however, are the levels of ozone which protect us all from damaging UV radiation and the abundance of other greenhouse gases, such as methane.

While it is possible to measure the concentrations of these gases from sensors stationed on Earth, such an approach suffers from several significant drawbacks. Two weaknesses are the time and considerable expense associated with deploying and maintaining a vast network of terrestrial instruments; another challenge is how to monitor the atmosphere over vast expanses of sea.



EU/Copernicus Sentinel 5P/KNMI



Thales Alenia Space

▲ Left: Sentinel-5P tropospheric nitrogen dioxide measurements over Europe, Africa, Middle East, and India from April 2018 (averaged). Air pollution emitted by big cities and shipping lanes is clearly visible.

Right: The Flexible Combined Imager undergoing mechanical testing. Lynred's four different infrared detectors on this instrument cover 11 infrared channels across the IR spectrum.

A far better option is to undertake extensive monitoring from space, using a constellation of orbiting satellites. Several missions that target this objective are already underway, such as Microcarb, a carbon dioxide monitoring mission led by the French space agency CNES and the European observation programme, Copernicus.

Detector chips

Efforts within the Copernicus programme include the Sentinel 5 mission, which is helping to track changes in ozone, air-quality and climate by monitoring a range of gases, including ozone, nitrogen dioxide, sulphur dioxide, aerosols and hydrocarbons. There are also plans to monitor carbon dioxide with the launch of an additional pair of satellites slated for 2025.

For an on-board instrument to serve in this environment, it is critical that it is lightweight, because of the substantial launch costs of around US $10,000 for every kilogram launched to orbit. This requirement makes lightweight devices that are based on a semiconductor chip an ideal choice for recording the concentrations of various gases from space.

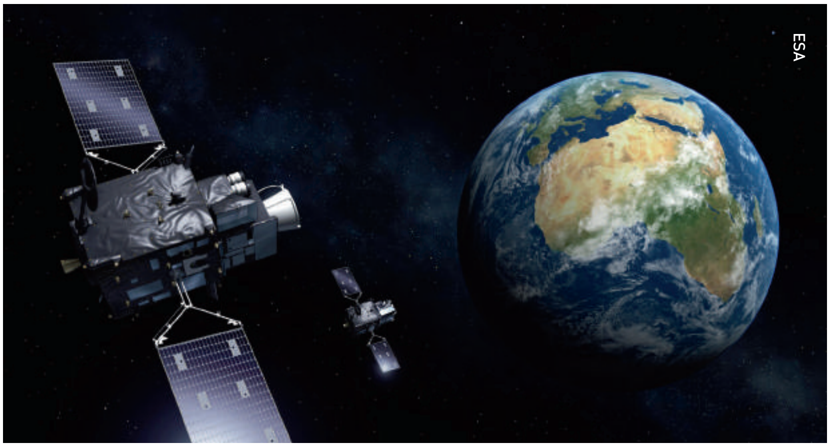
By far the most mature chip technology for making a detector is that based on the elemental semiconductor silicon. However, this material has a limited spectral range and, being unable to detect emission beyond 1.1 micrometres (μm), is incapable of detection the very long wavelengths needed to monitor the concentrations of a range of critical gases.

Several compound semiconductors - a class of material formed from combining two or more elements - are capable of stretching far further into the infrared. For applications requiring detection between 3 μm and 5 μm, the compound semiconductor indium antimonide is a contender. But when detection must span the mid- and far-infrared, as is the case for monitoring a number of important gases in the Earth's atmosphere, the leading material that possesses this capability is its distant cousin, mercury cadmium telluride (MCT). By adjusting its composition, this compound semiconductor alloy can span both the mid- and far-infrared, detecting radiation at wavelengths stretching out as far as 18 μm.

> MCT is preferred due to its robustness to harsh space environments and its heritage in space applications

Enhanced resolution

The next few years will witness the launch of many satellites equipped with MCT chips that cover different spectral ranges. These compound semiconductor devices lie at the heart of an imaging system known as the Flexible Combined Imager, which will be fitted to the Meteosat Third Generation (MTG) satellites scheduled to launch in 2022. The MCT chips included on these satellites will provide detection over 11 infrared channels spanning the spectral domain from 1.3 μm to 13.3 μm. Varying the separation between the pixels of this detector will allow data to be mapped with a spatial resolution that varies from 2 km to 0.5 km and enable the acquisition of an image of the Earth within as little as 10 minutes. The intensity maps generated by this instrument will enable scientists to monitor wind patterns;



▲ Meteosat Third Generation (MTG) Imaging and Sounding satellites will guarantee the continuity of data for weather forecasting from geostationary orbit into the next decades and will also provide advanced imaging capabilities, all-new infrared sounding and lightning imaging for warnings of severe storms.

observe fog, sandstorms and levels of dust and ice; and study fires and volcanic eruptions.

Yet another success story for the MCT detector is that it has been selected to provide detection in the shortwave infrared for the part of Europe's Copernicus Anthropogenic Carbon Dioxide Monitoring (CO2M) programme that monitors carbon dioxide emissions. For this project, detectors with more than a thousand pixels in both dimensions will be deployed to record the quantity of carbon dioxide generated by human

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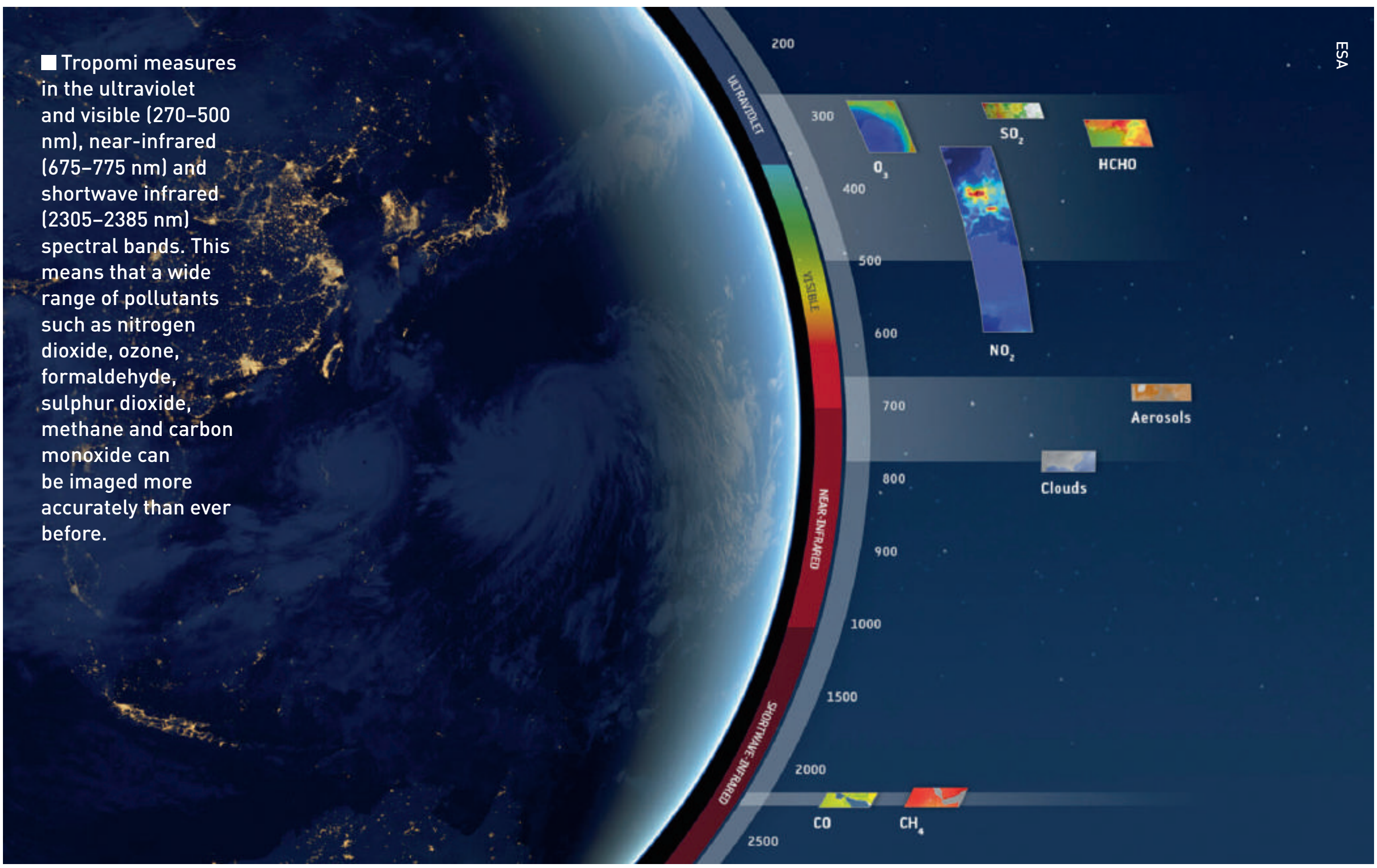
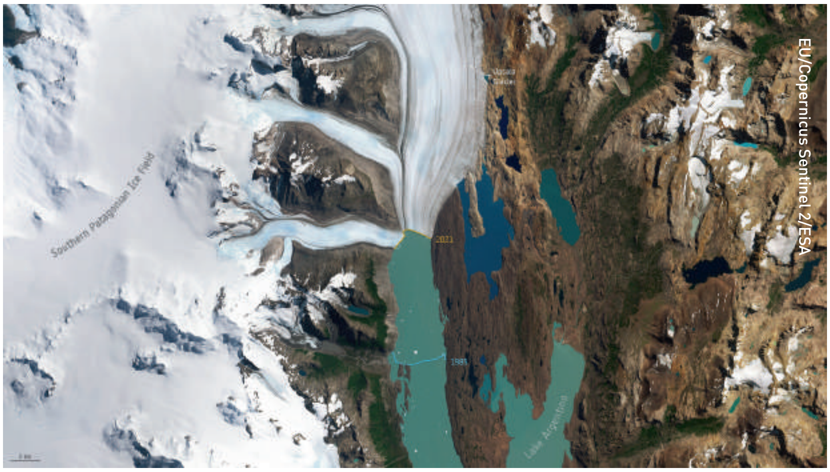
activity, as well as tracking the concentrations of other gases such as nitrous oxides and methane.

There are also plans to fit a linear short-wave infrared array on a high-resolution radiometer, which will measure land-surface temperatures derived from evapotranspiration (evaporation from the land surface combined with transpiration from plants). The detector due to be deployed for this task, which will play a key role in the Copernicus Land Surface Temperature Monitoring (LSTM) mission, will incorporate an array of four spectral lines. For each of these lines, detection is accomplished with an array of 1200 pixels in the cross-track direction and 12 pixels in the along-track scanning direction. By operating the



■ Tropomi measures in the ultraviolet and visible (270–500 nm), near-infrared (675–775 nm) and shortwave infrared (2305–2385 nm) spectral bands. This means that a wide range of pollutants such as nitrogen dioxide, ozone, formaldehyde, sulphur dioxide, methane and carbon monoxide can be imaged more accurately than ever before.



radiometer in a manner that incorporates time-delay integration - which utilises the 12 along-track pixels - the signal-to-noise ratio of this instrument increases, enabling the generation of high-quality intensity maps at 0.945 µm, 1.375 µm and 1.61 µm.

While these wavelengths are relatively short and could be addressed with other semiconductor materials such as indium gallium arsenide (InGaAs), MCT is preferred due to its robustness to harsh space environments and its heritage in space applications. Previous uses of MCT include the Sentinel 2 mission, another Copernicus mission launched in 2015, which provides detection at 1.3 µm, 1.6 µm and 2.2 µm.

Once the Land Surface Temperature Monitoring satellite has been launched into a low-Earth polar orbit, it will start to map rates of evapotranspiration with unprecedented fidelity. Every three days it will image the entire Earth, identifying the temperatures of individual fields with a spatial resolution of just 50 m, and a temperature resolution of only 0.3C.

Such high levels of precision - hundreds of times more detailed than current measurements from space - hold the key to realising the mission's primary objective, which is to aid the agricultural industry by monitoring the rate of evapotranspiration and thereby provide a more robust estimate of field-scale water productivity. The detector will also be instrumental in supporting the mapping and monitoring of soil compositions.

The next few years will witness the launch of many satellites equipped with MCT chips that cover different spectral ranges

Fabrication

The production of a mercury cadmium telluride detector involves some rather esoteric processes, making its fabrication a highly sophisticated task that few manufacturers have been able to master.

Back in the 1970s, engineers produced the first generation of MCT detectors, featuring a single line of pixels. To generate enough information to produce an image in the infrared, these devices were attached to complex, two-dimensional scanning systems.

For the detection of atmospheric gases on board a satellite, it is far better to use a two-dimensional array - as this can gather more data while trimming weight - and detectors with this feature have been available since the late 1990s. They are formed by uniting the MCT chip with a silicon backplane, known as the read-out integrated circuit (ROIC), that provides a read-out of each pixel element. Since then, the number of pixels has increased, while their size has diminished, allowing more detailed and informative images of the concentration of various gases to be produced from space.

Last but not least, these devices must be cooled. This requirement, which is in place for many forms of semiconductor detector operating in the infrared, prevents the dark current from swamping weak signals and rendering the signal from the detector of no use at all.

At first glance, the cooling requirement for MCT is challenging: to realise acceptable performance, the device must be maintained at a temperature between -140°C and -190°C, depending on the

▲ Left: The Copernicus Land Surface Temperature Monitoring (LSTM) mission will carry a high spatial-temporal resolution thermal infrared sensor to provide land-surface temperature measurements derived from evapotranspiration to improve sustainable agricultural productivity at field-scale in a world of increasing water scarcity and variability. The observations are also key to understanding and responding to issues such as climate variability, natural hazards including fires and volcanoes, and coastal and inland water management.

Above: Many glaciers in the Patagonian Ice Field, including the third largest, Upsala, have been retreating over the last 50 years due to rising temperatures. Observations and monitoring of the glacier by Sentinel 2 have revealed that it has retreated approximately 9 km between 1985 and 2021. Satellite data can help monitor changes in glacier mass and, subsequently, their contribution to rising sea levels.

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▼ Copernicus Sentinel-2A satellite image, captured on 4 February 2016, showing the Gosses Bluff crater in the Northern Territory of Australia, around 200 km west of Alice Springs. The crater, visible in the left-centre of the image is about 22 km in diameter. It was most likely formed 140 million years ago by the impact of a large comet or meteorite. The intense colours of the image represent the mineral composition of the land surface, which is clearly visible owing to the lack of vegetation.

detection wavelength. However, this temperature is just high enough to be within the reach of a relatively simple cooling system known as the Stirling cooler, which is essentially a refrigerator based on helium gas.

Today, there are just a handful of companies with the expertise to produce MCT detectors that are suitable for monitoring a range of gases from orbiting satellites. One company that has this capability, and is supplying detectors to all the missions outlined above, is Lynred, which is based near Grenoble, France.

With roots stretching back to 1986, Lynred has a tremendous track record in infrared detector development, and continues to invest in research and development to improve the MCT manufacturing process as well as the capabilities for advanced ROIC designs. This effort helps the company to maintain its position at the forefront of the production of infrared detectors for space applications, and allows it to play a key role in various projects for monitoring gases of concern. This includes the Copernicus programme, which will help scientists to understand changes to weather patterns, track various storms and monitor climate change.

While Lynred's detectors can't prevent climate change, they can certainly help to quantify its magnitude and inform the agricultural industry of how best to farm in the future. That represents an impressive contribution for a detector made from a little-known compound semiconductor, formed with manufacturing processes that are not used by mainstream chipmakers. ■

About the author

Philippe Chorier graduated in physics and optics from the Ecole Nationale Supérieure de Physique de Marseille, now the Ecole Centrale de Marseille (France). In 1996, he joined Sofradir (now Lynred) as a development engineer in charge of development and optimisation of infrared detectors, thermal and optical shielding. In 2002, he started working as a development programme manager, in particular in space applications. In 2007, he became space department manager in charge of space programmes. Since 2018, he has been space business development manager in charge of space business activity and its associated roadmap.