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Exploring Earth from Space

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Introduction

Today, satellites are changing the way we see our planet, helping us to map the impacts we are having on the surface and to understand better the way that natural phenomena, such as changes in dynamics of the water cycle, the atmosphere and magnetosphere, such as magnetic jerks and plasma jets, are affecting everyday life. The recent BBC series Earth from Space[1] shows us in awe inspiring detail, using colour imaging, just how humans are changing the surface of Earth and how animals and plants from individuals to populations and landscapes are responding. These images linked to in situ observations can shed light on multidecadal shifts in so many aspects of the Earth's outward appearance - landcover, glaciers, coastlines and urban spread. But behind these images lies a growing understanding of the processes controlling the changes.

Today, a vast array of satellites and their associated data streams are accelerating scientific investigation and discovery about Earth's dynamics at a pace that we could only have dreamed about 40 years ago. One reason for this upsurge in earth observation and space science is the transition from military to civilian applications. Another has been the opening up of access to satellite data and images at high resolutions.

In this lecture, I will look at how scientists have been able to answer questions about different aspects of our planet's workings using a myriad of instruments launched into space orbits on different satellites and show how this knowledge is helping us to understand and tackle the consequences of change on our lives.

At the end, I will explore why the idea of travelling to Mars and other parts of our universe is now being seen by certain groups of scientists and engineers as a necessary step for human survival and ask whether we can use the knowledge arising from the satellite missions to help build a more sustainable future here on Earth.

Earth Explorers

Over several decades, starting in the 1960s, the US National Aeronautics and Space Agency led the way in science and earth observation missions. Since then the European Space Agency and European national space agencies have designed and launched a series of missions to advance our understanding of the dynamics and biochemical and physical characteristics of the atmosphere, land and oceans. The major European programmes are the Earth Explorer and Copernicus. The aim of both programmes is ultimately to address questions with a direct bearing on societal issues that humankind will face in the coming decades such as the availability of food, water, energy and resources, public health and climate change.

The Earth Explorer launches began in 2009 and continue to today and include[2]:

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[1] https://www.bbc.co.uk/iplayer/episode/p072n7qd/earth-from-space-series-1-1-a-new-perspective

[2] https://www.esa.int/esa_multimedia/videos/2018/03

GOCE (Gravity field & steady-state Ocean Circulation Explorer) mission measured high-accuracy gravity gradients and provide global models of the Earth's gravity field and of the geoid. The geoid (the surface of equal gravitational potential of a hypothetical ocean at rest) serves as the classical reference for all topographical features. The accuracy of its determination is important for surveying and geodesy, and in studies of Earth interior processes, ocean circulation, ice motion and sea-level change.
SMOS (Soil Moisture and Ocean Salinity) mission has demonstrated the importance of low-frequency passive microwave sensors for understanding air–sea interactions. This could improve our ability to predict tropical cyclones.
CRYOSAT (Cryosphere Satellite) mission designed to track what is happening in the cryosphere, especially the dynamics of change in the polar regions
SWARM mission a constellation of 3 identical satellites carrying sophisticated magnetometers and electric field instruments to provide the best-ever survey of the geomagnetic field and its temporal evolution and the electric field in the atmosphere.
AEOLUS (Atmospheric Dynamics) mission to provide timely and accurate profiles of the world's winds to improve weather forecasts and climate research, predictions about extreme events such as hurricanes and information on aerosols and clouds, carrying a ground-breaking instrument - ALADIN – the first wind LIDAR in space.
EARTHCARE future mission for understanding the role that clouds and aerosols play in reflecting solar radiation back out to space and trapping infrared radiation emitted from Earth's surface.
BIOMASS future mission selected as 7th mission will provide crucial information about the state of our forests and how they are changing. The data will be used to further our knowledge of the role forests play in the carbon cycle.
FLEX future mission which aims to quantify photosynthetic activity and plant stress by mapping vegetation fluorescence.

So, let's look at what it takes to build and launch an instrument into space.

AEOLUS Diary of a Satellite Mission

Attempts to understand and forecast the wind date back to Aristotle in the 4th century BC. Today, wind profiles sampled down through the atmosphere are an essential element of accurate medium- to long-term weather forecasting, as well a key input for modelling climate change. Previously, this information was simply not available: the best equivalent came from ground-based sensors, aircraft and balloon-based radiosondes giving localised point measurements, which were then extrapolated through cloud tracking or computer simulations. Aeolus in orbit changes that: for the first time in history, wind fields can be mapped globally, on a three-dimensional basis.

The idea of flying a wind-surveying LIDAR in orbit dated back to the early 1980s, considered at one time for the International Space Station. This lidar technology was later applied to spacecraft rendezvous and docking for ESA's ISS-supplying ATV cargo spacecraft. ESA's space laser working group [3] recommended that a high-energy carbon dioxide gas laser be developed and demonstrated for aerial lidar. Later, in the mid-1990s, the development of space worthy laser-pumping diodes opened the way to a more compact solid-state version. The then 'Aeolus Atmospheric Dynamics Mission' was then planned for a post-2000 flight.

The ADM-Aeolus is designed to provide timely and accurate profiles of the world's winds and thus improve weather forecasts and climate research, predictions about extreme events such as hurricanes and information on aerosols and clouds. The satellite carries the ground-breaking instrument - ALADIN – the first wind lidar in space and is among the most ambitious lasers ever flown in space, passing over at us at local dawn or dusk. shining down to map Earth's otherwise unknown global wind field. It has a powerful laser, large telescope and a very sensitive receiver and works by emitting short, powerful pulses of ultraviolet light from a laser to deliver vertical profiles that show the speed of the world's winds in the lowermost 30 km of the atmosphere. The AEOLUS represents an enormous step forward in weather forecasting as provides continuous atmospheric data globally, in

[3] http://oa.upm.es/34897/1/Laser_sounding_from_space.pdf

place of observations, gathered from weather balloons released from various locations or from super-pressure balloons drifting in the upper atmosphere for up to one year, and models.

At the heart of Aeolus is the Atmospheric Laser Doppler Instrument, or Aladin. This is an ultraviolet lidar – 'laser radar' – whose 50 pulses per second are magnified by a 1.5-m-diameter telescope to shine through the entirety of the atmosphere from 320 km away in space. The short, powerful light pulse from the laser shoots through the atmosphere and then collects the light that is backscattered from particles of gas and dust and droplets of water. Within three one-thousandths of a second, this same telescope then gathers up the resulting laser backscatter from aerosol droplets, water vapour and actual air molecules across different atmospheric layers. On the same basis as a police radar gun, this backscatter's 'Doppler shift' is measured to derive wind velocities down to a few metres per second, taking a fresh sample every 200 km.

The time between sending the light pulse and receiving the signal back determines the distance to the 'scatterers' and so the altitude above Earth. There are two kinds of scattering - Rayleigh scattering, which is from molecules such as oxygen and nitrogen and is most efficient at scattering light at shorter wavelengths, i.e. blue and violet – which is why the sky looks blue; and Mie scattering which is from larger particles. As the scattering particles are moving in the wind, the wavelength of the scattered light is shifted by a small amount as a function of speed. The Doppler wind lidar measures this change so that the velocity of the wind can be determined.

The instrument preparation took more than two decades to design, build and test, during which innumerable, seemingly intractable problems were identified and overcome. Making a laser this intense was not straightforward. When a prototype version of Aladin was run, its laser optics degraded by 50% in less than six hours of operations - bad news for a proposed three-year mission and meaning that the mission could not fly until this problem was fixed. Solving the problems created new technology to benefit a range of future missions and gave ESA its world-leading Optics and Opto-Electronics Labs, along with a set of ISO-certified laser development standards for other laser-based missions, starting with the EarthCARE mission for clouds and aerosol monitoring.

Aladin runs on a synthetic crystal 'ND: YAG' laser, a common pulsed laser 'workhorse'. This crystal emits infrared laser light and a pair of 'non-linear crystals' subsequently convert this first into the green region of the visible spectrum then to the shorter ultraviolet wavelength we require. Selecting high-energy ultraviolet was extremely ambitious, but essential to achieve a detectable level of backscatter from air molecules, along with lower-altitude aerosols and dust (it also prevented any eye damage risk from visible wavelengths). The UV laser was designed to operate in vacuum, which simplified its thermomechanical design in light of maintaining lens alignment precisely.

But here is where the problems began. Rather than redesigning Aladin to work on a fully pressurised basis, small wisps of oxygen were released from a pair of 30 litre tanks. This oxygen flowed close to the optical surfaces that see the UV light, then gradually leaked out of the instrument enclosure.

The first inkling of trouble began with the early failure in orbit of NASA's 2003-launched IceSAT, built around an ice-mapping lidar instrument. At the same time, Aladin ground testing hit parallel problems, dominated by laser-induced contamination. Organic contaminants from the Aladin laser equipment – akin to the fumes giving a new car its smell – were being carbonised by the UV laser, accumulating on its lenses. These growing deposits then absorbed the laser heat, distorting and eventually darkening the carefully crafted optics. Laser experts began to look into this phenomenon. The first solution was to take extreme precautions to remove all organics, but this did not prove entirely possible – even metal surfaces could act as a source so that even at just a few parts per billion of organics, contamination was still introduced.

The team reached out to terrestrial UV laser users, such as France's Laser Mégajoule facility – employed to ignite nuclear fusion reactions – as well as the semiconductor industry. The answer was simply to inject a small amount of oxygen to allow the contamination to burn up in the laser heat, thus cleaning the lens. It worked in a matter of minutes. Just like humans, the laser had to breathe. The solution was very elegant because the burnt-up contaminants flowed out of the instrument along with this oxygen, in the form of carbon dioxide and water.

Roughly 25 Pascals of residual oxygen pressure were needed – just one four-thousandth of standard atmospheric pressure.

Contamination was only one of numerous challenges the instrument faced. The copious amounts of heat produced within the 30litre volume of the laser transmitter needed to be removed. This was done using 'heat pipes', which cool the laser by evaporating liquid and moving it to a space-facing radiator – analogous to human sweat glands. Aladin's electronics also need to operate on a steady, constant basis throughout their planned four billion laser shots. It appeared to the team that there were so many ways it could go wrong and yet it worked.

ESA's Directorate of Technology, Engineering and Quality set up a dedicated laboratory to demonstrate the self-cleaning method that was eventually utilised on the mission, and also proving the ability of Aladin's optics to withstand its high-laser intensities for the mission lifetime.

Last year I had the chance to be at the launch of ESA's Atmospheric Dynamics Mission – Aeolus from French Guyana, the spaceport from which many of the current Sentinel and Earth Explorer missions have left from. As can be seen from the time-lapse video[4] of the Aeolus preparation and launch on 22 August 2018, the instrument and satellite were shipped to the European Spaceport in French Guyana, as there were concern that fluctuations in the pressure in aircraft could damage the instrument. The launch was successful and within a week data were being delivered to Darmstadt in Germany ready for the calibration and validation. During this phase, field campaigns are being run all over the world to calibrate and validate the Aeolus data with measurements from the ground, using balloons and aircraft to compare with Aeolus data from space and even flying an aircraft directly under Aeolus' orbital path and taking more or less simultaneous measurements with an airborne version of the satellite instrument.

Assessing the accuracy of data being returned by a completely new technology in space is a challenging task but must be done before ESA can declare that the data good enough to be included in forecasts for example. Part of this process s gathering measurements of wind, aerosols and clouds from the ground, aircraft and from other satellites to compare with measurements being delivered by Aeolus. Since the launch, engineers and scientists have been dedicating their time to testing the measurements of the world's winds being gathered by Aeolus and feeding them into weather forecast and climate models for intercomparing.

In the latest review of the results from the Aeolus data investigations, the European Centre for Medium-range Weather Forecast (ECMWF) and the German Weather Service (DWD) showed that Aeolus winds are improving forecasts, particularly in the troposphere, which is the part of the atmosphere between the ground and about 16 km high. The wind profiles, especially over remote areas, are also proving to be very important for numerical weather prediction. Already, we have data indicating the strength of westerlies and easterlies that correspond with observations from direct measurements of the storm that hit the UK and parts of Europe on 10 March 2019 and data for intercomparing with the optical instruments on Sentinel-3 and the radar on Sentinel-1 for a fuller characterisation of Cyclone Idai that devastated Mozambique, Malawi and Zimbabwe. The value of having different satellite instruments observing the same weather event is important to improve the accuracy of weather forecasts and so that people affected by severe weather can take necessary action. In addition to seeing the benefits of Aeolus in weather prediction and storm tracking, the data are also helping to resolve the aerosol and cloud layer optical properties.

The largest improvement that Aeolus is giving us is in the tropics, over the oceans and in polar areas, where the atmosphere is currently not well sampled on small scales. By end of 2019 the Aeolus data will be ready for scientific research and for weather forecasting. Aeolus is a world first high-power UV laser instrument mission in space and will hopefully lead to many active laser missions in the future. It also showed the true value of close collaboration between scientists, industry and ESA to find innovative solutions to very tough technical challenges

[4] https://www.esa.int/spaceinvideos/content/view/embedjw/506258

Other Earth Explorers have revolutionized the data and information flows on virtually all aspects of the planet.

SMOS – Soil Moisture and Ocean Salinity Mission is a low-frequency passive L-band microwave to capture images of brightness temperature measures to calculate soil moisture and ocean salinity. Through the data coming from the satellite we have new information to study ocean circulation and salinity; tracking storms and hurricanes; estimating where the Arctic polar ice is thin enough to allow shipping to pass; mapping of droughts and thawing soils; provide crop-yield forecasts, estimates of risks of forest fires and carbon storage.

3D Earth

A thorough understanding of the 'solid Earth' system is essential for deciphering the links between processes occurring deep inside Earth and those occurring nearer the surface that lead to seismic activity such as earthquakes and volcanic eruptions, the rise of mountains and the location of underground natural resources. Thanks to gravity and magnetic data from satellites along with seismology, scientists are on the way to modelling inner Earth in 3D. Solid Earth refers to the crust, mantle and core. Because these parts of our world are completely hidden from view, understanding what is going on deep below our feet can only be done by using indirect measurements. Now scientists are using a range of different measurements including satellite data along with seismological models to start producing a global 3D Earth reference model. The model will make a step change in being able to analyse Earth's lithosphere, which is the rigid outer shell, and the underlying mantle to understand the link between Earth's structure and the dynamic processes within.

The satellites that are contributing to the solid earth work include *GOCE, SWARM* and a NASA mission called *GRACE* have provided insights into gravity, the geoid and the magnetosphere – all impossible to imagine from simply taking measurements on earth. GOCE - Gravity field & steady-state Ocean Circulation Explorer state-of-the-art gradiometer measures high-accuracy gravity gradients and provides global models of the Earth's gravity field and of the geoid to an unprecedented level of accuracy. The geoid (the surface of equal gravitational potential of a hypothetical ocean at rest) serves as the classical reference for all topographical features. The accuracy of its determination is important for surveying and geodesy, and in studies of Earth interior processes, ocean circulation, ice motion and sea-level change. The data from GOCE has allowed scientists to explore the earth's core dynamics, geodynamic processes and core-mantle interaction; generate a tectonic map and determine the 3D electrical conductivity of the mantle.

The global tectonic map has been created by researchers from Kiel University and the British Antarctic Survey using gravity gradients – the rate of change in the pull of gravity in different directions. These gravity gradients are used to create a curvature-based shape index, analogous to contour lines on a map, which can be interpreted as a tectonic map of the Earth. Surface topography can be stripped away to reveal the deep structure of the continents and oceans. Geological similar tectonic domains can exhibit distinct differences in satellite gravity gradients maps, which point to differences in the lithosphere – the solid crust and the molten mantle beneath. In combination with seismological results, gravity-gradient imaging offers a new window on Earth's structure. For the first time, seismological models and satellite observations can be integrated to provide a consistent image of the crust and upper mantle in 3D, needed to understand the coupling of plate tectonics and mantle dynamics. In remote frontiers like the Antarctic continent, where even basic knowledge of lithospheric scale features remains incomplete, the curvature images help unveil the heterogeneity in lithospheric structure, e.g. between the composite East Antarctic Craton and the West Antarctic Rift System.

Today, scientists are building a new global model of Earth's lithosphere and upper mantle by combining gravity anomalies, geoid height and gravity gradients complemented with seismic, thermal and rock information. Data from GOCE served as input for the inversion and is the first time that gravity gradients have been inverted on a global scale in such an integrated framework. While this is just a first step, 3D Earth offers tantalising insights into the deep structure of our world. For example, the new models of the thickness of the crust and the lithosphere are important for unexplored continents like Antarctica.

The *GRACE* - Gravity Recovery and Climate Experiment Measuring mission is also looking at distortions in the geoid for the purposes of estimating changes in surface water and mass balance changes in groundwater. The GRACE twin satellites, launched 17 March 2002, are making detailed measurements of Earth's gravity field changes and revolutionizing investigations about Earth's water reservoirs over land, ice and oceans, as well as earthquakes and crustal deformations. The two GRACE satellites have completed more than 13 years of continuous measurements! GRACE is a collaboration of the US and German space agencies (NASA and DLR) and together with ESA are supporting the continuation of the measurements of mass redistribution in the Earth system as a vital component of monitoring climate change.

The *SWARM* mission, another Earth Explorer, is a constellation of 3 identical satellites carrying sophisticated magnetometers and electric field instruments, is providing the best-ever survey of the geomagnetic field and its temporal evolution and the electric field in the atmosphere. It's most recent contribution to science has been to pinpoint the position and movement of magnetic north, an important input for smartphones.

Launched on 22 November 2013, *SWARM* is the fourth in series of pioneering Earth Explorer research missions, following on from *GOCE, SMOS and CryoSat*. The three identical Swarm satellites are measuring precisely the magnetic signals that stem from Earth's core, mantle, crust and oceans, as well as from the ionosphere and magnetosphere. The mission is dedicated to unravelling one of the most mysterious aspects of our planet: the magnetic field. Although invisible, the magnetic field and electric currents in and around Earth generate complex forces that have immeasurable impact on everyday life. The field can be thought of as a huge bubble, protecting us from cosmic radiation and charged particles that bombard Earth in solar winds. However, it is in a permanent state of flux. Magnetic north wanders, and every few hundred thousand years the polarity flips so that a compass would point south instead of north. Moreover, the strength of the magnetic field is constantly changing – and is currently showing signs of significant weakening.

Using SWARM data, scientists have been able to explore how the magnetic field is generated by an ocean of superheated, swirling liquid iron that makes up the outer core 3000 km under our feet. Acting like the spinning conductor in a bicycle dynamo, it generates electrical currents and the continuously changing electromagnetic field. Magnetism also come from minerals in Earth's mantle and crust, magnetosphere and oceans and solar weather. SWARM data are being used to identify and measure precisely these different magnetic signals, help explain phenomena such as magnetic jerks and plasma jets and yield a better understanding of why the magnetic shield is weakening.

The geomagnetic field models resulting from the mission will provide new insights into many natural processes, from those occurring deep inside the planet to weather in space caused by solar activity. In turn, this information along with measurements of atmospheric conditions around the orbiting satellites will give us further insights into space weather and radiation hazards, and be put to practical use to help improve the accuracy of navigation systems including those systems carried on satellites, to advance earthquake prediction and to improve the efficiency of drilling for natural resources.

Yet there are still areas where we have some way to go, such as in the field of prediction of volcanic eruptions. My own experience of the difficulty of establishing early warnings and predicting the precise timing of an eruption, comes from the late 1970s when I travelled to Oregon on the west coast of the USA to obtain field samples of brook trout *Salvelinus fontinalis*, a beautiful, small trout often out-competed by its more brutish brother the brown trout *Salmo trutta*. I was a graduate student studying the genetics and morphology across North America and had gone to Spirit Lake and rivers on the side of Mount Saint Helens. As it turns out, these were the last samples of this populations as Mount St Helens became active in March 1980. It took until 18 May for the explosion to occur during which time people really did not know which side was likely to blast. As we can see from satellite images of the intact peak of Mount St Helens and those after the eruption, the catastrophic flank collapse, avalanche, and explosion destroyed the rivers and lakes to the north and east. The scale of the eruption and the beginning of reclamation in the Mount St. Helens blast zone are documented in series of images captured by NASA's Landsat series of satellites between 1979 and 2011. The older images are false colour (vegetation is red) because earlier Landsat's could not "see" blue light[5]. It was not the largest or longest-lasting eruption in the mountain's history, but as the first eruption in the continental United States during the era of modern scientific observation, it was significant and has given scientists unprecedented opportunity to witness the intricate steps through which life

[5]https://www.youtube.com/redirect?v=UPpgqyxN2UE&event=video_description&q=http%3A%2F%2Fearthobservatory.nasa.gov%2FFeatures%2FWorldOfChange%2Fsthelens.php%3Fsrc%3Dyoutube&redir_token=ObCb1Bxyf6eJd9L8shkzqVvySBJ8MTU1ODQzMzA4MUAxNTU4MzQ2Njgx

reclaims a devastated landscape. However, it remains the case that we do not as yet have adequate satellite data to be able to forecast volcanic activity and eruptions as accurately as we would wish.

The Sentinel Family

ESA is developing a new family of missions called Sentinels specifically for the operational needs of the Copernicus programme. Each Sentinel mission is based on a constellation of two satellites to fulfil revisit and coverage requirements, providing robust datasets for Copernicus Services. These missions carry a range of technologies, such as radar and multi-spectral imaging instruments for land, ocean and atmospheric monitoring:

- **Sentinel-1** is a polar-orbiting, all-weather, day-and-night radar imaging mission for land and ocean services. Sentinel-1A was launched on 3 April 2014 and Sentinel-1B on 25 April 2016. Both were taken into orbit on a Soyuz rocket from Europe's Spaceport in French Guiana.
- **Sentinel-2** is a polar-orbiting, multispectral high-resolution imaging mission for land monitoring to provide, for example, imagery of vegetation, soil and water cover, inland waterways and coastal areas. Sentinel-2 can also deliver information for emergency services. Sentinel-2A was launched on 23 June 2015 and Sentinel-2B followed on 7 March 2017.
- **Sentinel-3** is a multi-instrument mission to measure sea-surface topography, sea- and land-surface temperature, ocean colour and land colour with high-end accuracy and reliability. The mission will support ocean forecasting systems, as well as environmental and climate monitoring. Sentinel-3A was launched on 16 February 2016 and Sentinel-3B will join its twin in orbit on 25 April 2018.
- **Sentinel-5 Precursor** – also known as Sentinel-5P – is the forerunner of Sentinel-5 to provide timely data on a multitude of trace gases and aerosols affecting air quality and climate. It has been developed to reduce data gaps between the Envisat satellite – in particular the Sciamachy instrument – and the launch of Sentinel-5 on13 October 2017.
- **Sentinel-4** is a payload devoted to atmospheric monitoring that will be embarked upon a Meteosat Third Generation-Sounder (MTG-S) satellite in geostationary orbit.
- **Sentinel-5** is a payload that will monitor the atmosphere from polar orbit aboard a MetOp Second Generation satellite.
- **Sentinel-6** carries a radar altimeter to measure global sea-surface height, primarily for operational oceanography and for climate studies.

The Copernicus Sentinels-1 and -2 are being used for many purposes already. The two identical Copernicus Sentinel-1 satellites carry radar instruments, which can see through clouds and rain, and in the dark, to image Earth's surface below. This means they can be used for tracking maritime traffic and

With air quality increasingly becoming a serious concern, the Copernicus Sentinel-5P satellite was launched from the Plesetsk Cosmodrome in Russia on 13 October 2017 to map a multitude of air pollutants around the globe. With its state-of-the-art instrument, Tropomi, it is able to detect and map pollutants such as nitrogen dioxide, methane, carbon monoxide and aerosols, all of which affect the air we breathe and our climate, more accurately and at a higher spatial resolution than ever before from space. It is an intermediary satellite which fills the gap between the past generation of atmospheric monitoring satellites, such as Envisat, and the future generation comprised of Sentinel-4 and -5. After the satellite was launched, Tropomi went through a planned decontamination process. The raw data from Sentinel-5P is being sent to the DLR German Aerospace Centre where it is processed and archived, to then be distributed to users worldwide to study air pollution.

The door that kept it sealed during this time was opened recently, allowing light to enter and the first images to be taken. One of these first images shows how ozone is distributed around the world. While ozone in the stratosphere is a good thing, protecting us from the Sun's ultraviolet radiation, lower down in the atmosphere it is a harmful pollutant. Ground level ozone is not emitted directly into the air but is created by chemical reactions between oxides of nitrogen and volatile organic compounds in the presence of sunlight. The first ozone retrievals of Copernicus Sentinel-5P show the closing of the ozone hole over the South Pole during November 2017. With a swath width of 2600 km, Sentinel-5P's Tropomi instrument can map global ozone on a daily basis and contributes to the Copernicus Atmosphere Monitoring Service to support public policies related to ozone monitoring and public health. Sentinel-5P is also mapping nitrogen dioxide over Europe. Caused largely by traffic and the combustion of fossil fuel in industrial processes, the high concentrations of this air pollutant can be seen over parts of the Netherlands, the Ruhr area in western Germany, the Po Valley in Italy and over parts of Spain. Sentinel-5P has also revealed high levels of pollution from power plants in India.

The Copernicus Sentinel-5P satellite imaged sulphur dioxide from the Mount Agung volcanic eruption on Bali, Indonesia, on 27 November 2017 and spewing out. At the same time, Copernicus Sentinel-1 InSAR data shows ground uplift on the flank of Mount Agung, which is on the island of Bali in Indonesia. The data show uplift between August and November 2017, prior to the eruption of Mount Agung on 27 November. The eruption was preceded by a wave of small earthquakes. A team led by Bristol University's School of Earth Sciences in the UK used radar data from the Copernicus Sentinel-1 radar mission and the technique of InSAR to map ground motion, which may be indicate that fresh magma is moving beneath the volcano. Their research provides the first geophysical evidence that Agung and the neighbouring Batur volcano may have a connected plumbing system.

Air pollution is a global environmental health problem, especially for those living in urban areas. Not only does it negatively impact our ecosystems, it considerably affects our health. According to the World Health Organization (WHO), around 8 million premature deaths per year are linked to air pollution, more than double of previous estimates. One of the pollutants with the strongest evidence of health effects is nitrogen dioxide. In the EU, the largest contributor to nitrogen dioxide emissions is the road transport sector, as well as pollution produced from industrial activities, and residential combustion. According to the Air quality in Europe report published in 2018 by the European Environment Agency (EEA), nineteen of the EU Member States recorded nitrogen dioxide concentrations above the annual limit value. Not only is nitrogen dioxide damaging the ecosystem, it also causes significant health issues contributing to respiratory problems ranging from causing cardio-pulmonary ailments, to exacerbating asthma and even impacting cognitive abilities. The spatial resolution of the satellite is so good that it is possible to pinpoint emissions in fine detail and also detect gradients of emissions in large cities. Data such as these will soon underpin the Copernicus Atmosphere Monitoring Service, and will be used to issue forecasts, and ultimately be valuable for helping to put appropriate mitigation policies in place.

Having access to free data from satellites has led to a proliferation of affordable instruments to take measurements on the ground. Students and schoolchildren through the Living Planet Symposium School Lab[6] are also being encouraged to develop air quality monitoring stations using Raspberry Pi computers and sensors for nitrogen dioxide, carbon dioxide and particulate matter, to measure ambient air quality conditions as well as temperature and humidity. In his way, citizens can contribute to the calibration and validation of Sentinel-5P and future satellite missions.

The Sentinel missions can also work together. A good example is on ice and the permafrost regions of the world. Ice is without doubt one of the first casualties of climate change, but the effects of our warming world are not only limited to ice melting on Earth's surface. Ground that has been frozen for thousands of years is also thawing, adding to the climate crisis and causing immediate problems for local communities. In Earth's cold regions, much of the sub-surface ground is frozen. Permafrost is frozen soil, rock or sediment – sometimes hundreds of metres thick. To be classified as permafrost, the ground has to have been frozen for at least two years, but much of the sub-surface ground in the polar regions has remained frozen since the last ice age.

Permafrost holds carbon-based remains of vegetation and animals that froze before decomposition could set in. Scientists estimate that the world's permafrost holds almost double the amount of carbon than is currently in the atmosphere. When permafrost warms and thaws, it releases methane and carbon dioxide, adding these greenhouse gases to the atmosphere and making global warming even worse. With permafrost covering about a quarter of the northern hemisphere, extensive thawing could trigger a feedback loop that could potentially turn the Arctic from a carbon sink into a carbon source. Thawing permafrost isn't just releasing more greenhouse gases into air – it's also changing the landscape and destabilising the ground, and so causing real practical problems for society.

[6] https://www.esa.int/spaceinvideos/Videos/2019/05/Air_quality_station;https://lps19.esa.int/NikalWebsitePortal/living-planet-symposium-2019/lps19/ExtraContent/ContentSubPage?page=5&subPage=1

Over 30 million people live in the permafrost zone, in towns that were built on firm ground. As the ground softens, the infrastructure that Arctic communities rely on is becoming increasingly unstable. Determined by temperature, permafrost is an essential climate variable. Through ESA's Climate Change Initiative, temperature data that have been collected over years are gathered to determine trends and to understand more about how permafrost fits into the climate system. Traditionally, direct temperature observations are made through boreholes. However, the measurement network is rather sparse because of the obvious remoteness and logistical issues in the Arctic. Therefore, other types of information that reflect change are needed to fill the vast gaps across the Arctic and other mountain regions.

To monitor permafrost a lot of different satellite data and in situ measurements are needed. Through an ESA project called Glob Permafrost, images are captured by the Copernicus Sentinel-2 mission, for example, which gives a camera-like view of how the land surface is slumping and eroding because of thawing permafrost. The Copernicus Sentinel-1 radar mission gives valuable information on widespread changes in topography. Sentinel-3, which carries thermal sensors, can provide information about the changes in the temperature of Earth's surface. Information on snow conditions and land cover can then be used as a proxy for soil properties. Both snow and soil regulate heat transfer, so they determine the actual impact of increasing air temperature on the frozen soil beneath. In this way, Bartsch has published the first global map of permafrost from 2000-2016 at a spatial resolution of 1 km, in *Earth Science Review*.

The Permafrost Information System, which consists of a database as well as a visualisation platform of satellite-derived information relevant for permafrost monitoring is also available. It includes the permafrost map and land-cover change information, ground subsidence, rock glaciers and information on lake properties for key regions. With the damage that thawing permafrost can unleash on the climate system and on the local environments, it is no surprise that this is a hot topic. Scientists are drawing on all resources at hand to understand and monitor the situation, which, in turn, arms decision-makers with the information they need to take action.

The future of space science and earth observation missions

In the coming decades, all the space agencies will look to become more agile and responsive to both scientific and commercial needs. The European Space Agency has 26 satellites in development and 14 in operations delivering services, earth explorers and science missions. These are driven by the growing demand for data and information, which is being delivered through free, full and open access and big data analytics under the legal framework for the Sentinel programme [7]. There are also new Meteosat missions planned for 2020 and beyond including Meteosat TG and MetOp SG. Already the MetOp systems are improving weather forecast by more than 40% and these are set to be even better with the new satellites, Sentinel and science missions. The exponential increase in satellite launches is now emerging with 220 between 2007 and 2018 and 562 planned from 2018-2022. All of these launches and satellites are set in a landscape of private endeavours and transformative technologies such as High-Altitude Pseudo Satellites, small satellites (CubeSats) and mega-constellations; 7B phones; the Internet of Things; cloud computing, Artificial Intelligence and machine learning; crowdsourcing and Big Data. Collectively, these will be able to provide services undreamed of until now. This is why the next period is referred to as the Entrepreneurial Space Age.

[7] ESA Sentinel Data Policy (Sep 2013) and EU Delegated Act on Copernicus Data and Information Policy (Dec 2013). Regulation (EU) No 377/2014 and Commission Delegated Regulations (EU) 1159/2013

There are also several big missions that will explore our Solar System. Launched in 2018, NASA's new telescope TESS (Transiting Exoplanet Survey Satellite) is hunting for planets outside our Solar System and scan the whole sky. It is expected to find 20,000 candidate planets in the first two years. NASA's Partaker Solar Probe will go closer to the Sun than any other spacecraft, diving in and out of its corona to analyse the solar wind. ESA's BepiColomba will study Mercury, the innermost planet in our solar system and is wrapped in thick thermal blankets to cope with the enormous amount of solar energy that it will be exposed to – the surface is 430ºC. NASA's James Webb Space Telescope is the largest and most advanced orbital observatory built and will look at the Universe in infrared. ESA's CHEOPS Characterising ExoPlanets Satellite will improve our understanding of how exoplanets are formed, and the Solar Orbiter will study the sun and inner heliosphere. NASA's Lucy will look at Jupiter's 6,000 plus trojans or asteroids and 16 Psyche will journey to this unique metal asteroid to investigate the origin of planetary cores. ESA's PLATO (Planetary Transits and Oscillations will hunt for extrasolar planetary systems and explore the properties of terrestrial planets in the habitable zone.

Going to Mars

At the same time, space scientists are now seriously planning for the final frontier that that is human space flight to other planets. The main focus is on Mars. Much of the recent attention has been on sending explorers and instruments to detect conditions on the surface. Mars is now a real operational endeavour with both Nasa and Mars One, a private company staffed by previous NASA and ESA employees, looking to put people on the Red Planet in 10 years using the SpaceXFalcon 9 rocket. Many questions and problems lie ahead: how to launch a colony ship, how to land, how would human beings cope, what would we do if something goes wrong? Humans will experience roughly one-third of the gravity on Earth, which means that bone and muscle waste rapidly and hand-eye co-ordination becomes impaired.

But many are asking why go to another planet? The simple answer is that with so many problems here on earth and our improved understanding and measurement of asteroids large enough to wipe out the human race, appearing on collision trajectories with Earth during the coming decades, we will potentially need to set up colonies elsewhere to ensure the future of human beings[8].

Many people want to go to Mars. In 2013, 202,686 people applied to go to Mars; in 2014 663 made it through to the first shortlist; the average age of candidates was 32, so will be 42 by departure in 2024. In 2016 6 teams of 4 individuals were selected for training.

I for one would rather stay here on earth – it a beautiful planet and one I want to help conserve and protect for future generations.

[8] https://www.youtube.com/watch?v=t9c7aheZxls