10.1098/rsta.2002.1124

Developments in space engineering and space science

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The objectives of the conference are outlined, followed by reviews of some highlights of recent developments in space engineering, space sciences and their practical benefits, which are not only becoming more evident but also of considerable commercial value. This paper concludes with a discussion of the future challenges of near-Earth space science and technology, especially the arrangements for operational monitoring and exploiting the results from a UK and European perspective.

Keywords: space engineering; space science; satellites; atmospheric science

1. Objectives of the conference

During the 1990s the UK's contribution to space science and technology began to grow again from its low level in the 1980s. There were some notable successes, and in some fields British teams were participating at the highest international level. The first objective of this meeting was to ensure that everyone working in these fields could hear about the latest developments and that industry, government and researchers could build on these developments in planning for the future.

Concerns had been expressed in the 1990s about the need in the United Kingdom (UK) for better industry–government coordination and better presentation of space science and technology achievements both to the public and to overseas countries. The latter task of presentation should be straightforward, since there are so many good examples to choose from, especially in Earth-observation and communication systems. Another criticism was that, although the UK was contributing sizeable funds to international projects, industry was not benefitting proportionally. Also, concern has been expressed about the future of space science experiments and Earth observation as a result of the responsibility for their funding moving from the former Science and Engineering Research Council to the Particle Physics and Astronomy Research Council and the National Environment Research Council. Despite the strong similarities in many of the scientific and technological aspects involved in missions for planetary science, near-space studies and Earth observation, they are in fact managed by different research communities, so that collaboration is limited. There are several professional societies (the Royal Astronomical Society, Remote Sensing Society, Royal Meteorological Society, etc.) dealing with different aspects of

One contribution of 25 to a Theme 'Science and applications of the space environment: new results and interdisciplinary connections'.

space science and separate arrangements for funding and organization, notably the European Space Agency (ESA) and the British National Space Centre (BNSC).

The technological aspects have now been brought together through the BNSC, and there is a growing exchange in the ESA and elsewhere between those running different types of mission. One result is that small-satellite technology is now being used more widely.

The meeting was successful in attracting excellent lectures and stimulating discussions amongst leaders in UK space science, but it was less successful in interesting junior researchers and engineers. This issue, which covers most of the material presented at the conference, will hopefully be read by a wide audience, including the future leaders in space science and technology. They might be interested to read an overview of the whole field—especially the aspects that are developing most rapidly, notably the increasing close linkage of data to computational models, smaller satellite systems, and their widening practical applications.

2. Developments in space engineering science

Recent developments in technology, especially those developed on Earth for other purposes, have led to many applications in space, including more detailed scientific investigations, more accurate and comprehensive environmental monitoring and improvement of practical engineering systems.

Space systems consist of platforms, their delivery system, the communication to ground and the means for distributing data. Until 20 years ago, each mission was a single satellite on a single rocket. Probably the greatest technological change since then has been the introduction of multiple-satellite systems such as the Global Positioning System or clusters of space satellites. Multiple satellites launched from the same rocket have become commonplace and a practical way to use launch resources most effectively. Such complex missions have only become possible as a result of the increased reliability in all the elements of space systems. Confidence that the majority of scientific experiments and operating systems will perform as planned has greatly increased.

There were some striking successes, even when quite new systems were being tried, such as with SOHO for the Solar System, UARS (Upper Atmosphere Research Satellite) and European Remote-sensing Satellite (ERS) (Taylor 2003) for detailed Earth observation and the very small-satellite missions for communication and broadband Earth observations (Sweeting 2001). It is notable that some means were found to reduce the cost of such missions enormously, either by miniaturization, as with the University of Surrey Satellites, or by assembly in a developing country using parts from more developed countries, as with the Indian Geostationary Satellite. Costs have also been reduced by using the intercontinental rockets left over from the 'cold war'. Of course there have been failures, some of which have been associated with the trial of new technology, such as the original 'Cluster' experiment on the newly introduced ARIANE 5 launcher systems.

Most of the organizations originally involved in the satellite and launcher systems were governmental but, in the USA and Europe, private companies have been involved as contractors in the space programme since the earliest missions. As a major contractor on European and Japanese experiments and operational systems explained, software systems in the ground segment have become steadily more reliable even though they have become increasingly complex. Nevertheless, sufficiently large errors have sometimes occurred that cause total failure of a mission; there still does not appear to be any automatic logic-checking systems to guarantee that these do not recur in future (Norris 2003). For very large systems, empirical testing of all the likely situations is the only reliable method, as recent research in computer science has illustrated quite convincingly (Ross Anderson 2002, personal communication).

Steady improvements in the overall systems would not have been worthwhile without comparable improvements in the sensitivity and accuracy of observing and measuring instruments on satellites.

There has been a substantial increase in the accuracy and range of measurements of the particles and plasmas occurring in the space environment. This has permitted detailed studies of the critical processes associated both with the persistence and with the periodic breakdowns of the magnetosphere that shelters the Earth and nearby satellites from the solar winds (Cowley *et al*. 2003).

Before a remote measurement is of any use, it is essential that the location of the satellite is known relative to the relevant observation and/or communication system of the mission. For current missions, location errors of low-Earth-orbiting satellites are less than 1 cm and may have to be even less than that for some planned missions. As with other instruments and system improvements, these have resulted from the introduction of global, radio-frequency tracking systems (e.g. the French DORIS system) *and* improved gravity force modelling, and understanding and modelling of many physical phenomena (such as electromagnetic and aerodynamic forces on satellites).

Active microwave radars on European satellites ERS1, ERS2, ENVISAT and the Canadian RADARSAT now enable variations in the elevation of the features of the surface of the Earth, such as the levels of volcanic lava (before and after eruption), lakes, ice sheets, sea level and even rivers, to be measured to an accuracy of ±10 cm, an improvement of *ca.* 50 cm over the past 10 years. These data enable the dynamics of solid and fluid geophysical phenomena, for example ocean currents, flows of very wide rivers, lake-level changes and movement of ice sheets, to be computed. Thence, predictions are possible for seasonal forecasts and many types of natural disasters. These measurements are also crucial for climate science and for improved long-term climatic variations. However, it appears that these remarkable measurement systems are not known about and therefore not applied by those with technical responsibilities for Earth movement (e.g. mud slides), hydrology and other branches of Earth science. Some organizational aspects of this problem are discussed in § 5.

There have been similar substantial improvements in remote measurements of surface temperature, using the along-track scanning radiometer (ATSR) developed at the Rutherford Appleton Laboratory (UK) with an accuracy for surface temperature of ±0.1 K. Since the error is only about one-third of the mean changes caused by global warming in the past 50 years (Houghton *et al*. 2001), this instrument is accurate enough to monitor these changes over the next decade as global warming continues.

These and other measuring systems are providing data that was not previously available. For these data to be used effectively in scientific research and for practical applications, they will need to be widely disseminated and analysed scientifically by relevant experts, who may not be space scientists. For example, remote-sensing instruments could formerly only provide measurements of the average concentrations of gases and particles integrated over the depth of planetary atmospheres. However, now they can begin to provide vertical profiles of water vapour (e.g. AMSU-B) and greenhouse gases (e.g. UARS), which are contributing to improved weather forecasts and a more critical examination of climate prediction (see § 3). The recent NASA TERRA satellite, with instruments MODIS and MOPPITT, and ENVISAT, launched in 2002, are now providing data on the pollutant gases and particles in the lower atmosphere, in areas of the world where there is little cloud, such as Los Angeles, and China. The measurements will only be provided over the UK in cloud-free areas larger than about 20 km × 20 km. So far these data are only provided every 10 days at a given location and only delivered after one or two days, which limits their use for operational environmental forecasts. But these delays could be reduced quite feasibly if the organizations and the scientists responsible for these research instruments consider it worthwhile to exploit their practical and operational value (Muller *et al*. 2001).

When new remote-sensing instruments are introduced they have to be calibrated against other measurements which may be taken on similar instruments on other satellites or by other instruments operating on different physical principles. This is essential when the instrument only records *changes* in a variable to be measured (e.g. water-surface level) or some quantity that indirectly indicates the physical variable to be measured (e.g. surface roughness). However, it is also necessary for checking the accuracy of instruments that use an ‘absolute’ method for measuring quantities, such as electromagnetic radiation. In the last 10 years, the calibration procedures for Earth’s atmosphere–ocean-observing instruments have become more reliable, more rapid, and more closely related to their practical and scientific purposes (Hollingsworth 2001). As well as comparing the measurements with those taken on the ground, e.g. surface level, roughness, temperature, etc., remotely sensed data are also compared over several months and over the whole globe with predictions from numerical atmosphere–ocean models that ‘assimilate’ data from millions of measurements globally. Systematic errors lead to recalibration and sometimes modification of the instruments.

As was pointed out in discussion (and is likely to become ESA policy for Earth-observing missions), there is every reason to apply these sophisticated, but well tried, data-assimilation methods to instruments used for other geophysical and planetary quantities. This approach may even stimulate the wider use of operational models in these fields, for example, monitoring and predicting the dynamics of the magnetosphere.

3. Space-based sciences

Through the use of new satellites and improved instruments, it has been possible to examine in more detail the main features of our planetary system and hence better understand them. We also now know that relatively small fluctuations and random events can have an enormous effect on any part of the system, for example on the climate and existence of life. As both of these aspects of the system have become more comprehensible, there has been growing public and political interest in exploiting the new scientific and technological capability for predicting the vagaries of the solar–planetary system and, in some situations, as we discuss in § 4, reducing their dangers to planet Earth. The recent landing of an instrument on an asteroid and the real possibility of affecting the trajectory of a near-Earth object are excellent examples of such interventions (BNSC 2000) and of new developments in space science linking up with space engineering.

(*a*) *Solar climate and processes*

Several Japanese, US, European and UK solar missions (SOHO, YOHKOH, TRACE, etc.) have led to a more comprehensive description of the variability of the magnitude and patterns of solar processes. With X-ray and occulting-disc images of the outer part of the solar atmosphere, the structure and huge outbursts of magnetic and plasma energy from the corona have been measured (Harrison 2003). Other measurements have not only quantified the large-scale features of the velocity field, and the smaller-scale surface and subsurface cellular motions, but also indicated the connections between surface and subsurface motion through compression waves, modulated by the shearing motions. These features probably reduce the predictability of solar compared with Earth 'weather'. However, as was remarked in discussion, no 'weather-forecast' model of solar surface/subsurface motion is in fact provided continuously using such data, and therefore it is difficult to know whether the various conjectured mechanisms and models are really consistent with the data. Earthbound meteorologists commented on their experience that the daily analysis of the Earth's atmosphere motions and ocean currents had greatly helped to identify the dominant mechanisms and also helped to eliminate erroneous concepts and features in models. For the 'solar-climate' with significant time-scale variations of decades, forecasts may well be more difficult than those for the Earth's atmosphere. This is a strong reason for mounting further solar missions in the future.

(*b*) *Magnetospheric dynamics*

Whereas every other aspect of the Solar System had been broadly predicted even before space flight began in the 1950s, this was not so for the magnetosphere, which is the large, comet-like region containing the Earth's magnetic field. Van Allen belts of charged particles trapped within it were also not predicted. Although the magnetospheric layer shields both the inner space around the Earth and the Earth's ionosphere and atmosphere from the dangerously intense energy of particles streaming from the Sun, this cannot be a steady process, because of variations in intensity of the solar wind, and because of waves and internal fluctuation in the Earth's magnetic field and ionosphere. The processes effecting this unsteadiness are being studied intensively (Cowley *et al.* 2003) with near-space missions measuring plasma and particle properties and magnetic fields. These missions are particularly valuable for testing theoretical models of the physics of extreme events when large local distortions of the magnetic field occur, leading to its diffusion across field lines. By using groups of satellites, the 'Cluster' project provides measurements of the particle–plasma distributions and vector gradients of particles and fields in the extensive dayside cusp regions and the 'tail' or 'wake' of the magnetosphere in the direction away from the Sun. It was exciting to learn how these space missions are continuing to throw up new surprises and conceptual questions about this vitally important region of the Earth's space environment. Unlike the situation with 'solar weather', there is now active research into developing operational forecasts based on current numerical models for the plasma and electromagnetic behaviour of the magnetosphere as it is forced by solar wind and other external fluctuations. Some plans are based on using the large computational data-collection systems available for weather forecasts. There may be scope for both research and operational collaboration between the large centres in Europe and the USA, which are currently considering these developments.

(*c*) *Earth's climate*

Many of the key concepts about the Earth's climate, especially about its variability and likely future changes, have emerged from space science and technology, notably studies of solar radiation (starting with Herschel in 1801), observations of other planets (e.g. Houghton 1991) and, in the past 40 years, from satellite measurements of the Earth's upper-atmosphere (Harries 2001; Taylor 2003). The first of the studies has been central to answering the questions about the changes of climate as a result of the suggestion that a rise in solar radiation between 1850 and 1950 may be at least as effective as greenhouse effects in raising the surface temperature on the Earth. In Haigh's (2003) review of the evidence, she supports this hypothesis and also the broad conclusion of the Intergovernmental Panel on Climate Change (Houghton *et al*. 2001) that the average temperature between 1950 and 2000 was caused by the increasing concentration of greenhouse gases. However, these conclusions have to be regarded as approximate, not least because the mathematical climate models may currently under-predict solar effects.

There are fundamental questions about how the very small fluctuations of solar ultraviolet and radiation interact with the variation of ozone in the lower stratosphere and atmosphere dynamics to produce significant climate effects. Some space science and meteorological groups, particularly in Denmark, have sought to explain the correlations between solar and climate fluctuations in terms of variations in solar and cosmic-ray particle fluxes and cloud formation.

Satellite measurements have recently provided some of the most direct confirmation of the processes that together make up the greenhouse effect for increasing global temperatures. Harries's (2001) study of the measurements of the greenhouse-gas-emission spectra over the past 40 years show unmistakably how their concentrations are increasing in the troposphere and stratosphere. He also reviewed the earlier measurements from a low-altitude polar-orbiting satellite, ERBE, which had provided some evidence for the reduced outgoing radiation because of it being trapped near the Earth's surface by the greenhouse gases. Since predictions of long-term climate trends require that this radiation monitoring be maintained, it is fortunate that the Meteosat second-generation stationary satellite of the European Meteorological Satellite Organisation will be carrying the Geostationary Earth Radiation Budget instrument (designed and constructed in the UK). However, since this will only cover about one-third of the globe, it would be highly desirable for an equivalent instrument to be provided by one of the other geostationary satellites: another task for improved international coordination.

Another technique for averaging measurements of the upper atmosphere is to make the measurements when the satellite is situated so that the instrument's line of sight is tangential to the planet and therefore passes through a large area of the atmosphere:

the technique of 'limb-sounding'. The NASA UARS includes an instrument from the University of Oxford designed on this principle, which in 1992, in combination with data from earlier UK experiments on the NASA Nimbus series of satellites, provided strong confirmation for cooling of the upper atmosphere as predicted by global climate models (Taylor 2003). The instrument also provided high-quality data on the distribution of chemicals in the upper atmosphere which have been assimilated into the forecast and climate computer models for upper-atmosphere chemical dynamics. These processes are now known to affect predictions of environmental factors (such as ozone, UV radiation and air quality), as well as some sensitive atmospheric motions, on monthly, seasonal and climate time-scales.

One of the reasons why climate change is so difficult to identify and why decisions based on these hypotheses are so puzzling to the public and controversial is because of the temporal and spatial variability of the climate changes. This is particularly true of the polar regions (King & Turner 1997). A poster presented by Laxon (2001) reported on satellite observations of average sea-ice surface distribution and depth in the Arctic Ocean, where there is a long-term trend in which the ice thickness decreases to about half of its average present value of 3 m in the next 50 years. However, these observations also show large statistical variability, which explains the great scatter in the trends derived from occasional or pointwise surface and subsurface measurements by ships and submarines. There are now several national and international programmes of research programmes to monitor and predict these variations by combining data from new remote-sensing instruments (e.g. ESA's CRYOSAT) with new approaches in climate, ice and ocean modelling. Recent research shows that this is a promising approach, with ice-thickness fluctuations correlating closely with climatic data for the melting and freezing seasons.

This is an excellent example of how data from space-based remote-sensing instruments are transforming many areas of geophysical research, leading to new techniques, concepts and questions. Rather belatedly, oceanography and hydrology are beginning to reap the same advantages in terms of measurements of flows and other processes that have benefited meteorology from the beginning of the space age. Sensitive measurements of ocean temperature (e.g. with the ATSR instrument on ERS1 and ERS2) and ocean-surface level (on the NASA–France TOPEX/Poseidon satellite) recorded over many months had in the 1990s provided definitive maps of the great ocean oscillation and ocean currents, just as the earliest satellites confirmed the 'classical' hypothesis about the measurement and growth of cyclonic systems and fronts. By the end of the 1990s these data, together with numerical models, enabled short-range and seasonal forecasts of ocean current, ocean temperature and surface waves to be provided operationally. Of course, this advance will only continue if there is a commitment by governments to provide operational oceanographical satellites, just as there is with meteorological systems.

As with fronts and waves in the atmosphere, there are similar mesoscale ocean phenomena that can be detected to within a kilometre. They can significantly affect ocean mixing and also produce intense local currents that may determine the forces on engineering structures and the movement of sediment (Robinson 2001).

The latter process helps to determine the most important topographic aspect of the ocean, namely the exact locations of the coasts and the variation of depth year by year. The latter can vary by 20 or 30% over 10 km as the result of bottom-sediment waves and can move and grow over several metres in the period of one year. These changes cause significant uncertainties in physical and biological studies of coastal oceanography. Instruments on the SEASAT satellites in the 1970s first showed that, by measuring the variable refraction of microwave signals from the pattern of surface ripples, caused by currents passing over the bottom sediment waves, it would be possible to detect them remotely, provided that the water depth is less than about 20 m. Research is continuing to turn this technique into a practical scheme by combining data from ERS1 and ERS2, RADARSAT and successor systems with active microwave instruments, together with tidal current and surface-wave calculations.

Instruments for detecting small movements or relative displacements at the surface of the Earth have also produced some striking insights into scientific problems of solid Earth geophysics. Movement of ice into the sea from the largest Antarctic glaciers has been quantified (Shepherd *et al*. 2001). The existence of slow rock displacement parallel to large-amplitude faults has been confirmed using interferometry of repeated images. With increasingly comprehensive coverage of all the Earth's major volcanoes from remote-sensing systems, the statistical patterns of their behaviour have become clear, and detailed measurements of levels and temperature of individual volcanoes have improved our understanding of the many mechanisms controlling the dynamics before and after eruption (Wadge 2003) (see also § 4).

4. Practical benefits

As with most practical applications of science and technology, those associated with space have initially been led by the technology rather than by user need. Also, defence interests were dominant, not least because cost was almost irrelevant. There were immediate advantages of moving to space-based weapons systems by using the communication, navigation and observation provided by Earth-orbiting satellites. This trend continues, with the defence agencies being at the forefront of the application of innovative space technology. Another reason for developing these very advanced and costly technologies is because they can provide a strategic advantage to an economically strong country through pressuring their opponents to follow in the same direction.

However, benefits to civil society and to commerce soon became apparent in the 1960s, as had famously been predicted by Arthur C. Clarke (1945) in his seminal article on geostationary communication satellites. Most of these space-based practical benefits have been in the form of more information delivered to people and to systems with qualitatively new data (e.g. from space-based observations) and/or with improvements such as greater speed, accuracy, and cheapness. The rapid development of computers and computational modelling is adding value to the space-based systems, to provide richer and more-integrated information for human or computer decisions. New operational system possibilities are continuing to emerge.

Communication and navigation applications of space technology have developed, as with others, primarily as a result of greater reliability and reduced costs of satellites, instruments and systems on the ground. But an equally important component has been the technological, organizational and commercial developments, especially the deregulation and wider use of TV licences, the growth of the Internet, and communication systems for mobile users such as ships, aircraft and of course people (Parker *et al*. 2001). With the enormous growth and living standard of the world's population, the demand for these systems grew much faster than could be met by the provision of land-based systems, especially in developing countries. There the space-based systems have partly contributed to arrangements for warning of natural disasters and for massive educational programmes, such as, for example, the Indian geostationary satellite INSAT, which provides both weather observation and communications channels.

Increasingly, developing countries are not following the Indian example, but rather are pursuing an alternative and much less costly approach of collaboratively launching groups of three to five small (100 kg) polar-orbiting satellites (Sweeting 2001), so that any one of the satellites passes over a position on the ground at least once a day. These systems also combine surveillance for defence or natural-disaster warning with communication facilities. The novel design of the electronic systems in these satellites enables them to be miniaturized and to have a robust performance. At the same time, using largely off-the-shelf components and redundant intercontinental missiles (e.g. from Russia) as launch vehicles ensures that the costs are much reduced. Recently, a wider range of measuring instruments has been installed on these small satellites, for example for monitoring concentrations of ozone (integrated through the atmosphere) at a spatial resolution now down to *ca.* 50 km. Increasingly, these systems are enabling both small and large organizations all over the world to participate in and develop new applications of these scientific measurements and monitoring operations, for example in local semi-commercial activities for agricultural planning, hydrology, environmental warnings for human health and transportation systems, etc.

The increasing use and therefore reliance on space-based communication, navigation and monitoring systems means that any disruption in their operation seriously disrupts the organizations and people that depend on them. The main cause of disruption, once the satellites are in orbit, is related to the sudden impact of intense fluxes of radiation and particles from the Sun. As explained in § 3, some of these events are associated with a brief breakdown of the magnetosphere and therefore of the shielding by the Earth's magnetic field. When such events are predicted in advance, even by a few minutes, it is possible for the satellite's altitude and the on-board instruments to be adjusted, through on-board or ground-based control systems, to minimize any likely impact (Coates 2001). Other possible 'space-weather' forecasts could be provided for the effects of meteor streams (Müller *et al.* 2003) and debris from orbital spacecraft (Crowther 2003). As with atmospheric variability, one needs to be able to make predictions in 'real time', but also to know the likelihood of events of varying severity over long periods into the future. Such predictions are essential for the designs of space-based systems and for those insuring these systems, just as weather and hydrological data are used for establishing insurance premiums at the Earth's surface.

Other commercial organizations are also interested in 'space weather'. They include airline operators (who are concerned about the health effects on aircrew of exposure to radiation and particle fluxes) and, on the ground, power and telecommunication companies. Their operations require predictions of when they will be disrupted by 'space' radiation and particle fluxes, which ionize the air at the top of the atmosphere and cause increased currents in the magnetosphere, leading to the currents from overhead electric lines 'short-circuiting' to the Earth, and which distort electromagnetic propagation. These practical and commercial concerns make it increasingly necessary to ensure the same level of continuity both in the organization and interpretation of results in satellite missions monitoring space weather as for those monitoring terrestrial weather. This requires similar capability for operational computer modelling and data handling. This is only likely at a few major centres, as is now being explored in Europe and the USA.

The benefits of advances in space science and technology are nowhere more visible and appreciated by individuals, politicians and organizations of every description than in the provision of more-reliable and longer range weather forecasts. Ten years ago the errors in forecasts for two days ahead in the Southern Hemisphere were nearly 50% greater than in the Northern Hemisphere, because of the scarcity of measurements at the surface and of balloon sounding stations. At that time satellite data were only beginning to make a small impact on numerical weather predictions (Hunt 1995). Since then there has been a marked improvement in the remotely measured temperature and ozone concentration (using AMSU-A and TOMS on the National Oceanic and Atmospheric Administration satellites) and the much more effective incorporation of the data into the operational prediction models, by using the actual calculated state of the atmosphere rather than some average state to translate measured radiances into temperature and wind profiles (Hollingsworth 2001). Because of the lack of ground-based data in the Southern Hemisphere, forecasts there are appreciably more reliant on satellite data than those in the Northern Hemisphere. The Southern Hemisphere forecasts are now at least as accurate as those of the Northern Hemisphere despite the total amount of data being less. This is probably because the Southern Hemisphere is mostly ocean and the weather patterns are less broken up by mountains and complex air–land interaction.

In many countries the greatest weather-related losses of life are caused by tropical cyclones. However, with the general improvement in global forecasts together with improved modelling of their intense vortical motions, there has been a 50% improvement in the accuracy of cyclone forecasts since 1994 and a huge reduction in casualty figures, though the insurance losses can still be enormous!

Online monitoring of other environmental data (e.g. oceans, air quality, land-surface features, etc.) is also being applied practically in many ways, especially in combination with computational-model-based predictions, which enable data from different instruments or systems to be combined to maximize benefit. A recent example is the operational system for warning airline operators of the location of volcanic dust from recent eruptions around the world (Sprinkle 2000): a system that not only combines vulcanological and meteorological data, but operational data-exchange arrangements between many nations and three international organizations (the International Association of Vulcanological Institutes, World Meteorological Organization and International Civil Aviation Organization). This arrangement perhaps indicates how space-derived data will be used in future.

5. Emerging issues

The themes on space instruments and systems, on scientific developments and practical benefits that emerged at the conference have already been summarized in §§ 2–4. In this final section we point to some of the issues for future planning and funding of missions to inner space, especially in relation to how they will be useful for terrestrial societies.

There is clearly now a much wider range of possible configuration and size of satellites and instruments to achieve given goals, whether they be scientific, technological, economic or political. The results of comparing different approaches now being applied in practice certainly indicate that increasing numbers of small satellites and constellations will be funded and launched in future. There will still be some, but fewer, larger geostationary satellites which are essential for certain measurements (Harries 2001; Taylor 2003). Very large systems for operation by 'man in space' would appear to have relatively few scientific or practical benefits on or near Earth that are economically viable. However, these large stations are likely to provide platforms for scientific study and exploration of far space and other planets, and perhaps make such studies less expensive than launching such missions from the Earth's surface. Of course the advocates of these costly programmes, especially in the USA and Russia, also argue that it is only when humans are involved in space missions that the public becomes really interested and will then support space programmes more fully through the political process!

For designing any type of operational and/or monitoring near-Earth space systems, the first question is how the system is to be maintained, since satellites have a finite life, either because of atmosphere drag or because their components wear out. This presents an organizational problem to scientific agencies in Europe, USA and Japan, who fund many research-orientated missions but whose data are widely used for operational purposes, for example those monitoring the atmosphere, ocean surface, cryosphere, solid Earth and near space. This issue is now being addressed in European discussions about the formation of a new framework for providing operational satellite data. Through such a framework it may be possible for government departments, agencies and research organizations to decide on a strategy that has hitherto been lacking for systematically providing continual geophysical monitoring, while maintaining an active programme of research-orientated missions. The organization would have to decide which particular missions should be selected, and how they should be funded. It is likely that any new arrangements will be closely linked to the existing operational organization, EUMETSAT, that is currently responsible for continuous monitoring of the atmosphere and ocean's surface, particularly for the purpose of operational weather forecasts and climate prediction. But perhaps the arrival of small-satellite systems may enable smaller operators to be chosen competitively to run parts of monitoring systems on fixed-term contracts.

The second vital question about any particular monitoring and/or operational system is how the data are to be processed for all the various possible uses for that system. It was emphasized that these decisions must be decided at an early stage in any project.

Presentations at this conference provided further confirmation that remotely sensed data are used most effectively when they are incorporated into numerical models. Firstly, this is the best method of using the data to describe the geophysical system as it is *at present* because: models translate the signals into physical variables more accurately; they can infer the state of the system between measuring points more accurately than simple interpolation; and they use the data of the system at previous times. Secondly, this approach is the best way of calibrating new remote-sensing instruments, because the numerical models of geophysical systems enable all the relevant observational data to be used for this purpose, through optimal assimilation of other kinds of measurements (e.g. at the surface) and also data from previous instruments. (Mathematical theory for the control of complex systems, which involves using incomplete data while disregarding possibly erroneous data, has greatly contributed to these new practices.) Thirdly, it is only the combination of observational data and models that enables *predictions* to be made, which are one of the main applications of the data. This paradigm for the use of remote-sensing data in geophysics, which has been developed to a high degree for atmospheric modelling and prediction, is now beginning to be applied to ocean dynamics and to the movement of sea and land ice. Plans are under way for operational modelling and forecasting of the magnetosphere and space weather. But a clear identification of clients and funding arrangements are needed before systems are introduced and the data widely distributed.

A much bigger application of this approach will be to the monitoring and prediction of near-Earth objects and space debris, which will require data from many different measurement systems being incorporated into relevant models, probably run at various centres and focusing on different objects. No complete system for addressing this problem yet exists.

The development and application of space science and technology both require larger organizations as well as more funding than laboratory-based science or even geophysical research. For specific space missions that last a finite time, special agencies have been set up in Europe (ESA), USA (NASA), Japan, China, India and increasing numbers of other countries. But, in most countries or groups of countries, these agencies focus on specific missions that last a finite time. Designated agencies or other arrangements do not generally exist to organize and fund missions to provide long-term monitoring for any aspect of geophysics, other than meteorology, where there are organizations (or clearly defined groups) having this responsibility and the funding available. However, for other areas of geophysics, there are in fact organizations that process the huge quantities of data involved and apply them for social, governmental and commercial purposes. Such organizations would have to transform some of their functions to participate in operational space-based systems and service delivery.

As discussions at the conference made clear, these organizational and financial problems will have to be overcome if the development of space systems and technology is in future going to yield the practical benefits that are possible, for example, in monitoring and predicting inner space and the magnetosphere, regional air pollution, volcanoes, hydrology, land processes and oceanography. Discussions are under way in the European Union to develop a new structure, based largely on existing organizations, to meet this challenge. One delicate question is to what extent can or should this role fall to EUMETSAT. On the one hand it has a substantial infrastructure, but on the other it is largely meteorological and climatological in its outlook! Should it take on wider responsibilities in the way that NASA's National Environment Satellite, Data and Information Services agency does in the USA? Similarly, the combined operational data collection and computer modelling of the European Centre for Medium Range Forecasting could also be used in these wider roles. The example of an international system for warning airlines about volcanic ash in the atmosphere, described in the previous section, shows just how complex any particular arrangement needs to be if it is to provide both monitoring data from various sources and predictions in a suitable form, and just for one particular class of end user, in this case the airlines.

This set of issues illustrates how space science and technology is only likely to prosper if there is strong collaboration between all the scientists and technologists in this field. There also needs to be collaboration with those in cognate fields who, on the one hand, may provide key ideas and techniques and, on the other, may find applications for the results of space-related research. It is generally agreed that current arrangements for this collaboration need to be strengthened, perhaps through more frequent meetings of the scientific and engineering institutions on different multi-disciplinary space-related themes as well as more open meetings of the relevant BNSC and research council committees. Generally the greatest number of researchers is drawn to discussion meetings when new funding is announced! Perhaps such events held by the BNSC and research councils could be coordinated with general 'science' meetings so as to stimulate a more effective UK space science and technology 'parliament'?

The last point was that the future of this field will also be strengthened in the UK with growing efforts to interest the public. The new National Space Centre museum at Leicester is an excellent initiative, as is the Beagle mission to Mars. TV programmes and TV news and, one might even add, science fiction are all contributing to public information and entertainment. They also play a valuable role in encouraging commercial users and investors in space science and technology.

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