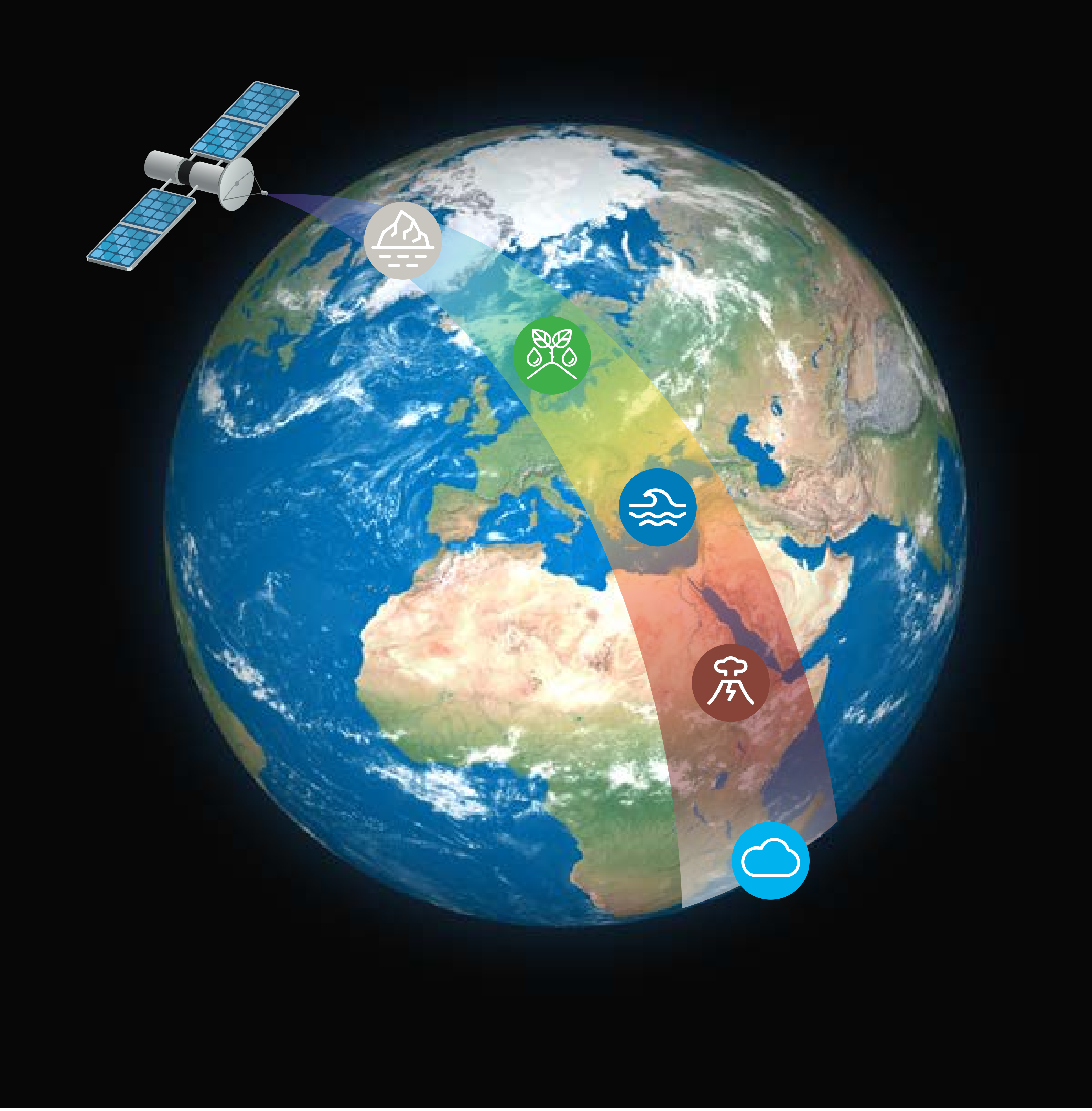

Earth observation research in the Netherlands

Strategic Plan 2020 - 2025

Colophon

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Earth observation research in the Netherlands

Strategic Plan 2020 - 2025

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1. Executive summary

This strategic plan is a joint effort on behalf of all Netherlands-based Earth Observation (EO) scientists. It is meant to inform both the scientific community itself and third parties, such as (national) government and science organizations, about the state of Earth observation research in the Netherlands and issues of common interest, as well as opportunities to increase strengths and opportunities for breakthrough developments. The document addresses EO research within the context of Earth sciences, whereby all sub-disciplines (atmosphere, land surface, solid earth, ice, oceans) are covered jointly. The overarching goal of this strategic plan is "*to strengthen and consolidate the position and coherence of Earth Observation research in the Netherlands*". It is a high-level strategic plan, addressing broad research lines and focussing on issues relevant to all sub-disciplines.
This strategy addresses the full chain of information needs, infrastructure developments and data applications, as well as the national support required to maintain this chain. In the context of this Strategic Plan, the term 'EO' refers to the use of satellites or other spaceborne platforms observing the Earth system. The objective of EO research is to improve the understanding of physical, chemical, biological and anthropogenic processes, feedbacks and interactions on Earth, as well as to devise effective tools to monitor such processes.

Global trends and societal challenges related to climate, environment, security, health, welfare and sustainable developments, require an enhanced and strategic response from many fields, including science. Many of such challenges are addressed in the international framework of the Sustainable Development Goals (SDG's). From the field of Earth sciences, an important part of the strategic response is aimed at a strongly improved understanding of 'System Earth'. EO research is a vital contributor to (scientific) progress in this field. The relevance of EO lies in the fact that it is the only available observation technique that can provide (near-)global coverage of the Earth, including remote and/or inaccessible land and ocean areas. Furthermore, it typically delivers sustained time series of observations, which are essential for monitoring and studying long-term global processes such as climate trends and landcover change. Satellite remote sensing complements and enhances other observation systems such as ground sensors or airborne observations. Alongside infrastructure in space, adequate infrastructure on the ground is therefore equally essential in order to optimize the use of satellite data for EO research. Such ground infrastructure can consist of e.g. measurement sites, modelling and computational infrastructures, and IT-related facilities for data access.

The most notable recent developments in EO are a strong increase in the number of satellites, and consequently, in the availability of satellite data, as well as the increase in spatial, spectral and temporal resolution of these data sets. Especially the EU's Copernicus EO programme, which provides free and open data and ensures continuity of observations, thus hugely facilitating the development of operational EO applications, is a game changer in the field. The quickly expanding availability of satellite data is prompting a rising use of data science technologies for EO, making it possible to analyse and integrate the significantly increased amounts of data and many different data types. All these aspects now greatly enhance the potential usefulness of EO for many scientific and societal challenges.

Netherlands-based EO scientists have built strong international positions along the full EO chain; from mission concept, design, development and operation, through data processing, retrieval algorithms, and modelling, to application in scientific and societal problems. EO research contributes to many questions outlined in the Dutch National Science Agenda (NWA), and provides essential information towards resolving many of the challenges outlined in the 'Knowledge and Innovation Agenda's' (KIA's) of the Dutch Topsectors. EO spin-off companies develop numerous applications in the private sector. However, in most EO research sub-disciplines, structural national collaborations are often lacking and the level of EO community organisation and representation is limited. The Dutch EO research field is perceived as fragmented.

A number of strategic challenges are outlined for various aspects of Dutch EO research. These concern aspects related to space infrastructure (sensors, instruments, observations), ground measurements (quality assessment, calibration, validation), modelling (algorithms, Earth System approach), data (integration, access and data science), people (collaboration, education) and programmatics (policy, funding). Based on these strategic challenges, seven key elements of the Dutch EO research strategy have been defined, each with a number of main objectives. The seven key elements of this research strategy are: 1. Excellent science, 2. Collaboration within EO research, 3. Optimal exploitation of national resources, 4. Connection to societal challenges, 5. Cultivation of EO infrastructure, 6. Connection to national and international research programmes/networks, 7. Education.

In a final step, recommendations have been extracted for each key strategic element, directed to both the scientific community and to government organisations and agencies. Main **recommendations to government organisations** are i) to foster, support and promote EO research, ii) to maintain/extend the current programmatic support for

Sentinel-5P with the Tropomi instrument on board for air quality monitoring. (© *ESA-ATG medialab*)

EO, and provide additional support especially for transfer of knowledge to societal applications and for EO education, and iii) to improve the balance between investments made in new satellite missions/instrumentation, in ground-based infrastructure (e.g. for calibration and validation of satellite data) and in data exploitation (data use).
Main **recommendations to the scientific community** are i) to utilize the full potential of available satellites, achieve an adequate modelling capacity, and exploit the resulting data to address scientific and societal challenges, ii) to increase interdisciplinary EO research and inter-community collaboration, iii) to synergetically exploit existing scientific/technological facilities, iv) to increase the contribution of EO research to SDG's, NWA and Topsectors/KIA's, v) to strengthen research activities aimed at calibration/validation, data exploitation and data science, vi) to optimize connections to (inter-)national research structures, and vii) to develop an integrated and coherent EO educational programme.
The complete recommendations can be found in chapter 7.

2

2. Introduction

Global trends and societal challenges related to climate, environment, security, health, welfare and sustainable developments, require an enhanced and strategic response from many fields, including from science. Importantly, many of such challenges are addressed in the international framework of the Sustainable Development Goals (SDG's). Nationally, in the Netherlands, many of these or similar challenges are being addressed in the research subjects of the National Science Agenda (NWA; Nationale Wetenschapsagenda). From the field of Earth sciences, an important part of the strategic response is aimed at a strongly improved understanding of 'System Earth'. Earth observation research is a vital contributor to (scientific) progress in this field.

Earth observation (EO), in general, is understood as a remote sensing technique to collect observations or data related to planet Earth, using sensors mounted on (stationary, moving or distant) platforms or vehicles. Here, the term 'EO' refers only to the use of satellites or other spaceborne platforms. Over the years, and in conjunction with the increasing capabilities of observation from space, the EO research field has developed into an indispensable contributor to the pursuit of a scientifically sound understanding of the current state of the Earth System, and its change over time. Hence, the objective of EO research is to improve our understanding of physical, chemical, biological and anthropogenic processes, feedbacks and interactions on Earth, as well as to devise effective tools to monitor such processes. As such, EO research supports a range of Earth science disciplines, such as climatology, agronomy, forestry, meteorology, oceanography, ecology, geology, soil science, hydrology, and civil and agricultural engineering. In this way, EO research contributes to addressing the global trends and challenges to the benefit of global societal developments.

EO research builds on a long scientific tradition dating back to the early 1970's, when the first satellite remote sensing data became available. Early developments typically took place within respective sub-disciplines of the Earth sciences (atmosphere, land surface, solid earth, ice, oceans), and Dutch EO research can boast of early successes in all of these. Netherlands (NL)-based scientists have built up strong international positions along the full EO chain; from mission concept, design, development and operation, through data processing, retrieval algorithms, and modelling, to application in scientific and societal problems. Depending on the specific scientific characteristics, each sub-discipline has its own focus, research objectives and achievements. Many scientists across the different sub-disciplines, however, perceive the Dutch EO research field as fragmented, and it is generally believed that scientific progress in this field will benefit from a stronger synergy between all sub-disciplines, leading to an enhanced scientific contribution to the global challenges mentioned above.

Therefore, scientists from all sub-disciplines of EO research have cooperatively developed this strategic plan, of which the overarching goal is "*to strengthen and consolidate the position and coherence of Earth Observation research in the Netherlands".* As such, the joint development and realization of this plan is already an important step towards this goal and it is beneficial to the EO research community itself. At the same time, the strategic plan is specifically meant to inform all relevant stakeholders outside the EO community, from scientists in near and more distant fields of science, to government organisations and funding agencies, on the relevance and urgency of Dutch EO research, the strategic developments that are taking place and are needed for the future, and the benefits Dutch and international society is expected to have from a strong and well-positioned Earth observation research community in the Netherlands.

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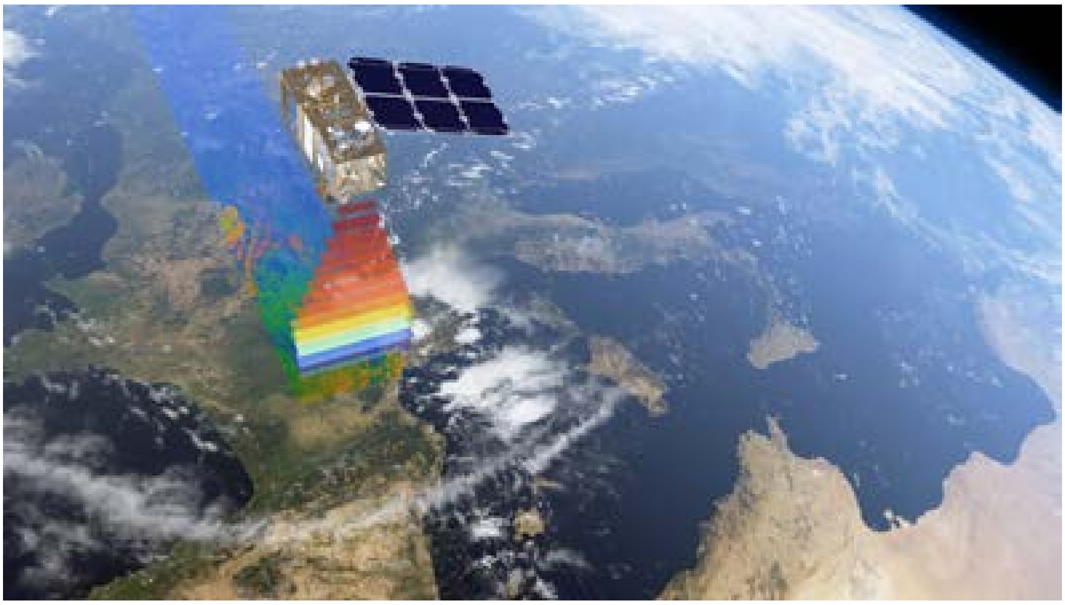
3. Scope, motivation and goal

The overarching goal of this strategic plan is "*to strengthen and consolidate the position and coherence of Earth Observation research in the Netherlands".*

An important strength of Earth Observation research is its **generic value** for many different sub-disciplines within the Earth sciences (e.g. atmosphere, land surface, hydrology, ecology, solid earth, ice, oceans). As a consequence, EO research expertise and activities in the Netherlands are distributed over several universities, groups and research institutes. EO scientists from each respective sub-discipline contribute to scientific and societal progress on overarching topics in climate and environmental science, and civil and agricultural engineering.
Amongst the various sub-disciplines, good positions have been established with respect to international organisations such as ESA, EUMETSAT, NASA, EU, GEO, UN, CEOS and ECMWF, as well as with other national and international science organisations, European EO projects, and funding agencies.

With the growing availability of EO data, possibilities of Earth system modelling and data science technology, and international needs for Earth system information, comes a growing need for further **collaborative efforts**. Specifically, this concerns interdisciplinary collaboration between different Earth Science subdomains and/or with other science domains, and a stronger dialogue with (non-academic) stakeholders in society, government and the commercial sector. Establishing a **greater coherence** within the full EO research community will strengthen its position, improve collaboration, and provide opportunities to address national and global challenges that cannot be addressed by individual or mono-disciplinary scientists alone.

Sea ice swirled into eddies caused by wind and ocean currents, observed by Sentinel-3B.
(© contains modified Copernicus Sentinel data (2018), processed by EUMETSAT, CC BY-SA 3.0 IGO)



Land monitoring by the Sentinel-2 multispectral mission. (© *ESA-ATG medialab*)

Such collaboration can be **scientific** and/or **infrastructural** in nature. An example is the recent joining of forces within the atmospheric research community in the Ruisdael Observatory, in order to address major themes of joint interest, notably water and carbon cycles, air pollutants, aerosols and their interactions. Another example is EPOS-NL, the Netherlands contribution to the European Plate Observing System, which has recently been established by the solid earth research community, and will address major themes of joint interest, notably the predictive modelling of the Earth's subsurface evolution.
The joint strategy laid out in this document aims to help strengthen the link between EO and infrastructures like Ruisdael and EPOS-NL, and other relevant Earth science initiatives related to (inter-)national large-scale infrastructures.

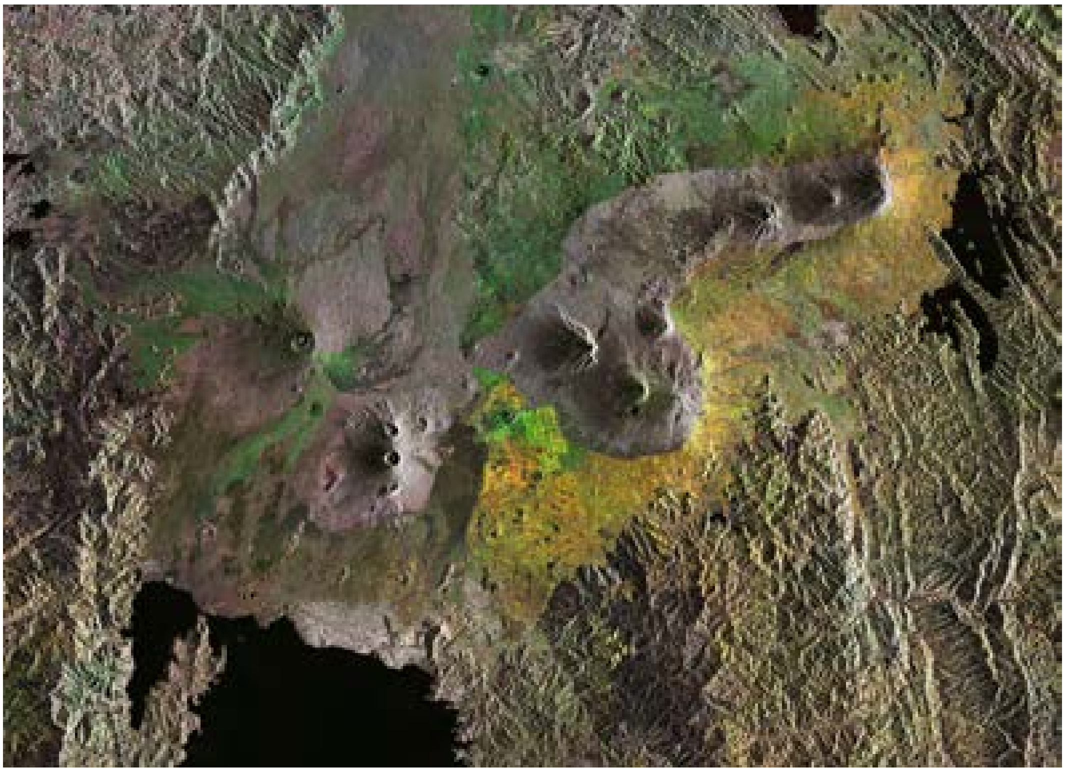
On a national level, the **societal relevance** of EO research is clear, but the embedding in the National Science Agenda and the Dutch Topsectors deserves particular attention. A stronger position of Dutch EO research within NWA and Topsectors will stimulate cooperation between the various research groups, as well as interaction with industry and other non-scientific stakeholders, strengthening the position of the Dutch remote sensing community.
Dutch consortia have been successful in the past in designing and developing new instrumentation, but application of the resulting data is as yet less developed. **Consortium building** on the data application side will position Dutch research more strongly within the landscape of European (research) funding programmes, and European and global research infrastructures for satellite data exploitation.

Overall, it is clear that both science and society can benefit much more from EO research when the position of the EO community *as a whole* becomes stronger, more embedded in both scientific and non-scientific communities, and more visible to all stakeholders in society.

Therefore, this document is a joint effort on behalf of the Dutch EO community to identify and address **shared goals and priorities**. It is meant to inform both the scientific community itself and third parties (e.g. (national) government and science organizations) about issues of common research that require more attention, as well as existing strengths and opportunities for new breakthrough developments. It also aims to help strengthen collaborations between EO research groups and make these collaborations more visible. This document identifies common interests and opportunities. It raises attention for the urgency of EO research in support of policy-making, and its contribution to issues related to human health, climate, environment, food security and biodiversity. This strategy addresses the full chain of information needs, infrastructure developments and data applications, as well as the national support required to maintain this chain.

The document is written by scientists from the Dutch EO research community[1]. It applies to **EO research** (cf. section 4.1) as part of the Earth sciences ((bio-)geosciences), whereby all sub-disciplines (atmosphere, land surface, solid earth, ice and oceans) are covered jointly. Within this (bio-)geoscientific framework, the developments, challenges and goals described here are those related to EO research (the use of satellite EO data) only.

This document is a **high-level strategic plan**, addressing broad research lines and focussing on issues relevant to all sub-disciplines. Detailed science questions and activities are not included, and specific sub-disciplinary considerations are left to research agendas in the respective fields.



Volcanoes in the Virunga Mountains, East Africa, captured by the Sentinel-1 radar mission. (© contains modified Copernicus Sentinel data (2016), processed by ESA, CC BY-SA 3.0 IGO)

[1] TUD, UU, VU, RUG, WUR, LEI, UT-ITC, UvA, KNMI, SRON, NIOZ, RIVM, TNO, Deltares

4

4. Relevance of Earth observation research; developments and opportunities

4.1 Description of Earth observation research

In order to achieve its objectives, the EO research field comprises activities related to the collection and (quality) assessment of raw and primary data (Level 0 and Level 1 data, respectively), retrieval of derived (bio-)geophysical products (Level 2 data), use or 'exploitation' (Level 3/4 data) and application of these data, see the table below.

Data collection	Data processing	Data exploitation & application
- Design and develop novel EO sensors and measurement techniques - Develop (raw/primary) data processing techniques and algorithms - Calibrate satellite observations, using on-ground or in-flight collected datasets	- Develop methods/algorithms for the retrieval of (bio-) geophysical and geochemical parameters from primary EO data - Develop data infrastructure for collecting, archiving, assimilating, interpreting and visualising of data - Assess (validate) and improve data quality, e.g. by comparison between satellite retrievals and independent measurements or data	- Improve understanding of (geo- and biophysical) processes by development of EO-based models describing Earth System processes or interactions - Develop methods to assimilate EO data, in-situ data, and expert knowledge, in order to reduce model/parameter uncertainty - Answer scientific questions or provide solutions to engineering and planning problems; Provide societal services (e.g. hazard monitoring, early warning)

In fundamental research, new information derived from the (scientific) exploitation of EO data is used to better understand (bio-)geophysical, natural and/or anthropogenic processes. A good example is the long-term monitoring of the formation and evolution of the Antarctic ozone hole. This includes the detection and quantification of trends, the interaction between observable variables and identification of causal relationships with external forces, the testing of hypotheses, the understanding and/or quantification of variables or processes of interest, and modelling/forecasting.
In applied research, EO data is used e.g. to generate management information for (policy) decision-making processes; to develop new remote sensing products for industry, government and science; to transfer scientific knowledge and capabilities to operational societal services (e.g. weather forecasting or environmental monitoring).

EO value chain: Satellite observations enable new user applications, and new user needs require new satellite solutions. EO scientists are involved throughout the whole chain.

4.2 Relevance of EO research

Satellite remote sensing as an observation technique offers unique capabilities that complement and enhance traditional surface-based and localized observation systems such as ground sensors or airborne observations. EO is the only available observation technique that can provide (near-)**global coverage** of the Earth, including remote and/or inaccessible land and ocean areas. For many parts of the world, ground-based data are scarce, not easily available, or absent, and EO data are the primary source of information. While the greater distance to the Earth impacts the data quality in terms of precision, accuracy and resolution in comparison to ground-based techniques, EO does have the advantage of using the same sensor globally, thus providing roughly uniform observation quality over immense areas. Furthermore, it is able to instantaneously provide a synoptic view of large regions, and it is unaffected by political borders. Altogether, this makes it a very useful technique to capture large-scale processes over the entire globe, and match global models of limited spatial resolution. Meanwhile, the spatial resolution of EO data is also becoming increasingly closer to, or even exceeds that of many high-resolution models and applications, including regional/local ones.

Long (e.g. (multi-)decadal) time-series are essential for monitoring and studying long-term global processes such as climate trends and landcover change. EO typically delivers such **long time-series** of observations of the same type, and with relatively high temporal sampling, since many satellites have multi-annual lifetimes and/or are replaced by follow-on satellites after they cease to be operational. Currently, detection, modelling and prediction of global change relies heavily on EO-detected trends, and linking the variability of EO-derived parameters to climatic factors. This involves knowledge of the fundamental physical and biogeochemical processes on Earth which determine our climate, weather, and land cover, but also the productivity of our agricultural systems, vulnerability of ecosystems and human settlements, and larger-scale (sub-)surface dynamics and geo-hazards.

Much EO data is **free and openly accessible**, stimulating its use in new applications, often in combination with complementary data from other sources like in-situ or airborne data. Thanks to the above, EO research contributes significantly to filling existing knowledge gaps related to Earth science. At the same time, it supports scientists in supplying the information required for (operational) applications and by policy makers developing relevant legislation. The added value of EO to industry and the economy has been shown in independent studies, indicating that e.g. investments in the EU Copernicus programme have led to a tenfold economic benefit thanks to better decisions, more efficient policy implementation, and savings due to better preparedness in case of natural disasters[2].

There are also important intrinsic **limitations** to EO. In general, a single technique like satellite remote sensing will often not provide all the necessary information, and thus needs to be augmented with other observing techniques. In terms of resolution, the superiority of one method over the other (e.g. satellite vs. Unmanned Aerial Vehicles (UAV's or drones) or surface measurements) will depend, among others, on the (spatial or temporal) scale of the problem at hand. Actual limitations of satellite remote sensing are mainly related to factors such as complexity, inflexibility, expense and reach. Satellite remote sensing is an indirect way of measuring, and requires calibration and validation of the geophysical products to international standards.

4.3 Timeliness of EO research

The urgency of mitigating global change has been emphasized in international agreements and protocols. Earth's **changing climate** manifests itself in many different ways, for example through increasing atmospheric temperatures and meteorological variability, warming and acidifying oceans, rising sea level, extreme events (e.g. floods, droughts), melting ice sheets and glaciers, changing ecology and land use, and increasing geo-hazards. EO research offers a capability for observing the status of the climate system and monitoring changes, in support of climate change mitigation actions and adaptation processes.

The world's **population is growing**, leading to new and more intense interactions between human activities and Earth's System. This becomes evident in relation not only to climate change, but also to the availability/management of natural resources, food security, energy transition, mineral exploration, air pollution, and natural hazards. Society increasingly relies on EO research and applications to help address these challenges, through the provision of knowledge and support to operational applications. This can

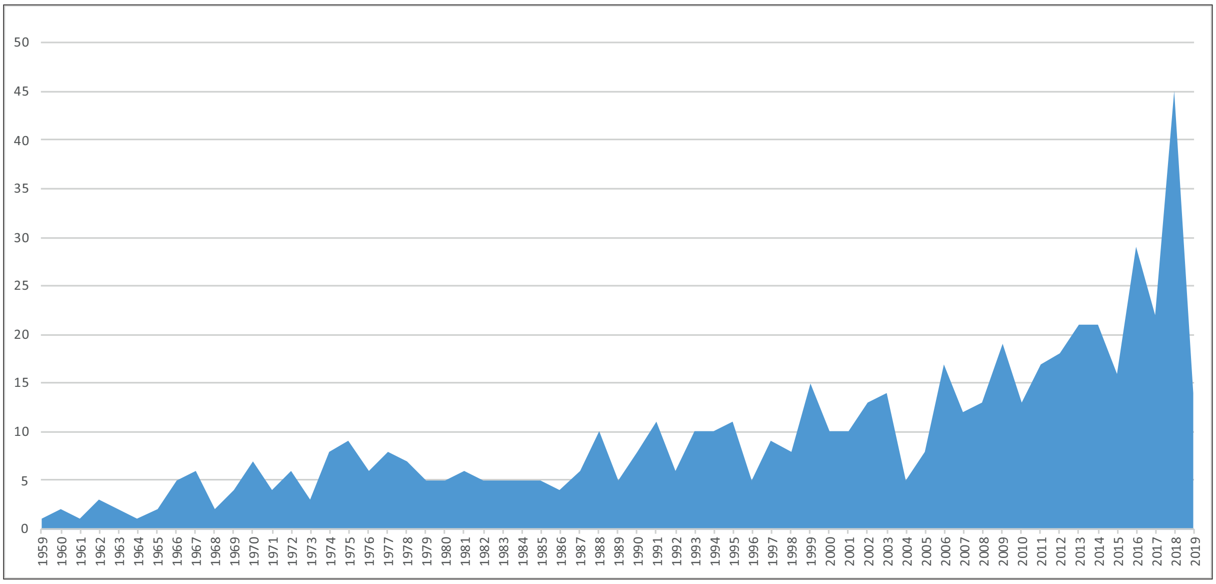
[2] https://link.springer.com/chapter/10.1007/978-981-10-3713-9_5#CR2

range from informed decision-making processes for policy makers and economists to emergency management/response (e.g. by providing data in Near Real Time). Nowadays, these societal applications demand not only descriptive, but also predictive knowledge, in order to prevent, mitigate and/or adapt to changing circumstances. EO data are essential input in many land surface, atmospheric and oceanographic models, used to simulate and forecast the behaviour of various environmental processes. As such, sustained EO data in combination with long-term modelling efforts will be instrumental in supporting the move towards a more sustainable and resilient society. Many of the issues at hand are addressed in the UN Sustainable Development Goals.

Besides changing environmental conditions, the timeliness of EO research is also related to recent **technological and infrastructural advances**. The full exploitation of the growing availability of data (including Near Real Time (NRT) availability of operational information) is made possible through the use of conventional, physically-based modelling and data assimilation, as well as new Artificial Intelligence (AI)-based data science approaches.

4.4 Main developments in the EO research domain

One of the most notable developments of the current period is a strong increase in the **number** of satellite platforms and virtual constellations, and consequently, in the availability of satellite data of various types, coverage, and quality. A key example are the Sentinel satellites of the EU-ESA Copernicus EO programme, which provides free and open data and promises continuity of observations. Furthermore, many other institutional and commercial EO satellites are already available or are being planned for operations in the next few years. This has led to strong improvements in the availability, accessibility, continuity and reliability of EO data, benefitting not only EO research, but the broader Earth sciences community, industry and society as a whole, by hugely facilitating the development of operational EO applications.



Number of EO satellites launched per year. Numbers taken from WMO OSCAR (World Meteorological Organisation - Observing Systems Capability Analysis and Review Tool https://www.wmo-sat.info/oscar/satellites).

The potential usefulness of EO data for many scientific and societal challenges is enhanced by the increase in spatial, spectral and temporal **resolution** of the collected EO data sets. In part, the increase in the amount, resolution, and quality of EO data is due to remarkable developments in satellite and sensor technology (e.g. miniaturization or sensor combination), and in standardisation and commercialisation. Recent developments show an increase in operational and planned constellations of small satellites such as CubeSats, often equipped with EO sensors of reasonable to good quality and increased data rates. The future deployment of such constellations will continue the increasing trend in observation frequency, amount of data, and continuous availability of observations.
Data providers, both governmental and commercial, are aware of the urgent need for EO-derived information and for commitment to continuous and reliable data provision. Besides responding to these needs, providers are also improving the accessibility of the data by implementing better data infrastructures and data processing and platform technologies.

Simultaneously, the availability of **complementary data** from non-satellite (airborne, ground-or ocean-based) sensors and sensor networks is increasing, strengthening the usefulness of both types of data sets.
New **data analysis** approaches applicable to combinations of multiple data types, multi-sensor fusion and data integration are expected to provide answers to challenges so far unsolvable due to lack of (the right type of) data or computing power. Novel data science approaches are also increasingly making it possible to tackle global problems locally in Near Real Time.

Although Earth scientists already have ample experience in multi-, inter- and cross-disciplinary research, many new EO research applications, especially those related to global (change) issues and sustainable development, require more and **new collaboration** initiatives. Examples of relatively new scientific collaborations include the development of coupled algorithms for atmosphere and land surface (e.g. for air quality monitoring), as well as an integration of solid earth and cryosphere research (e.g. for sea-level rise studies). Synergy is also emerging with fields that are relatively new to EO research but also address global change interactions, such as biology, biophysics, and ecology.

5

5. Earth observation research in the Netherlands

5.1 Dutch EO research field

For selected key figures on Dutch Earth observation research, see the Appendix in chapter 8.

Sub-disciplines
In **atmospheric research**, NL-based scientists have built a particularly strong position on the following subjects: atmospheric composition (air quality and climate forcing), meteorology (mesoscale dynamics, cloud processes), model development and data-assimilation, the definition and development of new satellite mission concepts, the development and design of new satellite instrumentation and supporting in-situ measurements (Ruysdael Observatory). The scientists from the atmospheric research community have a long-standing collaboration and a well-recognized (inter)national position. The community consists of scientists from KNMI, RIVM, RUG, SRON, TNO, TUD, UU, VU, LEI and WUR. For the development of national atmospheric satellite instruments (SCIAMACHY, GOME, OMI, TROPOMI, SPEX) they have worked closely together with Dutch space industry, government and ESA.

In the domain of **land research** (land surface, hydrology, ecology), NL-based scientists have developed strong expertise in the fields of both optical and microwave remote sensing since the early seventies, in areas ranging from instrument design to applications. Dutch EO research in the land domain is internationally recognized as having a strong position on topics such as hydrological and land surface modelling, agriculture, soil functioning, vegetation monitoring, land-cover mapping, and ecosystem and biodiversity monitoring. The EO expertise lies in the interpretation of multi- and hyperspectral optical, gravity, microwave, thermal and fluorescence observations. Strong expertise on in situ measurements is also present, however unlike the atmospheric domain, the land community currently does not have any national ground sites at its disposal, which is limiting national collaboration. The community consists of scientists from WUR, UT-ITC, TUD, UU, LEI, VU, UvA, RUG, TNO and Deltares.

The Dutch **oceanographic and coastal** EO community is well positioned within the international EO community on certain subjects in which it has a long-standing tradition. Dutch ocean and coastal research groups have a strong expertise in sea level research, ocean surface vector winds (wind scatterometry), ocean circulation (through Doppler radiometry for the surface), water quality/marine optics (with connections to marine biology, ecology and sedimentology) and coastal research (including biology, ecology, morphology, sedimentology, coastal applications and modelling). Furthermore, strong expertise lies in the development of retrieval algorithms, hydrodynamic modelling, ocean-climate modelling, and data assimilation techniques. The community consists of scientists from UU, TUD, UT-ITC, KNMI, NIOZ and Deltares. Water safety and water quality are key Dutch topics. Excellent capabilities have been demonstrated by sometimes small or scattered groups. It is felt that these groups could play an even larger role in ocean- and water-related research if the connection to key international projects would be facilitated.

The Dutch **cryosphere** community is not very large, however it is well developed in several EO fields, generating an overall very high qualitative research with a high international status and visibility. NL-based scientists are particularly strong in, among others, processing and the interpretation of satellite optical, gravity, microwave and laser altimetry data, and in applications of EO to modelling and studying the ice sheets of Greenland, Antarctica, Third Pole (the Himalaya-Hindu Kush and Tibetan region), and glaciers and ice caps. The community also has a strong tradition in in situ observations of the ice sheets (e.g., automatic weather stations), which remain essential for calibration and validation of EO data, and it has a strong collaboration and interaction with groups working on polar climate modelling, sea level research and solid earth. More in general, NL-based scientists provide essential input for current and future satellite missions relevant for ice research. The EO community consists of scientists from UU, TUD and KNMI.

In **solid earth** research, NL-based scientists in the field of EO have built an internationally strong and well-acknowledged position, despite their relatively small community. Solid earth scientists are active along the full chain from satellite mission and instrument design and development, to (geophysical) modelling and interpretation of solid earth related structures and processes. Dutch groups specifically have a strong position in solid earth modelling, mineral and geothermal exploration and data processing of InSAR, radar altimetry and gravity observations. They also have strong collaborations with groups working in cryosphere research and oceanography. The EO community consists of scientists from UU, TUD, VU and UT-ITC.

National and international collaboration (see also the Appendix)
NL-based EO scientists have a long-standing reputation of national and particularly international collaboration although this largely takes place within each respective sub-discipline. Nationally, many EO research activities are linked to programmes of academic research schools and research centres. Several working groups (atmosphere, land, water) are or were active, in which scientists from different organisations (universities and research institutes) discuss and coordinate their activities, in some cases also including participants from government, industry and the SME sector. In the context of specific satellite missions (ESA, NASA, EU), national scientific user groups are active. There are also many examples of research projects of national interest in which different research groups have worked together.

At the same time, however, in most sub-disciplines, structural national collaborations are often lacking and the level of EO community organisation and representation is limited. In part this might be due to historical developments, but it might also be due to a lack of large national scientific framework programmes, the fragmentation of the Dutch EO scientific landscape and the relatively small size of the EO research community as a whole. As part of the space policy of the Ministry of Education, Culture and Science (OCW), the Dutch government continues to fund the scientific use of space infrastructure for Earth Observation by means of the User Support Programme Space Research (“GO Programma Gebruikersondersteuning Ruimteonderzoek”). The GO programme contributes strongly to the position of EO research, although not specifically to the coherence of the EO community, as it is focused on individual PhD/postdoc research projects. The complementary programme to consolidate scientific approaches into policy-support applications was stopped more than ten years ago, hampering the application of novel EO techniques.

This lack of national organisation, however, has not prevented individual scientists and research groups to build strong international collaborations. In all EO sub-disciplines, NL-based researchers have strong international positions, e.g. as (Co-)Principal Investigators (PI's) of satellite missions, as lead investigators of or contributors to large international research programmes, as members of satellite mission/instrument development and science teams, scientific and/or mission advisory groups, satellite application development project teams, or contributors to satellite mission proposals within ESA, NASA, EU and other agencies and organisations, and research programmes such as Horizon 2020 (H2020).

Societal benefits

EO research has become an indispensable contributor to address many societal challenges related to the Earth's System and the human environment, see Box 5.1 for examples. On a national level, EO research may contribute to at least 13 of the 25 'routes' of the Dutch National Science Agenda NWA, see Box 5.2, by means of providing information on the structure of and processes in our physical environment. This is done by combining satellite EO data and complementary data from other sources, for the purpose of modelling, mapping, monitoring, inspection and prediction. Such information is important input for (national and local) policy- and decision-making. In much the same way, EO research can provide valuable information towards resolving many of the challenges outlined in the 'Knowledge and Innovation Agenda's' of 7 of the 10 Topsectors (see Box 5.3).

Finally, many applications are developed in the private sector by companies that are the spin-off of earlier EO research.

BOX 5.1 ***Societal benefit areas:***

Nationally, societal benefits are obtained in the fields of climate change and its impacts (e.g. extreme weather, sea level change, rising temperatures, ozone hole, greenhouse gas emissions, ice sheet mass loss, sea level rise); environment and health (e.g. air, water and soil quality/pollution, ocean plastic, fresh water availability); energy transition (e.g. geothermal energy, CO_2 storage); sustainable ecosystems; natural and anthropogenic (geo)hazards and safety (e.g. earthquakes, volcanoes, floods, droughts); land subsidence and deformation (e.g. Groningen, slope instability, surface displacement); agriculture and food security; infrastructure and spatial management; transport and mobility; natural habitats and nature preservation (e.g. land use change and deforestation, desertification, mineral exploration); circular economy.

BOX 5.2 ***NWA routes benefitting from EO research:***

1. The blue route: water as a pathway to innovation and sustainable growth
3. Circular economy and resource efficiency: sustainable circular impact
4. Sustainable production of safe and healthy food
5. Energy transition
6. Health care research, sickness prevention and treatment
9. Quality of the living environment
10. Living history
11. Logistics and transport in an energetic, innovative, and sustainable society
13. Measuring and detecting: anything, anytime, anywhere
16. Towards resilient societies
21. Smart, liveable cities
23. Sustainable development goals for inclusive global development
25. Creating value through responsible access to and use of big data

BOX 5.3 ***Topsectors benefitting from EO research:***

- Energy
- Agri & Food
- Horticulture & Starting materials
- Life Sciences & Health
- Water & Maritime
- High Tech systems & materials
- Logistics

Internationally, NL-based EO scientists play a significant role in addressing global societal challenges, especially/e.g. in the fields of climate change, (geo)hazards, environment and security, as seen in Box 5.1. This is mostly done through international organisations and platforms, such as the Copernicus Services, CAP, GEO, GEOSS, CEOS, WMO, IPCC, IFI's, SDG's, etc.

As has been indicated recently in the CEOS handbook[3] on EO for SDG's, EO is able to support the targets and/or indicators of most of the 17 Sustainable Development Goals, see Box 5.4. It provides the Global Indicator Framework of the SDG's with global measurements of the right coverage and timeliness, more timely statistical outputs, and an improved accuracy in reporting.

BOX 5.4 *All but two of the Sustainable Development Goals are supported by EO*

5.2 Key research-related aspects

Expertise

In most cases, EO research evolved within the context of the research programmes of each respective Earth science sub-discipline. Although several examples of interdisciplinary and/or cross-over research activities have led to important scientific results, many key or priority issues of current EO research can be understood more clearly within the context of each specific domain. These are described in Boxes 5.5-5.9.

[3] CEOS/ESA: Satellite Earth observations in support of the Sustainable Development Goals, Special 2018 Edition, ESA 2018

BOX 5.5 Domain: *Atmosphere*

Current EO research in the atmosphere domain focusses on topics that, due to their impact on current and future life on our planet, are both scientifically and societally highly relevant: weather, climate change, air quality and biogeochemical cycles. Related to *weather*, key research subjects are: data assimilation of new EO types; extreme weather; mesoscale weather forecasts; and improved solar and wind energy production planning.
Key research topics of *climate change* are: circulation and mixing of air; cloud processes; 3D radiation; air-surface interaction of momentum, heat and water; atmospheric trends in greenhouse gases, air pollutants, and aerosol; quantification of emissions at scale relevant for emission monitoring (industrial facilities, cities, to national scale); direct and indirect forcing of aerosols, chemical/physical speciation, physical/chemical transformation and removal; climate impact of land use / land use change, deforestation and agriculture; changes in the hydrological cycle, and impact on cloud formation, including cloud-aerosol interaction, and impacts on extreme weather; and the interaction between climate change and stratospheric physical, dynamic and chemical processes (e.g. ozone layer recovery).
With respect to *air quality*, key subjects are: photochemical pollution, emissions, chemical processing, regional/ long-range transport, mixing and removal of reactive gases; characterization of aerosol composition (chemical & optical properties), emission, secondary production, and chemical transformations; linkages between photochemical pollutants and climate forcing through ozone and aerosol formation (Climate and Clean Air Pact); and impacts of photochemical processes, including the impact of aerosols on radiation, on the oxidizing capacity of the atmosphere and the life time of longer lived greenhouse gases (CH_4, HCFC's).
Finally, on *biogeochemical cycles*: uncertainties in the carbon and nitrogen cycles at local, regional, global scales; natural feedbacks to climate change, air pollution, and land use / land use change; potential synergy with 'land' sphere, as many of the underlying research questions concern land-atmosphere interactions; dynamic exchange of gas-phase species (CO_2, DMS) between oceans and the atmosphere.

BOX 5.6 Domain: *Land*

Current EO research in the land domain focusses on the scientifically and societally relevant topics of the hydrological cycle, land cover change and sustainable land use,, biodiversity and security. These are addressed by improving the understanding and modelling of the relations between processes on the Earth's (land) surface and the signals of all kinds of EO sensors, and by the quantification of the exchanges of energy, water, carbon, and nutrients among system components.
Key applications related to the hydrological cycle are the remote sensing of rainfall, evaporation, soil moisture, and ground- and surface water levels, and water chemistry and salinity. Applications in land cover and sustainable land use focus on the effects of climate on land cover and vice versa, change detection, soil characterization, biodiversity and ecosystem functioning mapping, and photosynthesis monitoring. Key applications related to security include hazard modelling and risk assessment (floods, landslides, drought, coastal engineering, land subsidence, land degradation), improvement of sustainable agricultural production, land management, law enforcement and urban planning and design.

BOX 5.7 Domain: *Oceans*

In oceanography, the modelling of ocean dynamics and sea level on the basis of the very long observation records of satellite radar altimetry has become one of the most remarkable examples of EO research successes, as has ocean wind stress observation by scatterometry. In a way, current EO research in the oceans domain builds on these achievements, but at the same time new EO opportunities related to oceans, seas and coastal areas make it possible to address newer and more challenging/pressing scientific issues.
Key research topics include: direct measuring of surface currents, waves and air-sea interaction; estimating primary production in a wide range of waters, from the open ocean to inland waters; monitoring ecosystem functioning of oceans, seas and coasts (including harmful algal blooms and coral bleaching), also in response to climate change and human activities such as eutrophication of coastal and inland waters; determining the ocean contribution to the global carbon budget; remote sensing of shallow waters for bottom type and health assessment, and to support hydrodynamic models; determining the expression of large-scale open ocean variability on the coastal environment, in particular on inter-annual to decadal time scales; finding proven methods to detect plastic debris; measuring sea surface height from offshore to the beach; developing satellite methods to detect e.g., coastal (underwater) morphology, e.g., with lidar or radar; measuring highly dynamic processes, e.g., in coastal areas; measuring salinity near coasts, ice edges and high latitudes which still lack the necessary resolution and accuracy; reconstruction of vertical mixing in the upper ocean from satellite data (e.g. through wind and ocean color data); quantifying air-sea gas exchanges; monitoring transitions and changes of coastal waters/zones; quantifying contributions from glaciers and ice sheets; and improving estimations of phytoplankton size classes or functional types for a wide range of oceanic waters.

BOX 5.8 Domain: ***Ice***

The inaccessible nature and hostile environment of the Earth's ice-covered regions make EO an indispensable tool for cryospheric studies. The Earth's cryosphere interacts in many different ways, and on many temporal and spatial scales, with the other 'spheres', most notably the geosphere, hydrosphere and atmosphere. Current EO research in the ice domain therefore has strong relations to the other EO research fields. Key research topics include: glacier-ocean interaction models including frontal ablation and calving; present and future contribution (and timing) of the Antarctic & Greenland ice sheets to sea level rise; the role of ice shelf and ice cliff (in-)stability in the future of Antarctica; the melt-albedo-firn feedbacks in a warming climate and their role in sea level rise; improved firn correction models to correct altimetry data for non-mass related height changes (firn compaction); the role of meltwater retention in moderating the impact of the Greenland ice sheet on sea level rise; the inclusion of glacier mass budgets in Earth System models; a comprehensive overview of the state of continental glaciers; the effect of climate warming on extreme cryospheric events (such as heavy snow falls, icing, glacier outburst floods) and the thawing season of permafrost; and the 'polar gap' issue (i.e. reduced number of EO measurements at the poles).

BOX 5.9 Domain: ***Solid Earth***

A key overall research issue in solid earth research is the improvement of (geophysical and geodynamical) Earth models on all relevant temporal and spatial scales, from minutes (e.g. earthquakes) to millennia (e.g. post-glacial rebound) and millions of years (mantle convection), as well as from local (e.g. land subsidence) to global (e.g. plate motion) scale.
Several specific research topics in this domain, which are especially relevant for the Netherlands, include: a better understanding of land subsidence and associated processes at a local scale (an example are induced earthquakes in the Groningen area); regional scale tectonics and post-glacial rebound; and the study of the volcanic hazards in the Caribbean part of the Netherlands. In addition, several other topics are of key importance, notably: an increased integration of solid Earth models with geochemical models and geology; monitoring at subduction zone plate boundaries, e.g., mass changes, horizontal displacement and velocity fields; monitoring sub-ice bedrock topography which controls ice dynamics; and the use of multi-temporal optical, gravity, radar, multi- and hyperspectral data for understanding surface dynamics. Again, from these topics the interdisciplinary nature of EO research becomes clear.

Infrastructure

EO researchers have made, and are making, extensive use of the available **space infrastructure** in the form of EO satellites. This includes all past, operational and planned ESA EO missions, the Sentinel missions of the EU's Copernicus programme, EUMETSAT meteorological missions, NASA and NOAA EO satellites and national EO missions from other countries/agencies (traditionally Germany, France, Japan, Canada and Italy but more recently also China, India and Brazil). Also, in more recent years, the use of commercial satellites and (small) satellite constellations is increasing, although the cost of commercial data can be an issue especially for academic researchers. The Dutch research community not only uses the existing space infrastructure, but makes an important and internationally recognized contribution to this in the form of satellite instruments and mission design.

The spaceborne infrastructure is only part of the story, however. In order to optimize the use of satellite data for EO research, adequate infrastructure on the ground is equally essential. Such infrastructure can consist of e.g., in situ facilities such as measurement sites for field experiments, modelling and other computational structures, and IT-related facilities for data access.

In all domains, space infrastructure is used in synergy with surface- (ground/ocean) and air-based infrastructure, not only as an independent and complementary source of observational information, but also as an essential source of information for calibration and validation of satellite EO. **Surface-based infrastructure** includes in-situ and mobile sensors and sensor networks on land, sub-surface, in coastal areas and at sea (shipborne). Air-based infrastructure includes aircraft sensors, weather balloons and, in recent years, drones/UAVs and High Altitude Pseudo Satellites (HAPS). The expertise to model, integrate and exploit both satellite data and other (ground- and air-based) data is widely available within the Dutch EO community. It must be remarked, however, that while there is currently a strong growth in the availability of satellite data, the equivalent availability of relevant (long-term) Earth-based data sets and (national) observational sites is becoming a pressing issue. This is partly a matter of available budget, but also an issue of organisation of the EO community, its position within the broader science field and society, and government policy.

A 'System of systems': putting the data from all the different sensors together provides information which is more than the sum of the parts.

NL-based EO scientists have a long-standing track record in being involved in the initiation, development, operations and maintenance of **modelling infrastructure**. This ranges from mono-disciplinary models tailoring specific research questions (e.g. to model the reflection of a forest canopy), to large, global and multi-disciplinary Earth System models (e.g., for modelling the global carbon, water and mass cycles).

The innovative use of satellite data and the development of new applications relies to an increasing extent on the **computational and ICT service infrastructure**, and the capacity to transfer, process and archive large volumes of data. For this, the accessibility of high-performance computing centres – such as SURFsara - to scientists is critical, as local storage and processing is becoming increasingly unfeasible. Furthermore, recent developments in the field of data science can require expertise from outside the EO/Earth sciences, e.g. as provided by computer scientists. An important contribution here is made by the Netherlands eScience Center, which supports the collaboration between (EO/Earth) science experts and engineers trained in data science technologies.

International **data-related infrastructure**, for data access and computing activities, consists of e.g. data portals, data cubes, ESA/EU initiatives (TEPs, DIAS, Copernicus C3S database, CGS, CCI), Google Earth Engine, Amazon Web Services etc. NL-based scientists contribute to international data portals of e.g. ESA and Copernicus. National data infrastructure includes e.g. the KNMI Data Centre (for weather, climate and seismology), the Radar Altimeter Database System (RADS) (for sea level), and the national satellite data portal (optical and radar data over land). Besides this, national institutes contribute to various European/global databases in which EO and Earth-based data are combined.

6

6. Dutch Earth observation research strategy

6.1 Strategic challenges

The Dutch EO research community as a whole, although relatively small in each of its sub-disciplines, can rely on a substantial scientific heritage and has achieved a strong international position, see also the Appendix. Cooperation between experts on instrument design, calibration, data processing and exploitation has brought the Dutch community to the forefront of international developments, including, for example, (co-)PI roles in ground-breaking past and present missions with national instrument contributions in the atmosphere domain e.g. SCIAMACHY, OMI and TROPOMI.
The EO community continuously strives to improve the physical understanding of the observations, in order to optimise the exploitation of the available data. This requires a balance to be maintained between investments related to instrumentation, quality assurance and data use.

With global challenges becoming more comprehensive and complex, and EO data resources growing intensively, in certain cases a paradigm-shift will be needed in order to develop integrated solutions to global change issues. This requires an optimal application of all available resources (people, knowledge, facilities and information). As one of these resources, EO research deserves to be fostered, so as to ensure its continuing benefit for society at large. The major challenges and opportunities currently faced by the EO research community are in some cases specific to a single or a few EO domains, whilst in others they are common to all sub-disciplines. The focus of this strategy document is on the latter.

Sensors, instruments, space infrastructure
Although the amount of available EO data and the ICT capabilities to handle it are growing fast, the application potential of EO in addressing current and future user needs is so broad, that new EO sensors, instruments and missions will still be needed. First, timely launching of replacement space infrastructure is needed to ensure continuous availability of observations for long-term monitoring and prediction (long time records). Secondly, current and future challenges need innovative observation systems with new capabilities in terms of observation type and quality. In many cases, current performance with respect to measurement resolution and data quality is still insufficient to meet scientific and societal goals. It is crucial to increase the spatial, temporal and spectral resolution of satellite observations in order to benefit optimally from the advantages of EO over other observation sources. At the same time, depending on the specific (bio-) geophysical phenomenon, new types of technologies and sensors are needed to collect observations of certain parameters and physical properties that are currently not feasible or not accurate enough. This also requires the development and implementation of new or improved algorithms consistent with the new data types.

Technological developments of recent times (e.g. in the fields of miniaturization, standardisation, nano-technology, photonics, robotics and AI) are promising for the innovation of space infrastructure. Examples of new technology are e.g. integrated photonics (chips, sensors) and cold-atom sensors (e.g. for gravity field), whilst examples of space infrastructure becoming possible with new technological developments are e.g. polarimeters, more use of geo-stationary platforms and high altitude pseudo satellites, and the deployment and use of constellations of (small) satellites. With respect to the development of new space infrastructure the Dutch EO community can build on the strong national heritage in instrument development, data processing and modelling. The Dutch EO community offers strong opportunities for developing national infrastructure initiatives, as well as contributing to international ones.

Observations

Long, uninterrupted timeseries of observations are essential for many EO applications, particularly for climate (change) studies. In this field, many processes of interest occur at medium to long time scales, relative to the typical satellite mission duration, leading to a risk of observation gaps occurring in long-term monitoring and modelling activities. Overlap between subsequent/related sensors is therefore essential, not only for the prevention of data gaps but also to allow the inter-calibration needed to provide a timeseries of consistent quality. NL-based scientists from various sub-disciplines are, or have been, involved in ESA's Climate Change Initiative (CCI) which is dedicated to generating long timeseries of Essential Climate Variables (ECV's) from various EO data.

Despite the increase in availability of large-volume EO data, it remains a challenge to obtain full global data coverage (including the complete polar regions) in high spatial resolution and with frequent revisit times, matching the temporal and spatial scale requirements of the (geo)physical processes to be monitored.

Several EO applications are still limited by the accuracy and/or stability of the data, an issue that becomes more challenging with increasing demands on the spatio-temporal resolution of the data, and the developments towards smaller instrumentation. There are clear needs for improvement in the specification and description of quality aspects of the observations, including random and systematic errors (biases), accuracies and uncertainties. Quality should be assessed based on well-understood, traceable calibration and validation procedures. In several cases, there is a need for inter-calibrated time series of various observation types according to internationally agreed standards, for the merging of multi-sensor data and for the generation of integrated high-level products.

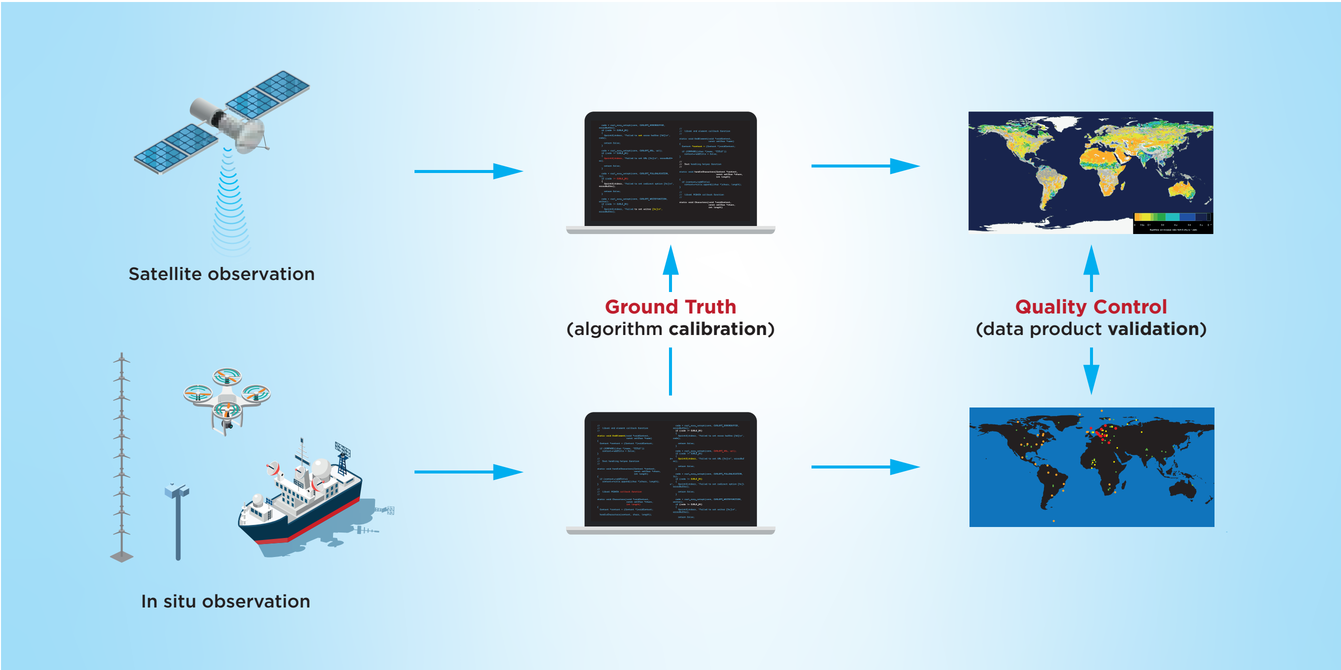
A different aspect is the existence of older or historical observations in archives and/or in the form of analogue maps (e.g. geological maps in the solid earth domain). Efforts should be put into disclosing and/or digitizing such data, as they can offer a valuable source of information in relation to new EO observations and also help mitigate the limitation of EO timeseries which are relatively short in relation to climatic signals.

In-situ, calibration/validation (cal/val)

Space-based remote sensing data and Earth-based/terrestrial data are in many ways complementary to each other. Each have their own advantages and disadvantages in terms of spatial and temporal coverage, and cost. In terms of information content, the two types of data can be used to complement or to validate each other.

A combination of both data types is vital for making the translation from satellite signals into (bio-)geophysical data related to the Earth's structure and processes. Ground-truthing is essential to correct, calibrate and/or validate (initially and/or continuously) the satellite instruments, as well as the resulting observations, processing methods and derived data products. The availability of ground-based data, e.g. from in-situ or airborne observation networks and sites, is therefore of critical relevance to EO research, and different types of cal/val will require different kinds of ground data.

Compared to the attention being given to the increase in availability of new EO data, more investments are urgently needed for the deployment and maintenance of (inter) national ground-based sensors, sensor networks and integrated observing systems or multi-sensor sites. This is especially pertinent for purposes of calibration and validation, as sustained/structural support for cal/val of EO data is currently limited.



The important role of in situ data and calibration/validation (cal/val) in the processing and application of EO data.

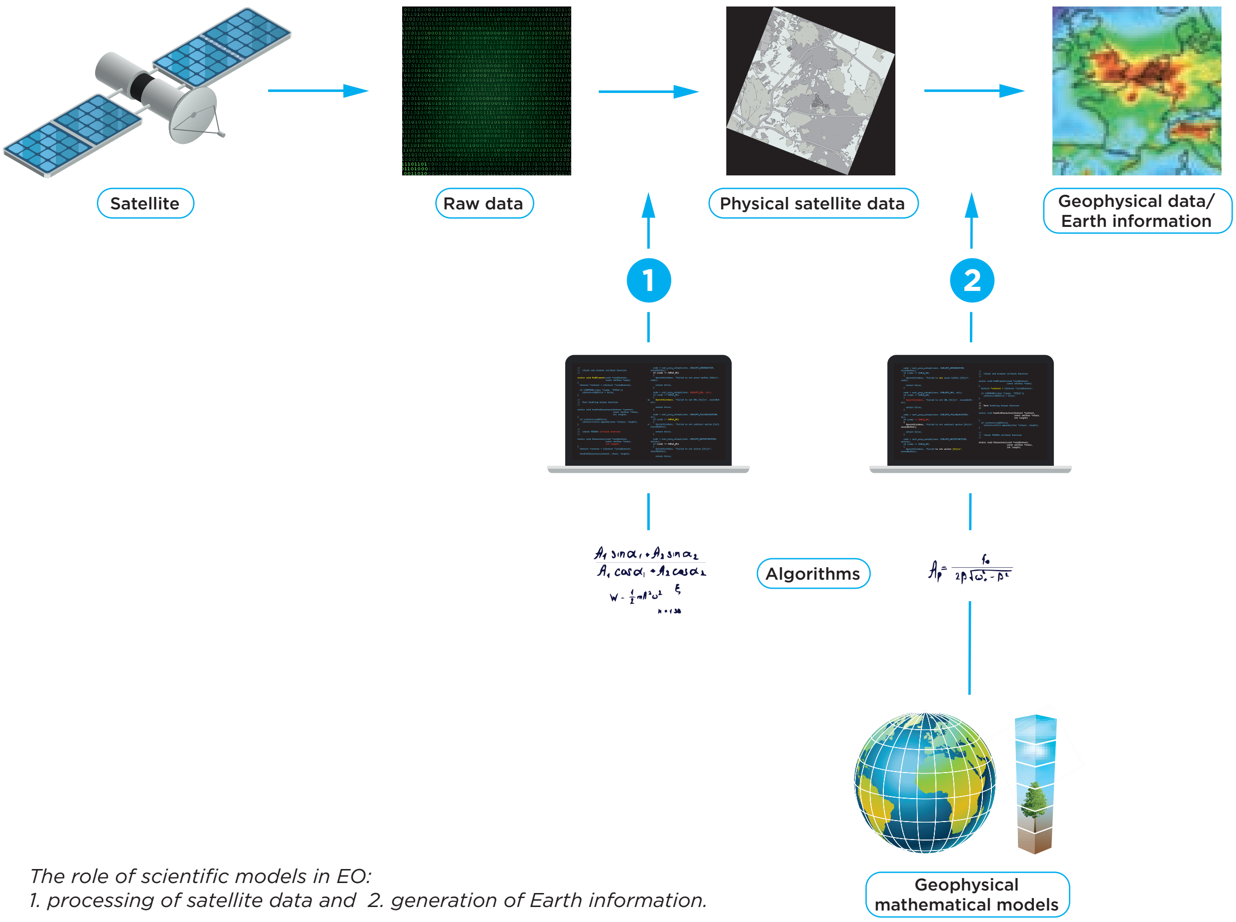
In some cases, investments could include the development of innovative new technology and sensors, in other cases existing sensors need to be maintained/installed on (mobile or static) networks and sites, or the networks themselves adapted/expanded to address emerging research questions. Where relevant, these investments should be done in collaboration with national and international (space) agencies. Validation networks may call for international coordination (e.g. Copernicus, CEOS) of national investments. Together with the structural (further) development of ground-based infrastructure, both measurement concepts and methods, and algorithms and protocols for cal/val purposes will simultaneously need to be developed, improved and/or operationalized.

Data integration

As a result of the great variety of (satellite, airborne and ground-based) sensors, integration of sometimes very different data sets has become a highly relevant issue in EO research. This is not only the case for the integration of satellite data with ground/airborne data, but also for satellite data originating from different sensor types (e.g. optical and radar data). The same applies to the integration of data sets having divergent characteristics in terms of e.g. quality, resolution, coverage, sensitivity, or accuracy. In retrieval models or data assimilation studies, for example, such data integration can lead to improved predictions. In general, the integration of different data sets can benefit the processing, quality assessment, dissemination and interpretation of the data. This can require multi-disciplinary collaborations between scientists from several EO domains. Furthermore, novel data science/Big Data technologies and concepts of machine learning or AI have become very relevant due to the sheer amount and variety of data involved.

Algorithms and models

In part due to the lack of coherence within the EO community, there is significant duplication of algorithms and models for quite similar tasks. However, an overview of their applicability and validity is often missing. As a result, inexperienced users might not use them in the correct or most efficient way. A collaborative effort would be required to provide the EO community with clearly described and open algorithms to be used in new EO research, in order to facilitate efficient exploitation of the available data.



The role of scientific models in EO:
1. processing of satellite data and 2. generation of Earth information.

Regarding model development, there is a constant need to keep up with developments in (satellite) data availability. This applies both to the application of novel computational techniques, e.g. from data science, and to the modification of the models in order to comply with e.g. new data types, increased spatial/temporal resolutions, large data volumes, and/or required output information. This can in turn require an improved understanding and/or representation of the physical, chemical and natural processes described by the models. Given the increasing coupling between the different EO sub-disciplines in terms of subject matter, this can also require closer inter-disciplinary collaboration between experts from different domains.

Data access and data science
The strong increase in the availability of sensors and thus, data, also leads to a strong need for novel techniques for accessibility and handling of large data sets. Involvement in the set-up of new (inter-)national storage systems, such as e.g. the EU Copernicus Data and Information Access Services (DIAS) for Sentinel data, is important to ensure that the needs of the Dutch science community are secured. In general, EO data are becoming more and more available through data portals and cloud-based infrastructures. This development may be an efficient one, but it should be ensured that the data can be used freely, openly, routinely and unrestrictedly. Furthermore, the data should come with clear descriptive information and meta data, as well as details about error estimation. The use of data portals can become more beneficial when specific algorithms for data (pre-)processing are included in the portal. The general perception of the research community is that in satellite remote sensing, investments in data provision and data use should be better balanced to ensure data being used.

The recent data increase also means that users need to develop new concepts and make use of completely new technologies for data access, download and processing. From ICT developments in the field of data science, e-science or Big Data analytics, many solutions are (becoming) available, including technologies such as machine learning and artificial intelligence. The EO community is currently in the early stages of integration of such technologies in EO research. Similarly, progress is being made with respect to the availability of sufficient computer resources (e.g. data management, storage and visualisation) and high-performance computing methods for the EO field. In several cases, data research infrastructures developed through national or international collaboration may facilitate joint processing and storage of data products. It is important that the computational performance of national centres such as SURFsara is maintained in line with international developments.

The emergence and uptake of new data processing technologies can change and improve the capabilities of the – (geo)physical, retrieval and data assimilation – models that EO scientists use. In a number of cases, the involvement of e-scientists in EO model development has already led to scientific results that would not have been possible if the data had been exploited with traditional methods only. Collaborations with national data science centres should therefore receive increasing support.

Finally, efficient use of the existing computational and modelling infrastructure also requires optimization and parallelization of the computer codes being used. Besides a closer cooperation with professional scientific programmers, this also calls for an introduction to high performance computing in the Earth Science educational programmes.

Earth System approach
Earth sciences are steadily progressing towards a more integrated “Earth System” approach. This requires a better understanding of the interactions among the Earth’s ‘spheres’ (atmosphere, geosphere, cryosphere, hydrosphere, biosphere and anthroposphere), together with the development of novel Earth System models. It also requires more emphasis to be put on a more comprehensive understanding of the available EO data, on the integration of varying data in new models, and on the opening of new research lines to properly exploit the data. This calls for a multi-disciplinary approach, in which different data sets, data processing algorithms, numerical models, and representation techniques are combined. Finally, this approach will bring to light unresolved issues concerning interactions/feedback mechanisms between Earth’s sub-systems on which knowledge is still limited or which are not (yet) fully represented in the models.

Collaboration

The capacity of Dutch EO research to address scientific and societal challenges will strongly increase with more coherence and collaboration within the EO community. The extent to which collaboration has already been established within each sub-discipline depends on the size of the group and (the length of) its track record. For example, in the atmosphere domain the collaborations are relatively long-standing and strong, while in i.a. the solid earth domain they can be further developed. However, the EO community as a whole clearly emphasizes the need to strengthen multi-disciplinary collaborations within the larger Earth science domain, in order to enhance EO research output and quality. This includes links between all the 'spheres' (sub-disciplines), between modelers, observational scientists and data scientists, as well as between all the EO observation regimes. Synergies that need further exploration and/or support are e.g. those between the atmosphere and land surface domains, the ocean and land/atmosphere domains and ice-ocean-atmosphere interaction. Solid earth gravity research has links with all other sub-domains and these links need to be further exploited. This Strategic Plan is a first joint effort of all EO research domains together to strengthen their collective position as a community.

At the same time, the Dutch EO community strives for more collaboration with the wider Earth sciences community. EO is sometimes perceived as a particular specialism, whereas it should be regarded as an indispensable enabler for scientific progress in all Earth science fields. In this context, the Nederlands Aardwetenschappelijk Congres (NAC), AardNed and the Netherlands Earth System Science Centre (NESSC) national platforms bring together all fields of research within the earth sciences, and as such should be supported to facilitate collaboration between the EO community and the wider Earth sciences community.

Programmatics, policy, funding

Government policies should foster the EO research community and support the strengthening of its position, e.g. by means of the organisation and implementation of prioritised EO research programmes. Such programmes would complement and enhance the research already undertaken under the NWA and Topsector programmes, which focus particularly on more short-term (development of) applications. Implementing long-term, more fundamental research in parallel is crucial for further developing the national EO field, and would also do justice to the fact that most EO research is to a large extent an international effort, in which NL-based scientists can hold valuable and widely acknowledged positions.

A tailored Dutch EO research programme should maintain a balance between investments in instrument development, development of (small) satellite missions, improving data quality (including calibration/validation activities), data processing (retrieval) techniques, model development and data exploitation. In doing so, care should be taken not to detract from the currently existing strengths of Dutch EO research. The programme would include (i) more flexible funding schemes with low latency that better enable NL-based EO scientists to participate in international projects, (ii) (co-)funding of Dutch scientific contributions to (current and future) international missions, and (iii) medium-sized collaborative research projects, in between large (inter)national mission programmes and individual PhD research. Research would be aligned with existing and related science programmes. The programme would have a long-term scope, in line with both the great scientific and societal challenges to be addressed and the duration of typical EO mission programmes.

Such programmatic support would provide a solid basis for enhanced valorisation of EO data and research, and allow it to reach more users and address needs perceived by the wider public as relevant and urgent. By better aligning what specialists measure with what users need, it would improve the visibility of EO research and broaden the support of society.

Education
At the basis of many of the above-mentioned strategic challenges lies the availability of well-trained personnel. In order to ensure the sufficient availability of future EO researchers, the visibility and coordination of remote sensing education in The Netherlands should be improved, and the position of EO research within Dutch higher educational programmes should be enhanced. Dutch education in EO remote sensing is currently scattered across different universities, whereby no single university offers a curriculum covering the full scope of EO remote sensing fundamentals. Better coordination is therefore needed between the courses on offer in different universities, in order to help interested students to find their way in the educational landscape. Furthermore, the skills of NL-based graduate EO students should be better aligned with the demand of (non-academic) employers, including skills such as data science and machine learning (e.g., TNO, Deltares, CGI), and business development (e.g. at the ESA business incubator centre).

6.2 Key elements and objectives

In order to advance towards the overarching goal of this strategic plan, namely *"to strengthen and consolidate the position and coherence of EO research in the Netherlands"*, seven key elements of the strategy are identified and described.

1. Excellent science
Based on the Dutch heritage and the challenges foreseen, it can be stated that the Dutch EO research sector is, and is determined to remain, a field of excellent science in its own right, while simultaneously serving to strengthen the excellence of the general field of Earth science. Main objectives here are:

- Based on scientific expertise, contribute towards, or initiate, the design, development, and operation of new satellite missions/instruments that fit within a national context or contribute to missions developed in international programme (e.g. ESA, EU, NASA). This should include missions which enable fast response to user needs and can provide cost-efficient observations.
- Consolidate the internationally leading position in radar, lidar, gravimetry, spectrometry and hyperspectral remote sensing;
- Achieve a consistent, traceable and validated relationship between satellite data and the state variables used in models, by means of:
  - development of data retrieval and modelling techniques, and determination of error budgets, for the scientific exploitation of the global datasets from those missions;
  - development of excellent national measurement and modelling infrastructure.
- Provide essential, high-quality input for scientific and policy reports;
- Be a leader in open science, making methods and data products freely available to the research community, in line with the Findable, Accessible, Interoperable, and Reusable ('FAIR') principle in relation to published data.

2. Collaboration within EO research
All Dutch EO research sub-disciplines recognize the need to collaborate both within their own discipline and inter-disciplinarily, and to build a stronger community in order to strengthen their position with respect to science, policy and society. Main objectives here are:

- Strengthen the cooperation of experts to cover, within the Netherlands, the full chain of missions, from instrument calibration, through data processing, to the delivery of societal services;
- Maintain and promote strong collaboration and synergy between the EO, modelling and observational communities;
- Achieve innovative and more effective solutions to scientific, engineering and planning questions by both 'horizontal' and 'vertical' cooperation among experts in the two dimensions of EO: the sensing techniques (solar reflective, orbit determination, thermal, radar, lidar, gravimetry) and the disciplines (atmosphere, land surface, solid earth, ocean, ice);
- Support existing interdisciplinary collaborations and initiatives that extend collaborations across disciplinary boundaries, e.g. (emerging) collaborations between Solid Earth and Cryosphere, Atmosphere and Land Surface, Atmosphere and Oceans, and Oceans and Land;
- Support interdisciplinary research collaborations focussing on (interfaces between) the global water cycle, carbon cycle and/or mass cycle;
- Collaborate in large European projects, e.g. within the EU's Horizon 2020 and Horizon Europe programmes.

3. Optimal exploitation of national resources
Dutch EO research will greatly benefit from jointly exploiting available national resources for advancing its position and (scientific and societal) output. This applies to funding resources as well as to technological and scientific capabilities. Main objectives here are:

- Support the integration and use of satellite data, including the development and testing of methods and models for the geophysical interpretation of satellite data, and assimilation of EO data in models;
- Cross disciplinary boundaries to exploit the synergetic use of data from different missions;
- Optimize the synergy between EO data and integrated observing systems;
- Utilise/balance available resources to increase the priority of cal/val activities and data processing from raw observations to geophysical variables;
- Benefit from developments in the field of small satellite missions;
- Ensure the continuation, and preferably extension, of national support for EO scientific research, e.g. through the GO and KNW programmes;
- Support Principal Investigator roles in relevant programmes (e.g. ESA Earth Explorers);
- Benefit from an internationally leading position e.g. to access extensive foreign EO resources.

4. Connection to societal challenges
EO research is by its features and strengths (monitoring capabilities, predictive value, independent information gathering, integrated Earth System approach) perfectly positioned to address (national and global) societal challenges as indicated by, amongst others, SDG's, NWA, and national Topsectors. Main objectives here are:

- Support the UN sustainable development goals (public health, food security, life on land and below water, climate, sustainable and safe living conditions, clean water and energy availability);
- Contribute to NWA routes as listed in box 5.2;
- Contribute to Dutch Topsectors as listed in box 5.3;
- Address the Dutch societal challenges listed in the Knowledge & Innovation Agenda's (KIA's): energy and CO2, agriculture and food, health, climate and water, transport, safe society;
- Implement a dedicated applied research programme to develop sustainable applications of EO research capabilities to address societal needs.

Specific contributions from EO of the atmosphere:

- Atmospheric composition and climate change monitoring
- Prediction of extreme weather
- Urban air quality monitoring and prediction
- UV exposure and the ozone layer monitoring
- National emission reporting and verification
- Wind and solar energy monitoring and forecasting

Specific contributions from EO of the land:

- Assessment of the effects of hazards, weather variability and climate change, e.g. on food security
- Monitoring and prediction of floods, droughts and water budgets
- Quantification of the CO2 uptake by ecosystems
- Characterisation of soils for agriculture
- Land use and land management assessments
- Monitoring of biodiversity and ecosystem functioning
- Monitoring of local (urban) climate and changes in surface temperature

Specific contributions from EO of the ocean:

- Monitoring and predicting (impacts of) regional and global sea-level rise and storm surges
- Monitoring water quality, (plankton) biodiversity and ecosystem functioning
- Mapping surface currents to assess dispersion of marine (plastic) litter and other pollutants
- Monitoring of winds, waves and ocean currents for coastal protection
- Monitoring oceanic CO2 uptake and drawdown through measuring air-sea exchanges

Specific contributions from EO of cryosphere:

- Monitoring the land ice contribution to current sea level rise
- Improving future sea level predictions by monitoring and modelling the behaviour of glaciers and ice sheets
- Early warning of ice sheet and ice shelf instability
- Forecasts of (near-)future water availability in high mountain areas

Specific contributions from EO of the solid earth:

- Observation and prediction of subsidence of low-lying regions
- Improved understanding of tectonic and magmatic processes that cause natural hazards, such as earthquakes and volcanoes
- Identifying and monitoring areas suitable for geothermal energy and CO2 storage
- Identifying potential for, and monitoring of mineral exploration

5. Cultivation of national EO infrastructure

For Dutch EO research to create the most value for science and society, the availability of sufficient and sustained infrastructure is essential, including resources and facilities for: cal/val, satellite instruments, technology, data exploitation, data science and model development. Main objectives here are:

- Maintain the strong EO infrastructure present in the Netherlands, for the development, operation and use of satellite missions, within and between disciplines;
- Continue to support initiatives for new missions and opportunities for national contributions to missions, thereby strengthening integration along the entire chain of data needs, mission design, operation and data use;
- Invest in in situ measurements, sites and networks, in order to strengthen EO calibration, validation and exploitation;
- Support cross-disciplinary research activities in the form of joint cal/val locations and activities (cruises, platforms), acquisition and use of sensors, and development of models and applications;
- Maintain expertise and facilities for data centres, data portals, data processing and (big) data analysis, and integrate these in international infrastructures. Maintain and prioritize accessibility to, and performance of, high-performance computing centres such as SURFsara;
- Improve usability of data portals including correction models to facilitate use of remote sensing data;
- Further support collaborations between EO scientists, computer scientists, visualisation experts, NL-eScience Center, and SURFsara, in order to guarantee adequate specialised programming support and thus optimally benefit from the available super-computing facilities;
- Support connections with international integrated research infrastructures (e.g. ICOS, ACTRIS, EPOS, AERONET).

6. Connection to national and international research programmes/networks

Dutch EO research contributes to and benefits from connections and collaboration with(in) national/international research programmes/networks. Maintaining and strengthening such connections requires joint efforts by various (scientific and non-scientific) stakeholders. Main objectives here are:

National connections to be maintained and strengthened, e.g. through jointly funded research projects:

- Dutch universities and Research Institutes (e.g. Deltares, TNO, ECN, NIOZ, SRON, KNMI, RIVM);
- Connection between universities and relevant public bodies, e.g. water authorities;
- EO research as part of the Ruisdael Observatory;
- Connections between EO research and Earth sciences, through e.g. AardNed, NESSC and NAC;
- Membership of EO scientists within national research schools;
- Strengthen the position of the Netherlands in ESA’s Earth Observation Envelope Programme (EOEP) and FutureEO programme, e.g. by also involving the Dutch Ministry of OCW.

International connections to be maintained and strengthened:

- Connections with EU/Copernicus, EUMETSAT and ESA, for European development, operation, and exploitation of new satellite missions;
- Connections with international organizations, committees and conventions (e.g. WMO, GCOS, GEO, UNEP, IGBP, FAO, ECMWF, CEOS, CLRTAP, WRI);
- Contributions to key scientific programmes and assessments (e.g. IPCC, IPBES, Global Land Outlook, EMEP);
- Connections to other space agencies and organisations e.g. NASA, CNES, DLR, JAXA, ISRO, CNSA, space agencies of other countries, commercial providers;
- Connections to the International Space Science Institute (ISSI);
- Presence in (inter-)national advisory EO bodies.

7. Education

Apart from the research itself, the sustainability of a strong Dutch EO research position and coherence depends on the availability of new scientists with state-of-the-art training in science-related issues, which in turn requires proper educational facilities. Furthermore, outreach activities are essential to create awareness among scientists, policy makers and the general public to justify investments and to be held accountable. Main objectives here are:

- Improve the visibility and overview of Dutch remote sensing education;
- Educate excellent young scientists;
- Increase cooperation between programmes that offer EO-related courses to identify the main gaps and duplications;
- Support EO summer schools organized jointly by different Dutch institutes;
- Better align the skills of NL-based graduate students with the (non-academic) demand side, e.g., skills in machine learning (e.g. TNO, Deltares, CGI) and business development (e.g. ESA business incubator centre);
- Integrate/enhance knowledge fields such as data science and visualisation in higher education programmes for remote sensing.

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7. Recommendations

Based on the key strategic elements described in the previous chapter, the following recommendations have been established. Recommendations are directed both to the scientific community itself (S), and to government organisations and agencies (G).

Recommendation 1: Excellent science
S: Increase the exploitation of satellite data for fundamental and applied research, enhance the utilization of the full potential of current and future satellites through open science practices, and achieve a full-scale and consistent modelling capacity for the use of satellite data for addressing scientific and societal challenges, while being transparent about limitations.
G: Foster and actively promote EO research based on its relevance for addressing national and global societal challenges; enable a fast response to opportunities for participation in space missions or research projects.

Recommendation 2: Collaboration within EO research
S: Increase collaboration between instrument development, data processing and modelling communities, better exploit the power of combining EO and terrestrial datasets, and increase the capacity for addressing integrated Earth System challenges.
G: Foster and actively support inter-, multi- and cross-disciplinary EO research by emphasizing it in national and international/European support programmes.

Recommendation 3: Optimal exploitation of national resources
S: Obtain and maintain support for EO research, both through funding applications as well as through increased and synergetic exploitation of technological and scientific facilities and resources.
G: Continue, and preferably extend, national support for EO research, e.g. through the GO and KNW programmes, and include consolidation of scientific approaches into policy-support applications.

Recommendation 4: Connection to societal challenges
S: Enhance the benefits of EO research to societal challenges by contributing to the – monitoring of the – Sustainable Development Goals and increasing the contribution of EO research to research programmes including the Dutch National Science Agenda, the Topsectors and their Knowledge and Innovation Agenda's.
G: Develop a funding programme supporting the transfer of knowledge to societal applications, and the assimilation of data into societal services.

Recommendation 5: Cultivation of national EO infrastructure
S: Consolidate the Dutch scientific excellence in new EO instrument development and at the same time strengthen research activities aimed at cal/val, data exploitation, and data science activities.
G: Maintain a strong Dutch EO infrastructure, and increase the support for data quality control, cal/val activities and infrastructure, data processing and modelling activities, relative to that for instrument and satellite mission development.

Recommendation 6: Connection to national and international research programmes/ networks
S: Maintain and strengthen connections to national and international research projects, programmes, academic and other research organisations and infrastructures to increase impact of Dutch EO research.
G: Maintain and support the position of Dutch EO research in national and international research, policy and stakeholder networks by facilitating and rewarding activities that strengthen this position; strengthen Dutch position in ESA's Earth Observation Envelope Programme and FutureEO programme e.g. by also involving the Dutch Ministry of OCW.

Recommendation 7: Education
S: Develop and maintain, through cooperative efforts within the academic EO research field, a substantial and future-proof national remote sensing educational programme, including graduate and master courses/programmes, summer schools, improved integration with growing knowledge fields such as data science, and better alignment with non-academic developments.
G: Support the development and maintenance of such a national remote sensing educational programme.

Abbreviations and acronyms

ACTRIS	Aerosol, Clouds and Trace Gases Research Infrastructure
AERONET	AErosol RObotic NETwork
AI	Artificial Intelligence
C3S	Copernicus Climate Change Service
cal/val	calibration/validation
CAP	Common Agricultural Policy
CCI	Climate Change Initiative
CEOS	Committee on Earth Observation Satellites
CGS	Collaborative Ground Segment
CH_4	Methane
CLRTAP	Convention on Long-Range Transboundary Air Pollution
CNES	Centre National D'Etudes Spatiales (National Centre for Space Studies)
CNSA	China National Space Administration
CO_2	Carbon dioxide
DIAS	Data and Information Access Services
DLR	Deutsche Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DMS	Dimethyl sulfide
ECMWF	European Centre for Medium-Range Weather Forecasts
ECN	Energieonderzoek Centrum Nederland (Energy Research Centre of the Netherlands)
ECV	Essential Climate Variable
EMEP	European Monitoring and Evaluation Programme
EO	Earth Observation
EOEP	Earth Observation Envelope Programme
EPOS	European Plate Observing System
ESA	European Space Agency
EU	European Union
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FAIR	Findable, Accessible, Interoperable, and Reusable
FAO	Food and Agriculture Organization
GCOS	Global Climate Observing System
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GO	Programma Gebruikersondersteuning Ruimteonderzoek (User Support for Space Research Programme)
GOME	Global Ozone Monitoring Experiment
H2020	Horizon 2020 Research and Innovation Programme
HAPS	High Altitude Pseudo Satellite
HCFC	Hydrochlorofluorocarbon
ICOS	Integrated Carbon Observation System

ICT	Information and Communications Technology
IFI	International Financial Institution
IGBP	International Geosphere-Biosphere Programme
InSAR	Interferometric Synthetic Aperture Radar
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
ISRO	Indian Space Research Organisation
ISSI	International Space Science Institute
IT	Information Technology
JAXA	Japan Aerospace Exploration Agency
KIA	Knowledge and Innovation Agenda's
KNMI	Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute)
KNW	Kennisnetwerkenregeling (Expertise Networks Programme)
LEI	Universiteit Leiden
NAC	Nederlands Aardwetenschappelijk Congres (Dutch Earth Sciences conference)
NASA	National Aeronautics and Space Administration
NESSC	Netherlands Earth System Science Centre
NIOZ	Koninklijk Nederlands Instituut voor Onderzoek der Zee (Royal Netherlands Institute of Sea Research)
NL	Netherlands
NOAA	National Oceanic and Atmospheric Administration
NRT	Near Real Time
NWA	Nationale Wetenschapsagenda (Dutch National Science Agenda)
NWO	Nederlandse Organisatie voor Wetenschappelijk Onderzoek (Netherlands Organisation for Scientific Research)
OCW	Ministerie van Onderwijs, Cultuur en Wetenschappen (Dutch Ministry of Education, Culture and Science)
OMI	Ozone Monitoring Instrument
PI	Principal Investigator
RADS	Radar Altimetry Database System
RIVM	Rijksinstituut voor Volksgezondheid en Milieu (Netherlands National Institute for Public Health and the Environment)
RUG	Rijksuniversiteit Groningen (University of Groningen)
SCIAMACHY	SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY
SDG	Sustainable Development Goal
SME	Small and Medium-sized Enterprise
SPEX	Spectropolarimeter for Planetary Exploration
SRON	Stichting Ruimte Onderzoek Nederland (Netherlands Institute for Space Research
TEP	Thematic Exploitation Platform

TNO	Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (Netherlands Organisation for Applied Scientific Research)
TROPOMI	TROPOspheric Monitoring Instrument
TUD	Technische Universiteit Delft (Delft University of Technology)
UAV	Unmanned Aerial Vehicle
UN	United Nations
UNEP	United Nations Environment Programme
UT-ITC	Universiteit Twente-Faculty of Geo-Information Science and Earth Observation
UU	Universiteit Utrecht (Utrecht University)
UvA	Universiteit van Amsterdam (University of Amsterdam)
VU	Vrije Universiteit (Free University Amsterdam)
WMO	World Meteorological Organization
WRI	World Resources Institute
WUR	Wageningen University & Research

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8. Appendix: Key figures on Dutch Earth observation research

Subdomains:
A=Atmosphere; L=Land; O=Oceans; S=Solid Earth; I=Ice

1. Dutch universities with EO research programs:

Institute	A	L	O	S	I	Research topics (keywords)
LEI		X				Ecology
RUG	X	X				Atmospheric composition
TUD	X	X	X	X	X	Atmospheric composition, Ice, Oceans, Solid Earth, Hydrology, Geoscience and remote sensing
UT-ITC		X		X		Hazards, Coastal waters, Urban and hydrology, Vegetation, Geo-information science and Earth observation
UU	X	X	X	X	X	Atmospheric composition, Ice sheets and glaciers, Physical and Biological Oceanography, Solid Earth, Geographical Hydrology, Geohazards, Land Degradation
VU	X	X				Atmospheric composition, Land surface remote sensing, Earth sciences, Fire research
WUR	X	X				Atmospheric composition, Land use change, Geo-information science

2. Academic/research schools with EO relevant research programs:

SENSE: Research School for Socio-Economic and Natural Sciences of the Environment (RUG, LEI, OU, PBL, RU, UT, IHE, UU, VU, WUR)
PE&RC: C.T. de Wit Graduate School for Production Ecology and Resource Conservation (WUR, UU, UvA, VU, NBC, NIOO)
BBOS: Buys Ballot Research School for Fundamental Processes in the Climate System (UU, WUR, VU, KNMI, NIOZ, SRON, RIVM, MPIC)
Boussinesq Center for Hydrology (TUD, UT-ITC, VU, UU, IHE, KUL, UG, VUB)
NESSC: Netherlands Earth System Science Centre (NIOZ, UU, RU, VU, WUR)

3. EO master (MSc) programs at Dutch universities:

TUD: Geoscience and Remote Sensing
UU: Climate Physics, Geohazards and Earth Observation
VU: Earth Sciences (incl. Environmental Remote Sensing course), Hydrology
WUR: Geo-Information Science & Remote Sensing
UT-ITC: Geo-Information Science and Earth Observation, Spatial Engineering

4. Other Dutch research institutes with EO research activities:

Institute	A	L	O	S	I	Research topics (keywords)
Deltares		X	X			Water research
KNMI	X		X		X	Atmospheric composition, ocean surface vector winds, wind profiles and upper air winds, clouds, radiation, precipitation, sea ice extent and backscatter mapping
NIOZ			X			Physical and Biological Oceanography
NLR		X		X		Spatial data infrastructure, surveillance
SRON	X					Instrument development, Atmospheric composition
TNO	X					Instrument development, Atmospheric composition

5. EO missions with NL-based PI positions:

SCIAMACHY, OMI, TROPOMI, SPEXone/PACE

6. Current and future EO missions with NL-based EO scientist participation in mission/ scientific advisory/study groups/teams/boards:

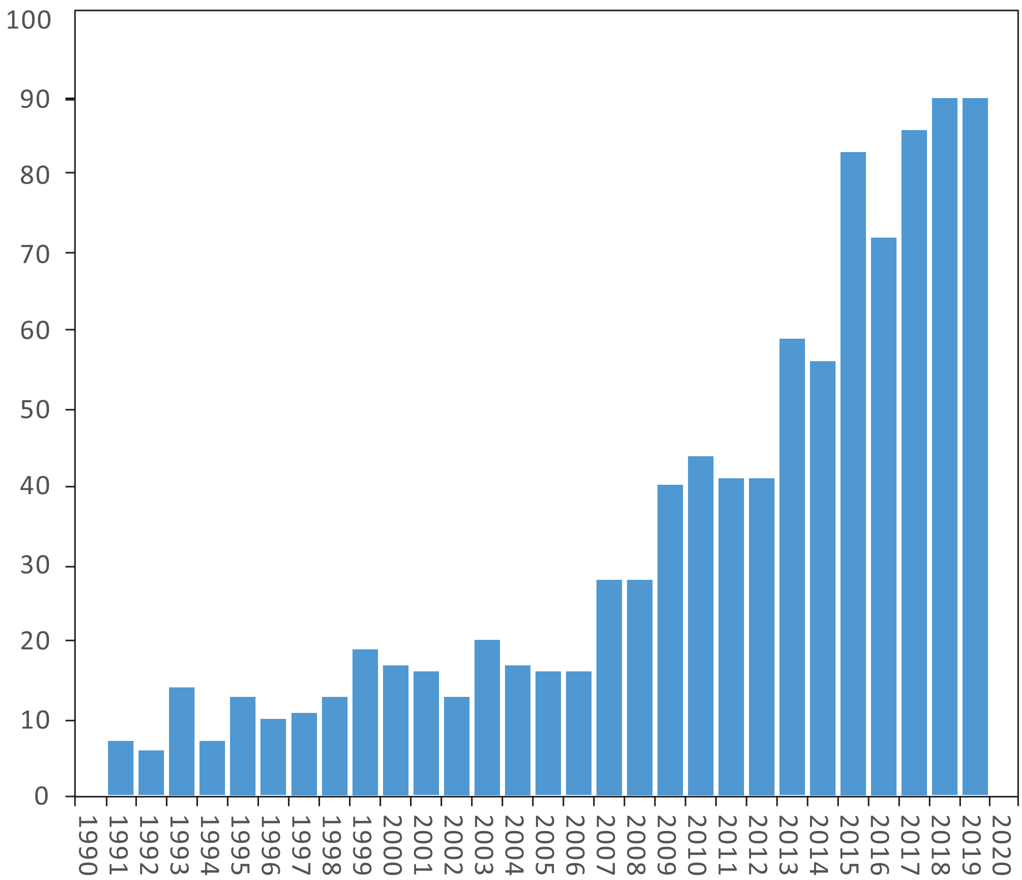
Mission	Agency
Aeolus	ESA
CHIME (Sentinel candidate)	ESA/EU
CO2M (Sentinel candidate)	ESA/EU
Cristal (Sentinel candidate)	ESA/EU
CryoSat-2	ESA
Daedalus (Earth Explorer candidate)	ESA
EarthCare	ESA
FLEX	ESA
HARMONY (Earth Explorer candidate)	ESA
Hydroterra (Earth Explorer candidate)	ESA
HyspIRI	NASA
Merlin	DLR/CNES
Meteosat (MTG)/FCI	EUMETSAT
Metop (EPS-SG)/3MI	EUMETSAT
Metop (EPS-SG)/GOME-2	EUMETSAT
Metop (EPS-SG)/RO	EUMETSAT
Metop (EPS-SG)/SCA	EUMETSAT
ROSE-L (Sentinel candidate)	ESA/EU
Sentinel-1	ESA/EU
Sentinel-2	ESA/EU
Sentinel-4/5	ESA/EU
Sentinel-6	ESA/EU
SKIM (Earth Explorer candidate)	ESA

7. (High-level) international organisations with EO relevance and NL-based scientific membership/participation:

CEOS	Committee on Earth Observation Satellites
CGMS	Coordination Group for Meteorological Satellites
GEO	Group on Earth Observations
IPCC	Intergovernmental Panel on Climate Change
ISPRS	International Society for Photogrammetry and Remote Sensing
UNFCCC	United Nations Framework Convention on Climate Change
WCRP	World Climate Research Programme
WMO	World Meteorological Organisation

8. Significant NWO grants/awards with EO relevance:

NWO Large-scale scientific infrastructure: Ruisdael Observatory
NWO Large-scale scientific infrastructure: European Plate Observatory System-NL



Number of Dutch EO science publications per year. Numbers taken from Web of Science (query on 'earth observation' excluding astronomy and telecommunication, filter for the Netherlands, results binned per year).

9. Satellite infrastructure (missions, instruments) with Dutch EO research contributions:

Mission/instrument	Agency	Subdomain	Instrument	Instrument building	Processing software
Aeolus	ESA	A	X		X
ASCAT-A, -B, –C	EUMETSAT	A, L, O, I	X		X
CFOSAT	CNSA/CNES	A, O, I	X		X
Cryosat-2	ESA	I, O			X
EarthCare	ESA/JAXA	A	X		X
ERS (1,2)	ESA	A, O, I			X
FLEX	ESA	L	X		X
GOCE	ESA	O, S, I	X		X
GOME (1,2)	ESA	A	X	X	X
GOSAT (1,2)	JAXA	A			X
GRACE/GRACE-FO	NASA	L, O, S, I			X
HY-2 (A,B)	CNSA	A, O, I			X
Merlin	DLR/CNES	A	X		
Metop (EPS-SG)/SCA	EUMETSAT	A, L, O	X		X
MODIS	NASA	A, L			X
OceanSat (2,3)	ISRO	A, O, I			X
OMI	NASA	A	X	X	X
ScatSat	ISRO	A, O, I			X
SCIAMACHY	ESA	A	X	X	X
Sentinel-1	ESA/EU	L, O, S, I	X		
SPEXone/PACE	NASA	A	X	X	X
TROPOMI	ESA/EU	A	X	X	X

10. Other Dutch contributions to EO relevant research infrastructure (ground/air/sea-based instruments, ground sites/observatories, data bases, processing tools, etc.):

	Ground/air/sea-based infra.	Ground sites/ observatories	Data bases	Processing tools	Other
Ruisdael Observatory, atmospheric measurement sites: Cabauw, Loobos, Lutjewad, Rotterdam ground sites and mobile airborne and on-ground facilities	X	X	X	X	
Ruisdael Observatory, mobile infrastructure: Instrumented Mobile Van and Trailer, Sky Arrow aircraft	X				
Corner reflectors for calibration InSAR missions (TU Delft)	X				
Geodetic GPS receivers for measuring tectonic motion and GNSS lab (TU Delft)	X				
PARSAX S-band radar at the campus of TU Delft	X				
Hyperspectral Cameras and spectrometers	X				
Goniometer facility (WUR)	X				
Unmanned Aerial Vehicle facility (WUR)	X				
Shipborne surveys/research (R.V. Pelagia, R.V. Navicula)	X				
MIDAC thermal range FTIR field spectrometer	X				
Bruker Vertex 70 VNIR and TIR spectrophotometer (UT-ITC)	X				
L, C and X-band ground-based radar system (TU Delft)	X				
Unmanned Aerial Remote Sensing Facility (UARSF)	X				
Laser Scanning Research Facilities	X				
Mode-S EHS airplane observations	X				
Cessna citation airplane (shared between NLR and TU Delft)	X				
Geodetic GPS receivers	X				
Argo global array of oceanic floats	X				
Automatic weather stations in: Arctic, Antarctic polar region, European Alps, Scandinavia		X			
EPOS-NL: Earth Simulation Infrastructure (ESI) at Utrecht University, the deep geothermal well (DAPWELL) and Petrophysics Lab (DPL) at TU Delft and the ORFEUS earthquake data centre at KNMI)		X			
Ground station for receiving cubesat data (TU Delft)		X			

	Ground/air/sea-based infra.	Ground sites/ observatories	Data bases	Processing tools	Other
Speulderbos field site (46 m tall tower) (UT-ITC)		X			
Twente soil moisture and soil temperature networks (UT-ITC): SMAP cal/val site		X			
In situ monitoring stations in the Dutch Delta and Wadden Sea		X			
Ruisdael Observatory, modelling infrastructure: DALES / HARMONIE			X	X	
GeoDesk (WUR)			X		
RADS: Radar Altimetry Database System (TU Delft)			X	X	
SURFsara (Cartesius/Grid) HPC infrastructure for data processing and analysis			X	X	
CMEMS Copernicus Marine Environment and Monitoring Service (KNMI)			X	X	
C3S Copernicus Climate Change Service (KNMI)			X	X	
CAMS Copernicus Atmospheric Monitoring Service (KNMI)			X	X	
Atmospheric composition models developed and maintained in NL: TM5, LOTOS-Eeros, DALES (incl. algorithms for satellite data assimilation)				X	
Copernicus Global Land Surface Data products (WUR)				X	
ILWIS open source geospatial solution toolboxes (UT-ITC)				X	
Vegetation radiative transfer models (SAIL, SCOPE)				X	
BFAST and BFAST monitor software for time series analysis (WUR)				X	
Clean-room (ISO 8, class 100,000 cleanroom) for testing small satellite subsystems (TU Delft)					X
Clean-room (ISO 6,5; US Fed 1000, 10) satellite instrument electronics, fine mechanics, lithography (SRON)					X
EUMETSAT Satellite Application Facilities: Ocean and Sea Ice, Numerical Weather Prediction, Atmospheric Composition, Climate Monitoring					X
GEO Capacity building resources (UT-ITC)					X
GeoScience and Spectroscopy Laboratory (UT-ITC)					X
Earth observation component in AfricaArray (public-private partnership, ITC)					X