The Measure of All Things

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The Measure of All Things:
Space Oceanography and the TOPEX/POSEIDON Mission, 1980s-1990s[1]

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The TOPEX/POSEIDON satellite mission to observe the oceans triggered the formation of the new specialty of space oceanography from the 1970s to 1990s. Previously, in the 1960s in the United States, traditional oceanographers had shown little interest in the possibilities of space and thus space engineers and physicists worked on the first missions (Seasat in particular). TOPEX/POSEIDON brought together two projects, one American (TOPEX) and the other French (POSEIDON). The gradual crystallization of the disciplinary specialty of space oceanography occurred by making available a platform of instruments able to meet an ensemble of varied needs. Battery failures just before the launch of the joint mission meant that the mission had to focus on the essentials (notably El Niño effects). Subsequently, the discovery of a significant rise in sea levels due to global warming resulted in space oceanography becoming a recognized specialty. The case of TOPEX/POSEIDON shows the original ways in which instruments gained a place in the very large range of oceanographic techniques.

Keywords: oceanography, space, satellite, specialty, sea levels, global warming

Introduction

In a recent book for the general public, Patrick Geistdoerfer situated the TOPEX/POSEIDON mission within the history of oceanography: the mission's results not only confirmed the rise in sea level correlated with climate change, but space technologies also "revolutionize[d] working methods in oceanography".[2] The posterity of the mission comes down to these two findings: first, TOPEX/POSEIDON provided the data validating the hypothesis of an increase in sea level; second, the satellite was the decisive element in transforming a scholarly discipline.

The purpose of this article is to understand precisely how these two aspects are related: What is the connection between a scientific discovery from satellite data and the shift in a field of research? The post-Kuhnian debates on normal science, models of the development of science, and the obsolescence of the concept 'discipline' to describe the contemporary forms of knowledge production have not yet resulted in a consensus for the future.[3] The notion of

[1] I would like to thank Michel Dubois, John Krige, Isabelle Sourbès-Verger, Arnaud Saint-Martin and Terry Shinn for their useful comments on this article. I would also like to thank the reviewers, Erick M. Conway and Simone Turchetti, whose remarks greatly enriched the paper.

[2] Patrick Geistdoerfer, *Histoire de l'océanographie. De la surface aux abysses* (Paris: Nouveau Monde Éditions, 2015), 179. All the citations originally in French have been translated by the translator.

[3] Michael Mulkay, ‟Development of a scientific speciality. Phage Group and origins of molecular biology,"*Minerva* 10, no. 1 (1972) : 51-82. ; Terrence Ball, . ‟From Paradigms to Research Programs : Toward a

‘discipline’ is still useful and relevant, even though detailed studies of the term’s current transformations show that scientists are frequently moving towards the borders of their disciplines to dialogue with other researchers in neighboring fields.[4]

Moreover, the relationship between the instruments used and the discipline that uses them is one of the most interesting avenues for research, not only for questioning the concept of ‘discipline’[5] but also for bringing to light the aspects of a specialization. Three main theories or currents have analyzed the relations between instruments and disciplinary specializations. The first focuses on the processes leading to the mastery of an epistemic area (whether initially ignored, to be conquered, or to be defended). The work of Ron Johnson, David Robins,[6] Bruno Strasser,[7] and Nicholas Mullins[8] illustrates this approach, which seeks to define the socio-epistemic stages of the progressive crystallization of interests and actors around an instrument. The second approach that studies the specialty / instrument relationship focuses on research careers. Daryl E. Chubin[9], Michael Mulkay,[10] and Gerald Geison[11] have defined concepts (*i.e.* intellectual migration, branching, and research schools) to capture the quasi-demographic changes involved in the formation of a specialty. Finally, the third approach starts with the instruments themselves and their material and epistemic specificities, to then understand the socio-cognitive rethinking that these instruments make possible. For example, in his study on crystallography, John Law identified the importance of the technical foundations of certain specialties[12]. Peter Galison, in reconstructing the history of microphysics in the 20th century, brought to light the relative autonomy of a community of

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Post-Kuhnian Political Science,”*American Journal of Political Science*, 20, no 1(1976) : 151-177. ; Michael Mulkay, “Three Models of Scientific Development,”*Sociological Review*23, no3 (1975) : 509-526; Andrew Abbott, *Chaos of Disciplines* (Chicago: The University of Chicago Press, 2001); Ernst Mayr, *What makes biology unique ? Considerations on the autonomy of a scientific discipline* (Cambridge: Cambridge University Press, 2004) ; Hans Poser, “Mathesis universalis and scientia singularis. Connections and disconnections between scientific disciplines,”*PhilosophiaNaturalis.*35, no1 (1998) : 3-21; Juliette Thompson Klein, *Crossing Boundaries : Knowledge, Disciplinarities, and Interdisciplinarities* (Charlottesville: University Press of Virginia, 1996); Stephen Turner, “What Are Disciplines ? And How Is Interdisciplinarity Different ?,” in *Practicing Interdisciplinarity* .ed. Peter Weingart, and Nico Stehr (Toronto: University of Toronto Press, 2000), 46-65; It should be noted that the hypotheses (more political than academic) on the end of disciplines and a new era of undifferentiated science have been discredited and have not been convincing, (Michael Gibbons, Camille Limoges, Helga Nowotny, Simon Schwartzman, Peter Scott, Martin Trow, *The New Production of Knowledge. The dynamics of science and research in contemporarysocieties* (Londres: Sage, 1994.). See Terry Shinn, “Nouvelle production du savoir et triple hélice. Tendances du prêt-à-penser les sciences,” *Actes de la recherche en sciences sociales*. no 141-142(2002) : 21-30. And Peter Weingart, “From ‘Finalization’ to ‘Mode 2’ : oldwine in new bottles ?,”*Social Science Information.*36, no 4(1997) : 591-613.

[4] Anne, Marcovich, Terry Shinn, “Where disciplinarity going ? Meeting on the borderland,”*Social Science Information.*50, no 3-4(2011) : 582-606.

[5] For a very broad view, see : Bernward Joerges, Terry Shinn, “Fresh Look At Instrumentation. An Introduction,” in *Instrumentation Between Science, State and Industrie*, ed. Bernward Joerges, and Terry Shinn (Dordrecht : Kluwer Academic Publishers, 2001), 1-13.

[6] Ron Johnston, Dave Robbins, “The Development of specialities in industrialized science”, *Sociological Review* 25 (1977) : 87-108.

[7] Bruno J. Strasser, “Totems de laboratoires, microscopes électroniques et réseaux scientifiques : l’émergence de la biologie moléculaire à Genève (1945-1960)” *Revue d’histoire des sciences* 55-1 (2002) : 5-43.

[8] Nicholas C. Mullins, “The development of a scientific speciality : The Phage Group and the origins of molecular biology” *Minerva* 10(1) (1972) : 41-82.

[9] Daryl E. Chubin, “ The Conceptualization of Scientific Specialities”, *The Sociological Quaterly* 17(4) (1976) : 448-476.

[10] Michael J. Mulkay, “Three Models of Scientific Development” *The Sociological Review* 23(3) (1975) : 509-526 ; Michael J. Mulkay, “The Model of Branching” *The Sociological Review* 24(1) (1976) : 125-133.

[11] Gerald Geison, “Scientific Change, Emerging Specialities, and Research Schools” *History of Science* 29 (1981) : 20-40.

[12] John Law, “The Development of Specialities in Science : the Cas of X-Ray Protein Crystallography” *Science Studies* 3(1) (1973) : 302.

researchers focused on the production of instruments[13]. Finally, Terry Shinn, in defining the technico-instrumental regime, identified the essential criteria of a 'generalizable' instrument that, because of its modularity, is able to circulate in different disciplines.[14] It is this third way, of approaching a specialty through its instrumentation, that has been adopted in the present study to examine the conditions for using the spatial data produced by Topex / POSEIDON. However, the specificities of satellite instruments (and in particular their low post-launch flexibility) call for re-evaluating the importance of technical modularity in defining a disciplinary specialty. Finally, the precedence of *in situ* oceanography enables us to compare and qualify the effects of the innovations of space oceanography.

The approach I follow in this article was also used by Simon Schaffer for demonstration devices in the eighteenth century: he studies the successive contexts of their use and the extent to which they could be used in contexts different than the ones for which they were originally built. This, in turn, determined the devices' capacity to withstand the tests done on them.[15] Thus, detailed attention to the broad context (and not only to the narrow conditions of their use in a strictly ethno-methodological approach) enables us to understand the major epistemological currents within which these devices exist.

TOPEX/POSEIDON was a Franco-American mission launched in 1992 that sought to better understand ocean movements. At that time, knowledge of liquid masses was the prerogative of a discipline created long before: oceanography. Originally based on *in situ* measurements of a variety of data (tidal movements, salinity, water temperature, winds, etc.), today this discipline includes satellite data among many other kinds of instruments.

How did the questions studied by traditional oceanography and space technologies of investigation come together? What were the points of connection and relation between these two broad groups of activities? What was TOPEX/POSEIDON's role in the creation of space oceanography as a specialty? Previous studies on the mission highlight the importance of making the accumulated scientific data available to the greatest number of people.[16] What were the initial concerns involved with data collection? How did these issues change over time? How was a user community created, and how was the funding of observation instruments institutionalized?

I will first briefly describe the features of space oceanography since the end of the Second World War. Then I will consider the way in which TOPEX, on the American side, and POSEIDON, in France, came into being. The national differences in the maturity of disciplines and the agreement for a common mission reveal the conditions of a dialogue between scientific and technical communities with different professional cultures. I will then focus mainly on the development of space oceanography in France. The purpose is to understand, in a particular geopolitical context (the end of the Cold War) how considerable epistemic transformations occurred around spatial oceanography in the French case.

The paper then turns to the actual making of the satellite and the ways in which the epistemological requirements 'materialized' in the onboard instruments. In addition, before takeoff, discussions about possible battery problems offer a wealth of information about the expectations of the discipline at the time of the launch in 1992. Then, the ways in which the

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[13] Peter Galison, *Image and Logic. A Material Culture of Micrphysics* (Chicago : The University of Chicago Press, 1997).

[14] Terry Shinn, "Formes de division du travail scientifique et convergence intellectuelle : la recherche technico-instrumentale" *Revue française de sociologie* 41,3 (2000) : 443-473.

[15] Simon Schaffer, "Machine Philosophy : Demonstration Devices in Georgia Mechanics,"*Osiris* 9 (1994) : 157-182.

[16] Erik M. Conway "Drowning in data : Satellite oceanography and information overload in the Earth sciences," *Historical Studies in the Physical and Biological Sciences.* 37, no 1(2006) : 127-151..

data was used, checked, and challenged in various publications during the mission signals the large-scale disciplinary shift of traditional oceanography towards space oceanography. The ensuing debates on the accuracy of measurements ensured the coherence of this new specialty through discussing and critically evaluating others' research.

The present study is based on a series of interviews with ten oceanographers and engineers working at CNES, the French Space Agency. I also analyzed the CNES archives, which contain all of the reports, preliminary studies, meeting minutes, follow-ups on issues, and discussions with the American engineers and researchers. Lastly, I had access to about fifty e-mails exchanged during the summer of 1992 between the various members of the French and American scientific teams on the eve of the TOPEX/POSEIDON launch.

Space Oceanography: A Brief Archaeology

To resituate the TOPEX/POSEIDON mission in the history of space oceanography, we must first mention some of the features of the field of oceanography in the United States and in France. After this overview based on secondary literature, I will then analyze the emergence of space oceanography as a specialty.

Oceanography as a discipline was created at the end of the nineteenth century at the intersection of the skills of chemists, biologists, physicists, and meteorologists. In fact, the disciplinary corpus was initially formed through exploration practices (measuring the wind, temperature, tracking currents, etc.).[17] In the inter-war period, the Scripps Institution of Oceanography headed by Norwegian oceanographer, Harald U. Sverdrup, was created in La Jolla, California. Disciplinary integration then progressed further as issues of marine ecology came to be added to previous questions relating more to geology.[18] The International Geophysical Year (1957-1958) was an opportunity for American oceanographers to promote their discipline and expand their technological abilities. As Jacob Darwin Hamblin rightly notes, the event was not initially focused on oceanography.[19] The purpose was simultaneously political (to highlight effective international cooperation) and scientific (obtaining synchronic data was required very early[20]). Georges Deacon and Edward Bullard, as part of the IGY, created a scientific program that sought to "make a major synoptic study of ocean circulation."[21] In addition to the major US oceanographic institutions (the Wood Holes Oceanographic Institution and the Scripps Institution of Oceanography), European researchers were also involved (such as the Norwegian Polar Institute).

This international cooperation on oceanography was very closely linked to the US Navy's military needs for the oceans. Naomi Oresekes has ably shown how the relationship between the US Navy and oceanographers was constructed. Although the International Geological Congress of 1939 could not be held in Washington because of the outbreak of war, the bases were laid for a unified scientific conception of oceanography[22]. During the Second

[17] Rozwadowski, Helen M. "Small World. Forging A Scientific Marine Culture for Oceanography,"*Isis.* 87 (1996): 409. For a broad historical perspective, see Eric L. Mills, *The Fluid Envelope of Our Planet. How the Study of Ocean Currents Became a Science* (Toronto: University of Toronto Press, 2009).

[18] Ronald Rainger, "Adaptation and the Importance of Local Culture: Creating a Research School at the Scripps Institution of Oceanography,"*Journal of the History of Biology* 36 (2003: 461-500. Also see : Eric L. Mills, "Useful in Many Capacities. An Early Career in American Physical Oceanography," *Historical Studies in the Physical and Biological Sciences.*20, (1990): 265-311.

[19] Jacob Darwin Hamblin, *Oceanographers and the Cold War. Disciplines of Marine Science* (Seattle : University of Washington Press, 2005) : 61.

[20] Ibidem : 66.

[21] Ibidem : 67.

[22] Naomi Oreskes, *The Rejection of Continental Drift. Theory and Methods in American Earth Science* (Oxford :Oxford University Press, 1999) : 262.

World War, the US Navy supported oceanographic research in order to improve the responses of its submarines.[23] Scientists took part in the Navy's expeditions in the Pacific to help with experiments on underwater acoustics. They took advantage of the opportunities offered by the military to further their research, but they had to work along with the Navy's programs.[24]

The interweaving of science and the military was particularly visible in the oceanography discipline throughout the Cold War. Simone Turchetti highlighted the importance of NATO's efforts to gather and produce knowledge about the oceans in connection with the monitoring of Soviet submarines.[25] This NATO involvement served US geopolitical interests as well as the US' political national security agenda.[26] In Europe, the Strait of Gibraltar became a privileged space for oceanographic research in connection with the geopolitical stakes of the Cold War. As Lino Camprubí and Sam Robinson have shown, the western Mediterranean became a focal point for understanding the global dynamics of ocean circulation.[27] The geopolitical competition with the USSR created tensions around the ideal of collaboration of researchers engaged in oceanographic research during the Cold War.[28]

Overall, scientific studies during the Cold War stabilized the contours of an oceanographic discipline that now had its instruments (bathyscaphes, acoustic analysis, tide gauges) largely derived from physics.[29]

In France, the institutions involved in this research were different. In the 1920s, the Marine Fisheries Scientific and Technical Board linked questions of marine resources to scientific interests. However, after the Second World War, the French government focused financial investments on marine stations at Roscoff, Marseille, and Banyuls-sur-Mer. Since the end of the 19th century, these stations have been particularly fruitful places for oceanographic research, as Josquin Debaz has shown.[30]

The support of CNRS, in particular in the 1950s, situated the discipline of oceanography within the academic landscape. The Centre National pour l'Exploitation des Oceans (CNEXO) was created in 1967, which merged in 1984 with the l'Institut Scientifique et Technique des Pêches Maritimes to become the l'Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER)[31]. At the same time, work by the military at the Service d'Hydrographie de la Marine resulted in the emergence of research on underwater acoustics.[32]

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[23] Ibidem : 263.

[24] Ronald Rainger, "Science at the Crossroads : The Navy, Bikini Atoll, and American Oceanography in the 1940s,"*Historical Studies in the Physical and Biological Sciences* 30, no 2 (2000): 349-371. Also see: 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, no 5 (2003): 635-666; Naomo Oreskes, "'Laissez-tomber' : Military Patronage and Women's Work in Mid-20th-Century Oceanography,"*Historical Studies in the Physical and Biological Sciences.*30, 2 (2000): 373-394.

[25] Simone Turchetti, "Sword, Shield and Buoys : A History of the NATO Sub-Committee on Oceanographic Research, 1959-1973", *Centaurus* 54 (2012) : 207.

[26] Ibidem : 226.

[27] Lino Camprubí, Sam Robinson, "A Gateway to Ocean Circulation. Surveillance and Sovereignty at Gribaltar" *Historical Studies in Natural Sciences* 46(4) (2016) : 429-459.

[28] Jacob Darwin Hamblin, *Oceanographers and the Cold War. Disciplines of Marine Science* (Seattle : University of Washington Press, 2005) : 140.

[29] Naomi Oreskes, *The Rejection of Continental Drift. Theory and Methodes in American Earth Science* (Oxford :Oxford University Press, 1999) : 288.

[30] Josquin Debaz, *Les stations françaises de biologie marine et leurs périodiques entre 1872 et 1914* PhD in history (2005), EHESS.

[31] Sur cette chronologie, voir : Lucien Laubier, "L'émergence de l'océanographie au CNRS : les conditions de la pluridisciplinarité" *La revue pour l'histoire du CNRS* 5 (2002).

[32] See Lucien Laubier, "L'émergence de l'océanographie au CNRS : les conditions de la pluridisciplinarité."*La revue pour l'histoire du CNRS* 6 (2002): 68-81.

French oceanography developed from several technological and epistemic lineages. In the late 1950s, the CNRS promoted the construction of bathyscaphes (first in connection with Professor Auguste Picard and then independently), notably the FNRS 3[33]. This means for ocean exploration was also borrowed by Jacques-Yves Cousteau, commander of the Merchant Marine who became director of the Oceanographic Museum of Monaco. Thus, in the 1960s, he developed a "plunging saucer" capable of reaching the "intermediate depths between those of diving suits and those for bathyscaphe"[34]. Subsequently, Cousteau began a campaign to disseminate this information to the general public through film and television[35]. Occupying the chair of oceanography at the Museum of Natural History in Paris, Henri Lacombe launched maritime campaigns on ships. In particular, he studied ocean flow exchange in the Strait of Gibraltar from the late 1950s[36].

Lacombe and Cousteau shared a very open and inclusive approach to oceanography. The former encouraged his students to visit the great American oceanographic institutions to improve their skills[37]. He also contributed, in the 1980s, to a project for large-scale integration of data: thus, in 1988, he combined his data on the Strait of Gibraltar collected in the 1960s with information collected since that time by boats, satellites, and planes[38]. As for Cousteau, in the 1970s he fought for satellites to be included in ocean exploration[39].

At the dawn of the 1960s, in France as in the United States, oceanography was an established discipline strongly connected to the military. The genesis of space oceanography was concomitant with a series of technical innovations in thermometric and spectral measurement.

In 1953, Henry Stommel, William von Arx, Donald Parson, and William Richardson used an "infrared airborne radiation thermometer over the ocean along the east coast of the United States".[40] Eleven years later, in an article in *Applied Optics*, E.D. MacAlister, of Scripps Institution of Oceanography, set out plans for an infrared optical instrument on the wing of a plane. Its purpose was to measure surface temperature correlated with wave height and several meteorological variables (wind speed in particular).[41] Thus, the first instrumental experiments were designed on general physical measurements of oceanic phenomena (temperatures, winds, wave height, etc.).

At the same time, at the National Aeronautics and Space Administration (NASA), geologist Peter C. Badgley, head of advanced missions at the Office of Manned Space Science since 1963, convinced his superiors "to sponsor investigations focused specifically on the study of Earth resources from space".[42] During the winter of 1964, he produced a list of

[33] J.-M. Pérès, "Trois plongées dans le canyon du Cap Sicié effectuées avec le bathyscaphe F.N.R.S. III de la marine nationale" *Bulletin de l'Institut Océanographique de Monaco* 1115 (1958) : 1-21.

[34] André Guilcher, "Un colloque d'océanographie géologique méditerranéenne" *Annales de Géographie* 73(395) : 69.

[35] Franziska Torma, "Explorer les sept mers. Vers un concept océanique et postcolonial de tropicalité" *Revue d'anthropologie des connaissances* 66(3) (2013) : 607.

[36] Claude Richez, "Professor Henri Lacombe" in *The Physical Oceanography of Sea Straits* ed. L.J. Pratt (Dordredcht : Kluwer Academic Publishers, 1989) : x ; H. Lacombe, P. Tchernia, C. Richez, L. Gamberoni, "Deuxième contribution à l'étude du régime du Détroit de Gibraltar" *Cahiers océanographiques* 16 (1964) : 283-327.

[37] Ibidem : x

[38] Paul. E. Laviolette, Henri Lacombe, "Tidal-induced pulses in the flox through the Strait of Gribraltar" Oceanologica Acta special issue (1988) : 13-27.

[39] E.C. Weaver, J.-.Y Cousteau, J. François, J.C. Aversen, L. Stuart, D. Nace, "Satellites as an aid to ocean exploration" *EOS, Transactions American Geophysical Union* 54(11) (1973) : 1113.

[40] G.A. Maul, *Introduction to satellite oceanograph* (Dordrecht: Martinus Nijhoff Publishers, 1985): 13.

[41] E.D. MacAlister, "Infrared Optical Techniques Applied to Oceanography I. Measurement of Total Heat Flox from the Sea Surface,"*Applied Optics.* 3, no 3 (1964): 609-612.

[42] Pamela E. Mack, *Viewing the Earth. The Social Construction of Landsat Satellite System* (Cambridge (Mass) : The MIT Press, 1990): 46.

studies to be done within this framework specifically targeting oceanography, as well as forecasting agricultural conditions throughout the world and analyzing natural resources in developed countries.[43] The (future) Apollo mission did not entirely overshadow other space research sectors; Badgley managed to create a long-term plan in which Earth observation was a step toward human space flight. Space oceanography thus became one of NASA's priorities. Even though the programs were not clearly defined (for the time being, they were only broad orientations), from then on studying the oceans was related to space research. The exploratory research conducted in particular at Woods Hole Oceanographic Institution helped frame the scientific goals, which were as ambitious as they were broad.

In the 1960s, NASA organized its applications programs around terrestrial data capture by offering two series of Earth remote sensing satellites: those for meteorology (Nimbus) and those for land observation (Landsat)[44].

In August 1964, Gifford C. Ewing organized a conference in Massachusetts "on the Feasibility of Conducting Oceanographic Explorations from Aircraft, Manned Orbital, and Lunar Laboratories".[45] Bringing together specialists in optics, imagery, marine biology, geophysics, and meteorology as well as engineers working on coastal vehicles, the purpose of the meeting was threefold: to establish the state of what was then an embryonic specialty; to discuss possibilities that this new field opened up; and strategic means for building a community of users to then obtain funding from space agencies. Ewing recognized on this occasion that "'Oceanography from a satellite'—the words themselves sound incongruous and, to a generation of scientists accustomed to Nansen bottles and reversing thermometers, the idea may seem absurd."[46] Ewing's speech had a clear performative purpose: indeed, many disciplines (such as meteorology or atmospheric studies) had integrated satellite techniques very early on. The aim here was to create and dramatize the break between oceanography and spatial oceanography. Technology issues were the focus of the meeting: with the limitations of 'traditional' oceanographic measurements from stations dispersed throughout the oceans' surface, and the uncertainties about the "burgeoning technology"[47]of space measurements, questions about instrumentation were preeminent in studying the oceans. The 150 oceanographers assembled did not try to arrive at a consensus about what space oceanography had to be; they tried to show "a restrained enthusiasm that has the ring of real scientific innovation". Whether they were positive or pessimistic, all the conclusions and the recommendations suggested sought to "stimulate fresh ideas".[48]

One of the first subjects that emerged – and which Ewing emphasized in introducing the conference – was the precise measurement of the sea level. Such precision would not only make it possible to estimate "the shape of the geoid", but also to define "the geostrophic current and barotropic distortions due to storms"[49]: the knowledge of tides, swells, and tsunamis would thus be transformed. From the start, altimetric precision was considered an essential pre-requisite (Ewing estimated that an accuracy to 5 cm over a surface of 1000 km^2

[43] Ibid., 47.

[44] Erick M. Conway, "Bringing NASA Back to Earth : A Search for Relevance during the Cold War" in *Science and Technology in the Global War* ed. Naomi Oreskes, John Krige (Cambridge (Mass.) : MIT Press, 2014) : 252-253.

[45] Gifford C. Ewing, ed., *Proceedings of Conference on the Feasibility of Conducting Oceanographic Explorations from Aircraft, Manned Orbital and Lunar Laboratories.Held at Woods Hole, Massachussetts, 24-28 Août 1964.* (Woods Hole (Mass) : Woods Hole Oceanographic Institution, 1965).

[46] Gifford C. Ewing, "Preface," in *Proceedings of Conference on the Feasibility of Conducting Oceanographic Explorations from Aircraft, Manned Orbital and Lunar Laboratories. Held at Woods Hole, Massachussetts, 24-28 Août 1964*, ed. Gifford C. Ewing (Woods Hole (Mass): Woods Hole, Massachusetts, 1965): vii.

[47] Ibid., vii.

[48] Ibid. vii.

[49] Ibid., viii.

would be ideal) and would enable satellites to make a "fundamental contribution…to the science of physical oceanography". Ewing continued by indicating that "far-reaching benefits would accrue to other branches of marine science, including biology, fisheries, geology, engineering, surveying, offshore drilling, and marine safety."[50] In a characteristic way, at this conference in 1964, the specialty question was posed in relational terms: space oceanography was conceived of in terms of the links that space oceanography researchers could build with those in other disciplines or specialties. It was not a question of substituting other theoretical-practical corpora for that of space oceanography, but rather of connecting the latter's (emerging) practices to other disciplines or specialties. Thus, the marine biology panel's recommendations (for example on bioluminescence enabling fish populations to be tracked or the concentration of chlorophyll detected by spectrometry)[51] went hand in hand with the panel's proposals "on wind waves and swell" and on obtaining "data relevant to describing features of the full directional spectrum of wind seas and swell, the frequency spectrum, the slope spectrum, and integrals of the frequency spectrum of the waves."[52]

Thus during this conference in 1964, it was clear that space oceanography was a possible new field of application for oceanography: technological developments (use of satellites and precision of measurement tools) and links with other disciplines or specialties (also likely to profit from the transformations enabled by satellites) formed the salient features of the changes underway. In the following years, attempts to establish a theory of the 'space oceanography' specialty multiplied. In 1967, researchers at the Geophysical Sciences Laboratory of the University of New York published an article on the potential benefits of satellite radar for oceanography. Supported by both NASA's Office of Space Science and Applications and the Spacecraft Oceanography Project of the US Naval Oceanographic Office, this article primarily identified the procedures for collecting altimeter data, which could then be used in analyzing the ocean surface, tides, tsunamis, and underwater geology.[53] The same year, Charles A. Lundquist of the Smithsonian Astrophysical Observatory wrote a report on satellite altimetry and determining orbits. Less centered on oceanography, this text set out the bases for technically resolving the problems of satellite altimetry. The issue of measurement precision for determining orbits was thus placed at the heart of research because that, in turn, conditions the quality of altimetric measurements.[54] While satellites such as GEOS-1, launched in 1965, started to give form to an entire body of practices making Earth an object of research and altimetry a method of precise measurement, until the eve of the 1970s space oceanography remained a specialty that only existed on paper. No mission was concretely undertaken to collect data and to translate the scientists' many questions into actual research.

At the 1964 conference, construction of the space oceanography as a specialty was not only based on cognitive issues; creating a community of users also meant seeking funding and targeting potential investments. For example, the conference was funded by NASA's Office

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[50] Ibid., viii.

[51] Carl L. Hubbs and Clarke George. "Recommandations of panel on Marine Biology." in *Proceedings of Conference on the Feasibility of Conducting Oceanographic Explorations from Aircraft, Manned Orbital and Lunar Laboratories. Held at Woods Hole, Massachussetts, 24-28 Août 1964,* ed. Gifford C. Ewing, (Woods Hole (Mass): Woods Hole, Massachusetts, 1965): 303

[52] W.J. Pierson Jr, "Recommandations of the panel on windwaves and swell," in *Proceedings of Conference on the Feasibility of Conducting Oceanographic Explorations from Aircraft, Manned Orbital and Lunar Laboratories. Held at Woods Hole, Massachussetts, 24-28 Août 1964* ed. Gifford C. Ewing, (Woods Hole (Mass): Woods Hole, Massachusetts, 1965): 351

[53] J. Arthur Greenwood, Alan Nathan, Gerhard Neumann, Willard J. Pierson, Frederick C. Jackson, Thomas E. Pease, "Oceanographic Applications of Radar Altimetry from a Spacecraft ?,"*Remote Sensing of Environment*.1, no 2 (1969): 71-80.

[54] Charles A. Lundquist, *Satellite altimetry and orbit determination, Research in Space Science, SAO Special Report n° 248, 18 août 1967* (Cambridge (Mass.) : Smithsonian Institution, Astrophysical Observation, 1967).

of Space Science and Applications. Moreover, organizing panels made it possible to call on experts from American government agencies and bodies that might be interested in the developments of satellite instrumentation. For example, the panel on optics was chaired by John F. Cronin of the Air Force Cambridge Research Laboratories;[55] the one on humans in space was led by Bernard Scheps of the U.S. Army Corps of Engineers, Geodesy, Intelligence & Mapping Research & Development Agency;[56] and Sidney R. Galler from the Office of Naval Research discussed the possible contributions of satellites to marine biology.[57] In addition to these contributions to the economy of space oceanography from public institutions, several conference participants also identified commercial outlets for satellite products. In the summary of the debates drawn up by Robert W. Stewart of the University of British Columbia, the main expectations for space oceanography were linked to their communications potential:

> It was widely agreed among contributors to the discussion leading to this paper that probably the most important use of satellites in oceanography would be as communication aids in transmitting information from instrumented buoys...Some participants feel that the only really valuable role of satellites in oceanography will be this one of communication, and that of navigation...Navigational satellites have frequently been discussed, and if the perfection of such devices can be achieved, the gain would be indisputable.[58]

In the same manner, in the field of marine biology, Carl L. Hubbs and George L. Clarke ensured that "monitoring of the commercial and sport fishing fleets, off our coasts and on more distant waters, such as Georges Bank, the Bering Sea, and the Antarctic, would also be of value".[59] Thus, discussions at the conference in Williamstown in 1964 were organized around the breakdown into cognitive fields and the institutional funding hoped for.

A new conference was held in Williamstown, Massachusetts from August 11-21, 1969. Sixty-five scientists took part in discussions and fifteen representatives of NASA were present. French engineers from CNES also travelled to the conference, in particular, Gérard Brachet. François Barlier represented the Observatoire de Paris. Since 1968, Barlier, together with Georges Balmino from CNES, had taken the first steps toward bringing CNES and the American scientists of the Smithsonian together on satellite monitoring.[60]

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[55] John F. Cronon, "Optics," in *Proceedings of Conference on the Feasibility of Conducting Oceanographic Explorations from Aircraft, Manned Orbital and Lunar Laboratories*. *Held at Woods Hole, Massachussetts, 24-28 Août 1964* ed. Gifford C. Ewing, (Woods Hole (Mass): Woods Hole, Massachusetts, 1965): 37.

[56] Bernard Scheps, "Man in space," in *Proceedings of Conference on the Feasibility of Conducting Oceanographic Explorations from Aircraft, Manned Orbital and Lunar Laboratories*. *Held at Woods Hole, Massachussetts, 24-28 Août 1964* ed. Gifford C. Ewing, (Woods Hole (Mass): Woods Hole, Massachusetts, 1965): 113.

[57] Sidney R. Galler, "Possible contributions of manned (and unmanned) satellites toward advancing the fields of marine biology and biological oceanography," in *Proceedings of Conference on the Feasibility of Conducting Oceanographic Explorations from Aircraft, Manned Orbital and Lunar Laboratories*. *Held at Woods Hole, Massachussetts, 24-28 Août 1964* ed. Gifford C. Ewing, (Woods Hole (Mass): Woods Hole, Massachusetts, 1965): 315.

[58] Robert W. Stewart, "Recommendations of the panel of currents," in *Proceedings of Conference on the Feasibility of Conducting Oceanographic Explorations from Aircraft, Manned Orbital and Lunar Laboratories*. *Held at Woods Hole, Massachussetts, 24-28 Août 1964* ed. Gifford C. Ewing, (Woods Hole (Mass): Woods Hole, Massachusetts, 1965): 19.

[59] Carl L. Hubbs and George L. Clarke, "Recommendations of panel on marine biology," in *Proceedings of Conference on the Feasibility of Conducting Oceanographic Explorations from Aircraft, Manned Orbital and Lunar Laboratories*. *Held at Woods Hole, Massachussetts, 24-28 Août 1964* ed. Gifford C. Ewing, (Woods Hole (Mass): Woods Hole, Massachusetts, 1965): 304.

[60] Interview with Michel Lefebvre, 15th january 2014

The objective of the Williamstown conference was to lay out a roadmap for actual research on satellite capture of geophysical, oceanographic, and geodetic information. For that, the organizers of the meeting (in particular William Mr. Kaula of the University of California, Charles A. Lundquist of the Smithsonian Astrophysical Observatory, and Lynn R. Sykes of Lamont Geological Observatory in Palisades, New York) recommended “that NASA undertake an integrated program, including both short-term components attainable by existing technology and longer-term components requiring appreciable development.”[61] This roadmap set out a chronology for the missions to be implemented. The objective was consciously chosen to be very broad:

> This report covers essentially those aspects of geophysics that can be aided by precise measurements of position, velocity, or acceleration with the use of objects outside the Earth. The fields involved are mainly solid-earth physics and those parts of oceanography concerned with water motion and the related shape of the sea surface. The instrument that links solid-earth and ocean physics most closely is the satellite-borne altimeter.[62]

The report then sets out a satellite program adapted to these general objectives: low-altitude satellites, with altimeters with a precision to around 10 cm to measure “the geopotential and mean sea level accurately enough to define the baroclinic and barotropic pressure field and thus to determine the general circulation of the oceans;” satellites launched to 350 km altitude (with a precision to around 1 meter) that would be able to measure “the variations of the gravity field to 250-km half-wavelength;” and finally, “long-baseline radio interferometry” technology to assess movements of the Earth’s crust.[63] All in all, oceanography “came out the big winner of the conference in Williamstown.”[64] While the geophysical sciences were certainly present at the discussions, they were secondary in the recommendations: knowledge of ocean circulation took precedence.

While the idea of organizing oceanography around space instrumentation seemed clearly established after the meeting in Williamstown, international competition, as well as the slow development of neighboring research fields (such as meteorology and environmental sciences in general), prevented the scientific issues involved from immediately crystallizing into a new specialty.

Throughout the 1970s, NASA's focus had been improving the performance of satellite instruments providing Earth observation data in order to satisfy the broadest possible American scientific community[65]. Overcoming technological limits was all the more crucial because the climate change issue was emerging and demanding reliable data. It was, therefore, an actual, specific research policy that the agency put in place. As Erick M. Conway has shown:

> By the late 1970s, scientists outside NASA had gotten interested in climate, too, in no small part because it had started to become a subject of policy debate. NASA’s leaders chose to respond to the 1978 National Climate Program Act by beginning to plan a comprehensive Earth-observation program to study climate processes[66].

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[61] *MIT, The Terrestrial Environment : Solid-Earth and Ocean Physics, NASA, Washington DC,* avril 1970, ix.
[62] Ibid.,1-1.
[63] Ibid., ix.
[64] Interview with Michel Lefebvre, 15th january 2014.
[65] Erick M. Conway, “Bringing NASA Back to Earth : A Search for Relevance during the Cold War” in *Science and Technology in the Global War* ed. Naomi Oreskes, John Krige (Cambridge (Mass.) : MIT Press, 2014) : 254.
[66] Ibid : 259.

It was not until 1989 that "Mission: Planet Earth" was accepted by the government, but many space initiatives had emerged meanwhile.

Starting in 1973, the Skylab space station had an S 193 altimetry radar[67]. The American satellite GEOS-C, which had already been planned in 1968, was launched in 1975 with an altimetric radar with an accuracy to 30 cm[68]. In service for three years, this satellite provided important data on the geoid[69]. But despite prior agreements that the data would be accessible to scientists around the world, the US Department of Defense managed to have the results classified, making it even more difficult to use the data[70]. Initially, the Department of Defense was involved in assembling the satellite[71]; the Defense Mapping Agency had purchased "three portable ground stations to capture the satellite's data over the Earth's land areas", [72] which conferred upon them an almost confidential character.

On the French side, the engineers and researchers at Williamstown took away good suggestions for developing space oceanography on the Old Continent. Right after the US meeting, Georges Balmino and Gerard Brachet wrote a "proposal for satellites with radar altimetry"[73] for CNES. For the French agency, the goal was to obtain satellite topography "of the ocean surface" which would interest "oceanography and meteorology…"[74] The timeline was decided: a satellite equipped with a space altimeter would be launched in 1973.

During this period, tests of adapted space instruments and technological innovations took priority on both sides of the Atlantic. Satellite tracking – which is fundamental because the quality of the oceanographic data depends on the precision of the altimeter measurements – was the key issue. CNES engineers successively developed the PEOLE, ISAGEX (International Satellite Geodetic Experiment), and STARLETTE satellites with laser tracking.[75] French attempts to associate American NASA engineers with their research failed. In particular, the PEOLE satellite sought to coordinate "all the laser stations in the world".[76] While all these attempts were not necessarily connected, they all highlight the primacy of instrumentation (*i.e.*, the satellite) in the early days of space oceanography. Michel Lefebvre, a former captain in the Merchant Marine, was hired by CNES to create a Department of Space Geodesy within the Mathematics Division. Working with Anny Cazenave, Gérard Brachet and Georges Balmino, Lefebvre started working at the Groupe de Recherche en Géodésie Spatiale (GRGS). He freely admits that "it was from this group that [French] space oceanography was born, not from oceanographers." Thus, it was expertise in space and not oceanography that was determinant, even required. When French engineers proposed the altimetric radar, DORADE (which was to be launched in 1976), strong competition from the

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[67] J.T. McGoogan, L.S. Miller, G.S. Brown, G.S. Hayne, "The S-193 radar altimeter experiment" *Proceedings of the IEEE* 62,6 (1974) : 793-803.

[68] Jean-François Minster, *La machine océan* (Paris, Flammarion, 1997): 123.

[69] H. Ray Stanley, "The GEOS-3 Project."*Journal of Geophysical Research.* 84 no B8 (1989) : 3779-3783. Wilson, W.S. "NASA's Oceanic Remote Sensing Plans for the 1980's." », in *Oceanography from space.*, ed. J.F.R. Gower (New York : Plenum Press, 1981): 15-17.

[70] Jean-François Minster, *La machine océan* (Paris, Flammarion, 1997): 123.

[71] R.J. Anderle, L.K. Belglass, M.G. Tanenbaum, *Accuracy of Computed Orbits of Geos-3 Satellite*n Naval Surface Weapons Center Dahlgren, mai 1976 : 1.

[72] Erick M. Conway, "Drowning in data: Satellite oceanography and information overload in the Earth sciences" *Historical Studies in the Natural Sciences* 37, 1 (2006): 134.

[73] CNES Archives, Georges Balmino, Gérard Brachet, Proposition de satellites avec altimètre radar, Projet « Dorade », CNES, Division Mathématiques et Traitement, Département « Calcul d'Orbites », Ref. GB/AC/0.372, s.d. [1969].

[74] Ibid., 2

[75] Jean-François Minster, *La machine océan* (Paris, Flammarion, 1997): 123.

[76] Interview with Michel Lefebvre, 15th january 2014.

Americans and similarity with GEOS-C cancelled its launch.[77] Above all, in 1978, Jet Propulsion Laboratory (JPL) developed and launched Seasat, with a very broad range of instruments (altimeters, infrared and microwave radiometers, etc.) "although the experiments on each of them were limited."[78] The satellite functioned only three months, but the results were sufficiently promising[79] that J.F.R. Grower, from Canada's Institute of Ocean Sciences organized a conference in Venice in May 1980 to explore the new avenues that the Seasat had opened up. The engineers' idea, that it was more about demonstrating the satellite's possibilities than a completely operational satellite, emerged in the course of the discussions:

> During some 3 months of orbital operations, Seasat – the first satellite dedicated to establishing the utility of microwave sensors for the remote sensing of the earth's oceans – collected a unique set of synoptic data on ocean winds, waves, temperature, and topography. After a half year of intensive analysis of a relatively small subset of this data, a multidisciplinary team of scientists, engineers, and analysts has concluded that the majority of goals for measuring geophysical parameters have been met. Consequently, the overall project objective of demonstrating the concept of a global, nearly all-weather, microwave surveillance capability has been accomplished.[80]

The demonstration, which was not merely a proof of concept, also helped in planning the work to come.[81] By making the SeaSat satellite into a demonstration *a posteriori*, the engineers deployed a new script for future satellites. What was a (relative) failure thus became a step in a long-term process of affirming a technology and a specialty. Following that, the MARSEN (Maritime Remote Sensing)[82] project confirmed the advantages of satellite oceanography research.

W. Stanley Wilson, member of NASA Headquarters, identified the reasons for rearranging the specialty in the wake of SeaSat's results. In particular, he believed that remote sensing was the advent of a "great potential for oceanography", not only for the "remote sensing community" but also for the "oceanographic community". Wilson set out the progress to be achieved in order to "have maximum impact on oceanography:" "We must be able to relate this time-varying two-dimensional near-surface information to the time-varying three-dimensional structure of the ocean". The goal was really to have a "closer coupling between the remote sensing and oceanographic communities…"[83] and therefore open this emerging specialty to a broader group of oceanographers.

He also announced the future satellites that would actually make this desired connection between the scientific disciplines: the National Oceanic Satellite System (NASS), TOPEX, and OCEAN SAR. Of the three, only TOPEX would become a reality.

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[77] Ibid.

[78] Jean-François Minster, *La machine océan* (Paris, Flammarion, 1997): 125.

[79] Jean-François Minster (then member of the Laboratoire d'Études en Géophysique et Océanographie Spatiale/Laboratory of Studies in Geophysics and Space Oceanography) pointed out the decisive aspect of the mission: "Seasat was extremely important because it made it possible to develop tools, all the sets of corrections in particular. It created a community, people who met and knew each other. It considerably helped build the [other] programs." (Interview with Jean-François Minster, June 16, 2014).

[80] G.H. Born, D.B., Lame, P.J. Rygh, "A survey of the Goals and Accomplishments of the Seasat Mission," in *Oceanography from space*, ed. J.F.R. Gower (New York : Plenum Press, 1981) : 3.

[81] Claude Rosental, "Anthropologie de la démonstration," *Revue d'Anthropologie des Connaissances.* 3, no 2 (2000) : 234.

[82] K. Hasselmann, R.K. Raney, W.J. Plant, W. Alpers, R.A. Shuchman, D.R., Lyzenga, C.L. Rufenach, M.J. Tucker "Theroy of synthetic apertur radar ocean imaging : A MARSEN viex" *Journal of Geophysical Research. Oceans* 90, C3 (1985): 4659-4686

[83] W.S. Wilson, "NASA's Oceanic Remote Sensing Plans for the 1980's." », in *Oceanography from space*, ed. by J.F.R. Gower (New York : Plenum Press, 1981): 15.

At the European level, the issue was raised in nearly similar terms: the European Space Agency also pushed for more scientific partnerships. A workshop was organized at Schloss Elmau in Germany in January 1978 so that a close link could be established between "all geophysics disciplines that employ or rely upon geodetic measurement techniques...."[84] Starting in 1991, the construction of a family of ERS satellites (European Remote Sensing Satellite) opened up avenues for European research on the oceans and the atmosphere. ERS-1 thus included "a single frequency altimeter and a radiometer". It would then provide data complementary to TOPEX/POSEIDON.[85]

Thus, space oceanography as a specialty was created almost without any oceanographers; it was primarily physicists and engineers who developed the satellite instrumentation, in France as well as in the United States.

The oceanographers, however, tried at the international level to bring the discipline closer to meteorologists. In 1973, the representatives of Global Atmosphere Programme, which aimed to provide a better understanding of the climate, wove closer contacts with the community of oceanographers via the Scientific Committee on Oceanographic Research (SCOR).[86] Between the communities of remote sensing, oceanography, and meteorology, the potential relationships were numerous and the opportunities for associations were rich. It should be noted that people working on space issues brought these fields together and oceanographers only intervened on the margins.

As we have seen, political concerns about climate grew stronger starting from the late 1970s. In 1978, the US Congress approved the National Climate Program Act, which required federal agencies to initiate research on climate change and NASA committed itself to this field[87]. Finally, in the United States, the convergence between oceanographers who had become interested in climate questions and space engineers took place in Chilton in January 1981, during a coordination meeting about the future satellites that could observe the ocean system.[88] Climate data and the models that they made possible offered a subject for experimentation for space oceanography, which was still emerging as a field. In January 1982, Robert Etkins and Edward S. Epstein, both members of the National Oceanic and Atmospheric Administration (NOAA), published a synthetic article in the journal *Science* on the global rise in sea level as an indicator of climate change. They placed their hopes in future satellite measurements.[89] NOAA's team of climatologists also pointed to the role of the polar caps in global climatic change:[90] they stressed that "satellite-borne radio altimeters, as

[84] S. Hieber, "Foreword," in *Space Oceanography Navigation and Geodynamics, Proceedings of a European Workshop held at Schloss Elmau, Germany, 16-21 janvier 1978*, ed. Guyenne, Huu Tan Duc, S. Hieber (Paris, Agence Spatiale Européenne, 1978): 1.

[85] A. Anderson, F. Gilbert, H. Grassl, E. Harrison, R. Hide, S. Houry, K. Lambeck, M. Lefebvre, J. Melosh, A. Morelli, R. Sabadini, D. Smith, C.-K Tai, G. Visconti, S., Wilson, C. Yoder, V. Zlotnicki, "Interaction with other disciplines and programs." In *The Interdisciplinary Role of Space Geodesy*, ed. Ivan I. Mueller, S. Zerbini (Berlin : Springer-Verlag, 1989): 114.

[86] B.J. Thompson, J. Crease, J., Gould, "The Origins, Development and Conduct of WOCE," in *Ocean Circulation and Climate : Observing and Modelling the Global Ocean.* Edi ? Gerold Siedler, John Church, John Gould, W.J. Gould (Londres : Academic Press, 2001): 33.

[87] Erick M. Conway, "Bringing NASA Back to Earth : A Search for Relevance during the Cold War" in *Science and Technology in the Global War* ed. Naomi Oreskes, John Krige (Cambridge (Mass.) : MIT Press, 2014) : 259.

[88] Ibid., 35.

[89] Robert Etkins, Eward S. Epstein, "The Rise of Global Mean Sea Level as an Introduction of Climate Change," *Science.* 214 (1982): 287.

[90] « Storm surges around melting ice claims », *New Scientist*, vol. 93, n° 1291, 4 février 1982, p. 306.

demonstrated on GEOS-3[91] and Seasat, can now measure the surface elevation of ice sheets to within about 2m."[92]

While the TOPEX/POSEIDON mission was being implemented, meetings between climatologists, space engineers, geodesists, and oceanographers became more frequent. In July 1988, a workshop was held in Erice, Italy on "The Interdisciplinary Role of Space Geodesy".[93] The conference was not centered on oceanography, but it emerged in a massive way in several presentations by the participants. The goal of the "workshop was to recommend geodetic and geomagnetic programs and missions, and the development of methods and instrumentation for their implementations..."[94] The interactions among researchers from various disciplines (mainly geodesy and meteorology) were many but not regular. About fifteen researchers took stock of the partnerships underway:

> As we strive to learn more about geodesy from satellite data, we are compelled to take into account that the data contain the effects of the atmosphere, noise, and bias to the geodesist but signal to the meteorologist. Thus, it is not surprising that branches of geophysics other than geodesy are directly involved in the proper interpretation of satellite data. The relation between atmospheric angular momentum and the length of day, for example, compels geophysicists to understand the fluid dynamics of the earth's cores and atmospheres and the coupling between them.[95]

Once again, the rhetorical effort here is focused on dramatizing the issues of disciplines. The goal was to draw up a research program that would come across as both new and more comprehensive than that of classical oceanography. However, this was actually less of a break between two fields and more the creation of a specialty that provides complementary information but does not revolutionize the discipline. Here, we can see all the argumentative force used to make a disciplinary break seem inevitable, even though this was not the case. However, we must not minimize the disciplinary power struggles at work in this process of specialization.

The uncertainty of the specialty transformations that space oceanography was experiencing also occurred within shifting power relationships. Representatives of the geodesy discipline, such as Allen Joel Anderson, a geodesist at the University of Santa Barbara in California, and Anny Cazenave, a geodesist at GRGS, thus stated in 1986, "Space Geodesy has become one of those unifying subjects for many scientific disciplines."[96] Geodesy certainly signaled the ability of space oceanography to provide new, complementary data that would be useful to other disciplines.

Space oceanography was constituted as a specialty through the data available (or likely to be), focusing on space instrumentation (both laser techniques for satellite tracking and data

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[91] GEOS-3 is another name for GEOS-C.

[92] Robert Etkins, Eward S. Epstein, "The Rise of Global Mean Sea Level as an Introduction of Climate Change," *Science*. 214 (1982): 289.

[93] Ivan I. Muller, S. Zerbini, S. (ed.) *The Interdisciplinary Role of Space Geodesy* (Berlin : Springer-Verlag, 1989).

[94] "Overview" », in *The Interdisciplinary Role of Space Geodesy*, ed. Ivan I. Muller, S. Zerbini, S. ((Berlin : Springer-Verlag, 1989): xi.

[95] A. Anderson, F. Gilbert, H. Grassl, E. Harrison, R. Hide, S. Houry, K. Lambeck, M. Lefebvre, J. Melosh, A. Morelli, R. Sabadini, D. Smith, C.-K Tai, G. Visconti, S., Wilson, C. Yoder, V. Zlotnicki, "Interaction with other disciplines and programs." In *The Interdisciplinary Role of Space Geodesy,* ed. Ivan I. Mueller, S. Zerbini (Berlin : Springer-Verlag, 1989): 103.

[96] Allen Joel Anderson, Anny Cazenave, "Preface," in *Space Geodesy and Geodynamics*, ed. Allen Joel Anderson, Anny Cazenave (Londres, Academic Press, 1986): vii.

collection) and not by the cognitive or theoretical issues of traditional oceanography. To understand how this specialty was grounded in material rather than theoretical issues, I will now focus on the TOPEX/POSEIDON mission.

POSEIDON: A Digest of Scientific Options

TOPEX and POSEIDON were two projects, one American, the other French, associated in a joint mission launched in 1992. By retracing the origins of these two sets of instruments, as well as the conditions of their association, I will examine the way in which a technological platform condensed, arranged, organized, and/or crystallized a variety of scientific options. Through analyzing this global observation of ocean currents at the mesoscale, I will delineate the underlying disciplinary issues as well as the cognitive coalitions at work.

In 1981, during a conference on the future of CNES, a group of CNES engineers headed by Michel Lefebvre proposed the POSEIDON project. Building on the preliminary results of Seasat, the mission "consists in embarking an altimetric radar on a satellite platform. Its first objective is to study the circulation of the oceans and the variability in circulation, the state of the sea, and ocean tides."[97] From the design phase, however, POSEIDON was not imagined as a *pure oceanographic instrument*. Rather, it took into account data series on sea ice, polar caps, and the regional deformation of the continents. It also planned to improve "knowledge of the Earth's geoid," to provide "significant information for cartography" and finally "to be used for clock synchronization."[98] Geodesy, geophysics, cartography, the physical study of time and timekeeping, and disciplines other than oceanography were mobilized in order to *give weight to and provide stability for* the satellite using all those fields' epistemological expectations. The CNES engineers who developed the project joined with some physicists and oceanographers (such as Jean-François Minster, a physicist at the Observatoire de Toulouse and Joseph Gonella of the Laboratoire d'Océanographie Physique du Muséum National d'Histoire Naturelle, to build their argument. Coordination between the engineers and the oceanographers was not simple and played out as may be expected with the cultural differences between two professional universes with different requirements. Philippe Gaspar, an oceanographer at CNES' subsidiary Collecte Localisation Satellites (CLS) in the 1980s, described the tense relations between the two communities:

> There were many wars over the specifications for measurement to 10 or 12 cm. We felt like we were beaten with a stick, as this was not enough for the oceanographers. We sought a specification acceptable for the engineers while knowing that by using filtering techniques, we could correct the errors. Because the errors of orbit are distinct from altimetric signals…we adopted a realistic strategy. We needed to specify something that would not frighten the engineers, that could be a powerful altimeter while remaining doable.[99]

Discussions between the researchers who had agreed to take part in the project and the engineers charged with making the specifications a reality thus proceeded by combining expectations: the oceanographers knew that the engineers did not want ambitious

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[97] M. Lefebvre, J.-F. Minster, J. Gonella, J.-P., Chassaing, J.-L. Fellous, C. Frankignond, F. Madelain "POSEIDON" in *POSEIDON*, ed. M. Lefebvre, J.-F. Minster, J. Gonella, J.-P.Chassaing, J.-L. Fellous, C. Frankignond, F. Madelain (Paris, CNES, 1983): 1
[98] Ibid., 1.
[99] Interview with Philippe Gaspar, 25 April 2014.

specifications (because they would consider them unfeasible) and the engineers were aware that low specifications allow them to deliver, in the end, better performance than expected.

In a certain way, this work undertaken by a small group around Michel Lefebvre was only the first stage to convince CNES, as well as the scientific communities potentially involved, of the benefits of POSEIDON. In a summary document in 1983, this group restated that the ocean was POSEIDON's principal research object. In this text setting out the broad outlines of the project, they argued that "the main problem" for attaining knowledge about the ocean "lies in obtaining systematic and continuous data."[100]At the dawn of the 1980s, the sophistication of the sensors allowed scientists "to accumulate and [to] transmit data automatically on temperatures, salinity, pressure, dissolved gases, current, and nephelometry… in large numbers".[101] It was precisely the duration of satellite monitoring that constituted its technical innovation. The promoters of POSEIDON within CNES insisted on the fact that satellite technology made it possible "to accumulate synoptic surface data and over multi-annual periods of time which are compatible with lengths of time characteristic of changes in the oceans: temperature, color of the sea, physical state of the ocean, topography, [and] surface constraints."[102] The oceanographic models of the circulation of water masses could "become more realistic" and approach weather models.[103] It was thus "altimetric measurements" that promised that POSEIDON's results would be very rich. "Altimetry for oceanography," said Philippe Gaspar, an oceanographer who worked on TOPEX/POSEIDON data, "is the equivalent of a barometer for the meteorologist. It is an infinitely useful measurement to which one never has access in real time. It is a very direct measurement when we look at the equations, the models."[104]

Arguments developed by Michel Lefebvre and his colleagues at CNES in 1983 still used a register of language for convincing. Engineers at the French space agency noted "that it is important…to show the importance and the feasibility of such satellite observatories. This is what the POSEIDON project proposes to do."[105] Situated between the preceding results of Seasat and the opening up of new scientific possibilities, the arguments supporting POSEIDON's instrumental platform dodged the question of the trials to come.[106] The future that Michel Lefebvre and his colleagues constructed (and which future, like the past on which it rests, determined the conditions of the project's implementation) was defined by maximizing disciplinary integration (*i.e.* many research sectors were involved) but that integration was differentiated (*i.e.* space oceanography was more important than the others in the research program). They did not seek to string the disciplines together like links in a chain, which would give weight to the POSEIDON proposal by the strength of their united interests. Instead, their proposal resembled an opening up to the greatest variety of possible disciplinary futures. To maximize the mission's chances of success and especially the possibility of obtaining new scientific results, the CNES engineers behind POSEIDON

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[100] M. Lefebvre, J.-F. Minster, J. Gonella, J.-P., Chassaing, J.-L. Fellous, C. Frankignond, F. Madelain "POSEIDON" in *POSEIDON*, ed. M. Lefebvre, J.-F. Minster, J. Gonella, J.-P.Chassaing, J.-L. Fellous, C. Frankignond, F. Madelain (Paris, CNES, 1983): 2. This problem has been referred to as under-sampling by Walter Munk ("Solving the Tidal Problem", *Notes and Records of the Royal Society of London* 54, 1 (2000): 116-119).

[101] Ibid., 2.

[102] Ibid., 2.

[103] Ibid., 2.

[104] Interview with Philippe Gaspar, 25th april 2014. Inter

[105] M. Lefebvre, J.-F. Minster, J. Gonella, J.-P., Chassaing, J.-L. Fellous, C. Frankignond, F. Madelain "POSEIDON" in *POSEIDON*, ed. M. Lefebvre, J.-F. Minster, J. Gonella, J.-P.Chassaing, J.-L. Fellous, C. Frankignond, F. Madelain (Paris, CNES, 1983): 3.

[106] Francis Chateauraynaud, *Argumenter dans un champ de forces* (Paris, Éditions Pétra, 2011): 120-121.

believed that mobilizing multiple fields of research would increase the possibilities of a significant discovery.

Figure 1: POSEIDON (M. Lefebvre, J.-F. Minster, J. Gonella, J.-P. Chassaing, J.-L. Fellous, C. Frankignond, F. Madelain (eds.), *POSEIDON*, Paris, CNES, 1983, p. 31)

The ocean was clearly the project's priority as developed by Lefebvre: the circulations that affect the oceans, the transfer of heat that the currents carry from the equator towards the pole, and their action on the climate were already starting to be known, but satellite observations provided unprecedented precision. From the end of the 1950s, Henri Stommel thus suggested modeling the physical functioning of the Gulf Stream. Based on a body of data from the "reversing bottle...thermometer...and...bathythermograph"[107] he designed a theory of oceanographic forces in the North Atlantic. Traditional experiments on ships (which can only measure hydrological density intermittently), the use of drifting buoys, damping networks (a group of fixed stations that measure currents, sea level, temperature, and salinity), meteorology, maregraphy (with tide gauges at the sea-bed), as well as tomography (using the propagation velocity of waves to determine water density) were the only instrumental tools available for oceanography before satellites.[108] This technology provided a good approximation of the synoptic and temporal capture of ocean currents. However, satellite technology made it possible to systematize the data and to obtain very precise data. It was thus less an epistemological revolution than that of a generalized increase in precision concerning the phenomena observed.

Lefebvre and his team thus set the requirements for the future satellite based on this potential added value of space technology. They underlined that "in order to study circulation at the mesoscale, it is important to have a dense covering of the space (1swath every 100 or 200 km) in order to identify and to monitor the swirls over a relatively short time (about a year)."[109] The choice is more difficult concerning synoptic coverage, since "modeling the oceans' circulation tends to increase with each oceanic basin." However, it was decided to

[107] Henry Stommel, *The Gulf Stream. A Physical and Dynamical Description* (Berkeley: University of California Press, Londres: Cambridge University Press, 1958): 12

[108] M. Lefebvre, J.-F. Minster, J. Gonella, J.-P., Chassaing, J.-L. Fellous, C. Frankignond, F. Madelain "POSEIDON" in *POSEIDON*, ed. M. Lefebvre, J.-F. Minster, J. Gonella, J.-P.Chassaing, J.-L. Fellous, C. Frankignond, F. Madelain (Paris, CNES, 1983): 10-15.

[109] Ibid., 18.

keep "a global cover" because "the majority of heat exchange between the ocean and the atmosphere is done in the polar zones where deep water is formed. Heat is transferred from the equator toward the poles and the ocean's impact is primordial in equatorial regions…"[110] A double series of requirements were thus connected to the TOPEX/POSEIDON project: first, technological advances enabled collection of new data (in particular from the synoptic point of view enabled by space instruments); and second, satellites enriched the scientific possibilities already established in the oceanography. For example, currents and heat had been well studied by traditional methods (especially for the North Atlantic and the Gulf Stream)[111]. But spatial oceanography made it possible to better understand the variability in time and space in the phenomena observed. For example, studies existed on the synoptic capture of oceanic flows (for example, the US Navy FLIP[112]); however, it was the satellite precision of this global view that would constitute space oceanography as a specialty. Monitoring and correcting for errors (in particular measuring the satellite's orbit) had to be compatible "with the subdecimetric precision sought."[113]

Once this oceanographic basis was set, the CNES engineers and their oceanographer colleagues then opened up the possibilities of using POSEIDON to other disciplines. They invited specialists in glaciology, geodesy, and climate to supplement the research program and to point out the research potential that this French satellite offered. Climatologist Claude Frankignoul believed that the data provided by POSEIDON would provide measurements of the "variations of the rise in sea level over many years."[114] William J. Campbell, a glaciologist at the University of Puget Sound in Tacoma, said that "the orbit of POSEIDON will provide…sea ice cartography with a precision of ±1km and a resolution sufficient enough to observe mesoscale processes at the border between frozen sea and the free sea-ocean."[115] Anny Cazenave, a geodesist at the GRGS of Toulouse, envisaged the "contribution of altimetry to geophysics." In particular, she pointed to the fact that "altimetric information enables useful verification of oceanic lithosphere models."[116] Geographers were also invited to give their opinion on the potentialities of POSEIDON. Alain Baudoin from the French National Institute of Geographic and Forest Information (IGN) thus stated "the interest of stereoscopic space images with high resolution for cartography at the medium scale."[117] Physicists (Jacques Rutman at the Laboratoire primaire du Temps et de Fréquence and Bernard Guinot of the International Time Bureau) indicated that in the field of "the metrology of time, the comparisons of distant clocks are far from being harmonized with time standards, even those of recent manufacture."[118] The American Global Positioning System (GPS) is

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110 Ibid., 19.

111 Jacob Darwin Hamblin, "Seeing the Oceans in the Shadow of Bergen Values" *Isis* 105,2 (2014) : 353-355.

112 Philip Rudnik, "Flip: An Oceanographic Buoy" *Science* 146, 3649 (1964) : 1268-1273.

113 Other errors are taken into account that could affect satellite monitoring and data transmission: disturbance by the nonhomogeneous gravitational field of the Earth, nongravitational forces (friction of the atmosphere), the disturbance of the radar signal in its atmospheric trajectory (steam, ionospheric electrons), and the radar waves reflecting on the waves (Ibid., 23-25).

114 Claude Frankignoul, "Climatorologie, océanographie et glace de mer," *in POSEIDON* ed. M. Lefebvre, J.-F. Minster, J. Gonella, J.-P.Chassaing, J.-L. Fellous, C. Frankignoul, F. Madelain (Paris : CNES, 1983): I-1-1.

115 William J. Campbell "Observations des calottes glacières et de la glace de mer," *in POSEIDON* ed. M. Lefebvre, J.-F. Minster, J. Gonella, J.-P.Chassaing, J.-L. Fellous, C. Frankignoul, F. Madelain (Paris : CNES, 1983):,VI-4-1.

116 Anny Cazenave, "Contribution de l'altimétrie à la géophysique," *in POSEIDON* ed. M. Lefebvre, J.-F. Minster, J. Gonella, J.-P.Chassaing, J.-L. Fellous, C. Frankignoul, F. Madelain (Paris : CNES, 1983): VI-6-1.

117 Alain Baudoin, "Intérêt des vues spatiales stéréoscopiques et à haute résolution pour la cartographie à moyenne échelle," *in POSEIDON* ed. M. Lefebvre, J.-F. Minster, J. Gonella, J.-P.Chassaing, J.-L. Fellous, C. Frankignoul, F. Madelain (Paris : CNES, 1983): VI-8.

118 Jacques Rutman, Bernard Guinoté, "Transferts de temps," *in POSEIDON* ed. M. Lefebvre, J.-F. Minster, J. Gonella, J.-P.Chassaing, J.-L. Fellous, C. Frankignoul, F. Madelain (Paris : CNES, 1983): VI-9-1.

satisfactory (in particular because all the errors are evaluated), but its main defect is "to be a military system" thus less accessible. Rutman and Guinot argued that a similar system "but in the form of a civil and public project"[119]with increased precision (10 nanoseconds instead of the 50 to 100 nanoseconds obtained by GPS) could be commissioned. Altimetry (and in particular the satellite monitoring of POSEIDON) should allow, in theory, these possibilities for temporal physics. Thus, POSEIDON's creators argued that the project received, from geophysics, glaciology, time measurement, and meteorology, "strong response and support from French scientific communities."[120]

Even though these projects were secondary, they were part of the overall building of project POSEIDON. These projects were part of an incremental dynamic as the specialty sought to bring together varied cognitive skills on a technological platform delivering a certain type of data. The collective text, published in 1983, by the CNES engineers as well as the oceanographers (in particular Jean-François Minster) and the geodesists (in particular Anny Cazenave) that they convinced, set out a typical argument for designing a project that offered as many opportunities as possible. In fact, it was not the disciplinary divisions that were highlighted, but rather what the project could do for each discipline that took part in the project.

While the project's creators wanted to bring together disciplines close to the emerging specialty of space oceanography, they did not want, however, to give the impression of a dispersion or a dissolution of the epistemological foundations on which POSEIDON rested. They argued in particular that:

> Research on climate dynamics is an exemplary unifying topic that can orient and bring together a broad scientific community including physicists of the atmosphere and the ocean, geochemists and glaciologists, paleontologists, and geographers. In particular, this program calls for close scientific co-operation between meteorologists and oceanographers who, whatever certain specialists might think, work with dynamic phenomena that are very similar and are governed by the same equations and same mechanics on a planetary scale.[121]

The climate, as a focal point for these disciplines studying the atmosphere and the terrestrial lithosphere, was a powerful rallying point for POSEIDON's creators. Yet bringing together meteorology and oceanography (at least in the proposal draft) was not to everyone's taste. Several of the oceanographers expressed their reservations to certain members in the field when the POSEIDON project was set out. Jacques Merle, oceanographer at the l'Institut de Recherche pour le Développement (IRD) and involved in the mission, admitted that,

> Generally, there was a great skepticism from the traditional oceanographical community that sometimes manifested as hostility, in Brest in particular, at the [French] Naval Hydrographic and Oceanographic Service.[122]

In particular, linking oceanography and climate caused virulent criticism. The 1983 report had indeed targeted the climate and its changes as an important issue in the years to come:

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[119] Ibid., VI-9-4.

[120] M. Lefebvre, J.-F. Minster, J. Gonella, J.-P., Chassaing, J.-L. Fellous, C. Frankignond, F. Madelain "POSEIDON" in *POSEIDON*, ed. M. Lefebvre, J.-F. Minster, J. Gonella, J.-P.Chassaing, J.-L. Fellous, C. Frankignond, F. Madelain (Paris, CNES, 1983): 41.

[121] Ibid. 12.

[122] Interview with Jacques Merle, 30th april 2014.

> It is certain that the climate, defined as the set of average values of meteorological variables and the physical environment, established in an appropriate space and time… has undergone significant variations over the course of historical time, and is even more marked during the periods of geological time. Other factors related to the biosphere slowly modify the chemical composition of the air and the oceans and, in this way, affect the radiation amount of the planet: in particular, we are thinking of the progressive increase in CO2, the state of the stratospheric ozone, and the load of dust and aerosols resulting from farming and industrial activities.[123]

While opening up space oceanography to climatology issues via POSEIDON was certainly present at the project's inception, we must not be anachronistic. Such a process would lead us to discern within the thickness of historical phenomena only those aspects that are directly relevant in our present, and thus over-interpret this scientific choice to link the two fields. The force of the links created is undeniable, and it increased in the early 1980s (and POSEIDON's creators never missed a chance to remind others that in France, there was a National Research Program for Studying Climate Dynamics[124] and that internationally, there were programs that promoted this research – I will come back to this). However, the various engineers and oceanographers interviewed in this study admit that the idea of bringing together climate and oceanography research was not an overarching concern at the time.[125]

Sabine Arnault, from the IRD, insisted on the fact that "the question of climate change was less present in the 1980s, but we thought about it because of the changes in measurements from the marigraph networks…"[126] Philippe Gaspar, at CLS,[127] stated that the oceanographers "did not have climate applications in mind…"[128] Jean-François Minster, an oceanographer at the Laboratoire d'Études en Géophysique et Océanographie Spatiale [laboratory for Research in Geophysics and Space Oceanography] at the launching of TOPEX/POSEIDON, argued that one of the main benefits of this research project was a better understanding of the El Niño phenomenon. But he added that "That led to the question of climate change, which was in the margins but might interest the media. We didn't really know what that meant."[129]

Thus, the climate constituted a sort of syncretic subject that interested public agencies and mobilized many disciplines in the sciences of the lithosphere and atmosphere involved in POSEIDON. As the mission was designed around space oceanography, this shift was more an orientation toward a research topic rather than a disciplinary reorientation (the climatologists were not involved in the discussions preceding the launch).

TOPEX: Emerging Space Oceanography

The French engineers initially thought of launching POSEIDON by coupling it with a SPOT (Satellite for Earth Observation) satellite. However, the American researchers and engineers, who already had experience with Seasat, had been working for a few years on the project TOPEX. NASA initially formulated the request for TOPEX in the line with Badgley's

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[123] M. Lefebvre, J.-F. Minster, J. Gonella, J.-P., Chassaing, J.-L. Fellous, C. Frankignond, F. Madelain "POSEIDON" in *POSEIDON*, ed. M. Lefebvre, J.-F. Minster, J. Gonella, J.-P.Chassaing, J.-L. Fellous, C. Frankignond, F. Madelain (Paris, CNES, 1983): 1.2.
[124] Ibid., 1.1.
[125] Ibid. 42.
[126] Interview with Sabine Arnault, 7th may 2014.
[127] A subsidiary of CNES, created specifically for oceanographic data processing.
[128] Interview with Philippe Gaspar, 25th april 2014.
[129] Interview with Jean-François Minster, 16th june 201

research.[130] In a general way, focusing the issues on oceanography was related to NASA's organizational chart, which links oceanography and Earth observation. In December 1979, the Office of Space and Terrestrial Applications (OSTA) asked engineers at JPL to design a study "for a satellite program of Earth altimetry."[131] Work on what would become the TOPEX project was "initiated in January 1980 in response to a NASA Headquarters' request to JPL to develop a conceptual design for an observational system for measuring and monitoring the global ocean circulation."[132] The project was supported by the Earth Science and Applications Division, Oceanic Processes Branch, which was part of the Office of Space Science and Applications (OSSA) at NASA. The TOPEX Study Team was formed at the beginning of the year 1980 and, at the same time, NASA "formed a science working group (SWG) under the chairmanship of Carl Wunsch of MIT."[133] The questions put to this group of scientists involved the research potentials opened up by altimetry measurements, the precision necessary for topographic measurements, and the errors that this kind of technique generates.[134] In its report, the SWG did not fail to note that,

> The most serious obstacle to understanding ocean circulation is the absence of any global means for observing it. At present, oceanographers rely on ships, buoys, drifting floats, and moored instruments, sources of information that are well suited to short-term (a few months) regional studies (areas a few hundred kilometers across). But no existing method permits observation on the global scale that is required to measure and understand the ocean as an entity.[135]

The conclusions of the group of American scientists were rather close to those of the French working on POSEIDON: it is important to know the large-scale movements of ocean water; the variations in the ocean surface can be measured by satellite altimetry, and sufficient precision can be obtained, as the GEOS-C and Seasat missions proved.[136] The data collected on ocean topography would be then integrated into the "models of the ocean's density field in order to determine the general circulation of the ocean and its variability."[137] Economic considerations (such as the commercial advantages that a better knowledge of the currents would enable in shipping) were also added to these scientific issues. Finally, very broad environmental questions about possible "catastrophic climatic changes and their implications for world food supplies and security"[138] were also raised.

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[130] NASA still remembered in 1987 its altimetry ambitions: to follow the three cycles. « three main cycles of the Earth system : the energy cycle, the water cycle, and the life cycle. The ocean is a key element in all of the three cycles. (…) Observing the ocean sot that we can understand, quantify, and predict the ocean's role in the ever-changing Earth system is a major objective of the Earth Observing System » (*Altimetric System. Earth Obsering System*, Volume IIh, Panel Report, 1987 : 1.). NASA's interest in the Earth system and its evolutions, prior to the Apollo missions, did not stop after the end of Moon exploration.

[131] CNES Archives, *Ocean Topography Experiment (TOPEX), JPL Study Team Prephase B Report*, NASA, JPL, septembre 1982, 1.1.

[132] CNES Archives, *Ocean Topography Experiment (TOPEX), Mission Description*, NASA, JPL, Juillet 1983, 1.1.

[133] CNES Archives, *Ocean Topography Experiment (TOPEX), JPL Study Team Prephase B Report*, NASA, JPL, septembre 1982, 1.1.

[134] Satellite Altimétric Measurements of the Ocean, Report of the TOPEX Science Working Group, JPL, NASA, 1[er] mars 1981, 1.

[135] Ibid., viii.

[136] Ibid., ix.

[137] CNES Archives, *Ocean Topography Experiment (TOPEX), JPL Study Team Prephase B Report*, NASA, JPL, septembre 1982, 2.1.

[138] Ibid., vii and viii.

The most notable difference with POSEIDON lies in the scientific community involved in the TOPEX project. In 1981, in the SWG's report, "auxiliary geophysical studies" were mentioned in an appendix. Coastal oceanography was mentioned as an obvious field of application for altimetric satellite data:

> Further progress in understanding the nature of surges, the focusing of waves, the dissipation of tides, and the dynamics of coastal currents requires measurements of winds, waves, and sea level, in regions where the bathymetry is well known, during times of strong winds, and especially during storms.[139]

Glaciology and meteorology were also mentioned as adjacent disciplines likely to benefit from TOPEX.[140] Space oceanography was thus the priority research field for the American scientists; the SWG did not base its argument on the kind of disciplinary eclecticism that characterized POSEIDON. In the Mission Description of 1983, only one scientific community was associated with the project – the oceanographers:

> The goals that the OSSA's Earth Science and Applications Division has established for the Oceanic Processes Program are (1) to provide a physically unambiguous and scientifically sound basis for observing oceans from space and (2) to provide an effective capability for applying these observations in solving oceanic problems. The oceanographic community will define the observational capabilities needed to solve such problems.[141]

Spatial oceanography was still, at this time in the United States, an emerging specialty. Most American oceanographers were not interested in satellite data until the 1980s. [142] Keeping space oceanography on NASA's agenda was ensured by William A. Nierenberg, physicist, director of the Scripps Institution of Oceanography from 1965 to 1986, and chairman of the NASA Advisory Council from 1978 to 1982. [143] Nierenberg, at the intersection of oceanography and the political and administrative field of space activities, was able to push the Scripps Institution of Oceanography toward space. However, he was not able to convince all members of the institution to pursue this specialty. [144] Even though his overtures towards other disciplines such as geophysics were moderate (they were probably less decisive than for POSEIDON, but they were still part of the project proposal's appendices[145]), these overtures testify to the progressive organization of a specialty (i.e. spatial oceanography) that was relatively malleable in its epistemic foundations.

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[139] Ibid., 76.

[140] Ibid., 77-78.

[141] CNES Archives, Ocean Topography Experiment (TOPEX), Mission Description, NASA, JPL, Juillet 1983, 2.1.

[142] Erick M. Conway, "Drowning in data: Satellite oceanography and information overload in the Earth sciences" *Historical Studies in the Physical and Biological Sciences* 37,1 (2006) : 127-151.

[143] Charles Townes, Walter Munk, "Obituary: William Aaron Nierenberg" *Physics Today* 54,6 (2001) : 74-75. I would like to thank Erick M. Conway for pointing out this reference.

[144] See : Naomi Oreskes, Erick M. Conway, "From Chicken Little to Dr. Pangloss: William Nierenberg, Global Warming, and the Social Desconstruction of Scientific Knowledge" *Historical Studies in the Natural Sciences* 38(1) (2008) :109-152. For an overview of Nierenberg's positions, see : William A. Nierenberg, "Science, Policy, and International Affairs: How Wrong the Great Can Be" *Environmental Conservation* 20,3 (1993) :195-197.

[145] The appendix on other possible research that TOPEX would enable starts with this idea : : « The primary goal of this report has been to investigate the usefulness of satellite altimeters for measuring geostrophic surface currents. Nevertheless, satellite systems designed to measure currents also produce information useful for other geophysical studies. An altimeter can measure variations in sea level near coa*STS* due to tides and storm surges,

Forging an Alliance

The TOPEX / POSEIDON mission must be re-situated within the more general context of space cooperation between France and the United States after World War II. In addition to including oceanography in NATO military questions, as we have seen, Franco-American relations were built around successive rapprochements and oppositions. For example, in 1978, French President Valéry Giscard d'Estaing's initiative to create "an international satellite monitoring agency (ISMA)"[146] was strongly rejected by the Americans, while it interested countries that did not have space programs[147]. Overall, starting from the Fourth Republic, France was committed to a policy of space independence. But this independence was not complete autonomy and France associated with both Soviet and American space experiments throughout the 1970s[148]. However, these relations were not without tensions, which is also the case with regard to uranium research[149].

The American and French missions thus had more in common than a family resemblance: they had the same goal and used the same new satellite technology. Yet even so, the associating the two experiments was not immediately considered. The first attempts took place at the end of 1982: for the first time, the question of a "possible collaboration in the area of ocean satellite altimetry"[150] was raised. On January 26, 1983, CNES representatives went to the United States to discuss what the scientific foundations might be for cooperating on a common altimetry project. The discussions were relatively tense. Michel Avignon, CNES engineer in the French delegation, reported the near-breakdown of negotiations:

> The only important issue for France was that ARIANE be used as the launcher. The Americans did not want any French experiments. It was not coordinated at the level of the agencies….We decide to get back on the plane if the Americans did not take our instruments. In the end, Stan Wilson [of NASA] said, "Stay tonight, you can leave tomorrow." Finally, the decision was given to us at the bar of Sheraton: "We have permission to give you 5% of the time, provided that your experiments do not make us lose data.[151]

The American engineers were caught between the new launch demands that meant they only envisaged launching by the space shuttle and the characteristics of an altimetric satellite, which made it difficult for a shuttle to put it into orbit. The French launcher ARIANE thus provided the opportunity for a conventional launch for TOPEX. Including POSEIDON on the

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can profile the shape of continental glaciers, and can map the topography of plains. The reflected altimeter pulse contains information about the roughness and composition of Earth's surface, information that can be used to deduce wind speed, wave height, the existence of ice cover over the oceans, and the type of snow cover on glaciers. Auxiliary observations used to correct the altimeter signal measure water vapor in the atmosphere and free electrons in the ionosphere. And information contained in the leading edge of the reflected altimeter pulse can be used to measure rain just above the sea surface on occasions when moderate to heavy rain is present » (Ibid., 73). Since auxiliary measurements were also planned to increase the quality of altimetric measurements, they were incorporated when creating the satellite's navigation systems.

[146] R.R. Subramanian, "Creation of an International Satellite Monitoring Agency" *Strategic Analysis* 3,5 (1979): 204.

[147] Isabelle Sourbès-Verger, "Mythe et réalités de l'espèce militaire" *Hermès* 24 (2002): 181.

[148] Philippe Varnoteaux, "La naissance de la politique spatiale française" *Vingtième siècle. Revue d'histoire* 77 (2003): 59-68.

[149] Matthew Anderson, "*Les liaisons dangereuses* : resouce surveillance, uranium diplomacy and secret Franch-American collaboration in 1950s Morocco " *The British Journal for the History of Science* 49,1 (2016): 79-105.

[150] CNES Archives, TOPEX/POSEIDON, Joint Working Group, Final Report, s.d., 1984, 1.2.

[151] Interview with Michel Avignon, 12 juin 2014.

technological platform was to some extent the price the Americans had to pay to use ARIANE.

Several meetings occurred in Toulouse and in Washington in April and May 1983; the co-operation was then judged “possible and highly desirable.”[152] The agreement between CNES and NASA was drawn up in September 1983: NASA’s administrator, James Beggs and the President of CNES, Hubert Curien, agreed on a feasibility study of a joint TOPEX/POSEIDON satellite platform, “with the inclusion of French instruments on the U.S. TOPEX satellite and a launch by the ARIANE launch vehicle.”[153] In 1987, a Memorandum of Understanding between the two agencies set out the role of each party. NASA had to provide an altimetric radar, a microwave radar, and a precise tracking system, while CNES had to provide an altimetric radar and another tracking system.[154]

On both sides of the Atlantic, there was a gradual crystallization of space oceanography as a specialty. It was not the epistemological foundations that brought the actors together, but the technical work of the engineers and physicists involved. Thus, it was the technological and instrumental substrate that produced data that were then delivered to the community, which drove this process. In this sense, spatial oceanography is primarily an instrumental specialty.

The scientific objectives of the TOPEX / POSEIDON mission were not exactly a synthesis of the two separate missions; overall, the balance of power was in NASA’s favor, and the TOPEX goals were the main ones advanced. Thus, the authors of a JPL report in 1989, repeated that,

> The goal of TOPEX is to increase substantially the understanding of global ocean dynamics by making precise and accurate observations of the oceanic topography for several years. The data obtained from these observations will be used by the oceanographic community.[155]

In no way were timekeeping or cartography involved; only the ocean was considered an object.

The modification of the French scientists and engineers’ objectives for TOPEX/POSEIDON is perceptible in a strategic planning document commonly called *The Purple Book* and written in March 1992 by Chet J. Koblinsky (of Goddard Institute in New York), Philippe Gaspar (of CLS in Toulouse), and Gary Lagerloef (of Science Applications International Cooperation in Washington). This exercise in applied futurology sketched out the contours of the tangible benefits of TOPEX/POSEIDON as well as those of missions to come. The interest of the mission for climate change, the place of the oceans in that complex mechanism, the need for a technology enabling global data capture—all these issues delimited the perimeter of a space oceanography centered on climate questions.[156]

Of course, connections with other disciplines were not completely excluded: specifying the objectives of future missions did not mean absolutely prohibiting other

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[152] CNES Archives, TOPEX/POSEIDON, Joint Working Group, Final Report, s.d., 1984, 1.2.
[153] Ibid., 1.2.
[154] CNES Archives, Memorandum of understanding between the United States National Aeronautics and Space Administration and the French Centre National d’Études Spatiales, for joint development of the TOPEX/POSEIDON Project, March 23, 1987, In*TOPEX/POSEIDON Project. Project Launch Policy*, NASA, CNES, Avril 1992, A.3.
[155] CNES Archives, *TOPEX Projec, TOPEX/POSEIDON Mission* Plan, JPL 1989, 2.1.
[156] J. Koblinsky, P. Gaspar, G. Lagerdoef, *The Future of Spaceborne Altimetry. Oceans and Climate Change, a long term strategy* (Washington D.C. : Joint Oceanographic Institution): v.

research fields. For example, geophysics data were likely to be available from the mass of information that TOPEX/POSEIDON was supposed to provide. Better knowledge of the geoid, lithospheric elasticity, and the shape of continental glaciers would be additional benefits of the mission.[157]

As we have seen above since 1978, NASA has had a research program on the climate. A framework document (completed in 1986), titled *Earth System Science. Overview: A Program for Global Change*[158] set out NASA's goals on climate change. NASA scientists and engineers would follow global initiatives in this area while pursuing their own agenda.

The World Ocean Circulation Experiment (WOCE) is a research segment of the World Climate Research Programme (WCRP). Over the period 1990-1998, through a vast group of experiments, this project sought to better understand the general circulation of the oceans as well as to provide models for predicting changes in oceans depending on atmospheric changes.[159] More generally, the goal was "to understand global climate dynamics and to predict decadal climate change."[160] Jean-François Minster, for the French scientists, and Carl Wunsch, for the American oceanographers, got involved in this program organizing climate research via TOPEX/POSEIDON.[161] Starting in 1985, the WCRP also developed the Tropical Ocean-Global Atmosphere (TOGA) project, which more specifically targeted ocean circulations and climate in tropical zones. TOPEX/POSEIDON would provide data to complement information collected *in situ* thanks to these two programs for climate monitoring.[162] In particular, El Niño was one of most remarkable phenomenon targeted by the TOGA program and for which the satellite mission was expected to provide relevant data.[163]

Centered on oceanography and framed by international programs on climate research, TOPEX/POSEIDON was a mission in which the actors (engineers and scientists; French and American) seem to have perfectly defined their epistemological and practical program. In fact, the resistance in France from the oceanographical community was still very strong. Calls for proposals sought, among other things, to counter this reticence. The call for proposals made by CNES in 1986 clearly details the scientific expectations of the mission:

> CNES requests proposals for using altimetric data from the combined TOPEX/POSEIDON [mission]. Preference will be given to research proposals aimed at increasing our understanding of the general circulation of the ocean, its variability, its interaction with the atmosphere, and the determination of ocean tides…[164]

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[157] Ibid., 41-45.

[158] NASA, *Earth System Science. Overview: A Program for Global Change*, Report of the Earth System Science Committee (Francis Bretherton, Chair), NASA, Advisory Council, 1986.

[159] CNES Archives, *Altimetric System. Earth Observating System, wol. IIh, Panel Report*, NASA, 1987, 18.

[160] World Occean Circulation Experiment, US WOCE Planning Report, n° 3, Contrinutions to the Planning of WOCE, Status Report on US WOCE Planning, janvier 1986, 1.

[161] CNES Archives, *Minutes of the 2nd Joint US/French Science Steering Groupe Meeting*, Goddard Space Flight Center, 10-11 mai 1984, 2.

[162] A. Anderson, F. Gilbert, H. Grassl, E. Harrison, R. Hide, S. Houry, K. Lambeck, M. Lefebvre, J. Melosh, A. Morelli, R. Sabadini, D. Smith, C.-K Tai, G. Visconti, S., Wilson, C. Yoder, V. Zlotnicki, "Interaction with other disciplines and programs." In *The Interdisciplinary Role of Space Geodesy*, ed. Ivan I. Mueller, S. Zerbini (Berlin : Springer-Verlag, 1989): 113.

[163] Ibid., 113.

[164] CNES Archives, Étude par altimétrie de la circulation océanique TOPEX/POSEIDON, Appel à propositions, 1986, 1.

Jacques Merle, of the IRD, said that at the time, traditional oceanographers (in particular tropicalists) felt almost entirely unconcerned by issues involved with space:

> At the beginning, TOPEX/POSEIDON did not interest the tropicalists at all, because the geostrophic relationship [*i.e.* the pressure differential driving the currents] does not work at the equator. However, TOPEX/POSEIDON sought to describe global oceanographical dynamics with the geostrophic relationship. Therefore, we suddenly woke up only four days before the deadline for the proposals of TOPEX/POSEIDON…We realized late that to observe the dynamic topography of the tropical oceans could be interesting, as that would reveal the thickness of the hot layer on top of the cold water…Afterwards, we [*i.e.* the tropicalists], became heated partisans in favor of altimetry and TOPEX/POSEIDON. We saw waves of various frequencies that undulated along the equator, whereas these waves had never before been observed. But the existence of these waves had been proven by theorists."[165]

Sabine Arnault, also with the IRD, helped draft the proposal for the French tropicalist oceanographers. Disregarding the "oceanographers with cold feet," she wrote a proposal for research to better understand the transport of water masses and heat in the tropical zones of the Atlantic. The proposal followed the TOGA and WOCE's recommendations very closely: to "develop a method of assimilation of altimeter data into Oceanic General Circulation Models (OGCMs) for the purpose of preparing an operational, permanent, three-dimensional now casting of the tropical Atlantic Ocean [a TOGA objective]" and to "derive from these models global circulation fields and a time series of mass and meridional heat transports across the tropical Atlantic region [a WOCE objective]."[166]

Arnault recognized that the oceanographers' fears were probably not entirely unfounded, in particular with regard to the "precision of measurements." But above all, it was the reorientation of the discipline that they feared:

> The fear was of losing their expertise, their know-how in their field… [As if they were saying] "What is it with these young whippersnappers with their toys who want to call everything into question!" They felt threatened.[167]

Although this reluctance existed, it was not the majority opinion, and a great many traditional oceanographers gradually integrated satellite data and methods into their corpus.[168] However, despite everything CNES and NASA were careful to plan a PR campaign at the end of 1991. The objective was "to quickly promote short-term demonstrations of the capacities of the TOPEX/POSEIDON mission. The purpose was to provide gradually but as soon as possible (3, 6, 9, and 12 months after launch) short demos of the relevance of the system choices and the varied examples of applications of the mission suitable for a broad dissemination to the public."[169] Who was meant by this 'public' was not specified, but the products offered (maps,

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[165] Interview with Jacques Merle, 30th april 2014.

[166] CNES Archives, J. Merle, S. Arnault, A. Morlière, J.M. Verstraets, Y. Ménard, L. Gourdeau, "Study of Mass and Heat Transport of the Tropical Atlantic Ocean Using Models and Altimeter Data." In *TOPEX/POSEIDON, Science Investigations Plan.* NASA, JPL, 1991, p. 90.

[167] Interview with Sabine Arnault, 7th may 2014.

[168] Ainsi, l'une des océanographes interviewée pour cette enquête, Rosemary Morrow, a travaillé à la fois sur des projets spatiaux comme TOPEX/POSEIDON et sur des campagnes de mesures à bord de bateaux (Alexis Chaigneau, Rosemary Moreau, "Surface temperature and salinity variations between Tasmania and Antarticao, 1993-1999" *Journal of Geophysical Research. Oceans* 108, C12 (2002): SFR 22-1-SFR22-8.

[169] CNES Archives, P.Y. Le Traon, *Produits de promotion de la mission TOPEX/POSEIDON*, CLS Groupe océanographique, novembre 1991, 2.

and "estimates of the levels of altimeter noise and [a] comparison with the noise levels on prior missions…"[170] show that the audience targeted was broad and extended even to the most reticent oceanographers.[171] Specifically, the great variety of data collected, the multiplicity of the disciplines involved, as well as the demonstrations reveal the ways in which NASA and the CNES patiently built a community of users. These "short demos" every three months testify to the agencies' desire to allow for progressive learning by scientists in the various disciplines that could benefit from TOPEX/POSEIDON data. This community-building occurred both in future prospects for "project management"[172] that might be of interest to those involved, as pointed out by Claude Rosental, and by creating a "relationship [between] actors who would probably not have met [otherwise]."[173]

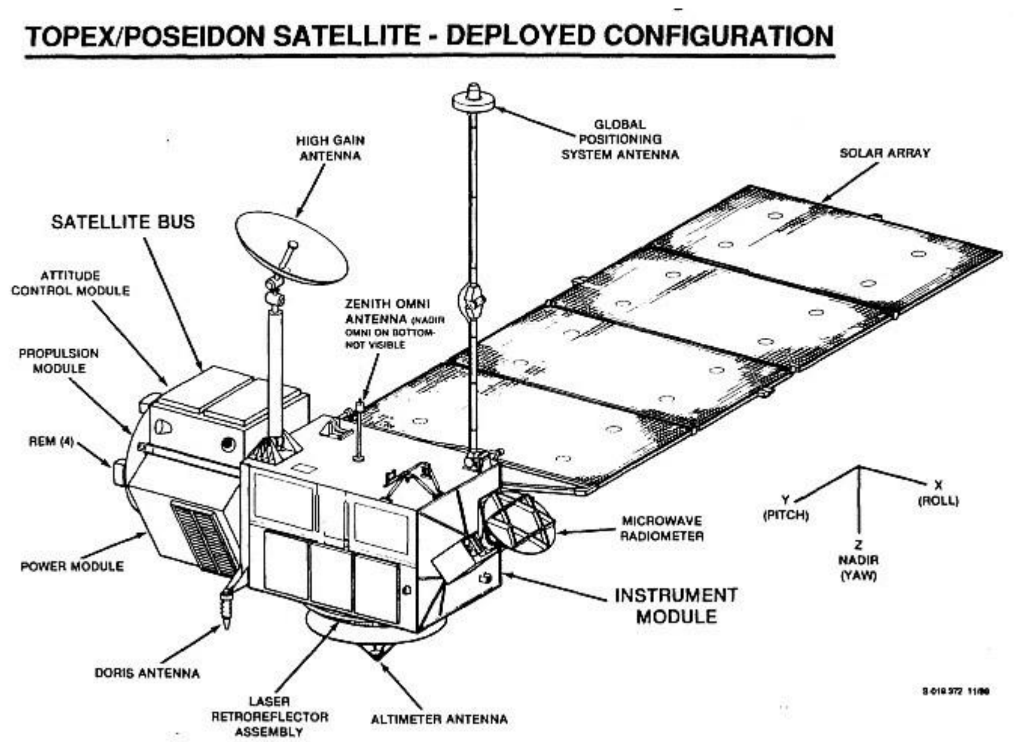

Figure 2: TOPEX/POSEIDON (CNRS Archives, Topex Joint Steering Group Meeting, Fairchild Space, May 10, 1990)

TOPEX/POSEIDON was thus involved in the progressive crystallization of the space oceanography as a specialty. Oceanography, traditionally focused on *in situ* techniques for observing the oceans and its tides, currents, etc., was in a way taken over by a small group of oceanographers and engineers in the early 1980s. TOPEX/POSEIDON functioned as a kind of technological injunction: it was hard to convince the scientists of the (potential) capacity for global collecting of oceanographical data, as they feared insufficient precision. Thus before the satellite's launch, the reorientation just described was only one possibility: as long as TOPEX/POSEIDON had not provided convincing results, this reorientation hung in suspense.

[170] Ibid., 4.

[171] On the very diverse groups involved in space demonstrations, see Rosental, *Les capitalistes de la science*,33-36.

[172] Claude Rosental, "Anthropologie de la démonstration."*Revue d'Anthropologie des Connaissances.* 3, no 2 (2000): 244.

[173] Ibid., 247.

The process leading to the launch is ideal for grasping the scientific stakes of the TOPEX/POSEIDON mission.

The Battle of the Battery

During the summer of 1992 a few days before the launch, a problem of importance emerged that dramatically challenged the disciplinary cohesion of the group of scientists working on the project. On July 21, 1992, Lee-Lueng Fu, head of Project Science on TOPEX/POSEIDON at JPL, wrote a long email to his colleagues in the Science Steering Group (SSG)[174] to inform them that the satellite batteries were probably defective.[175] They showed a potential deterioration that meant that a five-year mission, the duration initially planned, was unrealistic. These batteries, built by the American company Gates Aerospace after 1987, were part of a completely defective generic batch. The Project Office of JPL then formed two teams. The blue team had to measure the risks of the mission and potential alternatives. The red team had to check "the findings of the blue team." This double assessment of the defects was ideally intended to solve the problems of decreased battery life of the satellite, but the two teams did not manage to find the cause of the failures. The only tangible result on July 21, 1992, was that "prudent management of the charging and discharging of the batteries" would give a high "degree of probability of having a 3-year mission, and a high probability of a 2-year mission." Another option would be to delay the launch of TOPEX/POSEIDON for one to two years and use requalified batteries. The red team recommended immediate launch with a careful charging of the batteries and accepted the risk of a shorter mission. The only scientist on the red team (most were engineers) was Robert Stewart (from Scripps Institution of Oceanography and JPL); he was strongly opposed to this suggestion, stating, "No science impact had been assessed." It was precisely for this reason that Lee-Lueng Fu asked his colleagues of the Science Steering Group. The two engineers from JPL responsible for the technical preparation of TOPEX/POSEIDON wanted to have a clear vision of the consequences of reducing the mission to three to two years.

This immediate dramatization of the stakes (*i.e.* the reduction of the duration of the mission) reveals the most salient scientific issues at stake. Because the scientists had to quickly give a report about what would be possible to do in two years, the points of contention were immediately brought to light. At the end of his email, Lee-Lueng Fu asked them (even before the discussion had started) to "come up with quantitative statements such as the probabilities of hitting an El Niño in a 2, 3 or 5-year mission." During all the discussions that followed, the question of a complete monitoring of an El Niño cycle was continuously raised. However, this problem of El Niño had not been mentioned as essential during all the preceding phases. It is thus important to understand what justified this sort of argument in the precipitation before the launch.

The engineers were somewhat wary of the assessment the scientists would make. William Patzert, an oceanographer with JPL, noted semi-ironically, semi-seriously that "the engineers were more quantitative than most of the scientists will be."[176] The urgency triggered a 'moral dilemma': "Let's be careful to make a responsible recommendation. Biggies like this don't come along very often. They separate the men from the boys."[177] It was no longer possible to play at being curious scientists and have fun with expensive instruments; people

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[174] The Steering Group of the scientific part of the program.

[175] Personal Archives of Dudley Chelton, Email of Lee-Lueng Fu to the Science Steering Group, 21th july 1992.The elements which follow are drawn from the same email. The term "El Niño" is written without the tilde on N in the e-mails, so I have reproduced this spelling.

[176] Personal Archives of Dudley Chelton, Email of William Patzert to Lee-Lueng Fu, 23th july 1992.

[177] Ibid.

needed to behave as responsible adults having to make difficult decisions. This moral stiffening, with hints of treating the scientists like children, reveals the crystallization occurring within the SSG: through the sudden appearance of this issue, the "scientists" became a *de facto* collective, whereas previously they had been less clearly united. To have to provide recommendations based on the scientific impacts of reducing the mission forced the SSG to define its priorities as precisely as possible (which meant that its members had to agree on those choices). Thus, they had to define what, for space oceanography, the potential results of TOPEX/POSEIDON may be – if major discoveries were no longer possible, then at least the scientifically remarkable added value.

On July 24, Frenchman Lefebvre noted that a three-year duration was compatible with the "tidal objectives,"[178] while less than that would be less "comfortable." Consequently, the "tidal business" was not "a criterion for the decision which has to be made."[179] It was, therefore, El Niño that the scientists designated as a determinant, as Lee-Lueng Fu had indicated in his first email. Dudley Chelton, Associate Professor of Oceanography at Oregon State University and member of the SSG, contacted David Enfield, physicist-oceanographer at the Atlantic Oceanographic and Meteorological Laboratory of NOAA, asking him to provide the probabilities of detecting an El Niño over periods from one to six years, starting from the data available for the last two hundred years. The result was that probability ranged from 0.042 for one year to 0.888 for six years.[180]

Chelton thus gathered the preliminary estimates of the scientists involved with TOPEX/POSEIDON and concluded, in an email on July 24, 1992, that a three-year duration was "the absolute minimum tolerable."[181] He warned that any shorter duration would no longer be a scientific mission but a proof of concept to show the usefulness of GPS monitoring, double-frequency altimetry, and advances in estimating the ionospheric effects on altimetric monitoring.[182] The assessment of the scientific impact that Fu drafted thus very explicitly insisted on this idea of a minimum duration of three years. He specified that the seasonal variations were likely to be tainted with errors if the mission was only two years long.[183] The text circulated among the members of the SSG for comments and to finalize the report. Patzert from JPL was rather doubtful of the scientists' arguments. He thus noted in the margins of Fu's report on the section on seasonal variability, asking would it possible to "put it in language that non-scientists can understand?"[184] Patzert even went as so far as to ask whether the probability of observing El Niño within three years (38%) could not "in good conscience" be raised to "50%."[185]

Patzert, a member of JPL and an oceanographer, perfectly integrated the codes expected by the engineers of his organization. It was not a question of reformulating a phrase but producing a mission diagram that could reconcile the three-year battery lifespan with serious (and complete) observation of a phenomenon like El Niño. Chelton took offense at his request and reminded Patzert what he seemed to be ignoring about scientific practice:

> No, we cannot in good conscience up the probability for the next El Nino within 2 years to 50%. You know, Bill, from your past work with El Ninos. Look at the record

[178] Personal Archives of Dudley Chelton. Email of Michel Lefebvre to Lee-Lueng Fu, 24th july 1992.
[179] Ibid.
[180] Personal Archives of Dudley Chelton. Email of , David Enfield to Dudley Chelton, 24th july 1992.
[181] Personal Archives of Dudley Chelton. Email of William Patzert to Lee-Lueng Fu, Dudley Chelton et V. Slontnicki, 24th july 1992. Person
[182] Ibid.
[183] Personal Archives of Dudley Chelton, Email of Lee-Lueng Fu to SSG, 24th july 1992. Personnal
[184] Personal Archives of Dudley Chelton, Email of William Patzert to Fu, Dudley Chelton and V. Slontnicki, 24th july 1992.
[185] Ibid.

> of El Nino events since 1957...There has been only 1 case of successive El Ninos separated by less than 4 years, and that involved the 1969 marginal event.[186]

At the same time as these discussions among scientists, exchanges with NASA engineers continued. Linwood Jones, who in 1992 was a manager of satellite programs for the American agency, tried to reassure the SSG. Above all, he tried to soften the catastrophic tone that the scientific assessment seemed to take in the course of its being written. He did not disagree with the general plan, but he disapproved of the phrasing of certain sentences. He also reiterated that the experts did not know exactly whether the battery was bad, but they agreed, "that there is a high likelihood that with better attention to the operation of [their] batteries…we can expect 3 years of 'full capability satellite operations.'"[187]

Philippe Gaspar of CLS also took part in the email discussions. In particular, he worried about the future of the research field that he was heavily involved in (since CLS was supposed to be in charge of oceanographical data for TOPEX/POSEIDON). He pointed out that the document circulating under the name of *The Purple Book* sketched out future missions with high-precision altimetric measurements. He also supported the argument that the data set collected over three to five years would be of "enormous interest for many oceanographic studies." If ever the mission were not to proceed under conditions acceptable for science, then high-precision altimetry would become a science without a future for at least the length of one researcher's lifetime, and "all young scientists and engineers involved with it should better change field right now."[188]

The tension was at its height when Carl Wunsh, Professor of Oceanography at Massachusetts Institute of Technology (MIT) and member of the SWG, recommended keeping:

> The 3+2 scenario mainly for political reasons, and assurances that this was being done because of agency nervousness about upfront financial commitments. The SWG concluded that 3 years was MINIMAL if one were to justify the cost and the effort…

The conclusion was definitive and placed in the hands of the engineers – the sword to slice the Gordian knot of this intangible problem:

> If the engineers are convinced that only two years is probable, the loss of the science is too great to be tolerated, and the mission should be delayed UNTIL SUCH TIME as a 5-year mission is PROBABLE.…If the engineers are convinced that three years is probable…, then launch now would be MARGINALLY JUSTIFIED by the scientific plan for T[OPEX]/P[OSEIDON].[189]

Discussions between scientists having designed the experiments and NASA engineers were marked by a constant concern to make their arguments as clear and understandable as possible. Chelton thus took Fu's draft and suggested that the sentence indicating the scientific requirements should be altered: "The tone of this statement should be that the science community still stands behinds the original science requirements for TOPEX/POSEIDON.[190]" This process of reification made science and the scientific community into autonomous and totally homogenous agents and made the performativity of

[186] Personal Archives of Dudley Chelton, Email of Dudley Chelton to SSG, 26th july 1992.
[187] Personal Archives of Dudley Chelton, Email of Linwood Jones to SSG, 25th july 1992.
[188] Personal Archives of Dudley Chelton, Email of Philippe Gaspar to SSG, 27th july 1992.
[189] Personal Archives of Dudley Chelton, Email of Carl Wunsh to SSG, 26th july 1992.
[190] Personal Archives of Dudley Chelton, Email of Dudley Chelton to SSG, 26th july 1992.

these discourses inevitable. Setting the minimal duration at three years became the issue on which the SSG scientists created a consensus, in the name of general principles (science) and of macroscopic categories (the scientific community). Patzert, the oceanographer close to NASA engineers, decided to send them the final document written by the members of the SSG.[191] His position in between the two groups thus combined this reification with the *entre-soi* of engineers, who understand the difficulty of technical decisions:

> I am sure that you and the others that have the responsibility to weigh the facts and probabilities before making this difficult discussion – whether we will maintain our launch schedule or delay – is reached [sic] will seriously consider the above recommendation of the SSG. I personally trust your experience and judgment in this matter but feel responsible to communicate a strong message I have been given from some of our scientists: don't launch if the science goal is compromised. At a certain level, NASA's and CNES's credibility with the science community, as well as the American and French taxpayers, is on the line here. Although I realize that this is a stressful time for all of us – Program, Project, and science community – I am confident that a sensible decision will be reached.[192]

In the end, it was the taxpayer (as a distant but demanding entity concerned about the sums of money it gives to the space sector via taxes) and the scientific community who set the horizon of expectations for the SSG group.

Technical drama, the possible questioning of the mission, as well as the process leading to the scientists' consensus in producing a common text all enable us to unpack SSG's preconceived ideas. The frontier with the engineers is quite clear, even though some, like Patzert, tried to reconcile the groups' needs and play *go-betweens*. The issue of the defective batteries did not only bring to light what separates NASA engineers from SSG scientists but also revealed quite clearly the hierarchy (in terms of decisions and responsibilities) between the two groups. Thus as Chelton wrote to Patzert on July 26, 1992, a short time after the impact assessment had been sent to NASA, he had no idea how much weight their opinion would have with the engineers. However, he noted in talks with Linwood Jones "that politics will far outweigh science in favor of an immediate launch." The members of the SSG did not have the initiative (nor the institutional weight) to postpone the mission. Their recommendations counted, but nothing indicates that they would be systematically followed. The group of NASA engineers had considerable autonomy within the framework of the TOPEX/POSEIDON mission, which allowed NASA to be sovereign in its decisions. While awaiting the verdict of the engineers, the members of the SSG could not stop ruminating on their powerlessness. For example, on July 27, 1992, Chelton wrote to Andrew Bennett, an oceanographer at Oregon State University, that "Topex will quite probably be the last NASA altimeter satellite launched during [his] career as an oceanographer. I personally want to see it done right!"[193] In a second email, the same day, he continued: [194]

> Never in the history of NASA has a satellite launched with the goal of achieving a 2-year mission. On the other hand, most, if not all, missions have ended earlier than the

[191] Personal Archives of Dudley Chelton, Email of William Patzert to Carl Wunsch, Dudley Chelton, Lee-Lueng Fu, 26th july 1992

[192] Personal Archives of Dudley Chelton, Email of William Patzert to Linwood Jones, 26th july 1992.

[193] Personal Archives of Dudley Chelton, Email of Dudley Chelton to William Patzert, 26th july 1992.

[194] Personal Archives of Dudley Chelton, Email of Dudley Chelton to Andrew Bennett, 27th july 1992 (3h54 a.m.)

> intended goal. Extrapolating these previous experiences, there is a very real concern that a 2-year mission could become a 1-year mission.[195]

The dramatization operates here on levels that are very different: from the scientific career of the researcher to the history of NASA, the issues that the researchers kept turning over in their minds were not fixed solely on the objectives of the mission, strictly speaking. Well beyond expectations of results of altimetric measurements and oceanographic data, it was a broader perspective on space oceanography as a specialty that emerges from these impromptu electronic discussions while waiting for the engineers' decision.

The argument about the cost of TOPEX/POSEIDON is characteristic of this sudden broadening of the foundations for the mission. The same Dudley Chelton asked:

> TOPEX cost $700 million. In the wake of one failed satellite mission after another, can NASA face taxpayers after another bungled satellite mission that was recognized to have a high probability of failure prior to launch? It is flawed logic to launch just because of concerns about how to get back into the launch queue. Would it make sense for a sea-going oceanographer to go to sea anyway if his/her measurement apparatus was not functioning properly?[196]

The specter of the Challenger mission haunted them; the taxpayer, solicited for an important scientific mission, was rhetorically called on to measure the gap between the thinking of scientists centered on obtaining results (and the establishment of space oceanography as a specialty) and that of engineers, which was only concerned about the rate of launches. The financial question was important. A few months after launching TOPEX/POSEIDON, the General Accounting Office published a report on the costs of NASA programs, with the intention of completely revisiting the way to calculate estimated costs, in particular because NASA was chronically over budget. In the report, TOPEX/POSEIDON was credited with a supplement of 19% of its budget.[197]

In the end, the engineers, grouped together in the Fisk Review Board (named after its administrator, L.A. Fisk, Associate Administrator of the Office of Space Science at NASA) maintained the launch scheduled for August 10, 1992. The program manager, Linwood Jones, sought to be reassuring when announcing the news to the SSG:

> Only time will tell if the proper decision has been made, but I feel that everyone's opinion was heard and considered. There are many factors to be considered, but science has weighed most importantly. We have arrived at the conclusion that there is high likelihood that the mission obtain full (100%) altimeter operation for 3 years.[198]

This episode of the probable failure of the satellite batteries brings to light the modes of argumentation brought into play. For example, the SSG introduced the best documentation of the El Niño phenomenon as a new element in order to prolong the mission to the maximum. But the general framework of the mission did not depend on observing a complete El Niño. Lindwood Jones said as much when noting that "science has weighed most importantly,"

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[195] Personal Archives of Dudley Chelton, Email of Dudley Chelton to Andrew Bennett, 27th july 1992 (4h49 a.m.)
[196] Ibid..
[197] *Report to the Chairman, Subcommittee on Investigations and Oversight, Committee on Science, Space, and Technology, House of Representatives, NASA Program CoSTS, Space Missions Require Substantially More Funding Than Initially Estimated*, United States General Accounting Office, 31 décembre 1992, 8.
[198] Personal Archives of Dudley Chelton, Email of Linwood Jones to William Patzert, 3rd august 1992.

signaled that examining the South American El Niño current was not crucial when considering the other aspects of TOPEX/POSEIDON. Then, more implicitly, it was the future of space oceanography as a whole that crystallized the stakes involved: in a post-Challenger context, the SSG invested TOPEX/POSEIDON with a powerful capacity to bring together various disciplines. It was, therefore, the interconnecting of distinct future projections (initially about data over a maximum period, and then the future of space oceanography) that explains the multiplication of arguments mobilized by the researchers. Fundamentally, it was the future of the specialty of space oceanography that was challenged, sometimes with dramatic flair (for example the future of scientists' careers that could end because of a failed mission).

Itineraries of the Data: Publication and the Scientific Community

The first data received (and their transformation into images) astonished the researchers working on the project. Philippe Gaspar reported in impressionistic terms what happened when they saw the results:

> With Pierre-Yves Le Traon [also at CLS], quickly, after a few months of measurement, we had maps of the sea level every ten days… When we saw the map, we were amazed. You could immediately see in the northern hemisphere the swelling due to the dilation of the oceans…It was astounding, it was not yet climate, but seasonal variability.[199]

Sabine Arnault, from the IRD, recounted the same experience of fascination with the cartographic maps: "I remember the splendid map made by Bob Cheney for El Niño, with a Kelvin wave."[200]

Contrary to the process of interdisciplinarization observed by Sheila Jasanoff with ecological telemetry satellites, which integrate and incorporate skills from varied fields (ecology, oceanography, climatology)[201] to give meaning to the images, the TOPEX/POSEIDON maps gave form to what was not yet (for the French scientists) a full-fledged specialty. These maps showed physical phenomena that had never before been observed in their global range, and they also sketched out the potential of a field of research. These images were tangible evidence of the work of researchers in the specialty of space oceanography. In a certain way, these maps constituted dual proof of not only the oceanographical processes observed but also the existence of a specialty based on space instruments.

One of concerns of the oceanographers involved in TOPEX/POSEIDON related to measurement precision: the power struggle with the engineers had highlighted divergent cultures. The first report in 1994 showed performance much higher than expected: "the results indicate that the root-sum-square accuracy of a single-pass sea level measurement is 4.7 cm, more than a factor two better than the requirement of 13.7 cm."[202] The negotiations between

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[199] Interview with Philippe Gaspar, 25 April 2014

[200] Interview with Sabine Arnault, 7 May 2014.

[201] Sheila Jasanoff, "Heaven and Earth : The Politics of Environmental Images." In *Earthly Politics. Local and Global in Environmental Governance*, ed. Sheila Jasanoff, Marybeth Long Martello (Cambridge : The MIT Press, 2004): 44.

[202] Lee-Lueng Fu, Edward Christensen, Charles Yamarone Jr, Michel Lefebvre, Yves Ménard, Michel Dorrer, Philippe Escudier, *TOPEX/POSEIDON Mission Overview*, Jet Propulsion Laboratory, 1994 : 2 See also for a complete view on the precision of the data : Lee-Lueng Fu, Edward Christensen, Charles A. Yamarone Jr., Michel Lefebvre, Yves Ménard, Michel Dorrer, Philippe Escudier, "TOPEX/POSEIDON mission overview," *Journal of Geophysical Research*. 99, no C12(1994) : 24369-24381

the precision desired (by the scientists) and that finally obtained (by the engineers) was thus resolved in the best way possible, with much more precise and reliable measurements than what had been promised by the technical teams.

Tracing the itineraries of the results as they were published in specialized journals allows us to glimpse the progressive setting of the boundaries of a specialty. Space oceanography, as made possible by TOPEX/POSEIDON, centered on climate issues. However, the journals in which the first results were published clearly indicate the epistemological positions of the oceanographical community. It was in the *Journal of Geophysical Research* that 49 articles describing the results of the TOPEX/POSEIDON mission were published in a special issue in 1999. The *Journal of Geophysical Research* is rare in that is accepts very large thematic sections. For example, in 1989, a special issue of the journal was devoted to *The Airborne Antarctic Ozone Experiment (AAOE)*, allowing a thorough evaluation of the study[203]. More generally, the *Journal of Geophysical Research* publishes a large number of papers on the space sciences. As early as 1957, the journal published the first results on the distribution of ozone in the atmosphere [204]. It is a journal of reference for those who publish on space subjects, as I have shown with Emmanuel Davoust about French astrophysicists [205].

This general geophysics journal served as a privileged space for the community of space oceanographers.[206] “There was no problem publishing in the oceanography journals,” recalled Sabine Arnault. “There were, as always, several [possible] journals, and we would target one or the other.”[207] Thus, space oceanography as a specialty was structured through a generalist geophysics journal. Of course, there was no journal dedicated to space oceanography, but the choice of the *Journal of Geophysical Research* reflects a double movement: a certain form of relative autonomy vis-à-vis oceanography and second, a significant rapprochement with the space sciences.

Robert Cheney’s team at NOAA in 1994 reviewed the first TOPEX/POSEIDON measurements and pointed out the extraordinary precision obtained for a global view of sea level variations over seasonal and inter-seasonal scales of time.[208] The data compared with seventeen maregraphic stations in the tropical Pacific showed a satellite precision to 2 cm over a surface of several hundred square kilometers. The quality of the orbital measurements was so excellent that the stage of data correction could be skipped. These first results in 1994 were soon followed the year after by a succession of studies on the increase in global sea level.

R. Steven Nerem was at that time a geophysicist at NASA’s Goddard Space Flight Center at Greenbelt. He published a first article with E.J. Schrama, C.J. Koblinski and B.D. Beckley in the *Journal of Geophysical Research* on a “preliminary evolution of ocean topography from the TOPEX/POSEIDON mission.” The researchers concluded that the first measurements obtained were of excellent quality:

> The results suggest that the time-variable component of the error in the T/P altimeter measurements is 4cm (1σ) or better after improving the ocean tide model. This far better than the mission goal and is a significant improvement over previous missions.

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[203] *Journal of Geophysical Research. Athmospheres* 94(D9) (1989).

[204] S.F. Singer, R.C. Wentworth, “A methode for the determination of the vertical ozone distribution from a satellite” *Journal of Geophysical Research* 62,2 (1957) : 2099-308.

[205] Jérôme Lamy, Emmanuel Davoust, “Are Space Studies a Scientific Discipline in its own right ?” *Journal of Astronomical History and Heritage* 19,2 (2016): 200.

[206] Interview with Sabine Arnault, 7th may 2014.

[207] Ibid.

[208] Robert Cheney, Laury Miller, Russell Agreen, Nancy Dole, John Lillibridge, “TOPEX/POSEIDON : the 2-cm solutionn,”*Journal of Geophysical Research*. 99, C12 (1994) : 24555-24563

Nerem and his colleagues ended their article on a very optimistic note: "The preliminary evaluation presented here is only the beginning of a new era in satellite oceanography."[209]

A short time later, in May 1995, Nerem alone published an article in the prestigious journal *Science* titled, "Global Mean Sea Level Variations from TOPEX/POSEIDON Altimeter Data."[210] Geophysicist Nerem stated first that the "Satellites' altimeter measurements combined with a precisely known spacecraft orbit should provide improved measurements of global sea level change over shorter periods…" The principal difficulty previously lay in exactly determining the satellite's altitude, the "wet troposphere delay correction," as well as maintaining optimal calibration of the radar over the long term.[211] Nerem argued that for TOPEX/POSEIDON, these errors were now "greatly reduced."[212] In particular, he noted that the stability of the altimeter calibration guaranteed reliable results. He thus calculated the increase in the sea level: "+ 3.9± 0.8 mm/year during1993 to 1994."[213] Nerem's conclusion in the article in *Science* was also very speculative – at that specific moment of the experiment – since he admitted that we needed "considerably more altimeter data …before the global warming signal can be separated from the short-term sea level variation...Nevertheless, T/P demonstrates the precision necessary to detect variations in global mean sea level caused by changes in the Earth's climate.[214]

Nerem seemed to anticipate the general conclusion of the study done thanks to TOPEX/POSEIDON but recognized at the same time that the current state of the data collected (over too short a period) did not allow definitive conclusions.

In issue 100 of the *Journal of Geophysical Research* in December 1995, Nerem published, alone again, more detailed results on the rise in sea level. Nerem conducted "a detailed analysis of mean sea level variations determined with the T/P data…" while taking into account the "effects of the different measurement corrections on mean sea level..."[215] He did so by building a "database of collinear altimeter passes for the T/P 1-s data" by "coregistering each 10-day repeat cycle to a single reference ground track."[216] Nerem performed three series of corrections on the altimetry data: "the Inverted Barometer Correction,"[217] the "Ionosphere Correction,"[218] as well as the "Wet/Dry Troposphere Correction."[219] He also took into account the "effects of radio orbit errors"[220] and of the calibration of the altimeter.[221] His concluded that based on two years of altimetric data from TOPEX/POSEIDON, the estimated increase in global sea level was 5.8 mm/year with a dispersion of 0.7 mm/year.[222] What seems astonishing is that Nerem provided a result significantly different from the one published a few months earlier in *Science,* and he did not

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[209] R.S. Nerem, E.J. Schrama, C.J. Koblinsky, B.D. Beckley, "A preliminary evaluation of ocean topography from the TOPEX/POSEIDON mission," *Journal of Geophysical Research*, 99 ; C12 (1994) : 24582.
[210] Robert Steven Nerem "Global Mean Sea Level Variations from TOPEX/POSEIDON Altimeter Data," *Science*. 268, (1995) : 708.
[211] Ibid., 708.
[212] Ibid., 708.
[213] Ibid., 709.
[214] Ibid., 709.
[215] R.S. Nerem, "Measuring global mean sea level variations using TOPEX/POSEIDON altimeter data."*Journal of Geophysical Research* 100, C12 (1995) : 25136.
[216] Ibid., 25137.
[217] Ibid., 25139
[218] Ibid., 25141.
[219] Ibid., 25142.
[220] Ibid., 25143.
[221] Ibid., 25145-25146.
[222] Ibid., 25149.

explain the reasons that led him to revise his conclusions. Moreover, he did not even cite his own previous article.

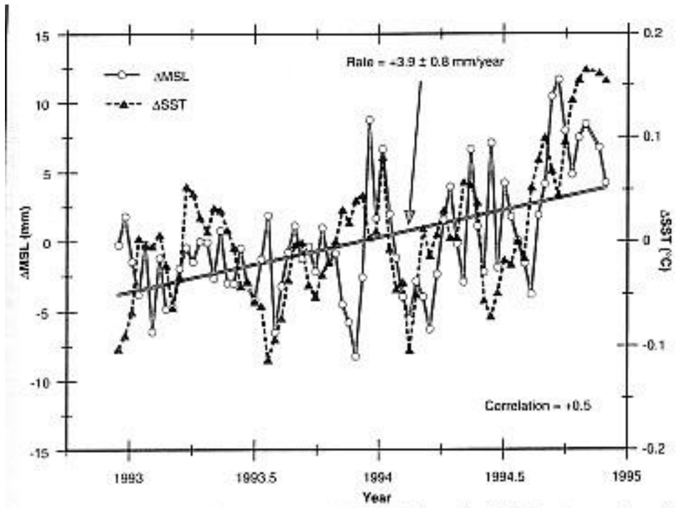

Fig. 1. Global mean sea level variations computed for each 10-day cycle of T/P altimetry covering cycles 9 through 81 (11 December 1992 to 5 December 1994), except for cycle 79, which was unavailable as of this writing. Also shown are global mean SST anomalies covering the same time period, derived from the weekly 1° by 1° SST fields of the National Meteorological Center (33, 34).

Figure 3: Increase in Sea Level Measured by TOPEX/POSEIDON (Robert Steven Nerem, "Global Mean Sea Level Variations from TOPEX/POSEIDON Altimeter Data", *Science*, vol. 268, May 5, 1995, p. 709)

The idea that the global increase in sea level may indicate climate change was not new. It had been suggested at the beginning of the 1980s by two climatologists from the National Oceanic and Atmospheric Administration (NOAA), Robert Etkins and Edward S. Epstein. In an article in the journal *Science* published in January 1982, they argued that it was now necessary to obtain comparative data on the sea level, the ocean surface temperatures, and polar ice so that a "consistent picture emerge."[223] Existing oceanographical satellites were thus seen as instruments making it possible to document (and to prove) the rise of the oceans, signs of a warming global climate. Climate models – whose epistemological importance in the field of climatology Paul N. Edwards had already highlighted[224]– were already widely used during the 1990s.[225] They enabled scientists to predict a global rise of temperatures from 1 to 4° C, which would lead to a general increase in sea level of 30 to 50 cm.

At the same time as Nerem's successive (and divergent) findings, other members of TOPEX/POSEIDON teams also sought to estimate the increase in sea level. Thus, a group from the GRGS (Jean-François Minster, Claude Brossier, and Philippe Rogel) published an

[223] Robert Etkins, Eward S. Epstein, "The Rise of Global Mean Sea Level as an Introduction of Climate Change," *Science.* 214 (1982):287.
[224] Paul N. Edwards, "Global climate science, uncertainty and politics : Data-laden models, model-filtered data," *Science as Culture.* 8, 4 (1999) : 437-472.
[225] James Rodger Fleming, *Historical Perspectives on Climate Change* (Oxford : Oxford University Press, 1998): 118-128 ; Hélène Guillemot, "Les modèles numériques du climat," in *Les modèles du futur. Changement climatique et scénarios économiques : enjeux scientifiques et politiques* ed. Amy DahanAlmedico (Paris : La Découverte, 2007): 95-97.

article on the “variation of the mean sea level from TOPEX/POSEIDON data”[226] in the same issue of the *Journal of Geophysical Research* as Nerem at the end of 1995. The data were compiled for the period from October 1992 to February 1995. The corrections applied took into account regional atmospheric pressure (in particular, the tropical areas were de-correlated from the others because they are so specific) and geophysical corrections (for the Earth's gravity field). The final result was announced quite cautiously. The authors found that the variations in mean sea level “can be essentially described by a drift of 4.1± 1mm/yr, annual variations of 2.7 mm amplitude, and fluctuation of 3.5 mm rms”[227]—yet another figure for sea level. All these interpretations converged in the direction of an increase in the sea level, but the differences between the results were still considerable. Nerem, by giving two very different figures and by arguing that global warming was the main cause in the rise of the sea level, seemed to want to get out ahead of all the teams working on TOPEX/POSEIDON data.

The quality of the conclusions depends largely on the corpus of data available. Nerem continued to update his results: in 1997, he announced two findings. In *Geophysical Research Letters*, in June, he coauthored an article (in particular with Jean-François Minster from the GRGS) where the value (after corrections) of the increase in the sea level was estimated at +2.1 ±1.2 mm per year.[228] In *Surveys in Geophysics* in May, he co-authored another article announcing that the increase in the sea level was + 2.8 mm per year.[229] From this point on, the conclusions became less speculative and the stress was put on waiting for a more substantial amount of data:

> However, because the T/P sea level rise estimates span only 4 years, the influence of interannual and decadal mean sea level variations cannot be ascertained, and thus the underlying change in mean sea level due to long-term climate change cannot be isolated.[230]

It was finally in 1998 that a team from GRGS (Anny Cazenave, K. Dominh, M.C. Gennero, B. Ferret) managed to summarize four and half years of data (from January 1993 to July 1997) to obtain a stable result that was substantially lower than that advanced by Nerem three years previously. They estimated the increase in sea level (for data collected between January 1993 and July 1997) at 1.40 ±0.2 mm per year. Nerem’s findings were analyzed in detail and severely criticized: he had not sufficiently corrected for electromagnetic bias: “This stresses the need for a careful control of all sources or errors affecting mean sea level estimates before these are used for climate studies.”[231] The authors concluded with the need for adjusting climate models and satellite altimetric data:

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226 Jean-François Minster, Claude Brossier, Philippe Rogel, “Variation of the mean sea level from TOPEX/POSEIDON data,” *Journal of Geophysical Research*, 100,C12 (1995) : 25153.
227 Ibid., 25161.
228 R. S. Nerem, B.J. Haines, J. Hendricks, J.-F. Minster, G.T. Mitchum, W.B. White, “Improved determination of global mean sea level variations using TOPEX/POSEIDON altimeter data,” *Geophysical Research Letters*, 24, 11 (1997): 1331-1334.
229 R.S. Nerem, K.E. Rachlin, B.D. Beckely, “Characterization of global mean sea level variations observed by TOPEX/POSEIDON using empirical orthogonal functions,” *Surveys in Geophysics* 18, no 2, 1997: 293-302.
230 R. S. Nerem, B.J. Haines, J. Hendricks, J.-F. Minster, G.T. Mitchum, W.B. White, “Improved determination of global mean sea level variations using TOPEX/POSEIDON altimeter data,” *Geophysical Research Letters*, 24, no 11, 1997: 1334
231 Anny Cazenave, K. Dominh, M.C. Gennero, B. Ferret, “Global Mean Sea Level Changes Observed by Topex-Poseidon and ERS-1.”*Physical and Chemistry of the Earth.* 23, 9-10 (1998) : 1071.

> Satellite altimetry will then provide important constraints on global climate models through the determination of absolute sea level changes, hence allowing an estimate of the 'true' volume and mass change of the oceans at interannual timescales.[232]

Nerem had tried to draw conclusions quickly from the first results from TOPEX/POSEIDON. This precipitation, as well as his haste to attach the increase in sea level to global climate change, explains the succession of differing results he published between 1995 and 1997. The need for long-range data sets and the importance of controlling all error parameters (in particular, the electromagnetic bias that Nerem neglected) finally resulted in the long-awaited findings. The checking by the other members of the TOPEX/POSEIDON project made it possible to constantly question hasty conclusions, and replaced empirical rigor at the heart of the method of space oceanography as a specialty.

Increased instrumental precision and the intensification of climate problems meant that the TOPEX/POSEIDON data were highly valued. The close succession of articles rectifying preceding measurements gave form to a community that, from then on, was polarized into groups around specific data (altimetry), sophisticated corrections (arising from the characteristics of satellites), and a specific methodology for the field. Grounding space oceanography in issues of global warming had results that greatly exceeded the ambitions of the disciplines working on TOPEX/POSEIDON. Jacques Merle, an oceanographer at IRD, recognized that "certain environmental science disciplines, which [previously] had little in common, came together through climatology."[233] His colleague at IFREMER, Bruno Voituriez, confirmed this opportunity: "With the climate, we oceanographers had an extraordinary opportunity because the discipline opened up. We really experienced a revolution in oceanography that was globalized thanks to the climate."[234]

When Cecile Cabanes, Anny Cazenave, and Christian Provost (of the Laboratoire d'études en géophysique et océanographie spatiale in Toulouse, France) drew up an assessment, in 2000, of the forty previous years of measurements of increase in the sea level, they stressed the importance of TOPEX/POSEIDON measurements in the ensemble of procedures for collecting data *in situ* and in space. Above all, these researchers stressed that the data they synthesized concurred perfectly with "sea level rise and estimate of climate-related contributions (on the order of 0.7 mm/year) as reported in the third IPCC assessment report… "[235] This broad view on the mean rise in sea level, as a reliable marker of global warming, constitutes the most remarkable result of TOPEX/POSEIDON. Above all, it signaled the clear and greater involvement of certain French researchers in the new community of space oceanographers. For example, after a doctorate in geophysics in 1975, Anny Cazenave shifted towards geodesy. Working in a small group around Michel Lefebvre in the 1980s and following the work of TOPEX/POSEIDON, she chose to change disciplines. As Sabine Arnault noted, the community of French space oceanographers was created around CNES engineers working on the ocean and some physicists interested in the subject, and then "was grafted onto another community, that of geodesists such as Anny Cazenave. The

[232] Ibid., 1074.
[233] Interview with Jacques Merle, 30th april 2014.
[234] Interview with Bruno Voituriez, 28th april 2014.
[235] Cécile Cabanes, Anny Cazenave, Christian Le Provost, "Sea Level Rise During Past 40 Years Determined from Satellite and In Situ Observations,"*Science* .294 (2001): 841. See J.A. Church, J.M. Gregory, "Changes in Sea Level, " in*Climate Change 2001 : The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* ed. J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, C.A. Johnson (Cambridge : Cambridge University Press, 2001): 639-693.

community of pure oceanographers and geodesists was less present than this community of ocean topographers."[236]

The El Niño phenomenon was the subject of later publications:[237] Nerem and several of his colleagues at the University of Texas A&M, the University of Texas at Austin and the University of South Florida published, in *Geophysical Research Letters* in 1999, an article on the "variations in global mean sea level associated with the 1997-1998 ENSO event."[238] By this work synthesizing the data, the American researchers operated a kind of epistemological reductionism that placed space oceanography at the crossroads of questions on seasonal variations and the climate warming.

In the end, TOPEX/POSEIDON functioned for eleven years. The data produced over this period,

> has contributed significantly to many topics of oceanography and geodesy….The extended mission has continued this excellent record in global mean sea level determination. Detection of climate signals requires multiple-decade records…, and T[OPEX]/P[OSEIDON] has greatly exceeded its design lifetime.[239]

The technological sophistication, along with the JASON mission that followed, allowed the research begun with TOPEX/POSEIDON to continue. But it was the shift to climate issues in this Franco-American mission that largely justified the use of that technology.

An issue of the journal *Deep-Sea Research II* from 2012 was entirely devoted to satellite oceanography and climatic change. Satellites are presented as "essential tools in the present monitoring of climate change…" Measuring the surface temperature of the oceans is regarded as "a key component in the analyses of global warming and its effects."[240] Since TOPEX/POSEIDON, satellites, an obvious instrument for a community of researchers examining the properties of the ocean, [241] have also become essential elements in understanding climate change. As we have seen, inscribing the mission in this issue of climate change, which turned out to be particularly rewarding, was not at all a given at the beginning. From the emergence of space oceanography in the United States in the 1960s to the consecration of satellites as a privileged tool for obtaining a global perspective on the state of the seas, the changes in the specialty were technical and political. However, they did not occur at the same level: it was precisely because these various levels were separated into a hierarchy of possibilities for scientists that TOPEX/POSEIDON reveals the Archimedean points of a specialty under construction.

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236 Interview with Sabine Arnault, 7th may 2014.

237 In particular, V.M Tiwari, C. Cabanes, C., K. DoMinh, A. Cazenave, "Correlation of interannual sea level variations in the Indian Ocean from Topex/Poseidon altimetry, temperature data and tide gauges with ENSO."*Global and Planetary Change* 43 (2004): 183-196. Certain researchers even tried models to predict El Nino from TOPEX/POSEIDON data : Ming Ji, Richard Reynolds, David W. Behringer, "Use of TOPEX/Poseidon Sea Level Data for Ocean Analyses and ENSO Prediction : Some Early Results."*Journal of Climate*.13, no1(2000) : 216-231.

238 Robert Steve Nerem, D.P. Chambers, Eric W. Leuliette, Gary T. Mitchum, B.S. Giese, "Variations in global mean sea level associated with the 1997-1998 ENSO event : Implications for measuring long term sea level change."*Geophysical Research Letters.*26, no19 (1999) : 3005-3008

239 Eric W. Leuliette, Robert Steven Nerem, Gary T. Mitchum, "Calibration of TOPEX/Poseidon and Jason Altimeter Data to Construct a Continuous Record of Mean Sea Level Change," *Marine Geodesy.* 27 (2004): 80.

240 Carlos Garcia-Soto, Jorge Vazquez-Cuervo, Pablo Clemente-Colón, Fabrice Hernandez, "Satellite oceanography and climate change," *Deep Sea Research Part II : Topical Studies in Océanographie* 77-80, (2012) :1-9..

241 See : Ola M. Johannessen, Stein Sandven, Alastair D. Jenkins, Dominique Durand, Lasse H. Pettersson, Heidi i Espedal, Heidi, Geir Evensen, Torill Hamre, "Satellite earth observation in operational oceanography,"*Coastal Engineering* 31(2000): 155-176

Emergence of a Specialty

The specialty of space oceanography emerged thanks to TOPEX / POSEIDON, particularly in France. However, the ways in which this specialty was constructed little by little were very different from traditional trajectories, such as those examined by John Law and Terry Shinn with instrumental plasticity and flexibility. In the case of space oceanography, the resource instrument (*i.e.* equipment placed on the satellite) is conceived of, designed, and operated mainly by physicists. It is not unknown by classical oceanographers, far from it. In fact, the space instrument is one of a very wide range of equipment and instrumental resources that can be used for the same research subject. As a result, conventional oceanographers continue to participate in data collection campaigns by boat, to take tide gauge measurements, and to collect satellite information.

The case of TOPEX / POSEIDON has made it possible to highlight the effects of major data on global warming: being able to precisely identify the increase in sea level. This information increased the visibility of space oceanography and its scientific legitimacy. TOPEX / POSEIDON's contribution to research on climate change helped to identify space oceanography as an epistemic resource that, while perhaps not fully stabilized, was at least available to researchers.

If we want to compare the oceanography specialty to Terry Shinn's model of science regimes, [242] we find that we have an instrument that does not have all the characteristics of a generic instrument (it is not modifiable after its launch), it assumes a certain flexibility of the researchers using it (since they also use other instrumental resources), and it organizes a relatively distinct epistemic space. The formation of space oceanography as a specialty was an original socio-epistemic process, which cannot be reduced to classical disciplinary frameworks or to the focus on instrumentation as is often studied. Here, the introduction of a new specialty was made possible by achieving major scientific results, by continuing an instrument program largely created by physicists, as well as by long-term international cooperation.

Compared with David Edge and Michael Mulkay's work on radio astronomy, spatial oceanography again stands out. Radio astronomy had gradually become separate from radiophysics and an independent specialty, with its own objects of research and its own methods. Radio astronomers then begin to train students and publish in astronomy journals. At the end of the 1940s, the break between physics and radioastronomy was clear, while the former had been the origin of the latter. [243]

Spatial oceanography, therefore, constitutes a unique case of scientific specialization. Based on instruments designed by physicists, the specialty offers a wide range of data that are compatible and complementary with other types of data from other instruments.

Translated from the French by Cynthia J. Johnson

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[242] Terry Shinn, Resarch Technology and Cultural Change. Instrumentation, Genericity, Transversality (Oxford, The Bardwell Press, 2008) : 171-182

[243] David O. Edge, Michael J. Mulkay, *Astronomy transformed. The Emergence of Radio Astronomy in Britain* (New York : John Wiley & Son, 1976): 383.