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Remote monitoring from space: the resolution revolution

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While the first successful launch of a reconnaissance satellite and the recovery of its photographic payload was conducted by the US in August 1960, the potential use of artificial earth orbiting satellites for remote monitoring purposes was recognised as early as 1946.[1] By 1955, considerable details about such spacecraft had been worked out, and the US air force had submitted technical requirements to various industrial firms.

A number of factors contributed to this development. First, it was possible to monitor a large area of the earth quickly and repeatedly with satellites. Coverage was improved by at least a factor of seven compared to aircraft, the traditional means of reconnaissance. A modern aircraft, such as the US SR71, flying at an altitude of some 25 kilometres (km), and at a speed of one km/second (km/sec), is capable of filming slightly more than 250,000 square km of the earth's surface in one hour.[2] A satellite like the French SPOT or the Indian IRS-1C or IRS-1D, travelling at around seven km/sec, and at an altitude of 800 km, can observe about 1,750,000 square km of the earth's surface in the same period. A satellite carrying a sensor with a one-metre resolution, such as the US Ikonos-2, could cover about 277,000 square km in one hour, almost the same as an aircraft. Second, it was not necessary to gain permission from the states over which satellites passed. This was established *de facto,* when the former Soviet Union launched its first satellite, Sputnik 1, on 4 October 1957, and no country objected to its overflights. Third, a satellite orbits at an altitude of at least 150 km—well beyond national airspace—and is unmanned. As a result, humans are not exposed to retaliation from an adversary, unlike reconnaissance aircraft pilots.

These kinds of considerations gave significant impetus to the development of different types of military satellites in general and observation satellites in particular.

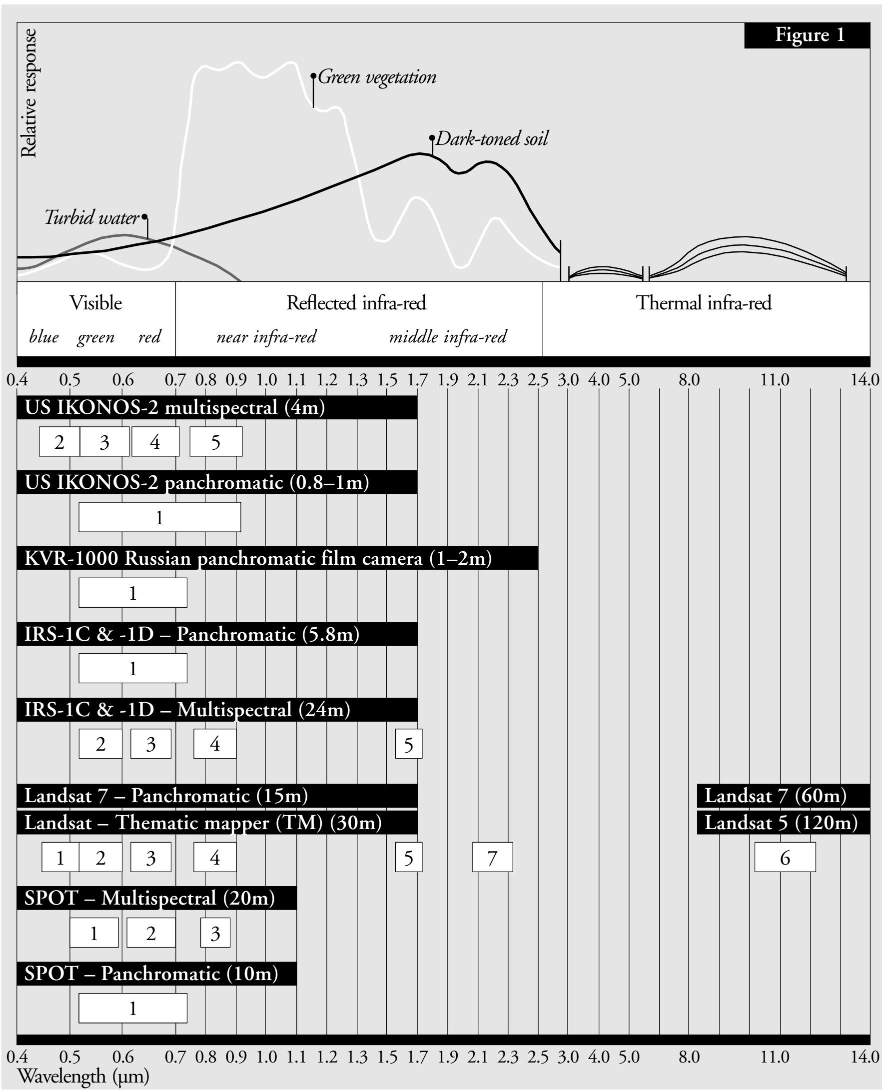
In fact military reconnaissance (optical) satellites have sensors with a resolution nearly 10 times better than the one-metre resolution of the current generation of commercial remote sensing satellites.

Observation satellites carry optical and radar sensors on board that are sensitive to electromagnetic (EM) radiation with wavelengths between 0.4 micro-metres (μm) and some tens of centimetres (see figure 1 on opposite page). In order to assess whether there has been a revolution in resolution, therefore, one needs to examine briefly what is meant by the term. An imaging sensor is characterised by a number of technical parameters, such as spectral, radiometric and spatial resolution. Only spectral and spatial resolutions are considered in this chapter.

Spectral resolution

A human eye can see light in wavelengths between 0.38 (deep blue) and 0.71 μm (red). Wavelengths beyond 0.71 μm move into the infrared (IR), which is invisible to the human eye. Reflected IR extends to two μm, and, beyond this, longer wavelength IR energy is sensed as heat. This spectrum extends from three μm to about 14 μm (see figure 1). The spectral resolution is the wavelength interval that is picked up by a detector. Usually the response of a detector to light is not sharply defined, but, as the wavelength increases, it rises to a maximum and then decreases (see figure 2a overleaf). Spectral resolution or bandwidth is then defined as the wavelength interval recorded at 50 percent of the peak response rate—0.10 μm in figure 2a, for instance. Consequently, the narrower the distribution curve or bandwidth, the better the resolution of a sensor.

Optical images can be divided into panchromatic, multi-spectral, hyper-spectral or ultra-spectral data. Bandwidth and the number of spectral bands distinguish between these categories. A panchromatic image, for example, is one in which data is acquired over a wide range of wavelengths in a single spectral band (figure 2a). In a multi-spectral sensor, data are collected simultaneously in at least three but no more than 10 regions of the EM spectrum with broad bandwidth (see figure 2b). Examples include the US Landsat, French SPOT and Indian IRS-1C satellites (see figure 1). A hyper-spectral sensor has a narrow bandwidth and several hundred spectral bands (figure 2c). The first such system was the US LewisSat, which orbited on 22 August 1997, with 384 spectral bands in the range of 0.4–2.5 μm and a spectral resolution of between five and 6.25 nano-metres. Unfortunately, contact with the spacecraft was lost by 27 August. However, a US company, Orbimage, is planning to launch a satellite with a hyper-spectral sensor in 2000. OrbView-4 is expected to have one-metre panchromatic, four-metre multi-spectral and four-metre hyper-spectral sensors on board. The latter will have 200 channels with a spectral range of 0.4–2.5 µm. Ultra-spectral sensors (see figure 2d) are still at the research and development stage, although they are expected to have a very narrow bandwidth and thousands of spectral bands.



Spatial resolution

The spatial resolving capability—generally referred to as resolution—is the sensor's ability to record small details. How small details or objects are discerned is complicated, since it depends on the spatial resolution capacity of the sensor and on characteristics of the scene, such as object shape and size, and contrast between the object and its surroundings. The resolution capacity or the resolving power of the sensor may be defined in a number of ways: for example, the smallest distance between two identical objects at the point at which they can be resolved as two objects. Such a definition is applied to a photographic image. In the case of an electro-optical device, this resolution may be defined as the area on the ground represented by each sensor cell or pixel. The smaller the pixel, the smaller the area, and, therefore, the finer the resolution. This area is often referred to as the instantaneous field of view (IFOV) or ground sampling distance. These two concepts can be related by a simple mathematical relationship. Under ideal conditions the IFOV is about half the resolution of a photographic image of the same scene.

In the case of a radar sensor—synthetic aperture radar (SAR)—the resolution depends on the length of the antenna. An SAR is a side looking radar with a relatively short antenna, which can be made to behave like a long antenna with a narrow beam. The longer the antenna, the better the resolution. But for space-based radar, there is a limit to the size of an antenna that can be carried in orbit. A long antenna can be synthesised by taking advantage of the satellite's motion in its orbit. Signals received by the short antenna as it moves through a series of positions along the flight path are combined to produce effectively a long antenna. In a radar image, brighter features mean that a large fraction of the radar energy was reflected back to the antenna, while dark features indicate that the antenna received little energy. For a particular wavelength, a number of factors influence the intensity of this so-called 'back-scatter' radiation. These include: the size of the object; the object's moisture content; polarisation of the beam; and the radar beam's angle of incidence. If an object is the same size or larger than the wavelength of the radar beam, it will produce a bright signal in the image. An object that is smaller than the wavelength will appear dark in the image.

Military reconnaissance satellites

At present only four countries have military reconnaissance satellites: China, France, Russia, and the US. Very little is officially known about their capabilities, but it is possible to make assessments based on leaked images from such satellites and, more recently, on data declassified by Russia and the US. Table 1 (overleaf)[3] summarises the development of US military reconnaissance satellites, measured in terms of spatial resolution. It can be seen that, over some 17 years, resolution of US military reconnaissance satellites has improved by at least a factor of 90. The French satellite, Helios 1, is reported to have a resolution of about one metre.

Some of the images from the US Key Hole (KH) series of satellites have appeared on the Internet, such as one of the Minerallye Vod airfield in the former Soviet Union (see figure 3). A US reconnaissance satellite (KH-4) with a resolution of between three and eight metres acquired this image.[4] From 1990, Russia started to commercialise some of the degraded data from its military photographic reconnaissance satellites. Figure 4 shows an image over an airfield in China, acquired by a Russian satellite using a KVR-1000 sensor (two-metre resolution). In figures 3 and 4, close ups of aircraft parked on the apron are enlarged and shown in the insets. Analogous details suggest that the images have similar resolutions.

Figure 2

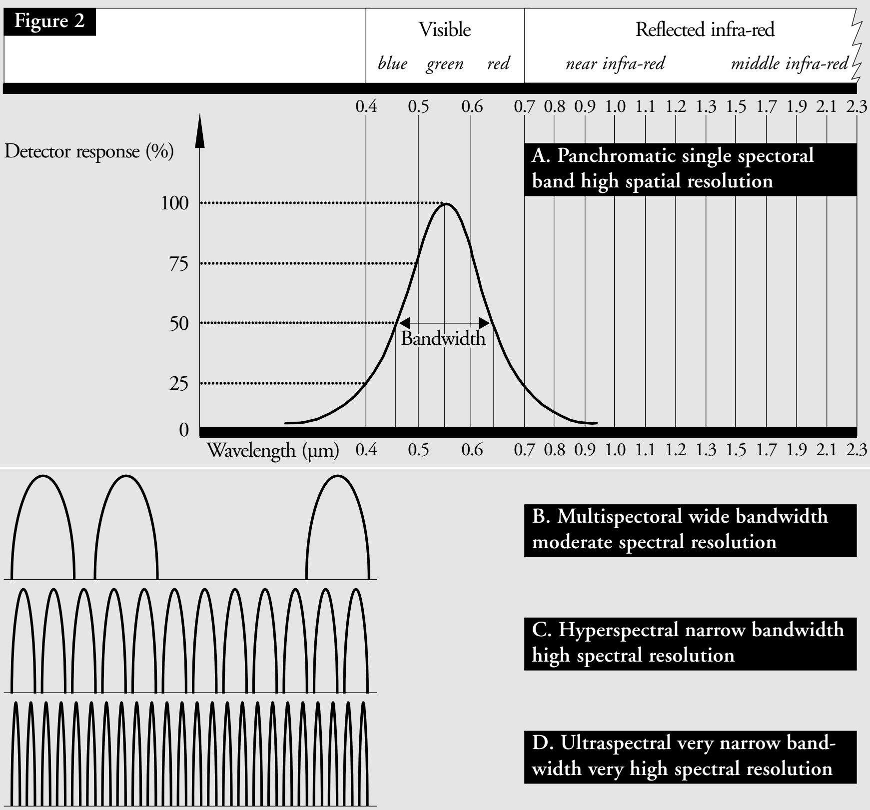


Table 1 Resolution of US Key Hole satellites

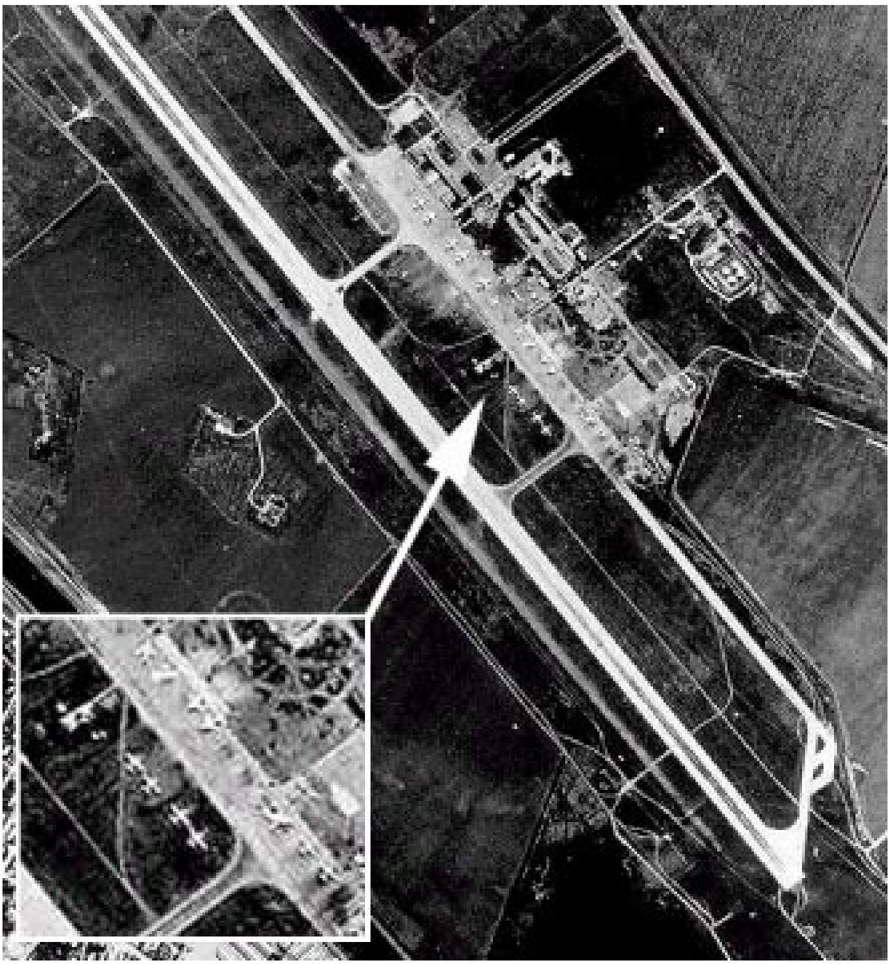
SATELLITE	PERIOD OF OPERATION	RESOLUTION (M)
KH 1–4	1959–1963	8–13
KH 4A	1959–1963	~3
KH 4B	1967–1972	~2
KH 6	1963	~2
KH 7	1963–1984	~0.5
KH 8	1963–1984	~0.15
KH 9	1971–1984	0.3–0.6
KH 11–12	1976–	~0.15

Civil remote sensing satellite

Commercially available remote sensing satellites now have capabilities similar to the military models of the 1970s. At present there are a number of countries launching and operating their own civil remote sensing satellites. The US has had such a programme since 1972—it launched Landsat-1, with a resolution of 79m, on 23 July. Six more Landsat satellites have been launched subsequently; only Landsat-6 did not achieve an orbit. Landsat-5 (launched on 1 March 1984) and Landsat-7 (launched on 15 April 1999) are both generating data in orbit. Landsat-5 and Landsat-7 have resolutions of 30m in the visible and IR bands, while the resolutions of the thermal band (band 6) are 120m and 60m respectively. In addition, Landsat-7 has a panchromatic band with a resolution of 15m.

The situation changed dramatically when US President Bill Clinton issued Presidential Decision Directive 23 (PDD-23) on 10 March 1994.[5] Under this Directive, private companies were encouraged to build and orbit satellites with high-resolution sensors, with a view to commercialising the data. But there are some conditions attached: 'The licensee will be required to maintain a record of all satellite tasking for the previous year and to allow the US Geological Survey (USGS) access to this record'. Moreover, 'During periods when national security or international obligations and/or foreign policies may be compromised, as defined by the Secretary of Defense or the Secretary of State, respectively, the Secretary of Commerce may, after consultation with the appropriate agency(ies), require the licensee to limit data collection and/or distribution by the system to the extent necessitated by the given situation'.

The US had already passed a law under which: 'No department or agency of the Federal Government may license the collection or dissemination by any non-Federal entity of satellite imagery with respect to Israel, or to any other country or geographic area designated by the President for this purpose, unless such imagery is no more detailed or precise than satellite imagery of the country or geographic area concerned that is routinely available from commercial sources'.[6]



Source: SPOT Image

Figure 3 shows an image of Minerallye Vod Airfield in the former Soviet Union acquired by the US KH–4 satellite (resolution between 3 and 8m).

Beside the US and Russia, Canada, France, India and Japan also sell imagery from their civil remote sensing satellites. An example of an image acquired by the French SPOT satellite (10m) is shown in figure 5. This shows a US strategic bomber base, where the possible deployment of B-52s can just about be detected on the

Source: SPOT Image

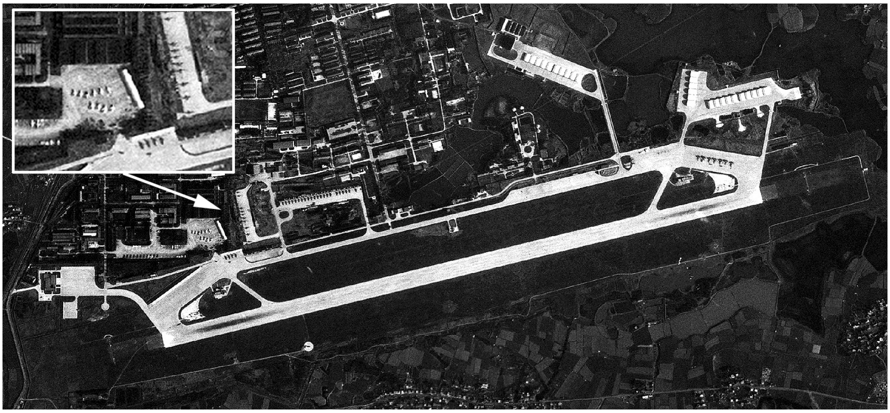
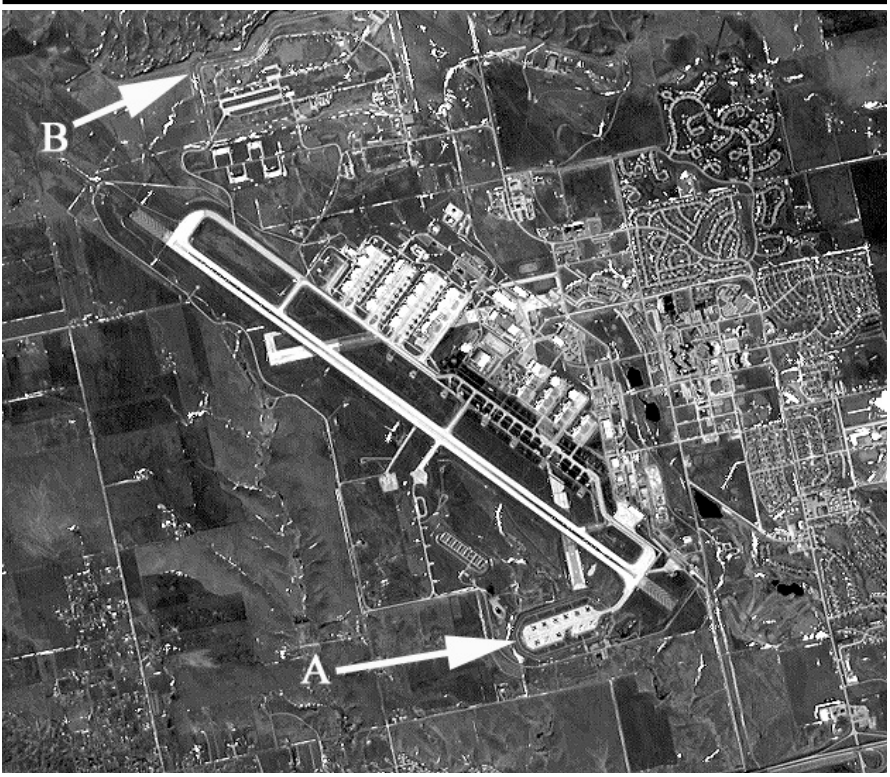


Figure 4 (above) A Russian satellite photograph of a Chinese air base (resolution is 2m). Figure 5 (below) shows an image of the US Ellsworth Air Force Base, acquired by the French SPOT satellite at 10m resolution. B-52s can be seen at A and a nuclear weapons storage site at B.

Source: SPOT Image



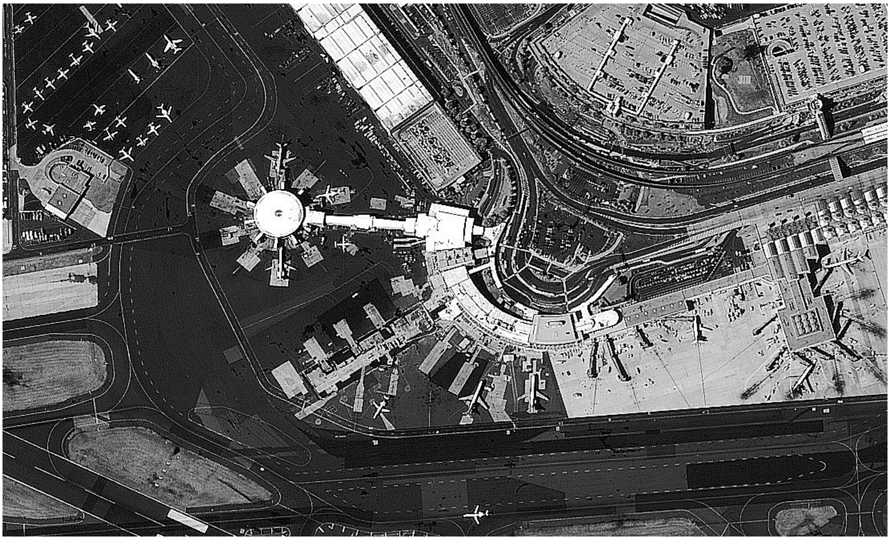


Figure 6 shows part of the Washington airport. The US Ikonos-2 satellite acquired this image at a resolution of one metre.

apron at A. A possible nuclear weapons storage area can also be seen at B. Figure 6 shows an image acquired by the US Ikonos-2 satellite over Washington. At this resolution, considerable details can be made out at the airport. Several types of aircraft can be seen, which could be identified, for example, with the help of *Jane's World Aircraft Recognition Handbook*.[7] Some current and future civil satellites are summarised in table 2 (overleaf).

It can be seen that, since the launch of Landsat-1, the resolution of sensors on civil remote sensing satellites has improved by a factor of about 80. As a result of Japan's concerns about North Korea's nuclear and missile programmes, it has decided to develop and launch a high-resolution (one metre) satellite, known as the Information Gathering Satellite.[8] The next generation of Indian remote sensing satellites is expected to have resolutions of 2.5m and one metre. Spectral coverage and spatial resolutions of some of the current satellites are shown in figure 1.

Table 2 shows that, apart from several optical satellites, there are a number of radar satellites in orbit today. While generating near photographic images, they carry SAR sensors that can be used day and night and in adverse weather conditions. It can be seen that the resolution of this type of sensor has also improved significantly since the launch of the first SAR sensor on the US Seasat satellite (resolution 25m) in June 1978. By contrast, the Canadian RadarSat in fine-beam mode has a resolution of around nine metres.

Table 2 Commercial remote sensing satellites

Country Satellite	First launch	Resolution in pixel size (m)		
		panchromatic	multi-spectral	thermal/IR
OPTICAL				
Brazil/China				
Zi Yuan CBERS I & II	1999–2001	20		
CBERS III & IV	–	5	10	40–80
France				
SPOT-4	1998	10	10	
SPOT-5	2002	2.5		
India				
IRS-IC,-ID	1995, 1997	5.8	25	
IRS-P5	1999–2000	2.5		
Israel				
Eros-A	1999	1		
Japan				
ALOS	2003	2.5	10	
Russia				
Resurs-F series	1989–98	2		
US				
KH-1 to 4	06/1959–12/1963	7.6		
KH-4A	08/1963–10/1969	2.7		
KH-4B	09/1967–05/1972	1.8		
Landsat-5	1984		30	120
Landsat-7	1999		15	60
Ikonos-1 did not achieve orbit, -2	1999	0.8–1	3–5	
Quickbird-1,-2	1999	0.8	4	
Orbview-3	2000	1–2	4	
Orbview-4		1–2	4/hyperspectral 8	
Earlybird-1	1997	3	15	
RADAR				
ESA				
ERS-1, and -2	1991 & 1995	25		
Japan				
JERS-1	1992	18		
Canada				
Radarsat	1995	9–100		
Russia				
Almaz-1B	1998	4–15		
US				
SIR-C	1994	8–30		

Some novel applications

Multi-spectral images in the near IR, as well as mid-, short- and long-wave IR, can be used to identify features, such as disturbed soil and vegetation, which may not be visible to the human eye. A sensor sensitive to long-wave IR can detect radiation emitted from heated buildings and discharged warm water that has been used to cool industrial plants, like nuclear facilities.[9] In the latter, there is a possibility of using a radar sensor to monitor the warm water plume from nuclear reactors.[10] In addition, a thermal IR sensor could detect buried structures if they generate heat.

Hyper- and ultra-spectral sensors could be used to detect subtle spectral differences in signatures that are too narrow to be discerned using simple three-band multi-spectral data. Moreover, such sensors could potentially identify specific materials, as well as components of aerosols, gas plumes and effluents. These may well find application in monitoring environmental and arms control accords, such as the 1992 Chemical Weapons Convention (CWC).

Such fine spectral resolution would enable exploitation of the unique spectral signatures that all objects have. If underground facilities have been constructed, for instance, stressed vegetation that grows on earth-covered bunkers could be distinguished from normal vegetation, since root growth, drainage and soil conditions are different. Furthermore, new high-resolution, commercially available images can be useful for, *inter alia,* cartographers, city planners and farmers, as well as for managing disasters like earthquakes, widespread human rights abuses and the mass movement of populations.

Legal and institutional issues

From the above survey it can be seen that the high quality of openly available images permits them to be used in a wide variety of ways. Yet, while they provide benefits, they also pose a serious challenge. For example data from remote sensing can also be used for weapons targeting purposes. Should controls be established over the distribution of high-resolution, commercially available satellite imagery?

To some extent this problem is dealt with by the 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (the Outer Space Treaty). Under Article VI, for instance, the 'States Parties to the Treaty shall bear international responsibility for national activities in outer space, including the Moon and other celestial bodies, whether such activities are carried on by governmental agencies or by non-governmental entities, and for assuring that national activities are carried out in conformity with the provisions set forth in the present Treaty'.[11] The thrust of the Outer Space Treaty is the preservation of space for peaceful purposes. The use of very high-resolution commercial satellite images for military reasons may not be regarded as a peaceful activity.

The first proposal to regulate specifically remote sensing activities from outer space was by Argentina in 1970. As a result, the Committee on the Peaceful Uses of Outer Space (COPUOS) recommended that the issue be placed on the agenda of the Legal Subcommittee: this was done in 1971.[12] Concerns were expressed, particularly by developing countries, about issues like national sovereignty, prior consent, and control by the observed state over the distribution of data acquired above its territory. However, the Soviet Union and the United States had been using reconnaissance satellites, orbiting between some 150–350 km, to observe most of the globe for years. As far as the international community is concerned, it was surprising that, by 1986, claims that satellite images were a sovereign national resource had dissipated and the Principles Relating to Remote Sensing of the Earth from Outer Space (Remote Sensing Principles) had been adopted by the UN General Assembly.[13]

Surprisingly the concerns were about resources and not national security. As far as it is known, the only state to have objected to satellite reconnaissance on the grounds of national security was Israel. This occurred in 1994, when a US firm called Eyeglass—later renamed Orbimage—was planning to establish a ground station in Saudi Arabia to receive very high-resolution images from its commercial satellites over the Middle East. In May 1995, Orbimage agreed not to collect image data over Israel. Tel Aviv also asked Washington to help protect it from satellite monitoring. Consequently, the US exercised its right to control shutter—when to take or not to take images— as envisaged in its 1992 Remote Sensing Act.[14]

The first high-resolution satellite data commercially released by Russia were from its military satellites and were in the form of photographic films. These were degraded to about 1–1.5m photographic resolution and then digitised. The digital data have a two-metre resolution (pixel size). The former could be compared directly with the US Ikonos-2 data, which have a one-metre resolution. As mentioned above, the Russian photographic product with 1.5m resolution is equivalent to a pixel resolution of about 0.8–1m. Ikonos quality data have thus been available from Russia since 1990.

Observations from space form a vital element of American and Russian national technical means (NTM) of verifying compliance with bilateral agreements. Not all nations have access to such capabilities, however, even though they are parties to several important multilateral arms control treaties. In this regard, neither the US nor Russia appears willing to share widely either the technology or the information obtained by NTM. The US provided limited access to satellite imagery, though, to the International Atomic Energy Agency (IAEA) and to the UN Special Commission (UNSCOM) on Iraq. The new commercially available data will clearly give impetus to multinational technical means (MTM) of verification.

In 1973[15] and 1978, France[16] proposed the creation of an International Satellite Monitoring Agency (ISMA), which would use remote sensing from outer space to verify arms control treaties and to monitor armed conflicts. A UN expert group studied the concept and its report was published in 1981.[17] As a result of resolution 43/81B, passed by the UN General Assembly in 1988, the role of the UN in the field of verification was examined by a Group of Governmental Experts, which concluded that the UN should seriously consider the multilateral aspects of verification.[18] Unfortunately, nothing came of these proposals.

The complexity of political problems associated with the creation and operation of an international system led some observers to propose the establishment of a Regional Satellite Monitoring Agency (RSMA).[19] The Western European Union set up the first RSMA in Madrid, Spain, in 1990; it was declared operational in 1991. It has been recommended that other RSMAs be established in Latin America, the Middle East, South Asia and East Asia. In all of these regions there is a need for such an agency and space capabilities exist. In 1999, Argentina proposed to the UN the establishment of legal principles to govern commercial activities concerned with outer space.[20] Presumably, such measures could also deal with remote sensing by satellites. If this were the case, then it is important that special consideration be given to monitoring arms control treaties, to establishing confidence-building measures and to assisting crisis prevention efforts.

Conclusion

This chapter has attempted to examine one aspect of verification capabilities: remote sensing by satellites. If improvements in resolution were to be taken as a measure of progress, then, over the past 25 years, this aspect has changed by a factor of almost 100. The first US remote sensing satellite, Landsat-1, had a resolution of about 80m. Now the US has launched a commercial satellite with a resolution of nearly 0.8m. A revolution in resolution of sensors on board civil remote sensing satellites has, therefore, taken place, giving rise to new applications. Among these are the monitoring of multilateral arms control treaties, including the 1970 Nuclear Non-Proliferation Treaty (NPT), the CWC and the 1996 Comprehensive Nuclear Test Ban Treaty (CTBT).[21] Although the CTBT is not yet in force, observations from space, serving as an additional element of verification to those already envisaged, could enhance its effectiveness.

There is some reluctance to use satellites for verification of multilateral arms control agreements. Nor are satellites being used multilaterally to monitor crisis areas in order to prevent escalation into armed conflict. States generally associate satellites with NTM. It is not widely appreciated that commercial satellites could also be very useful—with the added advantage that data are available to anyone.

While most nations still do not possess their own NTM, the concept of an international verification agency is gaining some recognition, with observation from space forming a critical element. Not only have the capabilities of civil remote sensing satellites improved dramatically, but the number of states launching and operating such satellites of their own is also growing. This must give the concept of a multinational technical means of verification considerable impetus. Even the idea proposed by France in 1978 of having an international satellite monitoring agency under the UN may not be unreasonable now.

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Endnotes

[1] Kenneth E. Greer, 'Corona', in *Corona: America's First Satellite Program,* Kevin C. Ruffner, (ed.), CIA History Staff, Center for the Study of Intelligence, Washington, DC, 1995, pp. 3–42.

[2] George Leopold, 'Verification technology grows in tandem with pressure to obey SALT II', *Defense News*, vol. 1, no. 50, 1986, p. 11.

[3] Ruffner, 1995; and Jeffrey T. Richelson, *U.S. Satellite Imagery, 1960–1999,* National Security Archive Electronic Briefing Book no. 13, www.gwu.edu.

[4] See www.fas.org.

[5] 'Foreign Access to Remote Sensing Space Capabilities', *Fact Sheet,* 10 March 1994, The White House, Office of the Press Secretary, Washington, DC, 1994.

[6] 'Prohibition on collection and release of detailed satellite imagery relating to Israel and other countries and areas', Congressional Record, National Defense Authorization Act for Fiscal Year 1997, US Senate, Washington, DC, 26 June 1996.

[7] Derek Wood, *Jane's World Aircraft Recognition Handbook*, Jane's Information Group Ltd., Coulsdon, Surrey, UK, 1992.

[8] Simon Mansfred, 'Mitsubishi eyes billion dollar spysat trough', www.spacedaily.com.

[9] Bhupendra Jasani, *et. al.,* 'Enhancing IAEA safeguards using commercial satellite imagery: A pilot study', UK and Federal Republic of Germany Safeguards R&D Programmes, SRDP-R240, JOPAG/12.95-PRG-265, Task A.16/JNT D882, November 1996; and 'Commercial satellite imagery and safeguards: Some case studies using multi-spectral and radar data', UK and Federal Republic of Germany Safeguards R & D Programmes, SRDP-R256, JOPAG/11.98-PRG-284, Task JNT D00988, November 1998.

[10] Bhupendra Jasani, 'Civil radar observation satellites for IAEA safeguards', *Journal of Nuclear Materials Management,* vol. XXVII, no. 2, winter 1999, pp. 29–34.

[11] United Nations Treaties and Principles on Outer Space, UN document A/AC.105/722, A/CONF.184/BP/15, UN, Vienna, 1999, pp. 3–7.

[12] UN document A/AC.105/101, 1971.

[13] UN Resolution 41/65, 3 December 1986; and UN Treaties and Principles on Outer Space, pp. 35–38.

[14] *Congressional Record,* 1996.

[15] Bhupendra Jasani, in *World Armaments and Disarmament, SIPRI Yearbook 1973,* Almqvist & Wiksell, Stockholm, 1973, pp. 73–74.

[16] UN document A/S-10/AC.1/7, 1 June 1978.

[17] 'Study on the implications of establishing an international satellite monitoring agency', UN Report A/AC 206/14, 6 August 1981.

[18] 'Verification in all its aspects: A study on the role of the United Nations in the field of verification', *UN document A/45/372,* 28 August 1990.

[19] Bhupendra Jasani, 'A regional satellite monitoring agency', *Environmental Conservation,* vol. 10, no. 3, 1983, pp. 255–256; and 'Verification of arms reduction in Europe from space', *Proceedings of a symposium on Observation satellites – a European means of verifying disarmament,* Assembly of Western European Union, Rome, 27–28 March 1990, pp. 62–69.

[20] UN document A/AC.105/C.2/L.215, 1999.

[21] Bhupendra Jasani, 'Verification of a Comprehensive Test Ban Treaty from Space: A preliminary Study', *UNIDIR Research Paper no. 32*, United Nations, Geneva, 1994.