Weather Satellites: Public, Private and Data Sharing. The Case of Radio Occultation Data

Gemma Cirac-Claveras

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Author: Gemma CIRAC-CLAVERAS

Affiliation: Postdoctoral fellow at Laboratoire Techniques Territoires Sociétés (LATTS), University Paris-Est

E-mail address: gemma.cirac@gmail.com

Full postal address: 14/20 Boulevard Newton – Plot C, 2e étage, Cité Descartes, Champs-sur-Marne, 77447 Marne-la-Vallée cédex 2

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Referee suggestions:

Samuel Randalls	Isabelle Sourbès-Verger
Department of Geography - University College London	Centre Alexandre Koyré - CNRS
Gower Street London, WC1E 6BT	27 rue Damesme 75013 Paris
s.randalls@ucl.ac.uk	isabelle.sourbes@cnrs.fr
+44 (0)20 7679 7575	+33 (0)1 40 78 26 32

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Keywords

Weather satellites, GNSS radio occultation data, data sharing, commercialisation, weather forecasting

Abstract

This article examines the contested process through which satellite weather data collection is being transformed from a governmental mission to one increasingly carried out by the private sector. As illustration of this controversial transformation, it addresses the debates raised in the US between some members of the National Oceanic and Atmospheric Administration, the Congress, private firms, academic meteorology and international observers between 2006 and 2017 regarding the commercialisation of data obtained from radio occultations using the Global Navigation Satellite System (GNSS-RO). It looks, in particular, at the arguments, discourses, viewpoints and perspectives of these involved actors. By focusing on one particular site of controversy –policies and practices of data distribution-, this case study emphasises a clash of values between conventional norms of meteorology and commercial imperatives driving the private sector with respects to data sharing. The main interest of this article pertains to the broader issue of changing the current model for data gathering, using and sharing in the face of growing commercialisation of weather satellites.

1. Introduction

On April 18, 2017, president Trump signed the Weather Research and Forecasting Innovation Act [101]. This Act requires the National Oceanic and Atmospheric Administration (NOAA, the federal organisation in charge of weather forecasting in the US) to consider commercial satellite weather data as a supplement, even as an alternative, to NOAA's satellite systems for acquiring weather data. In particular, it directs NOAA to begin operational data buys of data obtained from radio occultations using the Global Navigation Satellite System (hereafter GNSS-RO).

This Act –and the process leading to its signature- has been very controversial. It reflects changes in the framework for the production of some types of meteorological satellite data, beginning with GNSS-RO data: from government run space missions to commercial sourcing, which is likely, I will argue, to have consequences for gathering, sharing and using the data. Hailed by industry executives and many members of Congress as paradigm breaking, it has been criticised by some NOAA's officers, academic meteorologists and international observers as contrary to the scientific values and attitudes embedded in weather science –specifically with regard to data sharing, which is the focus of this article. Therefore, the case of GNSS-RO satellites system exemplifies a fundamental clash of values that shapes contemporary meteorology data policies -and more generally all scientific policy: between government ownership of systems and infrastructures (involving wide dissemination of data) or privatised data gathering (involving commercial data distribution).

By following, in particular, the fate of GNSS-RO data in the US between 2006 and 2017, this article discusses the fascinating, disturbing, complex and contested developments that are transforming satellite weather data collection from a governmental mission to one increasingly carried out by the private sector. It focuses on the debates and conflicts raised between some NOAA's executives, members of Congress, representatives of the main involved firms, academic scientists and forecasters. It focuses, specifically, on the discourses, strategies, perceptions, arguments, and viewpoints defended and spelled out by the involved actors. This case study provides a window onto important changes in the shape and dynamics of weather data collection, dissemination and consumption. It points to a particular consequence of the commercialisation of GNSS-RO data or the privatisation of public resources: changes in data sharing policies and practices. Therefore, the main interest of this article pertains to the broader issue of changing the current model for data gathering, using and sharing in the face of growing commercialisation of weather satellites –beginning with GNSS-RO satellites.

The first section (2) provides an historical contextualisation of commercial meteorology and debates about public and private systems of weather data collection. The second section (3) briefly introduces the GNSS-RO data source, it justifies its potential in improving weather forecasts, and presents current and future governmental missions to acquire it. The third section (4.1) elaborates on the claims-making activities, discourses and strategies of the promoters of a private commercial sector for GNSS-RO data, including pressures to pass legislation, which is discussed in the following section (4.2). The paper then turns to the tensions raised within NOAA, by addressing in particular one of the main sites of contestation: the policies of data redistribution. Within it, the paper first focus on the principles and practices of data sharing at NOAA (5.1) and then spotlights the limitations of one of the international arrangements aimed to facilitate the free flow of data, the Resolution 40 of the World Meteorological Organisation (5.2). In the conclusions (6), this article emphasises the clash between conventional norms of meteorology and the commercial imperatives driving the private sector with respects to data sharing. The article ends with updates on recent events occurred after Trump's signature of the Act.

This study draws to a large extent upon 22 carefully designed interviews carried out with members of NOAA (at the departments National Weather Service and NESDIS), of private companies (GeoOptics, PlanetIQ, Spire, GeoMetWatch and TempusGlobalData), university-based meteorologists, members of the University Corporation for Atmospheric Research (UCAR) and the American Meteorological Society, representatives of international weather organisations (EUMETSAT, WMO) and experts in space policy, conducted between January and June 2016. I am aware of the pitfalls oral histories can imply as reliable sources, yet experience has also proven the great value these recordings may have not only for this study but also for future historical research [22, 23, 25]. Additionally, oral sources have been combined, confronted and contrasted with archival material (at NOAA, NASA, US Congress, and WMO libraries), primary scientific literature, grey literature (official reports, commercial presentations, congress hearings transcripts, scientific papers, legislation, etc.), websites, as well as archives of different media outlets. All published sources are properly referenced following academic standards. However, oral sources will remain under anonymity in order to respect the will of some of the interviewees.

2. Early commercial weather

Over the decades space activities in the US have evolved from an almost exclusively governmental function to one increasingly carried out by private industry. As the critical industrial means for commercial space activities became available, a number of firms have progressively created markets in the domains of communications, launch vehicles, high resolution imagery, or materials processing in microgravity. In turn, legislation such as the Communications Satellite Act of 1962, the Land Remote-Sensing Commercialisation Act of 1984 or the Launch Services Purchase Act of 1990, to mention few, reinforced the commercialisation of these (and other) sectors [24]. In 1988, the Reagan administration issued a presidential directive which, for the first time, rendered commercial opportunities in space a major component of US space policy. Since then, all administrations have encouraged private-sector involvement in space. The weather sector was just another sector of potential commercialization.[1]

Undoubtedly, the economic value of weather –and of information about weather- has long been recognized and exploited [37]. Since the late 19th Century, the private sector has succeeded in progressively entering several areas of the meteorological profession, including manufacturing of weather instrumentation, studies of weather modification, forensic meteorology, risk management, media meteorologists, or weather data collection, to mention but a few [11, 12, 19, 78, 79].

One of the first areas in developing commercial weather was the provision of weather-related information, such as specialized forecasting services and consultancies for weather-sensible clients (industries of oil, power, agriculture, fisheries, Hollywood studios, leisure, etc.). During the 1930s and 1940s, a few private enterprises formed to make use of their own techniques, systems and analysis to provide a set of products that were valued by and paid for such clients. Then the US Weather Bureau (predecessor of NOAA's National Weather Service) developed several services in direct competition with the private sector that was emerging. This competition prompted moves towards separating public and commercial interests, with the former served by the Weather Bureau and the later by private sector companies [51]. As a ways to encourage the development of the private sector of meteorology forecasting –and this is of particular interest to our story-, in the 1950s, the Secretary of Commerce (the Administration responsible of the Weather Bureau since 1940) made government-collected data available to all at the only cost of reproduction and distribution. At the international stage, the World Meteorological Organization, a United Nations agency, also was very active in promoting the economic value of weather information, especially since the 1960s [37]. The next years saw rapid growth of commercial weather forecasting companies in the US, including the foundation of AccuWeather established by Joel Myers in 1962 –his brother Barry, who became CEO of the company in 2007 after having been part of its executive management since shortly after its founding, has been recently nominated as NOAA's administrator by Trump's administration. This growth, again, prompted

[1] The term "commercialisation" itself is unstable and contested. It has different meanings for different actors in different nations, academic disciplines and epochs. Moreover, other terms can be found to convey similar meanings, such as "privatization", "capitalization" or "commodification". The extent to which such concepts may be (or not) the most adequate to classify the process discussed in this paper is not a question that I attempt to resolve here. Instead, I shall employ all these concepts (mostly commercialisation and privatisation) as synonyms in a broad, flexible and practical manner understood as the process of transforming a good previously produced by government into one commodity produced by the private sector.

disputes and debates between private and Weather Bureau's meteorologists (renamed the National Weather Service in 1970, and placed within the newly created NOAA) about the extent of public-private cooperation, illustrating the fragility of the public-private relationship [78]. Since then, several regulatory frameworks have been established to separate areas of public and commercial interest, such as the National Weather Service and Related Agencies Authorization Act of 1999, which aimed to prevent competition between the government and private weather services following the general theme that the government should not be providing any meteorological services that the private sector can provide. Today, the increasing economic value of weather services, which has grown in step with improvements in forecast accuracy and timeliness, in computer, communication and visualisation technologies, and with the rise of a general concern in disruptive weather conditions, continues to strain such fragile public-private partnership in weather services provision. An example of such fragility is the attempt to pass the National Weather Service Duties Act of 2005, publicly supported by Barry Myers, which required the National Weather Service to stop providing weather information of general interest.

It shall be noted that this relationship between the public and the private sector in meteorology is particular to the US. Unlike the US, where the commercialisation of weather information was exclusively reserved to the private sector, in the late 1970s some European public national weather services began developing specialised products to provide targeted commercial information in the domains of agricultural risk assessment, air quality, transportation, construction, utilities and retail. In their need to recover costs of production and maintain infrastructures of data gathering, and taking advantage of the growing economic value of weather information, they committed to the commercial route and began charging fees for some of the weather data and information they produced [102].

Back to the US, remarkably, while weather forecasting, consultancy and analysis has a long, mature and thriving commercial sector, until now, the business of collecting data with satellites has been mainly owned and operated by governments or public organisations. In particular, satellite data collection for numerical weather modelling has previously been the exclusive purview of government agencies, such as NASA, NOAA or the Department of Defense.

In the early 1980s, there was one attempt to privatise the US weather satellite system. Shortly after president Reagan entered office, eager to reduce the federal budget and to transfer as many government functions as possible to the private sector, it was announced that the administration would promote the transfer of the satellite land remote-sensing system (Landsat) from the government to private ownership – the Carter administration had already initiated the examination of this question. The Department of Commerce (responsible of Landsat through NOAA) proceeded with a request for proposals from private industry. There were a variety of modes in which the private sector proposed to participate, from commercializing some parts of the satellite system (e.g. value-added services, data processing and distribution, spacecraft tracking, data acquisition, etc.) to all system ownership and operation. The most ambitious proposal came in 1981 from the private firm COMSAT to take on full responsibility of the Landsat system but only if the meteorological satellites were simultaneously transferred as well. COMSAT argued that the profits from selling weather data back to the government could be used to finance the long-term commercial development of land remote-sensing. In response to such inquiry, the administration then elected to widen the discussion of commercialisation to include the civil weather satellites as well [49].

A number of objections were raised, particularly to the suggestion of selling off weather satellites [38, 30, 73, 74, 105]. One debate particularly relevant to this paper revolved around the proprietary rights over the data collected. Such rights entailed that COMSAT charged fees for accessing and using the data. Back in the early 1980s, there were a number of reasons to oppose this idea. On the one hand, weather satellites were considered as an inherently governmental system, insofar as over 95% of the market for the data from weather satellites was the US government through agencies such as the National Weather Service of NOAA, the Air Force and the Navy, the Departments of Agriculture and Interior, the Corps of Engineers, or the Federal Aviation Administration. In particular, to be commercially viable, the COMSAT proposal required federal data purchases at an annual level of about $315–330 million per year. For the government to meet this amount, there would have to be either a substantial increase in the cost of weather data (unacceptable to federal agencies using the data) or there will be substantial direct subsidy payments to COMSAT [34]. Both solutions involved a form of governmental subsidy, which not only would inhibit the free market process and jeopardize the cost efficiency and reliability of data gathered with the satellites, but that also seemed antithetical to the underlying economic philosophy of the US [34]. Moreover, the US endorsed a concept of public, timely, non-discriminatory data dissemination to all. As a matter of fact, the US had championed the free and unrestricted dissemination of weather data throughout the world, through the promotion of bilateral data exchange agreements or of international arrangements for data sharing, especially within the World Meteorological Organisation. A disruption of the free and open distribution of satellite weather data, due to proprietary rights restrictions, could jeopardize the reciprocal international exchange of meteorological data upon which the US was vitally dependent.

In sum, by the early 1980s, members of Congress and main users of satellite weather data (public agencies, universities, private sector and meteorological industry, international partners) considered weather satellite data of most research, forecasting, military, foreign relations, public health and safety, and commercial benefit when widely shared [73, 74, 82] – as it will be demonstrated, today, American legislators seem to have drawn away from this argument. The Land Remote Sensing Commercialisation Act of 1984 was passed, which included a specific prohibition against the sale of any part of the meteorological satellite system to private industry, thereby reaffirming that it would remain in the public sector and that the data would be collected, archived and disseminated by public agencies freely and free of charge to users on an open and non-discriminatory basis [42] –and, in particular, this has been reaffirmed as the linchpin of satellite weather data policies at NOAA. However, as it will be further discussed, the issue of charging users for weather satellite data arose again in the 1990s as a result of cooperative agreements with other countries, especially in Europe, that took such an approach.

These debates very often cited the public argument and considered satellite weather data as pertaining to the sphere of public goods [73, 74, 82]. The extent to which satellite weather data may be (or not) considered as public good is a complex question that I do not attempt to resolve in this paper. Besides, one thing is the economic concept of public good as non-excludable and non-rivalrous, and another thing the more generalized perceived idea of the public good, something that is useful for the public generally

[36, 1]. Beyond these considerations, legislation directing NOAA to purchase GNSS-RO satellite data for weather forecasting from commercial satellite operators signals an era in which these data, and eventually perhaps, also other types of weather satellite data not only are being considered as a commodity to be bought and sold, but are also produced with private means. This article argues that this transition reflects a change in the values embedding meteorological practice.

3. GNSS-RO data and meteorology

GPS-RO data became a promising satellite data source for weather and climate research and forecasting only very recently, since the launching of the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) mission by NASA in 2006, in collaboration with Taiwan [97]. COSMIC consisted of a set of six satellites, each carrying a GPS-receiver, which measured the propagation time of radio signals between a GPS satellite and each of the COSMIC satellites as they rose or set behind the Earth relative to the GPS satellite. As the radio waves pass through the atmosphere, they are refracted and slowed, with the degree of bending reflecting the vertical variation in refractivity, which depends on temperature, pressure, and water vapour in the atmosphere. Using physical models and mathematical calculations, information on such meteorological parameters can be reconstructed from the bending angles [75].

Within a few months, GPS-RO data radically reshaped weather forecasting and research perspectives. In terms of quantity, COSMIC satellites took approximately 2,000 measurements every 24 hours in a nearly uniform distribution around the globe, helping to meet the demand for more global data needed for numerical models [2]. In terms of quality, according to an European Centre for Medium-Range Weather Forecast (ECMWF) study of 2011, for instance, COSMIC data contribute to reduce more than 10% the error of a 24h weather forecasting [13]. Already, data from COSMIC have been used to predict severe weather phenomena more accurately. In 2006, for instance, tropical storm Ernesto formed in the Atlantic Ocean. Traditional weather models failed to predict the storm's formation, but by adding COSMIC data to the model, predictions about the storm's formation were very similar to what was actually observed [2]. Besides improving weather forecasts, this technique has potential to help understanding climate, because measurements do not rely on any specific technology to be interpreted and they allow long-term comparison [3]. At the time of writing, more than 3,700 researchers from 88 countries are registered users of COSMIC data, despite the fact that only 3 satellites are still functioning and coverage has been dramatically reduced [81].

Given the potential of this technique, in 2007 the World Meteorological Organisation recommended continuing such observations operationally [103]. Also in 2007, the committee on Earth science and applications from space of the US National Research Council listed GPS-RO data as one of the high-priority of NOAA’s operational observations and missions [60]. For what matters, other organisations also launched radio occultation receivers for weather forecasting, including Eumetsat, which developed the instrument GRAS aboard Metop A (2006-2019), Metop B (2012-2024) and Metop C (2018-2023) and is currently developing a new version for its next generation of satellites to be launched from 2021 onwards.[2]

COSMIC was a research mission, which largely demonstrated the relevance of the radio occultation technique but did not fully meet the requirements for routinely operational weather forecasting. In conjunction with the atmospheric and climate scientific communities, NOAA designed COSMIC-2 as the operational follow on of COSMIC. As it was designed, COSMIC-2 consisted in two planes of six satellites each receiving radio waves from all existing navigation systems, the American GPS, the European Galileo, the Chinese Beidou and the Russian Glonass –whence the term Global Navigation Satellite System Radio Occultation (GNSS-RO). The receiver would be capable of tracking up to 12,000 profiles per day after the 12 satellites were fully deployed [31].

The first set of six satellites (those flying in equatorial orbit) are in development and scheduled to be launched in 2018, but in October 2017 NOAA decided to cancel the second set (polar orbit) [32]. There are a number of reasons explaining this cancellation. The most obvious one is of financial character. For FY 2017, NOAA requested $16.2 million for COSMIC-2: $8.1 million for the ground system (IT security, data processing, data assimilation, downlink of data from the first 6 satellites, etc.) and $8.1 million for the acquisition of data from polar orbiting satellites either through development of the second set of COSMIC-2 sensors or purchase and integration of commercial data [69] –which is an indicator of its commitment towards commercial data. The Senate Appropriations Committee approved only the $8.1 million for the ground system. The House Appropriations Committee approved the entire $16.2 million, but stipulated that none of the money may be obligated until NOAA assures that it has thoroughly reviewed potential commercial sources of the data [84]. Another reason points to the withdrawal of one of major's partner in COSMIC-2, the US Air Force. NOAA's budgetary request did not include the costs of launch service to place the second set of sensors in the polar orbit, assuming that the Air Force would take charge of that, just like for the first set of satellites in equatorial orbit. Yet, the Air Force finally did not commit to providing launch services -and no other launch provider for the satellites was identified. We are not discussing in this paper the role played by the Air Force or its relationship with NOAA in our GNSS-RO story. Presumably, the potential alternative of acquiring these data commercially underlay its decision –as much as it underlay decisions at the House and Senate. What is pertinent to this paper is that the cancellation of the second set of COSMIC-2 satellites reinforced one of the key arguments promulgated by the private sector camp since the early 2010s, that a potential data gap in weather sounding data was imminent.

4. GNSS-RO data go commercial

4.1. Strategies for commercialisation

[2] Radio occultation payloads are also carried on a number of other satellites, such as Oceansat since 2009 and Megha-Tropiques since 2011 (Indian Space Research Organisation), TanDEM-X since 2010 (German Aerospace Center), KOMPSAT-5 since 2013 (Korea Aerospace Research Institute), or PAZ since 2018 (Hisdesat). These are however missions that not fully meet demands for operational weather forecasting.

The commercialisation of GNSS-RO data has been a gradual process that began after the launching of the COSMIC mission and developed mostly throughout the 2010s. In 2007, under Conrad C. Lautenbacher's administration, NOAA initiated a campaign to identify commercial entities capable of providing the agency with satellite data for numerical weather forecasting [65, 66]. Benefiting from first achievements obtained in the domain of high resolution imagery by Digital Globe and Space Imaging in the 2000s and by the "new space" start-ups such as Skybox Imaging (today Terra Bella) and Planet Labs (today Planet) in the 2010s, the weather sector was identified as a new promising space-related sector for making business.

Within NOAA's campaign, gathering weather data with the technique of GNSS-RO was given top priority [67]. GNSS-RO data were seen as well suited for commercialisation: the technique was perceived as technologically simple and low cost, as the main infrastructure (navigation satellites) had already been deployed and maintained for other purposes. Moreover, the payload necessary to get the measurements was a radio signals receiver, that is, a small digital processor –light, easily embeddable in small spacecraft, and therefore cost affordable. On the other hand, studies have indicated that the benefits for weather forecasting increase with at least 100,000 observations per day -while the publicly funded COSMIC and COSMIC-2 missions "only" provide around 2,000 and 12,000 measurements per day respectively [4]. It therefore appeared that a commercial market could exist for GNSS-RO data.

Between 2007 and 2009, NOAA allocated some preliminary development funds to the companies Iridium and OrbComm (specializing in communications) as well as to GeoOptics (created in 2006 to specifically produce and sell GNSS-RO data) to study how to produce GNSS-RO data for NOAA [61]. In turn, the expected provision of data on an operational basis to NOAA fostered motivation of entrepreneurs and found a favourable relay towards more venture capitalists. Since 2007, at least 7 private companies have envisaged supplying GNSS-RO data for profit: the before-mentioned Iridium, OrbComm and GeoOptics, and also Planet Data, Tempus, PlanetiQ and Spire. After these initial years of intense activity at NOAA, the process of acquiring GNSS-RO data from commercial sources recessed after Conrad Lautenbacher's resignation at the end of 2009.

Debates heated again in 2012 after the election of Congressist Jim Bridenstine, a Republican from Oklahoma, Executive Director of the Tulsa Air and Space Museum & Planetarium with almost a decade active in the US Navy.[3] Since his election, commercial-based satellite weather data prevailed as one of Bridenstine's central political goals. Exemplary of his actions, as member of the Committee on Science, Space, and Technology, the committee with jurisdiction over NOAA at Congress, Bridenstine periodically held hearings that promoted debates on how to efficiently get satellite data for numerical weather prediction, in which commercial vendors were promoted [86, 87, 88, 89, 90, 91].

Bridenstine argued that commercial data constituted a more efficient use of public resources because the purchase of data from commercial satellite vendors could lead to best pricing and generate revenues through tax-paying jobs and data sales [6]. To him, the goal of using commercial sources was not just to reduce costs to the government and generate economic growth, but also to increase the resiliency of

[3] Jim Bridenstine was nominated by President Donald Trump as NASA's Administrator. He was confirmed by the US Senate and took office in April 2018.

weather satellite systems within a defense perspective. As member of the Armed Services Subcommittee on Strategic Forces he expressed concerns about the vulnerability of what he called the "billion-dollar Battlestar Galactica" spacecraft, namely large government-owned satellites [8]. "Our current space architectures are stovepiped, vulnerable, and expensive", he stated before the House Appropriations Subcommittee on Defense, and he argued in favour of "buying data and services, rather buying, owning, and operating custom systems" [8].

As part of his goal of advancing in the process of commercializing weather satellite data collection, Bridenstine allied with Washington representatives of private companies willing to enter the market of GNSS-RO data collection, especially with those of the firms GeoOptics and PlanetIQ. GeoOptics inaugurated the commercial collection of weather data with GNSS-RO data and was established in 2006, the same year as the launch of the COSMIC mission. It was founded by Thomas P. Yunck, an engineer at the Jet Propulsion Laboratory who had been developing methodologies to use GPS signals in geodetic and atmospheric studies since the early 1980s. PlanetIQ was funded six years later, in 2012, by Chris McCormick of Broad Reach Engineering, the company involved in the development of the receivers for the COSMIC mission. In fact, McCormick had been chief executive of GeoOptics until 2011, when he left to create his own business in the data sales market.

Their project was organised around a three-fold strategy, whose core message articulated market efficiency and bureaucratic inefficiency. First, private sector promoters convinced Congress of the value of satellite data (specifically GNSS-RO data) to American society and commercial vitality. In their presentations and Congressional testimonies they made sure to recall the recurrent dramatic weather phenomena like hurricane Katrina in New Orleans in 2005 or deadly tornadoes in Oklahoma and Mississipi in 2013. They highlighted that poor forecasts were associated to poor data [39, 57, 33]. For instance, in a congressional hearing in 2013, PlanetIQ CEO Anne Miglarese warned that "even the most powerful and sophisticated models are only as good as the observational data fed into them. There is no hope of producing an accurate weather forecast for tomorrow, let alone several days from now, without precise and detailed measurements of temperature, pressure, humidity, and other variables around the globe and from the Earth‘s surface to the top of the atmosphere" [52]. The example of superstorm Sandy over New York in 2010, whose trajectory could be predicted using data from European satellites, but not from their US counterparts, was often cited as a warning signal regarding both the importance of satellite data and the crumbling state of the US public weather satellite system [55, 26]. This prompted Congress to hold a hearing entitled "Restoring US Leadership in Weather Forecasting" in 2013, in which Jon Kirchner (President of GeoOptics), Barry Myers (CEO of AccuWeather), William Gail (CEO of Global Weather Corporation) and university professors supported the potential of commercially sourced data to multiply data provision [88].

Second, they depicted NOAA as an institution crippled by bureaucratic inefficiency. They accused the agency of deficient management of its own major weather satellite programs NPOESS and GOES-R, which had been in development since the 1990s and had experienced troubled legacies of schedule delays, cost overruns, missed milestones, technical problems, and removal of several key sensors reducing them in scope from early expectations [39, 52, 53]. As a matter of fact, the NPOESS program was cancelled in 2010, with costs having ballooned from $6.5 billion to $15.1 billion, and no satellites placed in orbit [96]. Such inefficiency, taking private sector representatives' terms, led to a potential "weather data gap", "weather data crisis" and "national crisis" [6, 52, 39] and prompted a series of public hearings and investigations [92, 93, 94, 95]. Bridenstine argued that "the paradigm of owning and operating large monolithic satellites is broken… instead of continuing down the path of large government-owned satellites that are prone to cost overruns and delays, we must look outside the box for new methods of providing essential weather data" [6].

Third, the private companies self-introduced themselves as the solution to the main problems of the American satellite system and NOAA's systemic mismanagement. They insisted that the injection of commercial data and the "genius of American private enterprise" were an alternative to perpetuating the existing potential data gap, schedule delays, and ballooning costs [39]. "In lieu of data infrastructure ownership", testified John Kirchner, President of GeoOptics, in 2013, "the government will foster a vibrant and innovative free market in satellite weather data, a new "weather data economy"" [39]. PlanetIQ's Anne Miglarese, for instance, affirmed that "only a fundamental shift in the procurement model that leverages the technical expertise and nimbleness of the private sector can reverse this troubling trend in the timeframe needed to mitigate this impending gap" [52]. In a position paper called "A better way to weather the satellite gap" published in December 2013 in Space News, she claimed that "merely funding the same billion-dollar satellite programs whose dysfunctional management by NOAA led to the gaps in the first place... fails to fix the fundamental problem—our nation's weather satellites are getting old, and the system for replacing them in a timely and cost-effective manner is broken" [53]. Private sector representatives praised for the need for a new business model for commissioning weather satellite systems and often mentioned the cases of communications and high resolution imagery as successful stories to be emulated in the weather field [20]. For instance, capital markets were to provide the funding for the development of the GeoOptics project, with the intention being that costs and benefits would be spread across all the user communities, national or international, with large clients such as NOAA playing an anchor role [48]. PlanetIQ defended a model similar to that applied in the high resolution imaging sector, which had initially depended on government contracts for development, revenue and cost recovery [55].

One central argument focused on the claimed ability of these companies to produce GNSS-RO data more cheaply than NOAA. At this point there is no basis to permit substantive evaluation because the lack of sound cost estimates renders difficult to assess whether the cost of private GNSS-RO data would be significantly lower than in a government led project -it is not the aim of this article to quantitatively determine if commercialization or privatization of GNSS-RO data is fiscally viable or not anyway. For instance, citing the argument of industrial competition, detailed figures such as costs associated to R&D, launching, maintenance and operations, insurance or indemnification, data processing and other, are not publicly available. Similarly, insufficient details are provided about NOAA's expected contribution in funding these costs: while GeoOptics and PlanetIQ argue that no US industry could possibly enter this field at the present time without some form of temporary government subsidy, details of the specific subsidy they request are not public (direct cash subsidy payments, loans or loan guarantees, guaranteed NOAA purchases of data services, federal users at a unit price higher than charged to other users, provision of free services, such as satellite launches, special tax incentives, R&D on advanced payload, processing software or assimilation algorithms, or other). This kind of secrecy about funding structures relates directly to the issue of data prices: should a firm be allowed to charge whatever it choses for weather data? Should there be a regulated rate structure? These are all very controversial issues still under discussion.

Also central to such narrative was to lobby Congress for terminating governmental missions, especially COSMIC-2, for the termination of such program would reinforce the perception of an imminent data gap, thereby easing the path for commercial options to flourish [52]. For instance, in 2013, Anne Miglarese assured that the private sector could supply GNSS-RO data that NOAA needed for weather prediction services. PlanetIQ also distributed a letter to members of Congress entitled "The Benefits of Public-Private Partnership in Weather and Environmental Data Collection." The text promoted a partnership in which the private sector would take over the function of gathering GNSS-RO data and the government would concentrate on improving weather forecasts through the purchase and use of these data [54].

In sum, the rise of the rhetoric for GNSS-RO commercialisation built on long-standing national attitudes in support of private enterprise, but it also reflected a business counter response to some types of federal research patronage that led, according to the rhetoric, to inefficient management of satellite programs at NOAA. Representatives of commercial vendors used congressional hearings, the press and their influence to promote their claims, to throw around ambiguous cost figures, to release alarming statements or to misrepresent the COSMIC-2 program, while hyping their companies as the ultimate solution for weather forecasting [21, 50].

4.2. Legislation at Congress

As described before, in 1992 the American government had formally prescribed the selling and privatisation of weather satellites systems, including their data [43]. This meant that enabling a market for GNSS-RO data could only be resolved through the intervention of the government changing legislation. Congress vigorously debated two bills sponsored by Bridenstine, the Weather Forecasting Improvement Act and the Weather Research and Forecasting Innovation Act in 2014 and 2015 respectively, which explicitly amended the existing legislation to enable commercialising with satellite weather data, specifically with GNSS-RO data [99, 100]. Although they were both approved by bipartisan agreements at the House, they never passed the Senate.

Yet, Congress kept putting pressure to NOAA and called the agency to elaborate a plan to obtain satellite data from commercial sources. In response, NOAA adopted its Space Commercial Policy in January 2016. This policy laid out the guidelines by which the agency will engage with the commercial sector to procure satellite data, with specific attention to GNSS-RO data [68]. Previously, in 2015, Congress authorised NOAA $9,000,000 to enter into contracts with private sector entities to provide GNSS-RO data [83] and in 2016 started a Pilot Project to evaluate the quality of such commercial data and their impact on weather forecast models [62] –actually, in 2016 Bridenstine proposed also a parallel commercial weather data pilot for the Department of Defense, arguing that it could benefit from access to data and services available from the commercial marketplace [8].

Two companies were commissioned to provide data by the end of 2017 for routine assimilation into NOAA's weather models [71]. Under these contracts, $695,000 were allocated to the long-term player GeoOptics, which had been preparing the ground for establishing a GNSS-RO data market since its creation in 2006. $370,000 were allocated to Spire Global Inc., created in 2012 to commercialise a crowdfunded nanosatellite that would carry sensors for gathering maritime intelligence. Spire had been set up by Peter Platzer, a physicist turned entrepreneur, with no formal training or previous experience in the weather domain. But he spotted a business opportunity and in 2015 announced the intention of providing weather data with a GNSS-RO payload. Unlike GeoOptics's business model, which requested some form of governmental subsidy, Spire's premise was that successful commercialisation would occur only in a competitive market where government guarantees were held to a minimum. It did not ask NOAA for prior investment; rather, it advocates for an open market for data within the weather industry, where NOAA is just a client amongst many others. The company PlanetIQ received no funding within this Pilot Project.

In the meantime, a third Act was introduced at Congress in January 2017, also called the Weather Research and Innovation Act. Almost identical to the previous ones, it passed House and Senate and was signed by president Trump becoming public law in April 2017 [101]. This legislative Act gave priority to further involve the private sector for acquiring satellite weather data. It made it far more obligatory for NOAA to procure, in particular, commercial GNSS-RO data for its numerical weather prediction models -followed by geostationary hyperspectral sounding data. With this legislation, the government not only decided to allow the private sector to sell GNSS-RO data but it urged NOAA, a governmental agency, to purchase it. This reflected a shift in the values embedding meteorological practice (as seen by legislators and decision makers) and was a remarkable step and presages a potential broad shift in the current practices of GNSS-RO data collection, utilisation and sharing –eventually extending to other types of weather satellite data.

5. Tensions and debates

In this long and tortuous path towards commercialisation, there are important issues of scientific and technical nature that must be carefully assessed by NOAA before acquiring and using commercial GNSS-RO data. These include learning to use such data in the first place, but also guaranteeing independent quality control of data, ensuring data sustainability in the long-term, managing long-term data preservation, or controlling IT security. Concerns include as well how to deal with the potential loss of in-house capabilities and expertise, what to do with existing governmental infrastructure, or how to come up against the raise of alternative weather data challenging NOAA's mandate to produce and disseminate them, stirring a long-standing debate on the respective roles of government and industry in the scientific enterprise in the US. Furthermore, as suggested before, debates also include disagreement around the degree of NOAA's economic participation needed in the commercial ventures and cost effectiveness of commercial GNSS-RO data sources.

In addition to these debates, there have been a number of reasons contributing to damage credibility of private efforts amongst GNSS-RO experts. For instance, in spite of promises for short-term launching expressed during Congressional hearings or through the press, first commercial GNSS-RO satellite was launched only in 2016 by the company Spire. GeoOptics followed in 2017 with two satellites that failed to provide data. PlanetIQ has yet to launch any satellite. Consequently, some NOAA executives find the prospect of commercial weather data "promising, but still quite nascent" [80]. Besides, for industrial competitiveness reasons, the private sector has been reticent to reveal technologies of gathering and processing. This secrecy renders very difficult testing and crosschecking by experts. Finally, defenders of public data argued that the private sector had attracted publicity with a cascade of hype, overpromises and disinformation, which contributed to get support from non-experts and confuse policymakers who got seduced by untenable "faster and cheaper" promises, taking the words of a reputed academic meteorologist.[4] The use of the media to widespread misleading statements, helped to create an atmosphere of scepticism vis-à-vis the availability of commercial GNSS-RO data in the near future.[5]

In the negotiations, key issues discussed included also how to enable a market of satellite weather data while still maintaining NOAA's policies of data sharing. It is to this specific point that we turn now.

5.1. NOAA's policy on data sharing

In general, NOAA adheres a full and open data policy, which promotes the dissemination of data gathered with US governmental-owned systems at marginal cost of reproduction and distribution without restrictions or fees. This includes data gathered with satellites operated by NOAA (NOAA, GOES, Suomi-NPP, Jason-3, DSCOVR and DMSP).

One might describe the principle of freely shared, widely disseminated data as part of the moral economy broadly accepted by professional meteorologists, originated in the seventeenth and eighteenth centuries, when such data were not only inexpensive to acquire but also entirely devoid of economic value, and rooted simultaneously in the global scale of weather, in the institutions that generate weather data and forecasts, and in the technological systems that permit those knowledge about weather to be created and shared [29]. However, beyond the idealistic language of data sharing, in the US such commitment has historically orchestrated national politics. As satellite data are concerned, the US began broadly promoting data sharing in the 1970s, when a foreign policy objective was the encouragement of international acceptance of American space activities –especially those related with remote-sensing of the Earth. Also, in order to gain domestic support during the post-Apollo period, American space activities reinforced their quest for social relevance [18]. The open dissemination of satellite data (about the atmosphere, land, ocean, etc.) for only the cost of reproduction was an effective ways to achieve both objectives. For instance, full delivery of data was an efficient means of facilitating scientific research and therefore maximize the scientific return of investments. Open access also constituted part of US mandate

[4] Interviews with several NOAA's officers, academic and professional meteorologists of universities, the American Meteorological Society and the University Corporation for Atmospheric Research, January-April 2016. As requested by some of them, identities are not provided to respect anonymity.

[5] Interview with an academic meteorologist, February 2016. Identity is not provided to respect anonymity.

to promote international collaboration without losing technical advantage [40]. In the end, these policies benefited those who had the resources to access data in the first place (e.g., logistics, technical, human, expertise, budgetary), and here the US had a leg up [41]. Also, in accordance with the underlying economic philosophy of the US, if the government pays to create data, those data should be freely available to the taxpayer who has financed its production. Of course, as suggested in the introduction, unrestricted data flow was also seen as an important step toward a more liberal commercial weather industry providing value-added services and products, since free access lows the cost of private forecasting activities and can provide competitive weather services. Finally, back to the specificity of weather data themselves, international data sharing was important –and still is- because it enables to share costs in the provision of global data that the US needs for weather forecasting, which is vital to its military, public health and safety, commercial and scientific interests [27, 28]. Processed weather data from American satellites are then distributed without cost to the user. In exchange, the US receives satellite or surface-derived weather data from third countries, also without cost. The American commitment to international free data flow is a ways to ensure the provision of all data that the US needs for weather forecasting, to foster the domestic commercial weather industry as well as to maintain foreign relations.

A major step in promoting such international weather data exchange occurred during the World Weather Watch (WWW). This was a program established in 1963 and coordinated by the WMO in collaboration with International Council of Scientific Unions (ICSU) and aimed to establish a cooperative network of meteorological observatories worldwide, together with telecommunications facilities and data-processing centers [27]. It included a geostationary satellite network in which US satellites were flanked by satellites provided initially by France, Japan, India, and eventually the USSR[6]. When a major field campaign of the WWW was conducted in 1978-1979 (called First GARP Global Experiment), processed data from all sources, including satellite, were distributed to over 150 countries participating at the WMO, without cost to the user. The WWW became the basic building block, in both a technological and policy sense, for the global environmental satellite observing system. And this system was based on the concept of meteorological data as public goods and organically tied to a tradition of unrestricted data exchange practices.

On the other hand, besides international or bilateral agreements with foreign partners, the origins of the national legal basis promoting free unrestricted weather data dissemination also go back to some decades ago. As mentioned before, in the 1950s, the Secretary of Commerce established a division of responsibilities between the public and the private meteorological sectors. In particular, it made government-collected data available to all at the only cost of reproduction and dissemination in order to encourage the development of the private sector of meteorology forecasting and products. In spite of such long established legislation, in documents, policies and reports, NOAA typically takes more recent law on open data as a basis to support its commitment to practices of full, open, and timely sharing and exchange of data, such as the Paperwork Reduction Act of 1995, the Office of Management and Budget Circular A-

[6] With the establishment of the European Space Agency (ESA) in 1975, the French satellite Meteosat became an ESA satellite. It was launched in 1977 as part of the First GARP Global Experiment of the WWW.

130 of 1996, the White House Memorandum on Increasing Access to the Results of Federally Funded Scientific Research of 2013, the White House Memorandum on Open Data Policy and the Managing Information of 2013. These documents consider information as a valuable resource and a strategic asset and they outline data management frameworks based on a number of principles, including full and open access. Accordingly, in 2006, NOAA issued its Policy on Partnerships in the Provision of Environmental Information and its Management of Environmental Data and Information (revised in 2010). The principle of data availability with no restrictions on distribution and reproduction access was manifested in both of NOAA's policies [63, 64]. In the recent years, such prior general initiatives on open data have evolved from barely addressing specifically environmental data to those of the 2010s, which aimed at stimulating the emerging potential for environmental data, including weather data, such as the National Strategy for Earth Observations of 2013 and the National Plan for Civil Observations of 2014, among many others. These documents encourage all civilian federal agencies that produce or manage environmental data to establish a publicly available open data policy as well as to provide non-discriminatory data access and dissemination. They adhere to the before-mentioned principle that access to data managed or paid for using federal funds should be made available to and useful for the public free of charge. All this legislation has become part of NOAA's official discourse promoting data sharing and the Agency uses to recall it in all its documents and policies.

The private sector interprets the applicable law in a different manner. It argues that while all these policies and practices have served the US well from the perspectives of maintaining good relations with other countries, securing acceptance of US activities in space, and maintaining the global flow of weather data, they can be revised to stimulate development of a commercial market for satellite weather data – especially GNSS-RO. To the private sector, the fundamental principle upon which Government policy is based is that Federal departments and agencies should not compete with citizens. This policy was first articulated by the Bureau of the Budget in a directive issued in 1955. Since 1966 this policy has been expressed in the Office of Management and Budget's Circular A-76, revised in several occasions, which states that the government should not engage in commercial or industrial activities were the private sector can provide them more efficiently and cheaply. In addition, the private sector defends that space-based commercial activity is promoted at least since the Commercial Space launch of 1984 and, specially, by the Commercial Space Act of 1998, which directs government agencies to purchase commercial capabilities when they are available and to refrain from conducting activities that preclude, deter or compete with commercial space activities [16]. The National Space Policy of 2010, and other legislation, reaffirms these commitments by promoting to the maximum the purchase and use of commercial space capabilities [58, 59, 17].

Private sector defenders often recall that, as a consequence of such legislation, several federal agencies now purchase satellite data from commercial systems (including NASA, the Department of Agriculture or the National Geospatial-intelligence Agency). In particular, as NOAA's officers admit, NOAA currently spends around $20 million dollars annually to purchase surface, aircraft and satellite data provided by commercial vendors [10]. This include, for instance, ground data to track lightning activity purchased to the company Vaisala or data on temperature and wind speed purchased to aircraft operators through the commercial network AMDAR. As for satellite data themselves, for instance, NOAA purchases ocean colour data from the SEAWiFS sensor operated by the company GeoEye. Synthetic aperture radar (SAR) data are purchased from commercial sources in Canada (Radarsat) and Europe (TerraSAR), allowing NOAA to more accurately detect and monitor ice [70]. In sum, private firms claim that commercial activity is not only supported and promoted by current legislation, but also already in place at NOAA. Commercialising GNSS-RO data would be just one more instance of such practice.

Yet private satellite data firms, in order to ensure profitability, must retain the property rights to their data and restrict reproduction and distribution through data licences, sales and fees. Controlling access to data is key to competitiveness. For instance, under NOAA's contract with the company GeoEye, data on ocean colour can be made widely available only 24h after its collection, when its commercial value has vanished. Similarly, NOAA's licence to use Radarsat's data is restricted to a percentage of the US Government's investment in the Canadian Radarsat program [61]. In other words, a change of NOAA's views of data sharing is a key condition for the private sector to make viable business. Particularly, in our GNSS-RO story, commercial data sources challenge the established regime of GNSS-RO data exchange. At this writing, data sharing conditions are being negotiated between NOAA and GeoOptics and Spire. For instance, some proposals involve negotiating a threshold of quantity of data that can be delivered without restrictions. But if users request more data than this fixed quantity, then fees would be charged – unless users are scientists, for whom all private companies agree in providing data for free.

One might conclude that there is an inherent conflict between the two principles: those favouring wide dissemination of meteorological satellite data (government ownership of weather satellites) and those favouring commercialized data distribution (privatised data-gathering). A clash of values ensues.

5.2. Resolution 40 and its limits

In their defence of unrestricted data sharing, representatives of NOAA often appeal to Resolution 40, a policy document adopted in 1995 unanimously by all members of the World Meteorological Organisation (WMO). During the 1970s and 1980s, as mentioned before, some governmental weather services in Europe had gradually began charging for access to weather data and value-added products as a way to recover back costs of production, maintain infrastructures and stave off private competition. This caused tensions between those public weather services committed to the commercial route and those, especially in the US, who considered the provision of profitable and marketable products to be a proper role for the private sector [102]. Concerns about this "data war" –as it was called- also rose within the WMO [106]. WMO claimed that the market was a poor form of economic organisation to produce scientific goods such as weather data because commercial interests were likely to lead to restrictive forms of data delivery. As a result, imbalances in access to market (between nations, individuals or entities) would result in difficulties for the most vulnerable in getting the data [106]. After years of debate a compromise was achieved, known as the Resolution 40, which became the key policy ruling the international regime of weather data exchange [104].

Resolution 40 encourages the free and unrestricted circulation of certain types of weather data while submits the rest to control and fees. Its language distinguishes between "essential" data (those data defined as "necessary for the provision of services in support of the protection of life and property and the well-being of all nations, particularly those basic data and products required to describe and forecast weather and climate"), which must be freely shared, and "additional" data, for which fees can be charged [104]. The Annex 1 of the Resolution provides some examples of surface, balloon and aircraft data considered as "essential". However, it does not specifically describe this category in the case of satellite systems. Instead, it considers as "essential" all "those data and products from operational meteorological satellites that are agreed between WMO and satellite operators" [104].

As is frequent in this kind of international arrangements, language led to various, often contradictory, considerations. In particular, NOAA and the private sector have very different views on what satellite data are to be freely shared. This issue is much complex than it appears because under the generic term of "satellite weather data" a myriad of items can be encompassed, from raw measurements, to images, to processed meteorological quantities, to forecasts, and so on –and each of them have specific technical, commercial, diplomatic or scientific values. For instance, one thing are raw data measured with the satellites (typically radiances, or bending angles in the case of GNSS-RO satellites) and another thing are the processed data transformed into forms of weather-related information (forecasts, indexes, analysis, etc.). To date, there are few organisations in the world –most of them government-funded, including NOAA, NCAR, EUMETSAT, etc.- knowledgeable enough and technically capable to use raw data in their weather models and transform them into some form of weather information. Actually, in NOAA's views, GNSS-RO raw data have proven to be so powerful in improving weather forecasting that they conform to WMO's definition of "essential" and therefore must be unrestrictedly shared.[7]

The private camp, by contrast, do not like to argue in terms of "essential" or "additional", because of the ambiguity of such terms. Instead, they prefer to argue in terms of economic value and market potential for the data. At a congressional hearing in 2016, for instance, Bridenstine claimed that his goal was to ensure "we're not destroying a market that would not otherwise exist" by providing more data for free than necessary [9]. When asked about the potentialities of such a market for GNSS-RO data, NOAA's executives are more than sceptical. It is not that a market does not exist for GNSSS-RO raw data, but that it is today principally a governmental market.

Moreover, advocates of free and unrestricted data access highlight that the "faster and cheaper" argument that has convinced US Congress is misleading. For one thing, the private sector claims that it "can deliver data to the US government more efficiently than NOAA's weather satellite programs" –as mentioned before, we do not have enough basis to assess such claim from an economic perspective. What matters to us is that, according to many NOAA's officers and academic meteorologists, private companies "cannot deliver data worldwide more efficiently than the global weather satellite constellation".[8] Along these lines, NOAA's executives like to recall that a global weather observing system exists, which include not only satellites owned and operated by public weather services in Europe, Japan, Russia, India, China, and

[7] Interviews with several NOAA's officers, January-April 2016. As requested by some of them, identities are not provided to respect anonymity.

[8] Interviews with several NOAA's and WMO's officers, January-June 2016. As requested by some of them, identities are not provided to respect anonymity.

others, but also non-satellite observing systems (surface stations, radars, balloons, buoys, etc.), with a system of data sharing between the organisations operating them. Testifying before Congress, Manson Brown, Deputy Administrator for NOAA, insisted that the US obtains great benefit from such a global system, since it receives three times the amount of data it contributes to the international community [10]. Promoters of governmental weather satellites question whether companies that make business out of selling data would likely establish a system in which data could be redistributed and available serving all areas of the globe, necessary for global weather forecasting. More alarmingly, some observers at WMO and universities have warned that if NOAA did not share government-acquired GNSS-RO data, foreign partners from which NOAA currently gets 2/3 of its data would perhaps retaliate. Because less data would be available to all, this would result in a progressive cascade of degradation of weather forecasting all over the world.[9] Interestingly, during the debates on the privatisation of the weather satellite system back in the early 1980s, this argument was also often cited and applauded by members of Congress. Apparently, it has been insufficient to convince Congress thirty years later.

On the other hand, the private sector camp emphasises that Resolution 40 allows the commercialisation of certain data. In their campaign to get support from Congress, it made sure to emphasize that international data sharing commitments not only are obstructive to domestic economic growth but also disadvantageous to accurate weather forecasting. Representatives of private companies condemned the fact that NOAA overstates the importance of its international data sharing commitments, thereby encumbering the growth of the national commercial sector by preventing markets from forming and thwarting industrial innovation [7]. In a comment on the draft of NOAA's Commercial Space Policy being elaborated in 2015, for instance, Anne Miglarese complained that NOAA "focuses more on the concerns of foreign stakeholders than on making the agency's capabilities more resilient and robust, as it largely overstates the importance of US data policy and international data sharing commitments… with the result being disadvantageous and inequitable to US weather industry interests" [56]. Along the same goals to get support from Congress, and as part of its aim to demonstrate NOAA's inability to efficiently manage satellite programs, the private sector stressed that NOAA's hesitation vis-à-vis commercial GNSS-RO data providers had the potential to deter agreements with the private sector resulting in a reduction of the quantity of GNSS-RO data potentially available and therefore hindering NOAA's pursuit of the public good through better weather forecasting [7]. On the other hand, the private sector also liked to note that NOAA's satellite systems already coexist with private means for data production, which are subject to some form of data access restriction. To them, this proves that there is room for flexibility on the full and open data distribution policy. Once again, they claim, this demonstrates NOAA's rigidity and inability to adapt to changing situations and to reap the economic reward that comes from such technological investments [45, 56]. In that sense, in a 2015 meeting, the House's Committee on Science, Space and Technology, chaired by Lamar Smith, a Republican from Texas, and with Jim Bridenstine as a member, even branded NOAA's position as "short-sighted" [85].

[9] Interviews with several WMO's officers and academic meteorologists, January-June 2016. As requested by some of them, identities are not provided to respect anonymity.

More generally, the private sector argues that Resolution 40 has become obsolete. It was created as a middle ground for the conflicting data policies of American and European national weather services in the 1980s and 1990s. But times are changing, the private sector contends.[10] More and more, American decision makers and legislators are drawing away from the public good argument that prevailed in those decades toward that of commercial viability. In sum, the private sector argues that the WMO policy framework is simply not sufficient to resolve the issues involved in the commercialisation of GNSS-RO data in the US.[11]

The involved parts hold different views on Resolution 40 and, more generally, on commercial GNSS-RO data development. The intensity of this rivalry can be seen, for instance, in the series of cross-letters published in specialised papers such as Space News or Satellite Today, notably in 2014 and 2015, between Conrad Lautenbacher, Jim Bridenstine, academic meteorologists and members of the American Meteorological Society [5, 46, 47, 44]. In turn, because weather forecasting is implicated in a range of critical spheres such as agriculture, transport, insurance, aviation or outdoor recreation, the case of GNSS-RO received tremendous amounts of public attention in generalist media such as The Washington Post, The New York Times, Forbes, Nature or Scientific American [76, 98, 77, 35].

As the debates pursued between 2007 and 2016, the fundamental positions expressed by both sides retained some deal of agreement, despite the polemics and some bitter underlying feelings: generally speaking, NOAA executives, meteorologists, members of Congress and the private sector retain similar views that commercial GNSS-RO data can contribute to advancing in weather forecasting (and meteorological and climate research too). Yet, it matters how these data are shared.

6. Conclusions

Focused on data sharing, considered traditionally one of the linchpins of meteorology, this article has emphasised a clash between conventional norms of meteorology and the commercial imperatives driving the private sector. It has opposed two binary viewpoints: that favouring government ownership of satellites and subsequent data dissemination and that favouring privatized data gathering and commercialised data distribution. Of course, this opposition does not imply that all members of Congress or representatives of private companies share the same views regarding commercialisation of GNSS-RO data or that all officers at NOAA and academic scientists are just against it. Very often, positions are nuanced and much more complex than simply for and against. In general, those protecting governmental missions welcome additional complementary data coming from commercial sources insofar as a set of standards for data quality, preservation, security or accessibility are guaranteed; just like private vendors are ready to share the data costless within certain circumstances (e.g. data for scientific research). However, this opposition is useful to emphasise the ongoing discussions in the US about the commercialisation of GNSS-RO data and their consequences for both gathering and sharing the data -

[10] Interviews with representatives of GeoOptics, PlanetIQ and GeoMetWatch, January-June 2016. As requested by some of them, identities are not provided to respect anonymity.

[11] Interviews with representatives of GeoOptics, PlanetIQ and GeoMetWatch, January-June 2016. As requested by some of them, identities are not provided to respect anonymity.

discussions that can be widen to other weather and environmental data too. In this regard, the case of GNSS-RO data exemplifies an important issue concerning weather and environmental data: are they resources for all to use or proprietary and reserved for private gain?

With a renewed belief in the free market, the story of GNSS-RO data illustrates the shifting context of both meteorology and space activities in the post-Cold War space age. The call for private mass-produced satellite weather data and the transformation of weather satellites from a publicly-funded factory to its eventual dissolution into several commercial firms offers a stark, substantive illustration of the ideological and political shifts in the turn of the 21st Century. It engages in the debates on the respective evolving role of government and business in the meteorological (and more generally scientific) enterprise. Thus this story adds to our understanding of the evolving place of science and technology in US political economy and the funding of science.

It is too soon to conclude whether the commercialisation of GNSS-RO data will finally succeed -and whether other kinds of weather data may follow, beginning with geostationary hyperspectral sounders. At the time of writing, the newcomer Spire has launched more than 20 satellites equipped with radio occultation sensors. Platzer and his team presented the data at the International Workshop on Occultations for Probing Atmosphere and Climate in September 2016, an annual meeting that brings together the leading academic scientists in the field. Also in September 2016, as part of its 370,000$ contract under NOAA's Pilot Program, the company delivered data to NOAA, making it the only company to have done so. GeoOptics launched its first satellite in June 2017. Three more satellites followed in July 2017 but they became inoperative after deployment. A fourth satellite was launched in January 2018. Data have not yet been provided to NOAA. PlanetIQ has yet to launch its first satellites. In September 2017, after assessing Spire's data, NOAA announced that the quality of the data furnished was not ready for operational numerical forecasting and postponed operational data buys [72].

The issue of quality data merits further clarification. Numerical weather works on the principle of data assimilation. Satellites do not measure directly temperature, wind speed or humidity –the meteorological quantities. Instead, instruments aboard satellites typically measure the radiance that reaches the top of the atmosphere at a given frequency, which are related to the meteorological quantities through complex equations. In the case of GNSS-RO systems, what it is measured are bending angles. Then raw measurements are incorporated –or assimilated- in powerful computers in order to obtain some weather-related information [14, 15]. This is a complex problem that must take into account the laws of thermodynamic and chemistry but also external information, such as initial and boundary conditions, hydrodynamics of the atmosphere, characteristics of the sensor, the orbit, and many other aspects. It requires computer power, time, money and expertise. As mentioned before, NOAA is one of the few organisations in the world capable to use raw data and transform them into some form of weather information. In other words, what NOAA demands are raw data. Yet, understandably, GeoOptics, PlanetIQ and Spire are not primary interested in the market of raw GNSS-RO measurements because it is limited and essentially governmental. Instead, they plan to make their own data assimilation and then put processed meteorological datasets and products on sale, given that a market already exists for weather quantities and other derived information. The question for NOAA is: will a market of processed meteorological datasets be appropriate to regulate the quality of raw measurements, which are the types of data of most interest for NOAA?

In October 2017, NOAA announced the cancellation of the second set of the satellites COSMIC-2. Also significant, Trump's administration nominated Barry Myers, founder of the billion-dollar commercial weather company AccuWeather who has openly defended a private system of weather satellites, as NOAA administrator. This highly controversial nomination has yet to be approved, but it presages further moves in the path for obtaining satellite weather data from commercial sources. Should it be the case, the resulting weather satellite system would embody a novel view of weather forecasting practices, a view in which data exchange may not be as fluid as it used to be.

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Oral sources

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