ARTICLE IN PRESS

ISPRS Journal of Photogrammetry and Remote Sensing xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

Who launched what, when and why; trends in global land-cover observation capacity from civilian earth observation satellites

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ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Land-cover mapping
Earth-observing satellite
Launch
End-of-life
Spatial resolution
Mission-cost

ABSTRACT

This paper presents a compendium of satellites under civilian and/or commercial control with the potential to gather global land-cover observations. From this we show that a growing number of sovereign states are acquiring capacity for space based land-cover observations and show how geopolitical patterns of ownership are changing. We discuss how the number of satellites flying at any time has progressed as a function of increased launch rates and mission longevity, and how the spatial resolutions of the data they collect has evolved. The first such satellite was launched by the USA in 1972. Since then government and/or private entities in 33 other sovereign states and geopolitical groups have chosen to finance such missions and 197 individual satellites with a global land-cover observing capacity have been successfully launched. Of these 98 were still operating at the end of 2013. Since the 1970s the number of such missions failing within 3 years of launch has dropped from around 60% to less than 20%, the average operational life of a mission has almost tripled, increasing from 3.3 years in the 1970s to 8.6 years (and still lengthening), the average number of satellites launched per-year/per-decade has increased from 2 to 12 and spatial resolution increased from around 80 m to less than 1 m multispectral and less than half a meter for panchromatic; synthetic aperture radar resolution has also fallen, from 25 m in the 1970s to 1 m post 2007. More people in more countries have access to data from global land-cover observing spaceborne missions at a greater range of spatial resolutions than ever before. We provide a compendium of such missions, analyze the changes and shows how innovation, the need for secure data-supply, national pride, falling costs and technological advances may underpin the trends we document.

1. Introduction

Land cover information is important because the land is where most of the seven-plus billion humans live most of the time. It meets the major part of our food, fuel, freshwater and fiber requirements (FAOSTAT, 2013) and shapes our planet's climate system (GCOS, 2003). The land is itself under pressure from climate change and from degradation processes such as desertification. A growing and shifting human population too changes and moves pressures on the land. As land is essentially a finite resource this leads to intense competition between land used to produce different food types, land for cash crops, sources of fiber, biofuels/bioenergy and for ever-increasing urbanization (De Castro et al., 2013). In recent years this competition has extended to include new dimensions such as carbon trading (Mollicone et al., 2007) and biodiversity offsetting (McKenney and Kiesecker, 2010). Our land-use marketplace now not only has to satisfy our fundamental resource requirements such as food and energy production, but it must also maintain and enhance land's role as a carbon sink and a support for biological diversity.

Decision makers and policy makers at national and international scales aim to find a balance between competing demands on the land resource. These policy goals usually aspire to keeping land resource use in balance with regenerative capacity. Land-use management plans stand the best chance of success if they are based on sound information concerning how, when and where land resources are being used and how this is changing. Such information is also an increasing part of the reporting obligations on Parties to multilateral environmental treaties such as the United Nations Framework Convention on Climate Change.

Earth orbiting satellites provide a unique vantage point from which to map, measure and monitor how, when and where land resources are changing across the globe (Townshend et al., 2008). Global land cover mapping from satellite implies mapping the

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http://dx.doi.org/10.1016/j.isprsjprs.2014.03.009

entire globe's land cover (Loveland et al., 1999; Friedl et al., 2002; Bartholome and Belward, 2005; Arino et al., 2007; Gong et al., 2013), though it can also mean more localized mapping of land cover at any specific location (Cihlar, 2000). But which satellites have the potential to provide observations useful for global land cover studies? How many are there? What sort of imagery do they provide and at what spatial resolutions? Who launched them and when? How has any of this changed since the first artificial satellite was launched in 1957?

The National Aeronautics and Space Administration (NASA) National Space Science Data Center's (NSSDC) Master Catalog lists 7075 spacecraft as launched between 4th October 1957 and 31st December 2013 (NSSDC, 2014). Of these, 879 were identified as contributing to earth science. Earth science is a broad discipline, which encompasses land cover issues, but clearly not all 879 missions can be used for global land cover mapping. To be useful for this a satellite must be able to produce images of the land surface, must be in some sort of near-polar orbit so that it can actually image any point on the globe, and the data from any such system must be accessible.

Civilian, commercial and military/intelligence gathering communities all fly polar-orbiting satellites with an imaging capability. The civilian systems are government owned, the commercial are government licensed but privately owned and the military/intelligence gathering platforms are government owned but with highly restricted access to the systems and their products (Baker et al., 2001). The imagers all systems carry have evolved over the years. The first generations of military systems used conventional photographic film with canister return systems, but digital imaging devices have long-since replaced these. The early civilian systems relied on television cameras, though these too soon gave way to other imaging sensors (Davis, 2007). Imaging systems useful for land cover mapping include panchromatic sensors (Carleer et al., 2005), multispectral scanners with a minimum of two sensors operating at red and near infrared wavelengths (Teillet et al., 1997) and synthetic aperture radar (Dobson et al., 1996). Side-looking real aperture radars (such as those flown on the Okean missions) also provide imagery but the spatial resolution from such systems is too coarse to image land cover features.

Civilian and commercial platforms can be grouped, but military have to be considered as a class apart. We do not discriminate between the government and privately owned systems as the data both generate are to all intents and purposes in the public domain. The data from intelligence-gathering/military missions are not. The Clinton Administration's executive order declassifying US' reconnaissance imagery from the 1960s and 1970s (Clinton, 1995) did see some of these old data released into the public domain. These have occasionally been used for land cover mapping (e.g., Tappan et al., 2000). But this is very much an exception and data from military systems are effectively inaccessible for civilian use. However, whilst military systems are not available to the civilian the opposite does not apply, and some civilian/commercial systems are used by the military. We consider such 'dual-use' platforms as available for global land cover mapping work, though restrictions on data distribution have occasionally been imposed in particular security situations (Baker et al., 2001).

If occasional dual-use restrictions, and blanket restrictions on data from military systems are the order of the day, what is the situation in the civilian/commercial sector? This varies enormously from mission to mission, but at least in principle all data from civilian/commercial spacecraft are available in the public domain (Harris and Browning, 2003). Sometimes users have to pay for these data and sometimes they are free. Some archives are web-enabled, easy to find, easy to navigate with excellent data access tools. Others are more obscure. Some providers of moderate spatial resolution data (typically 250 m to around 1 km) have applied a 'free-and-open' data policy for many years, the longest-standing example being AVHRR data from the NOAA satellites (Tucker, 1996). In contrast, data at finer resolutions always had to be paid for. This situation changed dramatically in 2008 when the United States made their past, present and future Landsat holdings available on a free-and-open basis (Woodcock et al., 2008). Some comparable systems, such as CBERS, have followed suit (Neves Epiphanio, 2011) and at the end of 2013 the European Union adopted a full free and open access policy for data at resolutions coarser than 10 m from its forthcoming Sentinel Earth observing missions (European Union, 2013). High resolution (less than 10 m) and very-high-resolution data (less than 5 m) are distributed on a commercial basis, though some of these data are available for free viewing via web services such as Google Earth and Bing. Whilst free viewing does not provide access to either entire archives or the original digital data, it has provided global studies of land cover and cover change with a valuable source of information for qualitative assessments of cover change and as a source of information for independent accuracy assessments and classification validation (Schneider et al., 2009; Giri et al., 2011).

Our aim in this paper is not to compare the relative merits of one mission with another for land cover information gathering, but is to build up a compendium of all missions with this potential. We identify the missions flying at any given time that carry an imaging device, occupy a near-polar orbit and provide data that is in principle available for civilian use. We ascertain the sovereign state owning each mission, describe the spatial resolution of the imaging sensors carried by such missions and determine the launch date and end-of-life for each mission. Finally we analyze the changes observed and discuss reasons why nation states launch such satellites (accepting as given that they want to know how, when and where land resources are changing).

2. Methods

Lists of Earth Observing satellites cataloguing sensor characteristics and launch date appear in many textbooks, but perforce these are quickly dated. There are a number of on-line resources that keep pace with new launches yet also document the old. In this study we used six primary sources of information, three run by agencies and three by enthusiasts. The three agency sources were the NASA master directory held at the NASA Space Science data center (NSDDC, 2014), the Committee on Earth Observation Satellite's Earth Observation Handbook (CEOS, 2014) and the Observing Systems Capability Analysis and Review tool OSCAR maintained by the World Meteorological Organization (OSCAR, 2014). The three enthusiasts' sources were Gunter's space page (Krebs, 2014), Zarya Soviet, Russian and International space flight (Christy, 2014) and real time satellite tracking (N2YO, 2014). Each mission we identified as a potential candidate was cross-referenced in all six sources. Whilst not all missions appear in all six, all do appear in more than one. Herbert Kramer's encyclopedic book was also used as an additional check for missions launched before 1st January 2001 (Kramer, 2002) and the eoPortal Directory maintained by the European Space Agency provided additional valuable cross checking (eoPortal, 2014). Mission-specific searches were also used to find corroborating evidence, usually from media reports and press releases, and on occasion we resorted to personal communications to answer specific questions. Using these resources we examined all launches up to 31st December 2013.

2.1. Exclusions and inclusions

If a satellite is in a near polar orbit it has the potential to observe any point on the planet's surface at some time (recognizing that the extreme poles themselves are often an exception). Variations in orbital elements and swath width will affect the revisit time of any particular mission, but the underlying principle of global coverage holds for all such systems and as a starting point all such systems are included. Geostationary missions, satellites in equatorial orbits or platforms such as the space shuttles and space stations do not have this capacity and so we exclude these.

The first satellite image of the Earth is usually attributed to the Television Infrared Observation Satellite (TIROS) 1 on 1st April 1960 (Davis, 2007) – and on 13th February 1965 the first global image of the Earth was obtained by its successor TIROS-9, (NASA, 2013a,b). These TIROS missions were for meteorology. The USSR also flew many meteorological satellites carrying television cameras between 1969 and 1996 (the Meteor 1,2 and 3 series). However, the spatial and spectral resolutions of these television camera systems were only good enough to observe land/water/cloud boundaries – not differentiate land cover types- and this compendium therefore excludes them. The compendium does include the 400 m spatial resolution panchromatic television camera carried on Argentina's SAC-A mission. Television camera-based systems are also included when specifically designed for land cover observations such as the Return Beam Vidicons flown on the first three Landsats and the red and near infrared cameras, which flew on India's Bhaskara satellites.

Later generations of meteorological satellites carried multispectral scanning instruments that did offer potential for global land cover mapping. In particular, the Advanced Very High Resolution Radiometer (AVHRR), which first flew on TIROS-N in 1978, and especially the modified versions of this instrument flying on subsequent missions, has proven value for land cover and vegetation studies (Tucker, 1996). Many oceanographic missions also carry optical instruments with the requisite channels for land cover studies and sometimes SARs. For example Seasat, despite its name, provided the first high-resolution SAR images for land cover mapping (Evans et al., 2005). Meteorological missions carrying the AVHRR (or equivalent instruments) and oceanographic missions with requisite instrumentation are included in the compendium.

The compendium also includes missions from the USA's Defense Meteorological Satellite Program carrying the Operational Linescan System; this sensor is sensitive to visible and infrared radiation and is probably best known for its nighttime imaging (Elvidge et al., 1997) though the data have been used in diverse land cover mapping programs (Schneider et al., 2003; Small et al., 2005).

We exclude all reconnaissance missions that deny access to data for civilian use. The technical specifications of such missions are rarely openly documented, which also makes it difficult to include them in any compendium. Known reconnaissance missions that are omitted include France's Helios, Japan's IGS satellites, Germany's SAR Lupe, Israel's TecSAR, India's Risat 2, China's Yaogan, the US Key Hole series, and Multispectral Thermal Imager, the USSR's early Almaz and Resurs F satellites and North Korea's short-lived Kwangmyongsong 3.

CubeSats, which measure 10 by 10 by 10 cm and weigh just over 1 kg have been identified as potential spaceborne earth imaging platforms (Puschell and Stanton, 2012). Indeed, imaging devices have been put on these tiny platforms and launched on at least two occasions (Japan's K-SAT on 20th May 2010 and Romania's Goliat on 13th February 2012), but unfortunately without successful imaging in either case. We do not include these CubeSat demonstrators in our compendium.

More success has been had with the larger triple CubeSat format, which is three CubeSats connected in series. The multiple CubeSat approach is being pioneered by the US' Planet Labs. Planet labs' Dove-2 and 1 demonstrators were launched on 19th and 21st April 2013, with two more (Doves 3 and 4) launched on 21st November 2013. The Dove missions successfully collected Earth images at spatial resolutions of 3–5 m, though the Dove-1 prototype only lasted a week because of the low orbit this specific Dove satellite used (Wall, 2013). Doves 2–4 were in a higher orbit and are still operational. During the week following 11th February 2014 a further 28 Dove imagers were deployed from the International Space Station to form the largest constellation of satellites from a single operator ever launched together (Planet Labs, 2014). This may well come to be regarded as a milestone in global land observations but the deployment occurred after our 31st December 2013 cut off point, and the constellation is not included in our compendium, though the four preceding Doves are listed.

Skybox is another commercial project that aims to fly a multi-platform constellation of Earth imagers. Their first platform, SkySat-1 (a somewhat larger 120 kg microsatellite) was launched on 21st November 2013, along with Dove-3 and 4. SkySat-1 is included in the compendium as it carries a high definition video camera and a digital imager capable of providing sub meter resolution imagery in red, green, blue, near-infra red and panchromatic bands. SkySat-1's successors will form a constellation of 24 satellites, scheduled for launch in 2014 (Butler, 2014).

Finally we recognize that spaceflight is far from being a risk-free operation. Failures are usually not as systematically documented as the successful launches, but our compendium references ten notable failed systems from the civilian/commercial world (NOAA-13, IRS-1E, Landsat 6, DMSP-F05, Okean-O1-4, EarlyBird, Ikonos, QuickBird-1, BADR-B and CBERS-3). We include these because they were part of planned programs with land cover monitoring potential. All the design, build and launch costs associated with a successful mission were incurred, but unfortunately no images were acquired, either because of failure at launch or because communications with the satellite failed.

2.2. Creating a first order compendium

For all satellites included in the compendium we document four metrics; launch date, end-of- (imaging) life, sensor spatial resolution and ownership.

2.2.1. Launch date

The date when post-launch imaging operations actually begin is undoubtedly the most pertinent date. For example, Landsat 8 was launched on 11th February 2013 and started imaging on 18th March 2013 (Irons and Loveland, 2013). However, such reporting is the exception, not the rule. Start of imaging operations is not documented for most missions. Launches by their nature are exceptionally difficult (probably impossible) to hide; various government offices and amateur enthusiasts track them and media interest usually accompanies a launch. As a consequence launch dates are well documented. This provides one invariant characteristic of all missions. Identical launch dates are usually reported by all six of the primary sources we used. Occasionally different dates are presented. In these instances mission-specific searches were used to find corroborating evidence, usually from media reports and press releases associated with launch events. Such reporting tends to be ephemeral and cannot be referenced. This analysis considered launches up to 31st December 2013.

2.2.2. End-of-life

End-of-life is more equivocal than launch. In some cases instrument failure ends a given mission's useful life as a source of global land observations, in other instances communication with the satellite itself fails, control of the platform may be lost or a satellite may be intentionally decommissioned and deorbited. For example, the last image from Landsat 5 was obtained on 6th January 2013, whereas the satellite was shut down on 5th June 2013 (USGS,

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2013). Another example is the CZCS sensor on the Nimbus-7 satellite. This sensor could not be reactivated after a temporary shutdown in 1986, whereas other sensors of the satellite continued to deliver data until 1995. As the CZCS sensor was the only one of interest for land cover observations, we report the end-of-life for this sensor, not the end-of-life for Nimbus-7.

Wherever possible we identify the date each mission acquired its last transmitted image of the Earth. This may be announced in a press release or media report, personal communication with satellite operators and science teams or through more formal resources such as the satellite status records maintained by satellites' operators (NOAA, 2013) and the World Meteorological Organization on behalf of the Coordination Group for Meteorological Satellites (WMO, 2014). We also use the end-of-life reports registered by operators in the CEOS Earth-Observation handbook and entries in OSCAR.

2.2.3. Spatial resolution

Mission documents provided by the satellite operator and/or sponsoring space agency and/or manufacturer usually describe sensor specifications. The three agency sources (NSSDC, CEOS and OSCAR) often reproduce this information too. We differentiate between panchromatic, multispectral and synthetic aperture radar (SAR) sensors, reporting each as a separate class. Some sensors are able to provide data at two or more spatial resolutions (e.g. MODIS on EOS-Terra); in these instances we flag the highest (i.e. most detailed) resolution the sensor provides. Some missions carry more than one sensor, which capture data at different resolutions (e.g. the HRV and VGT instruments flying on SPOT-4); all sensors are treated individually. Where a sensor provides high resolution in panchromatic mode and lower resolution in multispectral mode (e.g. ETM+), then these are treated as separate and both resolutions are reported. Some SAR missions, such as Canada's Radarsat, offer variable resolution image acquisitions; as with the optical systems we flag the highest quoted.

There is no consensus concerning spatial resolution classes or nomenclature. What might be 'high resolution' in one application area may well be 'low' in another; land cover datasets at 1 km resolution for example may seem 'low' resolution when compared with a 30 m product, but land cover information at 1 km resolution is high resolution if used in a global assessment or in a combination with a climate model running with a 100 km horizontal cell size. Perceptions change as technology changes too – the 'high resolution' of the 1970s is certainly not considered 'high' four decades later. We propose five classes; 0.5–4.9 m (very high resolution), 5.0–9.9 m (high resolution), 10.0–39.9 m (medium resolution), 40–249.9 m (moderate resolution) and 250 m–1.5 km (low resolution). Any such grouping is somewhat arbitrary; the low resolution class acknowledges the threshold of 250 m established for global monitoring of land transformations (Townshend and Justice, 1987), the moderate and medium resolution classes include imagery available through 'free-and-open' data policies. The high and very high resolution classes reference commercial distinctions. The upper limit of 50 cm is set because US Government licensing limits unrestricted distribution of spatial data to this resolution.

2.2.4. Ownership

Government and/or private organizations finance satellite programs. Such entities may hail from a single sovereign state, may be a partnership of states, may be a space agency serving many states, as in the case of the European Space Agency (ESA), or may be from a geopolitical group that no longer exists, such as the Union of Soviet Socialist Republics (USSR). This paper attributes each mission to a single sovereign state, which is often transparent, but not always. In the case of partnerships we report the major funder's home sovereign state where this is known, e.g., France for SPOT (though we acknowledge that Belgium and Sweden together fund part of the programme) and Germany for TerraSAR (again acknowledging the partnership includes EADS Astrium, which is a global company). We give parity to China and Brazil in their partnership for CBERS and to Europe and USA for MetOp. The European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) and ESA missions are flagged as European (acknowledging that the constituent member states of each organization differ slightly). All USSR missions prior to 26th December 1991 are assigned to the Russian Federation; launches by other nations associated with the Commonwealth of Independent States are assigned to them as such events occurred post 1991. Where ownership has changed with time, such as the RapidEye missions, we flag the original launching state.

2.3. Creating a second order compendium

The first order compendium provides a benchmark for missions theoretically capable of land cover imaging globally, but we recognize that some have not (yet) been used for this purpose. This may be because they are too new (or too old), less well adapted, have other primary applications such as meteorology or oceanography and are not seen as land missions, maybe because of data access limitations and/or restrictive data access policies or because they are (were) only made known in languages less widely used than English. Recognizing these circumstances we produced a more targeted compendium by running Scopus searches (SciVerse Scopus, 2013) to identify the use of remote sensing images in research.

All queries were carried out in February 2014 with the search term "mission name" AND "land cover". This identifies missions that either have been used for land cover monitoring, or missions that have been recognized as having the potential for such monitoring – at least from a research perspective.

There are some limitations to this approach. First of all, the search phrases were in English, which is also the language best covered by the Scopus search engine. This introduces a linguistic bias. There might also be a temporal bias, as the Scopus coverage is most likely not as good for the 1970s and the 1980s, and because the number of articles published has increased over the years. Also note that citations in Scopus refer to scientific articles, although scientific analysis is only one usage of satellite imagery. The addition of "land cover" to the query was necessary to avoid articles with a focus on topics such as the technical details of a mission, meteorology or oceanography. We acknowledge that many articles are related to land cover without mentioning this specifically in the abstract or keywords; however, we assume this will mainly affect the absolute number of hits and to a lesser degree cause bias between missions. The opposite might also be true, some satellites have been mentioned in articles about land cover monitoring without having been actually used or considered for such use. This is still a minority of the satellites we have investigated, and will mainly affect those with a low number of hits.

Some excluding phrases were added to the query when necessary to exclude false hits where the mission name could be confused with common names. For example the "Suomi National Polar-orbiting Partnership" mission is often abbreviated to NPP, which picks up many net primary productivity publications; the "Meteor" missions likewise returned many irrelevant hits, as did NMP-EO-1, usually just referred to as EO. No attempts were made to find the number of hits for Monitor, although a query with "Monitor E1" gave zero hits. In some cases the sensor on any given mission is more widely cited than the mission that carries it. This is particularly the case for the satellites Terra and Aqua, both with a MODIS sensor, and Terra also with the MISR sensor. We then searched for misr OR modis OR terra OR aqua and treated this as one program. For Envisat, we also included MERIS, and for NOAA

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we included AVHRR; adding VGT to SPOT did not have a significant impact on the number of hits.

3. Results and discussion

3.1. Land-cover observing polar-orbiters in flight

The first mission to meet all requirements for observing land cover globally is Landsat 1, launched on 23rd July 1972. This and subsequent missions are listed in Appendix A.

Fig. 1 shows the period from launch to end of (imaging) life for all satellites except the failed missions. The operational periods for all 197 successfully launched missions are presented in chronological order.

Since the 1970s the number of satellites with a land cover observing capability has increased year after year. Taking 1st August as one arbitrary date we can track the change in the number of operational missions over time; on 1st August 1972 there was one mission in orbit; by 1st August 1982 the number of satellites flying had increased to eight, by 1st August 1992 there were twenty such missions, by 1st August 2002 there were thirty-nine and by 1st August 2012 eighty-three. A further 19 satellites were successfully launched between 1st August 2012 and 31st December 2013, whilst only four reached end-of-life; nearly 50% of the 197 earth observing polar orbiters ever successfully launched were still operational by the end of 2013.

Fig. 2 extracts the number of satellites operating for all years for the entire series. This confirms that the number of operational missions has not just increased, but has increased more quickly over time.

3.2. Launches and longevity

The number of satellites operating at any given date depends on the longevity of each mission and the number of satellites launched. Longevity is governed by a number of factors, which

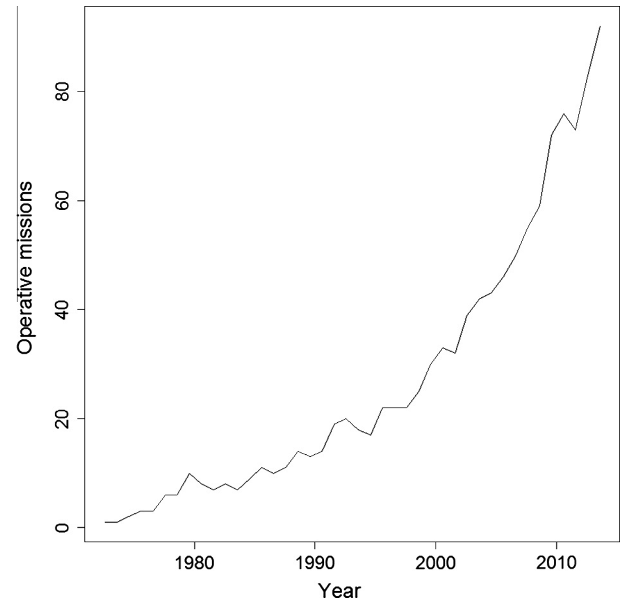

Fig. 2. The number of near-polar orbiting, land imaging civilian satellites operational as of 1st August 1972 to 2013.

include the durability of components, susceptibility to atmospheric drag governed by size, shape, attitude, spin rate and mass, shielding from solar radiation, orbit, and the amount of fuel the satellite carries. Fuel consumption and other factors can be modeled to estimate the operational life of a satellite. This is part of the debate on the financial viability of any mission as cost per expected day's operation can be calculated in advance. Actual rates of fuel consumption depend on issues such as the precision with which the launch was carried out (and thus how much post-launch positioning is required), what degree of orbital stability is achieved (and thus how much in-flight correction is required) and increasingly

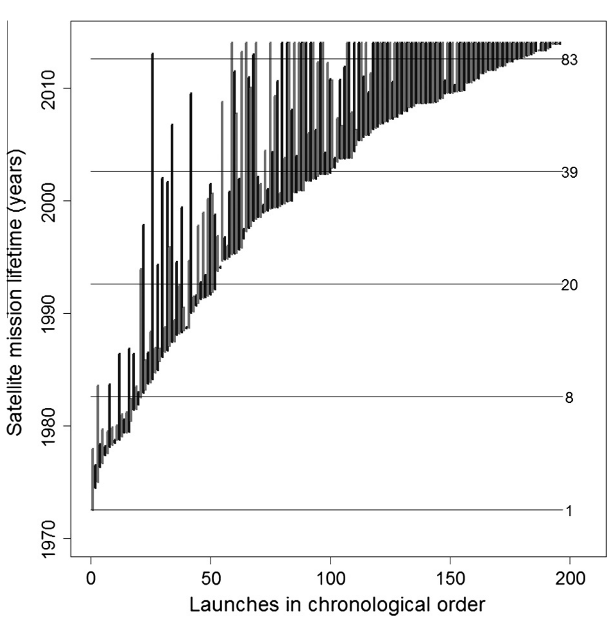

Fig. 1. The lifespan of all near-polar orbiting, land imaging civilian satellites shown in chronological order. The grey and black vertical bars denote the lifespan of each individual satellite – the tonal variation is to improve readability. The horizontal lines demark 1st August each decade from 1972 to 2012. The number to the left of each horizontal line denotes the number of satellites operational on this date.

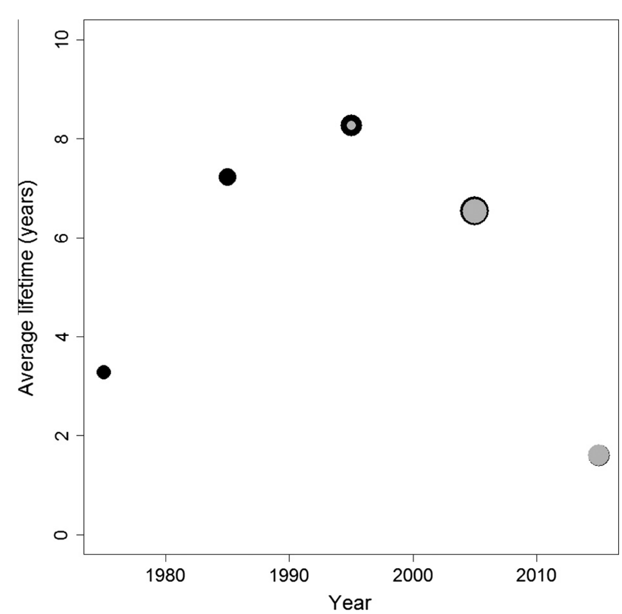

Fig. 3. Average mission lifetime for all near-polar orbiting, land imaging civilian satellites launched per decade. The size of the circle is proportional to the number of missions/decade. The black tone denotes the number reaching end-of-life and the grey indicates the number still flying. Note that the average lifetime for the 1990s, 2000s and 2010s will continue to lengthen, as many of the satellites launched in these decades are still operational.

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how many collision avoidance maneuvers are required because space junk is a growing problem (Ornes, 2012).

Fig. 3 shows the average lifetime of all missions per decade. Those missions launched in the 1970s and 1980s have all reached end-of-life. Between these two decades average operational life more than doubled, growing from 3.3 to 6.7 years. In the 1990s average operational life again increases, to 8.6 years, and importantly will continue to increase, as many of the satellites launched in this decade are still operational. The figure for the last two decades is lower, as many of these missions are only at the beginning of their operational lives. The longest operating earth observing satellite (so far) was Landsat 5. This was the only satellite from the early 1980s (1st March 1984) still working in 2013 (last scene acquired on 6th January 2013). This is testimony to the high quality of the design, build and components used in the bus and payload as well as management of the system such that fuel consumption, battery-life and any other consumables were used optimally.

Fig. 4 provides further confirmation of the trend towards greater longevity. This shows the percentage of missions in any given decade that failed in 3 years or less. In the 1970s more than half failed in the first 3 years, but during the last decade less than a fifth of all missions failed so quickly.

Fig. 5 shows the number of satellites launched each year. In the 1970s on average two satellites per year were launched. In subsequent decades this grew to 2.7, 4.8, 7.4 and in the last decade has risen to twelve. In 2008 thirteen individual satellites were launched and in 2013 the total reached fourteen launches in a single year; countries are launching more satellites and the number of sovereign states launching land-cover observing satellites is also growing (Fig. 6).

3.3. The globalization of global land-cover observations

Fig. 6 shows all years in which different sovereign states launched a satellite with global land cover observing capabilities. Country abbreviations appear in bold if a SAR was launched during that year; otherwise all launches were optical imaging systems.

In 1972 the USA was alone in flying land cover observing missions, but by 2013 another 33 sovereign states had acquired this capability. Russia (the pioneer of artificial earth orbiting satellites)

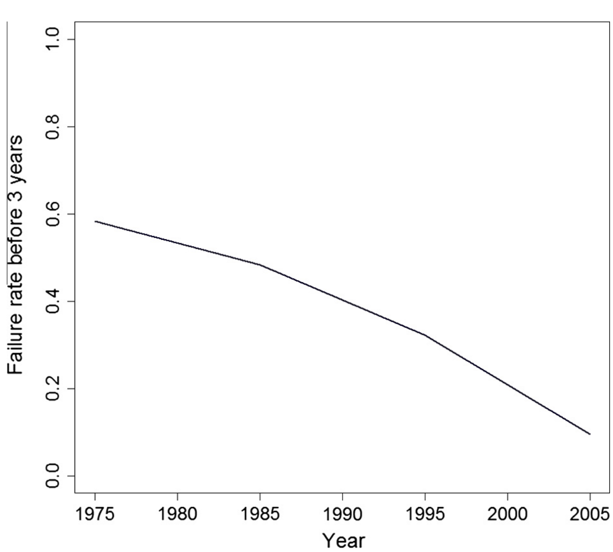

Fig. 4. The percentage of all near-polar orbiting, land imaging civilian satellites failing in less than 3 years of operation per decade (1970–2010). Note that at-launch failures are excluded.

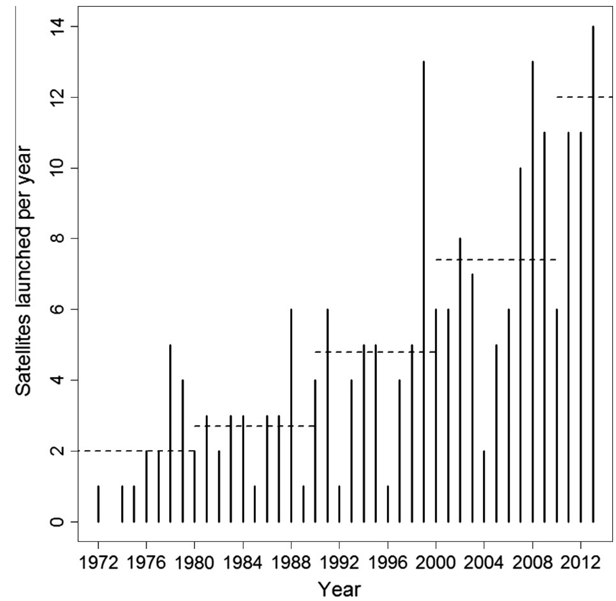

Fig. 5. Number of individual near-polar orbiting, land imaging civilian satellites launched per year. The horizontal dotted lines denote the average number launched per decade (1970s–2010s), which are 2, 2.7, 4.8, 7.4 and 12 respectively.

and other emerging national economies such as India and China soon followed; Europe and Japan were also among the early developers of this technology.

However, the last 15 years have seen rapid geopolitical expansion of ownership; the hegemony of the few, so apparent in the 1970s and 1980s, is breaking, at least for optical systems.

Fig. 6 also shows that once a sovereign state has launched an imaging satellite it tends to follow this up with subsequent launches. SAR systems remain in the hands of a much smaller number of sovereign states than their optical counterparts. Only the USA, Russia, Japan, Canada and Europe (including ESA, Italian and German missions) flew such missions – until India and China joined this select group in 2012 and South Korea launched its first SAR in 2013.

Fig. 7 shows those parts of the world that have launched land-cover observing satellites, and it also indicates how many they have launched. The US is undeniably the major player in this field, having launched almost a third of all the successful missions ever flown. Russia is not too far behind, accounting for around 14% of all success stories and the other emerging national economies (Brazil, China, India even South Africa) are definitely players in this new geopolitical arena. The gaps in the map are equally revealing; Central Asia is exclusively observed by others; Australasia has a long history of land cover mapping from satellite yet lacks an independent capacity; and much of Africa and the Middle East are yet to start in earnest, though there are pioneer states flying imaging systems from these regions.

The numbers for Europe combine members of the European Union, the European Economic Area and those countries belonging to the European Space Agency (though Canada is displayed separately) and the European Organization for the Exploitation of Meteorological Satellites (with Turkey being displayed separately).

Why are so many sovereign states investing in their own earth-observing missions? The immediate answer is that they want to know how, when and where land resources are changing. Analysis of the origins of the first such missions, the Landsat program, identified five main drivers. These were the need for better information, national security, commercial opportunities, international cooperation and international law (Lauer et al., 1997). These five drivers

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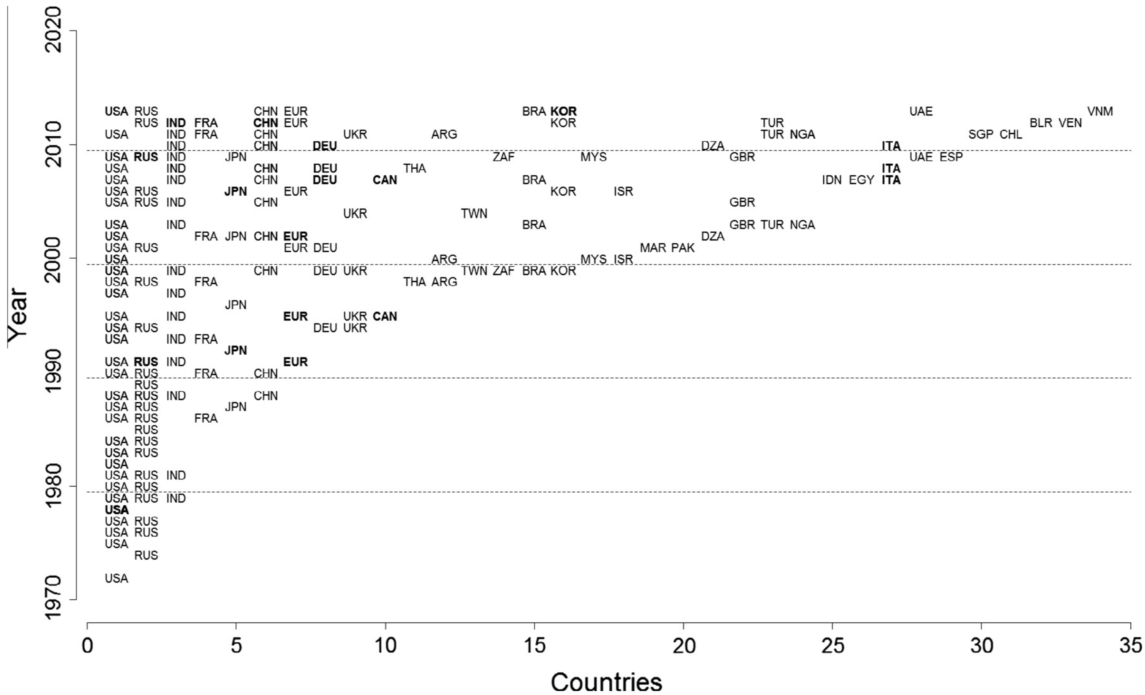

Fig. 6. Years in which sovereign states launched one or more near-polar orbiting, land imaging civilian satellites. Bold denotes launch of at least one SAR sensor. Horizontal dotted lines demark the end of each decade. Names are abbreviated using ISO 3166 country code A3.

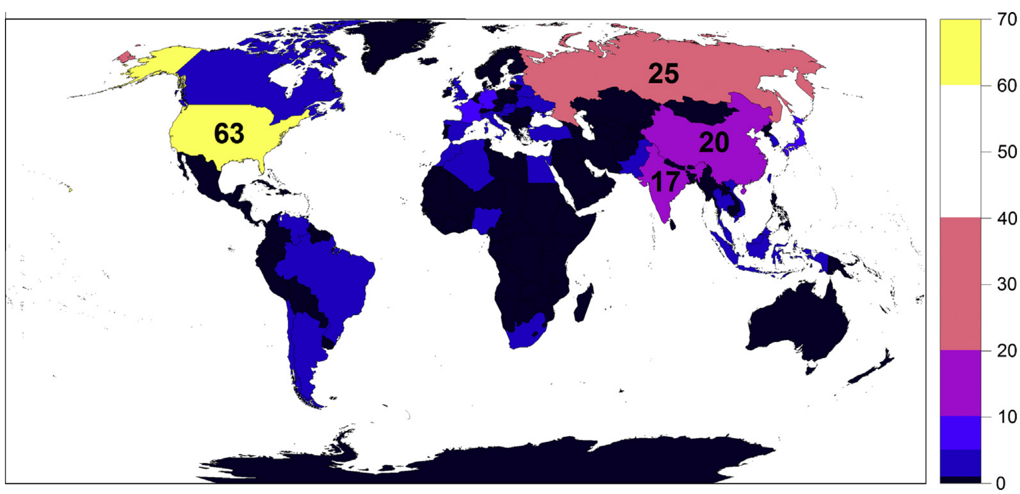

Fig. 7. Map showing the total number of near-polar orbiting, land imaging civilian satellites launched by (or on behalf of) different geographical regions between 23rd July 1972 and 31st December 2013. The legend to the right of the map shows the number according to 7 groups; 0; 1–5; 6–10; 11–20; 21–40; 41–60; 60–70. Note that no region falls into the 41–60 category. The numbers of launches made by the top four individual countries (India, China, Russia and USA) are specifically cited – note that collectively Europe has launched 30 missions.

are valid for other programs as well as Landsat. We propose four additional factors that may encourage countries to spend money on satellites capable of observing the land (or at least help justify such expenditure). These are promoting innovation, securing independent data-supply, falling mission costs and changing technology; and reinforcing national identity.

3.3.1. Innovation

Sovereign states see developing and expanding technological capabilities as a significant element of innovation and economic development – and the space sector is a critical technology area (Altenburg et al., 2008). This is appreciated by emerging economies, the developing world and advanced industrial economies alike. For example, NASA has published annual technology utilization reports since 1974, which highlight the spinoffs from NASA programs (Rademakers et al., 2013). Participating in space programs also forms a direct means of educating and training new generations of scientists and engineers, especially in the developing world where such opportunities remain limited (Boroffice, 2008).

3.3.2. Securing independent data-supply

Sovereign states also want their own systems because the data they collect have strategic value. Land cover information now supports many national and international decision-making processes. As sovereign states come to rely on such information assuring independence of data supply becomes more important. Protecting against breaks in data flows from third parties, controlling geographic areas where data are acquired and avoiding data collection 'waiting-lists' become essential. Sovereign states and regions seek increasing control over earth-observing technology. For example Africa as a region has made clear statements concerning the continent's desire to avoid being a passive consumer of earth observation data (Ngcofe and Gottschalk, 2013), and over the last decade the European Commission and ESA have built an entire earth observation program around this premise. Europe's Global Monitoring for Environment and Sustainability (GMES) programme provides a framework for services in domains such as emergency response, land, ocean and atmosphere monitoring and climate change (CEC, 2009, 2013). The GMES program, now renamed Copernicus, has already built a series of technologically advanced imaging satellites (the Sentinels), the first of which was successfully launched on 3rd April 2014. This multi-billion euro program (CEC, 2013) is of course there to promote European innovation and industrial growth, but it is also intended to prepare national, European and international legislation on environmental matters, which calls for a guaranteed, sustainable and controlled data supply.

3.3.3. Falling mission costs and changing technology

Owning and running a mission to supply Earth observation data from space comes at a cost. Unfortunately we are unable to document mission costs in a systematic fashion because this information has seldom been made public. For many missions the financial aspects are considered commercially confidential, politically sensitive or have simply been lost in the mists of time.

However, there are some examples where costs are known. The costs associated with the largest civilian earth-observing satellite launched so far (the European Space Agency's Envisat) cost 1450 million euro to build (ESA, 2013). It carried 11 different sensors, measured 10 by 4 by 4 m and weighed 8200 kg. Launching this enormous piece of equipment cost 140 million euro. Developing the ground segment cost a further 160 million, and annual running costs were 60 million euro. The US too has gone on record concerning the costs of the Landsat 8 program; the flight segment (satellite and sensors), the launch, 100-days of in-flight commissioning and system engineering totaled USD 855 million (Irons, 2013). South Africa's microsatellite Sumbandilasat programme costs too are in the public domain (Martin, 2012; SunSpace, 2013); around 100 million rand was spent on the program (this is equivalent to just over 9 million euro at the time of launch). Sumbandilasat carried a single sensor, measured 0.7 by 0.5 by 0.5 m and at 81 kg was more than a hundred times lighter than Envisat.

The examples above show that the cost of a satellite program varies hugely from mission to mission. Smaller and lighter satellites are cheaper to build and launch than their larger and heavier counterparts (Xue et al., 2008), so it is small surprise that Earth observation and environmental monitoring have been identified as particularly important markets for SmallSat technology (Foust et al., 2008). Whilst the costs for any sovereign state contemplating an earth observation program based on SmallSat technology are lower than previously possible (Sandau, 2008), making direct cost comparisons between observing systems is fraught with difficulties. This is because of the range of differences between missions. Missions vary greatly concerning sensor and platform performance specifications. There are also differences in the realization and validation of these specifications. Other cost factors include associated ground segment costs such as data downlinks, data processing, archiving and distribution. Envisat imaged the Earth for over 10 years, Sumbandilasat for less than one; effectively Sumbandilasat cost more per kg per month of operation than Envisat.

Nevertheless, the reduced costs associated with SmallSat technologies have undoubtedly contributed to the increase in the number of missions. Thailand's TMSat-1 launched 10th July 1998 and South Africa's SUNSAT, launched 23rd February 1999 are early examples from the Earth Observation community. And whilst precise figures are unavailable, the latest satellite to follow this trend, SkySat-1 "was built and launched for more than an order of magnitude lower cost than traditional sub-meter imaging satellites" (Skybox Imaging, 2014). New business models combined with SmallSat technology, such as the data sharing and common ground segment pioneered by the Disaster Monitoring Constellation (da Silva Curiel et al., 2005) have also broadened the ownership base. Lower costs and such innovative business models have at least allowed, and maybe actively encouraged, new sovereign states to enter the field.

Lower costs and smaller/lighter platforms have also stimulated initiatives such as the simultaneous launch of constellations like the five-platform RapidEye program. The triple CubeSat format which uses of off-the-shelf components from the automotive, smartphone and high-end digital camera manufacturing industries has also significantly 'slashed' costs (Butler, 2014), which is one reason why this technology is the basis for previously unimaginably large constellations of 28 platforms.

3.3.4. National identity, national pride

Securing access to data and controlling the technology are unquestionably important to sovereign states. However, the benefits of earth observing programs extend into more nebulous territory too, namely national pride. South Africa's scientific and engineering capacities were enhanced by the experience of designing, building and flying Sumbandilasat, but the country also gained social benefit and kudos from the program (Martin, 2012). Self-esteem, the good opinion of others and reinforcing national identity and sense of purpose are not obvious justifications for space programs, but they are among the hidden-benefits (Belward, 2012).

Evidence of national pride in an Earth Observation system is difficult to document. There is often transient reporting in mainstream media accompanying a launch, such as the News Gateway to Vietnam's reporting surrounding Vietnam's first remote sensing satellite launched on 7th May 2013 (Tuitrenews, 2013). On occasion too a satellite's failure can spark sentiments of pride, as exemplified by ENVISAT's loss (Brumfiel, 2012).

The postage stamp may be considered as one physical source of evidence. A recognized part of any nation's iconography, stamps are intended to take messages of national preoccupations beyond a nation state's borders (Covington and Brunn, 2006); as Covington and Brunn put it "through its stamp issues the state can decide 'what it wants to show to others about itself'". National pride in Earth observing capabilities from space is evident in the wide range of nations proclaiming their success in this field through postage stamp issues. At least 20 satellite series (and far more individual platforms) have appeared on the stamps of as many countries. Documenting this in detail is beyond the scope of this paper, but it suffices to say that enough are out there for specific catalogues to be produced (World Space stamp catalogue, 2010) and for un-manned satellite philately to list environmental satellites as a class of their own (Hilger and Toth, 2014).

It also appears that some nations without an Earth observation programme feel the lack. For example, Australia, a significant gap in the map of earth-observing satellite ownership shown in Fig. 7 has vigorously pursued a public debate around the argument that "It is not good enough for Australia to be lost in space" (Commonwealth of Australia, 2008) and as of 1st July 2013 this country has established a Space Coordination Office to implement a "Satellite Utilization Policy" (Commonwealth of Australia, 2013).

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3.4. Increasing resolving power, consistent horizons

Mission technology progresses over time (the increase in longevity is testimony to this). Sensor performance is no exception; for optical systems advances occur in optical designs, radiometry, signal-to-noise ratios, dynamic range, sensor saturation, cross scene uniformity- and spatial resolution among other factors; SAR systems too evolve – better physical antenna elements, improved synthesis of these, more and better echo captures, better pulse generators and the like. Fig. 8 shows how the spatial resolution of sensors on land-cover observing satellites has changed over the last four decades, plotting the highest resolution for 5-year periods for the different sensor types.

3.4.1. Optical sensors

In any five-year epoch panchromatic data are always acquired at a finer resolution than multispectral. However, both panchromatic and multispectral imaging now takes place at much finer spatial resolutions than in previous decades. SPOT 1 acquired the first 10 m resolution panchromatic images in 1986, then the 6 m limit was surpassed in 1995 by IRS-1C. The meter mark was broken in 1999 by IKONOS, half-meter by WorldView 1 in 2007 and a year later GeoEye 1 was acquiring panchromatic imagery at a resolution of 41 cm. Multispectral imaging began at resolutions of around 80 m with Landsat 1 in 1972, hit the 30 m mark a decade later with Landsat 4 in 1982, reached 16 m with AVNIR onboard ADEOS 1 in 1992, and 4 m with Orbview 3 in 2003, reached below 2 m in 2008, once again with GeoEye-1 and finally reached the sub-meter mark with SkySat-1 in November 2013, albeit in photographic format for general release.

3.4.2. SAR sensors

Only 19 missions from a total of 197 carry SAR imagers. Even the first SAR imaging systems provided medium resolution data. The USA's Seasat mission provided 25 m resolution L band imagery for around 105 days in 1978, but then there was a gap of 13 years till Europe's ERS-1 started providing 30 m resolution C band data in 1991. Russia's ALMAZ 1B provided 30 m resolution S band in 1991 too, and a year later Japan's JERS-1 took L band imagery down to 18 m resolution (Rosenqvist, 1996). The first high resolution SAR imagery came from Canada's Radarsat 1 in 1995; this mission provided C band imagery at various resolutions down to 8 m. Very high resolution SAR finally became available in 2007 and 2008 with Italy's first CosmoSkymed and Germany's TerraSAR, both of which provided X band imagery at 1 m resolution; even new entrants into SAR imaging launch very high resolution systems (India and China both launched their first civilian SARs in 2012 and South Korea its first in 2013). The only break with continuity in the trend to higher resolution over time is Russia's Meteor M N1. Launched in 2009, this mission provides 500 m resolution X band imagery. However the main use of these data is for sea ice mapping, not land cover. Some other SAR imagers, such as Radarsat, also provide data at similar resolutions for ice mapping.

3.4.3. Continuity

Whilst there is a trend to finer resolution imaging over time, some spatial resolutions are continuously maintained. Figs. 9a and 9b reports the number of sensors in each resolution class launched per year (Fig. 9a is multispectral and Fig. 9b panchromatic, SAR are not shown). The trend of increasing resolution is apparent in the emergence of the 'high' and 'very high' resolution classes at the end of the last Century. This is particularly evident for the panchromatic sensors. Higher resolution panchromatic sensors permanently displace the lower resolution, with one exception namely the 15 m panchromatic sensor flown on Landsat 8.

The evolution of multispectral sensors' resolution is not as one-way as the panchromatic. Resolution has improved, but not at the expense of the coarser resolution systems. The consistency with which 'moderate', 'medium' and 'low' resolution multispectral sensors are launched is notable. Hardly a year goes by without one or the other, or indeed all three classes being represented. The wider horizons (broader swath widths) of these lower resolution sensors are very desirable, and lower spatial resolution means less data to handle (which for global studies is a consideration even with the increases in computing power governed by Moore's Law). Indeed, sensors in these classes provide all the existing wall-to-wall global land cover datasets; the NOAA AVHRRs (Loveland et al., 1999); EOS

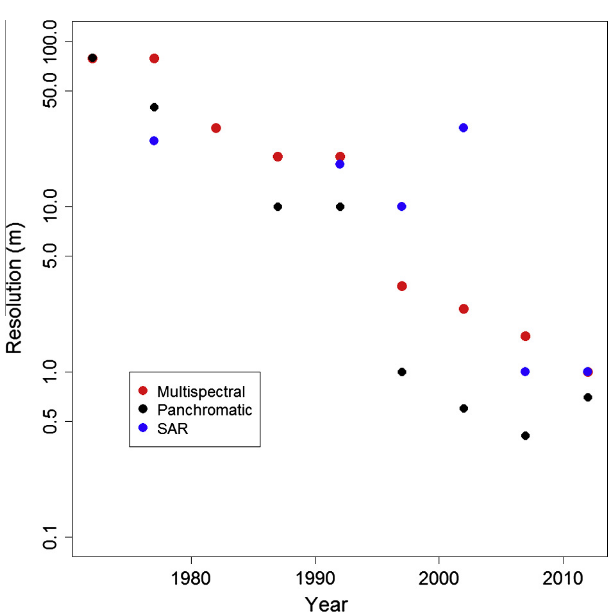

Fig. 8. The highest resolution (meters) achieved from any panchromatic, multispectral and/or SAR sensor onboard a near-polar orbiting, land imaging civilian satellite in each 5 year period's launches (the figure does not take individual missions' lifespan into account).

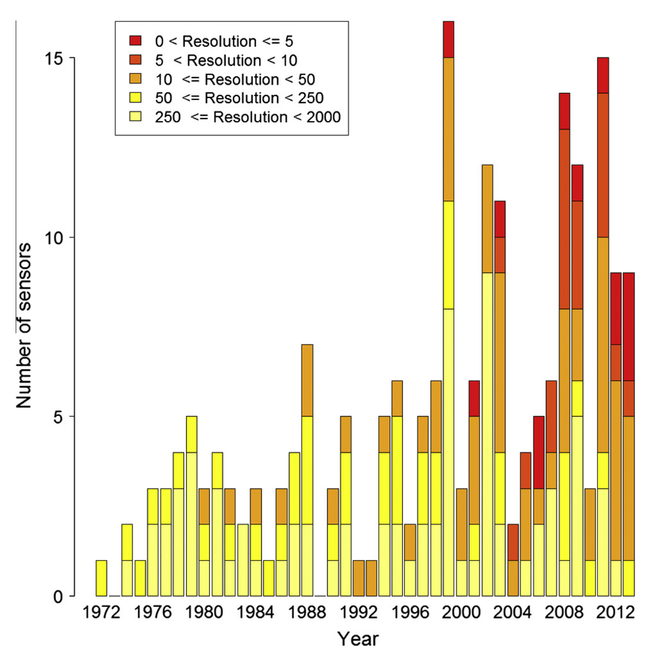

Fig. 9a. Number of multispectral sensors at different spatial resolutions flying on near-polar orbiting, land imaging civilian satellites per year.

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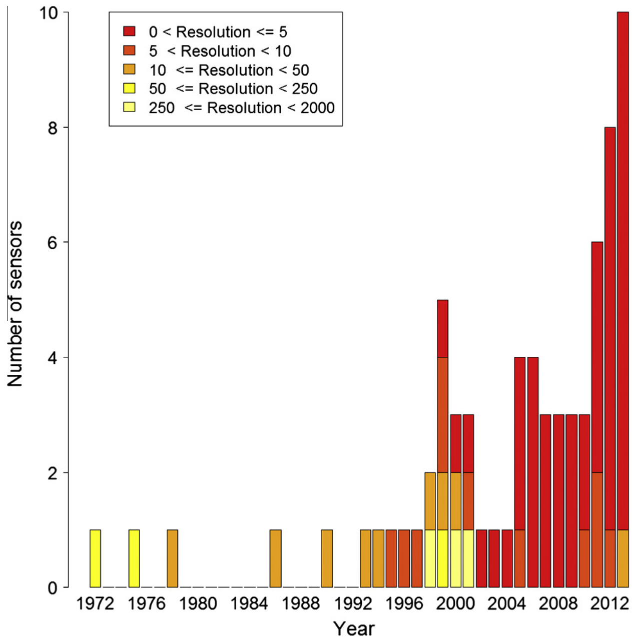

Fig. 9b. Number of panchromatic sensors at different spatial resolutions flying on near-polar orbiting, land imaging civilian satellites per year.

MODIS (Friedl et al., 2002); SPOT VGT (Bartholome and Belward, 2005); Envisat MERIS (Arino et al., 2007); and Landsat TM/ETM (Gong et al., 2013). These global land cover maps do show increases in spatial resolution, from 1 km in the case of the AVHRR and VGT based maps, to 300 m for MERIS, 250 for MODIS, and 30 m for the Landsat TM/ETM product. This is partly because new sensors were launched, partly because changes in data policy concerning moderate resolution meant that TM/ETM data were freely accessible from 2008 onwards and partly because computer power had increased to the point at which processing multi-channel global data sets at 30 m resolution was a realistic proposition. The trend towards higher resolution is accompanied only by slight increases in classification accuracy (Yu et al., 2014). Improving the accuracy of global land cover maps remains a key challenge for the community. Merging data from different platforms with different spatial/spectral/temporal resolutions is one route being increasingly explored (Ban et al., 2010; Vaglio Laurin et al., 2013) and combing the power of resources such as Google Earth and Bing with crowdsourcing is another (Fritz et al., 2009).

3.5. What's in a name?

Table 1 shows the results of the Scopus search endorsing each program's (not individual satellite) use, or potential use, in land cover work. This lists all programs in groups according to Scopus entries in increasing orders of magnitude. Those programs that are linked to Scopus entries fall into distinct clusters depending on the exact number of entries returned in the search.

Some of the missions with zero Scopus entries may be absent because of the linguistic bias in the search and/or because the data were not readily available. The programs of the former USSR are underrepresented for these reasons. Some of the microsat missions, such as the TUBSAT programme, may be absent from the list as their ground segment is more focused on exploring technical capabilities and gaining experience with data handling, rather than running a mission with the goal of disseminating data to a broad user community (eoPortal, 2014). Other missions attract zero entries in Scopus because insufficient time has passed for the platform to gather data, for these data to be analyzed, results written up, paper published and the reference to appear in the Scopus database. The recent launches such as SkySat-1, VNREDSat-1A and Gocturk 2 fall into this category. Others may be excluded because their primary mission has goals other than land cover.

Table 1
The number of Scopus entries found when searching for 'mission name' and 'land cover'. Missions are grouped according to the range of entries detected. Full counts are reported in Appendix A.

Group 1 0	Group 2 1–5	Group 3 5–50	Group 4 50–500	Group 5 500–5000
Meteor	SSOT	MOS	CBERS	NOAA (742)
Okean	RISAT	SAC	TerraSAR	SPOT (924)
TUBSAT	Bhaskara	Orbview	JERS	EOS (1501)
TMSat	Feng-Yun	Nimbus	NMP	Landsat (3900)
SUNSAT	Almaz	Cartosat	Radarsat	
TungSat	EROS	THEOS	ALOS	
BIRD	Sumbandilasat	KOMPSAT	ERS	
HaiYang	Oceansat	Seasat	IRS	
Monitor	GOSAT	Resourcesat	Envisat	
Topsat	RazakSat	Formosat	GeoEye	
Egyptsat	Pleades	ADEOS	WorldView	
MS	Resurs	RapidEye		
Dubaisat	Metop	DMSP		
Alsat		Proba		
TianHui		Cosmo-Skymed		
X-Sat		DMC		
Sich		Huan-Jung		
RASAT				
Suomi NPP				
Zi Yuan				
Kanopus Vulkan				
BelKa				
VRSS				
Gocturk				
Planet Labs				
Gaofen				
VNREDSAT				
STSAT				

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The experimental mission TopSat, which focused on operational disaster management work, is an example.

Those receiving less than 500 entries generally comprise recent missions (MetOp), historical (Bhaskara), those that are marginal to land-cover mapping (such as the Coastal Zone Color Scanner and Seasat) and missions providing very high resolution imaging (WorldView, GeoEye). All the global land-cover mapping workhorses, except Envisat, receive at least 500 entries. Envisat's MERIS sensor is the most recent entrant into the field of missions used for global (as in wall-to-wall) land cover maps, which may in part explain this. Another possible contributing factor may be the data access governing datasets of large volume from Envisat. These can fall into the 'Restrained dataset' category, which whilst still free require the submission of a project proposal to ESA (the satellite's operator) and acceptance of that proposal by ESA, who may apply a maximum quota for product delivery (ESA, 2012). One could imply from the relatively low number of Scopus entries related to the use of Envisat for land-cover research that even mildly restrictive data access policies have a negative impact on research use. Opening archives and easing access to data certainly has the opposite effect, as amply illustrated by the new science and applications emerging from the changes to free and open access of Landsat (Wulder et al., 2012). The US National Geospatial Advisory Committee adopts an unequivocal position in this respect too stating that 'Charging for Landsat Data would inhibit data analysis in scientific and technical analyses' (Federal Geographic Data Committee, 2012).

Data from Landsat's TM were only very recently used for global wall-to-wall mapping (Gong et al., 2013), but the heritage of this program for land cover mapping more generally is pretty unassailable. Landsat may fall into the same group as the missions carrying VGT, MODIS and AVHRR but it receives more than double the number of entries of its nearest neighbors in terms of the number of Scopus entries (details in Appendix A). The name change, from the program's original 'Earth Resource Technology Satellite' to 'Landsat' certainly proved perceptive. But it is more than a name. The utility, quality and continuity of the program are manifestly demonstrated in the number of papers. Landsat is the longest running program, which allows the scientific communities time to build experience with the system, time to develop and refine land-cover mapping approaches and produce papers that appear in Scopus. Continuity also promotes operational uses because users are sure that data flow will be sustained, hence it is worth investing in a service that uses these data. Continuity is also crucial for climate observations. Landsat is currently the only satellite program to provide a consistent, cross-calibrated (Chander et al., 2009) set of records stretching back over more than four decades, which in turn means the program occupies a key position in the provision of terrestrial essential climate variables (Trenberth et al., 2013).

4. Conclusions

This paper shows just how fast the Earth observing domain is changing; trying to document who launched what, when and why is really trying to hit a moving target. Our results show that Earth observing satellites reach end-of-life at irregular (and sometimes unexpected) intervals and new ones are being launched in greater numbers almost year-on-year. This paper is therefore a snapshot of the state of affairs at the end of 2013.

Nevertheless our analysis reveals a number of trends: Lower costs associated with smaller platforms and use of off-the-self components, a greater desire for control of technology and data flows, innovation and education, even national pride may be contributing to the dramatic expansion in the geographic regions of the world owning and operating spaceborne systems capable of gathering global land cover information and contributing to the increasing numbers of such platforms flying.

We have shown that organizations in a growing number of sovereign states are choosing to fly satellites with some capacity to image land cover anywhere on our planet's surface. This is true for both optical and SAR systems, though SAR systems are still the prerogative of fewer regions. However, even this advanced technology is becoming more widespread.

The individual satellites in a country's program should ideally improve with successive launches. But, as exemplified by the Landsats these should also be cross-calibrated, thus assuring both continuity and evolution. Cost may well be a driving factor, but should not drive down quality. Programme costs rise as performance specifications, their execution and their validation rise. Of course programs can (and do) use off-the-shelf technology from other industries (this is part of the cost cutting associated with the innovative triple CubeSat approach) but they can also use the tried and tested technologies of preceding missions. The European Copernicus program for example commissioned two satellites per class and MODIS sensors were flown on both NASA's Aqua and Terra satellites. This economy of scale helps control development costs and shortens build, testing and delivery schedules.

Longevity too is clearly on the increase; components last longer, design improves and in-flight management has got much better at conserving fuel and other consumable elements of a mission. Whether longevity will continue to increase in the same manner though is questionable. Extending lifetime from 3 to 9 years is probably more achievable than from 9 to 27 years (Landsat 5 notwithstanding). The marginal gains of extending lifetime beyond 10 years or so also deserve consideration. Sensor technology evolves and the benefit of launching newer and better sensors might be higher than from developments leading to extended longevity. The move from 8-bit to 12-bit radiometric resolution in the Landsat program for example is already proving highly beneficial (Roy et al., 2014).

At around 83 kg weight and with a diameter of less than 60 cm the very first artificial satellite ever launched would be classified as a SmallSat, or even a microsat today. We had to wait almost 40 years before the first microsat and the first SmallSat with potential for global land cover imaging were launched (respectively the Technical University of Berlin's TUBSAT B launched in 1994 – which admittedly failed after 39 days, and Surrey Satellite Technology's TMSat-1 in 1998). In the closing months of 2013 the Planet Labs and Skybox demonstrators have continued to extend the trend to 'smaller' and 'cheaper'. These new systems will certainly change our ability to observe our planet's land cover, but global land cover and cover change studies still need tightly specified, well-calibrated multispectral measurements across a range of wavebands (Roy et al., 2014).

The success of a mission, at least in terms of its use for land cover work, does not just depend on successful design, build, launch and flight operations but also on its data acquisition strategy, its capacity for archiving, cataloguing, caring for data, its data access policy, and its ability to make the data easy to find and easy to physically obtain. Restrictive data policies and convoluted data access systems should be avoided. The trend to full free and open data access is on the rise, even for higher resolution data. Landsat paved the way and others are following. Such an approach is also a core element of the Group on Earth Observation's Global Earth Observing System of System's goal of data sharing and data management (GEO, 2012; Withee et al., 2004). Even new commercially driven programs such as Planet Labs and SkyBox hope to make their data available free to academics and non-government organizations (Butler, 2014). The future of Earth observing from space seems set fair to provide more people with more data than ever before.

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Satellite launches are no longer rare. The view of Earth from space now verges on the mundane. Thanks to Google Earth and Bing these views are a near every-day experience for countless people. But there is a risk in such familiarity. It becomes easy to take global land cover observations for granted, which should not happen. Securing the continuity of programs such as Landsat, SPOT, NOAA, CBERS, IRS, JERS, Resurs, DMC and others requires vision, dedicated and talented scientists, engineers and mission operators as well as funds. The civil domain will continue to design, develop, build, launch and operate Earth Observing satellites. The CEOS earth observation handbook's 2014 update (CEOS, 2014) states "CEOS agencies are operating or planning around 260 satellites with an Earth observation mission over the next 15 years. These satellites will carry around 400 different instruments". Of course not all are imaging platforms, but the statement of intent is clear; civil agencies around the world remain committed to Earth Observation from space. Commercial ventures such Planet Labs and SkyBox are going to provide additional data streams for land cover studies. These ventures have the potential to add high-temporal revisit to the Google Earth and Bing democratization of high-spatial resolution views of our Planet from space. And although the 50 cm upper limit on spatial resolution for data distribution set by the US is extremely likely to remain in place commercial operators are pursuing ever-finer resolution; Digital Globe's forthcoming WorldView 3 mission should provide 31 cm panchromatic and 1.24 m multispectral imagery by the end of 2014 (Digital Globe, 2014).

In this paper we have emphasized land cover, but of course the missions we list can be used for many other purposes. Even the front-runner system from our Scopus search on land-cover, Landsat, finds application in water use, drought, agriculture, forestry, snow and ice, generation of essential climate variables, freshwater and coastal area studies, as well as land cover, condition, disturbance and change (Roy et al., 2014). However, from a purely hypothetical standpoint those interested in acquiring land cover information from earth observing satellites have more missions at their disposal offering a greater range of spatial resolutions than ever before. Not all the relevant satellites flown or flying have (yet) been used for land cover mapping in a formal way, but someone somewhere has learned something about our planet's land cover from every one of the 197 missions identified in this paper.

Acknowledgements

We have made every effort to report launch, end-of-life and payload accurately, but we are aware that the transient nature of some of the resources we used, a paucity of public domain documentation for some programs and the linguistic partiality of our work may introduce bias and some (undetected) errors; corrections/additions are warmly welcomed. We would like to thank the dedicated people who maintain the six comprehensive launch and mission databases and web sites we used. We would also like to thank Jim Irons (NASA) and Tom Loveland (USGS) for information on the Landsat program, Stephen Mackin (DMCii) for confirming TMSat-1 end of life and Nick Waltham (STFC) for valuable information on the TUBSAT imagers and missions.

This research was funded by the European Commission's 7th framework programme for research and technological development direct cost actions at the Joint Research Centre. The views expressed in this paper are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.isprsjprs.2014.03.009.

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