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Future of Remote Sensing for Geohazards and Resource Monitoring

Tim J Wright
COMET, School of Earth and Environment, University of Leeds.

Abstract

Remote Sensing technology, observing systems and analysis methods are advancing at a bewildering and exhilarating pace. In this chapter, I offer a personal perspective on future development in this field, focusing on applications in geohazards and resource monitoring. Remote sensing is already offering operational data streams in some areas of geohazard and resource monitoring. Future data streams will offer higher spatial and temporal sampling of phenomena, likely supplied by a mix of public and private providers. Collectively, these will enable the development of reliable monitoring systems. Developments in machine learning and modelling will ensure that new data streams can be translated into the information required by decision makers. Collaborations are required that span traditional disciplinary boundaries.

1. Introduction

I have been working in remote sensing since the mid-1990s, primarily investigating geohazards in an academic setting. During that time, I have witnessed the incredible advances in observing technologies, which dramatically improved our ability to monitor geohazards and resources. Integrated and coordinated observing programmes like the European Commission's Copernicus programme[1] are now providing key data sets and services operationally. New constellations of Earth Observing satellites from commercial organisations such as Planet acquire optical imagery anywhere on Earth daily, at a spatial resolution better than 1 m [2,3]. Scientists are beginning to use machine learning algorithms to mine these massive data pipelines for useful information, in applications ranging from volcano monitoring[4] to finding scarce groundwater resources[5]. In this chapter I will speculate on what the future holds in the short-to-medium term, focusing on how we can exploit remote sensing technologies to better mitigate disaster risk and to monitor scarce resources.

This contribution is a personal perspective and is not intended as a comprehensive review. I will focus on three key areas of advance. The first is technological advances in the sensors and supporting technologies (storage, transmission, platforms). The second is what I will refer to as the observation programmes, which encompasses the complex ecosystem of public and provide providers of remotely-sensed data. The third area is the methodological and analytical advances, encompassing the methods that are transforming data into information that is useful for scientists and decision makers and the tools that are democratising the use of remote sensing data. I will end the chapter by discussing the areas where I think effort should be focused in the medium term to accelerate future progress.

2. Future Advances in Sensing Systems

The technology of sensors and the platforms on which they fly have been area of continual rapid progress. I'll split the discussion into three sections: passive sensors, active sensors, and sensing platforms.

2.1. Passive optical sensing systems

Passive optical systems capture images of the Earth's surface and atmosphere using reflected sunlight or radiated thermal energy. Since the launch of the Earth Resources Technology satellite (later renamed Landsat-1) in the early 1970s, optical imagery has been a key remote sensing tool for geohazards and resource monitoring. Passive remote sensing imagery is the most intuitive data to interpret and provides powerful products that decision makers can easily understand and use.

The significant trend over the last few decades has been an increase in the capabilities of passive systems to provide ever higher spatial and spectral resolutions. Until the mid-1990s, only moderate resolution (10-100 m) data sets were available for public use, from systems such as Landsat and SPOT. The decision by US President Clinton in 1994 to allow US companies to launch their own high-resolution sensing systems led to the launch of IKONOS-1 and -2 in 1999 and, at the same time, Russia declassified high-resolution imagery from their military systems. Optical data with 1 m spatial resolution was available for the first time to non-military users able to pay.

At the time of writing (2019), several commercial organisations operate optical systems with spatial resolutions of a few metres or better. For example, one company operates more than 130 optical satellites with spatial resolution of 3 m or better[3], and Digital Globe's WorldView-3 satellite, launched in 2014, offers imagery with a spatial resolution of 0.31 m. High-resolution imagery can be acquired at short notice anywhere on Earth. Although cost remains a significant limitation for many users in hazard research, imagery is often provided free of charge following major disasters via the international charter for space and major disasters and is also often available for any user via portals such as Google Earth (see section 4.1 of this chapter). The number of high-resolution optical satellites looks set to keep on increasing as the cost of build, launch and operation decreases.

Digital Elevation Models (DEMs) are extremely valuable for geohazard assessment, with applications including tectonic geomorphology[6], landslide hazard assessment[7], and modelling flows from volcanic eruptions[8]. Stereo optical imagery can be used to derive DEMs at a spatial resolution ~2 times lower than the source imagery[9]. Several modern satellite systems, such as the Pleiades system[10], offer along-track stereo or tri-stereo imagery, which minimises any distortions due to changing surface conditions or illumination. Significant processing efforts are underway to produce DEMs with a spatial resolution of a few metres for the entire planet from optical imagery. Led by scientists in the US, who have access to large volumes of data from the Worldview satellites, a significant initial release was the ArcticDEM, which covers the entire land surface north of 60°N at 2 m spatial resolution[11], as well as the volcanoes of the Aleutians and Kamchatka peninsula. In the near future, other regions should be released at this spatial resolution, which is a dramatic improvement on the 30 m DEMs that are currently openly available.

Several commercial organisations are also now beginning to offer high-resolution satellite video – multiple images per second of a fixed location during a satellite overpass of around 90 s[12]. The primary aim of these images is for applications such as traffic monitoring, but the parallax created by the motion of the satellite along its orbit means that these data also have the potential to be used for the creation of very-high-resolution elevation models with resolutions significantly better than 1 m. In the future, these datasets may become widely available, but it is likely that their application in the medium term will be limited to high value commercial targets such as cities and ports.

During and following volcanic eruptions, a major hazard for aviation and health is the gas and ash in the atmosphere. For monitoring the spatial distribution and evolution of volcanic emissions in the atmosphere, spatial resolution is less important than spectral resolution, which controls the ability to identify volcanic emissions, and temporal resolution, which allows timely warnings to be issued. Detection and discrimination of gas and ash relies on absorption features in the thermal infrared (TIR) and/or ultraviolet (UV) parts of the spectrum, and current systems use both of these. IASI is a hyperspectral "Infrared Atmospheric Sounding Interferometer". The sensor flies on METOP-A and -B and provides more than 8000 spectral samples in the TIR for each pixel, which have a 12 km diameter at nadir. Each satellite provides global coverage every 12 hours and because they operate in the TIR they can provide images day and night[13]. Retrievals from IASI have been developed that can extract SO_2 and ash content[14,15], as well as estimates of the vertical distribution of these in the atmosphere[16]. An alternative method for measuring the distribution of SO_2 is to exploit absorption features in UV spectra. The most recent of these sensors is Tropomi, onboard the EU Copernicus Sentinel-5 precursory mission, which acquires UV hyperspectral data daily with a spatial resolution of 7 x 3.5 km and converts these to estimates of SO_2 concentration[17]. Future developments are likely to see improvements in the spatial resolution and detection limits for these systems such that they can increasingly be applied for monitoring rates of passive degassing at volcanoes[18].

For monitoring and rapid response over large regions, geostationary satellites developed for weather forecasting can offer the best views of rapidly evolving volcanic eruptions. The Japanese Himawari-8 system, for example, positioned at 140.7 E, offers full disk imagery with a resolution of 500 m every 10 minutes and every 2.5 minutes over Japan[19]. Himawari-8 is not hyperspectral, but the 2 km resolution TIR bands can nevertheless be used to detect SO_2; the data can then be used to track volcanic plumes in real time as they evolve[20]. TIR sensors on geostationary or polar orbiting platforms can also be used to identify emissions from hot lava and hence to track eruption rates[21] or provide alerts of new eruptive activity[22]. Future developments are likely to see improved temporal sampling, smaller pixel sizes, and increased sensitivity through improved radiometric and spectral resolutions. Integration of data from the various systems available already has the potential to provide continuous monitoring of the Earth's subaerial volcanoes – this capability will only improve.

Optical systems are likely to remain critical to geohazards and resource monitoring. New systems will be developed that improve spatial, spectral, radiometric and temporal resolutions. However, there will remain limits, both physical and practical, to the capabilities of individual systems – we will not see a hyperspectral geostationary system offering full disk views every second at 1 m resolution. Even if this was physically possible, the data volumes would be impractical. Optical systems are also limited by cloud cover and those that use reflected rather than emitted radiation can only operate during hours of daylight. However, by combining data from different systems we can already obtain invaluable data for response, monitoring and research, and capabilities will improve steadily in coming years.

2.2. Active sensing systems (SAR and LiDAR)

Active sensing systems, including SAR (Synthetic Aperture Radar) and LiDAR (Light Detection And Ranging), are tools for imaging the earth's surface using electromagnetic waves emitted from an artificial source, usually on the platform itself. Because the source of illumination is on the platform itself, such systems can operate day or night. SAR uses energy in the microwave part of the spectrum and the long wavelength energy has the added advantage of being able to penetrate through cloud cover. Section 2 of this book describes many of these active techniques in more detail.

SAR images have four applications that are most relevant for geohazards and resource monitoring. Firstly, the amplitude of the backscatter imagery can be examined to assess changes in the ground surface, for example as might be caused by a lava flow, building collapse or changing water level in a reservoir[23-26]. Secondly, interferograms can be formed between two images acquired at different times from a similar location by differencing the phase information of the signal (Chapter 2.2 of this book). These can be used to show how the ground has moved between the two acquisitions[27] or to track how a pixel has moved through time[28]. The ground movement data can be used in a wide variety of applications including showing the accumulation of strain on tectonic faults[29], tracking magma movement under volcanoes[30], and monitoring subsurface water resources[31]. Thirdly, the coherence of the interferogram, a measure of the change in the scattering properties of a pixel, can be used to map changes in the ground surface properties, again perhaps caused by building collapse or the deposition of fresh lava[32,33]. Finally, topography and changes in topography can be measured by creating DEMs from interferograms, most usefully from systems such as TanDEM-X, where the transmitted signal is received simultaneously by two satellites at different positions[34]. These can be of great value in a range of applications where ground movement is very large or the ground surface changes are incoherent, for example during the growth of volcanic lava domes, when large landslides occur, or for monitoring the extraction of resources from active open cast mines.

Like passive optical systems, the technology in SAR systems on orbiting platforms has gradually improved over the last few decades. SAR systems can use their phased array antennae to operate in several different modes with varying spatial resolutions and image areas. For example, in its highest resolution mode ("staring spotlight") TerraSAR-X can acquire images over small areas (~4 x 4 km) with a spatial resolution as high as 0.25 cm[35,36]. Publicly-funded SAR satellites such as Sentinel-1A and -1B, part of the EU's Copernicus programme, have generally opted instead to acquire lower resolution data over much larger areas – Sentinel-1 swaths are 250 km wide in its standard "interferometric wide swath" mode, meaning the whole Earth's surface can be imaged with a spatial resolution of ~4 x 20 m every 6 days if both satellites are used[37,38]. Commercial SAR operators such as ICEYE and Capella Space are now launching fleets of relatively low-cost SAR missions capable of acquiring high-resolution data over small areas at short notice. SAR data is available in several different wavelengths from different satellite systems, although only C-band data from Sentinel-1 is currently acquired systematically over the whole globe and made available free of charge for all users.

The number of SAR systems in orbit is increasing[6] and future missions will continue to provide ever expanded coverage at a variety of revisit times, wavelengths, spatial resolution and coverage. The joint US-India NISAR mission, scheduled for launch in 2024, is particularly promising for geohazards and resource monitoring as it will provide free and open data and processed results for the whole globe at L-band[39]. Here, however, I just want to highlight a few areas where the longer-term future may bring radically different observations that could have powerful applications in geohazards and resource monitoring. The first of these is in the area of interferometric SAR (InSAR). Conventional InSAR measures the component of ground movement in the satellite line-of-sight direction of the satellite. Because the line of sight is usually approximately east-west and inclined 20-50° from the local vertical, only east-west and vertical motion can be well resolved by combining data from ascending and descending satellite passes[40]. To obtain information about the along-track (approximately north-south) motion, the radar beam can be split into forward and backward facing components. The difference between the forward and backward interferograms is sensitive to along-track motion[41,42]. However, because the angular separation between forward and backward-facing beams is relatively small in current systems, the sensitivity to along-track motion is poor for most SARs currently flying. The unusual sweeping and burst acquisition pattern made by the Sentinel-1 TOPS mode means that Sentinel-

1 is slightly more sensitive to along-track motion in the burst overlap regions, but it still much less sensitive to along-track motion than to line-of-sight motion[43].

Future systems have been designed that could improve the sensitivity to North-South motion and enable 3D ground movement to be measured. The SuperSAR concept[44] would achieve this with a single platform and antenna by transmitting and receiving two beams that are strongly squinted forwards and backwards. By combining data from the two ascending beams and the two descending beams, 3D ground movement can be measured, although there is a time difference between the acquisitions on the ascending and descending passes. The Harmony mission[45], selected as ESA's Earth Explorer 10 mission, aims to achieve a similar goal using two passive receiver satellites flying in tandem with Sentinel-1D when it is launched in the 2020s. When flying in formation along the satellite track, the combination of the Harmony satellites and Sentinel-1C or -1D will enable along-track motion to be measured. When flying in across-track mode, they would enable updated DEMs to be generated rapidly.

An even more radical proposal is for a geosynchronous SAR system. This was first proposed in the 1970s[46] and was revisited by NASA in the early 2000s[47]. Geosynchronous SARs work by integrating very long apertures along an orbit an orbital path that sits at the geostationary distance but inclined off the equator – the result is that the orbit makes a figure of 8 pattern on the Earth's surface. By pointing the beam at a focused area and integrating over long segments of the orbit, multiple measurements of ground movement and atmospheric conditions can be made every day[48]. The Hydroterra mission was unsuccessful for ESA's Earth Explorer 10 competition but the concept will likely be revived for future missions. In the long-term, a fleet of geosynchronous SARs could provide deformation data globally with very short revisit times.

Whether it is using geosynchronous or low-earth-orbiting SARs, we are set for a data rich future. For rapid response to hazardous events this is invaluable. 20 years ago, it would usually take weeks to obtain the first radar data following a major event such as an earthquake. With Sentinel-1 today we can usually obtain imagery within a few days. In the not-too distant future, there will be multiple radar acquisitions from different satellites each day, providing data that will improve decision making and the response of teams on the ground.

LiDAR is a powerful tool for measuring the Earth's surface shape and texture on a variety of spatial scales[49,50]. Scanning LiDAR instruments mounted on aircraft can produce high resolution, accurate digital elevation models; vegetation can be stripped out by processing the LiDAR waveform to extract the final echo, which usually comes from the ground rather than the vegetation canopy[51]. Many countries are acquiring systematic LiDAR data sets and making these available free of charge, facilitated by organisations like Open Topography[52]. However, airborne surveys are expensive for individual users and impractical for repeat monitoring in most circumstances.

Satellite LiDAR has the potential to provide repeated information about surface topography as well as data about the atmospheric conditions along the laser path, but it is challenging to build a system capable of making useful measurements from satellite orbits. ICESat1 was the first practical LiDAR flown in space and was operated by NASA from 2003 to 2009[53]. The laser pulses on ICESat1 had approximately 70 m diameter and were separated by 170 m along track. These were sufficient for the primary task of monitoring the cryosphere, but were too course for the majority of applications in geohazards and resource monitoring. ICESat2, launched in September 2018, is a considerable advance on IceSAT1. It senses data using 6 beams, each with pulses that have a footprint of around 45 m. The pulse repetition frequency is 10 kHz, corresponding to 0.7 m on the ground, so in effect there are 6 continuous tracks of measurement, organised as 3 pairs; the paired tracks are 90 m apart and there is a 3.3 km gap between each pair[54]. ICESat2 revisits the same tracks every 91 days, meaning that data should be useful for some applications in geohazards and resource monitoring, particularly in monitoring forestry[55]. The GEDI system installed on the international space station in 2019 has even higher density, collecting data in 8 beams separated by 600 m[56]. However, the spatial resolution of the data will remain a significant limiting factor for most geohazards and resource monitoring applications. ESA will also fly a LiDAR on the EarthCARE mission, due for launch in 2024. This is primarily aimed at monitoring the atmosphere, and could have practical applications for monitoring volcanic emissions[57].

Continuing advances in technology will lead to future satellite LiDAR missions that will provide rapid revisit for high-resolution topographic models. NASA's most recent decadal survey[58] highlights the key requirement for a move from track-based satellite lidar to swath coverage with the Earth Science community emphasising the need for 1 m resolution coverage, comparable to airborne LiDAR. However, the timescales for implementing such a mission objective remain unclear.

2.3. Observing platforms

I want to briefly highlight two trends in the development of observation platforms that have important implications for the future development of earth observation for geohazards and resource monitoring. The first of these is the development of "Cubesats", which are small platforms built in standard dimensions of 10 x 10 x 10 cm (1U). Cubesats can be 1U, 2U, 3U or 6U size and weigh less than 1.3 kg per U[59]. They are typically launched in bundles reducing the cost by orders of magnitude compared to conventional large satellite systems. The low cost has opened the earth observation space market to a number of commercial vendors, and it is even practical for universities to launch their own low-cost satellite systems. I'll discuss some of the new observation programmes below (section 3.2).

The second major development that is having an impact for geohazards and resource monitoring is the development of unmanned aerial vehicles (UAVs or "drones") as practical platforms for targeted earth observation. Using simple cameras and other sensors, UAVs are increasingly being used in geohazards research for monitoring areas that are dangerous or time-consuming to access, and to provide higher-resolution data sets than are available from space. Data can be used in applications ranging from topographic change mapping[60] to volcanic gas sampling[61]. Increased automation of the platforms and the development of low-weight sensors will likely see an increase in the use of UAVs for applications in hazards and resource monitoring in future years.

3. Future Advances in Observation Programmes

In this section, I want to address the wider ecosystem of public and private observation programmes that sets the framework within which individual missions and sensors fly. I'll touch on the differences between flagship systems and observation programmes offered by the space agencies for public good and the lower cost missions increasingly being flown by the commercial sector. I'll discuss efforts by operators of satellite data to coordinate data acquisition and supply for disaster response and speculate on future developments.

3.1. Big data and public observation programmes

The widespread availability of massive, open data streams, particularly from the European Commission's Copernicus programme, are fuelling rapid growth in the update of Earth Observation data for research and commercial applications. Data downloads for the EU Copernicus programme have increased by 133% from 2016-2019 and economic activity by companies providing value added services has been growing at 15% per year in Europe[62]. This growth is the result of deliberate strategic investment designed to meet the needs of society.

For geohazards and resource monitoring, we often require large stacks of data, systematically acquired over extended periods of time across much of the planet[6]. To acquire such data sets traditionally requires significant investments in robust spacecraft, capable of acquiring data for large parts of their duty cycle and transmitting the resultant large data sets back to a ground segment capable of handling the data volumes produced. Although this paradigm is being challenged by new constellations of low-cost platforms, only public providers are likely to be in a position to acquire systematic global data sets over extended periods of time. And only public providers are likely to be in a position to make the data available free of charge to all users.

The acquisition of systematic global data sets has been an ambition of organisations including NASA and ESA, but making the data free of charge for all users has been a gradual process. NASA led the way by making the entire Landsat archive and new acquisitions available for all users in 2008[63]. This led to the number of Landsat images being used jumping from fewer than 40,000 per year prior to 2008 to around 20 million downloads in 2017[64]. ESA have for a long time made limited data sets available free of charge to scientific users, but the development of the Copernicus programme saw all data streams made fully available free of charge to all users for the first time[65]. Copernicus is a programme coordinated by the European Commission and operated by ESA. Europe has invested €8.2 billion in Copernicus from 2008 to 2019; the latest economic assessment is that in the period 2018-2020 alone the investment will generate economic benefits in the range €16 to €21 billion[62].

Large observation programmes such as Copernicus are set to continue for the next few decades at least, and I would anticipate other countries also contributing free and open data for the greater good of society. The increasing availability of data relay satellites[66] enables very large data sets to be acquired and beamed straight back to Earth for analysis in near real time.

3.2. Space 2.0 and the commercial sector

Data from commercial low-cost satellites cannot yet compete in terms of data quality and volume with the data provided by systematic public sector observation programmes. However, this is an area that is developing at pace. Before 2014, the majority of Earth Observation satellites launched into orbit were medium (>500 kg) or large (>1000 kg) and typically fewer than 40 were launched in any one year. In 2017, a similar number of medium and large EO satellites were launched, but over 200 EO satellites were launched in total, with most being commercial satellites in the micro (< 100 kg) and nano (< 50 kg) categories[62].

This proliferation of small, low-cost, commercial satellites is sometimes referred to as Space 2.0[67]. The satellites often have limited capability individually, in terms of duty cycle or data transmission bandwidth, but when operated as a constellation, such as the 130 satellites operated at present Planet Labs, these small satellites can provide daily (or better) monitoring services, often at very high resolution, that are beyond the capabilities of any single large satellite with a global monitoring objective[3]. Much of this growth is backed by venture capital, but this investment is predicated on long-term insatiable demand for the high-resolution data streams that can only be provided by commercial organisations. The European Commission has been very careful to not compete directly with services and data streams provided by commercial operators, and I anticipate that the commercial sector will continue to grow. Unless a single organisation such as Planet gains an effective monopoly, competition between providers should make prices of the data streams more affordable for applications in geohazards and resource monitoring.

3.3. Coordination for geohazards and resource monitoring

The proliferation of Earth Observation satellites and programmes is bewildering for many users and impractical for many applications and, even if the data sets from different providers are available to an analyst, they can be difficult to use together. Several initiatives are attempting to tackle these issues, particularly in the realm of geohazards, where there is a pressing need to monitor sites at risk of potential disasters and to respond to crises quickly enough that the results can be useful for decision makers.

One notable initiative is the "International Charter: Space and Major Disasters" (http://disasterscharter.org). The charter is supported by most public providers of Earth Observation satellite data. It can be triggered by national representatives across the world, at which point data providers agree to acquire data over an area impacted by a potential disaster and make that data available to dedicated analysis teams. Those teams process and interpret the data, making products that are easily digestible by end users. Since it was founded in 1999, the International Charter has been triggered over 600 times to date (33 times in 2018[1]) in events ranging from hurricanes and floods to earthquakes and eruptions.

While the Charter deals only with disaster response, the Committee on Earth Observing Satellites (CEOS) has been developing activities with a wider remit to use EO data for disaster risk management[68], in response to the 2012 Santorini Report on satellite Earth Observation and Geohazards[69]. From 2014 to 2017, CEOS ran a series of disasters pilot projects in the areas of seismic, volcanic, flood and landslide hazards and demonstrator projects are currently being implemented for volcanic and seismic hazards. The approach is somewhat different to the charter and is focussed on making sure data are acquired and available throughout the disaster management cycle to the research and monitoring community. This enables monitoring approaches to be developed by teams of scientists in conjunction with local monitoring agencies and decision makers. For example, during the pilot programme on volcanoes, a coordinated team of international scientists and were able to work directly with local monitoring agencies to help inform decisions and alert levels and response at volcanic crises including a period of unrest in 2014 at Chiles-Cerro Negro volcano in Ecuador/Columbia[70] and the 2016 eruption of Masaya in Nicaragua[71], and were able to coordinate acquisition strategies to ensure data were available for all 319 volcanoes in Latin America, most of which had no ground-based monitoring[72].

The EC Copernicus programme also recognised the need to develop value-added products as well as simply providing data. They developed a series of Copernicus Services, which provide results and products aimed at end users rather than EO scientists. Of particular interest is the Copernicus Emergency Management Service, which aims to provide information to assist in emergency response for different types of disasters, both natural and man-made[73]. With ever more Earth Observation satellites acquiring data of interest to the hazards community, continued efforts to coordinate EO activities will be important in the future. If correctly organised, coordinated constellations of sensors operated by different public and private providers have the potential to respond to most events within hours, and to provide monitoring data streams that will be invaluable for managing disaster risk.

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[1] https://disasterscharter.org/web/guest/charter-activations

4. Future Advances in Data Analysis Methods

The final area of development that I want to cover in this personal perspective on the future of Earth Observation for geohazards and resource monitoring is the development of new methods for data analysis. I'll cover developments that are making data streams available online and analysis ready, discuss crowd sourcing of information and the impact of social media, and finally touch on developments in machine learning and modelling, which are likely to result in the biggest changes in the way we use EO data over the next decade or so.

4.1. Online services, the cloud and Analysis Ready Products

We have I think become rather blasé about the fact that wherever we live on Earth we can get an aerial view our home at high resolution through free portals like Google Earth[74]. What we are typically viewing when we open Google Earth is copyright aerial and/or satellite imagery purchased by Google and made available through their platform. Although users cannot download or manipulate the imagery, the simplicity of the interface and the ability to insert additional layers has made this a powerful system for sharing and visualising geospatial data. These systems have democratised the use of remote sensing data – users do not need to expert remote sensing specialists to use an apply remote sensing data for their own applications.

Google have also developed Google Earth Engine, a cloud-based service that enables users to conduct their own processing and analysis on a vast array of publicly-available data sets, including the full archives from Landsat and Sentinel missions[75]. This is one of a number of cloud platforms that now exist with the aim of allowing individual users and commercial providers to develop services that exploit earth observation imagery; the EO browser from Sentinel Hub, for example, allows users to easily create simple visualisations of the latest data without being an expert in remote sensing technology and image processing[2]. With programmes such as Copernicus producing Terabytes of data every day, it is not feasible for most users to hold their own data archives; processing big data sets on dedicated servers situated next to the data is likely to be a growing trend in the community.

Rapid analysis for geohazards and resource monitoring will be facilitated by the development of Analysis Ready Products – imagery that has been pre-processed to make common corrections and processing steps such as orthorectification and geocoding. In the geohazards domain, several groups are processing Sentinel-1 data to produce analysis ready interferograms, time series and velocity fields[76-78], and are making these available through platforms like ESA's Geohazards Exploitation Platform[79] and the European Plate Observing System, EPOS[80]. In the commercial realm, companies such as TRE-Altamira (https://site.tre-altamira.com/) and Satsense (http://www.satsense.com) are providing interactive tools for viewing high resolution processed deformation products derived from a range of satellites, and the Copernicus European Ground Motion Service is providing deformation products from Sentinel-1 over all of Europe[81]. I anticipate that in the future very few analysts monitoring geohazards or resources will process their own InSAR data; instead, they will rely on public or commercial service providers for the data and focus their efforts on building methods that exploit the data.

4.2. The power of the crowd

Social media has made the world a smaller place in many walks of life. In the area of geohazards research, crowdsourcing of information has become a key part of the response to major disasters[82] and I expect this to continue in the future. One way that the power of the crowd has been harnessed is through citizen science activities. A good example occurred following the 2015 Nepal earthquake, when DigitalGlobe and Airbus imagery were made available via interactive mapping portals; the public were asked to contribute to damage and landslide mapping. This resulted in the rapid production of data products that were of direct use in the emergency response[83]. Information, such as earthquake locations can also be mined directly and rapidly from social media posts, potentially even beating traditional seismological location methods for speed[84].

Social media has also changed the way that scientists respond to disasters, with a global network of scientists sharing data, links, and ideas quickly and openly during volcanic crises and in the aftermath of earthquakes using platforms such as twitter[85,86]. These sometimes lead to formal collaborations and publications that would not have occurred without that initial virtual interaction[87]. Social media interactions must be handled with care, as one risk is that confusing, false or alarmist information is communicated to the public, creating unnecessary additional panic[88]. However, social media will not go away, and my view is that

[2] https://apps.sentinel-hub.com/eo-browser/

on balance it makes a positive contribution to our response to geohazards. Guidelines will need to be developed to help scientists and monitoring agencies use and benefit from social media.

4.3. Machine Learning and Modelling

A common request from end users in geohazards and resource monitoring is to receive information with which they can make decisions, rather than pretty pictures or raw data. Traditionally, this has been achieved through specialist analysts examining data streams and processing these to provide the information required by decision makers. The increase in the volume and breadth of data streams now available is making it increasingly hard for any analyst to exploit all available data streams efficiently. A suite of Machine Learning methods, including increasingly sophisticated Artificial Intelligence algorithms, are being applied to challenges in geohazards and resource monitoring. At the same time, models are being build that are increasingly powerful for predicting the behaviour of the sub-surface.

One example where machine learning has already made good progress is volcano monitoring. Two approaches published to date seem promising. The first uses blind source separation algorithms such as independent component analysis to identify and separate the different contributing parts to interferograms over volcanoes, which might contain contributions from topographically-correlated atmospheric noise, turbulent atmospheric noise, as well as surface deformation from a number of different processes such as deep inflation of a magma source and flank instabilities facilitated shallow surface faulting[89,90]. By tracking how these signals evolve through time at individual volcanoes, it should be possible to flag when a volcano behaves unusually. A second approach uses more sophisticated machine learning approaches such as convolutional neural networks to classify interferograms as to whether they contain deformation or not. Using >30,000 automatically generated interferograms from the COMET-LICS system[78], Anantrasirichai and colleagues[4] were able to train an algorithm so that it could select around 100 interferograms that it thought contained strong evidence of volcanic deformation. Of these, a trained human analyst suggested just under half showed real deformation. Further improvements could be obtained by training the algorithms with synthetic examples of deformation[91].

In the future, I expect the application of machine learning and artificial intelligence to become much more routine and widespread in all areas of geohazard and resource monitoring, and to evolve to become more of a predictive tool. For example, algorithms could be developed that use optical and radar date from satellite with digital topography and weather models to make predictive forecasts for landslide failure[92], or use satellite measurements of volcanic degassing and deformation with ground-based seismicity data to provide real-time estimates of the probability of future eruptions of the kind provided at present by expert elicitations[93]. The possibilities are vast and hugely exciting for the discipline.

Machine Learning algorithms are, however, blind to the physical processes that are causing the observations, and this can potentially limit their predictive power. For example, if we want to understand how a volcano or oil field is behaving and incorporate different observations to make a prediction of future behaviour, then the more traditional approach is to build a physical model of the system[94-96]. This can be much more labour intensive than machine learning, but if the model is good then it can be potentially more powerful – providing information on the properties of the subsurface as well as predictive power[97]. Huge advances in computational power have led to an increasing sophistication of models and I expect this to continue. A significant challenge for geohazards will remain in the time it takes to build a useful model – it is far easier to build a model retrospectively after an eruption has occurred than to build and deploy it in real time during a crisis. Nevertheless, I expect that the simple kinematic modelling toolkits now available[98] will evolve into tools that incorporate more of the dynamics of physical systems[97,99].

5. Conclusions

In this chapter I have offered a personal and inevitably biased perspective on the future development of remote sensing for geohazards and resource monitoring. I hope I have convinced the reader that it is an exciting time to work in this field, with incredibly rapid changes in the observation technologies, the availability of big data streams through coordinated public and private observation programmes, and new developments in data analysis. To embrace this exciting future, we will all need colleagues and collaborators with different and diverse skills. We need specialists in the observing technologies to develop new sensors, engineers, and specialists to build, launch and operate the platforms, data engineers who can build systems that can archive the vast quantities of data that are produced by these systems and make them available on demand to users. We need computer scientists developing new machine learning and artificial intelligence algorithms for analysing the data streams. But we must not also neglect the hazard and resource specialists who understand the processes that are being observed, who can build models of these processes, and who are willing to get their boots muddy in the field to provide vital data and observations that can't be made with remote sensing. And we should not neglect the end users of our data who want information that can help make vital and life-changing decisions. We must maintain disciplinary excellence but be willing and open to collaborations that cross traditional disciplinary boundaries and borders. In many ways the future of remote sensing is of course already with us. It is an exhilarating area to be working.

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