Factories of Satellite Data

Remote Sensing and Physical Earth Sciences in France

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Drawing upon the experiment POLDER conceived in 1984, this paper explores how a system for collecting, producing, archiving and diffusing satellite data in support of different domains of the physical Earth sciences was constituted between 1985 and 2005 in France, a system that presented major departures from the one prevailing during the first 25 years of the history of space technologies. This system promoted the broad delivery and use of a specific form of satellite data, entailed a growing intervention of non-academic institutions in the data-handling and divided the scientific community into those who produce the data, those who consume them and those who curate them. It postulated that experimenters had no longer entire control of the experiment and that data were no longer their property. I associate this regime of practices with the introduction of remote-sensing techniques for observing the Earth – achieved in France mainly through radiometry. I finally suggest strong connections between the history of physical Earth sciences and these changing practices of collecting, producing, storing and disseminating satellite data.

INTRODUCTION

On December 18, 2013, the French space agency (Centre National d'Etudes Spatiales, CNES) convened a meeting in Toulouse to bid farewell to the satellite PARASOL, which was deliberately shut off after 9 years of gathering data at around 700 km above the Earth's surface. The satellite carried a radiometer called POLDER (POLarisation and Directionality of the Earth Reflectance) that measured, from multiple angles, polarised light emitted by a point in the surface or in the atmosphere with a space resolution of around 6×7 km^2 at nadir. Physicists who had conceived the experiment back in 1998,

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as well as atmospheric and climate scientists whose research POLDER had supported during almost a decade, presented oral presentations. Most of them stressed how POLDER had improved the models of bidirectional reflectance needed to study the vegetation; how it had enabled measuring properties of clouds indispensable to understand the water cycle; how it had helped study the sources and transport of different species of tropospheric aerosols; how it had permitted quantifying the effects of clouds and of aerosols on Earth radiation budget; and how, more generally, it had contributed to atmospheric and climate sciences.[1]

Even though many of the speakers had been active during the early developmental stages of the experiment, they majorly decided to remember POLDER as an achieved instrument, whose success was measured by its ability to advance scientific knowledge in these fields. Attention drawn to scientific results is consistent with the fact that atmospheric and climate scientists, along with oceanographers, marine biologists, ecologists, glaciologists or, broadly speaking, physical Earth scientists, in the twenty-first century take satellite data for granted as a tool in their investigations. While this may leave the impression that these scientists were amongst the first in soliciting satellite experiments at the dawn of the space age and that the broad utilisation of satellite data naturally followed from that,[2] in fact, during the first 20 years of space activities, the scientific programmes of space agencies basically supported studies on astronomy, solar and cosmic physics and high energy physics or magnetism, which were commonly known by the actors as 'space sciences'.* Physical Earth sciences such as physical oceanography, atmospheric chemistry, ecosystems ecology, marine biology or climatology only penetrated the scientific programmes of major space agencies in the late 1970s, when measuring specific features relevant to those fields began being sponsored by NASA.[3]

On the other hand, the way in which scientists decided to remember POLDER overlooks that all these scientific achievements were also technical accomplishments of remote-sensing techniques. In particular, the presentations at the Toulouse meeting highlight the extent to which focusing on data utilisation seemed to have eroded the contexts and processes of data gathering, production, storing and dissemination as they became 'infrastructured'.[4] They ignored that the use of data also has a history, one which remains a missing chapter in the historiography of the space age. Yet, studying the history of data use is necessary to enhance our understanding of space

* 'Space sciences' is an actors' category. It may be helpful to clarify that satellites observing the Earth for weather forecasting and resources survey had been launched in the United States since the 1960s and 1970s respectively, and they were certainly used for scientific purposes. What matters for the present analysis is that they were not considered by the actors as belonging to the scientific programming of space agencies, but as being applications.

history as well as to figure out how information obtained with space technologies, commonly used to advance both scientific knowledge and policy-related objectives, is constructed. Immersed as we are in 'information societies', processes, people, institutions, practices, expertises and technologies devoted to produce, conserve and use data cannot be neglected by historians of sciences and technologies.[5]

In focusing on the POLDER experiment – which belongs to the first round of French instruments specifically designed to gather data on the Earth and its environmment – this paper aims to remove the curtain that usually surrounds satellite data-handling and examines how a system of data gathering, production, storing and distribution was installed in France between approximately 1985 and 2005. I explore the motivations and resources of those who designed the system, rooted in the overriding desire to demonstrate utility and to ensure the creation of a community of scientists that would in the future not only use the data but also solicit the launch of satellites. I examine how the resulting data-handling system contributed to give remote-sensing techniques authority in the domains of physical Earth sciences, and I note some of the elements contributing to its consolidation as the norm for satellite data mass production by 2005, applicable to the following rounds of launches and still in force at the time of writing. In discussing how the data-handling system was delineated and established during this period, I emphasise the transformation of the system prevailing during the traditional 'era of space sciences' into new regimes of practices prompted by the encounter of digital radiometry and scientific disciplines such as oceanography, atmospheric chemistry, marine biology, ecology or climate sciences, all well-established long before the advent of satellite remote sensing.

DIGITAL RADIOMETRY, OPTICAL PHYSICS AND THE ORIGINS OF POLDER

PARASOL flew from 2004 to 2013. But the POLDER instrument inside this satellite was the third of a line of polarimeters first proposed in 1984 by a group of physicists and engineers headed by Pierre-Yves Deschamps, an optical physicist who dedicated his career to remote sensing of the oceans. As a student at the University of Lille in the mid-1960s, he was introduced to Professor Lewis Kaplan of the Jet Propulsion Laboratory associated with NASA, and who was a long-time advocate of using infrared radiometry to derive the temperature of the atmosphere.[6] This became the topic of Deschamps' doctoral research – defended in 1968 – in which he built an infrared radiometer and used the measured energy to retrieve the temperature not of the atmosphere but of the sea surface.[7] This work was supervised by Professor Jacqueline Lenoble, another physicist who, after her stay at the Jet Propulsion Laboratory, had become one of the few French experts solving the problem of the propagation of light in scattering milieus (especially the atmosphere) – a problem that constituted the fundamental theoretical question for interpreting aircraft or satellite remote sensing data gathered with optical devices, including radiometers.* In 1974, Lenoble created a laboratory that drew together a group of around ten graduates and postgraduates, including Deschamps, who were working on different aspects of this problem. The new Laboratory for Atmospheric Optics (LOA) affiliated itself with the faculty of physics of the University of Lille and with the National Centre for Scientific Research (CNRS).[8] By the early 1980s, LOA had become a school of remote sensing in France, training future scientists in the optical principles needed to solve the inversion problem essential to interpreting satellite data.

By the time LOA was set up in 1974, the use of optical devices as technology for remote sensing of the Earth was just starting, and it coincided with the introduction of digital devices as light sensors.[9] The main instruments carried by American satellites such as the weather satellites TIROS and NIMBUS (first launched in 1960 and 1964 respectively), the Earth survey programme LANDSAT (first launched in 1972) and the military surveillance programme CORONA (operational since 1962) were television-based or photo-based cameras, whose data were processed to produce pictures. Once processed, analysis of these images used techniques of photo-interpretation of contrasts, textures, geometries or proportions to visually identify familiar forms corresponding to cloud patterns, geological structures, crop parcels, icebergs, urban features and other topographies.[10] Remote sensing was constructed against this approach to satellite data: optical devices measure the energy emitted by corps and use physics of light to derive some of their properties. Remote sensing required knowledge on electromagnetic theory, radiation transfer or spectral signatures – as well as on instrument-building and digital data processing – and the bulk of such expertise was located in physics laboratories specialising in optics, in centres of computer sciences or engineering research, but not in institutes of oceanography,

* Remote sensing is an indirect measurement, meaning that one does not measure directly, but by means of (for instance) electromagnetic radiation as an information carrier. This means that one has to reconstruct from the measurements of light the unknown quantity that one is interested in. This reconstruction is called ‘retrieval’ or ‘inversion’ and requires analysing how the milieu through which the light is propagated alters it. In the case of satellite remote sensing, the milieu is the atmosphere, whose scattering and absorption properties change in function of its chemical composition, the weather conditions, the solar input and many other factors.

ecology, glaciology or climatology, most of which relied on long-established in-situ data collection practices.*

In the United States, the transition towards remote sensing occurred during the 1970s, culminating with the launch of NIMBUS-7 in 1978, which carried eight different optical instruments.[11] In France, radiometry also became the technical choice for its first programmes of Earth observation: the weather satellite METEOSAT proposed in 1968 and the Earth survey satellite SPOT in 1977. There were many scientific and technical reasons to abandon photo-interpretation techniques in favour of such physics-based remote sensing, including the wider range of wavelengths that could be measured and provide more information, or the end-to-end digitalisation of the processes of data collecting, transmitting, storing, processing and analysing, which promised more efficient data handling. But another reason has a greater cultural foundation: by adopting physical theory, precise measuring and mathematical formulation – all hardly attainable through visual analysis – satellite promoters of remote sensing attempted to give the technique the prestige that the discipline of physics achieved after the world wars. In so doing, knowingly or not, the promoters of remote sensing were participating in a process, underway from at least the turn of the twentieth century, to place traditional field sciences on a more 'rational' and modern basis.[12]

Pierre-Yves Deschamps, just like most of his colleagues in the Laboratory for Atmospheric Optics during that decade, became involved in radiometric remote-sensing work.[13] He was primarily interested in developing inversion algorithms to interpret the radiometric measurements of the energy emitted by oceanic surfaces in terms of physical and biological properties like sea temperature or the content of phytoplankton, salt and other molecules, sediments or pollutants. Particularly significant were his studies of methods for correcting radiometric signals from atmospheric perturbations. Between 1975 and 1980, he was chosen principal investigator of a number of American instruments and prepared and exploited data from the Advanced Very High Resolution Radiometer aboard weather satellites, from LANDSAT's radiometers, the Heat Capacity Mapping Radiometer or the Coastal Zone Colour Scanner aboard NIMBUS-7. He organised field campaigns of national and European scope, he supervised numerous doctoral research projects at LOA and he was often called as scientific advisor on plans to promote the use of remote sensing amongst public administrations in France.[14]

* It is quite common for some actors to restrict the use of the term 'remote-sensing' to activities related to high resolution imagery. I take in this paper a broader meaning including all instrumentation measuring the light emitted by the Earth-atmosphere system from a distance.

In 1983, he moved to the Technical Centre of the French space agency in Toulouse. After having worked with surface and aircraft instruments and with American satellite data, he wanted to bring his own radiometer in orbit.[15] While this could not be done on university budgets like those of the Laboratory for Atmospheric Optics, by contrast, in 1980, the French space agency had created a specific division, the Division of Thematic Studies, intended to develop novel instruments and, above all, to find out methods of application of the data in support of scientific questions related to vegetation, the oceans and the atmosphere.[16] The division was directed by Gilbert Saint, a signal-processing engineer who had joined the space agency in 1973 to prepare the data processing for the satellites METEOSAT and SPOT; the other core members included Alain Podaire, Jean-Marie Durand, Yann Kerr and Cathérine Leprieur, experts in data-processing, electronics and optical engineering. This team, with Deschamps, felt that it could gain a lot by bringing their research up for discussion before the users of their techniques and data, namely, the academic scientific community.[17] With this aim, the Technical Centre of CNES joined with a major representative of academia, the National Centre for Scientific Research (CNRS), to create a new laboratory. The Laboratory for Studies and Research in Space Remote Sensing (LERTS) was established in 1985 with a focus on designing novel satellite-based techniques in support of scientific questions related to vegetation, the oceans and the atmosphere.[18] The radiometer POLDER, conceived and developed in close collaboration with the Laboratory for Atmospheric Optics, is one instance of the experiments proposed during the 1980s that involved scientists from LERTS (Figures 1 and 2).

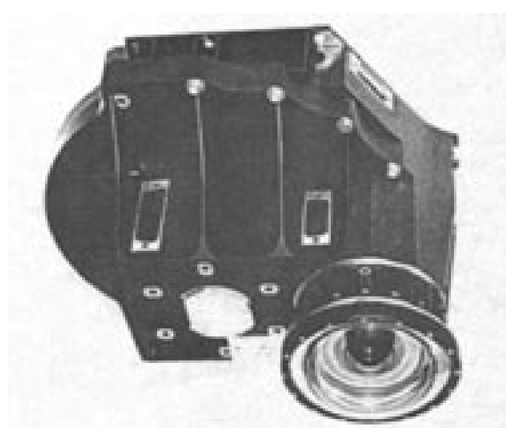

Figure 1. POLDER opto-mechanical block. Source: Minutes, 12/6-9/1994, *Minutes of the first ADEOS Symposium/Workshop*, Ref. PA/TR/OZ/1186/NSD/941234, digital archives of CNES, Paris.

In 1986, Pierre-Yves Deschamps and Alain Podaire of LERTS, Maurice Herman of LOA, Marc Leroy of the Technical Centre of CNES and others sent a proposal to a number of chairs of the space agency, including the Programme Managers Jean-Louis Fellous and Géneviève Debouzy. They proposed that POLDER be launched as a ‘passenger’ payload of the third satellite in the SPOT

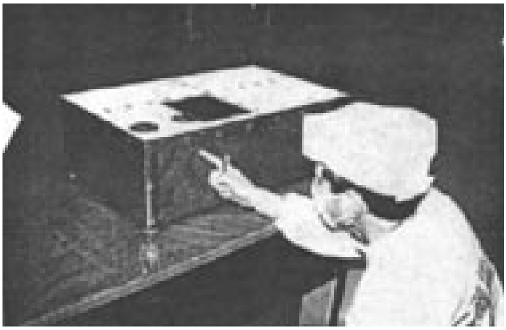

Figure 2. POLDER instrument. Source: Minutes, 12/6-9/1994, *Minutes of the first ADEOS Symposium/Workshop*, Ref. PA/TR/OZ/1186/NSD/941234, digital archives of CNES, Paris.

programme.* The objective was to use polarised light measured from multiple directions to retrieve some properties of tropospheric aerosols.[19] Suspended aerosols are absorbing and scattering agents and therefore perturb the propagation of light across the atmosphere. Consequently, the inversion techniques necessary to retrieve physical properties of the emitting object depend on precise characterisation of the content and species of aerosols and of their radiative effects. Thus, the main mission of POLDER was to gather data on aerosols with the ultimate goal of improving atmospheric corrections over the oceans and vegetation surfaces. As a secondary goal, POLDER's data also were intended to be used in oceanic, atmospheric or vegetation research, although nothing precise was proposed in these fields.

Alain Ratier, manager for oceanic and atmospheric programmes at CNES, supported the project and he provided 1,100,000 francs for the period 1987 to 1990 toward the realisation of an aircraft version of the radiometer.[20] Maurice Herman at LOA coordinated this prototype, which was used to study the feasibility, technical specificities, calibration methods, inversion algorithms, scientific potentialities and limitations of the instrument in view of its eventual 'satellisation'; a number of field campaigns and flights were conducted between 1989 and 1991.[21] Before that, in 1985, in an experiment also sponsored by the space agency, Maurice Herman had placed a polarimeter in a balloon to test its ability for detecting aerosols' smoke over the ocean.[22] The role played by aircraft, balloons and, more generally, fieldwork (surface stations, buoys, ships, etc.) in the preparation of space missions, deserves notice here. Likewise, fieldwork is relied on again after the launching of the satellite; conducting field campaigns for collecting 'ground-truths' and comparing them to the data retrieved from satellite measurements is fundamental for assessing the quality of satellite data. Paradoxical as it may seem, at least at first glance, as space technologies mature and become more sophisticated, the legitimacy of their data depends on their anchoring to the

* In 1981, Professor Pierre Morel, at that time assistant General Director of CNES, announced that SPOT satellites were put at disposal for carrying secondary instruments, insofar they were compatible with the technical specifications of their main payload. These instruments were called 'passengers'.

ground. Traditional fieldwork has never been abandoned in favour of satellite remote sensing technologies; instead, I suggest that, as part of the processes of accommodating the new technology within pre-existing practices, practitioners conjured both in a way that they became organically tied and could not be disassociated.

Hierarchies of CNES did not agree to place POLDER inside SPOT-3, and the search for a satellite to carry POLDER, between 1988 and 1989, led Deschamps and his team to send proposals elsewhere. They asked NASA to consider POLDER as payload for its Earth Observing System, they asked the USSR to carry POLDER in one of its METEOR satellites or in the space station MIR and they asked the European Space Agency (ESA) to carry POLDER inside the Environmental Polar-Orbiting Platform (later renamed ENVISAT).[23] The momentum for POLDER's launch came, however, from an opportunity to engage an institutional long-term collaboration with the Japanese National Space Development Agency (NASDA).[24] Pierre-Yves Deschamps responded to a Japanese 'announcement of opportunities' released in 1988, calling for instruments to be put inside a gigantic spacecraft of around 4,860 kg and 4×4.5×5 m^3 – the Advanced Earth Observing Satellite (ADEOS) – to be launched by 1995 as part of the ambitious Japanese satellite Earth observation programme; Alain Ratier considered this programme to be one of the 'most credible ones' and saw France's participation in it as enabling a partnership amongst equals.[25] The polarimeter POLDER was pre-selected in 1989 by NASDA, together with seven other instruments designed by different Japanese institutions and NASA.[26] On August 17, 1996, a Japanese H-2 launcher brought the satellite ADEOS into orbit. A second prototype was launched, POLDER-2, on December 14, 2002, aboard the Japanese satellite, ADEOS-II.* A third version of the instrument was launched on December 18, 2004, aboard the French satellite PARASOL, first proposed in 1998 by the physicist Didier Tanré, who was another of Jacqueline Lenoble's first disciples at LOA. Thus, POLDER-1 became one of the first instruments sponsored by CNES in support of physical Earth sciences. Other early instruments included the oceanographic radar altimeter POSEIDON (to be launched in collaboration with NASA), the radiometer SCARAB that measured the Earth's radiation budget (to be carried by a Soviet satellite), the radiometer VEGETATION that studied continental ecosystems (inside a satellite of the programme SPOT), and the spectrometer MERIS to study marine biology (inside the Environmental Remote-sensing Satellite (ERS) of the European Space Agency).

* Both satellites suffered similar fates: the solar panel failed to power the equipment and transmission of data to ground station ended approximately 10 months after launch.

PLANNING THE DATA SYSTEM AND CONSTRUCTING MEANINGFUL DATA

The Japanese space agency confirmed a definitive flight-ticket for POLDER in May 1990, and Jacques-Louis Lions, the president of CNES, gave a green light to fabrication of the space version of the radiometer. The POLDER project then entered the routines of project management at the Technical Centre of CNES. A plan was carefully defined, a budget of 199,000,000 francs from 1991 to 1998 was endowed, up to eighteen engineers were charged full-time to POLDER's technical developments, and a specific team of managers was set to work exclusively in the project, headed by Jean-Michel Martinuzzi, acting as Project Manager and advised by Alain Podaire as Project Scientist.[27] This team served as the overall coordination group of the mission, taking the responsibility for overseeing instrumental, scientific and industrial developments and, equally important, for incentivising the utilisation of the future data to be generated by POLDER as well as organising its production, storage and distribution. In this task, they were closely advised by Pierre-Yves Deschamps and Maurice Herman, and they established a more permanent working group, which included physicists from LOA such as François-Marie Bréon, just returned from his postdoctoral fellowship at the Scripps Oceanographic Institute in California, and Didier Tanré, expert in radiation transfer in the presence of aerosols.

Prior to the 1980s, with the notable exception of the SPOT satellite programme, CNES space experiments were conducted following the traditional norms, beliefs and practices set in motion during the 1960s when most space-related experiments used sounding rockets instead of satellites.[28] The experimenters proposing the flight, usually physicists who represented only one domain of the so-called 'space sciences' (e.g., aeronomy, solar and cosmic physics, high energy physics, astronomy, magnetism), assumed entire responsibility and control of the experiment from the conception of the instrument to its manufacture in the laboratory, tests, calibration and correction of the data, its reformatting, transformation into pertinent variables, analysis and interpretation. Data were 'home-made' and, along with the processing algorithms, remained the property of the experimenters, who actually were also the users of the data because data were rarely shared with outsiders. Data conservation was not always ensured after publication.[29] In a way, space sciences were caught between Big Science projects incarnated by space-technologies and small-scale laboratory physics in which data-handling was confined to the experimenter and his or her collaborators.[30]

By contrast, POLDER had been developed by physicists and engineers, and it deliberately targeted a larger audience of external physical Earth scientists. But the performance and possibilities of such an experiment remained to be demonstrated before this audience who, in those early days of remote sensing, simply did not know about these techniques.[31] POLDER's strong orientation toward technical development (recall that its primary goal was to test a novel instrumental configuration and its applicability to correct radiometric signals) raised reluctance amongst academic scientists, who often qualified the instrument as a mere 'technological exercise' and questioned its scientific pertinence.[32] It was argued, for instance, that some oceanic features occurred at space scales in the order of 1 km or less (e.g, small eddies, meanders and coastal effects). How could POLDER, with a coarse resolution of 6×7 km^2, have any scientific value?[33] Just before POLDER's approval by the Administration Council of CNES in September 1990, the Committee for Scientific Programmes, a scientific policy advisory body comprised of academic experts in atmospheric, ocean, vegetation or climate studies, classified the instrument as a 'second priority'. They went as far as to assert that 'at this stage, the continuity of POLDER cannot be justified on scientific terms'.[34] The message was clear: Deschamps must demonstrate its legitimacy as a tool for academic research.[35] Stakes in this were equally important to CNES's institutional goals, because the community of Earth scientists was growing in importance in national and international research agendas. It was crucial for the space agency to convince marine biologists and atmospheric, vegetation and climate scientists of the utility, even the indispensability, of satellite data for their investigations – beginning with POLDER's. For the creation of a community of future satellite-data users and requesters could only benefit the space agency in the long term, as in a changing world, in which the Cold War context that had given birth to space agencies was fading away, they would contribute to justifying the perpetuation of space activities.

By 1990, when POLDER's data system began to be designed, Martinuzzi and the members of his working group perceived that the modality of data-handling that had prevailed since the dawn of space-related experiments in France was inefficient. On the one hand, the proprietary character of the experiment and its data prevented outsiders from analysing data and seeing original results. Moreover, since data remained under the exclusive control of the experimenters, it was impossible for external peers to verify the experimenters' results. These practices did not allow maximising the scientific return of the space technologies and, even worse, they damaged the credibility of the data, of the experimenters producing and using it and of the sponsoring space agencies.*

* All these concerns had been already spelled out in the United States in a study of the Space Science Board in 1978. The conclusions were published in *Data Management and Computation. Volume 1: Issues and Recommendations* (Washington, 1982) but we have not found clear evidence that French scientists, engineers and managers had access to it.

To overcome this handicap, the working team decided to make POLDER's data available to anyone requesting them. Adoption of this principle expressed a fundamental transition between a view of data as proprietary to the instrument-builder and a view of data as belonging to external users. In this move, Martinuzzi, Deschamps and the others were inspired by developments promoted by NASA, which had been campaigning for the open access of all kinds of environmental data, satellite or not, since the early 1980s.* Full delivery of data was an efficient means of facilitating scientific research, even though some scientists feared too much concurrence and pleaded for exclusive access – a point to which I will come back later on. Open access also constituted part of NASA's mandate to promote international collaboration without losing technical advantage.[36] In the end, these policies benefited those who had the resources to access data in the first place (e.g., logistics, technical, human, expertise, budgetary), and here the United States had a leg up.[37] In particular, NASA's policies may be seen as part of the set of propaganda tools deployed for counterweighting a number of controversial programmes that were just being approved in the early 1980s, beginning with the Strategic Defense Initiative, also known as Star Wars.

POLDER's researchers and, more generally, the French space agency were not concerned by the same preoccupations as NASA and the US; however, NASA's laboratories such as the Goddard Space Flight Center and the Jet Propulsion Laboratory constituted references for most of the researchers of LERTS, LOA and in-house CNES' technical departments. Deschamps, for instance, travelled frequently to California (JPL and Scripps) and established close working relationships with American colleagues since his participation at NIMBUS-7 and the Heat Capacity Mapping Mission in the 1970s – as a matter of fact, one of his students from his time at LOA, Robert Frouin, obtained a permanent position at Scripps. In an illustrative example of what has been labelled by John Krige as 'NASA's softpower',[38] I argue that social networks such as Deschamps' influenced the POLDER team's choices on the principles ruling their data system.[39] Besides, POLDER followed chronologically the realisation of the TOPEX/POSEIDON oceanographic radar altimetry mission, a project managed in cooperation with the Jet

* For instance, in 1990, the US Congress signed the Global Change Research Act, which provided, inter alia, for a data system largely based on NASA's propositions established for the programme Earth Observing System (the text of the Act is available at: http://www.globalchange.gov/about/legal-mandate (accessed 11 August 2015). NASA also promoted open access abroad, through the preparation of international research programmes such as the International Geosphere-Biosphere Programme (which ultimately was an internationalisation of the US Global Change Research Programme) and within international organisations like the Committee on Earth Observations Satellites.

Propulsion Laboratory. Even if only to easy day-to-day efficiency in joint technical work, the French teams of CNES working in this project began adopting NASA's set of practices as soon as 1984 and, by extension, they tended to apply them in the rest of the CNES-sponsored missions, including POLDER.[40]

A second principle driving the data-system consisted of delivering the data free of cost. While aligning again with American policies, this contrasted with the data policies of the two existing Earth observation satellite programmes in which France had been involved, SPOT and METEOSAT. From its inception in the mid-1970s and echoing LANDSAT's experience, SPOT's landing imaging datasets were treated as commercial commodities that had to be purchased.* Contrarily, METEOSAT's data had been originally conceived to be shared without restrictions, at least amongst the participants of the experiment Global Atmospheric Research Programme for which the satellite had been conceived in the first place; however, this policy had evolved during the 1980s, as the programme was transformed into an operational one after the launching of METEOSAT: today, some of the data are to be delivered free of cost, while some other data are subject to specific fees.†

A third important strategy of POLDER's team for demonstrating the pertinence of satellite data was to render radiometric measurements gathered by the polarimeter interpretable to physical Earth scientists. If data were to be used by scientists external to the experiment, and not trained – or not interested – in directly interpreting the instrumental measurements of energy per steradian, the data must suit their representations of the Earth as a parametric system ruled by equations describing the processes occurring in the oceans, land surfaces or atmosphere. In 1993, the influential atmospheric chemist Gérard Mégie, working at the Service for Aeronomy, observed that

* In 1984, the French space agency ultimately established a specific centre called SPOT-Image, for delivering the data to users for making profitable the investments. Numerous researchers who had begun their careers in the 1970s as experts of data processing at the French space agency migrated to this lucrative effort. This was the case, for instance, of Gilbert Saint, the first director of LERTS who, in 1991, left the laboratory and moved to SPOT-Image.

† The principle ruling the present EUMETSAT data policy is that the data considered as 'essential' are delivered to anyone free of cost, in accordance with Resolution 40 of the World Meteorological Organisation. The rules to access the rest of the data depend primarily on the instrument, delay of delivery, degree of processing, origins and objectives of the user. For instance, some of the raw data is openly accessible to anyone, as long as the user has previously purchased a specific antenna casting the frequencies directly from the satellites and the software to read them. Some other data are subject to specific fees. For example, in 2015, to receive hourly already-processed data from the radiometer SEVIRI, television broadcasters must pay an annual basic tax of 2,000,000 euros plus additional fees related to the audience of the TV channel, the type of use of the data (e.g., internal consultations and public showing of images), and the GNI of the country the user belongs. The Principles on Data Policy are available at http://www.eumetsat.int/website/home/AboutUs/LegalInformation/DataPolicy/index.html (accessed 11 August 2015).

'the scientific interest of data acquired by space means essentially results in the ability of interpreting the variables effectively measured in terms of pertinent geophysical variables'.[41] Along the same lines, Yann Kerr, one of the five initial researchers of LERTS, described the task of recovering, reformatting, coding, dating, calibrating or correcting data as an 'obstacle course' to the use of data 'that could take several years', and he argued that the job of a scientist consisted in 'making science and not chasing the data, in interpreting data and not writing down data processing algorithms'.[42] Thus, POLDER data had to be delivered in a ready-to-be-used format or what came to be known as 'geophysical' parameters, such as the size of the aerosols, form of the cloud droplets, area of the vegetation leaves, the content of phytoplankton or, more generally, the temperature, sea level, wind speed at the surface or concentration of ozone in the stratosphere (to mention just a few illustrative examples of physical, chemical, biological and climatic variables).

In parallel, as the development of POLDER advanced between 1988 and 1995, the volumes of data to process became concrete. POLDER was amongst the first Earth observation instruments to incorporate digital sensors, which meant, among other things, that larger torrents of data would be collected. POLDER's data were to be downlinked from the satellite to the Japanese antennas at a rate of 882 kilobit per second, around 35 gigabytes of data per day during the three years that POLDER was meant to function. NASDA would sent tapes containing one week of collected data to CNES by post, resulting in about 150,000 magnetic tapes. Once in France, POLDER's data would be processed on the ground as quickly as it was received or it would accumulate uncontrollably – processing meant correcting, calibrating and transforming the recorded signals into 'geophysical' variables. Then the data would be distributed on request by means of CDs or DVDs to interested scientists. Moreover, because a second prototype of POLDER was planned to be launched by 1999, scientists suggested conserving POLDER-1's data for approximately 10 years after the end of the mission in order to reprocess and combine it with POLDER-2's data.[43] The exploitation of such a system was an industrial project, which required the implementation of a specifically devoted ground segment, which expected to mobilise around 40 persons at a cost of 6,000,000 francs per year in France.[44] But, LOA and LERTS had no technical resources, human expertise and budget to cope with that – to give a comparative figure, all the permanent researchers of LERTS and LOA together totalled, by 1992, less than 30.[45] Podaire, Deschamps, Herman, Bréon and others became aware that the body of data that the polarimeter would return would be so vast that it would overwhelm them, and much of the data would never be examined and therefore be lost.[46] As a solution, they struggled to get more support from CNES in the data handling.[47] To them, the space agency was not only perceived as the entity best placed in technical terms to deal with the avalanche of data but also the most responsible in moral terms to promote its actual utilisation.[48]

CNES's leadership, however, was caught between competing forces. On the one hand, Project Manager Jean-Michel Martinuzzi had a clear request from the experimenters asking for CNES's involvement during development and operational stages of POLDER's data handling. Echoing that request, the departments of computer sciences at the Technical Centre in Toulouse were immersed in a parallel internal debate regarding the role of the space agency vis-à-vis the environmental-data information systems that the French government planned to implement, and they campaigned for CNES's involvement.[49] These requests resonated as well with competition dynamics vis-à-vis other major space agencies, like NASA, ESA and NASDA, which were all assuming responsibilities in the management of environmental-satellite data – how could the French space agency afford not to develop its own data system? On the other hand, CNES saw its mandate as the development of new technologies and had less interest in their routine operations. Typically, after funding the first stage of a technology's development, CNES withdrew and left responsibility for the second stage of exploitation to external agencies.[50] Of course, such a mandate was also a way of reducing costs – POLDER's initial data system had been underestimated and, by 1992, elevated to the 60 per cent of the total budget originally allocated to POLDER.[51]

ENTER PHYSICAL EARTH SCIENTISTS

With all these debates on the table, Martinuzzi announced in 1990 that CNES would design and fund the developmental and testing phases of the data-handling system, but it would not maintain and operate it during POLDER's three functioning years.[52] Thus, after a testing period of time, it would be transferred to an external institution that would take over responsibility for its routine operation. Several options were studied, including the establishment of a data-centre at the University of Lille, the collaboration with a centre that managed data obtained with ESA's Environmental Remote-sensing Satellite (ERS) located in Brest, and collaboration with a project proposed by two French companies, AEROSPATIALE and ACRI in Villefranche sur Mer, to handle the data collected by the future ESA's spectrometer MERIS.[53] CNES felt that a long-term collaborative approach was essential. POLDER was, after all, only one of a number of experiments related to the physical Earth sciences sponsored by CNES, and in the following ten years, a number of instruments were planned for launching, including a second prototype of POLDER, a second one of SCARAB or the spectrometers MERIS, SCIAMACHY or GOME, all inside ESA's satellites. Ideally, starting with POLDER's data, this data-handling system eventually would be capable of handling the production, archiving and diffusion of the data gathered by all these other instruments. Ultimately, a partner was found in the governmental organisation devoted to coordinating research related in nuclear energy, the Atomic Energy Commission (CEA).[54] As an institution managing nuclear data since its creation in 1945, CEA had the technical expertise, logistics, budget capacity and manpower to deal with large amounts of data in routine ways[55] – after all, in the digital era, data obtained with synchrotrons or with satellites was all alike.

In addition to the capacity to cope with data, CEA had another attraction. Following a reconfiguration of the research landscape in France during the 1980s, a new laboratory had been created in 1991 at CEA's site in Saclay: the Laboratory for Modelling the Climate and the Environment (LMCE) embraced a scientific programme based on ocean and atmospheric physics emphasising the use of satellite data to study marine and continental biomasses. Joining this new laboratory, a number of nuclear physicists had converted to climate sciences, including Jean Poitou, to whom POLDER's data management was entrusted. The LMCE was not only institutionally bound to CEA, but also to a new research institution in development since 1989: the Space Institute for the Earth's Environment would be formally constituted in 1994 under the name of the Institute Pierre Simon Laplace. The establishment of this new institute had been instigated by Gérard Mégie and aimed to federate all the laboratories specialising in different disciplines of the physical Earth sciences in the Parisian region.[56]

These institutional linkages were important to CNES' institutional goals of gaining visibility amongst Earth scientists and increasing the number of scientists using and soliciting satellite data. Indeed, through LMCE, POLDER's data was easily connected to a number of reputable laboratories working in the fields of oceanography, atmosphere and vegetation studies, among them the Laboratory for Dynamical Meteorology (LMD), the Service for Aeronomy (SA), the Laboratory of Marine Physics and Chemistry (LPCM), the Centre for Research on Earth and Planetary Physics (CETP) and the Laboratory for Dynamical Oceanography and Climatology (LODYC). Together they totalled more than 50 per cent of the French scientific effort in these fields. Institutional bonds were soon reinforced by personal ones. For instance, François-Marie Bréon, since the 1980s one of the most active physicists involved in the preparation of POLDER, became in 1992 one of the first scientists recruited at LMCE and also became central in encouraging the use of the instrument and its data amongst his new colleagues. This is how, between 1991 and 1993, the initial team of physicists made up of Deschamps, Herman, Bréon and others, was enlarged to include the meteorologist Géneviève Sèze, the expert on the Earth's radiation budget Jean-Louis Duvel, the marine biologist Annick Bricaud, the atmospheric chemists François Dulac and Fabienne Maignan, and the oceanographer Jean-Claude Duplessy, of LMD, LPCM and LMCE.

Assisted by these specialists, POLDER's experimenters devised new approaches for eliciting information from polarised light and struggled to define a scientific programme credible to Earth scientists – as I will point out in a while, these Earth scientists did not only contribute to defining such a programme but also played a role in negotiating the particulars of the data policy. In turn, through their connections with wider accredited academic experts in atmospheric physics, oceanography or vegetation studies, this enlarged team became better placed for communicating this information to other Earth scientists. By 1993, they had defined a programme centred on studying the variability and cycle of tropospheric aerosols, quantifying the role of photosynthesis from the continental biosphere and oceans in the global carbon cycle, and understanding the effects of the clouds and aerosols on climate[57] – a call for proposals for creating an international scientific team was issued in 1994.[58]

In the light of this chronology regarding the definition of the scientific goals of the POLDER experiment, one might be tempted to consider it as an instance of techno-push. Arguably, POLDER makes a case in which science did not drive the development of the instrument, but rather it followed it. At its inception in 1984, POLDER was a polarimeter in search of scientific problems in the domains of Earth sciences, and because of that, it had been opposed by some members of the committee of experts advising CNES's scientific policy. However, this unidirectional description does not capture the dynamics between physicists and Earth scientists that was established between 1989 and 1995. The scientific questions informing the POLDER research programme were not invented by experimenters from scratch. Rather, because Deschamps and the others were well aware that POLDER must demonstrate that it could serve academic research, they sought advice from experts and convened on questions that figured amongst those that Earth scientists wanted to investigate. There were some Earth scientists at the Laboratory for Dynamical Meteorology, the Laboratory of Marine Physics and Chemistry and the Laboratory for Modelling the Climate and the Environment who thought that identifying a scientific programme in an ad-hoc process because it could be addressed by a given technology was not at odds with quality science, and they became involved in POLDER's preparation and came to consider it as a laboratory tool. For those who believed otherwise – that this was an inappropriate procedure for performing experiments – POLDER remained nothing more than a 'technological exercise'.[59]

POLDER'S DATA POLICY

In a 1991 meeting, Jacqueline Perbos, responsible for POLDER's data-system at CNES, proposed an industrial-data-management system for POLDER, which resonated with NASA's guidelines. According to this system, data is conceived as an object that has been transformed in successive stages: it is translated first from the objects under observation into the measurements of light, then to a signal that can be downlinked from the satellite, then into physical, chemical or biological properties, then perhaps into images or maps, and so on. Based on this idea, the data-management system distinguished different levels of data in function of the technical processing with which they had been treated (Figure 3).* Level zero data were signals that came down from the satellite ADEOS to the Japanese antennas and which were shipped to CNES's ground stations within four weeks from being received – four weeks was the time estimated to record the data in tapes and for delivery by postal service from Japan to France. Level one data represented the signals that had been transformed into the kind of measurements effectively done by the polarimeter (radiances), filtered, located and dated, calibrated pixel per pixel and interpolated in space grids corresponding to approximately 6×7 km^2. This data remained the property of CNES and, with few exceptions, was delivered only to the scientists involved with POLDER. From these measurements of level one, the 'geophysical' parameters of level two were retrieved by using the inversion algorithms developed by the

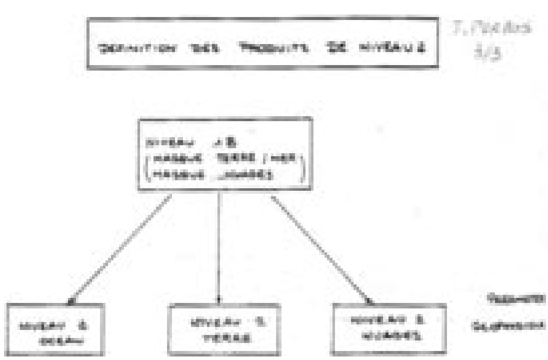

Figure 3. Schema of the organisation of the data production and diffusion following successive levels of POLDER data processing. Source: Minutes, Alain Podaire, 4/25/1991, *Compte-rendu de la réunion du groupe mission POLDER*, Ref. RE/SUTE/D/N°2002, digital archives of CNES.

* The first description of such data levels that I have found at CNES is included in the handbook edited by CNES, *Mathématiques spatiales pour la projection et réalisation des l'exploitation des satellites* (Toulouse, 1984). The author of the chapters devoted to data management, Michel Avignon, confirmed via personal communication that he borrowed the system from the Jet Propulsion Laboratory of NASA.

experimenters and carefully coded and integrated in the computing software. These retrievals represented 12 different parameters, including the cloud fraction, the bidirectional surface reflectance to derive vegetation properties, the thermodynamic phase of clouds' water droplets, the size of tropospheric aerosols and their refraction index and the content of chlorophyll of oceanic waters.[60] This type of data was delivered to external Earth scientists.

The particulars for delivering level two data, or 'geophysical data', were a bone of contention, especially concerning the timing, as the recently arrived Earth scientists involved in POLDER pleaded for restricting accessibility of this data by external Earth scientists. They offered four explicit reasons: the time necessary to control the quality of the data; the dangers of data misuse, because the few extant specialists might not be capable of providing peer-review for all results eventually published from the massive data distribution; the fear that a lot of scientists would be examining the same datasets, which increased pressure to be the first to find an original result as well as to achieve concurrence; and, connected to that, their desire to retain the exclusivity of being the first to publish, which they considered as a reward for the investments in the preparation of the instrument and the data. By contrast, physicists like Pierre-Yves Deschamps, with no stakes in physical Earth sciences research, campaigned for a broader unlimited access to data, arguing that it fostered scientific excellence by promoting competition. Jean-Michel Martinuzzi and other managers of CNES, in their role of promoting widespread use of satellite technologies, also aligned with him, noting that the temporal data embargo was detrimental to the eventual development of applications towards the socio-economic spheres, such as real-time forecasting air or sea pollution, weather forecasting or the surveillance of the state of the oceans, all of which needed rapid and regular access to data.

Negotiations resulted in a compromise: during a period of six months, only the scientists involved with POLDER could access the 'geophysical data'; after this temporal embargo, access would be open and free. This period, called the 'validation phase', was devoted to data quality control before allowing publication. As suggested earlier, the validation phase involved comparing retrieved satellite data with 'ground-truths' obtained through fieldwork at surface stations and, especially, from aircraft flights and ship journeys. So central were these field practices that they are now an inherent part of any space programme and, as such, receive significant funding from space agencies. For instance, in 1993, CNES and NASA sponsored the installation and routine functioning of a worldwide network of ground-photometers to gather continuous data on atmospheric aerosols in order to assess the quality of POLDER's retrievals (and also those obtained with other satellite instruments). The AErosol RObotic NETwork (AERONET), as it was named, today has around 600 ground stations.[61]

Because of technical issues related to the computer system, to scientific problems with the calibration algorithms and the funding of aircraft field campaigns, POLDER's 'geophysical' datasets were first publicly mass-released in August 1998, two years after the launching instead of the six months as initially planned. Meanwhile, the solar panels of ADEOS failed in June 1997, ending communication – data transmission and reception – between the satellite and ground station. This fatal conjuncture of events gave rise to the paradoxical situation that when the system was ready to routinely disseminate the data, there was no more incoming data to be disseminated. Consequently, the exploitation of POLDER's data was never transferred to the Atomic Energy Commission and the collaboration with the space agency on that subject ended.

Debates about what access to what data still continue today and recurrently appear as new instruments are launched. However, although the details differ in every experiment (e.g., duration of the embargo, membership of the team with privileged access), the rules established for managing POLDER's data became the overall rules on which a number of data systems were established during the 1990s for the data of the first round of satellites launched in that decade. For instance, a system for handling radar altimetry data obtained with POSEIDON was set up at the Technical Centre of CNES in 1989.[62] In 1991, the year when the European Environmental Remote-sensing Satellite (ERS) was launched, the European Space Agency established a data centre located in Brest.[63] Gérard Mégie encouraged the creation of a data system dealing with satellite data in the domain of atmospheric chemistry within the future federation of Parisian laboratories, which was in the course of being founded.[64] The Laboratory for Dynamical Meteorology instituted CLIMSERV, which diffused data about the Earth's radiation budget, nebulosity and water vapour obtained with the radiometer SCARAB; the Network for Detection of Stratospheric Changes of the Service for Aeronomy, the Centre of Plasma Physics Data of CNES and the Service for Aeronomy, are other examples of data centres being established. These were, however, all dispersed developments, often created as a result of solicitation by a community related to a satellite instrument and without perspective beyond that community and the life of the satellite.

As the second round of satellites in support of the physical Earth sciences began developing, Earth scientists, physicists and space managers gathered together in 1998 at the fifth scientific meeting sponsored by CNES, and they decided to coordinate all these on-going efforts.[65] A working group was set up, chaired by the physicist Philippe Waldteufel of the Service for Aeronomy and composed of a number of scientists from various universities and CNRS and supported by CNES's staff, which issued a report in October 1999 making a clear recommendation: data centres specifically devoted to producing, archiving and disseminating 'geophysical' parameters must be established by means of a collaboration between CNES and the scientific institutions – first and foremost, though not exclusively, CNRS – distributed across the territory and structured by scientific areas instead of by satellites or instruments. They were named 'thematic poles'.[66]

In 1999, Anne Lifermann, who had replaced Alain Podaire as POLDER's Project Scientist in 1994, assembled scientists related to the new experiments being prepared. Among them were some related to POLDER, such as François-Marie Bréon, Jean Poitou, Marc Leroy or Didier Tanré (who was by then also the Principal Investigator of the experiment PARASOL proposed in 1998), as well as Robert Kandel of the Laboratory for Dynamical Meteorology and Jacques Pelon of the Service for Aeronomy, principal investigators of the second SCARAB prototype and of a new infrared radiometer. The goal was to establish a thematic pole devoted to coping with data from all space missions related to atmospheric physics, beginning with those obtained with POLDER-2, scheduled for a launch in 2000. The data centre was named Interactions Clouds Aerosols Radiation Energy (ICARE). Because of successive delays in technical development, in defining computational needs and data-flow rates, in budget allocation, in designation of responsibilities, and decisions concerning the location of the computing centre (Lille or Paris) and its funding, ICARE was not ready for the launching of POLDER-2, even though the launch was delayed until 2002. In the end, ICARE was scheduled to be operational for the launching of PARASOL in 2004.[67]

That year, a convention constituting ICARE was signed by the directors of CNES, CNRS, the Regional Council and the University of Lille.[68] As praised in Waldteufel's report of 1999, the technical branch of ICARE, located in the University of Lille, was equipped with powerful computers and researchers who optimised the data-inversion algorithms to be compatible with industrial routine production. They operated the chains of data production; elaborated periodic reprocessing of data as new algorithms were developed; implemented directories, catalogues and libraries; chose the format of the data files; updated the databases; obtained exogenous data and information to complete them; periodically changed storage medias; distributed reading software and documentation to users, and so forth. The staff of the data centre was comprised of experts in computer and information sciences who ensured proper data curation.

ICARE became only one of numerous 'thematic poles' or data centres – such as POSTEL, located in Toulouse, for managing data on continental vegetation – that were created in France between 1999 and 2005. Former data services like those devoted to physical oceanography, atmospheric chemistry or the Earth's radiation budget were reorganised to accomplish the functions of the 'thematic poles'. As such, the creation of these data centres reflected a major continuity in the ways of organising data that began being collected with the first generation of space missions using POLDER, POSEIDON, SCARAB, ERS and other instruments from NASA. They were built to fit current practices, and they contributed to the normalisation, by 2005, of a specific modality of industrial-satellite data being produced and disseminated in France. 'Geophysical' parameters were carefully archived and accessible through the online databases (after a temporal embargo), while intermediate data levels were not considered as deliverable items and remained the property of CNES. Likewise, more elaborate forms of data, including long-term homogeneous data-series or datasets combining satellite data with data obtained in other domains (e.g., economic statistics, demographic trends) were not furnished at these data centres.

CONCLUSION: 'ERA OF SPACE SCIENCES AND 'ERA OF EARTH SCIENCES'

During the 1980s and 1990s, as the instruments devoted to gathering data in support of the Earth sciences for the first round of launches were conceived, realised and launched, the overriding goal of their promoters, space managers and experimenters, was to demonstrate that satellite remote-sensing techniques were credible tools for investigations and that quality academic science could be done using these techniques. With this shared agenda during the early stages of preparing POLDER's data system in 1990 to 1995 and closely following the precepts installed at NASA, Martinuzzi, Perbos, Podaire, Deschamps, Herman, Bréon and others, decided that POLDER's data had to be delivered for free and in some form of 'geophysical' parameters to outsiders, after a temporal embargo. With the establishment of numerous data centres – let me call them 'factories of data' – specifically devoted to mass production and diffusion of data, the French system became normalised around 2005 for most of the programmes devoted to support of the physical Earth sciences.*

This new regime of practices departed in at least two features from the previous one that prevailed during the 'era of space sciences' before the 1980s. First, the factories of mass production and dissemination opposed the idea, deeply rooted in the culture of traditional space scientists, that scientists who proposed an instrument and prepared the data analysis should have complete control of the experiment and exclusive access to the resulting data. Instead,

* The weather and high resolution imaging programmes (satellites succeeding METEOSAT and SPOT) are not considered part of the scientific programming of CNES and are ruled by specific norms.

non-academic institutions, CNES in the first place, intervened in the data handling, endowing specific technical, budgetary, logistic and human resources and becoming the proprietor of certain types of data. Second, this data industrialisation contributed to hardening the division of what had been, before the 1980s, one single community of 'space scientists'; the community became increasingly separated into those who produced the data, those who used it and those who curated it – as has been also noted by the historian Erik Conway in his analysis of radar altimetry missions in the United States.[69] Industrial production, stratification of labour and production of homogeneous and standard material are common attributes of some scientific ventures, especially those related to Big Science endeavours at least since the late-nineteenth century, and similar attributes have been observed in the management of astronomical data, the production of biologic material (like inbred mice) or more recently the organisation of the data involved in the Genome project.[70] The space managers, optical physicists, digital data processors and instrumentalists who were first in promoting satellite remote sensing in support of the physical Earth sciences in France not only encouraged the use of novel techniques in these long established disciplines, but they also brought to the fore different professional groups, institutions, scientific disciplines, social organisation, sources of funding and property rules. They set into motion a new set of practices, values and norms for performing scientific investigations with space technologies that differed from those established by the 'space sciences'. In particular, during the 'space sciences era', the experiment, the experimenter, the measurements and the data or information made a single whole, indivisible package. By installing this system for data production and diffusion, promoters of remote sensing created the idea of 'satellite data' as standardised, mass-producible, mass-reproducible, widespread and public (with some conditions); the idea was of data being an autonomous item with no visible link to the experimenter, to the satellite, to the instrument or to the methods of processing.

To be sure, space agencies did not abandon traditional disciplines and methodologies – astronomy, high energy physics and geomagnetism are still central to major space agencies like NASA, ESA, CNES and JAXA (successor of NASDA as the Japanese space agency). However, since their introduction in the 1980s, Earth observation missions and the set of practices they introduced have consumed increasing attention – at least in France.* They

* This can be seen by looking at the relative budget of both groups of activities – in 1985, the French space agency budget allocated 100 times more to Earth observation programmes than to the 'space sciences'. This relative difference subsequently shrunk over time (especially after the renovated interest for space exploration and missions to Mars); however, in 2005, it was still four times larger for the physical Earth sciences.

would inform a second period of the history of space-related research – let us call it the 'era of physical Earth sciences'.[71]

NOTES

1 Slides that accompanied the oral presentations of this meeting are available on http://smsc.cnes.fr/PARASOL/Fr/GP_actualites.htm (accessed May 25, 2015).

2 Studies that belie this view can be found in John Krige, 'Crossing the Interface from R&D to Operational Use: The Case of the European Meteorological Satellite', *Technology and Culture,* 41:1 (2000): 27–50; and Chunglin Kwa, 'Local ecologies and Global science: Discourses and Strategies of the international Geosphere-Biosphere programme', *Social Studies of Science*, 35:6 (2005): 923–950.

3 For a history of atmospheric scientific programmes at NASA, see Erik M. Conway, *Atmospheric Sciences at NASA: A History* (Baltimore, 2008).

4 This is precisely one of the attributes of 'infrastructures': their internal workings are black boxed. See Geoffrey C. Bowker and Susan Leigh Star, *Sorting Things Out: Classification and Consequences* (Cambridge, 1999) and Paul N. Edwards, *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming* (Cambridge, 2010).

5 On information society see Manuel Castells, *The Information Age: Economy, Society and Culture* (Cambridge, 1996 and 1997).

6 One of his most quoted papers is Lewis D. Kaplan, 'Inference of atmospheric structure from remote radiation measurements', *Journal of the Optical Society of America*, 49:10 (1959): 1004–1006.

7 Pierre-Yves Deschamps, 'Etude et réalisation d'un radiomètre infrarouge', PhD. diss., University of Lille, 1968.

8 Reports, Jacqueline Lenoble, October 1975, *Rapport Scientifique de 1974–1975*, Ref. 20111087/49, Archives Nationales, Pierrefitte sur Seine.

9 The effects of introducing electronic sensors, such as CCDs, for gathering data have been examined, in the case of astronomical research, by Robert W. Smith and Joseph N. Tatarewicz, 'Replacing a Technology: The Large Space Telescope and CCDs', *Proceedings of the IEEE*, 73 (1985): 1221–1235; and Elizabeth A. Kessler, *Picturing the Cosmos: Hubble Space Telescope Images and the Astronomical Sublime* (Minneapolis, 2012).

10 Some of these satellites, especially of the programmes NIMBUS and LANDSAT, also carried radiometers, but they were often considered as secondary instruments and learning to interpret this data took a longer time. See, for instance, Paul Rey, 'La télédétection des ressources terrestres au CNES: De la photo-interprétation à la télédétection des ressources naturelles', *La Recherche Spatiale*, XII:5 (1973): 12–20.

11 Soviet spacecraft also abandoned photo and video-cameras in the 1980s, as described in Gérard Joly, *Traitements des fichiers-images* (Paris, 1986).

12 Historians of cold war sciences have argued that the increasing support of government funding in the US after the world wars, especially from the military, led to a domination of physical methods in field sciences. See, for instance, Ronald E. Doel, 'Constituting the Postwar Earth Sciences: the Military's Influence on the Environmental Sciences in the USA after 1945', *Social Studies of Science,* 33:5 (2003): 635–666. However, the 'modernisation' of field sciences, through the introduction of rational and quantitative methodologies, was an undergoing process since at least the turn of the twentieth century, as has been shown in the case of meteorology by Frederik Nebeker, *Calculating the Weather: Meteorology in the Twentieth Century* (New York, 1995), and in the domain of biological field sciences by Robert E. Kohler, *Landscapes and Labscapes: Exploring the Lab-Field Border in Biology* (Chicago, 2002).

13 Some doctoral studies conducted at LOA between 1974 and 1980 help illustrate their focus on remote sensing, both theoretical and experimental. See Jean-Luc Deuzé, 'Etude de polarisation du rayonnement par les milieux diffusants: Application à la polarisation localisée de Vénus', PhD. diss., University of Lille, 1974; Colette Brogniez, 'Calcul approché des flux radiatifs en milieu diffusant: Applications aux mesures de Venera 8', PhD. diss., University of Lille, 1975; Michel Viollier, Contribution à l'étude du rayonnement rétrodiffusé par l'océan: Applications à la télédétection de la chlorophylle', PhD. diss., University of Lille, 1976; Didier Tanré, 'Etude de l'influence des aérosols sur le rayonnement terrestre rediffusé', PhD. diss., University of Lille, 1977; Thierry Phulpin, 'Utilisation de la radiométrie infrarouge multispectrale pour la détermination de la température de surface', PhD. diss., University of Lille, 1978. See also Reports, Jacqueline Lenoble, between 1974 and 1980. Ref. 20111087/49. Archives Nationales, Pierrefitte sur Seine.

14 Reports, Jacqueline Lenoble, between 1975 and 1980, Archives Nationales, Pierrefitte sur Seine.

15 Interview, Pierre-Yves Deschamps, 2/6/2014, Lille.

16 Press communication, Gilbert Saint, 1/29/1985, *Communiqué de presse sur la création du Laboratoire d'Etudes et de Recherches en Télédétection Spatiale*, Ref. 20111087/382, Archives Nationales, Pierrefitte sur Seine.

17 Report, André Berroir, Automne 1983, *Rapport d'évaluation de la proposition ERA pour la création du Laboratoire d'Etudes et de Recherches en Télédétection Spatiale*, Ref. 20111087/382, Archives Nationales, Pierrefitte sur Seine.

18 Agreement, 1/1/1985, Fréderic d'Allest and Pierre Papon, *Convention fixant les règles d'organisation et de fonctionnement du Laboratoire d'Etudes et de Recherches en Télédétection Spatiale*, Ref. MJ/VC-210/84, digital archives of CNES, Paris.

19 Project, Michel Laporte, Marc Leroy, Alain Podaire, Pierre-Yves Deschamps, Maurice Herman, Richard Santer and Yves Fouquart, February 1986, *Proposition de passage SPOT-3, POLDER: Polarisation et Directionalité des Réflectances*, personal archives of Pierre-Yves Deschamps.

20 Report, Alain Ratier, 10/5/1989, *Note de synthèse sur POLDER*, Ref. PC-NT-0-055-CN-890900, digital archives of CNES, Paris.

21 In 1989, Ratier also allocated 950,000 francs to the industrial Matra for a two-year preliminary study of a space version of the instrument. Ibid.; and Report, Pierre-Yves Deschamps and Jean-Pierre Deshayes, 2/6/1990, *Dossier de programme POLDER*, Ref. PC-BC-0-56-CGS, digital archives of CNES, Paris.

22 Maurice Herman, et al., 'Stratospheric aerosol observations from a balloon-borne polarimetric experiment', *Applied Optics*, 25:19 (1986): 3573–3584.

23 Report, Pierre-Yves Deschamps, 11/24/1989, *POLDER Mission Specification*, Ref. PC-SP-0-025-CGS-891100, digital archives of CNES, Paris; Project, Pierre-Yves Deschamps, 3/5/1989, *Proposition d'emport de l'instrument POLDER sur Meteor ou MIR dans le cadre de la Coopération Franco-Soviétique*, Ref. PC-RP-0-017-CGS-890309, digital archives of CNES, Paris; Report, Jean-Pierre Deshayes, 6/25/1990, *Fiche de renseignements de POLDER sur GLOBSAT*. Ref. PG-RP-2-098-CGS-900602, digital archives of CNES Paris.

24 Report, Conseil d'Administration du CNES, 4/4/1991, *Dossier de programme POLDER/ADEOS*, Ref. PA-BC-0-443-CN-910320, digital archives of CNES, Paris.

25 Minutes, Alain Ratier, 23/11/1990, *Mission au Japon. 29 Octobre – 2 Novembre 1990. Points Sallants*, Ref. RA/RE/SU/TE 90.259 bis AR/AR, digital archives of CNES, Paris. Translated by the author.

26 Letter, Hiroyuki Osawa to Pierre-Yves Deschamps, 8/31/1989, Ref. PC-BC-0-56-CGS, digital archives of CNES, Paris.

27 Report, Jean-Michel Martinuzzi, 3/28/1995, *Budget et coût à achèvement du projet POLDER/ADEOS*, Ref. PA.BC.0.674.CN-CT/ED/DI/PO-93.169, digital archives of CNES, Paris.

28 The Director of Programmes of CNES, Pierre Morel, estimated in 1963 that around 100 sounding-rockets and 8 satellites would be launched per years between 1964 and 1973. Project, Piere Morel, October 1963, *Proposition d'un plan national de développement des recherches spatiales. 1964–1973*, non-referenced, digital archives of CNES, Paris.

29 These beliefs were made clear by space scientists lecturing in the 1981 edition of the annual courses on space technologies organised by CNES at the University of Toulouse, which that year especially was dedicated to space experiments. These lectures were compiled in a handbook edited by CNES, *La technologie des expériences scientifiques spatiales, Volume IV: Traitement des données des expériences spatiales* (Toulouse, 1981).

30 On Big Science see Peter L. Galison and Bruce Hevly, eds., *Big Science: The Growth of Large-Scale Research* (Stanford, 1992).

31 Isaac Revah, Director of Earth and environment programme at CNES, expressed these challenges in 'L'étude du climat et de l'environnement: les apports de l'espace', *Les Cahiers du MURS*, 30/31 (1993): 79–92.

32 Project, Gérard Mégie, 10/11/1990, *Pour un Institut Spatial de l'Environnement Terrestre*, Archives of the Laboratory for Dynamical Meteorology, Paris.

33 Minutes, Alain Chedin, 6/5-6/1990, *Réunion du groupe Terre-Atmosphère-Océan-Biosphère du Comité de Programmes Scientifiques* Ref. PC-CR-0-125-CN-900604, digital archives of CNES, Paris.

34 Ibid. Translated by the author.

35 Report, Pierre-Yves Deschamps, 3/28/1991, *Présentation des enjeux, des objectifs et du contenu du programme POLDER/ADEOS: Comité des Programmes Scientifiques du CNES*, Ref. PA-BC-0-441-CGS-910321, digital archives of CNES, Paris; or Report, Pierre-Yves Deschamps, 5/9/1990, *Proposition de passage en phase B pour l'expérience POLDER*, Ref. PC-BC-0-58-CGS-900503, digital archives of CNES, Paris.

36 The role of NASA in implementing American foreign affairs' objectives has been analysed in John Krige, 'NASA as an Instrument of U.S. Foreign Policy' in eds., Steven J. Dick and Roger D. Launius, *Societal Impact of Spaceflight* (Washington, 2007).

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