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Earth observation from space – The issue of environmental sustainability

Sylvie Durrieu [a,*], Ross F. Nelson [b]

[a] UMR TETIS Irstea-Cirad-AgroParisTech/ENGREF, Maison de la Télédétection en Languedoc-Roussillon, 500, rue J.F. Breton BP 5095, 34196 Montpellier Cedex 05, France
[b] Code 618, Hydrospheric & Biospheric Sciences Laboratory, NASA/GSFC, Greenbelt, MD 20771, USA

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ABSTRACT

Remote sensing scientists work under assumptions that should not be taken for granted and should, therefore, be challenged. These assumptions include the following:

1. Space, especially Low Earth Orbit (LEO), will always be available to governmental and commercial space entities that launch Earth remote sensing missions.
2. Space launches are benign with respect to environmental impacts.
3. Minimization of Type 1 error, which provides increased confidence in the experimental outcome, is the best way to assess the significance of environmental change.
4. Large-area remote sensing investigations, i.e. national, continental, global studies, are best done from space.
5. National space missions should trump international, cooperative space missions to ensure national control and distribution of the data products.

At best, all of these points are arguable, and in some cases, they're wrong. Development of observational space systems that are compatible with sustainability principles should be a primary concern when Earth remote sensing space systems are envisioned, designed, and launched. The discussion is based on the hypothesis that reducing the environmental impacts of the data acquisition step, which is at the very beginning of the information stream leading to decision and action, will enhance coherence in the information stream and strengthen the capacity of measurement processes to meet their stated functional goal, i.e. sustainable management of Earth resources. We suggest that unconventional points of view should be adopted and when appropriate, remedial measures considered that could help to reduce the environmental footprint of space remote sensing and of Earth observation and monitoring systems in general. This article discusses these five assumptions in the context of sustainable management of Earth's resources. Taking each assumption in turn, we find the following:

(1) Launch is not benign, but study is [illegible] associated with rocket combustion by-products.

(3) Minimization of Type II error should be considered in situations where minimization of Type I error greatly hampers or precludes our ability to correct the environmental condition being studied.

(4) In certain situations, airborne collects may be less expensive and more environmentally benign, and comparative studies should be done to determine which path is wisest.

(5) International cooperation and data sharing will reduce instrument and launch costs and mission redundancy. Given fiscal concerns of most of the major space agencies – e.g. NASA, ESA, CNES – it seems prudent to combine resources.

1. Introduction

Until the middle of the 20th century, environmental sciences could still be based on leisurely methods of data collection which were compatible with the relatively slow speed of environmental

* Corresponding author. Tel.: +33 (0)4 67 54 87 32; fax: +33 (0)4 67 54 87 00.
E-mail addresses: sylvie.durrieu@teledetection.fr (S. Durrieu), ross.f.nelson@nasa.gov (R.F. Nelson).

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changes and with the scales of studies [1]. Presently, constantly improved and updated information is a given for resource monitoring and management as they can capture the dynamic nature of environmental conditions such as climate change, water allocation, as well as soil and biodiversity loss [2].

As early as in 1969, in the first editorial of the *Remote Sensing of Environment* journal, Simonett [1] stated that "the quickening of science, and resource use, and the demands of society have increased the urgency to obtain quantitative, timely information about the environment at a variety of scales in space and time". He posited that observations made using ground-based sensors, aircraft, and space platforms could help to meet these information requirements [1]. Three years later, the launch of the Earth's Resources Technology Satellite ERTS-1, later renamed Landsat-1, marked the beginning of the Landsat era, thereby providing significant impetus for the development of environmental applications based on remote sensing data at local to global scales [3]. Some of the most common applications in the remote sensing world, such as agriculture or water management, can be traced back to research performed on specific landscape features identified by Kondratyev et al. [4] on one of the first Landsat 1 images recorded in July 1972. Navalgund et al. [5] classified the current remote sensing applications into the following categories: sustainable agriculture, water security, environmental assessment and monitoring, disaster monitoring and mitigation, and infrastructure development. Other fields of research such as fisheries management, weather and climate studies have also benefited from the development of the remote sensing sector [5]. More recently, remote sensing data have more been instrumental in advancing the fields of ecology, biodiversity and conservation [6].

As environmental impacts of human activity make resource management more and more complex and as, at the same time, our understanding of complex natural processes increases, our need for critical information layers at appropriate spatial and temporal scales and extents increases too [2]. The growing number of theme-specific satellites, noted by Navalgund et al. [5], reflects a technological response that can help to overcome such limitations, thereby facilitating natural resource management.

The relevance of such spaceborne theme-specific missions can be taken as a given from the measurement point of view. However, the premise that spaceborne observation can best provide information for sustainable management of Earth resources should be subjected to more critical debate. Indeed the sustainability of Earth observation from space is not as evident as it might seem, a point that is seldom discussed.

The paper, which is partially based on a previous work [7] aims to take a fresh look at measurement processes designed to support the monitoring of Earth resources and to promote debate about the role of remote sensing from space within the context of sustainable management of these resources. Sustainability is defined as the capacity to endure, and sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [8]. In this paper, we look at Earth observation sustainability from two different directions. First, given the number of space launches to date, the amount of space debris currently in orbit, and the expected number of future launches, can we safely assume access to orbit for operational environmental missions in the future? Second, given a full accounting of the environmental costs associated with space launches, are satellites necessarily the best way to sustain the flow of measurements needed to monitor the status of Earth's environment?

The common thread of this paper is the idea that to increase efficiency and durability of observation and measurement systems designed to support sustainable management of the Earth resources, those measurement and monitoring systems should, themselves, be as sustainable as possible. In short, this means that the environmental, social, and economic cost of a mission must be less than the corresponding returns. Referring to ecological engineering principles [9,10], environmental impacts from the system production stage to its end of life should be better understood and taken into account. This would enable the design of measurement systems capable of providing valuable information for managers while minimizing their inevitable environmental impacts. Forgetting to limit those impacts when designing an observation system is liable to lead to suboptimal or even inappropriate solutions.

Section 2 examines two issues that challenge the assumption that spaceborne Earth observation systems are sustainable. Section 2.1 calls into question the basic assumption that Earth-orbiting platforms will always be available to the civilian remote sensing community. Section 2.2 focuses on the environmental impacts of space activity on the Earth and reports on how these impacts affect sustainability. Section 3 presents some unconventional points of view that, in our opinion, are required to address the sustainability issue of space-based Earth observation systems. In this section we also suggest using environmental life cycle assessment as an analysis tool that might be particularly relevant to help reaching these goals. Section 4 details possible initiatives that follow naturally if these non-traditional points of view are deemed valid and that might be taken to mitigate impacts associated with space missions and improve sustainability of Earth observation systems. We addressed some issues that are common to all remote sensing missions. In addition a study case was chosen, i.e. vegetation lidar missions, to illustrate a few case-specific possible actions. Section 5 summarizes and concludes.

2. What can put the sustainability of Earth observation from space in jeopardy?

In what follows, sustainability is considered with respect to durability, space debris, and with respect to space activity as an Earth pollution source.

2.1. Uncertainties about the durability of Earth observation from space

2.1.1. Historical context, current state and outlook for space activity

The development of the space sector began in 1957 with the launch of Sputnik, the first artificial, Earth-orbiting satellite. The total number of launches since 1957 exceeded 5000 during year 2009 (see Fig. 1) and the mean annual number of launches over the ten last years has been slightly higher than 65 [11]. Even though the number of launches per year have trended downward since the end of the cold war in 1991 (Fig. 1), the total number of operational satellites has continually increased due to a rise in both the lifetime and mean number of satellites per launch.

The development of space activities has long been driven by the political and military aspirations of the USA and Russia, the two main players in this sector. One of the peace dividends from the end of the cold war was the rise in commercially viable applications – e.g. telecommunication and Earth observation – and the emergence of new space powers, which led to the whole-scale transformation of the space sector. This transformation affected space programs but also space activity architecture as a whole, affecting both military and civilian applications [12], paving the way for the emergence of new features which are specific to the current set of active satellites. There are currently close to 1000 active satellites in orbit, operated by 41 countries and several international consortiums [13]. Fig. 2a and b shows the distribution of satellites according to orbit classes and scientific/commercial disciplines,

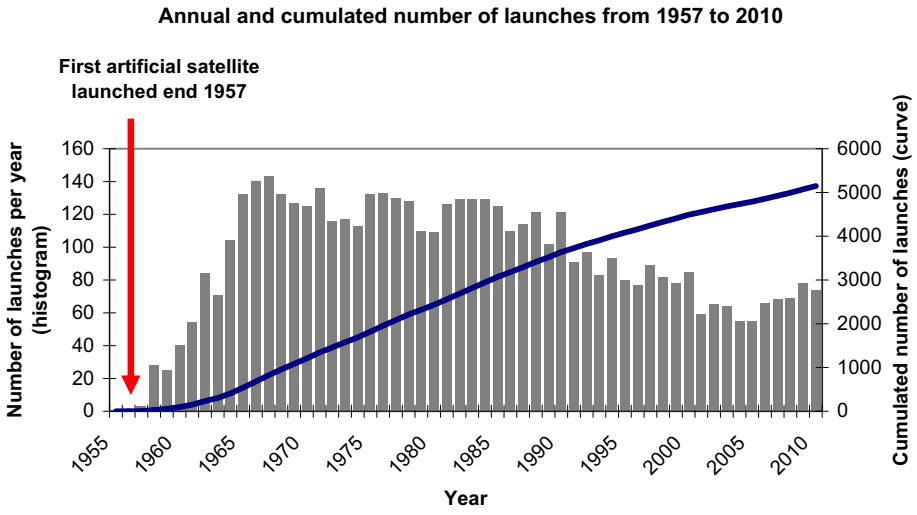

Fig. 1. Evolution of the number of launches since 1957. The histogram represents the number of annual launches (*Y* left axis) while the curve represents the cumulated number of launches since the first artificial satellite arrived on orbit (*Y* right axis). This figure results from the analysis of data from McDowell's database [11].

respectively. Of the 135 active Earth observation satellites, 120 are on LEO. The profound changes in the space sector led to a reduction in public investments that have weakened the space sector [12], at least when using launch activity as a yardstick. However, according to Pasco [12], projects that bring space to society rather than the reverse, such like the European initiative for the Global Monitoring for Environment and Security (GMES), recently renamed Copernicus, could bolster this sector. Furthermore, there is a noticeable trend towards the development of both micro-satellite technology – thereby making space technology more affordable for developing countries – and the deployment of multi-satellite constellations. It can be assumed that all these factors will result in an ongoing increase in the number of active satellites.

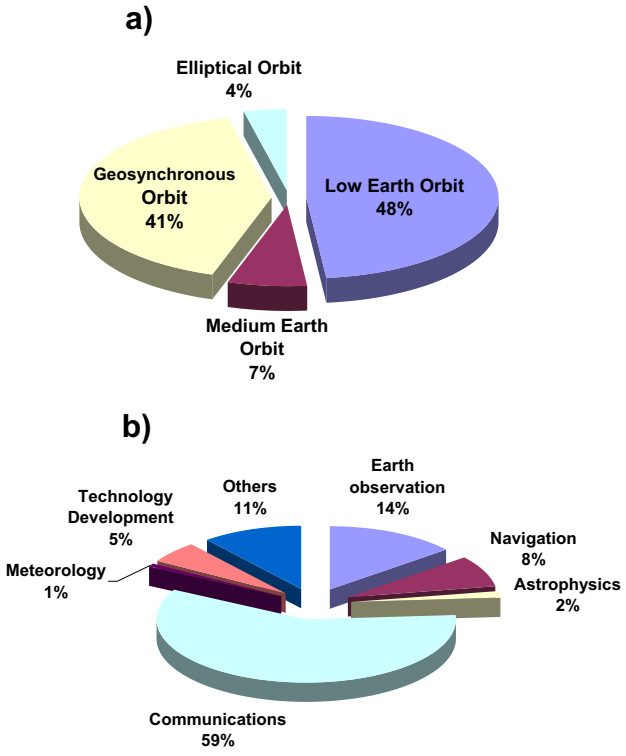

Fig. 2. The several kinds of active satellites. a) Distribution of the 957 currently active satellites according to orbit class: Low Earth Orbit (LEO) refers to orbit with altitudes between 80 and 1700 km; Medium Earth Orbit (MEO) for orbits between 1700 and 35 700 km; Geosynchronous Orbit (GEO) for orbits with altitudes of approximately 35 700 km; Elliptical orbits have a non-constant altitude. b) Distribution of active satellites among seven disciplines according to their use. These figures are based on the analysis of data from the UCS database [13].

2.1.2. Space debris and threats to future orbital activities

Space development has resulted in an increase in the amount of space debris to such an extent that orbital debris is currently a threat to spacecraft health and safety [14]. Space debris is made up of non-functional satellites (23%), upper stages of launchers (18%), functional debris (14%), e.g. bolts, belts, and fragments (45%) originating from collisions, launcher upper stages and spacecraft explosions. The current number of catalogued objects, i.e. objects larger than 5–10 cm at Low Earth Orbit (LEO) altitudes and 30–100 cm at Geosynchronous Orbit (GEO) altitudes, which are tracked by the US Space Surveillance Network, is about 16 000 and is increasing by several hundreds per year [14,15]. Estimations of non-catalogued objects vary depending on the source. According to the French Space Agency (CNES) estimates, there are roughly ~200 000 objects with sizes ranging between 1 and 10 cm and ~35 million of between 0.1 and 1 cm [16].

Most objects making up orbital debris populations, and around 40% of debris greater than 1 mm in size, is located in LEO [16] (see Fig. 3). LEO space debris mitigation is a critical issue for space activity sustainability. Up to now four accidental collision events have already been recorded [16] along with three other suspected collisions [17]. A collision between a satellite and a piece of debris larger than 10 cm would lead to loss or explosion of the satellite. To prevent collisions involving catalogued debris, alert systems for high-risk conjunction events have been developed by space agencies, permitting them to implement avoidance manoeuvres when necessary [14,17]. Non-catalogued debris ranging from 1 to 10 cm can also generate very significant damage due to their kinetic energy but the collision risk can only be studied statistically through analysis of impacts on dedicated experimental platforms or on launchers and large space debris that return to the Earth surface. Table 1 reports collision probabilities. These probabilities are a function of particle flux, which, in turn, depends on altitude, vehicle surface area and time spent in orbit.

A simulation model of LEO predicted that, even with no future launches, the critical tipping point where the population of artificial space debris would grow at a faster rate than the natural decay rate

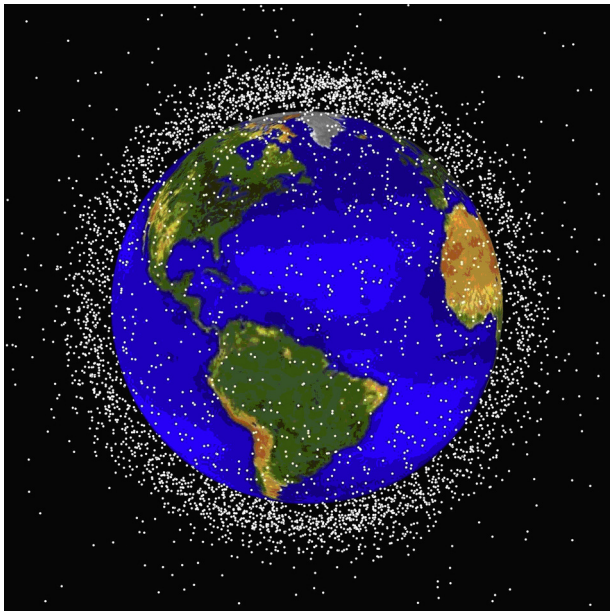

Fig. 3. Representation of space debris in LEO (© NASA).

could be reached in about 50 years [18]. The eventuality that LEO could be rendered inaccessible by a chain reaction of debris collisions – perhaps for thousands of years – is underlined by several authors [18–21]. In this context, the successful Chinese FengYun 1C anti-satellite weapon test in 2007, which significantly increased the probability of collision, has been widely condemned [18,22].

2.2. Space activity as a source of pollution contributing to the deterioration of the Earth's environment

The risks linked to space activities that are most frequently discussed in the popular literature are on-orbit collision risks, which threaten the commercial exploitation of space, and risks to people on the ground during debris re-entry. We will discuss now a topic which has seldom been addressed: the role of space activities as a source of pollution for the Earth's environment. We will focus on environmental impacts that are related to launch, life on-orbit, and end-of-life stages.

2.2.1. Environmental impacts during launch and orbit insertion

The launch stage is responsible for two main kinds of pollution. The first one is the immediate return-to-Earth of the accelerator stage which separates from the launcher after fuel exhaustion. The accelerator stages are not systematically salvaged and seldom reused. To give an idea of the material quantity that can return to Earth, the two empty accelerators of Ariane 5 (mainly composed of steel) weigh about 38 tons each. The second source of pollution is related to propulsion system functioning. Most spacecrafts depend on a rocket engine for propulsion. Approximate emission levels for the main propellant types are given in Table 2.

Table 1
Probability of collision over one year according to debris size for a satellite with a 20 m^2 surface area at an orbital altitude similar to SPOT, i.e. 825 km. (Source: CNES [16]).

Debris size	>0.1 mm	>1 mm	>1 cm	>10 cm
Probability of collision over 1 year	1	0.5	3×10^{-3}	2×10^{-4}

Table 2
Approximate emissions for the four main propellant types (one solid and three liquid) given as mass fraction for each propellant. The total mass fraction exceeds unity because of the assumption that air mixed into the plume oxidizes CO and H_2 (source: Ross et al. [23]).

Propellant type	N_2	$CO_2 + CO$	$H_2O + H_2$	ClO_x, HO_x, NO_x	HCl	Alumina soot
Solid (NH_4ClO_4/Al)	0.08	0.27	0.48	0.1	0.15	0.33
Cryogenic (LOX/H_2O)	–	–	1.24	0.02	–	–
Kerosene (LOX/RP-1)	–	0.88	0.30	0.02	–	0.05
Hypergolic (UDMH/N_2O_4)	0.29	0.63	0.25	0.02	–	Trace

Local impacts of launch events are sometimes studied by space agencies. It is the case for example at the French Guiana Space Center (CSG). At each launch, about 600 measurements are taken at several distances from the launch zone and include concentration measurements of hydrochloric acid, nitrogen dioxide, hydrazine and alumina. These measurements show that impacts are mainly confined to the vicinity of the launch area (<2.3 km) where high levels of HCl and Alumina concentrations have been recorded (see Table 3).

Impacts were found to be low at intermediate distances (up to 8 km) and non-significant beyond. Impacts on water quality, vegetation and fauna are also monitored and up to now no significant negative impact has been noted [23]. In order to minimize local environmental impacts caused by Space activities, the Guiana Space Centre (CSG) also pays particular attention to both the transport and storage of substances for launcher and satellite propulsion. Filling procedures are also carefully monitored; substances which escape during launcher and satellite filling procedures are trapped and neutralized (http://www.cnes-csg.fr/web/CNES-CSG-en [23],).

Besides transient changes near the launch site, which affect the lowermost troposphere, emissions, albeit small, may cause lasting global changes in the stratosphere. As in the case of aircraft, spacecraft rocket emissions include greenhouse gases that directly add to radiative forcing and warming, such as CO_2, and compounds that indirectly contribute to production or loss of greenhouse gases such as ozone and methane [24]. Furthermore, water vapour and soot, which are components of condensation trails, are also responsible for positive radiative forcing and contribute to warming [25]. The amount of emitted gases is trivial compared to other sources. For example annual CO_2 emissions are estimated to be several kilotons compared to emissions of several hundred kilotons from aircraft, which, in turn, accounts for between 2 and 3% of the total emissions from all activities [24–26].

Table 3
Example of maximal concentrations of HCL and alumina measured during an Ariane 5 launch (flight 185, August 24, 2008). Near field refers to a distance from launch site <2.4 km and far field from 2.4–24 km. Measures are compared to human toxicity thresholds (source: http://www.ggm.drire.gouv.fr/).

	Maximal near field concentration (mg/m^2)	Maximal far field concentration (mg/m^2)	Toxic limits defined for humans
Ion CL – (HCL)	5136.2	89.84 (measured at 4.35 km)	90 mg/m^3: irreversible effect after 30 min exposure, 700 mg/m^3: lethal effect after 30 min exposure
Alumina	94.68	3.49	Acceptable mean exposure value for workers = 10 mg/m^3 during 8 h, 5 days/week

However, rocket combustion products are the only human-produced pollutants injected directly into the middle and upper stratosphere. Up to now, few authors have studied phenomena occurring in higher atmospheric strata associated with rocket emissions. Impacts of emissions in the stratosphere are liable to be more important than impacts of emissions occurring in the troposphere. First, atmospheric circulation in the stratosphere is characterized by faster horizontal mixing of gases. Thus emissions will spread throughout the stratosphere layer and will be longer lasting [24]. Second, the specific composition of the stratosphere will give rise to specific reactions. The stratosphere includes the major part of the ozone layer and is characterized by a low water vapour concentrations. Indeed, atmospheric water vapour concentration decreases with altitude and over 99% of water vapour lies within the troposphere. While climate response seems to be independent of where CO_2 emissions occur (http://www.co2offsetresearch.org/aviation/DirectEmissions.html), the increase in forcing due to water vapour emissions in the stratosphere is significant compared to a similar water vapour emission in the troposphere [25]. Emitted compounds also contribute to ozone depletion in several ways. Some of these substances are highly reactive radicals – NO_x, HO_x, ClO_x – that are directly involved in catalytic cycles, thus leading to an increase in the ozone removal rate. As catalysts, they can have huge impacts even if present in only trace amounts. A single radical molecule can destroy up to 10^5 ozone molecules before being deactivated – for example through reactions that remove radicals from the cycle by forming reservoir species – and transported out of the stratosphere. Other emitted compounds contribute to an increase in tropospheric radical reservoirs. For example, particles such as alumina and, possibly soot particles, are responsible for the liberation of radicals from the radical reservoirs present in the stratosphere. Concerning solid rocket motors, emitted HCl is in itself a radical reservoir. Furthermore, while water vapour emissions are widely considered inert, H_2O, which is emitted by all rocket engines, is the source gas for HO_x radicals and contributes to the formation of ice particles also responsible for ozone loss. Ozone loss linked to water vapour is highly nonlinear and difficult to predict [24]. The ozone layer is protected by international agreements that limit the production of substances causing ozone depletion (i.e. the Montreal Protocol on Substances That Deplete the Ozone Layer). Ross et al. [24] demonstrated that if the Space Shuttle had met its original goal of weekly launches it would have been responsible for an ozone loss close to a quantity that Ross et al. [24] deemed to be the upper limit acceptable to the international community that established the Montreal protocol to protect the stratospheric ozone layer, even when taking into account the unique contribution of space activity.

2.2.2. Environmental impacts during on-orbit life

Several compounds are also released in the upper atmospheric layers during the on-orbit lifetime of LEO satellites. First, the atmospheric drag in LEO causes orbital decay and the platform has to be repositioned occasionally. This is usually performed using nozzle-based systems, and hydrazine is the most favoured monopropellant. The highly exothermic catalytic decomposition of hydrazine produces jets of hot gas and thus thrust. The emitted gas is composed of ammonia (NH_3), hydrogen (H_2) and nitrogen (N_2). Second, the presence of a diffuse atmosphere slowly erodes satellite platforms. Atomic oxygen, the predominant component in the LEO atmosphere, is responsible for the degradation of thermal, mechanical, and optical properties of exposed materials [27]. It interacts with hydrocarbon polymers (e.g. Kapton, Teflon, Mylar…) that are used to thermally insulate and protect parts of the satellite. In a recent study, Banks et al. (2011) [28] developed a model to assess the oxygen erosion yield according to the molecular characteristics of several polymers. The experimental data they used shows that erosion yields (expressed as the volume lost per incident atomic oxygen atom in cm^3/atom) vary from a factor of about 90 between the most and least resistant polymers. According to these results Kapton, a commonly used spacecraft material, is a moderately resistant polymer. Important Kapton mass losses have already been observed, e.g. up to 35% reported by NASA on the STS3 shuttle mission [29]. Even if this announced rate is open to discussion due to possible inconsistency in dehydratation states between pre- and post-flight mass measurements [28] the above mentioned studies demonstrate that a significant portion of the insulation materials used to protect the satellites can be released into the LEO domain in the form of volatile oxidation products.

2.2.3. Environmental impacts associated with satellite end-of-life

The on-orbit lifetime of non-active satellites and other debris depends on the presence and density of the terrestrial atmosphere. Atmospheric density decreases the greater the distance from the Earth but, at a given altitude, it also varies as a function of several factors including solar activity and latitude. Atmospheric drag slows down orbiting objects, leading to their return to Earth within a time period that depends on the orbit altitude (e.g. ISS lifetime orbiting at 300–400 km would be ~6 months to 1 year, SPOT lifetime orbiting at 825 km – about 200 years) [16]. During atmospheric re-entry objects are intensively heated and part of the material is sublimated, thus slightly changing atmosphere composition, though probably with insignificant impact. Large pieces of debris can also return to Earth. On average a piece of large orbital debris (radar cross-section > 1 m^2) falls back to Earth once or twice a week. Most of them (>70%) will impact water bodies [30]. Casualty risks are more closely associated to natural re-entries, including premature ones as in the case of launch failure. Launch failure rates reported for the April 2009–September 2009 period was one failure for every 39 launches [31]. Casualty risks are currently estimated to be lower than the risk associated with meteorite impacts [16]. However both controlled and natural re-entries are a potential source of orbital debris returning to Earth. For instance, during the controlled Mir re-entry, while the initial mass in orbit was around 140 tons, 30 tons of debris fell into the Pacific Ocean [16].

The re-entry of Phobos-Grunt is a recent example of accidental re-entry. The main objective of this Russian mission was to study Phobos, one of the moons of Mars. The satellite was launched in November 2011 but the spacecraft failed to exit the Earth's orbit and fell into the Pacific Ocean on January 15, 2012. Onboard, there remained about 11 tons of unused highly toxic propellant: the unsymmetrical dimethylhydrazine (UDMH). Fuel tanks are likely to have exploded high above the Earth and some experts suggested that the propellant was burnt. However other experts think that part of the material that vaporized could have re-condensed into small particles that may remain in the upper atmosphere for many years and influence, even if in a minor way, atmospheric chemistry (http://www.space.com).

The re-entry of the Upper Atmosphere Research Satellite (UARS) in September 2011 is another recent example of uncontrolled natural re-entry, but one which occurred after the satellite had ceased its scientific life in 2005. NASA estimated that twenty-six satellite components, weighing a total of more than 500 kg, may have reached the Earth surface (http://www.nasa.gov).

Another environmental threat from space activities comes from the use of nuclear reactors. Such reactors generate substantial amounts of electrical power. Their use on military satellites is behind the increased spatial resolving power of on-board radars and does away with the need for large solar sails. Decreasing the satellite cross-sectional area is paramount, thereby making localization more

difficult and lowering risks of hostile actions from anti-satellite systems (ASAT) [32]. The radioisotope thermoelectric generators have also enabled missions such as the Apollo Lunar surface experiments and interplanetary missions that require travel to areas where sunlight intensity and temperatures are low and where radiation belts are very severe [33]. Since 1961, the United States and the former Soviet Union have flown at least 43 radioisotope thermoelectric generators and 36 nuclear reactors to provide power for respectively 24 US and 37 Soviet single or multiple reactor space systems [33]. Several nuclear-powered space vehicles are known to have fallen to Earth, e.g. Transit in 1964 or Cosmos-954 in 1978, and were responsible for the release of radioactive elements in the atmosphere and on the Earth's surface [32]. Current knowledge makes it very difficult to assess environmental impacts and the amount of radioactivity that would reach the Earth surface in case of the disintegration of a reactor core, in particular in the upper atmosphere, during accidental re-entry [32].

In Section 2.2, we have only discussed environmental impacts from launch to satellite end-of-life. During launches and re-entries chemical components and debris are released in all atmospheric layers and part of them falls back to Earth. Based on current knowledge we can only say that, due to its specific characteristics, space activity is a source of casualty risk and also contributes to Earth pollution with a pollution capacity difficult to assess but with potentially high risks. But for many manufactured products a significant portion of the environmental impact is not directly linked to product use but rather to its manufacture and transport [34]. Therefore, impacts associated with launcher, platform and instrument manufacturing, and those impacts related to the functioning of the ground segment should also be carefully examined. Unfortunately these impacts have not been studied until now and we found no study report or paper dealing with this topic. The only actions we could identify in order to fill this gap are those recently initiated by the European Space Agency, ESA, within the frame of the Clean Space initiative [35]. First results should be available soon.

3. Toward sustainable Earth observation systems

Remote sensing scientists view satellite data acquisition as the first step in an information stream that ultimately leads to informative products, decisions and actions based on those products, additional questions stemming from recent research, and perhaps follow-on missions to address the most important outstanding questions. However, prior to the acquisition of the first byte of data, consideration should be given, to uncertainties associated with the durability of Earth observation from space and a lack of knowledge on the consequences of space activities on the Earth's environment. Also, in keeping with the transparency[1] quality of a measuring instrument, as a community, we should do our best to ensure that the methods used to observe and measure the Earth's environment interfere least with that environment. For example, when measurements are acquired to assess carbon pools and fluxes, with the aim of better understanding the carbon cycle and climate change, the measuring system should contribute as little as possible to the global carbon cycle.

We suggest points of view that, if shared, naturally lead to consideration of questions concerning the environmental sustainability of Earth observation systems.

3.1. Integrating environmental considerations when designing systems

First we should shift from a view where systems are designed to meet measurement objectives that consider primarily economic and technical constraints, to a more holistic view that considers an individual system as a contributor to the whole satellite set and that includes consideration of interactions between remote sensing systems and the Earth's environment, including environmental impacts from the system production stage to its end of life. This would enable the design of measurement systems capable of providing valuable information for sustainable management of the Earth resources while reducing to a minimum their inevitable environmental impact. This would thus help remove the contradiction that currently exists between the environmental impact of space activities and the purpose of the Earth remote sensing mission, which is to assist sustainable management of the planet. But this would also require major and challenging changes.

Acquisition processes are currently designed based on usual measurement quality criteria, e.g. degrees of precision and of accuracy, and are mainly determined by economic costs, technological readiness levels, and technical constraints. A perspective that considers sustainability would also include environmental and social dimensions. As the environment underpins both society and the economy [36], an essential step in designing measurement processes that respect sustainability principles is to integrate environmental dimension when evaluating the data acquisition process as regards sensor performance and data quality. For instance, should a country spend $1 billion on its own space radar to ensure control of the data if better or similar data could be acquired less expensively by (1) cooperating with international partners or (2) utilizing aircraft radar systems to better effect? The correct answer to this question becomes even more obvious if environmental concerns are taken into account, though such treatment excludes more ambiguous though important concerns such as national pride and maintenance of technological readiness.

Tools designed to assess environmental impacts exist and could be used at several levels to better take into account environmental concerns in the evaluation of Earth observation data and products supply chain. Le Pellec-Dairon [37] proposed a novel approach to better assess the environmental value of Earth observation data. This approach requires one to evaluate the economic value of environmental goods and to move from this value to the value of Earth observation data that are used to improve Earth resource management. Certainly, assigning an economic value to an environmental good can be challenging, possibly subjective and probably arguable. As with any qualitative versus economic comparison, one central issue becomes assigning a defensible monetary value to, for instance, a vista, a hiking path, a clean river, or, in the case of satellite missions, closure of the global carbon budget, a 10% increase in the precision of a biomass estimate, or a more accurate map of deforestation. That said, Le Pellec-Dairon [37] developed such an approach to help improve the efficiency of the strategy for Earth observation mission management and to select the missions with the largest positive effects, including economical, political, technical and environmental values. However, the proposed approach only considers the total economic value of the environmental information supplied by Earth resources missions and will remain incomplete while this value is not weighed against the economic value of environmental degradation due to the manufacture, launch, on-orbit maintenance, and eventual destruction of the mission hardware.

We think that using tools such as environmental LCA can be an effective way to assess environmental impacts of space activity and to improve sustainability of Earth observation systems and thus

[1] In the field of Metrology and Units of Measure, transparency is the ability of a measuring instrument not to alter the measurand – term and definition approved by ISO, the International Bureau of Weights and Measures (BIPM), the International Electrotechnical Commission (IEC), the International Organization of Legal Metrology (OIML).

increase efficiency and environmental value of the Earth data production chain. Environmental LCA methods and procedures have already been standardized (ISO 14040 and ISO 14044). LCA are multi-criteria, quantitative approaches that enable assessment of environmental impacts associated with all the stages of a product's life from-cradle-to-grave (i.e. from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling) [34]. Environmental impacts are assessed through either midpoint or endpoint indicators derived from the inventory of fluxes of both raw materials and pollutants. Ozone depletion, climate change (in practice all the greenhouses gazes emissions are transformed into an equivalent of emitted CO_2 according to their warming capacity and taking into account their lifetime), land use change, acidification, nutriphication, natural resources depletion (such as minerals, fossil fuel…) are examples of indicators provided by LCA, when a midpoint impact category, or problem-oriented approach, is chosen. Impacts are translated into environmental themes. Endpoint modelling, also called damage-oriented approach, can also be used but is considered more uncertain. Indeed endpoint impacts result from the combination and the transformation of midpoint environmental impacts into issues of concern such as damages on human health (e.g. number of cancers), on ecosystems (e.g. loss of habitats), on natural resources…

We suggest that environmental LCA methods and mid-point impact indicators be considered as one of a number of tools and metrics that could be employed to facilitate, for instance, comparisons between different mission scenarios or to optimize a given mission. In addition to improving the coherence between the data acquisition step and the end goals of some space missions, it can be argued that acting to develop a space activity with reduced environmental impacts on both Earth and space has advantages for space sector. ESA has adopted a pioneer position in this area with its Clean Space initiative [35] and, among the arguments put forward to justify this initiative, some are worth highlighting:

- Laws evolve, and the space community should expect environmental law to eventually address space-related activities, especially those having to do with launch and space debris. The development of eco-friendly space policies and programs is one way to proactively address legal evolutions that are liable to lead to disruption of classical space-qualified materials and processes. Among candidate green technologies are development of green propellants to replace hydrazine or other toxic liquid propellants, replacement of chromates used for surface coating and bonding, green electronics, and reductions in bulk machining that are sources of raw material waste. Hydrazine has already been included in the list of substances of very high concern by the European Community Regulation on chemicals and their safe use that deals with the Registration, Evaluation, Authorization and Restriction of Chemical substances (REACH).
- By acting proactively, ESA expects to be well positioned to help shape future laws, thereby making it easier to comply with future regulations.
- The act of encouraging industrialists to develop and adopt eco-designs and eco-technologies promotes innovation and is thus an efficient way to make industry more competitive in world markets.

3.2. The benefits of changing our relationship with statistics

Secondly, with regards to environmental risk management, it would be necessary to shift from minimizing Type-I error, i.e. rejecting the null hypothesis (or status-quo) when it is true, to reducing Type-II error, i.e. reducing the chance of accepting the null hypothesis when it is false [9]. Usual scientific approaches tend to minimize Type-I error. This allows us to achieve high levels of confidence in the decision in order to reject a null hypothesis and accept that some sort of change has occurred or that a "new" condition exists. When applied to environmental management, minimizing Type I error means that we need to be virtually-certain that environmental or ecological damage has occurred (due to space activity in our case) before we would accept the alternative hypothesis [9]. The net effect of relying on such an approach – when determining if and what actions must be taken – is that the damage would have already been done by the time the test alerts us of the need to act. With respect to prevention, mitigation, or remediation, this course of action is counterproductive. In order to calculate Type II error, the analyst would have to define an alternative hypothesis, i.e. that condition beyond which intolerable damage would be done or a tipping point is reached. Such an alternative could take the form of a chemical concentration at a particular altitude, a radiation level, or a collision probability. Furthermore, for low-probability high-impact events – e.g. LEO becomes inaccessible for hundreds of years – Taleb et al. [38], who analysed common errors in the way risks are managed, maintain that it is more efficient to reduce the impact of threats we cannot control rather than to focus on statistical predictions of such events. This is why, the development of space debris mitigation and removal technologies like those considered by ESA in the context of its Clean Space program are essential. Debris mitigation/removal research complements research conducted to collect information on small debris, i.e. those objects not detected with current methods, and to model the behaviour of the space debris environment [35]. Innovation in this area can also have spin-off benefits for the space industry sector allowing an early positioning on emerging markets that might replace part of the space sector traditional markets if a stronger regulation of the use of space became effective.

3.3. Revisiting common ideas in the remote sensing and space activity sectors

It would be useful to qualify three commonly held arguments for remote sensing data that are taken as a given. First, from a strictly economical point of view, space remote sensing is considered cost effective for end-users, especially given that much of the data are freely available, e.g. Landsat, MODIS. But this statement does not take into account all national funding invested in space activity. Consideration of the full range of expenditures might indicate that, for certain space missions, airborne solutions may be more viable and may provide better data from the standpoint of seasonality, spatial coverage, and higher radiometric and spatial quality at a lower cost. This is especially true when the mission objective addresses national or regional concerns rather than continental or global concerns. Second, field data are often described as being costly and time consuming [39] and in many instances this common idea is correct. In south-eastern Alaska, for instance, the cost of establishing and measuring one US Forest Service field plot in 2013 is estimated to be $9000 USD. That said, such costs should not imply that remote sensing data, sometimes "free", can replace field observations. Field measurements are essential for calibration/validation steps in most remote sensing data processing approaches, and also provide information that cannot be acquired by other means, e.g. assessment of local biodiversity, soil properties, presence/absence of rare species, estimates of downed woody debris, regeneration. Remote sensing will never replace the need to make field measurements and maintaining sufficient field observation networks and field expertise remains essential. Third, it is worth noting that, for the space activity sector, any object (satellite, piece of launcher…) is considered as recycled

when it has been destroyed during its re-entry into the atmosphere or has fallen back to the Earth's surface. This is very remote from the notion of recycling in the context of sustainable development. The Earth's capacity to sequester human waste is limited [36] and recycling aims to reduce waste. Furthermore a part of so-called "recycled" spacecraft is in reality composed of pollutants emitted into the atmosphere or deposited on the ground.

4. Potential measures to improve environmental sustainability of Earth observation systems

Embracing the unconventional points of view presented in the previous section leads to suggestions on suitable actions that could help to design more efficient Earth observation systems and networks.

In order to illustrate some of the suggested actions we will rely on a study case: the design of lidar systems for forest monitoring. The first sub-section presents this study case and sets out the general context, the required data on sustainable management of forests, and some spaceborne solutions that have been under study. The second subsection suggests some measures that might be adopted when planning an Earth observation space mission. In the third subsection the scope of the discussion is extended to incorporate airborne missions in an Earth observation network.

4.1. Study case: lidar, a valuable technology to improve sustainable management of forest ecosystems

While sustainable management of forests is recognized to be crucial for the future of mankind, forest ecosystems are heavily impacted by climate change, natural hazards and anthropogenic pressures, particularly deforestation and degradation. Over the last decade, about 13 million hectares (0.33% of total forested area) were converted to other uses or lost through natural causes each year [40]. Robust systems for measuring, assessing, and reporting key forest parameters, e.g. biomass, carbon, must be developed in order to define appropriate management practices and policies to address the challenge of sustainable management of forest resources and to strengthen forest-based climate change mitigation strategies [41–44]. The utility of lidar has been widely demonstrated with respect to forest structure measurements and biomass estimation [45–54]. This is also the case in closed-canopy tropical areas supporting high biomass forests greater than 200 t ha^{-1} [55,56], where optical vegetation indices and volumetric radar measurements typically saturate [57].

Consequently a spaceborne lidar that acquires vegetation height and canopy closure measurements, when employed as a global sampling tool – either alone or in combination with optical and radar imagery – and supported by ground observations would appear to be a promising solution to estimate aboveground forest biomass and carbon at a global scale. Indeed such a solution would combine the beneficial measurement properties of spaceborne remote sensing, i.e. acquisition of global information that is consistent both in space and time, with lidar technology. A detailed review of measurement requirements for the assessment of biomass, biomass change and carbon flux, biodiversity and habitat, is provided by Hall et al. [58]. The authors identified several requirements for lidar measurements which notably include the following [58]:

- global coverage of forested areas;
- based on 25 m footprints, measurements, of forest height with 1 m accuracy at zero slope, of forest vertical structure with a 1–2 m accuracy and of canopy cover measures accurate to within 10%;
- a spatial sampling in order to have a mean canopy height within 1–2 m for 1 ha and 1 km grid cells (50 cloud-free observations per 250 m grid cell would be required to achieve the required height accuracy at 250 m);
- contiguously sampled profiles for primarily ecological reasons, e.g. estimation of height correlation length scales and height distributions, but also technical and practical ones, e.g. ground finding and local structural context;
- a temporal resolution enabling the production of two annual biomass maps in order to capture seasonal variability and to monitor annual biomass change and a minimum of a 5-year observation period to capture the successional dynamics of forest ecosystems.

ICESat, an ice mission which collected data useful to terrestrial studies from 2003 to late 2009, was the first spaceborne lidar system designed to measure terrestrial surfaces. Despite the ice-centric design, several studies used ICESat/GLAS data to estimate forest structure and biomass at regional scales [56,59–64]. Lefsky [64], Simard et al. [65], and Los et al. [66] have demonstrated the global capabilities of space-based GLAS measurements while Nelson [67] outlines some of the limitations associated with GLAS-based biomass estimates. ICESat-2, scheduled for launch in 2016, will be the second lidar mission dedicated to Earth surface monitoring. It is also primarily designed to characterize and monitor polar ice, and includes among its secondary scientific objectives measurement of vegetation canopy height as a basis for estimating large-scale biomass and biomass change [68]. However data simulations have demonstrated that ICESat-2, in its current design, will not replace the recently shelved DESDynI vegetation lidar mission [69]. Even under ideal conditions – clear sky, night-time data collect, minimal topography – we expect the ground signal to be lost at canopy closures exceeding ~96%, thus making calculation of canopy height problematic in closed-canopy forest growing in areas with appreciable local topography.

Scientists have designed and proposed to space agencies space lidar missions with forest measurement and monitoring as primary scientific objectives (e.g. VCL, LVTM, Carbon-3D, DESDynI-Lidar, LEAF, SpeCL… [69–74]). All proposals – US, ESA, and Japan – have thus far been unsuccessful; none have been launched. The Vegetation Canopy Lidar (VCL) was selected in March 1997 by NASA as the first Earth System Science Pathfinder (ESSP) spaceflight mission and was scheduled for launch in January 2000 [75]. The mission was discontinued due to unexpected technical limitations that precluded construction of the lasers within the initial quoted cost. The reasons underlying the decision to discontinue the lidar part of the DESDynI mission, a vegetation measurement and monitoring mission initially approved by NASA, are unknown even to scientists that were directly involved in the project. It was cancelled by the US government as an austerity measure, but we guess that it may have been jeopardized due to what was seen by budget or science managers as mission overlap with ICESat-2. With respect to ESA's LEAF project, the evaluators estimated that the mission was technically feasible but above budget (+15% above the recommended industrial ceiling cost). The evaluators acknowledged that the mission could have been complementary to the BIOMASS mission, a P-band Synthetic Aperture Radar (SAR) also dedicated to biomass estimation that was selected as one of the three candidates for the 7th Earth Explorer mission. The evaluation team also mentioned the possible mission overlap between LEAF and ICESat2 or DESDynI, which was not yet discontinued when the LEAF project was submitted. The chosen revisit period, i.e. 3 years, and the fact that the same individual laser pulse locations cannot be revisited were identified as shortcomings. SpeCL, a large footprint multi-frequency lidar with the capacity to revisit previous spots, was

not selected but rather was shortlisted by ESA. This may be interpreted as an additional evidence of the acknowledgement by ESA of the scientific interest of vegetation space lidar missions, even if from a technological point of view revisiting previous spots is, practically speaking, currently not achievable in the civilian space sector.

In May 2013 BIOMASS radar mission was selected by the ESA's Earth Observation Programme Board to become the seventh Earth Explorer mission. However, while we have the benefit of hindsight about the capacity of lidar systems to provide valuable information for biomass estimation, there are still uncertainties and open scientific questions about the potential of the BIOMASS system to provide the expected information, in particular in forests with very high biomass levels. In 2011, several projects were submitted to NASA (GEDI project), JAXA (i-LOVE project), and ESA (GRAIL project) that would involve embedding on the International Space Station (ISS) either a vegetation lidar system or a blue and green carbon system, i.e. a dual frequency lidar to assess biomass both on land and in oceans and coastal waters. These projects would partially replace the DESDynI lidar mission. Only the project submitted to the JAXA, renamed MOLI, is currently selected for further studies. The project submitted to NASA was rejected despite the fact that the evaluation committee acknowledged its high scientific value [76]. In December 2012, the decision of non-selection for the GRAIL project was also communicated by the ESA to the principal investigator.

Considering this international context, we will rely on this example to illustrate some of the actions that are suggested in the following subsections in order to help to increase sustainability of Earth observation systems, with a focus on systems dedicated to forest biomass monitoring.

4.2. Improving sustainability of space remote sensing

Due to geopolitical constraints, satellite-based solutions seem to be the only way that is currently available to acquire data globally. Furthermore they guarantee a higher data consistency than what can be expected from airborne solutions that are managed at regional or national levels and also facilitate user access to data. However, when designing space missions, actions that are in keeping with the above-mentioned considerations could be taken, thereby making them more compatible with environmental sustainability principles. Two main challenges hamper the sustainable development of space activity: space debris, which threaten the activity itself, and the sector's potential negative impacts on both space and Earth environments.

4.2.1. Mitigation and remediation of space debris

According to Williamson [77], ethical and code policy for space should include protection of the various orbital zones surrounding the Earth given their importance as a commercial and scientific resource by formalizing debris mitigation measures. Space agencies, e.g. CNES, ESA, NASA, have already developed guidelines to mitigate space debris. At an international level, the United Nations Committee for the Peaceful Uses of Outer Space (UN COPUOS) has already taken a keen interest in space debris and in the use of nuclear energy in space. But, as a consultative body, it has no legislative power [21,77]. Bradley and Wein [18] demonstrated that achieving full compliance with the 25-year spacecraft deorbiting guidelines could maintain the lifetime risk from space debris at a sustainable level. Williamson [15] underlines that despite their potential efficacy, technological solutions to space sustainability will not be effective without the development of international policies and laws to support and promulgate them. He presents several initiatives and places for discussion and negotiations that could contribute to the establishment of such international policies [15]. However the consequences of heeding the advice from Taleb etal. [38] concerning low-probability high-impact events would be 1) to do everything in our power to reduce space junk by developing, for example, orbital debris removal operations as proposed by Weeden [20], 2) to do our utmost to mitigate future launch pollution and debris, thereby keeping space as pristine as practically possible, and 3) to think about alternatives to spaceborne solutions in case LEO becomes inaccessible.

Even if it has a limited contribution to current space debris environment, ESA clearly expresses its willing to tackle questions concerning space debris mitigation and remediation within the frame of its Clean Space program. Among the planned actions are the following [35]:

- for space-debris mitigation: develop compact, robust and autonomous systems for de-orbiting of spacecraft in LEO, develop end-of-life passivation of propulsive and power systems to lower the risk of spacecraft break-up, develop spacecraft designed to break-up during re-entry in such a way as to avoid large space debris impacting the Earth surface ("Design for Demise" concept);
- for space-debris remediation: develop hardware to approach, dock with, and control a spacecraft scheduled for de-orbit or sizeable debris soon to de-orbit so as to fully control reentry to assure the best environmental (and societal) outcome.

4.2.2. Mitigation of environmental impacts

To better grasp this issue of damage related to space activity on the Earth's environment, research is needed to assess the behaviour of materials released into the upper atmospheric layers by launch vehicles, fuels, and re-entry debris. A unique characteristic of space activity is that it is the only human activity that releases elements into the upper atmospheric layers where concentrations of natural compounds are low. Consequently even the introduction of elements in small quantities can greatly affect atmospheric composition and chemistry; as evidenced by the effects of reactive radicals on the ozone cycle [24]. Impacts of space activity on complex processes occurring in upper atmospheric layers have been little studied until now and there is a clearly a lack of knowledge on the potential consequences of space activity on atmosphere composition and on radiative transfer.

In addition to site impact studies performed on industrial sites (e.g. launch site), environmental life cycle assessment (LCA) could be used more generally to help quantify the environmental impacts of Earth observation systems and to identity critical stages where these impacts might be mitigated. Environmental LCA could also be used to compare several mission scenarios and to help choose the scenario that will provide data meeting the information requirements specified by scientists and end-users while leading to the lowest environmental impact level.

In this field, ESA has adopted a pioneer position and has started using LCA to study environmental impacts of a whole mission, from the early research stages to the mission end-of-life, including all the tests required to check the system resistance to hostile space environment, i.e. high temperature gradients and radiation. Convinced of the benefits of green-technology development (see Section 3.1), one of ESA's objectives is to generalize the assessment of environmental impacts of space activity and to develop a framework, with databases and tools, dedicated to this activity that could be used by European space agencies and industry [35]. A preliminary version of this LCA tool is currently being implemented to model environmental impacts of missions (launchers and satellites) representative of various application fields [35]. First results will be of great interest as it is the first study in this field.

Furthermore, if we see each mission as an activity contributing to space activity as a whole and therefore as a contributor to the problems discussed in this paper, very simple measures can be proposed to improve sustainability of space activity from this point forward. First, if we consider space as a limited resource we should strive to use it parsimoniously and to launch a satellite embedding a measurement system only when a high level of confidence on the system's capacity to meet measurement requirements has been reached. Second priority might be given to missions with longer lifetimes in order to reduce the number of launches, space debris, and to lessen environmental damage. Third, priority might also be given to international missions in order to reduce mission duplication, e.g. multiple X, C, L-band radars, multiple ~30 m Landsat-like clones, or multiple satellite constellations embedding very high resolution imagers. Consideration should also be given to the use of existing space infrastructure. For instance, the International Space Station (ISS) hosts relatively short-lived (e.g. 2 year) systems that allow instrument engineers to test, refine, and improve their instrument designs and allow scientists to assess the utility of the data products. These packages may truly be recycled since they're carried to and from the ISS on cargo spacecraft and placed in exterior slots specifically designed for Earth remote sensing experiments. Further experiments could be conducted during the remaining lifetime of the ISS (current expectation, ~10 years).

4.2.3. Actions specific to the study case

When scientists define mission requirements they tend to favour the acquisition of a maximum amount of data. For a vegetation lidar mission this is liable to reduce the mission life-time, given that laser life-time is typically driven by number of emitted pulses rather than time in orbit. This is why, to optimize mission specifications while adhering to the principles and recommendations that mitigate environmental impacts of the mission, we suggest the following:

- Identify the best trade-off between measurement contiguity and laser life-time considerations. The choice can then be made whether to give priority to a longer lifetime and noncontiguous measurements or to contiguous measurements with a resulting shorter lifetime. Due to space activity sustainability issues, the added value of contiguous lidar measurements should be carefully examined. Currently, studies that involve regional biomass or carbon assessments tend to treat satellite orbits as observational units, i.e. clusters, rather than considering individual laser shots as separate observations (e.g. [59,62,63]. Such an approach precludes any need to account for along-track, within-orbit spatial autocorrelation. If laser lifetime is not a concern, then contiguous, along-track measurements make sense since spatial adjacency makes it easier to find and track ground while increasing the number of individual pulse observations available to characterize a particular cover type or stratum. If laser lifetime is a limiting factor, then fewer shots spaced further apart would suffice.
- Explore the lidar signal dynamic in forests to make sure that the pulse characteristics are capable of supplying a signal from both the ground and the forest canopy under a wide variety of canopy conditions, from sparse to very dense. Analyses of ICESat/GLAS data, a large-footprint waveform system, have highlighted some limitations in forest height assessment in dense forests where an underestimation of height has been observed (see e.g. [78]). Sparse forests challenge analysts processing GLAS data for a different reason; the canopy may be so diffuse, e.g. high boreal forests, that no discernable canopy signal is returned [67]. Shrublands present a third problem, that being the fact that the signal from short-statured vegetation, though dense, may be convolved with the pulse width (ICESat/GLAS, 6 ns FWHM) such that waveforms from flat surfaces and waveforms from shrublands are essentially identical. ICESat-2, a photon-counting, moderate footprint (10 m diameter) space lidar due for launch in 2016, may be unable to retrieve ground reliably under very dense forest canopies that exceed 95–96% canopy closure. To be fair, ICESat-2 is an ice mission that is expected to meet stringent performance criteria associated with measurement and monitoring of ice sheets, sea ice, and glaciers. Vegetation measurements are of secondary concern.
- Evaluate the added-value created by coupling a very high spatial resolution multispectral imager with the lidar. Such an imager, if accurately boresighted, would provide contextual and geolocation information contemporaneous with the lidar acquisition that could help to improve both accuracy of inversion models used to estimate forest parameters from lidar data and extrapolation of biomass estimations. This coupling could thus help achieving the target level for biomass measurement accuracy with a reduced amount of lidar measurements compared to what would be required without imager.

However, while sustainability issues are not considered as crucial, the model "more data is better" is likely to last and priority is likely to be given by default to lidar missions providing higher measurement densities without studying the above mentioned issues and, thus, to the detriment of mission life-time.

If one of the projects submitted to embed a vegetation lidar onboard the International Space Station were approved, measurements of the Earth's forests south of 51.6°N over the lifespan of the ISS would be available. There are several points which argue for such a solution. First, the operation of an ISS lidar would obviously be physically and operationally supported by existing infrastructure. Second, the means to transport the lidar to the ISS and to service the lidar while operating aboard the ISS would depend on a transportation system that is already used to maintain the crew and station. Third, as the ISS was originally conceived to promote international cooperation, we expect that the space agencies would be willing to work together on an ISS lidar system, therefore sharing experiences and costs and avoiding the development of multiple satellite systems providing duplicated data. Lastly, while the system would be designed to acquire ranging and possibly active spectral measurements on tropical and temperate forests, it would be a technology demonstrator from which lessons could be learned to prepare future space missions.

4.3. The contribution of airborne missions to a more sustainable Earth observation network

4.3.1. Comparing spaceborne and airborne missions to optimize their respective contributions

The rigid technical specifications associated with space technology and related industries might give rise to environmental impacts during system manufacturing (for both the satellite and the launcher), deployment, and operational phases that would be greater than those associated with deployment of an aircraft system able to provide data that meet the same requirements. For a given mission, then, it would be worth checking to see if a space system is the best solution from an environmental viewpoint taking into account, among other factors, data requirements, multipurpose uses of data, and number of satellites launched at the same time by a given launcher. The results of a comprehensive, comparative analysis are hardly predictable. To our knowledge, no paper has been published that indicate trends or that suggest

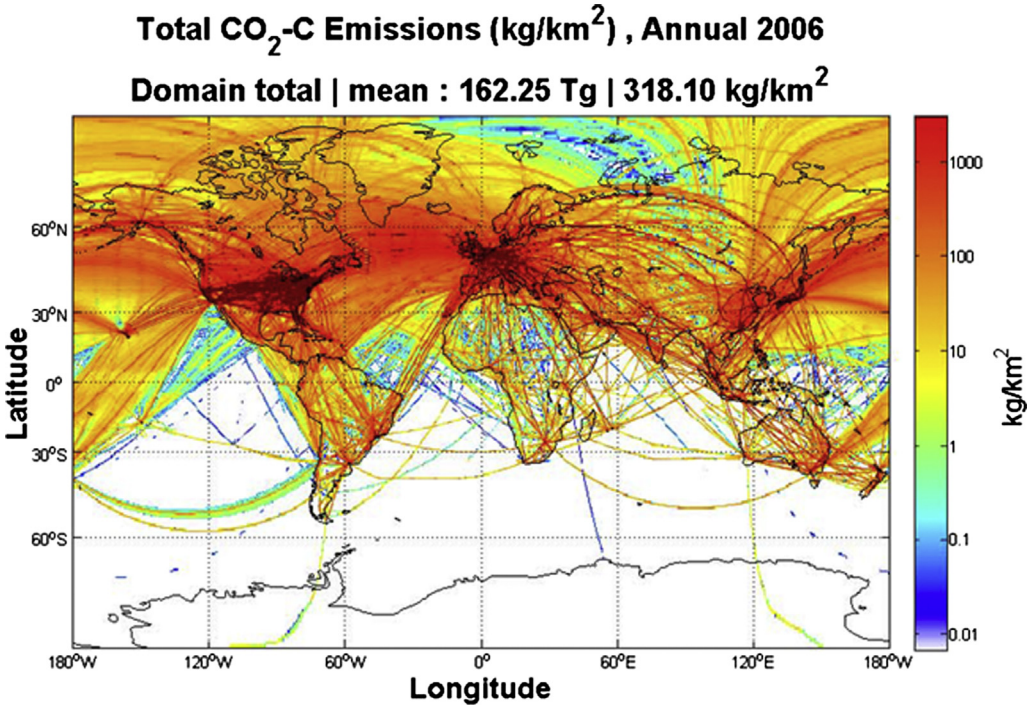

Fig. 4. Main commercial aircraft lines. This figure, adapted from Wilkerson et al. [26] according to the CC Attribution 3.0 license, shows the total CO_2–C emitted from commercial aviation for the year 2006 and indirectly gives an idea of commercial traffic density worldwide.

criteria that favour satellite missions, other than the aforementioned need for a global perspective.

Friend underlines the necessity, but also the difficulties associated with adding new data quality criteria to assess data quality in a world of value pluralism [79]. We believe that an LCA-like approach might be the best way to combine the complementary available measurement processes to provide the data sets that will best meet the data requirements in the context of minimizing environmental impacts. Indeed they would facilitate the assessment and comparison of the several available measurement methods, i.e. spaceborne and airborne systems but also field campaigns, thereby providing elements to determine the cost/benefit trade off that takes into account environmental aspects in addition to metrological and economic ones. Attempts to integrate social impacts might also be considered using societal life cycle assessment (SLCA) methodologies [80]. LCA could be used to help decide if priority should be given (1) to series of short-lifetime satellites or ISS instruments acquiring dense lidar measurement samples, (2) to a long lifetime satellite acquiring sparser measurement samples completed, where and when needed, using airborne systems to increase sampling density in space or time, (3) or to the use of airborne systems alone.

4.3.2. The place of airborne missions for our study case

Considering our study case, exploring the place of airborne missions in an observation network dedicated to forest and biomass monitoring is particularly relevant. Indeed, in the current international context, two missions are likely to be launched with worldwide biomass measurements as a primary or secondary objective, i.e. the BIOMASS radar mission and the ICESat2 lidar mission. Lidar and radar data are complementary and lidar ranging data will be available, even if not optimized for vegetation, especially in very dense forests. While no vegetation lidar mission exists, it could be worth considering an airborne solution to complete measurements acquired by ICESat2, especially over dense forests, in order to improve global biomass estimations.

Moreover lidar lends itself well to the development of innovative and alternative solutions because even sampled measurements are highly relevant. Traditional lidar acquisitions with topographic airborne systems are cost prohibitive, in particular for developing countries. Developing low cost, light systems designed specifically for forest resource assessment, e.g. PALS [81] or LAUVAC systems [82,83], might be one way to provide accurate forest inventory capacities to developing countries. By thinking "outside the box", could we embed light lidar systems on commercial jet aircraft? This could diminish both cost and environmental impacts. In the study from Wilkerson et al. (2010) that analyses emission data from global commercial aviation, a map shows the total CO_2–C (kg/m^2) emitted for the year 2006 along the main commercial aircraft lines. This map gives an idea of the distribution of the main commercial aircraft lines over the world and of commercial traffic density worldwide (Fig. 4). It can be seen that all terrestrial areas, except the Antarctic, are covered, albeit at greatly varying flight line densities. Handling such data sets acquired on these commercial routes would certainly be challenging from a statistical standpoint but might become an efficient and solution.

5. Conclusion

Without doubt, global data sets provided by the plethora of Earth remote sensing satellites have greatly improved our understanding of Earth systems. We do not argue against such acquisitions. We do, however, argue that a change in perspective concerning space-based measurements is needed. Simply put, our changed perspective would place sustainability and environmental concerns on an equal footing with the more traditional view where measurement quality is assessed through metrology properties alone and where measurement processes are designed to take into account mostly economical and technological constraints. This holistic approach would integrate interactions between remote sensing observation systems and the Earth's environment. This

new perspective would require that the measurements needed to monitor Earth resources be acquired at regional and global scales in accordance with sustainability principles and with our commitment to reducing environmental impacts. For instance, LCA analyses may indicate that the objectives of some projects may be better met by an extensive, long-term airborne campaign rather than with a new satellite launch. We recognize that these analyses are complicated and may introduce ambiguous imponderables (e.g. national pride, technological primacy, data control) that are near-impossible to quantify in terms of, for instance, a CO_2 budget. However, many projects or missions are not necessarily cutting-edge and may, in fact, be redundant with, or worse, less capable than, satellites currently acquiring data globally. Software and databases exist that can facilitate the decision-making process, but they must be adapted to model space activity impacts to be effective. The European Space Agency (ESA) is currently developing an LCA tool that will facilitate implementation of LCA studies for some of its missions. And ESA intends to generalize the use of such approaches in the European space activity sector.

Such goals strengthen the capacity of measurement processes to meet their stated functional goal, i.e. sustainable management of Earth resources. Currently, space remote sensing is mainly driven by economic and technical considerations; sustainability is simply assumed. There are notable uncertainties concerning the future of LEO accessibility and on the effects of pollution concomitant with space activity. We suggest some measures that could help to design future observation systems in a more sustainable way. To this end, studies that carefully assess the environmental impacts of the several measurement approaches currently available should be considered. As a study case, we focus in the last part of this paper on vegetation lidar missions, the principal scientific objectives of which would be the measurement and monitoring of forest structure. Several spaceborne vegetation lidar projects have been proposed by scientists to space agencies, but to no avail thus far. Such remote sensing solutions would be very useful in the development of much needed monitoring systems for measuring, assessing, and reporting key forest parameters such as biomass and carbon. However, we are convinced that durability of forest observations that rely on spaceborne lidar systems would be increased by taking into account the issues discussed in this paper and by exploring some of the avenues suggested here to improve the sustainability of these remote sensing systems. To reach such a goal the first step is to increase awareness of the issues addressed in this paper, issues which are rarely mentioned and discussed. Acquiring data in accordance with sustainability principles increases their quality in the value-pluralism context of sustainable development. The ESA has reached the same conclusions, even if some of the arguments that they put forward concern the wellbeing of space industry. The Clean Space Office, which is part of the ESA policy department, is a pioneer in this area and has initiated studies to directly address such issues. We look forward to their initial reports and expect that their results will provide concrete examples and criteria to foster debate on many of the issues discussed in this paper.

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