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The social value of Earth observation: A new evaluation framework for public high-tech infrastructures

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ABSTRACT

This paper addresses the main challenges of evaluating the socio-economic impact of high-tech infrastructures, using Earth observation (EO) as an example. EO is a critical domain of the space economy, providing valuable insights into planet Earth's natural and societal aspects. As national agencies invest in high-tech infrastructures like EO, there is a growing need for evaluate their socio-economic returns (not to be confused with their financial returns). However, there is no clear consensus on how to assess such social impact.

Building on a new field of studies of social cost–benefit analysis of research infrastructures and the socio-economic impact of investment in the space economy, we propose a new evaluation framework that considers the various stakeholders along the EO value chain.

This approach can be adapted to evaluate the socio-economic returns of other high-tech public infrastructures, such as telescopes, particle accelerators, genomic platforms, synchrotron light sources, supercomputers and cloud infrastructures.

1. Introduction

Evaluating the socio-economic impact of public projects and policies in fields such as transport, water, energy, health and environmental services has a long tradition dating back to seminal works over the past centuries (Dupuit, 1844; Prest and Turvey, 1965; Sassone and Schaffer, 1978; Drèze and Stern, 1987, Boardman et al., 2018). However, until very recently, economists have been unable to provide a comprehensive framework for analysing the benefits of government investment in science-based and high-tech fields generating new knowledge such as particle accelerators, genomic platforms, synchrotron light sources, astrophysics and space exploration. Florio (2019) builds on work at European Organization for Nuclear Research (CERN) and elsewhere, providing the first comprehensive discussion of the evaluation of social benefits and costs of large-scale research infrastructures generating new knowledge. Other case studies include Battistoni et al., 2016; Castelnovo et al., 2018; Giffoni and Vignetti, 2019; Fabre et al., 2021.

Nonetheless, a few challenges arise when evaluating these high-tech fields. First, the benefits accrue to a diverse community of stakeholders in the knowledge economy; hence, it is crucial to recognise who is directly and indirectly affected by the investment and the different processes through which the benefits manifest. This community includes a variety of new agents whose benefit estimation has never been contemplated beyond the usual notion of science as a public good (Salter and Martin, 2001).

A second crucial challenge relates to assigning a value to intangible items, such as the value of knowledge generated through infrastructure; however, while transport or energy infrastructure provides services easy to identify and quantify, knowledge is not always measurable with proxy indicators for quantitative analysis, e.g. patents. Thus, the socio-economic value of such output is often unknown because the market signals are uncertain or absent.

Another critical issue is that generating new knowledge is not a simple input–output process. New knowledge is often generated by combining different sources; hence, it becomes challenging to determine the source of benefits.

This paper contributes to evaluating the socio-economic impact of high-tech public infrastructures that provide new knowledge with a detailed case study of EO, a strategic segment of the space economy, which this study considers only for its civil use. EO collects various chemical, biological and physical information regarding Earth using remote sensing technologies and provides digitalised knowledge at the

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scale of Big Data (GEO, 2020). On the one hand, EO contributes to advancing the space manufacturing and digital industries. On the other, it contributes to creating cutting-edge services and applications for national and local governments, public and private firms, scientists and citizens with a tremendous potential socio-economic impact (PwC, 2016; Tassa, 2019; Song and Wu, 2021). Examples of EO applications include the study of the hydrology of the Greenland Ice Sheet and the Mediterranean terrestrial water cycle (ESA, 2019). Refer to ESFRI, 2018 and EC, 2019 for several other case studies. More than other research infrastructures, EO satellites target sustainable developmental goals beyond economic productivity and employment (Thacker et al., 2019; Im, 2020), which enables further elucidation of crucial issues such as climate change monitoring, natural disaster management and resource efficiency.

In recent years, market opportunities in space manufacturing and the digital industry have attracted the private sector; however, the public sector still drives the development of the industry (OECD, 2021). In the New Space Economy paradigm, private companies work with governmental institutions to fulfil commercial purposes; moreover, companies and governments pool resources and capabilities in partnerships, define new business models and exploit new commercial applications and services (Weinzierl, 2018).

Globally, national space agencies and country coalitions are increasingly investing in EO technologies. According to the Union of Concerned Scientists (2022), approximately 21% of the 5467 satellites in orbit are EO satellites (1130); there were only 16% in 2014. Furthermore, 190 EO satellites were launched worldwide between 2009 and 2018, more than half (54%) within large and public space programmes of agencies like the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA) and the Japan Aerospace Exploration Agency. Additionally, 52 countries are willing to launch at least one EO satellite by 2028 (Euroconsult, 2019). Hence, despite the increasing involvement of the private sector, EO infrastructures require significant government financial efforts involving taxpayers (Jacob and Hallonsten, 2012). Thus, a comprehensive understanding of the socio-economic benefits of this investment, with tremendous potential to address current and future social and environmental concerns but unclear returns, has become crucial.

Different socio-economic evaluations and impact assessments of space investments have been conducted over the years (OECD, 2019). Current assessments employ quantitative or qualitative techniques and typically focus on a single segment of the value chain without providing a clear approach or conclusive methodology to capture EO value for society at large (Pogorzelska, 2018; Craglia and Pogorzelska, 2019; Hof et al., 2012; OECD, 2019). This paper offers the first systematic approach based on social cost–benefit analysis (CBA). We provide a coherent and structured applied welfare economics framework for weighing the costs of the infrastructure against the peculiar benefits accruing to a wide range of social groups, allowing us to extend recent advances in the CBA of large research infrastructures and identify specific hurdles in the space economy context. We believe that highlighting the specific challenges of EO impact evaluation can provide new ideas for other science-intensive and high-tech public investments. Therefore, we propose the following research questions:

1) How can we value the net socio-economic impact of building, operating and exploiting an EO infrastructure?
2) What are the critical uncertainties and challenges of this socio-economic impact analysis?
3) What lessons can be learned from the EO case studies that can be extended to other high-tech investments for knowledge creation?

This paper is organised as follows. Section 2 presents i) the EO sector, ii) a critique of some current evaluation approaches used in the space literature and iii) our approach and its advantages. Section 3 introduces the benefits accruing to each category of stakeholders, explains the main estimation challenges, proposes possible estimation methods and presents a set of simple empirical equations. Section 4 summarises and concludes the paper.

2. Background and literature review

2.1. Economic dynamic of EO satellites

Since the beginning of the 21st century, the EO sector has rapidly expanded, attracting increasing attention from governments and private investors. Besides critical military applications, the civil use of EO, combined with recent advancements in the digital domain, is becoming one of the fastest-growing segments of the space economy. Forecast sees EO revenues double from EUR 2.8 to 5.5 billion from 2021 to 2030, with the EO data market growing annually by 3.5% (CAGR), reaching almost EUR 800 million in revenues in the next 10 years (EUSPA, 2022); however, it is not the market significance but the potential of non-market benefits that seems interesting.

This paper focuses exclusively on high-tech space infrastructures whose main functional components are in Earth's orbit (Georgescu, 2020). We do not consider other sources of EO data, e.g. aeroplanes, drones or balloons, which are of local interest and depend strictly on meteorological conditions for effective operation. For example, unmanned aerial vehicles like drones can provide Earth observation data but rely on an infrastructure - like telecommunication facilities - serving a limited area and with limited autonomy. Conversely, the satellite constellations are a material infrastructure - the meaning of immobile, non-circulating capital goods that essentially contribute to the production of goods and services (Buhr, 2003) - partly in orbit into space and partly on the ground to control the satellites and store imagery and other collected data. The data are collected and processed and elaborated through advanced digital techniques such as machine learning and artificial intelligence to extract meaningful information and produce applications and services used for different purposes and users. Major agencies like ESA, CNSA and NASA employ EO satellite constellations in low and middle Earth orbit. More recently, commercial operators, such as Dove satellites from Planet, Aleph-1 from Satellogic and UrtheDaily/OptiSar from Urthecast, launched low-cost constellations in very low Earth orbit (Rodriguez-Donaire et al., 2022).

The EO value chain can be divided into four main segments. First, the *upstream* sector relates to the production and maintenance of the infrastructure that collects the data and includes different actors such as space agencies and manufacturing firms. This sector is the most relevant, with approximately EUR 7 billion in global revenues in 2017 (PwC, 2019).

Second, the *midstream* sector includes companies and organisations that work with data acquisition, archiving, pre-processing and delivery of services to facilitate and enable the creation of applications (Pogorzelska, 2018; PwC, 2016). Until a few years ago, this sector was considered peripheral to the EO value chain (Pogorzelska, 2018). In some studies, it is either part of the upstream or downstream sector (e.g., PwC, 2019); however, EO is generating tremendous advancement in information technology and communication (ICT), and midstream actors are increasingly pushing the technological frontier of the EO industry. Besides a growing number of ICT firms and start-ups, tech-giants like Google, Amazon and Oracle have also entered the market (PwC, 2016).

Third, the *downstream* sector consists of all actors that elaborate EO pre-processed data to extrapolate meaningful information and provide EO final services and applications for users. Downstream operators mainly include small and medium companies with high technological know-how, developing commercial applications from satellite data, geo-information firms, consultancy companies, research institutes with artificial intelligence expertise and hardware/software development companies (PwC, 2016). The global EO downstream market is estimated to be between EUR 2.6 and 2.8 billion (PwC, 2019). Companies like

Planet Labs, iCEYE and Spire operate in upstream and downstream markets.

The last segment includes the *final users* of EO services and applications; moreover, it embraces public and private actors using such services for different purposes as *direct final users* (e.g. associations of farmers are increasingly using EO precision farming services to manage their crops more efficiently by increasing yields and reducing the use of chemicals and waste of water). At the bottom of the value chain, *indirect final users* benefit from the EO services acquired by direct final users. Sometimes, these users are unaware of profiting from the existence of the service (e.g. in precision farming, final consumers buying better products at lower prices and the general population benefitting a cleaner environment thanks to the reduction of chemicals). Benefits in this last category are enormous, although still unexpressed and primarily unmeasured.[1]

Most benefits stemming from EO accrue to these stakeholders only when certain conditions are in place. Despite the increasing commercial use of space, private actors may fail to capture the total potential value because space has some characteristics of a public good. Space is a shared resource and the satellite infrastructure within it can create problems of natural monopoly and coordination. The difficulty in appropriating technology spillovers (Tassey, 2004) and the existence of imperfect and asymmetric information related to innovative high-tech projects are challenges in the space industry, as in many others (Tassey, 2008).

The argument of market failures calls governments to action. More importantly, the implications of the space economy on society are potentially enormous and require the active involvement of the government in the sector (Weinzierl, 2018). Considering the importance of the public debate and the magnitude of the impact of the space economy on society, appraising and assessing the social benefits of space infrastructures (versus the private ones) is more relevant than ever.

2.2. Evaluation approaches in the literature

Different socio-economic evaluations and impact assessments of space investments have been conducted over the years (OECD, 2019, 2020) with quantitative and qualitative techniques (Pogorzelska, 2018; Craglia and Pogorzelska, 2019; Hof et al., 2012; OECD, 2019). All these works evaluate single segments of the EO value chain, such as the upstream and downstream sectors or final users.

For the upstream sector, most studies are present in the 'grey' space literature and discuss only financial revenues and job creation (e.g. OECD, 2007; 2019; Canadian Space Agency, 2019; PwC, 2016); however, from a CBA perspective, new jobs should be considered infrastructure costs (EC, 2014) as people are needed to build, operate and exploit the infrastructure together with other fixed and operating costs (EC, 2014). Additionally, financial revenues from the sale of goods or services fail to capture the project's overall social benefits and, in most cases, capture the firm's income coming from procurement activities that is actually a cost of the infrastructure.

Other studies rely on input–output and general equilibrium analysis and usually evaluate the investment effect from the upstream industry to the whole economy (OECD, 2007; NASA, 2013). This accounting approach applies average input–output coefficients transferred from other sectors, such as aviation and shipping. There are several reasons why input–output analysis may fail to capture the full socio-economic benefits of an investment. First, it is designed to measure an investment's direct and indirect economic impacts, such as changes in output, employment and income. While these are necessary measures of economic performance, they do not necessarily capture the broader socio-economic benefits such as health and education improvements. Economic output is a poor statistic for welfare effects when, as typical of scientific projects, many impacts are outside market transactions (Florio, 2019). Second, many socio-economic benefits are intangible and may not be captured by traditional economic measures. Furthermore, input–output analysis does not account for externalities. It assumes that all economic impacts are internal to the system and externalities, such as impacts on education or social costs, are insignificant. Lastly, input–output analysis fails to disentangle the effect for each stakeholder involved, which can vary significantly. It focuses on short-to-medium-term economic impacts and may not capture the longer-term socio-economic benefits associated with an investment, such as improvements in a research capacity or education.

Other methods adopt a survey methodology based on direct interviews with firms to estimate the industrial effects of the upstream sector (B.E.T.A 1980, 1988; PwC, 2016b), but again without estimating its societal value.

A growing body of research has also investigated the transfer of technologies and related economic benefits stemming from the upstream sector using theoretical and empirical methodologies (Venturini and Verbano, 2014). Case studies, surveys and input–output analyses are the primary source of empirical evidence, while studies relying on econometric analysis are a minority (Åberg and Bengston, 2015; Petroni and Verbano, 2000; Martin and Tang, 2007). Bach et al. (2002) presented the results from a series of studies to evaluate spin-offs and transfer of technologies based on direct interviews with contracting firms (B.E.T.A 1989; Cohendet, 1997). FAA (2010) and the UK Space Agency (2010) have conducted other analyses based on national and regional economic growth. Considering few exceptions - such as the OECD (2019) that uses some other impact indicators of transfer of technologies, including lives saved/not lost and lives improved - most studies focus on economic benefits only.

In the last 20 years, some studies applied various methodologies to evaluate the socio-economic benefits of the final use of EO services and applications (PWC, 2016; WMO, 2015; Hof et al., 2012; Craglia and Pogorzelska, 2019) drawing on varying techniques, including the value of information (Macauley, 2006; Gallo et al., 2018), simplified CBA, (Booz and Co, 2011; Halsing et al., 2004;) and cost-effectiveness analysis (a looser simplified version of CBA where only costs are considered, not the benefits. Dawes et al., 2013) amongst others. Each method has its advantages and disadvantages (Hof et al., 2012; Smart et al., 2018). One of the most effective and popular methods is the value chain approach (e.g. Sawyer et al., 2019, 2020), which consists in tracing the impact (usually on added value or income) of the use of the EO services through subsequent steps within the final segments of the EO service value chain, from first-tier direct users to other indirect users to the whole society at large. Each step assesses and sums up benefits to obtain the value. While this approach is informative, the whole value chain method should carefully select the counterfactuals. Gross benefits should be compared with the alternative techniques available for inspection, which are increasingly challenging to forecast empirically when the chain effect is expected to occur further downstream (Florio and Morretta, 2021). Additionally, this method considers single case studies without providing conclusive methodologies to capture the whole EO value for society at large. This paper proposes an effective way to estimate and quantify benefits of high-tech infrastructures along the whole value chain. By focusing on the socio-economic value rather than financial value or simple economic impact, a CBA can help decision-makers determine whether the benefits of an intervention outweigh the costs and by how much. This information is critical for maximising social welfare and selecting the interventions that generate the greatest net benefits for society.

[1] Preliminary attempts of quantification have been provided by the European Association of Remote Sensing Companies (EARSC) in a collection of case studies on Copernicus sentinel benefits. See: https://earsc.org/sebs/all-cases/ (last access February 2023).

2.3. Applied welfare economics approach

CBA is a helpful applied welfare economics tool that quantifies a project's socio-economic value in monetary terms. This method has a long and well-established tradition in the socio-economic impact analysis of different infrastructures (Drèze and Stern, 1987); however, until recently, it was not developed for research and development (R&D) projects, including research infrastructures (EC, 2014, 2021; Florio, 2019). In the space sector, some simplified CBAs have also been conducted to estimate the value of EO programmes, such as GMES/Copernicus or weather satellites (Booz and Co, 2011; Gray, 2015; Eumetsat 2014; Yuan et al., 2016; Borzacchiello and Craglia, 2011; Lafaye, 2017); however, these CBAs focus exclusively on the estimation of the benefits of the final segment of the value chain, i.e. the final users.

Indeed, market prices do not even exist for many inputs and outputs of an EO programme, or if available, they do not reflect the value for society; hence, social CBA introduces significant corrections to evaluate costs and benefits at their *shadow prices* as a proxy of their *marginal social values* (MSV). Our approach rejects the neo-classical perspective of mimicking market price equilibria, thus adopting a broader view of signals relevant to social welfare maximisation (Florio and Pancotti 2023). From the producer perspective, shadow prices may coincide with the long-run *marginal production cost* (MPC), representing the cost of producing an additional unit of a good or service and holding everything else constant (Dréze and Stern, 1990). From the consumer side, shadow prices reflect the *willingness to pay* (WTP), representing the maximum price at which a consumer would buy a unit of that good or service (Breidert, 2007). Consumers can state this either directly (*stated preference method*) or indirectly through specific techniques (*revealed preference method*) (Johnston et al., 2017). In other cases, the MSV results from a combination of MPC and WTP methods.

CBA estimates the shadow prices of costs and benefits in incremental terms relative to a counterfactual or 'without project' scenario and discounted to bring the value flows back or forward to a common date by using an appropriate social discount rate (see Zhuang et al., 2007; Harrison, 2010; and EC, 2014 for selected countries). Indeed, benefits and costs occur in different periods along the time horizon of the project, which is usually quite long. The model sums all discounted costs and benefits, including positive and negative externalities, to calculate the *net present value* (NPV) as follows:

Net Present Value (NPV) = *Present Value of Social Benefits–Present Value of Social Costs*

This well-known summary indicator reflects the net benefit of the infrastructure from the perspective of the society; moreover, it does not concern profitability, as an infrastructure with positive NPV may generate losses in financial terms. We prefer this approach because it allows for estimating all social costs and benefits accruing to different stakeholders involved in the value chain under a unique, comprehensive and coherent framework; however, it is vital to acknowledge the limitations of this method. First, the estimation of social values may depend on individual preferences and subjective biases of the evaluator, leading to different conclusions about the net benefits of a project. CBA may also be limited by data availability, specifically for complex projects. Additionally, benefits and costs that occur in the future are forecasted and discounted to reflect the time value of money; however, this can lead to uncertainty and time inconsistency problems where future costs or benefits are undervalued or overvalued relative to present costs or benefits. This situation is why CBA is usually complemented by sensitivity and forecasting analysis based on Monte Carlo simulations (EC, 2014). Another limitation is that the WTP is derived from hypothetical scenarios, which may not accurately reflect real-world behaviour (Johnston et al., 2017). WTP values may also be influenced by an individual's income or wealth and social norms and may not be generalisable across different populations or settings; therefore, ad hoc measures are needed to mitigate these biases (Johnston et al., 2017). With an application to CERN, Giffoni and Florio (2023) discuss in detail how to manage contingent valuation experiments about citizens' support of investment in science, finding that such support is greater in France and Switzerland than actual implicit taxes paid by citizens.

3. The socio-economic impact of EO infrastructures

3.1. The benefits of EO programmes

An important issue related to estimating the total benefits of an EO programme is the clear identification of multiple agents that can be directly or indirectly affected. An extensive review of the current fragmented literature (hundreds of scientific articles and reports in the grey literature related to research infrastructures and EO; list available upon request) indicates that stakeholders who may take advantage of investment in the EO programme along the value chain includes several types of firms that are mentioned as follows: those operating in the upstream, midstream and downstream sectors; firms in other industrial sectors; users of ICT systems; research institutes and scientists; EO programme's workforce; final users of EO services and applications; other users of EO data; and users of cultural facilities related to EO.

In this paper, for space reasons, we omit the discussion on the social costs of EO, which, apart from the discussion on space debris, is rather standard. We also consider the *non-use value* of EO programmes when, for example, a generic taxpayer would be happy to contribute to funding the infrastructure regardless of its actual use (Graham, 1981; Boardman et al., 2018; Johansonn and Kristrom, 2015; Florio and Giffoni, 2020; Giffoni and Florio, 2023).

Furthermore, other benefits outside the scope of the analysis might include strategic and reputational benefits accruing to the space agencies or countries investing in the EO programme. One such example is the Apollo programme, which secured national prestige and symbolic benefits to the USA beyond practical use. Military use of EO is also not considered.

3.2. Direct benefits to firms in the upstream, midstream and downstream sectors

From a theoretical perspective, firms may benefit from an EO investment in various ways; the first is the new knowledge the firm acquires through *learning by doing,* stemming from new technological and challenging tasks the firm is called to face (Arrow, 1962; Cohen and Levinthal, 1990; Edquist et al., 2000; Autio et al., 2003).

Another benefit relates to new knowledge generated through *learning by an interacting* process, referring to the ability to learn (intentionally or unintentionally) by interacting with others (Autio et al., 2004; Jaffe et al., 2000). *Knowledge and technological spillovers* are particularly relevant in, but not exclusive to, the upstream sector, where firms collaborate to achieve a common objective, or large space agencies often act as a learning environment for their supplier companies (Castelnovo et al., 2018). An increase in *reputation* might be an additional advantage.

From a CBA perspective, a main challenge is attaching a monetary value to the new knowledge acquired by the firm, regardless of the channel through which it manifests. A convenient method is to proxy the WTP for the new knowledge by using the incremental shadow profit of a sample of firms involved in EO, compared with a counterfactual group of companies with similar characteristics and operating in similar sectors (but not in EO). Table 1 reports *equations* 1a, 2a and 3a for the three segments. The shadow profit can be estimated by observing the EO firms' revenues, fewer costs (or other performance indicators such as return on sales) and possibly using income gross of taxes, interest and depreciation. The shadow profit of the counterfactual group can be used for comparison; examples of techniques are difference-in-differences, discontinuity design and matching approach (Gadd et al., 2009; Mouqué, 2012). In ex-ante evaluations, future profits can be forecasted by studying similar research infrastructures (RI) in other contexts, as Florio et al. (2016b) explained. Regardless, immediate sales and new

Table 1
Value of new knowledge in the upstream, midstream and downstream segments.

	STAKEHOLDER & TYPE OF BENEFITS	ESTIMATION FORMULA	DESCRIPTION
1a	*Firms in the upstream sector:* • Learning by doing • Learning by interacting • Knowledge spillovers • Increase in reputation	Incremental profit $\sum_{up=1}^{UP}\sum_{t=\varepsilon}^{T}\frac{\Delta\pi_{up\ t}}{(1+sdr)^t}$	$up=(1,2,3\ldots UP)$ number of firms in the upstream sector. $\Delta\pi_{up}$ = incremental shadow profits (or other profit margins) estimated by using income gross of taxes, interest and depreciation of firms involved in EO and a counterfactual group of firms not involved in EO. ε = time since the firm started EO activities.
2a	*Firms in the midstream sector:* • Learning by doing • Learning by interacting • Knowledge spillovers • Increase in reputation	Incremental profit $\sum_{mid=1}^{MID}\sum_{t=\varepsilon}^{T}\frac{\Delta\pi_{mid\ t}}{(1+sdr)^t}$	$mid=(1,2,3\ldots MID)$ number of firms in the midstream sector. $\Delta\pi_{mid}$ = incremental shadow profits (or other profit margins) estimated using income gross of taxes, interest and depreciation of firms in EO and a counterfactual group of firms not in EO. ε = time since the firm started EO activities.
3a	*Firms in the downstream sector:* • Learning by doing • Learning by interacting • Knowledge spillovers • Increase in reputation	Incremental profit $\sum_{down=1}^{DOWN}\sum_{t=\varepsilon}^{T}\frac{\Delta\pi_{down\ t}}{(1+sdr)^t}$	$down=(1,2,3\ldots DOWN)$ number of firms in the midstream sector. $\Delta\pi_{down}$ = incremental shadow profits (or other profit margins) estimated using income gross of taxes, interest and depreciation of firms involved in EO and a counterfactual group of firms. ε= time since the firm started to be involved in EO activities.

Authors' elaboration. Note: sdr = social discount rate; $t=(0,1,2,3\ldots T)$ = time horizon of the programme.

jobs created from the procurement activity should be excluded from this computation despite many reports doing so (e.g. OECD, 2007; 2019; Canadian Space Agency, 2019; EARSC, 2019; PwC, 2016;). Indeed, higher revenues deriving from procurement are infrastructure costs, while changes in net output at shadow prices capture the medium- and long-term benefits.

Alternatively, we can track (or forecast) and value the number of new patents (Schmookler, 1966; Hall et al., 1986; Bastianin et al., 2021) instead of net output. Castelnovo et al. (2022) provide a relevant example, general to engagement in upstream space activities. They focus on the procurement activity of the Italian Space Agency over 15 years, assessing the causal impact of public procurement on suppliers' patenting activity by implementing a novel quasi-experimental design; however, this method could underestimate the value of innovation generated through learning mechanisms (Florio and Sirtori, 2016). For example, inventors cannot patent new organisational processes that lead to higher profits.

Another critical challenge of this estimation is the extent to which EO has contributed to the incremental performance because information such as the amount of investment in EO activities, the value of the procurement contract in EO, the contribution of EO data to the creation of a specific service is not always available. Specifically in the downstream sector, it is challenging to determine the portion of benefits that derives from using EO data, as these are often used in combination with other sources of information. Estimations or integrating quantitative data with qualitative information could help solve this problem.

Additionally, when new knowledge contributes to new firms, a further benefit in this category is the value of new *start-ups* and *spin-offs*; from a CBA perspective, it is not easy to appraise this value. First, in ex-post evaluation or forecast ex-ante, one should know the number of start-ups and spin-offs generated due to EO. Second, one should establish an expected lifetime or survival rate and an expected shadow profit as in *equations* 1b, 2b and 3b (Table 2) for the three segments. These elements can be retrieved by looking at similar infrastructures or statistical databases of firms in similar sectors or arranging ad hoc surveys; see EC (2014) for further details.

3.3. Benefits to firms in other industrial sectors

Another critical benefit stemming from EO infrastructures is the transfer of technologies to other sectors (Bozeman, 2000; Venturini and Verbano, 2014). For example, NASA has documented over 2000 cases of transfer technologies between 1976 and 2018, including commercial applications in health and medicine, transportation, public safety, consumer goods, agriculture, environmental resources, computer technology, manufacturing and energy conversion and use (NASA, 2017). Over the last decade, ESA has generated over 150 technological innovations that transferred from the space industry into non-space applications.[2]

Knowledge spillovers lead to the spread of ideas from one individual or sector to another; thus, this source of transfer is not costly because

Table 2
Value of start-ups in the upstream, midstream and downstream segments.

	STAKEHOLDER & TYPE OF BENEFITS	ESTIMATION FORMULA	DESCRIPTION
1b	*Sturt-ups in the upstream sector* • Start-ups • Spin-off	Value of start-ups and spin-offs $\sum_{s_{up}=1}^{S_{up}}\sum_{t=0}^{T}\frac{\pi_{s_{up},\ t}}{(1+sdr)^t}$	$s_{up}=(1,2,3\ldots S_{up})$ number of start-ups and spin-offs stemming from the upstream sector $\pi_{s_{up}}$ = expected shadow profit of start-ups and spin-offs
2b	*Sturt-ups in the midstream sector* • Start-ups • Spin-off	Value of start-ups and spin-offs $\sum_{s_{mid}=1}^{S_{mis}}\sum_{t=0}^{T}\frac{\pi_{s_{mid},\ t}}{(1+sdr)^t}$	$s_{mid}=(1,2,3\ldots S_{mid})$ number of start-ups and spin-offs stemming from the midstream sector $\pi_{s_{mid}}$ = expected shadow profit of start-ups and spin-offs
3b	*Sturt-ups in the downstream sector* • Start-ups • Spin-off	Value of start-ups and spin-offs $\sum_{s_{down}=1}^{S_{down}}\sum_{t=0}^{T}\frac{\pi_{s_{down},\ t}}{(1+sdr)^t}$	$s_{down}=(1,2,3\ldots S_{downs})$ number of start-ups and spin-offs stemming from the downstream sector $\pi_{s_{down},}$ = expected shadow profit of start-ups and spin-offs ε = time since EO data are available for elaboration by downstream intermediate users

Authors' elaboration. Note: sdr = social discount rate; $t=(0,1,2,3\ldots$ T) = time horizon of the programme.

[2] ESA, science & exploration. Spin-off technologies: https://www.esa.int/Science_Exploration/Space_Science/Spin-off_technologies#:~:text=Over%20the%20last%20ten%20years,industry%20into%20non%2Dspace%20applications.

knowledge tends to spread freely, and when is not, it is because of intellectual property rights that have costs and terms, for instance patents. However, it may cause valuable innovation and growth (Aghion and Jaravel, 2015). A promising method to assess the value of spillovers from EO is to study the patents developed in other fields or to value spin-offs in other industries, carefully avoiding double counting. In the first case, transfer of technologies may arise when firms cannot detain or patent the knowledge they generate; hence, another party files a patent on a derived concept (Catalano et al., 2021a). *Equation 4a* (Table 3) appraises the social benefit considering the yearly profit the holder expects to earn from the patent or the net of the expected profit without the patent (the counterfactual) (Florio, 2019)[3]; for example, looking at firms in similar sectors. The patent's value should also incorporate additional knowledge externalities, like the production of additional streams of patents, the average rate of exploitation of first-tier patents and the value of citations (see Florio, 2019). One can forecast the average rate of exploitation of patents by examining similar scientific fields or infrastructures, or other indicators can be used to capture the technological and economic value of patented inventions (Squicciarini et al., 2013).

The second method considers spin-offs (*equation 4b* in Table 4). NASA and ESA have issued several publications presenting successful spin-offs (for example, Szalai et al., 2012), business incubation and technology transfer initiatives in various sectors. As previously explained, one method to estimate such benefit would be to forecast the number of spin-offs created by the EO programme in other fields, establish an expected lifetime or survival rate and estimate their expected shadow profits by looking at similar infrastructures or statistical databases or arranging ad hoc surveys; however, estimating this benefit is not simple. It requires a clear understanding of which technology transfers derive from EO upstream activities rather than other space domains (such as space exploration, navigation and telecommunication); therefore, a more detailed investigation of the technology is recommended, often with the support of surveys or interviews with experts. A counterfactual approach may consider start-up birth rate and survival elsewhere when such data are available and appropriate for difference-in-differences or other econometric approaches.

Table 3
Value of knowledge spillovers; patents.

STAKEHOLDER & TYPE OF BENEFITS		ESTIMATION FORMULA	DESCRIPTION
4a	*Firms in other industrial sectors* • Technology transfers • Knowledge spillovers	Marginal social value of patents $\sum_{p=1}^{P}\sum_{t=0}^{T}\frac{(\Delta PRIV_{pt} + EXT_{pt})}{(1+sdr)^t}$ where EXT_{pt} = $\sum_{p=1}^{P}\sum_{t=0}^{T} use \frac{\Delta PRIV_{jt}}{Ref_p}$	$p = (1, 2, 3\ldots P)$ = patents stemming from the EO programme and registered by third parties. $\Delta PRIV_{pt}$ = marginal private value of patents measured as the yearly profit the holder expects to earn thanks to the patent, net of the expected profit without the patent. EXT_{pt} = knowledge externalities measured as the production of additional streams of patents. *use* = average rate of exploitation of patents proxies by the average number of citations received. Ref_p is the average number of references included in the bibliography of additional patents citing *p*.

Authors' elaboration. Note: sdr = social discount rate; $t = (0, 1, 2, 3\ldots T)$ = time horizon of the programme.

Table 4
Value of knowledge spillovers; spin-offs in other sectors.

STAKEHOLDER & TYPE OF BENEFITS		ESTIMATION FORMULA	DESCRIPTION
4b	*Spin-offs in other industrial sectors* • Spin-offs	Value of spin-offs $\sum_{s_{TT}=1}^{S_{TT}}\sum_{t=0}^{T}\frac{\pi_{s_{TT}\ t}}{(1+sdr)^t}$	$s_{TT} = (1, 2, 3\ldots S_{TT})$ number of spin-offs in other sectors. $\pi_{s_{TT}}$ = expected shadow profit of spin-offs.

Authors' elaboration. Note: sdr = social discount rate; $t = (0, 1, 2, 3\ldots T)$ = time horizon of the programme.

3.4. Benefits to users of information technology and communication (ICT) systems

Users of ICT systems can substantially benefit from investment in EO infrastructures as these are contributing to significant advancements in ICT, fostering the development of different tools and solutions such as cutting-edge software, artificial intelligence techniques and the internet of things or cloud computing, amongst others (Pogorzelska, 2018).

The increasing collection and use of EO data create new and stimulating challenges in data acquisition capabilities, storage, analysis, interpretation, transmission, distribution and information security. Solutions to these challenges may create free *knowledge spillovers*, for example, in the form of new software, cloud computing tools or new machine learning and data analytics approaches that may become available in the public domain. While such benefits may also stem from cutting-edge technologies developed within the upstream sector (for example, new software to operate satellites), they mainly arise from the midstream and downstream sectors. For example, the project TOLOMEO (tools for open multi-risk assessment using EO data) (CORDIS, 2019) promoted the development of free and open-source software solutions to develop human settlement mapping techniques. Thus, researchers can develop tools for assessing issues such as human exposure to climate change, deforestation risks, Earthquakes and flood vulnerability. ESA, NASA and other national space agencies[4] provide other examples of free software related to EO. Similarly, innovative cloud computing systems and algorithms developed within EO open science may find applications in different fields, enabling multidisciplinary interactions and reinforcing the need for knowledge sharing (Mathieu and Aubrechtv, 2018).

In the case of benefits to users, adopting the MPC method is not informative, as the cost to include an additional user can be negligible (Dolado, 2001). Therefore, the WTP approach is a more appropriate estimation method (Raghu et al., 2009), as expressed in *equation 5* (Table 5). With the stated preferences method, the analysis would

[3] Profits must be evaluated at shadow prices, gross of tax, interest and depreciation and other distortions.

[4] See for example: European Space Agency (ESA*), Open Source Software Resources for Space Downstream Applications* https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Radio_Frequency_Systems/Open_Source_Software_Resources_for_Space_Downstream_Applications%20 or Belgian Earth Observation, *Satellite data*, https://eo.belspo.be/en/more-free-data-software among others (last access, June 2023).

Table 5
Value of knowledge spillovers in ICT.

STAKEHOLDER & TYPE OF BENEFITS		ESTIMATION FORMULA	DESCRIPTION
5	*Users of ICT systems* • Knowledge spillovers	ICT users' WTP $\sum_{ict\_user=1}^{ICT\_USER} \sum_{j=1}^{J} \sum_{t=0}^{T} \mathrm{WTP}_{ict\_user\ j\ t} / (1+sdr)^t$	$j = (1, 2, 3..\ J)$ ICT technologies spilt-over from EO technologies. $ict\_user = (1, 2, 3\dots\ ICT\_USER)$ number of users of spilt-over ICT technologies.

Authors' elaboration. Note: sdr = social disco.

require statistical data based on contingent valuation experiments (see Arrow et al., 1993; Johnston et al., 2017 for further details). With the revealed preferences method, one could examine market prices and the average number of users of similar products or forecast the value of time saved by users (see EC, 2014 and Florio et al., 2016b) by implementing a specific ICT product or by designing ad hoc surveys (Koundouri et al., 2021). The counterfactual is provided here through survey data when users are invited to reveal alternative options and their costs, including the opportunity cost of time.

3.5. Benefits to the scientific community

Projecting, building, operating and exploiting EO programmes requires a vast community of scientists and private and public research institutes, including universities and R&D firms departments, which may benefit from this investment. One of the main benefits of the EO programme for scientists and researchers directly or indirectly involved is the opportunity to generate or acquire new knowledge against a counterfactual where they need to look for alternative sources of data on Earth across space and time.

Most of the time, new knowledge does not have a concrete application to take more effective decisions, and it simply contributes to expanding understanding of specific issues in different subjects (Morretta et al., 2022); however, it is possible to assume that any meaningful knowledge is ultimately embodied in scientific publications that convey scientists' research findings worldwide and provide a valuable indication of the knowledge production in each sector (EC, 2014; Florio, 2019; OECD, 2019).

From this perspective, one possible way to forecast the socio-economic benefits of an EO infrastructure for the scientific community is to assign a value to the stream of publications deriving from the infrastructure whose number can be retrieved from different databases (e.g. SCOPUS). This socio-economic value can be appraised differently (see Rousseau et al., 2020 for a review). An innovative method proposed by Morretta et al. (2022) evaluates, in monetary terms, the scientific publications related to a constellation on Italian EO satellites. By adopting the MPC method, the increased cost associated with producing an additional publication (Drèze and Stern, 1987; Boardman et al., 2018) depends on the scientists' salary and the time dedicated to that research (Florio et al., 2016a, Morretta et al., 2022). This socio-economic value must also be augmented by the value of the influence of the publication, which can be a function of the number of citations (Harzing, 2010; Waltman et al., 2013; Carrazza et al., 2016; Morretta et al., 2022). The shadow price of citation is estimated using the opportunity cost of time a scientist utilises to read and cite a publication (Florio et al., 2016; Florio, 2019). In this way, the present value of publications as a proxy of the benefits for the scientific community (generated in the first round from the existence of an EO infrastructure) can be estimated as explained in *equation 6* (Table 6; see Morretta et al., 2022). Other estimation methods, such as the WTP, can be contemplated, although with several drawbacks (see Florio, 2019; Rousseau et al., 2020).

3.6. Human capital

One of the most critical socio-economic benefits of public investment in RIs is the contribution to human and social capital accumulation (Catalano et al., 2021b). EO infrastructures are often designed as collaborations involving universities, research laboratories and firms (sometimes also from different countries), thus becoming a collective intelligence environment (Malone and Bernstein, 2015). They are exceptional human and social capital incubators for workers at different levels, especially for early-career researchers (ECRs) (Catalano et al., 2021b). Indeed, space agencies actively promote the engagement of ECRs through specific programmes (see, for example, learning

Table 6
Value of scientific publications.

STAKEHOLDER & TYPE OF BENEFITS		ESTIMATION FORMULA	DESCRIPTION
6	*Scientific Community* • Generation/ acquisition of new knowledge	Value of scientific publications $= \sum_{t=0}^{T} EO_t * MPCpub_t/(1+sdr)^t + \sum_{t=0}^{T} CIT_t * MPCpub_t/avRef_t/(1+sdr)^t$ Here, $MPCpub_t = (w_t * h_t)/(y_t)$	EO = number of EO related publications. $MPCpub$= marginal cost of publications w = average gross annual wage of scientists. h = average share of time researchers spends in producing their publications (assumed 50%). y = average scientific productivity, which is a function of the total number of publications produced (also outside EO) CIT_t = total number of citations received by EO. $avRef$ = average number of publications included in the bibliography of the documents citing EO publications.

Authors' elaboration. Note: sdr = social discount rate; $t = (0, 1, 2, 3\dots\ T)$ = time horizon of the programme.

opportunities provided by ESA[5] or NASA[6]).

For ECRs, having the opportunity to study or work in such a vibrant and stimulating environment brings several benefits, including the possibility of expanding their skills and knowledge and building a network with established professional and renowned scientists, which is needed and in nearly all workplaces, including outside research (Camporesi, 2001; Boisot et al., 2011; OECD, 2014) .[7]

The private return of human capital is defined as the additional salary ('premium') earned due to an extra year of schooling, as modelled by Mincer (1974), who also includes job training and experience, beyond schooling, as a driver of future earnings. In this case, the private return of human capital can be measured in terms of the expected incremental lifelong salary earned, over the entire career, by ECRs who have spent part of their educational period in an EO programme compared with a 'peer' who has not benefitted from such experience (counterfactual). Significant educational fields include climatology, oceanography, forest science, geology, urban planning, human geography and built environment.

Tracking the careers of students' cohorts over long periods is not always feasible because of insufficient data; hence, some authors have used case studies (Anderson et al., 2013a; 2013b) or surveys to ECRs based on the expected salary premium as a result of the experience at the infrastructure (Camporesi et al., 2017; Catalano et al., 2021b). With this approach, it is possible to estimate the premium by comparing the expected salary of ECRs that have worked or studied at the EO infrastructure or in a downstream activity with a counterfactual expected income without such hands-on experience. This framework allows the expected present value of human capital and social accumulation benefits to be defined as the sum of the expected increasing earnings gained by the ECRs, from the moment they leave the programme until the end of their career, as in *equation 7* (Table 7; see Catalano et al., 2021b).

Table 7
Value of new skills and social connections for workers.

STAKEHOLDER & TYPE OF BENEFITS		ESTIMATION FORMULA	DESCRIPTION
7	*EO programme's workforce: Human and social capital* • Acquisition of skills and networking opportunities	Expected Salary Premium $\sum_{ecr=1}^{ECR}\sum_{t_{HC}=\varphi}^{\mathcal{T}}\mathbb{E}(\pi_{ecr\ t_{HC}})/(1+sdr)^{t_{HC}}$	$ecr = (1, 2, 3\ldots ECR)$ early career researchers in the EO programme. $\mathbb{E}(\pi_{ecr\ t_{HC}}) =$ expected increasing earnings gained by the ECRs during the time t_{HC} from the moment he/she leaves the programme(φ) until the end of his/her career $\mathcal{T}$.

Authors' elaboration. Note: sdr = social discount rate; $t = (0, 1, 2, 3\ldots T)$ = time horizon of the programme.

3.7. Benefits to final users of EO services and applications

The benefits of new information captured by the downstream industry ultimately accrue to final users of EO services and applications. *Direct final users* are mainly national and local governments, public and private firms and individuals who use the application or service made available by intermediate users in various fields (see PwC, 2019), which is the case of public administrations that adopt new services showing ground motion based on EO data to build and manage road infrastructures (Sawyer et al., 2020). This service provides crucial information contributing to decreasing road construction and maintenance costs. At the bottom of the value chain, indirect final users benefit from the EO services acquired by direct final users, for instance, drivers that enjoy more efficient and safe road infrastructures.

With EO, direct final users can deliver services to groups of citizens (e.g. in the case of governments) or customers (e.g. in the case of private companies, for example, in the field of insurance or electricity) by saving costs, gaining efficiency, increasing efficacy and quality (see EARSC, 2023), for a review of case studies of EO applications and benefits. Such benefits accrue to other agents more indirectly through a chain of transmission mechanisms and are possibly the largest.

Our framework uses contingent evaluation methods to appraise the WTP of direct final users for the EO service (*equation 8a*, Table 8). Alternatively, the revealed preference method can appraise the benefit by looking at the incremental efficacy or efficiency (or other profit margins) of final users delivering a public/private service using an EO application and a counterfactual group delivering the same service without using EO (*equation 8b*, Table 8). Unfortunately, incremental efficacy or efficiency information is not readily available in public datasets and should be collected through ad hoc surveys. Furthermore, this WTP should be net of the cost for producing the service sustained by downstream users as in the first part in both the alternative equations; however, regardless of the selection of the evaluation method, another criticality is that EO services often use EO data in combination with other sources. Hence, it becomes difficult to determine and allocate the paternity of EO data benefits (*quantification dilemma)* (PwC, 2016); therefore, quantitative analyses should be integrated with qualitative ones, such as arranging expert interviews.

Another critical issue is capturing the benefits along the final segment of the EO value chain (from direct to indirect users) and other non-market effects and positive externalities, such as improved air quality, reduced traffic accidents or lives saved thanks to EO service (EC, 2014). The benefits can be tremendous, although still unexpressed and mostly unmeasured. This quantification is uncommon within the space sector, where such effects are often discussed qualitatively. In this evaluation, welfare economists can offer significant support to the space community, adapting lessons learned from other subjects and using a plethora of tools to be considered, necessarily, case by case (EC, 2014) (See *equation 9*, Table 9). For example, to value the greenhouse gas (GHG) emissions saved thanks to EO services such as precision farming or air quality monitoring, EC, 2014 suggests estimating the amount of emission saved (e.g. in terms of t-CO_2 per unit of fuel burnt and kg CO_2 per kilometre travelled), calculate the CO_2 equivalent emissions using global warming potential and finally apply a unit cost for CO_2 equivalent expressed in Euro/tonne (EC, 2014). Similarly, non-market effects of EO services that allow for saving lives (e.g. Froment et al., 2020) or improving quality of life can be evaluated with different methods, including the value of the statistical life[8] and quality-adjusted life-years

[5] European Space Agency (ESA), *entry level and research programmes*: http://www.esa.int/About_Us/Careers_at_ESA/Entry_level_and_research_programmes (last access, June 2023).

[6] NASA SCIENCE, *learn science*: https://science.nasa.gov/learners/learner-opportunities (last access, June 2023).

[7] We conservatively focus on ECR's only as we assume that tenured professionals' careers and salary are influenced by other factors such as management capabilities, capability to attract funds etc. (Florio, 2019).

[8] This is the marginal rate of substitution between income (or wealth) and mortality.

Table 8
Value of knowledge of EO products and services for direct final users (8a and 8b are alternative methods).

	STAKEHOLDER & TYPE OF BENEFITS	ESTIMATION FORMULA	DESCRIPTION
8a	• *Direct final users* • Improved efficiency/ efficacy of public/private services provided	Willingness to pay for the service $\sum_{t=\lambda}^{T} \sum_{service=1}^{SERVICE} \text{Cost}_{service,\ t}/(1+sdr)^t - \sum_{d\_user=1}^{D\_USER} \sum_{service=1}^{SERVICE} \sum_{t=\lambda}^{T} \text{WTP}_{d\_user,\ service,\ t}/(1+sdr)^t$	Cost $_{service}$ = Cost of the service sustained by the intermediate users. *service* = (1, 2, 3… *SERVICE*) number of EO services or applications. *d_user* = (1, 2, 3… *D_USER*) number of direct final users of EO services or applications. $\Delta\pi_{service}$ = incremental efficacy or efficiency (or other profit margins) of final users delivering a service using an EO service or application and a counterfactual group delivering the same service without using EO. WTP = willingness to pay for the EO service or application. λ = time since the EO service or application became available to the final user.
8b	• Reduced Costs of provisions of public/private services provided • Improved revenues • Improved public/private services provided	Incremental efficacy or efficiency $\sum_{t=\lambda}^{T} \sum_{service=1}^{SERVICE} \text{Cost}_{service,\ t}/(1+sdr)^t - \sum_{d\_user=1}^{D\_USER} \sum_{service=1}^{SERVICE} \sum_{t=\lambda}^{T} \Delta\pi_{d\_user,\ service,\ t}/(1+sdr)^t$ $\sum_{t=\lambda}^{T} \sum_{service=1}^{SERVICE} \text{Cost}_{service,\ t}/(1+sdr)^t - \sum_{d\_user=1}^{D\_USER} \sum_{t=0}^{T} \frac{\Delta\pi_{service\ t}}{(1+sdr)^t}$	

Authors' elaboration. Note: *sdr* = social discount rate; t = (0, 1, 2, 3… *T*) = time horizon of the programme.

Table 9
Value of knowledge of EO products and services for indirect final users.

	STAKEHOLDER & TYPE OF BENEFITS	ESTIMATION FORMULA	DESCRIPTION
9	*Indirect final users* • Non-market effects *1)* Externalities	*Value of the externality* $\sum_{t=\lambda}^{T} \sum_{service=1}^{SERVICE} \text{EXT}_{service,\ t}$	EXT $_{service,}$ = externalities from the services and other non-market effects. λ = time since the service became available to final users.

Authors' elaboration. Note: *sdr*= social discount rate; t = (0, 1, 2, 3… *T*) = time horizon of the programme.

(QALY)[9] (Viscusi, 2008). Regardless, the analysis must always be based on the incremental approach, which compares the net benefits of a scenario 'with EO' with a counterfactual scenario without EO or with alternative solutions.

3.8. Benefits to users of EO data

Besides firms, a sizeable community of other users, including research institutes, students and simple citizens, can access and use EO data for different purposes. A critical benefit to this community relates to the mechanism of the *open data* model, which allows users to access free data with an interesting temporal resolution and low and medium spatial resolution, as in Copernicus and Landsat. Hence, users receive input for their activity openly and freely, boosting the number of uses in many fields (Pogorzelska, 2018).

In our framework, an effective way to appraise the benefits of free and open EO data is to adopt a contingent valuation method that effectively appraises the economic benefits of goods or services not bought and sold in markets (Portney, 1994). This method allows monetising the benefits through surveys that reveal the users' WTP or the amount they are willing to accept for not having access to the data (Miller et al., 2013), as in *equation 10* (Table 10). This method estimated the annual benefit for US users of Landsat imagery, which was approximately USD 1.8 billion in 2011, twice the cost of building and launching the Landsat 8 Operational Land Imager (NASA, 2021). Landsat imagery also provided domestic and international users an estimated USD 3.45 billion in benefits in 2017 (Straub et al., 2019). An alternative way to estimate this benefit can be by observing the cost or value of time saved by data users gauged in terms of the hourly salaries of the users multiplied by the time saved (see EC, 2014 for further details). Survey data might help estimate the time saved; however, an important issue is to avoid double counting. Indeed if open data have already contributed to firms' increased profit (see section 3.2.1), patents in other sectors (3.2.2), scientific publications (see section 3.2.5) or applications and services (see section 3.2.7), this benefit should not be counted twice. Moreover, in principle, only the difference in opportunity costs of access, compared to alternative data sources, are relevant; however, it must be stressed that there is no alternative to EO data in many cases, as aeroplanes or drones cannot cover any area of the planet in regular observation cycles.

3.9. Benefits accruing to users of leisure and cultural facilities related to EO

Another benefit of EO programmes is acquiring basic knowledge, culture and leisure via cultural facilities, including traditional media and social networks, citizen science and on-site tourist visits to the EO programme (Florio, 2019). Nowadays, millions of people visit different EO programmes daily by browsing the internet, accessing websites, watching videos online, reading books, reports and newspapers and engaging in discussions on different social media (including using ad hoc EO social media, e.g., Snapplanet[10]). Citizen science, which refers to various scientific activities and projects carried out by citizens, is also rapidly growing in EO, particularly in projects where people monitor the environment (see Fritz et al., 2017 for a complete discussion and lists of citizen science projects related to EO). Furthermore, scientific tourism has also become increasingly popular. Space programmes like the NASA *Kennedy Space centre* attract millions of visitors annually, and people are willing to travel from different places to visit exhibitions and guided tours and attend events with cultural and educational content.

From a CBA perspective, the marginal social value of this cultural and leisure benefit can be appraised by looking at the users' WTP for on-site or virtual visits at the RI, according to *equation 11* (Table 11). When resources are freely accessible, as in the case of social media or other internet resources, the opportunity cost of users' time can be a proxy for WTP. Hence, to estimate the benefit of virtual visits, it can be helpful to retrieve or estimate different analytics on web traffic volumes, such as the number of accesses and average time of the virtual visit, number of tweets, posts on Facebook and number of views per average video length (Del Rosario and Catalano, 2018). The opportunity costs of users' labour time can be estimated by studying the average salary (e.g. proxied by the

[9] This is a unit of measurement for valuing health outcomes. It is designed to capture in one single measure an individual's gain in utility from improvement in both quality of life and length of life. https://www.sciencedirect.com/topics/medicine-and-dentistry/quality-adjusted-life-year (last access, February 2023).

[10] SNAPPLANET: The social network for Earth observation https://copernicus-masters.com/winner/snapplanet-the-social-network-for-Earth-observation/ (last access, February 2023).

Table 10
Value of EO open data for users.

STAKEHOLDER & TYPE OF BENEFITS		ESTIMATION FORMULA	DESCRIPTION
10	*Users of EO open data* • Crucial input in the form of public good	Willingness to pay for open data $\sum_{od\_user=1}^{OD\_USER} \sum_{d=1}^{D} \sum_{t=\varepsilon}^{T} \text{WTP}_{od\_user\ d\ t} / (1+sdr)^t$	d= (1, 2, 3.. D) = number of open datasets. od_user = (1, 2, 3… OD_USER) number of users of different open datasets. **WTP** = willingness to pay (or willingness to accept). ε = time since EO data are available for elaboration in open mode.

Authors' elaboration. Note: sdr = social discount rate; t = (0, 1, 2, 3… T) = time horizon of the programme.

Table 11
Value of basic knowledge, culture and leisure for the general public.

STAKEHOLDER & TYPE OF BENEFITS		ESTIMATION FORMULA	DESCRIPTION
11	*Users of leisure and cultural facilities* • Acquisition of cultural and leisure utility	Willingness to pay for on-site or virtual visits $\sum_{g=1}^{G} \sum_{c=1}^{X} \sum_{t=0}^{T} \mathbf{WTP}_{gxt} / (1+sdr)^t$	x = (1, 2, 3… X) cultural and leisure goods generated by the EO programme. g = 1, 2, 3… G is the number of users of cultural and leisure goods. **WTP** = willingness to pay (or willingness to accept).

Authors' elaboration. Note: sdr = social discount rate; t = (0, 1, 2, 3… T) = time horizon of the programme.

gross domestic product per capita) in different users' countries and the number of working days per year to monetise the time spent using such leisure and cultural facilities (Feather and Shaw, 1999; Surdam, 2015; Del Rosario and Catalano, 2018). A similar approach can be used to appraise the value of leisure goods in traditional media.

Similarly, a common approach to proxy the WTP for a tourist trip is the *travel cost method*. This method captures the benefit obtained from visiting a place that cannot be inferior to the cost of reaching the site, including accommodation and on-site expenditures and the opportunity cost of time and labour (Clawson and Knetsch, 2013; Feather and Shaw, 1999). This information can be retrieved by looking at statistical visitors from different geographical areas and estimating the weighted average travel costs (see Del Rosario and Catalano, 2018 for further details); however, this approach suffers from several limitations as a trip is usually made for several purposes, and ordinary citizens are also interested in learning about several space domains, not only EO. Therefore, it is not easy to apportion; however, statistics from social media platforms and websites may provide fine-grain information on the interest of individual users on different subjects, providing a direct counterfactual about the options for allocating leisure time.

Another method consists of estimating the WTP through an ad hoc survey with the well know limitations, but also with the advice offered by the literature in this area, specifically in environmental economics (Arrow et al., 1993; Johnston et al., 2017; Florio, 2019; Giffoni and Florio, 2023), including the possible distortive effect of an increased use of resources as result of the increased efficiency, namely the Javons' paradox (Alcott, 2005).

3.10. Non-use value of EO

In CBA, the non-use value refers to the value people place on the infrastructure, even if they do not directly use or benefit from it. Non-use values are typically divided into option and existence values. *Option value* refers to the value people place on the ability to use space infrastructure at some point (Graham, 1981). For example, people may be willing to pay to support the development of EO infrastructure because they believe it could be valuable for future generations, even if they do not expect to use it themselves. *Existence value* refers to the value people place on knowing that the infrastructure exists, even if they do not plan to use it or directly benefit from it. This value is often associated with the desire to expand human knowledge and understanding and monitor the Earth. Including non-use values can be crucial in providing a more comprehensive understanding of the value of the infrastructure beyond direct economic benefits. Florio and Giffoni (2020) provide an in-depth discussion on non-use values and the WTP of generic taxpayers for large-scale projects (formula 12, Table 12). They use contingent evaluation methods to estimate the non-use value of the potential future particle accelerators at CERN.

Conclusions

This paper identifies and addresses challenges for analysing the socio-economic impact of high-tech infrastructures providing knowledge services and technological advancement.

The main challenge lies in setting a metric and attaching a value to intangible outputs, such as knowledge, while understanding transmission mechanisms along the value chain and the diverse community of stakeholders. Identifying new evaluation approaches that the traditional literature has never contemplated becomes crucial, for instance, to estimate the value of innovation generated through learning mechanisms, technological spillovers, open data and scientific publications, amongst others. Hence, this study represents an unexplored area compared to traditional transport, energy or other infrastructure CBA.

After assessing other current evaluation approaches, this paper suggests a new framework with an application to EO. We also appreciate the integration of quantitative methods with qualitative ones, particularly to determine the paternity of EO benefits (*quantification dilemma)*. From this perspective, solving the analytical issues in the EO sector is helpful in other contexts that share the same importance for governments investing in science and high-tech infrastructures generating knowledge.

A new contribution of our study is how it considers multiple and heterogeneous stakeholders, including firms, users of ICT systems, early career researchers, the scientific community, final users of EO services and applications and users of cultural facilities and society at large. To the best of our understanding, no other paper has tried to theoretically integrate the different impacts of knowledge creation in this field. Disentangling the benefits from a theoretical and an empirical perspective

Table 12
Non-use value.

STAKEHOLDER & TYPE OF BENEFITS		ESTIMATION FORMULA	DESCRIPTION
12	*Existence and Option Value*	$\sum_{t=1}^{T} \mathbf{WTP}_{taxpayer\ t} / (1+sdr)^t$	$\mathbf{WTP}_{taxpayer\ t}$ = willingness to pay (or willingness to accept) of taxpayers.

Authors' elaboration. Note: sdr = social discount rate; t = (0, 1, 2, 3… T) = time horizon of the programme.

for each stakeholder without double counting and omissions is critically important, which is unsystematically done in earlier literature. Hence, the infrastructure's NPV is given by the sum of the benefits accruing to these stakeholders, less the social costs, everything discounted.

We believe such challenges are encountered in other high-tech and science-based sectors and infrastructures. Although our contribution moves the assessment of public infrastructures forward, some caveats remain.

1) First, in our framework, benefits (and costs) are always expressed in monetary values even when they are not market goods such as saved human lives or air quality improvement. Furthermore, when the NPV is positive, the EO programme brings a positive value to society, regardless of its financial profitability. Given the externalities implied in EO (and similar knowledge-creating programmes), it is important not to misunderstand that any monetary value is just a metric and is unrelated to market prices, which can be non-existent or biased in social welfare terms.
2) Second, in ex-ante evaluations, forecasted benefits and costs are stochastic variables and should be considered at their expected value arising from an underlying probability distribution, according to the risk analysis framework. Moreover, we avoid uncertainty, which is crucial to forecast the social impact of the infrastructure, because of the stochastic nature of many variables involved in the computation, something that should be discussed more in-depth in ex-ante evaluations of EO programmes (EC, 2014).
3) Third, a qualitative analysis is suitable to identify other benefits, such as the strategic value of undertaking the EO programme (including defence, national security, environmental movements and peace), but this paper does not consider these.
4) Fourth, our approach is conservative and comprehensive and facilitates the identification and estimation of different types of benefits along the value chain; however, it may create problems because some benefits may be interrelated with each other or a clear distinction amongst stakeholders (e.g. upstream, midstream and downstream) is not always obvious. Hence, it is essential to carefully identify, discuss and avoid possible overlapping and double counting between benefits accruing to each actor category.

Despite the abovementioned limitations, the current study has implications for space agencies and national government planning processes, as this study emphasises the ability of our approach to appreciate the socio-economic impact of EO infrastructures. A clear and reliable understanding of the overall value - economic, social and environmental - of these cutting-edge infrastructures can increase awareness and willingness of society to engage in these large-scale, long-term public investment; moreover, it can provide decision-makers with the tool to correctly direct limited resources toward innovative solutions that target social and environmental needs besides economic growth. While this contribution is relevant for EO infrastructures, considering the pervasive diffusion of its use and applications, it is even more relevant to consider how the framework we delivered with this paper can serve as a model to other public, high-tech, science-based or extensive research infrastructure increasingly important for citizens and societies and still object of public investment and evaluation.

CRediT authorship contribution statement

Valentina Morretta: Conceptualization, Methodology, Writing – original draft. **Massimo Florio:** Validation, Writing – original draft, Supervision. **Matteo Landoni:** Writing – review & editing, Supervision, Project administration.

Data availability

No data was used for the research described in the article.

References

Åberg, S., Bengtson, A., 2015. Does CERN procurement result in innovation? Innov.: Eur. J. Soc. Sci. Res. 28 (3), 360–383.
Aghion, P., Jaravel, X., 2015. Knowledge spillovers, innovation and growth. Econ. J. 125 (583), 533–573.
Alcott, B, 2005. Jevons' paradox. Ecol. Econ. 54 (1), 9–21.
Anderson, J., Asaadi, J., Carls, B., Cotta, R., Guenette, R., Kiburg, B., & Penning, B. (2013a). Snowmass 2013 *young physicists science and career survey report*. arXiv preprint arXiv:1307.8080.
Anderson, J., Brock, R., Gershtein, Y., Hadley, N., Harrison, M., Narain, M., & Prebys, E. (2013b). *Benefits to the US from physicists working at accelerators overseas*. arXiv preprint arXiv:1312.4884.
Arrow, K., Solow, R., Portney, P.R., Leamer, E.E., Radner, R., Schuman, H., 1993. Report of the NOAA panel on contingent valuation. Fed. Regist. 58, 4601–4614.
Arrow, K., 1962. The economic implications of learning by doing. Rev. Econ. Stud. 29 (3).
Autio, E., Bianchi-Streit, M., Hameri, A.-P., 2003. Technology Transfer and Technological Learning Through CERN's Procurement Activity. CERN, Geneva. CENR 2003–005.
Autio, E., Hameri, A.P., Vuola, O., 2004. A framework of industrial knowledge spillovers in big-science centers. Res Policy 33 (1), 107–126.
B.E.T.A, 1988. Study of the Economic Effects of European Space Expenditure. *Technical report, Results Vol. 1, Reports for the European Space Agency*. Université Louis Pasteur, Bureau d'Économie Théorique et Appliquée of the University of Strasbourg, Strasbourg.
B.E.T.A, 1989. Indirect Economic Effects of ESA Contracts on the Canadian Economy. Université Louis Pasteur, Bureau d'Économie Théorique et Appliquée of the University of StrasbourgBureau d'économie théorique et appliquée, Strasbourg.
B.E.T.A, 1980. Economic Benefits from ESA contracts. *Technical report, Final Reports For the European Space Agency*. Université Louis Pasteur, Bureau d'Économie Théorique et Appliquée of the University of Strasbourg, Strasbourg.
Bach, L., Cohendet, P., Schenk, É., 2002. Technological transfers from the European space programs: a dynamic view and comparison with other R&D projects. J. Technol. Transf. 27 (4), 321–338.
Bastianin, A., Castelnovo, P., Florio, M., Giunta, A, 2021. Big science and innovation: gestation lag from procurement to patents for CERN suppliers. J. Technol. Transf. 1–25.
Battistoni, G., Genco, M., Marsilio, M., Pancotti, C., Rossi, S., Vignetti, S., 2016. Cost–benefit analysis of applied research infrastructure. Evidence from health care. Technol. Forecast. Soc. Change 112, 79–91.
Boardman, A.E., Greenberg, D.H., Vining, A.R., Weimer, D.L., 2018. Cost-Benefit Analysis: Concepts and Practice. Cambridge University Press.
Boisot, M., Nordberg, M., Yami, S., Nicquevert, B., 2011. Collisions and Collaboration: The Organization of Learning in the ATLAS Experiment at the LHC. Oxford University Press.
Booz & Co, 2011. Cost-benefit Analysis For GMES. European Commission: Directorate-General For Enterprise & Industry. https://www.copernicus.eu/sites/default/files/2018-10/ec_gmes_cba_final_en.pdf.
Borzacchiello, M.T., Craglia, M, 2011. Socioeconomic Benefits from the Use of Earth observation. JRC Scientific and Technical Reports, Publication Office, Luxembourg.
Bozeman, B., 2000. Technology transfer and public policy: a review of research and theory. Res. Policy 29 (4–5), 627–655.
Breidert, C., 2007. Estimation of Willingness-to-Pay: Theory, Measurement, Application. Springer Science & Business Media, Berlin.
Buhr, W., 2003. What is infrastructure? Department of Economics, School of Economic Disciplines, University of Siegen, Siegen. Discussion Paper No. 107-03. https://www.econstor.eu/handle/10419/83199.
Camporesi, T, 2001. High-energy physics as a career springboard. Eur. J. Phys. 22 (2), 139.
Camporesi, T., Catalano, G., Florio, M., Giffoni, F., 2017. Experiential learning in high energy physics: a survey of students at the LHC. Eur. J. Phys. 38 (2), 025703, 2017.
Canadian Space Agency (2019) The state of the Canadian soace sector report 2019, https://asc-csa.gc.ca/pdf/eng/publications/2019-state-canadian-space-sector-v2.pdf.
Carrazza, S., Ferrara, A., Salini, S., 2016. Research infrastructures in the LHC era: a scientometric approach. Technol. Forecast. Soc. Change 112, 121–133.
Castelnovo, P., Florio, M., Forte, S., Rossi, L., Sirtori, E., 2018. The economic impact of technological procurement for large-scale research infrastructures: evidence from the Large Hadron Collider at CERN. Res. Policy 47 (9), 1853–1867.
Catalano, G., Giffoni, F., Morretta, V., 2021b. Human and social capital accumulation within Research Infrastructures: the case of CER. Ann. Public Cooperat. Econ. https://doi.org/10.1111/apce.12317.
Catalano, G., López, G.G., Sánchez, A., Vignetti, S., 2021a. From scientific experiments to innovation: impact pathways of a Synchrotron Light Facility. Ann. Public Cooperat. Econ.
Clawson, M., Knetsch, J.L., 2013. Economics of Outdoor Recreation. Abingdon, Routledge.
Cohen, W.M., Levinthal, D.A, 1990. Absorptive capacity: a new perspective on learning and innovation. Adm. Sci. Q. 35 (1), 128–152.
Cohendet, P., 1997. Evaluating the industrial indirect effects of technology programmes: the case of the European Space Agency (ESA) programmes. In: Proceedings of the OECD Conference" Policy Evaluation in Innovation and Technology", BETA. Strasbourg, France. Université Louis Pasteur. *Available on*-line. http://www.oecd.org/dataoecd/3/37/1822844.pdf.
CORDIS (2019). *Tools for open multi-risk assessment using Earth observation data*. https://cordis.europa.eu/project/id/269115 (last access, February 2023).

Craglia, M., Pogorzelska, K., 2019. The economic value of digital earth. Manual of Digital Earth. Springer, Berlin, pp. 623–643.
Dawes, S., Burke, G., Pash, A., Dye, T., 2013. Socioeconomic Benefits of Adding NASA Satellite Data to AirNo. NASA. https://www.ctg.albany.edu/media/pubs/pdfs/sti_finalreport.pdf (last access, February 2023).
Del Rosario Crespo Garrido, I., & Catalano, G. (2018). *Cultural effects at CERN* (No. CERN-ACC-2018-0048). FCC-DRAFT-MGMT-2018-003.
Dolado, J.J, 2001. On the problem of the software cost function. Inf. Softw. Technol. 43 (1), 61–72.
Drèze, J., Stern, N., 1990. Policy reform, shadow prices, and market prices. J. Public Econ. 42 (1), 1–45.
Dupuit, J., 1844. De la mesure de l'utilité des travaux publics, *Annales des Ponts et Chaussees*, 2d ser., Vol. VII, reprinted in *Revue française d'économie* 10.2 (1995): 55-94. Translated by Barback, R. H. (1952). On the Measurement of the Utility of Public Works. Int. Econ. Pap. (2).
EARSC, (2019). *A survey into the state & health of the European EO service industry*. EARSC, the European Association of remote sensing companies, https://space-economy.esa.int/storage/downloads/mEScTp8RvRsxSb8WHHMGqQMnEl2r1BN44C8hFpos.pdf.
EARSC, (2023), *Case Gallery. Long study report*. EARSC, the European Association of remote sensing companies, https://earsc.org/sebs/all-cases/.
EC- European Commission (2014). *Guide to cost-benefit analysis of investment* projects. Economic appraisal tool for Cohesion Policy. https://ec.europa.eu/regional_policy/sources/docgener/studies/pdf/cba_guide.pdf.
EC- European Commission (2019). *European Research infrastructure what research infrastructures are, what the Commission is doing, strategy areas, funding and new*, https://ec.europa.eu/info/research-and-innovation/strategy/european-research-infrastructures_en.
Edquist, C., Hommen, L., Tsipouri, L., Tsipouri, L.J, 2000. Public Technology Procurement and Innovation, 16. Springer Science & Business Media.
ESA, 2019. Projects, *EO Science for Society*. European Space Agency. https://eo4society.esa.int/projects/.
ESFRI (2018) 'Roadmap and strategy report on research infrastructure' http://roadmap2018.esfri.eu/media/1066/esfri-roadmap-2018.pdf.
EUSPA (2022). *Earth Observation Market*, European Union Agency for the space programme, https://www.euspa.europa.eu/european-space/euspace-market/Earth-observation-market.
Eumetsat, 2014. The Case for EPS/Metop Second Generation: Cost Benefit Analysis - Full Report, European Organisation for the Exploitation of Meteorological Satellites. Darmstadt. https://www.wmo.int/pages/prog/sat/meetings/documents/PSTG-3_Doc_11-04_MetOP-SG.pdf.
Euroconsult (2019) *Satellite-Based Earth Observation Market Prospects to 2028,* https://www.euroconsult-ec.com/31_October_2019#:~:text=Paris%2C%20Washington%20D.C.%2C%20Montreal%2C,services%20derived%20from%20Earth%20observation (last access June 2023).
FAA, 2010. Commercial Space Transportation: 2009 Year in Review, Federal Aviation. Administration's Office of Commercial Space Transportation (FAA/AST), Washington, DC.
Fabre, R., Egret, D., Schöpfel, J., Azeroual, O, 2021. Evaluating the scientific impact of research infrastructures: the role of current research information systems. Quant. Sci. Stud. 2 (1), 42–64.
Feather, P., Shaw, W.D., 1999. Estimating the cost of leisure time for recreation demand models. J. Environ. Econ. Manag. 38 (1), 49–65.
Florio, M, 2019. Investing in Science: Social Cost-Benefit Analysis of Research Infrastructures. MIT Press, Cambridge.
Florio, M., Giffoni, F., 2020. A contingent valuation experiment about future particle accelerators at CERN. PLoS One 15 (3), e0229885.
Florio, M., Morretta, V., 2021. Earth observation and economic studies: a cross-fertilisation perspective. Space Policy 57, 101429.
Florio, M., Sirtori, E., 2016. Social benefits and costs of large scale research infrastructures. Technol. Forecast. Soc. Change 112, 65–78.
Florio, M., Forte, S., Sirtori, E., 2016a. Forecasting the socioeconomic impact of the Large Hadron Collider: a cost–benefit analysis to 2025 and beyond. Technol. Forecast. Soc. Change 112, 38–53.
Florio, M., Forte, S., Pancotti, C., Sirtori, E., Vignetti, S., 2016b. Exploring cost-benefit analysis of research, development and innovation infrastructures: an evaluation framework. Dev. Innov. Infrastruct.: Eval. Framework *(February 2016)*.
Florio, M., Pancotti, C., 2023. Applied Welfare Economics. Abingdon, Routledge.
Fritz, S., Costa Fonte, C., See, L., 2017. The role of citizen science in Earth observation. Rem. Sens. (Basel) 9 (4), 357.
Froment, R., et al., 2020. Use of Earth observation Satellites to Improve Effectiveness of Humanitarian Interventions. UCL-Université Catholique de Louvain, p. 2020. *STENTOR report. 2020.* No.
Gadd, H., Hansson, G., Månsson, J., 2009. Evaluating the Impact of Firm Subsidy Using a Multilevel Propensity Score Approach. Centre for Labour Market Policy Research (CAFO), School of Management and Economics, Vähjö University. *Working Paper Series* n. 3.
Gallo, J., Bernknopf, R., Lev, S., 2018. Measuring the socioeconomic value of data and information product derived from Earth observations and other geospatial product. In: Kruse, J.B., Crompvoets, J., Pearlman, F. (Eds.), GEOValue: the Socioeconomic Value of Geospatial Information. Taylor & Francis Group, London, pp. 33–48.
GEO - Group on Earth Observations, 2020. What is Earth observation? https://www.Earthobservations.org/g_faq.html.
Georgescu, A., 2020. Critical Space Infrastructures. Edseds. In: Schrogl, K.-U., Hays, P.L., Robinson, J., Moura, D., Giannopapa, C. (Eds.), Handbook of Space Security. Springer, New York, United States of America, pp. 227–244.
Giffoni, F., Vignetti, S., 2019. Assessing the socioeconomic impact of research infrastructures: a systematic review of existing approaches and the role of cost-benefit analysis. L'industria 40 (1), 75–102.
Graham, D.A., 1981. Cost-benefit analysis under uncertainty. Am. Econ. Rev. 71 (4), 715–725.
Gray, M, 2015. Public Weather Service Value for Money Review. UK Met Office, London. https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/about-us/what-we-do/public-weather-service/pws_value_for_money_review_-_march_2015.pdf (last accessed June 2023).
Hall, B.H., Griliches, Z., Hausman, J.A., 1986. Patents and R&D: is there a lag? Int. Econ. Rev. 27 (2), 265–283.
Halsing, D., Theissen, K., Bernknopf, R.L., 2004. A Cost-Benefit Analysis of The National Map, 1271. US Department of the Interior, US Geological Survey.
Harrison, M. (2010). Valuing the Future: the social discount rate in cost-benefit analysis. *Available at SSRN 1599963*.
Harzing, A.W., 2010. The Publish or Perish Book: Your guide to Effective and Responsible Citation Analysis. Tarma Software Research, Melbourne.
Hof, B., Koopmans, C., Lieshout, R., Wokke, F. (2012). *Design of a Methodology to Evaluate the Direct and Indirect Economic and Social Benefits of Public Investments in Space*. SEO rapport, 42.
Im, J., 2020. Earth observations and geographic information science for sustainable development goals. GISci. Rem. Sens. (Basel) 57, 591–592.
Jacob, M., Hallonsten, O., 2012. The persistence of big science and megascience in research and innovation policy. Sci. Public Policy 39 (4), 411–415.
Jaffe, A.B., Trajtenberg, M., Fogarty, M.S, 2000. Knowledge spillovers and patent citations: evidence from a survey of inventors. Am. Econ. Rev. 90 (2), 215–218.
Johnston, R.J., Boyle, K.J., Adamowicz, W., Bennett, J., Brouwer, R., Cameron, T.A., et al., 2017. Contemporary guidance for stated preference studies. J. Assoc. Environ. Resour. Econ. 4, 319–405. https://doi.org/10.1086/691697.
Koundouri, P., Chatzistamoulou, N., Davila, G., Giannouli, A., Kourogenis, N., Xepapadeas, A., Xepapadeas, P., 2021. Open Access in scientific Information: sustainability model and business plan for the infrastructure and organisation of OpenAIRE. J. Benefit-Cost Anal. 12 (1), 170–198.
Lafaye, M., 2017. Benefit assessment of the application of satellite Earth observation for society and policy: assessing the socioeconomic impacts of the development of downstream space-based Earth observation applications. Satellite Earth Observations and Their Impact on Society and Policy. Springer, Singapore, pp. 93–103.
Macauley, M.K., 2006. The value of information: measuring the contribution of space-derived Earth science data to resource management. Space Policy 22 (4), 274–282.
Malone, T.W., Bernstein, M.S, 2015. Handbook of Collective Intelligence. MIT Press, Cambridge.
Martin, B.R., Tang, P., 2007. The Benefits from Publicly Funded Research. Science Policy Research Unit, University of Sussex.
Mathieu, P., Aubrechtv, C, 2018. Earth Observation Open Science and Innovation. Springer Nature, p. 2018.
Miller, H.M., Richardson, L., Koontz, S.R., et al., 2013. Users, Uses, and Value of Landsat Satellite Imagery—Results from the 2012 Survey of users, File report 2013–1269. US Geological Survey. https://pubs.usgs.gov/of/2013/1269/pdf/of2013-1269.pdf.
Mincer, J., 1974. Schooling, experience, and earnings. Hum. Behav. Soc. Instit. (2).
Mouqué, D., 2012. *What Are Counterfactual Impact Evaluations Teaching Us About Enterprise and Innovation Support?*, Regional Focus, 02/2012, DG Regional and Urban Policy. European Commission, Brussels.
NASA (2013). *Nasa socio –economic impacts.* April 2013. Report by The Tauri Group. https://www.nist.gov/system/files/documents/2017/05/09/NASA-Socio-Economic-Impacts-2013_SEINSI.pdf.
NASA (2017). *NASA's technology transfer activities*, Nov. 20, 2012 (Last Updated: Aug 7, 2017), https://www.nasa.gov/open/technology-transfer.html.
NASA (2021). Landsat, https://www.nasa.gov/mission_pages/landsat/main/index.html.
OECD, 2007. The Space Economy at Glance. OECD, Paris. https://www.oecd-ilibrary.org/docserver/9789264040847-en.pdf?expires=1616590126&id=id&accname=guest&checksum=E0E7BE0945823EB7DDAF283A5F81510E.
OECD, 2014. Report on the Impacts of Large Research Infrastructures on Economic Innovation and on Society. Global Science Forum report, OECD Publishing, Paris. Case studies at CERN.
OECD, 2019. The Space Economy in Figures: How Space Contributes to the Global Economy. OECD Publishing, Paris. https://doi.org/10.1787/c5996201-en.
OECD, 2021. Space economy for people, planet and prosperity. In: OECD paper for the G20 Space Economy Leaders' Meeting, Rome, 20-21 September 2021. https://www.oecd.org/sti/inno/space-forum/space-economy-for-people-planet-and-prosperity.pdf.
OECD, 2020. Space sustainability The economics of space debris in perspective. In: Undseth, M., Jolly, C., Olivari, M. (Eds.), *OECD Science, Technology and Industry Policy Papers*, No. 87. OECD Publishing, Paris. https://doi.org/10.1787/a339de43-en.
Petroni, G., Verbano, C., 2000. The development of a technology transfer strategy in the aerospace industry: the case of the Italian Space Agency. Technovation 20 (7), 345–351.
Pogorzelska, K., 2018. EOVALUE: Review of EO Market Studies. European Commission Joint Research Centre, Ispra. https://ec.europa.eu/jrc/communities/sites/jrccties/files/eovalue_d2.1_revieweomarket_studies_v1.pdf.
Portney, P.R., 1994. The contingent valuation debate: why economists should care. J. Econ. Perspect. 8 (4), 3–17.
PwC (2016) Study to examine the socioeconomic impact of Copernicus in the EU Report on the Copernicus downstream sector and user benefits October 2016.

PwC, 2016b. Socioeconomic Impacts form Space Activities in the EU in 2015 and Beyond – June 2016. European Commission.

PwC (2019). *Copernicus market report*, 164 pages, ISBN 978-92-79-98973-5, doi:10.2873/011961.

Raghu, T.S., Sinha, R., Vinze, A., Burton, O., 2009. Willingness to pay in an open source software environment. Inf. Syst. Res. 20 (2), 218–236.

Rodriguez-Donaire, S., Garcia-Almiñana, D., Garcia-Berenguer, M., et al., 2022. Strategic similarities between Earth observation small satellite constellations in very low Earth orbit and low-cost carriers by means of strategy canvas. CEAS Space J. 14, 767–784. https://doi.org/10.1007/s12567-022-00462-z.

Rousseau, S., Catalano, G., Daraio, C., 2020. Can we estimate a monetary value of scientific publications? Res. Policy 50 (1), 104116.

Salter, A.J., Martin, B.R., 2001. The economic benefits of publicly funded basic research: a critical review. Res. Policy 30 (3), 509–532.

Sawyer G., Boyle D., Khabarov N. (2020). G*round motion monitoring in Norway* European Association of remote sensing companies, sentinels benefits study (SeBS) https://earsc.org/sebs/wp-content/uploads/2020/07/Ground-Movement-Monitoring-in-Norway-final.pdf.

Sawyer, G., Oligschläger, C., Oligschläger, N., 2019. A Case Study: Growing Potatoes in Belgium, European Association of Remote Sensing Companies. Sentinels Benefits Study (SeBS). https://earsc.org/sebs/wp-content/uploads/2019/08/1_full-report-Growing-Potatoes-in-Belgium.pdf.

Schmookler, J., 1966. Invention and Economic Growth. Harvard U. Press, Cambridge.

Smart, A., Coote, A., Miller, B., Bernknopf, R., 2018. *A review of socioeconomic valuation methods and techniques,* chapter 10. In: Kruse, J.B., Crompvoets, J., Pearlman, F. (Eds.), (2018). *GEOValue: the Socioeconomic Value of Geospatial Information.* CRC Press.

Song, Y., Wu, P., 2021. Earth observation for sustainable infrastructure: a review. Rem. Sens. (Basel) 13 (8), 1528.

Squicciarini, M., Dernis, H., Criscuolo, C. (2013). Measuring patent quality: indicators of technological and economic value. https://www.oecd-ilibrary.org/science-and-technology/measuring-patent-quality_5k4522wkw1r8-en.

Straub, C.L., Koontz, S.R., Loomis, J.B., 2019. Economic Valuation of Landsat imagery. U. S. Geological Survey. Open-File Report 2019–1112doi.org/10.3133/ofr20191112.

Surdam, D.G., 2015. The economics of leisure. Century of the Leisured Masses: Entertainment and the Transformation of Twentieth-Century America. Oxford University Press.

Szalai, B., Detsis, E., Peeters, W., 2012. ESA space spin-offs benefits for the health sector. Acta Astronaut. 80, 1–7.

Tassa, A., 2019. The socioeconomic value of satellite Earth observations: huge, yet to be measured. J. Econ. Policy Reform. 23 (2020), 34–48, 1.

Tassey, G., 2004. Underinvestment in public good technologies. J. Technol. Transf. 30, 89–113.

Tassey, G., 2008. Modeling and measuring the economic roles of technology infrastructure. Econ. Innov. N. Technol. 17 (7–8), 615–629.

Thacker, S., Adshead, D., Fay, M., Hallegatte, S., Harvey, M., Meller, H., O'Regan, N., Rozenberg, J., Watkins, G., Hall, J.W., 2019. Infrastructure for sustainable development. Nat. Sustainabil. 2, 324–331.

UK Space Agency, 2010. The Size and Health of the UK Space Industry. Swindon.

Union of Concerned Scientists (2022), *UCS Satellite Database In-depth details on the 5,465 satellites currently orbiting Earth, including their country of origin, purpose, and other operational details*, May 1, 2022, https://www.ucsusa.org/resources/satellite-database (last access, 06/02/2023).

Venturini, K., Verbano, C., 2014. A systematic review of the Space technology transfer literature: research synthesis and emerging gaps. Space Policy 30 (2), 98–114.

Viscusi, W.Kip, 2008. How to value a life. J. Econ. Finance 32 (4), 311–323.

Waltman, L., van Eck, N.J., Wouters, P., 2013. Counting publications and citations: is more always better? J. Informetr. 7 (3), 635–641.

Weinzierl, M., 2018. Space, the final economic frontier. J. Econ. Perspect. 32 (2), 173–192.

WMO - World Meteorological Organisation (2015). *Valuing weather and climate: economic assessment of meteorological and hydrological services*. WMO N. 1153.

Yuan, H., Sun, M., Wang, Y., 2016. Assessment of the benefits of the Chinese public weather service. Meteorol. Appl. 23 (1), 132–139. https://doi.org/10.1002/met.1539.

Zhuang, J., Liang, Z., Lin, T., De Guzman, F. (2007). *Theory and practice in the choice of social discount rate for cost-benefit analysis: a survey* (No. 94). ERD working paper series.