

Weather Satellites:

Critical Technology in an Uncertain Environment



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Executive Summary

In 2011, the United States experienced 14 weather disasters costing \$1 billion or greater, more than occurred in any other year on record. The second-greatest number occurred in 2012, with 11 billion-dollar disasters.¹ Weather has a significant impact on the nation through severe storms such as these, affecting businesses and individuals alike on a daily basis. More than 90% of the data in U.S. three- to seven-day weather forecasting models comes from satellites.² U.S. weather satellites provide billions of dollars in benefits through improved early warnings and by informing the decisions of companies in many industries, including aviation, energy, and agriculture.

The United States is currently developing its next generation of weather satellites, which will include major technological advancements that will significantly improve capabilities for weather forecasting. These programs are making good progress toward their current launch dates, however, they are operating in a very challenging environment. In 2013, the Government Accountability Office added “mitigating gaps in weather satellite data” to its list of 30 high-risk government operations.³

Originally expected to launch in 2009 as part of the National Polar-orbiting Operational Environmental Satellite System (NPOESS) program, the next operational polar-orbiting weather satellite system is now expected to launch in 2017 under the Joint Polar Satellite System (JPSS) program. The eight years added to the original launch date for the next-generation system has created a substantial risk of a gap in satellite data, which NOAA officials estimate will most likely last at least a year and a half, and result in degradation in the accuracy of three- to seven-day weather forecasts.⁴ If any additional delays or unexpected failures occur, the gap could last even longer.⁵ The U.S. polar-orbiting weather system originally included satellites in two different orbits, but it was later reduced to only cover one orbit. A partnership with Europe has helped to ensure continued coverage in the other orbit, but for its own portion of the constellation, the United States will soon have to rely on a satellite originally designed for research, not for operations.

The second component of the U.S. weather satellite system, which consists of geostationary weather satellites, has also experienced delays and other challenges. These satellites continuously monitor weather developments over the United States and are essential for tracking the development of severe weather events, such as tornadoes and hurricanes. Originally planned for launch in 2012, the next-generation geostationary weather satellite, Geostationary Operational Environmental Satellite R-Series (GOES-R), is now scheduled for launch in 2015.⁶ The three-year postponement is not expected to cause a gap in coverage, but the United States may temporarily be without a backup GOES satellite in orbit for the first time in more than a decade. To meet the new schedule and to save approximately \$5 billion over the lifespan of the program, a major instrument was removed from the satellite. Though the satellite will still be capable of achieving its mission and will greatly improve on current geostationary satellites, removing this instrument decreased the capabilities from the original design.

Action must be taken to ensure the long-term success of the U.S. weather satellite system. As a government service with one of the most well-demonstrated and straightforward benefits to the nation, future weather satellite programs should be properly selected, managed, and funded to help prevent the type of delays that have left current satellite programs in this precarious situation. The United States should invest in advanced technology development to provide improved weather forecasting capabilities in the future. Weather satellites help to save lives and save money, and we must ensure that this crucial technology is not neglected.



Recommendation 1: Program offices should provide accurate and stable life-cycle cost estimates for weather satellite programs, and Congress should respond with full and stable funding for these programs, including JPSS, GOES-R, and the Constellation Observing System for Meteorology, Ionosphere, and Climate 2 (COSMIC-2).

While recent progress in both next-generation weather satellite programs has been positive, stability in program requirements, high-confidence cost estimates, and full funding are required to ensure they remain on track. Ever-growing life-cycle cost estimates, as seen in the NPOESS program, cause policymakers and the public to lose confidence in these estimates and make well-informed policymaking nearly impossible. At the same time, unstable budgets and lower-than-requested funding for these programs exacerbate the problem, leading to delays in development and increasing life-cycle costs. These issues have resulted in a near-certain satellite data collection gap that will reduce the U.S. capability to forecast weather. In addition, focusing on the top-line budget numbers, rather than the budget needed for the mission to succeed or the return on investment, has led to short-sighted decisions that will cost taxpayers more in the long run. These budget and funding issues must be addressed.

Recommendation 2: The United States should seek opportunities to increase international cooperation on weather satellite programs to help decrease costs and increase capabilities.

The United States is already involved in a number of international agreements related to weather satellites that increase its capabilities while saving taxpayer money. The nation operates a joint polar-orbiting weather satellite constellation with Europe, in which each partner provides weather data critical for both regions. The United States engages in international exchanges of weather satellite and research satellite instruments, getting free rides for its instruments and receiving other countries' instruments for inclusion aboard its satellites.⁷ The United States also has an opportunity to collect valuable radio occultation data in partnership with Taiwan, a program that would provide the United States with the full value of the satellite constellation for a fraction of the cost of the overall system. The United States should take advantage of these opportunities and actively pursue others.

Recommendation 3: The United States should explore the potential for working with commercial weather satellite data providers to augment current weather satellite capabilities and improve weather forecasting.

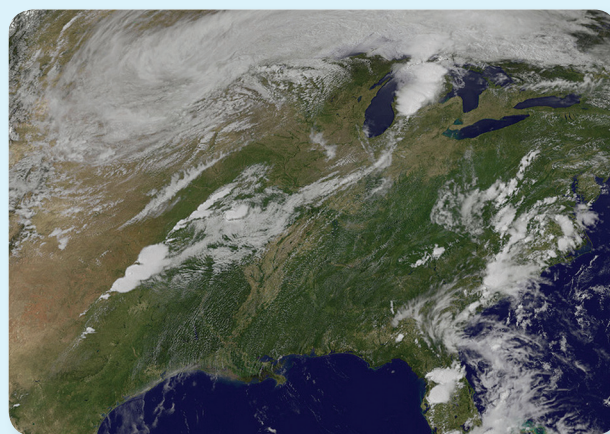
A number of companies have been established to build weather satellites or sensors to collect important weather data, using advanced techniques such as hyperspectral sounding or radio occultation. In some cases, these companies' proposed systems would have capabilities not present in the current or planned U.S. weather satellite system, and adding these capabilities could improve the nation's forecasting ability. Data buys have the potential to be less expensive than full satellite procurement, but their business models may be difficult to reconcile with the U.S. policy of free and open data sharing on an international basis, which is essential to global weather forecasting as well as the value-added sector. The United States should explore the potential of these options while maintaining its commitment to free and open exchange of meteorological data, looking for partnerships that can reduce costs or increase capabilities.

Recommendation 4: The United States should conduct a comprehensive review of its weather satellite program portfolio to determine the correct level and distribution of funding to achieve the desired capabilities.

In order to keep system development costs down and minimize delays in launch, the United States has removed several advanced instruments from its next-generation weather satellite systems and has reduced the complexity and capabilities of some remaining instruments. Given the billions of dollars and thousands of lives affected by weather in the United States each year, leaders should carefully evaluate whether scaling back the planned capability of the United States to accurately forecast weather is truly in the best interest of the nation and should also consider providing additional funding to improve capabilities. The weather satellite system in the United States is an area that requires careful consideration regarding levels and types of investment, and a thorough review of future plans would help to ensure that the United States has a weather satellite system appropriate for the needs of the country.

Introduction

Weather affects the decisions that individuals, companies, and governments make on a regular basis. Accurate forecasting can help individuals save time and companies save money, and severe weather warnings save lives. The United States is currently developing the next generation of polar and geostationary weather satellites, both of which will provide significant technological advancements and improve weather forecasting. Unfortunately, both next-generation systems are now expected to launch years later than originally planned, and system costs are billions of dollars higher than original estimates. Launch delays in the polar-orbiting weather satellite program have created a situation in which the United States will likely have a gap of more than a year in satellite coverage during which the accuracy of weather forecasts will degrade. Some instruments originally planned for inclusion on the satellites have been reduced in capability or removed altogether. Both programs are making important progress toward current launch dates, but the environment in which they are now operating is quite challenging. Looking forward, the United States must provide funding to minimize the gap in weather satellite coverage to the greatest extent possible. At the same time, the government should explore options for increased cooperation with international and commercial organizations to improve the efficiency and stability of weather data collection in the future. With a view to the long term, the United States should reevaluate funding levels and portfolios for weather satellite programs, recognizing the significant benefit that weather forecasting capabilities bring to the nation.



The tornado that killed 23 people in Moore, Oklahoma, was created by the line of thunderstorms seen on the left in this GOES-13 image. Credit: NASA/NOAA GOES Project, Dennis Chesters

Benefits of Weather Satellites

When you watch the daily weather report on television, you are seeing the results of satellite observations. When you check the weather online to see if you will need an umbrella for the day, that prediction is based on satellite data. When evacuation of an area is recommended due to severe weather, this too is based in part on satellite data.⁸

Weather satellites are critical to the ability to monitor and predict the weather. Before weather satellites were first developed in the early 1960s, measurements were taken manually using instruments on the ground and on weather balloons.⁹ Even with many professionals taking measurements in different areas of the country multiple times per day, it was very difficult to get an accurate view of the overall atmosphere and weather patterns. Weather satellites make it possible to continuously monitor the land and atmosphere over large swaths of the Earth.

Weather reports are not just convenient for deciding what to wear each day or whether to take an umbrella to work. Each year, the data provided by weather satellites helps to save lives and provides billions of dollars in benefits.

Accurate forecasting of hurricanes and tornadoes allows people to protect property and evacuate areas that are at risk. As the accuracy of forecasts has improved, people have been given more time to react and there have been fewer unnecessary evacuations.

Weather satellites provide measurable economic benefits. In the United States, more than 155 million people live in coastal areas, and there are approximately \$3 trillion in real estate investments along the Atlantic and Gulf coasts.¹⁰ Hurricane tracking and intensity information is critical for protecting both people and property. Accurate weather forecasting also allows for more efficient irrigation of crops, conserving water and reducing the energy needed to pump the water. Accurate temperature forecasts help to improve energy demand forecasts, allowing for efficiencies in the energy sector. Knowledge of weather systems and volcanic ash movements allows air traffic controllers to plan safe and efficient routes. Accurate forecasting of climate trends, such as extended droughts, can allow individuals and organizations to better prepare for and mitigate the effects.

The next generation of weather satellites will offer improved environmental data, with the predicted benefit of the geostationary satellite program to the U.S. aviation, energy, agriculture, and recreational boating industries estimated at nearly \$7 billion over its expected 13-year operating period. This is a significant effect, especially because these industries represent only a fraction of the nation's economic activity that would benefit from improved weather information. The benefit to the United States derived from the ability of the next-generation geostationary system to improve cyclone forecasting is valued at \$450 million in the first year of operations alone.¹¹

U.S. Weather Satellite System Overview

There are two types of weather satellites: geostationary and polar-orbiting. In the United States, these satellites are operated by the National Oceanic and Atmospheric Administration (NOAA). They have historically been referred to as the Polar-orbiting Operational Environmental Satellite (POES) and Geostationary Operational Environmental Satellite (GOES) systems. A new generation of polar-orbiting satellites, known as the Joint Polar Satellite System (JPSS), is currently being developed by NOAA as a follow-on to the POES system. The U.S. Department of Defense (DoD) also has polar-orbiting weather satellites, as part of the Defense Meteorological Satellite Program (DMSP). The next generation of DoD weather satellites is currently being considered, although funding for this activity has been very low because the DoD still has a number of spare DMSP satellites that have been completed but not yet launched.



The GOES-O satellite, later renamed GOES-14, is shown here during preparations for launch in Florida in 2009. GOES-14 is currently acting as the on-orbit backup for the U.S. geostationary weather satellite constellation. Credit: NOAA

Polar-Orbiting Weather Satellites

Polar satellites orbit close to the Earth, allowing them to take precise measurements and to circle the globe approximately 14 times a day. They orbit nearly north-south around the Earth (a polar orbit), so over the course of its 14 orbits, each satellite is able to monitor the entire Earth twice per day. Although it cannot provide continuous coverage of any one area, the polar satellite system does provide comprehensive monitoring of the entire globe.

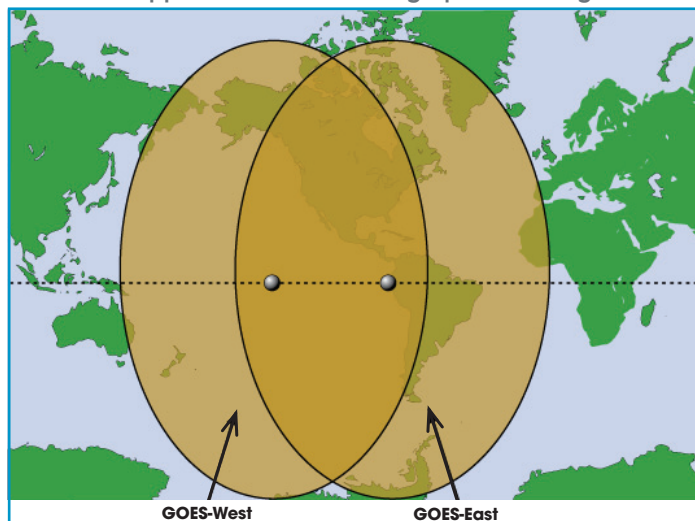
In addition, polar satellites are placed in a sun-synchronous orbit, which means that they cross a given latitude at the same solar time each day so that a particular area is seen under the same lighting conditions every time it is visited. This makes it easier to detect changes that have occurred between visits. Historically, NOAA has ensured the availability of an operational satellite in a mid-morning orbit (a satellite whose daylight crossing of the equator occurs in the morning) and an afternoon orbit (a satellite that crosses the equator in the afternoon).¹² Based on a 1998 agreement with the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), as well as follow-on agreements, NOAA now obtains data from the mid-morning orbit from EUMETSAT and no longer needs to develop its own satellites for this orbit.¹³ In addition to the most recent satellites in each orbit, which are the primary source of weather data, both organizations also maintain older satellites in each orbit to allow for intercalibration after launch and as secondary sources of data.¹⁴

Polar satellite data is most valuable in determining the overall state of the atmosphere, which is critical for weather and climate models. Forecasts produced using these models are the basis for three- to seven-day weather predictions. Monitoring of atmospheric conditions done by the polar satellite system is also useful for ongoing research to better understand the nature of weather and climate systems.¹⁵

Geostationary Weather Satellites

Geostationary satellites are located approximately 36,000 kilometers (22,000 miles) from Earth, allowing them to orbit in sync with the Earth's rotation. From the ground, satellites in this orbit appear to be hovering over one spot on the Earth. The great distance allows these satellites to view the entire disk of the Earth, and the special orbit allows them to continuously monitor this area. The United States operates two GOES satellites at all times—GOES East and GOES West—to ensure full coverage of the United States. It also maintains a spare satellite in orbit that can be moved into place if one of the operational satellites fails.¹⁶

FIGURE 1: Approximate GOES Geographic Coverage



Sources: GAO-10-799, NOAA (data), MapArt (map)

The primary function of the GOES system is the provision of timely weather information, including warning of developing storms.¹⁷ The ability of GOES to continuously monitor one area is essential for intensive data analysis.¹⁸ With this system, it is possible to watch the development and evolution of cloud formations and storms continuously over a large area. GOES is able to observe and help predict severe weather events such as thunderstorms, tornadoes, flash floods, and snow storms. It can also be used to monitor other environmental events, including dust storms, volcanic eruptions, and the spread of wildfires.¹⁹

Satellite Radio Occultation

The current operational weather satellite program includes the two types of satellites described above. An additional type of system, which uses satellite radio occultation, has been shown to provide significant benefits in operational weather forecasting.²⁰ Radio occultation satellites in low Earth orbit receive signals from Positioning, Navigation, and Timing (PNT) satellites, such as the U.S. Global Positioning System (GPS), that have traveled through the Earth's atmosphere. Based on an analysis of how these signals have been bent and delayed as they travel from the PNT satellites to the radio occultation satellites, it is possible to determine a great deal of very accurate information about the composition of the atmosphere.

NOAA, in collaboration with the Taiwan National Space Organization (NSPO), the National Science Foundation, NASA, the U.S. Air Force, and the University Corporation for Atmospheric Research (UCAR), developed a proof-of-concept system that was launched in 2006. The data from the six-satellite Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC), was extremely accurate. Within a year, NOAA began using the data operationally, greatly improving the agency's weather forecasting accuracy.²¹ COSMIC provides about 3,000 soundings a day, but research has shown that additional soundings would continue to improve forecasts.²² NOAA currently uses radio occultation data from a variety of international missions; however, as research missions, these satellites often do not provide the timeliness or reliability of a dedicated constellation like COSMIC.²³ NOAA's requests for funding to continue and upgrade its own satellite radio occultation data collection through participation in the COSMIC-2 program have not been approved.²⁴

U.S. Weather Satellite System at Risk

The JPSS and GOES-R programs are both in development and are currently maintaining their revised schedules and remaining within the programs' planned margins for cost. However, due to the delays in the startup of these contracts, prior problems and delays within NPOESS, and early uncertainty on the acquisition plan for GOES-R, the current programs are in a challenging position, where gaps are expected in the collection of certain types of data. Given this situation, inadequate funding or unforeseen technical problems could result in further delays, which could result in damage to U.S. weather services—particularly the ability to accurately forecast weather.

The first next-generation polar-orbiting operational weather satellite was originally expected to launch in 2009 as part of the NPOESS program, which was canceled in 2010. Now part of the JPSS program, the next-generation satellite is projected to launch in 2017. In the near-term, the United States plans to rely on the Suomi National Polar-orbiting Partnership (NPP) satellite, launched in 2011, for operational weather data, even though this satellite was originally intended for research use only. However, because NPP has an expected lifespan of only five years, and potentially less, NOAA officials still expect a gap of more than a year in polar weather satellite coverage.²⁵ This would directly result in degradation of the accuracy of three- to seven-day forecasts, which rely on polar-orbiting satellites for more than 80% of their observational data.²⁶

To illustrate the effects of this gap, the National Weather Service looked at how its predictions for major storms in the past would have been different if polar weather satellite data from the afternoon orbit had not been available. One result showed that the amount of snowfall in the Washington, D.C., area during the 2010 blizzard would have been underestimated by a factor of two. Snow forecasts would have been at least 10 inches too low, leaving businesses and individuals seriously unprepared for this major storm.²⁷ In 2013, scientists in Europe showed that if no polar-orbiting satellite data were available, forecasts would have projected that Hurricane Sandy, which devastated areas along the northeast coast, would remain at sea. Using this critical data, they were able to accurately predict, with five days' warning, that Sandy would turn back toward land. Advanced warning of the storm allowed people to better prepare, saving lives and property.²⁸

The geostationary weather satellite program has been unable to meet original budget and schedule plans. Originally intended for launch in 2012, the next-generation geostationary weather satellite, GOES-R, is now scheduled for launch in 2015.²⁹ This delay could result in the United States operating without a spare satellite in orbit. This means that if one of the currently operating satellites fails, or if a problem with GOES-R occurs, the United States may have to reduce its monitoring capabilities to just one geostationary satellite, a change that would reduce the capability for monitoring and predicting severe weather events, especially hurricanes. Alternatively, the United States could attempt to arrange for coverage by an international satellite, a method that has been used in the past and for which international agreements have been developed.³⁰

In addition to the schedule delays, both satellite systems will also be less capable than originally planned. While both will provide important technical improvements over existing satellites, a number of advanced instruments were reduced in scope or removed altogether. This means that U.S. weather monitoring capabilities will not improve as much as originally anticipated. To evaluate how these challenges should be addressed, it is important to understand the development process that resulted in these outcomes. While the polar and geostationary weather satellite programs have followed different paths, they face a number of common challenges.

Development Challenges: NPOESS and JPSS

Historically, NOAA has cooperated with NASA to develop and operate polar-orbiting weather satellites for the civil community, while the DoD has developed and operated its own system of polar-orbiting weather satellites for the military community. Many times over the years it was suggested that these programs should be merged. In 1994, due to budget pressure, President Clinton announced a plan to combine the two programs and create the National Polar-orbiting Operational Environmental Satellite System (NPOESS). This was expected to lead to significant cost savings because only one system development effort would be required, rather than parallel satellite development for two independent systems. In addition, fewer satellites would be built and launched, and fewer ground systems and operators would be required. Under a tri-agency integrated program office, the government/contractor program staff was expected to be approximately half of what would be needed to manage two separate development programs.³¹

From 1995 to 1997 the program went through a concept and technology development phase, and from 1997 to 2002 the focus was on program definition and risk reduction. During this phase, the program office took a number of risk reduction actions, such as deferring developments of some data products and beginning development of critical new sensors early (contracts for early development on six sensors were awarded in the late 1990s). When possible, new sensors were based on existing sensor technologies. The NPOESS Preparatory Project (NPP) was seen as a risk reduction activity as its goal was to launch years before the first NPOESS satellite was needed, giving scientists an early opportunity to work with critical sensors, ground control, and data-processing systems. In January 2012, NPP was renamed the Suomi National Polar-orbiting Partnership.³²

In 2002, the NPOESS project was estimated to cost \$6.5 billion, including development and operations through 2018. It would include NPP, to be launched first, in 2006. NPOESS itself would be made up of a constellation of six satellites—one operational and one secondary in each of three orbits, with the first operational satellite launched in 2009.³³ The NPOESS satellites would include 13 sensors, incorporating updated versions of the traditional imaging and sounding technology as well as new environmental sensors useful for weather and climate monitoring.

In August 2002, the development and production contract was awarded to TRW (later purchased by Northrop Grumman), and the program began its engineering and manufacturing development and production phase. However, by this time, the cost and schedule of the program had already begun to slip. Delays in launching a DMSP

satellite had caused the overall launch schedule for DMSP satellites to be pushed back, so that the last DMSP satellite would be launched in 2010 rather than 2009. Because of this planned delay, DoD reduced funding for NPOESS by about \$65 million between fiscal years 2004 and 2007. Within the NPOESS program, NOAA was required to provide no more funding than DoD, so a corresponding reduction in funding by NOAA also occurred for those years. This shift caused a 21-month delay in the date the first NPOESS satellite would be available for launch. This also extended the overall lifetime of the project to 2020, increasing life-cycle costs. Although efforts had been taken to reduce risks in sensor development, many of the sensors had already experienced cost increases, schedule delays, and performance shortfalls.³⁴

FIGURE 2: Changes in NPOESS and JPSS Life-Cycle Cost Estimates and Estimated Satellite Launch Dates³⁵

Date of Estimate	Life-Cycle Cost Estimate (current-year \$ in billions)	Life-Cycle End	NPP Launch	First NPOESS Sat Launch
Aug 2002	\$7.00	2018	May 2006	Apr 2009
Jul 2003	\$7.00	2020	Oct 2006	Nov 2009
Sep 2004	\$8.10	2020	Oct 2006	Nov 2009
Aug 2005	\$8.10	2020	Apr 2008	Dec 2010
Jun 2006	\$12.50	2026	Jan 2010	Jan 2013
Dec 2008	\$13.95	2026	Jan 2010	Jan 2013
Jun 2009	\$14.95	2026	Jan 2011	Mar 2014
Feb 2010	\$15.1 – 16.45	2026	Sep 2011	2014
JPSS-Only				
				JPSS-1 Launch
May 2010	\$11.90	2024	Sep 2011	2015
Dec 2011	\$14.60	2028	Oct 2011 (completed)	2017
Jun 2012	\$12.90	2028	Oct 2011 (completed)	2017
Jun 2013	\$11.30	2025	Oct 2011 (completed)	2017

Sources: GAO-10-558, GAO-12-604, NOAA FY 2014 Blue Book

NPOESS cost and schedule issues continued, and the cost estimate had risen to \$8.1 billion by 2004. Cost increases were attributed to technical development issues in key sensors, the delays due to budgetary change, and the need for additional risk mitigation funds and increases in management reserves. By this time, the trend of increasing cost and schedule overruns in the NPOESS program was clear.³⁶ By 2005, the Government Accountability Office (GAO) was referring

to the NPOESS program as “a program in crisis.”³⁷ Cost estimates had risen to approximately \$9.7 billion. The GAO contended that technical challenges were likely to persist, costs to grow, and schedule delays to increase. In addition to technical risk, the GAO concluded that a lack of executive leadership and timely decision making had contributed to program issues.³⁸



The Suomi NPP satellite orbits the Earth from pole to pole about 14 times a day, flying over almost every area of the globe twice. This “blue marble” image was created from multiple images taken by the VIIRS instrument on January 4, 2012. Credit: NASA

In late November 2005, it was determined that NPOESS was more than 25% over budget, automatically triggering a review of the program by Congress. Any decisions about the future of the program were on hold until this review, called a Nunn-McCurdy certification process, took place in June 2006. The restructuring resulted in a reduction of the number of satellites and sensors, so that only four satellites (in two orbits), rather than the originally

planned six satellites (in three orbits), would be built, and they would carry nine sensors each. The United States would rely on European satellites operated by the EUMETSAT for data from the mid-morning orbit. As part of the agreement, Europe would in turn rely on U.S. satellites for data in the afternoon orbit. Four climate and space environmental sensors were removed from the program. Four others were replaced with simpler, less capable, versions. The launches of the first two satellites were delayed three and five years, respectively, and the cost of the new program was estimated at \$12.5 billion, almost twice the original program estimate.³⁹ With the delays, the NPP satellite, which was originally meant to be a demonstration satellite for new sensors and not an operational asset, would also now act as a platform for providing continuity of weather and climate data if predecessor satellites degraded or failed.⁴⁰

Even after the restructuring, the program continued to experience schedule delays and cost growth. By June 2009, the life-cycle cost estimate had risen to \$13.95 billion, and program officials estimated that there would be further cost growth due to ongoing technical issues in sensor development. Delayed launch schedules meant that a single launch failure could result in a gap in satellite coverage from three to five years.⁴¹

By May 2010, 16 years had passed and \$5 billion had been spent since the NPOESS program began, yet not a single satellite had been launched.⁴² Amid these challenges, the Office of Science and Technology Policy, part of the Executive Office of the President, announced that the NPOESS program would be disbanded, and NOAA and the DoD would once again undertake separate acquisitions. NOAA has responsibility for satellites in the afternoon orbit and is developing JPSS for this purpose. The DoD has responsibility for the morning orbit and is responsible for developing its follow-on weather satellite program accordingly.⁴³ Due to this change, it was necessary to slow development work due to potential contract liabilities and funding constraints, causing further risk of gaps in satellite data.

Because the DoD still has two DMSP satellites that have not been launched, it is not yet developing a next-generation weather satellite, instead spending a minimal amount of funding appropriated in FY 2012 to study future requirements.⁴⁴ No funds were appropriated for follow-on weather satellite-related activities in the FY 2013 Consolidated and Further Continuing Appropriations Act, and no funds were requested in the President's FY 2014 DoD Budget Request.⁴⁵ GAO warns that the remaining two DMSP satellites were built in the late 1990s and may not work as intended by the time they are launched, due to their advanced age.⁴⁶

Shortly after restructuring, JPSS plans had to be reassessed when the program received less than half of the funding requested for FY 2011.⁴⁷ In late 2011, JPSS life-cycle costs through fiscal year 2028 were estimated at \$14.6 billion, including \$3.3 billion in NOAA sunk costs. The \$2.7 billion increase from the previous estimate was due to the extension of the program from 2024 to 2028, the addition of a free-flyer program to allow the launch of instruments that would not fit on the medium-sized JPSS bus, and the slowdown in activity caused by the low level of funding received in 2011.⁴⁸ NPP was launched in October 2011. The satellite was successfully activated and the instruments were commissioned, ensuring that each is responding to commands and operating as expected. NOAA is now conducting calibration and validation activities, which ensure the data provided by the satellite is ready for operational use. The agency expects this process to be complete by the end of 2013.⁴⁹

In its FY 2013 budget request, NOAA reduced the JPSS program life-cycle cost estimate to \$12.9 billion, and in its FY 2014 budget request this was further reduced to \$11.3 billion.⁵⁰ To do so, NOAA proposed in its FY 2014 budget, which has not been passed as of June 2013, to transfer climate sensors originally planned for JPSS-2 and Free Flyer-2 to NASA (which included additional funding in its FY 2014 budget request for these activities).⁵¹ No longer responsible for building or funding the Clouds and Earth's Radiant Energy System (CERES), the Ozone Mapping and Profiler Suite-Limb (OMPS-Limb), or the Total Solar Irradiance Sensor (TSIS), NOAA plans to

launch JPSS-2 two years earlier than previously expected, which could help mitigate potential gaps. Limiting the life-cycle estimate to 2025 and moving the Free Flyer-1 program to a separate line item within the budget also contributed to the apparent reduction in the estimate of JPSS life-cycle cost.⁵² The two largest challenges remaining in the JPSS program are mitigating the gaps in satellite data collection and the reduction in satellite capabilities.

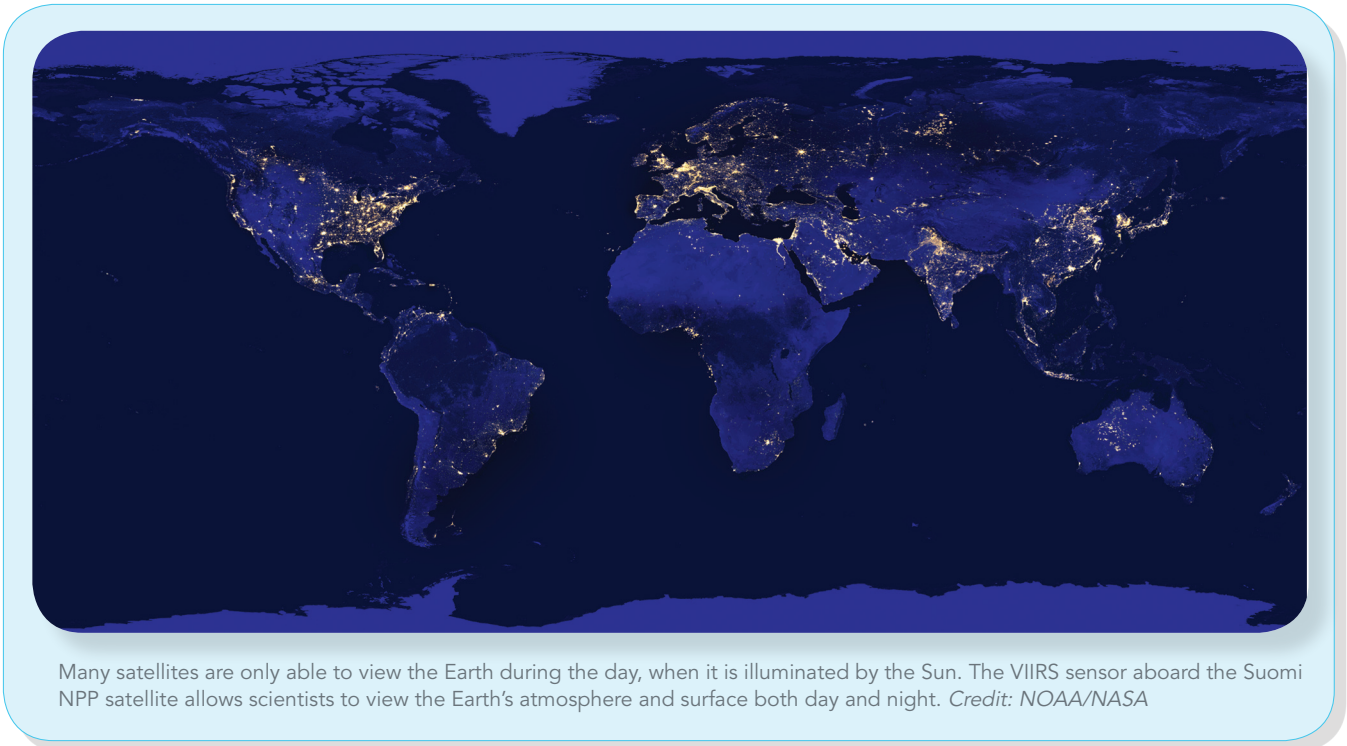
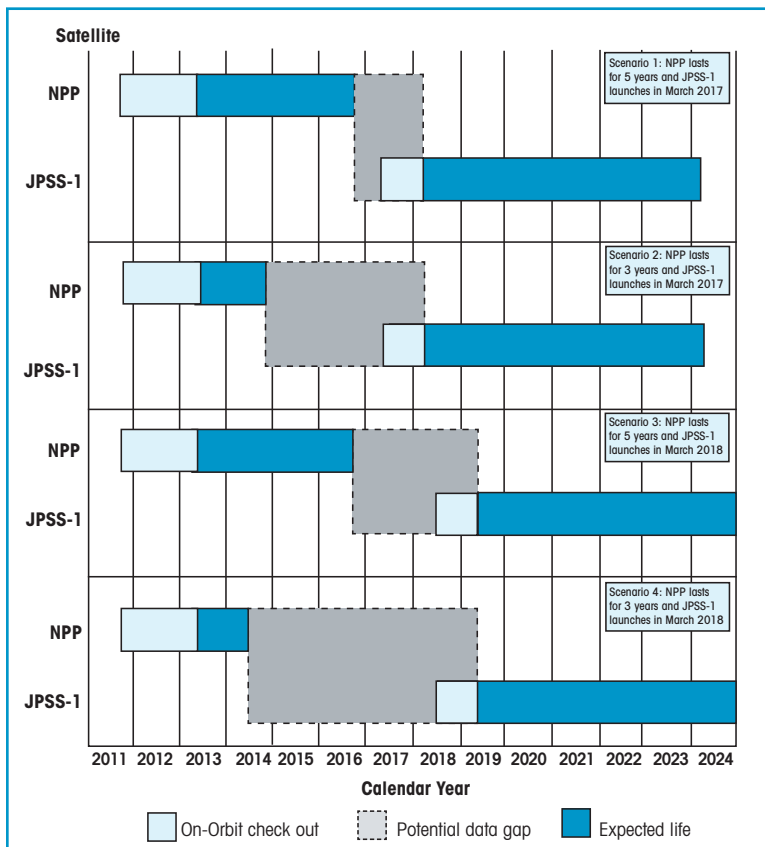


FIGURE 3: Potential Gaps in Polar Satellite Data in the Afternoon Orbit



Sources: GAO analysis of NOAA data, GAO-12-604.

Likely Gaps in Satellite Coverage

In 2002, when the program began, the first NPOESS satellite was expected to be launched into an afternoon orbit in 2009. By 2013, the original program had been canceled, and the launch date for the new satellite was 2017—an 8-year slip in schedule over an 11-year period. As launch dates for the first NPOESS satellite (now JPSS-1) were pushed back repeatedly over the years, a gap in polar-orbiting weather satellite data collection in the afternoon orbit became more and more likely. Now, a gap in satellite data is nearly certain to occur. The GAO estimated that this gap could range from approximately a year and a half to more than three years.⁵³

The exact duration of the gap will depend in part on the lifespan of the currently operating satellites, including the Suomi NPP satellite. Originally designed for

research use, not operational data collection, the satellite has a design life of just five years, which would mean it would stop collecting data in 2016, a year before JPSS-1 is launched. However, NASA managers have expressed concern with some NPP sensors, suggesting that NPP may only have a 3-year lifespan. If this happens, the gap in data collection would grow to more than three years. If the JPSS-1 program continues the pattern of development and launch delays of the NPOESS program, if JPSS-1 suffers a launch failure, or if NPP sensors degrade or die earlier than expected, the gap could be much greater.⁵⁴

As mentioned earlier, the data provided by polar-orbiting satellites is essential to accurate weather forecasting, particularly three- to seven-day forecasts. Gaps in satellite data will substantially degrade these forecasts, both for the United States and for its partners in Europe.⁵⁵ It is possible that instruments will last longer than their design life, which could help reduce a gap. However, relying on instruments that are past their design life is risky, and the likelihood of these instruments failing increases over time.

Reduction in JPSS Capabilities

JPSS-1 will carry five instruments that will take a combination of weather and climate-relevant measurements. The new technologies developed for the system will improve the timeliness and accuracy of future weather forecasts. JPSS is designed to capture up to five times more environmental data four times faster than current operational polar-orbiting satellites.⁵⁶

Like past polar weather satellites, JPSS satellites will carry imaging and sounding equipment, and it will use new technologies to improve on past capabilities. The Visible Infrared Imager Radiometer Suite (VIIRS) will provide images of clouds and land cover, improving on the precision of past weather satellites. The Cross-track Infrared Sounder (CrIS) will provide more accurate 3D pictures of temperature and moisture in the atmosphere. It will have greater vertical and horizontal resolution than past sounders, and it will look at more than 1,000 infrared spectral channels. This instrument will improve short-term weather monitoring and will be vital to understanding climate trends. A second sounder, the Advanced Technology Microwave Sounder (ATMS), will work with CrIS to measure atmospheric temperature and moisture. The ATMS is based on microwave sounding units currently flying on NOAA's POES, but it requires less volume, mass, and power. Combined with data from CrIS, ATMS will help to improve short- to medium-range weather forecasts.⁵⁷

In addition, JPSS-1 will carry two new instruments that were not included on polar weather satellites in the past. In some cases, their inclusion represents a transition from research status, in which the measurements were collected by NASA's research satellites, to operations status, in which NOAA will commit to collecting these measurements on an ongoing basis. The Ozone Mapping and Profiler Suite (OMPS) examines the concentration of ozone in the atmosphere at different altitudes. This is important for monitoring global climate and also fulfills a U.S. treaty obligation to monitor global ozone concentrations. While NPP carried the full instrument suite, JPSS-1 will only carry one portion of the instrument, limiting its capability, and JPSS-2 may not carry the instrument at all. The CERES instrument will help to improve weather forecasting and climate modeling by providing data on how clouds affect the Earth's energy balance (the energy coming in from the Sun and radiating out from the Earth). Lack of understanding of this effect is currently one of the largest sources of uncertainty in climate models. As with OMPS,



The Suomi NPP satellite underwent electromagnetic interference testing, shown here, in preparation for its October 2011 launch. Credit: NASA

FIGURE 4: Sensors Planned for NPOESS and JPSS Satellites⁵⁸

Sensor	NPOESS	NPOESS	NPOESS	JPSS
As of date	2002	2006	2008	2013
Advanced Technology Microwave Sounder	Dark blue	Dark blue	Dark blue	Dark blue
Aerosol Polarimetry Sensor	Dark blue	White	White	White
Conical-scanned Microwave Imager/Sounder	Dark blue	Gray	Gray	White
Cross-track Infrared Sounder	Dark blue	Dark blue	Dark blue	Dark blue
Data Collection System	Dark blue	Dark blue	Dark blue	*
Earth Radiation Budget Sensor	Dark blue	Gray	Gray	†
Global Positioning System Occultation Sensor	Dark blue	White	White	White
Ozone Mapper/Profiler Suite	Dark blue	Gray	Dark blue	†
Radar Altimeter	Dark blue	White	White	White
Search and Rescue Satellite Aided Tracking System	Dark blue	Dark blue	Dark blue	*
Space Environmental Sensor Suite	Dark blue	Gray	Gray	White
Total Solar Irradiance Sensor	Dark blue	White	White	* †
Visible/Infrared Imager Radiometer Suite	Dark blue	Dark blue	Dark blue	Dark blue

Key: Dark blue signifies that the sensor will be included on the satellite as originally planned. Gray signifies that a legacy or simplified version of the sensor will be launched. White signifies that this instrument will not be flown.

Items marked in gray: The Conical-scanned Microwave Imager/Sounder was replaced with a less complex microwave imager/sounder. The Earth Radiation Budget Sensor and the Space Environmental Sensor Suite were replaced with legacy sensors (the Clouds and the Earth’s Radiant Energy System and Space Environment Monitor, respectively). The Ozone Mapper/Profiler Suite is made up of both a limb and nadir component. While both flew on NPP, only the limb instrument will fly on JPSS-1.

* The Total Solar Irradiance Sensor, Data Collection System, and Search and Rescue Satellite Aided Tracking System are expected to fly on Free Flyer-1, not on the JPSS satellites.

† The President’s FY 2014 Budget Request includes the Clouds and Earth’s Radiant Energy System (CERES), the Ozone Mapping and Profiler Suite-Limb (OMPS-Limb), and the Total Solar Irradiance Sensor (TSIS) on JPSS-1, but not on JPSS-2. Responsibility for the instruments formerly planned for JPSS-2 would be transferred to NASA.

Sources: GAO-08-518, GAO-10-558, NOAA

CERES is a less-capable version of the originally planned Earth Radiation Budget Sensor, and it may only fly on the NPP and JPSS-1 satellites, not on JPSS-2. The FY 2014 President’s Budget Request proposes transferring to NASA the responsibility for the OMPS and CERES instruments originally planned for JPSS-2.⁵⁹

Although the sensor could not fit on the JPSS satellite bus, NOAA has also committed to flying the Total Solar and Spectral Irradiance Sensor (TSIS), another new instrument. As a payload on NOAA’s Free Flyer-1 satellite, TSIS will measure the Sun’s total output. This is important for understanding the state of Earth’s energy balance, which is critical for understanding climate change. Plans to launch the second TSIS sensor on a second free flyer were not approved, and responsibility for this instrument was transferred to NASA.⁶⁰

While the technological advances described above are important, they are significantly diminished compared to original plans for the next-generation weather satellite system, and this decrease in capabilities directly reduces the benefits of the JPSS program to the nation.⁶¹ In addition to the instruments that were reduced in scope, some instruments were removed altogether, including the Aerosol Polarimetry Sensor, the Conical-scanned Microwave Imager/Sounder, the Radar Altimeter, and the Space Environmental Sensor Suite. The Aerosol Polarimetry Sensor would have taken precise measurements of clouds and aerosols in the atmosphere. This type of data is used by the U.S. Air Force for military airborne planning and operations and is also a significant area of uncertainty in current climate research. The Radar Altimeter measures variances in sea surface height and ocean surface wind speed. This data is used by the marine cargo industry for routing and scheduling shipping routes, by the U.S. Navy for military logistics and planning, and by the petroleum industry in offshore drilling operations.⁶² With no plans to include these instruments on JPSS, many of these capabilities may not be available for more than a decade.

Challenges in Development: GOES-R

Like the polar-orbiting satellite program, the next-generation geostationary satellite program has experienced cost increases, schedule delays, and reductions in scope from early expectations. The GOES-R system was originally estimated to cost \$6.2 billion through 2034 and was planned for launch in 2012. In 2006, a program office review suggested that costs could reach \$11.4 billion, which led to a reduction in the scope of the requirements for the satellite series.⁶³ The program was reduced from four satellites to two (with the option to purchase two additional satellites), limiting the life cycle of the program to 2028. In addition, one of the three originally planned instruments was removed completely, which significantly decreased GOES-R cost estimates and reduced the risk of unacceptable schedule delays. However, two remaining instruments, the Advanced Baseline Imager (ABI) and Geostationary Lightning Mapper (GLM), both experienced technical challenges that led to cost increases.

Despite the reduction in scope, by 2009, the cost estimate had risen to \$7.67 billion through 2028, and the launch date had been moved to 2015.⁶⁴ In 2012, the estimate was revised again, to an estimated life-cycle cost of \$10.9 billion, and the launch of GOES-R was changed to late 2015. However, the cost increase in this case was due in part to the decision to exercise the option to buy two more GOES-R series satellites as part of the program, increasing the program lifespan to 2036.⁶⁵ The GAO warns that program reserve funds are being depleted quickly, and further cost increases and delays may occur in the future.⁶⁶ Like JPSS, the primary challenges currently faced by the GOES-R program include gaps in data collection and reductions in satellite capabilities.

Potential Gaps in Data Collection

This delayed launch schedule of GOES-R could leave NOAA without a backup satellite in geostationary orbit for the first time in more than a decade. If GOES-14 or -15 were to fail prematurely, this could result in a gap in satellite coverage.⁶⁷ The GAO has recommended that NOAA develop procedures to deal with this possibility. It has also recommended that NOAA develop continuity plans in the event that further delays in GOES-R launch dates occur.⁶⁸ One of the options that NOAA may choose involves temporary coverage by an international satellite, an option that has been used in the past and for which NOAA has already developed international agreements.⁶⁹

Reductions in GOES-R Scope

The GOES-R system represents the first major technological advance in GOES instrumentation since 1994.⁷⁰ GOES-R series satellites will have much greater weather monitoring capabilities due to the inclusion of two new instrument suites.



The Advanced Baseline Imager, developed for the GOES-R satellite series, will improve every product the current GOES imager produces and will provide new products that enhance weather forecasting.
Credit: NOAA/NASA

The Advanced Baseline Imager (ABI) will be the primary instrument for monitoring Earth's weather and environment. While the current system has five different channels (spectral bands), ABI will have 16. With these additions, ABI will provide three times as much spectral information, four times the spatial resolution, and more than five times faster temporal coverage than the current system. This means that when experts are watching storms develop, for example, the greater amount of spectral information allows them to better distinguish different aspects of the system, such as types of clouds or wind speeds. The greater spatial resolution means they can see storms develop in greater detail and know more precisely where the storm is located and where it is moving. Faster temporal coverage means that the image will refresh more quickly, making it possible to observe changes in the storm over small time

periods. The ABI is expected to improve every product that the current GOES imager produces as well as to make the creation of new products possible. The benefits from the ABI are projected to be \$4.6 billion over the lifetime of the series. Savings come from a variety of weather-affected areas. For example, improved tropical cyclone forecasts can help to reduce unnecessary evacuations and allow fewer weather-related flight delays.⁷¹

The second important weather-monitoring instrument on the GOES-R series is the Geostationary Lightning Mapper (GLM). No previous GOES satellite has included a sensor to monitor lightning. GLM will monitor cloud-to-cloud and cloud-to-ground lightning activity throughout the day and night. Increased lightning activity can provide an early indication of storm intensification and severe weather events. Analysis of this data can also help to provide tornado warning lead time and reduce false alarms.⁷²

Despite these impressive improvements, GOES-R does not include the full set of capabilities originally included in its design. As part of the 2006 reduction in scope, NOAA removed the Hyperspectral Environmental Suite (HES). This instrument would have provided information on atmospheric moisture and temperature profiles that would have supported weather forecasting and climate modeling. It would also have provided higher resolution and faster coverage than the atmospheric sounder instrument on the GOES satellites currently in orbit.⁷³ NOAA had planned to use the new sounding products that HES could produce to improve the lead times for weather warnings. For example, along with technical advances in other areas, those included in HES could have helped to increase lead times associated with severe thunderstorm warnings from an average of 18 minutes in 2000 to as much as two hours by 2025, and could help to increase the lead times associated with tornado warnings from an average of 13 minutes in 2007 to as much as one hour by 2025.⁷⁴ However, HES was not seen as the highest priority instrument on GOES, and studies showed that it was not essential to the traditional GOES weather-monitoring mission.⁷⁵

NOAA will be able to ensure continuity of currently available products based on GOES data using the Advanced Baseline Imager, which will be capable of providing many of the products that would have come from HES. Although in some cases the ABI will provide comparable spatial resolution, and in a few cases it will have even finer resolution than the current sounder, it was also determined that data from the ABI would be less accurate than the existing sounder in producing many of the products.⁷⁶ Although HES presented a significant step forward in technology development, it also represented a very serious potential for major cost growth and schedule delay. It was determined that removing the instrument was necessary in order to emphasize the primary mission of the GOES program.

With respect to GOES-R, reductions occurred not only in the technology, but also in plans for data use. NOAA reduced the overall number of satellite products—the formatted output of the data provided to end-users—from 81 to 34, with a contract option to add 31 products if funding allows. Some of these optional products include aircraft icing threat, turbulence, and visibility.⁷⁷ Nine of these 31 are products that are currently produced using the existing GOES system but will not be produced under the new system unless the contract option is exercised.⁷⁸ In some cases, the next-generation system will provide less to the end-user than what they currently receive.

Recommendation 1: Program offices should provide accurate and stable life-cycle cost estimates for weather satellite programs, and Congress should respond with full and stable funding for these programs, including JPSS, GOES-R, and the Constellation Observing System for Meteorology, Ionosphere, and Climate 2 (COSMIC-2).

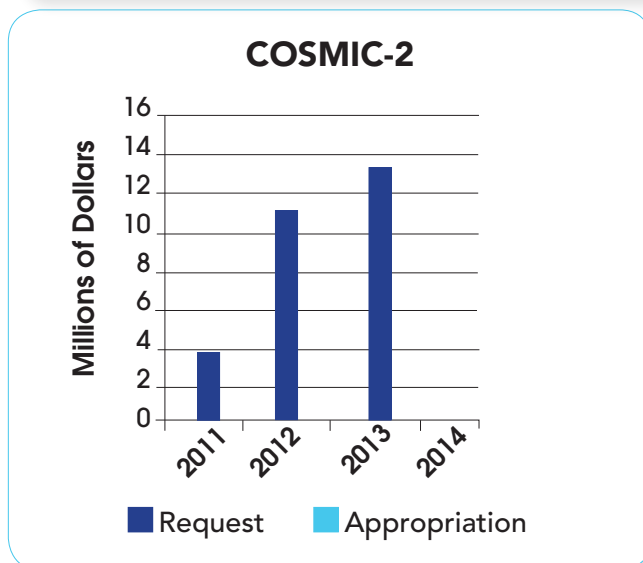
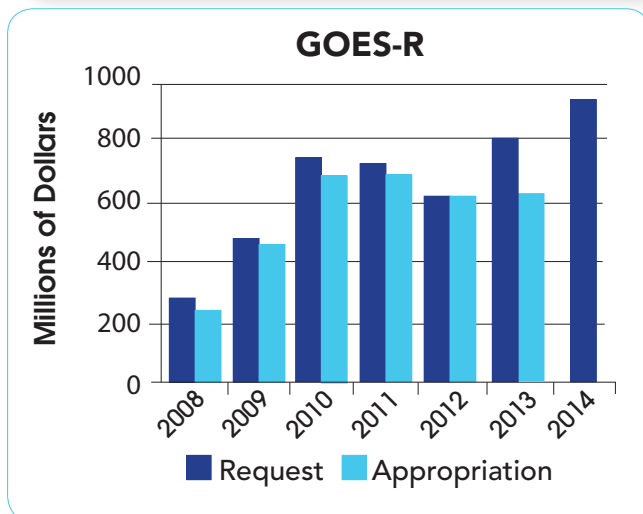
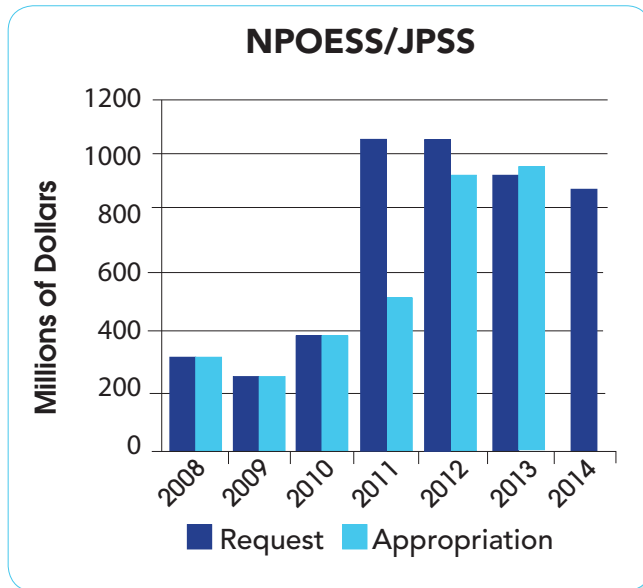
One of the most striking aspects of both next generation weather satellite programs has been the many increases in life-cycle costs. The polar-orbiting program began in 2002 as a \$7 billion joint military and civilian program to develop six operational satellites, and by 2013 it was an \$11 billion civilian-only program to develop two primary operational satellites, with fewer instruments, fewer capabilities, and later launch dates. GOES-R began as a \$6 billion program in 2006 and is now an \$11 billion program missing one of its primary instruments, leading to significantly reduced capability. It is imperative that programs develop accurate and stable life-cycle cost estimates. This requires fully defined schedules, as described by GAO, and inclusion of adequate cost and schedule reserves. Although recent NOAA testimony before Congress stated that life-cycle estimates are now solid, GAO has expressed concern about the potential for future problems in both weather programs, leading to their inclusion on GAO's high risk list.⁷⁹ NOAA should address this issue and provide accurate and stable life-cycle cost estimates for all weather satellite programs. This can be very challenging when developing new technologies, particularly early in the program when technology development requirements are still being studied. Increased understanding based on these initial studies can lead to an upward revision of overall costs and even to a legitimate need to reduce original scope of the program. However, estimates at all times in development should be as accurate as possible.

It is important that these estimates are made with the long-term benefit of the nation in mind. An overemphasis on budget levels has led, on numerous occasions, to decisions that do not provide the best value for the United States in the long term. For example, when increasing life-cycle costs led to a reorganization of GOES-R in 2006, one of the actions taken to lower costs was to reduce the number of satellites procured from four to two (with the other two left as contract options). Although this action removed about \$3 billion from the life-cycle cost of the program, it did so primarily by shortening the lifespan of the program. The United States would have still required the same number of satellites in the long term, but if options for the additional two satellites were not exercised, they would require an entirely new contract and program. Building multiple copies of a satellite or instruments that are already being developed is almost certainly cheaper than beginning a new development program, so this action to reduce GOES-R program costs would likely lead to increased costs to the taxpayer in the long term. This particular decision was reversed in 2012, but the original decision led to time and effort lost on program planning and scheduling that was not necessary.

Similarly, recent efforts to reduce JPSS program costs included actions such as moving components of the program to a separate budget line item or transferring sensors to another agency. Although creating a separate line item for instruments originally planned as part of JPSS does decrease the cost of the JPSS program on paper, it does not provide any true savings to the taxpayer. Similarly, transferring back to NASA sensors that had already undergone the difficult research-to-operations transition does not save the taxpayer money, it simply moves the cost of these instruments from NOAA's budget to NASA's. In doing so, it also causes significant confusion about how the operational requirements for data from those instruments will be addressed, whether the instruments can be used operationally, and which agency will be responsible for ensuring future continuity of those instruments. In developing life-cycle estimates and the associated yearly budgets, NOAA and Congress should emphasize smart, long-term decisions over shortsighted efforts to reduce costs now.

Although technical and managerial challenges contributed to launch delays and life-cycle cost increases, inadequate and unstable funding were also major drivers of these problems.⁸⁰ Weather satellite programs repeatedly received lower funding than requested. The lack of adequate funding forces changes in schedule that delay milestones.

FIGURE 5: NPOESS/JPSS, GOES and COSMIC-2 Budgets



As program development is stretched out, overall life-cycle costs increase. In FY 2011, NOAA requested approximately a billion dollars for the JPSS program and received less than half that amount. This forced the JPSS program office to slow work on JPSS-1 while prioritizing the near-term launch of NPP. This led directly to later launch dates for JPSS-1 and -2 and an increase in the likelihood of a gap in satellite data collection, which puts lives and property at risk.⁸¹ GOES-R has also repeatedly received lower funding levels than requested, and the GOES-R program office lists program funding stability as the highest risk to its overall life-cycle costs.⁸² Finally, despite the widely recognized success of the COSMIC program, Congress has repeatedly declined to provide any funding for COSMIC-2. Data from GPS radio occultation satellites improves forecasts that affect billions of dollars across many industries. Although this data would not completely remedy the likely gap in data collection, it could help to mitigate the effects.⁸³ Congress should fully fund these three weather satellite programs to prevent further launch delays, mitigate potential data gaps, and avoid slowdowns that lead to increased life-cycle costs.

Recommendation 2: The United States should seek opportunities to increase international cooperation on weather satellite programs to help decrease costs and increase capabilities.

Weather does not stop at a nation's boundaries. Accurate weather prediction requires information about atmospheric conditions around the world. The World Meteorological Organization (WMO), an agency of the United Nations, includes members of 191 states and territories.⁸⁴ Although every country uses weather data, and many countries operate Earth observation satellites that are used for research purposes, there are only seven operators of weather satellites: the United States, Europe, India, Russia, China, Korea, and Japan. Only four of these—the United States, Europe, Russia, and China—operate polar-orbiting weather satellites.⁸⁵

Source: NOAA Blue Books for Fiscal Years 2008-2014

Weather satellites provide an excellent opportunity for international cooperation, because all countries require the same types of global data for numerical weather forecasting models. Rather than building redundant systems to collect this data, it is possible to coordinate data collection. One way to do this is through joint constellation planning, in which each partner is responsible for developing satellites for one portion of the constellation. The United States and Europe have taken the first steps toward doing this in the Initial Joint Polar System (IJPS) and the Joint Transition

FIGURE 6: Operational Weather Satellites as of June 2013

GEO Satellites	Polar Satellites
United States (NOAA)	
GOES-12	NOAA-15
GOES-13	NOAA-16
GOES-14	NOAA-18
GOES-15	NOAA-19
	Suomi NPP
United States (DoD)	
	DMSP-F13
	DMSP-F14
	DMSP-F15
	DMSP-F16
	DMSP-F17
	DMSP-F18
Europe (EUMETSAT)	
Meteosat-7	Metop-A
Meteosat-8	Metop-B
Meteosat-9	
Meteosat-10	
India (ISRO)	
INSAT-3A	
INSAT-3C	
INSAT-3E	
Kalpana-1	
Russia (RosHydroMet)	
Electro-L N1	Meteor-M N1
China (CMA)	
FY-2D	FY-3A
FY-2E	FY-3B
FY-2F	
Korea (KMA)	
COMS-1	
Japan (JMA)	
Himawari-6/ MTSAT-1R	
Himawari-7/ MTSAT-2	

Source: World Meteorological Organization

Activities (JTA) agreement. Under these agreements, the United States collects data in the afternoon orbit and Europe collects data in the mid-morning orbit.⁸⁶ This type of cooperation led to significant cost savings for the United States, which was able to reduce its collection responsibilities from two orbits down to one, and reduce its planned civilian satellite program from four satellites to two, without reducing the quantity or quality of data. The United States is currently developing a follow-on agreement to the IJPS and JTA. These types of partnerships can be challenging because they rely on mutual trust. The gap in polar-orbiting data collection between the end of the NPP satellite and the launch of JPSS will affect Europe in a similar way to the United States, but Europe did not have a vote in management and budgeting decisions that affected this gap. Despite the difficulties, it is important that the United States maintains this key partnership with Europe and looks for opportunities to expand, increasing benefits. One option would be to bring Russia and China, the two additional countries that currently operate polar-orbiting weather satellites, into the partnership, further sharing costs and benefits. This is particularly useful as other countries begin to improve their data collection capabilities.

The United States also partnered very successfully with the Taiwan National Space Organization (NSPO) on the COSMIC program. As part of this partnership, the United States was able to get valuable data from a constellation of GPS radio occultation satellites that significantly improved forecasts without paying the full cost of this constellation. The United States currently has the opportunity to continue this successful partnership with the development of COSMIC-2. Congress should embrace this opportunity and provide funding for this program.

International cooperation can also take the form of an exchange of satellite instruments. This reduces costs and promotes interoperability. It is often less expensive to develop two identical copies of an instrument rather than developing two unique instruments. The instrument copy can be flown on a partner satellite. This allows the United States to get twice the amount of data without paying for a second satellite launch. Using the exact same instrument also ensures that the data collected by each satellite is very easy to compare or integrate. If a partner nation develops additional instruments as part of the exchange, this allows the United States to increase the capability of its satellites by adding the new instrument without facing any of the development costs associated with creating that instrument. This type of exchange was done very successfully as part of the current agreements with Europe, but it may not be continued in the future. The United States should retain this element of the agreement and look for other opportunities for instrument exchanges that can lower costs and increase capabilities for the United States.

In some cases, the United States develops special arrangements to access data from other nations' satellites. This is the case for Japan's Global Climate Observation Mission 1 - Water (GCOM-W1) satellite, which the United States will use to meet operational requirements that would otherwise be difficult to achieve. As part of a Memorandum of Understanding with the Japan Aerospace Exploration Agency (JAXA), NASA will provide ground support for the satellite by processing, archiving, and distributing data from the Advanced Microwave Scanning Radiometer 2 (AMSR2). The instrument will provide data that helps to forecast severe storms, monitor sea ice, and predict the onset of climate phenomena, such as El Niño and La Niña.⁸⁷ A great deal of satellite Earth observation data is shared freely. The United States can benefit by taking advantage of these foreign data sources and by actively encouraging other nations to increase the amount of data that is shared.

Finally, international cooperation can help to reduce risks in the event of unexpected satellite failure. The Coordination Group for Meteorological Satellites (CGMS), which works closely with WMO, helps to facilitate these arrangements. Contingency plans have been used in the past; for example, Europe's Meteosat-3 replaced GOES-7 in order to continue monitoring the Atlantic region, and GOES-9 was moved westwards over the Pacific Ocean to fill gaps between Japan's GMS-5 and MTSAT-1R satellites.⁸⁸ The United States currently has agreements with Europe and Japan to provide geostationary satellite coverage in the event of the loss of a GOES-East or GOES-West satellite.

The international nature of weather and weather monitoring makes this activity particularly well suited for international cooperation. Existing international agreements have allowed the United States to reduce costs and increase capabilities in an efficient way. It is important that the United States continue to support these types of arrangements by providing funding and meeting the obligations of these agreements. The United States should also look for additional opportunities to share costs internationally.

Recommendation 3: The United States should explore the potential for working with commercial weather satellite data providers to augment current weather satellite capabilities and improve weather forecasting.

Just as international cooperation offers the potential for decreased costs and increased capabilities, working with commercial entities may also be beneficial for the U.S. weather program. Purchasing data from commercial entities is not a new activity for NOAA, which purchased ocean color data for many years from the Sea-viewing Wide Field-of-view Sensor (SEAWiFS) hosted aboard the Orbview II satellite operated by remote sensing company GeoEye. Synthetic aperture radar (SAR) data is purchased from commercial sources in Canada and Europe, allowing NOAA to more accurately detect and monitor ice. This data helps the U.S. National Ice Center to create products identifying safe navigational routes through ice-covered waters.

In FY 2008, NOAA developed a formal process to get information on the commercial sector's capabilities, allowing the agency to better assess the feasibility of future partnerships. The weather information obtained from commercial sources would supplement GOES-R and JPSS. After an initial request for information was posted by NOAA, a conference was held to allow government representatives to present agency missions, goals, and requirements related to Earth observation. Following this event, NOAA developed a series of request for quote (RFQ) solicitations to establish price validation and technical feasibility studies for using commercial services to meet their requirements. The solicitations were released in three sets over the course of 2008 and 2009. NOAA awarded RFQ study contracts worth \$25,000 each to a number of companies in relation to each of these sets, as described in Figure 7.⁹⁰

Through its analysis of the first set of RFQ contracts, NOAA determined that there are services for environmental data collection with potential value for the government. These include total solar irradiance monitoring via a

FIGURE 7: NOAA Contracts for Studying Feasibility of Commercial Weather Observations

Study Contract Award Date	Company	Observation Requirement	
Mar 2008	Iridium	GPS Radio Occultation	
	Orbcomm		
	GeoOptics		
	Iridium	Solar Irradiance	
			Orbcomm
			Microsat Systems
	Space Services	Solar Wind	
	Space Services	Coronal Mass Ejection	
	Orbcomm		
Jun 2009	Iridium	Earth Radiation Budget	
	Orbital Sciences		
	Sierra Nevada Corporation		
	Surrey Satellite Technology US		
	Iridium	Sea Surface Height/ Topography	
	Surrey Satellite Technology US		
	ITT Space Systems	Geostationary High Spectral Atmospheric Profiles	
	Space Systems/ Loral		
	Surrey Satellite Technology US		
	ITT Space Systems	Ocean Color	
	GeoEye		
	Mississippi State University		
Sep 2009	Iridium	Ozone Profiles	
	Orbital Sciences		
	Sierra Nevada Corporation		
	Orbital Sciences	Aerosol Particles	

Source: U.S. Department of Commerce, Office of Space Commercialization

Two relatively new companies, GeoOptics and PlanetiQ, both aim to develop constellations of GPS radio occultation satellites. PlanetiQ plans to launch a 12-satellite constellation, which could be ready two to three years after construction of the satellites begins, soon enough to help mitigate gaps in data collection if the decision to build is made quickly. The company estimates the cost to the government would be less than \$70 million a year.⁹³ GeoOptics has plans for an even larger constellation of GPS radio occultation satellites, with 24 or more satellites planned over eight years. GeoOptics plans to make data from its constellation free to all researchers and developing countries. The company will also offer a worldwide license for purchase by any entity or group that would allow the data to be freely shared. The first spacecraft is expected to launch in 2014, with a fully operational 12-satellite constellation in orbit by 2017.⁹⁴

government-developed payload hosted on a commercial satellite, solar wind data purchased from commercial industry, and GPS radio occultation data either purchased commercially or collected via government-developed payloads launched on a constellation of commercial satellites.⁹¹

In September 2010, the Commercial Remote Sensing Regulatory Affairs Office within NOAA granted GeoMetWatch a license to operate a private Geostationary Hyperspectral Imaging/Sounding System. The proposed system can include up to six satellites in geostationary orbit, providing products for advanced environmental and weather observations. With NOAA's Hyperspectral Environmental Suite (HES) removed from GOES-R, GeoMetWatch's instrument would offer a valuable capability that the U.S. government does not currently possess. It would collect data in 1800 different spectral channels; current U.S. geostationary sounders collect data in about 18 channels. This capability makes it possible to distinguish between the movements of water vapor, carbon dioxide, and other elements of the atmosphere, each of which reflects light in a unique way. The data collected by this instrument has the potential to greatly improve weather forecasting, particularly the development of hurricanes and other extreme weather events. The instruments are expected to be launched as hosted payloads on commercial communications satellites. The first GeoMetWatch sounder is expected to launch aboard the AsiaSat Communications satellite in 2016 and provide data over the Asia-Pacific region.⁹²

Despite strong interest from industry, there are numerous challenges to using commercial data sources to supplement NOAA's core satellite systems. One of the primary reasons that commercial data purchases are less expensive than satellite ownership is because the fixed costs of the system are shared with other customers. However, NOAA follows a full and open data policy that allows it to widely distribute its products and services. This is essential in fulfilling its missions related to public safety and global environmental monitoring. U.S.-collected weather data is used by nations around the world and forms the backbone of the commercial value-added weather industry in the United States. This open data policy may conflict with the proprietary data management incentives of the commercial space sector. If NOAA purchases a fully open license that allows it to share the data freely, then it would likely be the only customer for the company because other organizations would get the data from NOAA for free. In this case, it is not clear whether the system would be less expensive than traditional government procurement methods.

Further, NOAA is also prohibited by law from leasing, selling, transferring to the private sector, or commercializing its weather satellite systems. This could become a barrier if the acquisition of commercial data sources is seen as an attempt to commercialize NOAA weather satellites. In addition, NOAA requires Earth data records and measurements that meet the strict technical requirements of the scientific community. These accuracies and tolerances are often more stringent than commercial operations.

Despite these challenges, benefits from partnerships with industry are still possible. Commercial entities are often thought to be more efficient, with incentives to reduce operating costs to increase profits. Innovative new ideas in the commercial sector may lead to new technologies for which the government does not have to pay research and development costs. Creative licensing agreements, for example, those based on timeliness of the data, may provide opportunities for meeting necessary requirements. The United States should actively seek opportunities for commercial partnerships that meet its requirements while reducing costs and increasing capabilities.

Recommendation 4: The United States should conduct a comprehensive review of its weather satellite program portfolio to determine the correct level and distribution of funding to achieve the desired capabilities. The first three recommendations are built upon the premise that there are good and timely opportunities for the United States to improve the efficiency of its weather satellite programs. The United States should provide accurate and stable budget estimates, choose forward-looking budget savings rather than shortsighted options, and provide full and stable funding for existing programs. The opportunities to improve efficiency through partnerships with other nations and the commercial sector are increasing. These partnerships can save U.S. taxpayers money and improve capabilities while side-stepping costly and time-consuming development cycles. The United States should carefully examine these opportunities and determine the best distribution of funding among different types of partnerships and programs. However, increasing efficiency is not enough on its own. With billions of dollars of property and productivity and thousands of lives at stake, the United States must determine whether it is providing the correct level of funding, management, and strategic direction for its weather systems.

On May 20, 2013, a tornado swept through the small town of Moore, Oklahoma, killing 23 men, women, and children.⁹⁵ While residents in Moore received their first warning 16 minutes before the tornado touched down and 36 minutes before the tornado reached their town, average tornado warning lead-time (between the initial warning and the touch-down of the tornado) is only 13 minutes.⁹⁶ Just days later, the House Subcommittee on Environment held a hearing titled, "Restoring U.S. Leadership in Weather Forecasting." The committee asked whether anything could be done to improve forecasting time for tornadoes. As noted previously, the HES instrument originally planned for inclusion on GOES-R would have, in combination with other advances such as the improved capabilities

provided by ABI and GLM, helped to increase tornado warnings to approximately one hour, significantly increasing the time people have to find shelter. However, seven years earlier, insistence by Congress that GOES-R keep costs down led to this potentially lifesaving instrument being removed from the satellite. The decision was believed to save approximately \$5 billion over the lifespan of the program and prevent delays in GOES-R that could have led to unacceptable gaps in geostationary weather satellite data.⁹⁷ However, given the thousands of lives that could have been affected by just the tornado-warning improvement provided by this technology, it is worth considering whether this decision ultimately is in the best interest of the nation.

Making these types of trade-offs is difficult. Weather and climate affect almost every industry and every individual, and accurate weather forecasts can help save billions of dollars. However, government funds are not unlimited, and increasing funding in any area is challenging in such difficult economic times. Nevertheless, the government has a responsibility to make these decisions carefully and with all necessary information. If Congress chooses not to provide additional funding to maintain a weather satellite sensor, it should be informed of exactly what capabilities are being lost. The United States should conduct a comprehensive review of its weather satellite portfolio to determine the correct level and distribution of funding to achieve the desired capabilities.

Conclusion

Weather satellites are critical to our ability to monitor and predict the weather, and improvements in satellite capabilities lead to improved weather forecasts that can help save lives and property. In the United States, both the geostationary and the polar-orbiting weather satellite systems are undergoing a major upgrade in capabilities. In the course of their development, both efforts have faced challenges that led to cost overruns, schedule delays, and reductions in capabilities. Both projects now run a risk of gaps in satellite coverage, which could lead to a reduction in U.S. capability to accurately forecast weather, including severe storms. Understanding how these programs developed helps to identify both lessons for the future and also the ongoing challenges that need to be addressed.

Adequate funding and close management oversight will be required to minimize the danger of gaps in satellite coverage. It is essential that these systems are provided to ensure that U.S. citizens and industries as well as others around the world continue to get the weather forecasts they rely on for decision-making and daily activity. In addition, the United States should investigate the possibility of increased cooperation with other nations and with commercial organizations.

Decreases in planned sensor capabilities and products for these satellites could mean that the United States does not capture all of the potential benefits of advances in modern technology. If the United States did develop these capabilities, improvements in weather prediction, such as significantly more timely warnings of severe storms or tornadoes, could help to save lives and property. Weather satellites are essential to daily life, and the capabilities they provide should not only be continued without degradation but also improved as we move forward as a nation.

If you have questions about this paper, please contact research@spacefoundation.org. To learn more about the Space Foundation, visit www.spacefoundation.org. Space Foundation research products can be found at www.spacefoundation.org/research.

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Endnotes

- ¹⁴“Billion Dollar Events.” *Billion-Dollar Weather/Climate Disasters*. NOAA, n.d. Web. 28 June 2013. <<http://www.ncdc.noaa.gov/billions/events>>.
- ²United States. NOAA. *Continuing Oversight of the Nation’s Weather Satellite Programs – An Update on JPSS and GOES-R*. By Kathryn D. Sullivan. NOAA, 27 June 2012. Web. 28 June 2013. <<http://www.legislative.noaa.gov/Testimony/Sullivan062712.pdf>>.
- ³*High-Risk Series: An Update*. Rep. no. GAO-13-283. United States Government Accountability Office, Feb. 2013. Web. 28 June 2013. <<http://www.gao.gov/assets/660/652133.pdf>>.
- ⁴Polar-orbiting Environmental Satellites: Changing Requirements, Technical Issues, and Looming Data Gaps Require Focused Attention. Rep. no. GAO-12-604. GAO, 15 June 2012. Web. 28 June 2013. <<http://www.gao.gov/assets/600/591643.pdf>>.
- ⁵“Joint Polar Satellite System (JPSS).” *JPSS Launch Schedule*. NOAA, n.d. Web. 28 June 2013. <http://www.jpss.noaa.gov/launch_schedule.html>.
- ⁶United States. NOAA. *Continuing Oversight of the Nation’s Weather Satellite Programs – An Update on JPSS and GOES-R*. By Kathryn D. Sullivan. NOAA, 27 June 2012. Web. 28 June 2013. <<http://www.legislative.noaa.gov/Testimony/Sullivan062712.pdf>>.
- ⁷United States. NOAA. *Agreement Between the United States National Oceanic and Atmospheric Administration and the European Organisation for the Exploitation of Meteorological Satellites on an Initial Joint Polar-orbiting Operational Satellite System*. Washington: n.p., 1998. Print.
- ⁸“The GOES Program History.” *Geostationary Operational Environmental Satellite*. NASA, 22 Apr. 1999. Web. 28 June 2013. <<http://goes.gsfc.nasa.gov/text/history/goes/>>.
- ⁹“Missions: TIROS.” *Television Infrared Observation Satellite Program*. NASA Science, 30 Apr. 2013. Web. 28 June 2013. <<http://science.nasa.gov/missions/tiros/>>.
- ¹⁰“NOAA Economics.” Economics and Social Benefits of NOAA Data & Products. NOAA, n.d. Web. 27 May 2010. <<http://web.archive.org/web/20100527173057/http://www.economics.noaa.gov/?goal=weather&file=obs/satellite/goes/>>. *Water Markets of the United States and the World: A Strategic Analysis for the Milwaukee Water Council*. Rep. University of Wisconsin-Milwaukee, 1 Nov. 2010. Web. 28 June 2013. <<http://www.thewatercouncil.com/wp-content/uploads/2012/04/EDA-Report.pdf>>.
- ¹¹“NOAA Economics.” *Economics and Social Benefits of NOAA Data & Products*. NOAA, n.d. Web. 27 May 2010. <<http://web.archive.org/web/20100527173057/http://www.economics.noaa.gov/?goal=weather&file=obs/satellite/goes/>>. *An Investigation of the Economic and Social Value of Selected NOAA Data and Products for Geostationary Operational Environmental Satellites (GOES): A Report to NOAA’s National Climatic Data Center*. Rep. CENTREC Consulting Group, 28 Feb. 2007. Web. 28 June 2013. <<http://www.centrec.com/resources/reports/GOES%20Economic%20Value%20Report.pdf>>.
- ¹²“Why Polar-orbiting?” *National Polar-orbiting Operational Environmental Satellite System*. NOAA Satellite and Information Service, 2 Feb. 2009. Web. 28 June 2013. <<http://web.archive.org/web/20090822023330/http://www.ip.noaa.gov/index.php?pg=yorbit>>. “NOAA’s Geostationary and Polar-Orbiting Weather Satellites.” *NOAA Satellite Information System*. NOAA, 28 Mar. 2013. Web. 28 June 2013. <<http://noaasis.noaa.gov/NOAASIS/ml/genlsat.html>>.
- ¹³United States. NOAA. *Agreement Between the United States National Oceanic and Atmospheric Administration (NOAA) and The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) on Joint Transition Activities Regarding Polar-orbiting Operational Environmental Satellite Systems*. U.S. State Department, 24 June 2003. Web. 28 June 2013. <<http://www.state.gov/documents/organization/152189.pdf>>. United States. NOAA. *Agreement Between the United States National Oceanic and Atmospheric Administration and the European Organisation for the Exploitation of Meteorological Satellites on an Initial Joint Polar-orbiting Operational Satellite System*. Washington: n.p., 1998. Print.
- ¹⁴“POES Spacecraft Status Main Page.” *POES Status*. NOAA Office of Satellite Operations, 9 May 2013. Web. 28 June 2013. <<http://www.oso.noaa.gov/poesstatus/>>.
- ¹⁵United States. NOAA. *Continuing Oversight of the Nation’s Weather Satellite Programs – An Update on JPSS and GOES-R*. By Kathryn D. Sullivan. NOAA, 27 June 2012. Web. 28 June 2013. <<http://www.legislative.noaa.gov/Testimony/Sullivan062712.pdf>>.
- ¹⁶“GOES Project.” Geostationary Operational Environmental Satellites. NASA, 5 Nov. 2012. Web. 28 June 2013. <<http://web.archive.org/web/20130118090712/http://goes-n-o-p.ndc.nasa.gov/>>. *NOAA GOES-N,O,P – The Next Generation*. N.p.: n.p., n.d. NASA, NOAA. Web. 28 June 2013. <http://www.osd.noaa.gov/GOES/GOES-NOP_Brochure.pdf>.
- ¹⁷“The GOES Program History.” *Geostationary Operational Environmental Satellite*. NASA, 22 Apr. 1999. Web. 28 June 2013. <<http://goes.gsfc.nasa.gov/text/history/goes/>>.
- ¹⁸“NOAA Weather Satellites.” *Marine Forecasts*. NOAA’s National Weather Service, 10 July 2003. Web. 28 June 2013. <<http://www.weather.gov/om/marine/wxsat.htm>>.
- ¹⁹“The GOES Program History.” Geostationary Operational Environmental Satellite. NASA, 22 Apr. 1999. Web. 28 June 2013. <<http://goes.gsfc.nasa.gov/text/history/goes/>>.
- ²⁰Cucurull, L., J. C. Derber, and W. Lapenta. “Assessing the Benefits of Assimilating GPS RO Profiles into Global Numerical Weather Prediction Models.” Lecture. WMO Workshop. Sedona, Arizona. 22 May 2012. World Meteorological Organization. Web. 28 June 2013. <http://www.wmo.int/pages/prog/www/OSY/Meetings/NWP5_Sedona2012/1b5_Cucurull.pdf>.
- ²¹United States. NOAA. Budget Office. *FY 2011 Blue Book: Chapter 3: NOAA Procurement, Acquisition and Construction*. NOAA, n.d. Web. 28 June 2013. <http://www.corporateservices.noaa.gov/nbo/11bluebook_highlights.html>.

- ²²Berger, Brian. "Funding Uncertainty Could Hobble U.S.-Taiwan Weather Satellite Mission." *Space News*. N.p., 31 May 2013. Web. 28 June 2013. <<http://www.spacenews.com/article/civil-space/35576funding-uncertainty-could-hobble-us-taiwan-weather-satellite-mission>>.
- Harnisch, Florian, Sean Healy, Peter Bauer, and Stephen English. "Estimating the Optimal Number of GNSS Radio Occultation Measurements for Numerical Weather Prediction: ESA Funded GALILEO Science Study." Lecture. 2nd IROWG Workshop 2012. Estes Park, CO. Mar. 2012. Web. 11 July 2013.
- ²³Cucurull, L., J. C. Derber, and W. Lapenta. "Assessing the Benefits of Assimilating GPS RO Profiles into Global Numerical Weather Prediction Models." Lecture. WMO Workshop. Sedona, Arizona. 22 May 2012. World Meteorological Organization. Web. 28 June 2013. <http://www.wmo.int/pages/prog/www/OSY/Meetings/NWP5_Sedona2012/1b5_Cucurull.pdf>.
- Berger, Brian. "Funding Uncertainty Could Hobble U.S.-Taiwan Weather Satellite Mission." *Space News*. N.p., 31 May 2013. Web. 28 June 2013. <<http://www.spacenews.com/article/civil-space/35576funding-uncertainty-could-hobble-us-taiwan-weather-satellite-mission>>.
- ²⁴Berger, Brian. "Funding Uncertainty Could Hobble U.S.-Taiwan Weather Satellite Mission." *Space News*. N.p., 31 May 2013. Web. 28 June 2013. <<http://www.spacenews.com/article/civil-space/35576funding-uncertainty-could-hobble-us-taiwan-weather-satellite-mission>>.
- ²⁵*Polar-orbiting Environmental Satellites: Changing Requirements, Technical Issues, and Looming Data Gaps Require Focused Attention*. Rep. no. GAO-12-604. GAO, 15 June 2012. Web. 28 June 2013. <<http://www.gao.gov/assets/600/591643.pdf>>.
- ²⁶United States. NOAA. *Continuing Oversight of the Nation's Weather Satellite Programs – An Update on JPSS and GOES-R*. By Kathryn D. Sullivan. NOAA, 27 June 2012. Web. 28 June 2013. <<http://www.legislative.noaa.gov/Testimony/Sullivan062712.pdf>>.
- ²⁷Hamilton, Jon. "Blind Eye in the Sky: Weather Satellites Lose Funding." *NPR*. N.p., 17 June 2011. Web. 28 June 2013. <<http://www.npr.org/2011/06/17/137251742/blind-eye-in-the-sky-weather-satellites-lose-funding>>.
- Freedman, Andrew. "NOAA Warns Weather Forecasts Will Suffer from Budget Cuts." *Washington Post*. N.p., 31 Mar. 2011. Web. 28 June 2013. <http://www.washingtonpost.com/blogs/capital-weather-gang/post/noaa-warns-weather-forecasts-will-suffer-from-budget-cuts/2011/03/31/AFKsct9B_blog.html>.
- ²⁸"Study Shows Polar-orbiting Satellite Data Was Key to Pinpointing Sandy's Track and Time of Landfall." *Study Shows Polar-orbiting Satellite Data Was Key to*. NOAA News, 11 Dec. 2012. Web. 28 June 2013. <http://www.noaanews.noaa.gov/stories2012/20121211_poesandsandy.html>.
- Samenow, Jason. "Without Polar Satellites, Forecast for Superstorm Sandy Would Have Suffered European Analysis Finds." *Washington Post*. N.p., 21 Nov. 2012. Web. 28 June 2013. <http://www.washingtonpost.com/blogs/capital-weather-gang/post/without-polar-satellites-forecast-for-sandy-would-have-suffered-european-analysis-finds/2012/11/21/651a4c2a-3401-11e2-9cfa-e41bac906cc9_blog.html>.
- ²⁹United States. NOAA. *Continuing Oversight of the Nation's Weather Satellite Programs – An Update on JPSS and GOES-R*. By Kathryn D. Sullivan. NOAA, 27 June 2012. Web. 28 June 2013. <<http://www.legislative.noaa.gov/Testimony/Sullivan062712.pdf>>.
- ³⁰United States. NOAA. *Implementing Agreement Between the United States National Oceanic and Atmospheric Administration, Department of Commerce and The Japan Meteorological Agency on The Backup of Operational Geostationary Meteorological Satellite Systems*. Tokyo: n.p., 2005. Print.
- United States. NOAA. *Agreement Between the United States National Oceanic and Atmospheric Administration and the European Organization for the Exploitation of Meteorological Satellites on Back-up of Operational Geostationary Meteorological Satellite Systems*. Washington: n.p., 1993. Print.
- ³¹"The National Polar-orbiting Operational Environmental Satellite System (NPOESS)." NOAA Public Affairs, Aug. 2002. Web. 28 June 2013. <<http://www.publicaffairs.noaa.gov/grounders/npoess.html>>.
- ³²Powner, David A. *Polar-orbiting Environmental Satellites: Project Risks Could Affect Weather Data Needed by Civilian and Military Users*. Rep. no. GAO-03-987T. GAO, 15 July 2003. Web. 28 June 2013. <<http://www.gao.gov/new.items/d03987t.pdf>>.
- ³³United States. *Restructuring the National Polar-orbiting Operational Environmental Satellite System*. N.p., 1 Feb. 2010. Web. 28 June 2013. <http://www.whitehouse.gov/sites/default/files/npoess_decision_fact_sheet_2-1-10.pdf>.
- ³⁴*Polar-orbiting Operational Environmental Satellites: Restructuring Is Under Way, but Technical Challenges and Risks Remain*. Rep. no. GAO-07-498. GAO, 27 Apr. 2007. Web. 28 June 2013. <<http://www.gao.gov/assets/260/259754.pdf>>.
- ³⁵*Polar-Orbiting Environmental Satellites: Agencies Must Act Quickly to Address Risks That Jeopardize the Continuity of Weather and Climate Data*. Rep. no. GAO-10-558. GAO, May 2010. Web. 28 June 2013. <<http://www.gao.gov/assets/310/304904.pdf>>.
- Polar Satellites: Agencies Need to Address Potential Gaps in Weather and Climate Data Coverage: Statement of David A. Powner*. Rep. no. GAO-11-945T. GAO, 23 Sept. 2011. Web. 28 June 2013. <<http://www.gao.gov/assets/590/585368.pdf>>.
- Polar-orbiting Environmental Satellites: Changing Requirements, Technical Issues, and Looming Data Gaps Require Focused Attention*. Rep. no. GAO-12-604. GAO, 15 June 2012. Web. 28 June 2013. <<http://www.gao.gov/assets/600/591643.pdf>>.
- ³⁶*Polar-orbiting Environmental Satellites: Information on Program Cost and Schedule Changes*. Rep. no. GAO-04-1054. GAO, Sept. 2004. Web. 28 June 2013. <<http://www.gao.gov/new.items/d041054.pdf>>.
- ³⁷*Polar-orbiting Operational Environmental Satellites: Technical Problems, Cost Increases, and Schedule Delays Trigger Need for Difficult Trade-off Decisions: Statement of David A. Powner*. Rep. no. GAO-06-249T. GAO, 16 Nov. 2005. Web. 28 June 2013. <<http://www.gao.gov/new.items/d06249t.pdf>>.
- ³⁸*Polar-orbiting Operational Environmental Satellites: Technical Problems, Cost Increases, and Schedule Delays Trigger Need for Difficult Trade-off Decisions: Statement of David A. Powner*. Rep. no. GAO-06-249T. GAO, 16 Nov. 2005. Web. 28 June 2013. <<http://www.gao.gov/new.items/d06249t.pdf>>.
- ³⁹*Environmental Satellites: Polar-orbiting Satellite Acquisition Faces Delays; Decisions Needed on Whether and How to Ensure Climate Data Continuity: Statement of David A. Powner*. Rep. no. GAO-08-899T. GAO, 19 June 2008. Web. 28 June 2013. <<http://www.gao.gov/assets/130/120457.pdf>>.
- ⁴⁰*Environmental Satellites: Polar-orbiting Satellite Acquisition Faces Delays; Decisions Needed on Whether and How to Ensure Climate Data Continuity*. Rep. no. GAO-08-518. GAO, May 2008. Web. 28 June 2013. <<http://www.gao.gov/new.items/d08518.pdf>>.

- ⁴¹*Polar-orbiting Environmental Satellites: With Costs Increasing and Data Continuity at Risk, Improvements Needed in Tri-agency Decision Making.* Rep. no. GAO-09-564. GAO, June 2009. Web. 28 June 2013. <<http://www.gao.gov/new.items/d09564.pdf>>.
- ⁴²*Polar-Orbiting Environmental Satellites: Agencies Must Act Quickly to Address Risks That Jeopardize the Continuity of Weather and Climate Data.* Rep. no. GAO-10-558. GAO, May 2010. Web. 28 June 2013. <<http://www.gao.gov/assets/310/304904.pdf>>.
- ⁴³United States. *Restructuring the National Polar-orbiting Operational Environmental Satellite System.* N.p., 1 Feb. 2010. Web. 28 June 2013. <http://www.whitehouse.gov/sites/default/files/npoess_decision_fact_sheet_2-1-10.pdf>.
“The Future of Polar-orbiting Satellites.” *Information and History.* NOAA Office of Satellite Operations, n.d. Web. 28 June 2013. <<http://www.oso.noaa.gov/history/future-polar.htm>>.
- ⁴⁴Keller, John. “Air Force Kicks off Program to Define Next-generation Weather Satellites and Sensor Payloads.” *Air Force Kicks off Program to Define Next-generation Weather Satellites and Sensor Payloads.* Military and Aerospace, 15 June 2012. Web. 28 June 2013. <<http://www.militaryaerospace.com/articles/2012/06/air-force-kicks-off-program-to-define-next-generation-weather-satellites-and-sensor-payloads.html>>.
- ⁴⁵United States. Department of Defense. Air Force. *Department of Defense Fiscal Year (FY) 2014 President’s Budget Submission Justification Book Volume 2 of 3: Research, Development, Test & Evaluation, Air Force.* USAF, Apr. 2013. Web. 28 June 2013. <<http://www.saffm.hq.af.mil/shared/media/document/AFD-130408-066.pdf>>.
United States. Cong. Senate. *Congressional Record – Senate.* S. Rept. N.p., 11 Mar. 2013. Web. 28 June 2013. <<http://beta.congress.gov/crec/2013/03/11/CREC-2013-03-11-pt1-PgS1287.pdf>>.
- ⁴⁶*High-Risk Series: An Update.* Rep. no. GAO-13-283. United States Government Accountability Office, Feb. 2013. Web. 28 June 2013. <<http://www.gao.gov/assets/660/652133.pdf>>.
- ⁴⁷United States. NOAA. Budget Office. *FY 2013 Blue Book.* NOAA, n.d. Web. 28 June 2013. <http://www.corporateservices.noaa.gov/nbo/13bluebook_highlights.html>.
- ⁴⁸⁻⁴⁹*Polar-orbiting Environmental Satellites: Changing Requirements, Technical Issues, and Looming Data Gaps Require Focused Attention.* Rep. no. GAO-12-604. GAO, 15 June 2012. Web. 28 June 2013. <<http://www.gao.gov/assets/600/591643.pdf>>.
- ⁵⁰United States. NOAA. Budget Office. *FY 2013 Blue Book.* NOAA, n.d. Web. 28 June 2013. <http://www.corporateservices.noaa.gov/nbo/13bluebook_highlights.html>.
United States. NOAA. Budget Office. *FY 2014 Budget Blue Book.* NOAA, n.d. Web. 28 June 2013. <http://www.corporateservices.noaa.gov/nbo/14bluebook_highlights.html>.
- ⁵¹United States. NASA. Budget Office. *FY 2014 President’s Budget Request Summary.* NASA, n.d. Web. 28 June 2013. <http://www.nasa.gov/pdf/750614main_NASA_FY_2014_Budget_Estimates-508.pdf>.
- ⁵²United States. NOAA. Budget Office. *FY 2014 Budget Blue Book.* NOAA, n.d. Web. 28 June 2013. <http://www.corporateservices.noaa.gov/nbo/14bluebook_highlights.html>.
- ⁵³⁻⁵⁵*Polar-orbiting Environmental Satellites: Changing Requirements, Technical Issues, and Looming Data Gaps Require Focused Attention.* Rep. no. GAO-12-604. GAO, 15 June 2012. Web. 28 June 2013. <<http://www.gao.gov/assets/600/591643.pdf>>.
- ⁵⁶“First JPSS Antenna Installed as NOAA Continues to Highlight Consequences of Budget Shortfall.” *First JPSS Antenna Installed as NOAA Continues to Highlight Consequences of Budget Shortfall.* NOAA, 7 June 2011. Web. 28 June 2013. <http://www.noaanews.noaa.gov/stories2011/20110607_jpss.html>.
- ⁵⁷*Polar-orbiting Environmental Satellites: With Costs Increasing and Data Continuity at Risk, Improvements Needed in Tri-agency Decision Making.* Rep. no. GAO-09-564. GAO, June 2009. Web. 28 June 2013. <<http://www.gao.gov/new.items/d09564.pdf>>.
Environmental Satellites: Strategy Needed to Sustain Critical Climate and Space Weather Measurements. Rep. no. GAO-10-456. GAO, Apr. 2010. Web. 28 June 2013. <<http://www.gao.gov/new.items/d10456.pdf>>.
- ⁵⁸*Environmental Satellites: Polar-orbiting Satellite Acquisition Faces Delays; Decisions Needed on Whether and How to Ensure Climate Data Continuity.* Rep. no. GAO-08-518. GAO, May 2008. Web. 28 June 2013. <<http://www.gao.gov/new.items/d08518.pdf>>.
Polar-Orbiting Environmental Satellites: Agencies Must Act Quickly to Address Risks That Jeopardize the Continuity of Weather and Climate Data. Rep. no. GAO-10-558. GAO, May 2010. Web. 28 June 2013. <<http://www.gao.gov/assets/310/304904.pdf>>.
“JPSS-1 Instruments.” *Joint Polar Satellite System (JPSS).* N.p., n.d. Web. 28 June 2013. <<http://www.jpss.noaa.gov/instruments.html>>.
“Suomi NPP Instruments at a Glance.” *Joint Polar Satellite System (JPSS).* N.p., n.d. Web. 28 June 2013. <http://www.jpss.noaa.gov/instruments_interactive.html>.
- ⁵⁹*Polar-orbiting Environmental Satellites: With Costs Increasing and Data Continuity at Risk, Improvements Needed in Tri-agency Decision Making.* Rep. no. GAO-09-564. GAO, June 2009. Web. 28 June 2013. <<http://www.gao.gov/new.items/d09564.pdf>>.
Environmental Satellites: Strategy Needed to Sustain Critical Climate and Space Weather Measurements. Rep. no. GAO-10-456. GAO, Apr. 2010. Web. 28 June 2013. <<http://www.gao.gov/new.items/d10456.pdf>>.
- ⁶⁰*Polar-orbiting Environmental Satellites: With Costs Increasing and Data Continuity at Risk, Improvements Needed in Tri-agency Decision Making.* Rep. no. GAO-09-564. GAO, June 2009. Web. 28 June 2013. <<http://www.gao.gov/new.items/d09564.pdf>>.
Environmental Satellites: Strategy Needed to Sustain Critical Climate and Space Weather Measurements. Rep. no. GAO-10-456. GAO, Apr. 2010. Web. 28 June 2013. <<http://www.gao.gov/new.items/d10456.pdf>>.
<http://www.spacenews.com/article/civil-space/35178amid-jpss-changes-free-flyer-1-payload-remains-the-same#Ucx0PD7F18t>
- ⁶¹*Polar-orbiting Environmental Satellites: With Costs Increasing and Data Continuity at Risk, Improvements Needed in Tri-agency Decision Making.* Rep. no. GAO-09-564. GAO, June 2009. Web. 28 June 2013. <<http://www.gao.gov/new.items/d09564.pdf>>.
Environmental Satellites: Strategy Needed to Sustain Critical Climate and Space Weather Measurements. Rep. no. GAO-10-456. GAO, Apr. 2010. Web. 28 June 2013. <<http://www.gao.gov/new.items/d10456.pdf>>.

- ⁶²*Polar-orbiting Environmental Satellites: With Costs Increasing and Data Continuity at Risk, Improvements Needed in Tri-agency Decision Making.* Rep. no. GAO-09-564. GAO, June 2009. Web. 28 June 2013. <<http://www.gao.gov/new.items/d09564.pdf>>. *Environmental Satellites: Strategy Needed to Sustain Critical Climate and Space Weather Measurements.* Rep. no. GAO-10-456. GAO, Apr. 2010. Web. 28 June 2013. <<http://www.gao.gov/new.items/d10456.pdf>>.
- ⁶³*Geostationary Operational Environmental Satellites: Steps Remain in Incorporating Lessons Learned from Other Satellite Programs.* Rep. no. GAO-06-993. GAO, Sept. 2006. Web. 28 June 2013. <<http://www.gao.gov/new.items/d06993.pdf>>.
- ⁶⁴*Geostationary Operational Environmental Satellites: Improvements Needed in Continuity Planning and Involvement of Key Users.* Rep. no. GAO-10-799. GAO, Sept. 2010. Web. 28 June 2013. <<http://www.gao.gov/ereport/GAO-10-799>>.
- ⁶⁵“Lockheed Martin Tapped for 2 More GOES Satellites.” *Space News*. N.p., 15 May 2013. Web. 03 July 2013. <<http://www.spacenews.com/article/civil-space/35338lockheed-martin-tapped-for-2-more-goes-satellites>>.
- ⁶⁶*Geostationary Weather Satellites: Design Progress Made, but Schedule Uncertainty Needs to Be Addressed.* Rep. no. GAO-12-576. GAO, June 2012. Web. 28 June 2013. <<http://www.gao.gov/assets/600/591914.pdf>>.
- ⁶⁷*Geostationary Operational Environmental Satellites: Acquisition Has Increased Costs, Reduced Capabilities, and Delayed Schedules: Statement of David A. Powner.* Rep. no. GAO-09-596T. GAO, 23 Apr. 2009. Web. 28 June 2013. <<http://www.gao.gov/new.items/d09596t.pdf>>.
- ⁶⁸“Improving Acquisition of Weather Observing Satellites.” *High-Risk*. GAO, 6 Jan. 2012. Web. 28 June 2013. <<http://web.archive.org/web/20120106050248/http://www.gao.gov/highrisk/agency/doc/improving-acquisition-of-weather.php>>.
- ⁶⁹United States. NOAA. *Implementing Agreement Between the United States National Oceanic and Atmospheric Administration, Department of Commerce and The Japan Meteorological Agency on The Backup of Operational Geostationary Meteorological Satellite Systems.* Tokyo: n.p., 2005. Print. United States. NOAA. *Agreement Between the United States National Oceanic and Atmospheric Administration and the European Organization for the Exploitation of Meteorological Satellites on Back-up of Operational Geostationary Meteorological Satellite Systems.* Washington: n.p., 1993. Print.
- ⁷⁰*Geostationary Operational Environmental Satellites: Steps Remain in Incorporating Lessons Learned from Other Satellite Programs.* Rep. no. GAO-06-993. GAO, Sept. 2006. Web. 28 June 2013. <<http://www.gao.gov/new.items/d06993.pdf>>.
- ⁷¹“Advanced Baseline Imager (ABI).” *GOES-R*. NOAA and NASA, n.d. Web. 28 June 2013. <<http://www.goes-r.gov/spacesegment/abi.html>>.
- ⁷²“Geostationary Lightning Mapper (GLM).” *GOES-R*. NOAA and NASA, n.d. Web. 28 June 2013. <<http://www.goes-r.gov/spacesegment/glm.html>>.
- ⁷³*Geostationary Operational Environmental Satellites: Steps Remain in Incorporating Lessons Learned from Other Satellite Programs.* Rep. no. GAO-06-993. GAO, Sept. 2006. Web. 28 June 2013. <<http://www.gao.gov/new.items/d06993.pdf>>.
- ⁷⁴*Geostationary Operational Environmental Satellites: Acquisition Has Increased Costs, Reduced Capabilities, and Delayed Schedules: Statement of David A. Powner.* Rep. no. GAO-09-596T. GAO, 23 Apr. 2009. Web. 28 June 2013. <<http://www.gao.gov/new.items/d09596t.pdf>>.
- ⁷⁵Schmit, Timothy J., Jun Li, James J. Gurka, Mitchell D. Goldberg, Kevin J. Schrab, Jinlong Li, and Wayne F. Feltz. “The GOES-R Advanced Baseline Imager and the Continuation of Current Sounder Products.” *Journal of Applied Meteorology and Climatology* 47.10 (2008): 2696-711. Web. 3 July 2013. <<http://journals.ametsoc.org/doi/pdf/10.1175/2008JAMC1858.1>>.
- ⁷⁶*Geostationary Operational Environmental Satellites: Acquisition Is Under Way, but Improvements Needed in Management and Oversight.* Rep. no. GAO-09-323. GAO, Apr. 2009. Web. 28 June 2013. <<http://www.gao.gov/new.items/d09323.pdf>>. Schmit, Timothy J., Jun Li, James J. Gurka, Mitchell D. Goldberg, Kevin J. Schrab, Jinlong Li, and Wayne F. Feltz. “The GOES-R Advanced Baseline Imager and the Continuation of Current Sounder Products.” *Journal of Applied Meteorology and Climatology* 47.10 (2008): 2696-711. Web. 3 July 2013. <<http://journals.ametsoc.org/doi/pdf/10.1175/2008JAMC1858.1>>.
- ⁷⁷⁻⁷⁸*Geostationary Operational Environmental Satellites: Improvements Needed in Continuity Planning and Involvement of Key Users.* Rep. no. GAO-10-799. GAO, Sept. 2010. Web. 28 June 2013. <<http://www.gao.gov/ereport/GAO-10-799>>.
- ⁷⁹*High-Risk Series: An Update.* Rep. no. GAO-13-283. United States Government Accountability Office, Feb. 2013. Web. 28 June 2013. <<http://www.gao.gov/assets/660/652133.pdf>>. United States. NOAA. *Continuing Oversight of the Nation’s Weather Satellite Programs – An Update on JPSS and GOES-R.* By Kathryn D. Sullivan. NOAA, 27 June 2012. Web. 28 June 2013. <<http://www.legislative.noaa.gov/Testimony/Sullivan062712.pdf>>.
- ⁸⁰Young, Tom. *NPOESS Independent Review Team Final Report.* Rep. N.p.: n.p., 2009. Print.
- ⁸¹*Polar Satellites: Agencies Need to Address Potential Gaps in Weather and Climate Data Coverage: Statement of David A. Powner.* Rep. no. GAO-11-945T. GAO, 23 Sept. 2011. Web. 28 June 2013. <<http://www.gao.gov/assets/590/585368.pdf>>.
- ⁸²*Geostationary Weather Satellites: Design Progress Made, but Schedule Uncertainty Needs to Be Addressed.* Rep. no. GAO-12-576. GAO, June 2012. Web. 28 June 2013. <<http://www.gao.gov/assets/600/591914.pdf>>.
- ⁸³Cucurull, L., J. C. Derber, and W. Lapenta. “Assessing the Benefits of Assimilating GPS RO Profiles into Global Numerical Weather Prediction Models.” Lecture. WMO Workshop. Sedona, Arizona. 22 May 2012. World Meteorological Organization. Web. 28 June 2013. <http://www.wmo.int/pages/prog/www/OSY/Meetings/NWP5_Sedona2012/1b5_Cucurull.pdf>. Berger, Brian. “Funding Uncertainty Could Hobble U.S.-Taiwan Weather Satellite Mission.” *Space News*. N.p., 31 May 2013. Web. 28 June 2013. <<http://www.spacenews.com/article/civil-space/35576funding-uncertainty-could-hobble-us-taiwan-weather-satellite-mission>>.
- ⁸⁴“WMO in Brief.” *About Us*. World Meteorological Organization, n.d. Web. 28 June 2013. <http://www.wmo.int/pages/about/index_en.html>.
- ⁸⁵“Satellite Status.” *World Meteorological Organization*. WMO, n.d. Web. 28 June 2013. <<http://www.wmo.int/pages/prog/sat/satellitestatus.php>>.

- ⁸⁶United States. NOAA. *Agreement Between the United States National Oceanic and Atmospheric Administration (NOAA) and The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) on Joint Transition Activities Regarding Polar-orbiting Operational Environmental Satellite Systems*. U.S. State Department, 24 June 2003. Web. 28 June 2013. <<http://www.state.gov/documents/organization/152189.pdf>>.
- United States. NOAA. *Agreement Between the United States National Oceanic and Atmospheric Administration and the European Organisation for the Exploitation of Meteorological Satellites on an Initial Joint Polar-orbiting Operational Satellite System*. Washington: n.p., 1998. Print.
- ⁸⁷“U.S.-Japan Scientific Cooperation Strengthened with Launch of New Environmental Monitoring Satellite.” *NOAA News*. NOAA, 17 May 2012. Web. 28 June 2013. <http://www.noaanews.noaa.gov/stories2012/20120517_usandjapan.html>.
- ⁸⁸“CGMS Working Group III.” *Coordination Group for Meteorological Satellites*. DGMS, n.d. Web. 28 June 2013. <<http://www.cgms-info.org/cgms/working-groups/working-group-iii>>.
- ⁸⁹“Home.” *U.S. National Ice Center and Naval Ice Center*. N.p., n.d. Web. 28 June 2013. <<http://www.natice.noaa.gov/>>.
- ⁹⁰“Commercial Space-Based Earth & Space Weather Observations.” *Government as Customer of Space Commerce*. Space Commerce, n.d. Web. 28 June 2013. <<http://www.space.commerce.gov/general/commercialobservations.shtml>>.
- ⁹¹United States. U.S. Department of Commerce National Oceanic and Atmospheric Administration. National Environmental Satellite, Data, and Information Service. *Acquisition of Space-based Scientific Data from Commercial Sources to Supplement NOAA’s Weather and Climate Observation Requirements: Report to Congress*. N.p., 2010. Web. 28 June 2013. <<http://www.space.commerce.gov/library/reports/2010-03-commercial-observations.pdf>>.
- ⁹²U.S. NOAA. *Private Remote Sensing License Public Summary*. N.p., 15 Sept. 2010. Web. 28 June 2013. <http://www.nesdis.noaa.gov/CRSRA/files/NOAA_announcement_GMW_Finalv4_corrected.pdf>.
- Belfiore, Michael. “Next-Gen Weather Sats Will See the Sky in 1800 Colors.” *Popular Mechanics*. N.p., 1 May 2013. Web. 28 June 2013. <<http://www.popularmechanics.com/science/environment/next-gen-weather-sats-will-see-the-sky-in-1800-colors-15417675>>.
- ⁹³“Private Firm Could Fill Weather Satellite Gap.” *USA Today*. N.p., 25 Mar. 2013. Web. 28 June 2013. <<http://www.usatoday.com/story/weather/2013/03/25/weather-satellite-gap-private-company-planetiq/2018047/>>.
- “White Papers.” PlanetIQ. N.p., n.d. Web. 28 June 2013. <<http://www.planetiq.com/white-papers/>>.
- ⁹⁴“The Constellation.” *GeoOptics*. N.p., n.d. Web. 28 June 2013. <http://geooptics.com/?page_id=58>.
- “Our Mission.” *GeoOptics*. N.p., n.d. Web. 28 June 2013. <http://geooptics.com/?page_id=17>.
- ⁹⁵“Annual Fatal Tornado Summaries.” Storm Prediction Center. NOAA’s National Weather Service, n.d. Web. 28 June 2013. <<http://www.spc.noaa.gov/climo/torn/fatalmap.php>>.
- ⁹⁶Bender, Michael C. “Oklahoma Tornado Alert Gave Residents 36 Minutes Warning.” *Bloomberg*. N.p., 21 May 2013. Web. 28 June 2013. <<http://www.bloomberg.com/news/2013-05-21/tornado-alert-gave-moore-oklahoma-residents-36-minutes-warning.html>>.
- “Tornadoes 101.” NOAA. N.p., n.d. Web. 28 June 2013. <<http://www.noaa.gov/features/protecting/tornados101.html>>.
- ⁹⁷*Geostationary Operational Environmental Satellite, Series R (GOES-R) Independent Review Team (IRT) Report*. Rep. N.p.: n.p., 2007. Print.
- United States. NOAA. *Oversight Hearing on Geostationary Operational Environmental Satellites: Progress Has Been Made but Improvements Are Needed to Effectively Manage Risks: Written Testimony*. By Mary Kicza. N.p.: n.p., 2007. Print.