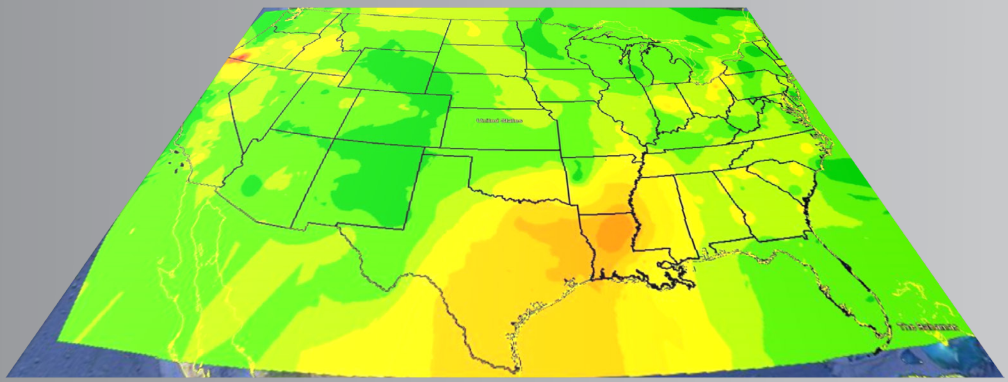
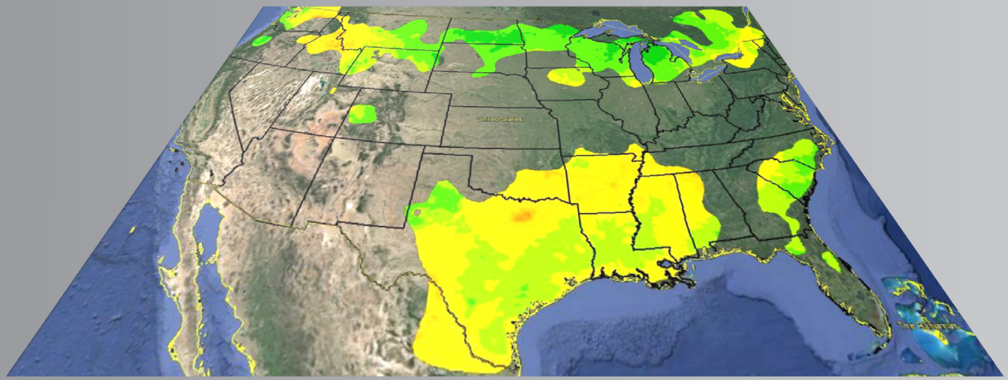
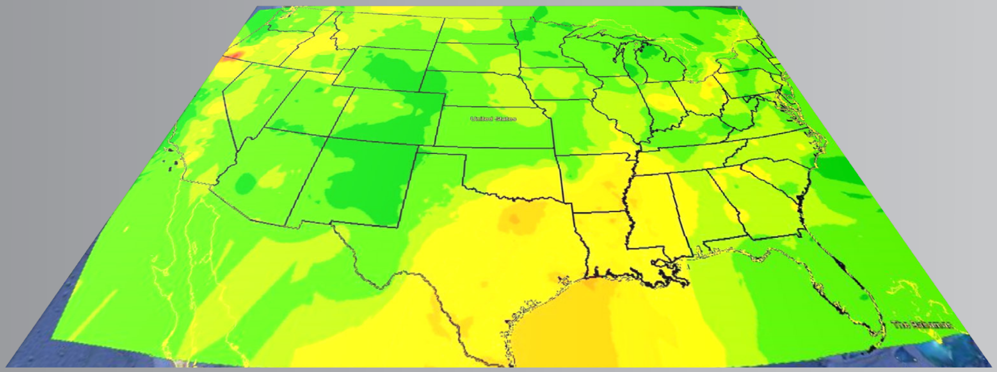
Socioeconomic Benefits of Adding NASA Satellite Data to AirNow







NASA

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

Center for Technology in Government

STi Sonoma Technology, Inc.

Socioeconomic Benefits of Adding NASA Satellite Data to AirNow

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STI-910404-5789

October 4, 2013

Acknowledgments

The Applied Sciences Program in the Earth Science Division of the NASA Science Mission Directorate sponsored this study through the United States Environmental Protection Agency. Sonoma Technology, Inc. managed and directed this project. The Center for Technology in Government at the State University of New York at Albany/SUNY performed the interviews and developed the document.

The authors would like to thank all the interviewees for their time and valuable input. A complete list of the interviewees can be found in Appendix B.

In addition to the authors, the following people contributed to the report: Hilary R. Hafner, ShihMing Huang, Fred Lurmann, Marina Michaels, Angela Ekstrand, Jennifer DeWinter, Chelsea Jennings, and Jana Schwartz.

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Executive Summary

1. Introduction and Background

Exposure to elevated ambient fine particulate matter ($PM_{2.5}$) concentrations is associated with adverse cardiovascular and respiratory health effects. The U.S. Environmental Protection Agency's (EPA) AirNow program provides the public with easy access to national ambient air quality information using the Air Quality Index (AQI). The AQI is a standardized index for reporting air quality based on health effects for five major air pollutants: ground-level ozone, $PM_{2.5}$, carbon monoxide (CO), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2).

AirNow presents near-real-time hourly AQI conditions and daily AQI forecasts, with maps of interpolated AQI levels on national, regional, and local spatial scales. This information is converted into AQI forecasts and distributed to the public and media (e.g., *USA Today* and CNN). To better map these data sets, the AirNow program has developed a system called the AirNow Information Management System (IMS) (Dye et al., 2008) that blends (or fuses) different data sets.

However, there are some challenges to providing a nationwide AQI map. Most notably, the United States surface air quality monitoring network is too sparse in many areas. The real-time ambient air monitoring network that is used to inform the public about adverse air quality conditions does not cover all regions in the continental United States. More than 42 million people reside in populated places farther than 40 km from the nearest $PM_{2.5}$ monitor and, therefore, have no information or possibly inaccurate information on real-time exposure to $PM_{2.5}$ (**Figure 1**). From a public health perspective, there are substantial health benefits for people who take protective action to avoid exposure to high outdoor $PM_{2.5}$ concentrations.

> Satellite data can help fill gaps in ground monitoring networks.

One way to provide additional $PM_{2.5}$ information for these unmonitored areas is to use $PM_{2.5}$ estimated from satellite aerosol optical depth data to fill the monitoring gaps. A recent NASA-funded project, AirNow Satellite Data Processor (ASDP), developed a system for EPA to routinely estimate surface $PM_{2.5}$ concentrations from satellite data and then fuse these estimates with routine surface $PM_{2.5}$ monitor observations in the AirNow system.

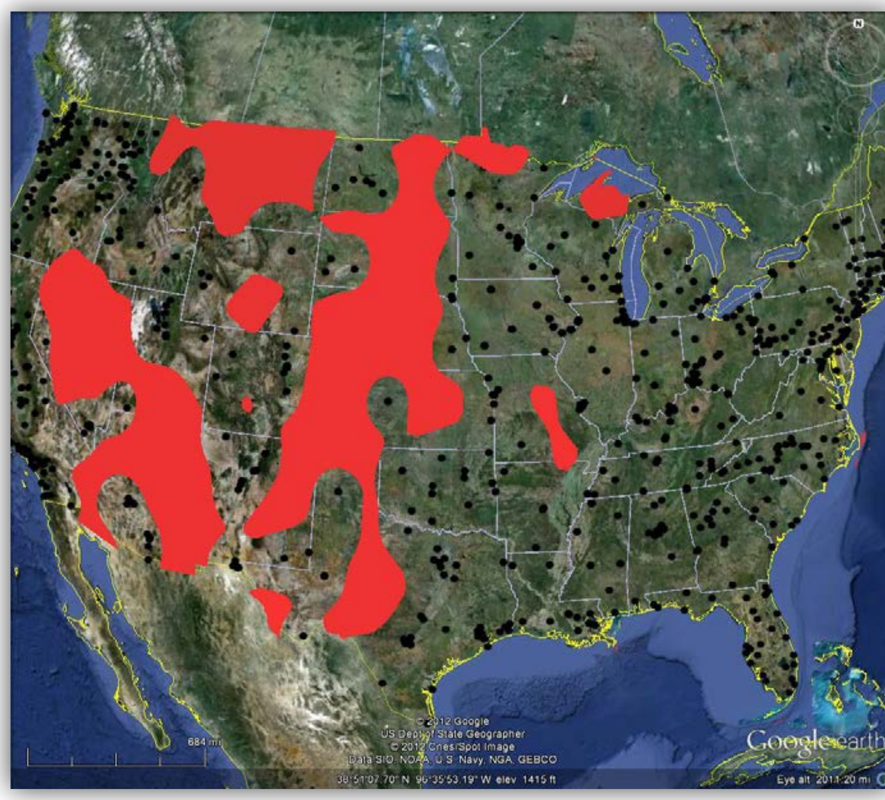

Figure 1. AirNow surface $PM_{2.5}$ observations (black dots). The red areas are regions without monitors and with no air quality information.

2. Approach

This study evaluated the socioeconomic and economic benefits of adding NASA satellite data to AirNow. The benefits were evaluated using two approaches:

1. Face-to-face interviews in three case study locations (Denver, Colorado; Atlanta, Georgia; and Kansas City, Missouri) to assess the public value or community-level benefits.
2. Analysis of cost savings of using satellite data instead of installing new monitors to provide air quality information for public health decisions to populations in currently unmonitored locations.

The case studies used the Public Value Framework (Cresswell et al., 2006) to show how different types of value could emerge for different stakeholder groups. Once the value types are identified and goals are set, measures can be specified and quantitative assessment (and achievement) becomes more feasible. The salient value types in this study are

- Financial — impacts on current or anticipated income, asset values, liabilities, entitlements, and other aspects of wealth, or risks to any of the above.

- Mission — impacts on the ability of a public agency to achieve its core mission and goals.
- Strategic — impacts on economic or political advantage, or opportunities, goals, and resources for innovation or planning.
- Political — impacts on personal or corporate influence on government actions or policy, role in political affairs, or influence in political parties or prospects for current or future public office.
- Social — impacts on family or community relationships, social mobility, status, and identity.
- Stewardship — impacts on the public's view of government officials as faithful stewards or guardians of the value of the government itself in terms of public trust, integrity, and legitimacy.

3. Results

Community-Level Benefits

NASA's recent report, *Measuring Socioeconomic Impacts of Earth Observations*, urges government managers and decision makers to look for new ways to quantify the socioeconomic benefits of projects and programs (National Aeronautics and Space Administration, 2013). In the area of air quality, this need to quantify benefits applies not only to federal government agencies; it is equally important to state and local governments and to non-profit organizations that are all challenged by budget cuts and increased demands for service. The NASA report highlights a number of "impact assessment approaches" to help quantify the value of earth science data.

> "We're missing a better understanding of how much emissions in rural areas and upwind transport impact largely urban non-attainment areas."

The case studies conducted during this project revealed that measuring the socioeconomic benefits requires a thorough and fine-grained understanding of specific interviewees' (or users') needs. While all interviewees found benefits in using satellite-enhanced data, the different potential applications of satellite-enhanced data by interviewees (or users) revealed that the range of benefits is wide. The following list summarizes the socioeconomic benefits of satellite-enhanced AirNow data and provides some specific examples; details are available in the body of this report and in the case study summaries in Appendix A.

Satellite data could

- **Fill gaps in the ground sensor network** *(financial, mission, strategic, and stewardship value)*. A consistent theme across all of the interviews was that both the satellite data and the fused product could fill coverage gaps in the existing monitoring network. In Kansas City, for instance, officials noted "we're missing a better understanding of how much emissions in rural areas and upwind transport impact largely urban non-attainment areas." Gaps in the monitoring network are addressed today by estimating or extrapolating air quality measurements from sensors at the monitoring sites to areas farther away. However, an expert at an EPA Regional Office stated, "[AirNow interpolation] just smears it [pollution] out [in complex terrain] and that probably is not a reality, so the satellite and the fusion may help resolve some of those issues."
- **Support design and deployment of the regulatory monitoring network** (*financial and mission value*). A combination of economic, geographic, and political factors prevents states from placing ground sensors in all the places needed to provide complete coverage. Satellite data could help states identify those areas where the expensive investment in an additional monitor could provide the greatest value. For example, experts from EPA Region 4 concurred with state officials, saying, "It'd be great to see if one of our monitors is often surrounded by something picked up in the [satellite] data that's a max concentration…And then the question is, what's creating that hot spot? Is it upper atmosphere? Or occurring more at ground level?" Information like this would make the satellite product a "good tool as far as network assessment [goes]."
- **Improve regional and local analysis of air quality conditions, from microscale environments to interstate pollution transport** (*mission, social, and stewardship value*). All the experts we interviewed recognized the potential value satellite data could provide to the analysis of both regional and localized air quality conditions. Satellite data could increase confidence in the coverage, accuracy, and timeliness of the information that state and local governments use for air quality forecasting; advisories due to special events such as smoke from fires; or routine regulatory activities such as issuance of burn permits. For example, satellite data could greatly refine the monitoring in micro-scale environments, such as the high mountain valleys of Colorado, where frequent and extreme changes in terrain make the interpolation of ground sensor data especially unreliable. Georgia officials described how satellite data could help them understand pollution effects from inversions that create large areas of stagnant air over the center of the state, where the coverage of ground monitors is the sparsest, and Missouri officials noted the importance of being able to understand the transport of pollution from huge areas of prescribed burning in the Flint Hills area of Kansas.
- **Improve understanding of the potential impact of industrial development and unregulated activities** (*mission, strategic, political, and stewardship value*). In all three cases, emerging and growing industries outside the main population centers are generating air quality concerns. In the Kansas City region, for example, a new Burlington Northern Santa Fe (BNSF) intermodal transport facility will open in late 2013. While the modern capabilities of the new BNSF facility will help reduce overall air pollution because there will be "less congestion, less

idling,...electric cranes versus diesel cranes and a lot of improvements in both process and technology," the site of the facility itself is "pristine nature...they are not building on a brown field." Satellite monitoring could track the effects of this development in more detail.

- **Support state-level air quality programs and longer range planning and priority setting** (*mission value*). Satellite data could assist in documenting exceptional events, developing and promoting active adoption of state implementation plans, setting priorities, and providing broader context for state-level regulation and enforcement activities. The field services staff we interviewed in Denver recognized that satellite data could provide useful context by allowing them to look at historical patterns or "hot spots" of air quality concerns that could then be used to prioritize inspections. Southern Georgia near the Florida border is a large area of frequent prescribed burning. In that region, only two monitors support the ability of counties to look at air quality as a determining factor in deciding the number and scope of burn permits to issue. "Every one of these counties has an office that permits for that county...If they had [relevant air quality data], they might decide 'Well, I'm only going to issue a couple thousand acres this day instead of 20,000.'"
- **Support state and local public health programs** (*mission, social, and stewardship value*). The satellite products could provide an important information resource for agencies and researchers to investigate the link between air quality and health effects. For example, the deputy director of the Kansas City Health Department stated, "what I hope can come from [the satellite products] is the ability to look at more data analysis to allow us to anticipate health impacts, particularly as it relates to emergency room visits, doctor visits, [and] provider visits related to asthma and upper respiratory illness" and to the impacts on poor and minority neighborhoods that are more exposed to pollution.
- **Enhance public health and policy research** (*mission value, stewardship value*). Researchers identified two main types of potential value from satellite data: improving the granularity, spatial coverage, and validity of air quality data for public health and policy analyses; and providing data to extend this kind of research beyond urban centers to rural and agricultural areas. One researcher discussed how improved air quality data in rural agricultural areas could support research on how various air quality conditions impact the health and productivity of farm workers—studies that would have both public health and economic value.
- **Support science education and workforce development** (*social value, mission value, political value*). Many opportunities exist for incorporating satellite products in science curricula and increasing student interest in science,

> Many opportunities exist for incorporating satellite products in science curricula and increasing student interest in science, technology, engineering, and math.

technology, engineering, and math. The satellite products could provide a learning tool for using and understanding maps and spatial relationships, and for exploring how scientific information like air quality data is collected, managed, and used. According to the Clean Air Campaign school program director in Atlanta, satellite products could be used to teach students about air quality conditions not only for their state but for their own communities and help them "place themselves within the data."

Economic Benefits

We analyzed and evaluated the potential cost savings of using satellite data instead of installing additional ground monitors to provide air quality information in currently unmonitored areas, where approximately 18.1 million people live. We found that satellite data could provide daily $PM_{2.5}$ information to 82% of the people living in unmonitored locations (Figure 2). In contrast, if 74 additional monitors were to be placed in population centers of greater than 25,000 people, that would only extend coverage to 44% of the people living in unmonitored locations and would cost an estimated $25.9 million USD for purchase, installation, and operation for five years. The cost of using the satellite data is negligible.

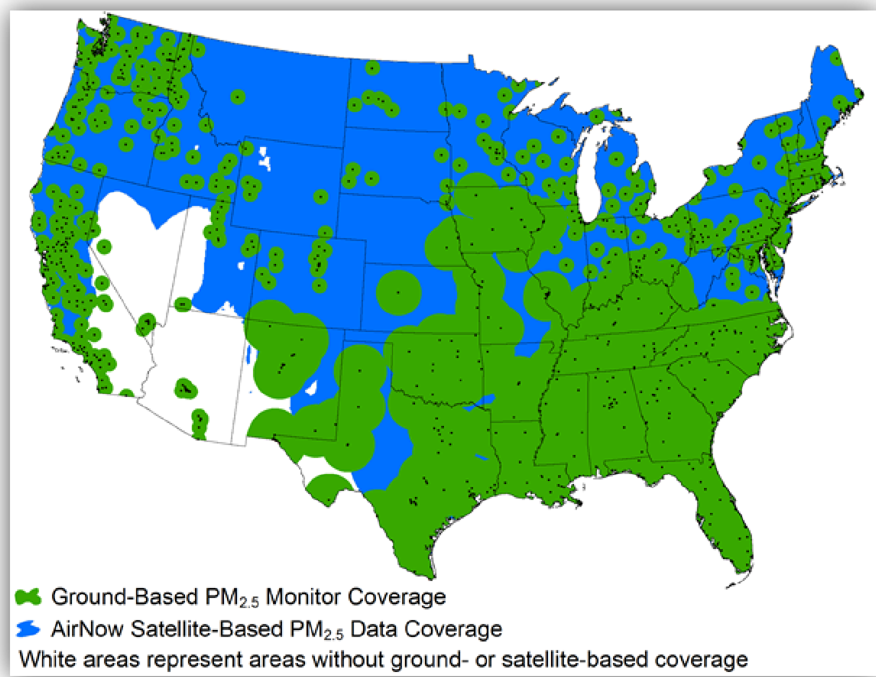

Figure 2. Map of $PM_{2.5}$ data coverage in the contiguous United States. Black dots represent monitor locations used in the analysis.

4. Users' Recommendations

Interviewees represented different stakeholder groups and consequently offered different kinds of recommendations regarding the future development and use of satellite data and fused data products. The interviews revealed a clear tension between the interviewees' desire for more information that is useful but not of regulatory quality, and the desire for accuracy and consistency across data sources to demonstrate compliance and avoid unwarranted actions or mixed messages to the public, businesses, or local communities. Users' recommendations include

- **Compare satellite data to monitor data to verify and improve quality and credibility.** Satellite data would be a new source for most users of air quality information. Therefore, the quality and reliability of that data need to be assured. According to one state expert, "The extent to which the satellite data agrees with monitored data relatively close to the monitors is a good thing."

> Satellite data would be a new source for most users of air quality information.

- **Invest in technologies that allow data from ground sensors and from satellite sensing to be gathered, compared, and fused for the same time periods.** Nearly all interviewees noted that the potential benefits of satellite data, and especially of a fused product, depend on finding a way to synchronize the data from the ground and satellite sources. For example, one air quality expert commented that the current two passes of the satellite that occur in late morning and early afternoon do not capture certain pollutant peaks that occur throughout the day, such as rush hour and high processing times at factories and other facilities.
- **Provide meteorological data to complement the satellite data.** Forecasters told us the value of satellite data would be greatly enhanced if time-matched meteorological information were also provided. The combination of pollution measures and weather patterns would help them produce better pollution forecasts and help them better understand the transport of pollutants across distances.
- **Provide satellite imagery and data separately from a fused ASDP product.** Many interviewees said that the separate map representations of the satellite data and the AirNow data were more helpful than looking at the fused product alone. The separate representations readily showed the difference (or agreement) in the readings and helped users interpret their implications.
- **Support research in satellite sensing technologies that permit measurement of other pollutants, especially ozone.** Both $PM_{2.5}$ and ozone are serious health hazards, especially with long-term exposure. Interviewees could see definite benefits of satellite data for filling in the gaps and improving the granularity of $PM_{2.5}$ data, but some pointed out it would be especially useful to have data on ozone because ozone is a more insidious health risk and the more prevalent pollutant.
- **Provide training and technical support to both scientific and administrative users of ground sensor data, satellite data, and fusion products.** Data users need information and

training about the nature and limitations of the satellite data in order to make informed judgments about whether and how to use that data. Scientists, administrators, regulators, communication professionals, and educators can all generate value if they have the right knowledge and skills to use the data for their different needs.

- **Design different kinds of products to meet the needs and capabilities of different users.** Because of the complexity and limitations of satellite data, most interviewees were cautious about making the satellite data directly available to the public, noting that interpretation demands more than a layperson's knowledge of and appreciation for the data and what the data represent. Others advocated for products and educational tools specifically for different kinds of users, including members of the public. One interviewee said, "I think we all agree it's incredibly important to be transparent and give the public the information, but if you're not helping to interpret that information, I'm not sure what the value is."
- **Improve the organization and usability of the AirNow.gov website.** Several interviewees outside the air quality agencies were not fully aware of the range of information and links on AirNow.gov, and others noted that the site is very data-driven and therefore suitable for expert users, but not accessible and useful for general users. One interviewee commented that the accessibility, usability, and value of the current AirNow website could be improved for public consumption by an expert evaluation from someone who specializes in user experience.

1. Introduction

Exposure to elevated ambient fine particulate matter ($PM_{2.5}$) concentrations is associated with adverse cardiovascular and respiratory health effects. The U.S. Environmental Protection Agency's (EPA) AirNow program provides the public with easy access to national ambient air quality information using the Air Quality Index (AQI). The AQI is a standardized index for reporting air quality based on health effects for five major air pollutants: ground-level ozone, $PM_{2.5}$, carbon monoxide (CO), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2).

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Figure 3. AirNow surface $PM_{2.5}$ observations (black dots). The red areas are regions without monitors and with no air quality information.

From a public health perspective, there are substantial health benefits for people who take protective action to avoid exposure to high outdoor $PM_{2.5}$ concentrations.

One way to provide additional $PM_{2.5}$ information for these unmonitored areas is to use $PM_{2.5}$ estimated from satellite aerosol optical depth (AOD) data to fill the monitoring gaps. A recent NASA-funded project, AirNow Satellite Data Processor (ASDP), developed a system for EPA to routinely estimate surface $PM_{2.5}$ concentrations from satellite data and then fuse these estimates with routine surface $PM_{2.5}$ monitor observations in the AirNow system.

Figure 4 is an example of the ASDP products used in this study. The figure shows 24-hour average $PM_{2.5}$ concentrations obtained from AirNow (left panel), satellite-estimated $PM_{2.5}$ concentrations (middle panel), and the fusion of satellite and ground monitor data (right panel). The dots show the monitor locations and concentrations. The hatched areas in the left panel are locations that are too far from monitors for interpolations to be valid, so they are not reported to the public. Areas shown in white in the middle panel were obscured by clouds, so therefore no satellite estimate was calculated. The panel on the right represents the fusion of the two data sources, indicating how the sensor data can be enhanced with the finer granularity and better coverage of the satellite readings.

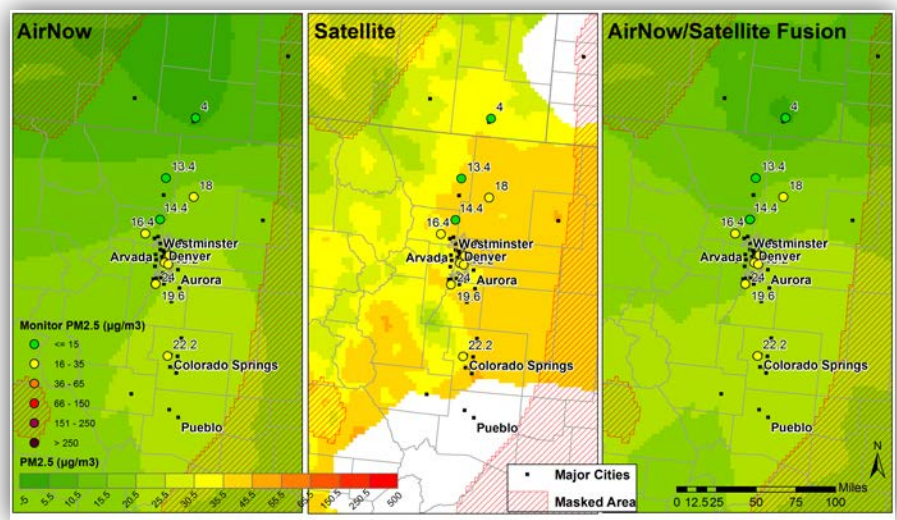

Figure 4. Example of the ASDP products used in the case studies for Colorado on June 6, 2011. The dots represent the ground monitor locations, numbers represent the 24-hour average $PM_{2.5}$ concentrations, and red hatching represents masked regions. The left panel shows interpolated ground observations from AirNow; the middle panel shows satellite-estimated $PM_{2.5}$; and the right panel shows the fusion of AirNow and satellite-estimated $PM_{2.5}$ data.

1.1 National Air Quality Monitoring and AirNow

The Clean Air Act, last amended in 1990, requires EPA to set standards for six criteria pollutants that make up the National Ambient Air Quality Standards (NAAQS): CO, NO_2, ozone, particle pollution, SO_2, and lead. All are considered harmful to public health and the environment. The NAAQS sets two kinds of standards to protect the public health and welfare:

- Primary standards provide public health protection, including protecting the health of "sensitive" populations such as asthmatics, children, and the elderly.

- Secondary standards provide public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings.

This study is concerned with two criteria pollutants: ozone and $PM_{2.5}$. NAAQS for ozone is 0.075 parts per million (ppm) by volume (measured as an 8-hour average). For $PM_{2.5}$, the standard is 35 micrograms per cubic meter of air (μg/m^3) for the 24-hour average, and 12 μg/m^3 for the annual average.

State-operated networks of more than 2,000 monitors located throughout the United States measure ozone and $PM_{2.5}$. These networks were established as part of the implementation of the Clean Air Act and are in place for the primary purposes of determining compliance with the NAAQS and for informing both state- and national-level assessments and policy decisions related to air quality improvement. States perform extensive quality checks on these data and report data quarterly to EPA to be used to assess compliance with, or "attainment" of, the NAAQS.

EPA operates the AirNow program to provide AQI information to the public and the media in real time. Data from the monitoring networks flow directly from the monitors to AirNow. As the national repository of real-time air quality data and forecasts for the United States, AirNow simplifies air quality reporting to the general public by combining concentrations of five criteria pollutants (all except lead) into a single index available to the public every day. The AQI is divided into six categories associated with different levels of threat to human health (Figure 5). For example, an AQI of 50 or less indicates "good" air quality and is indicated by the color green in maps or scales. An AQI of 151-200 is labeled "unhealthy" and indicated by red. Each level beyond "good" includes recommendations for reducing exposure.

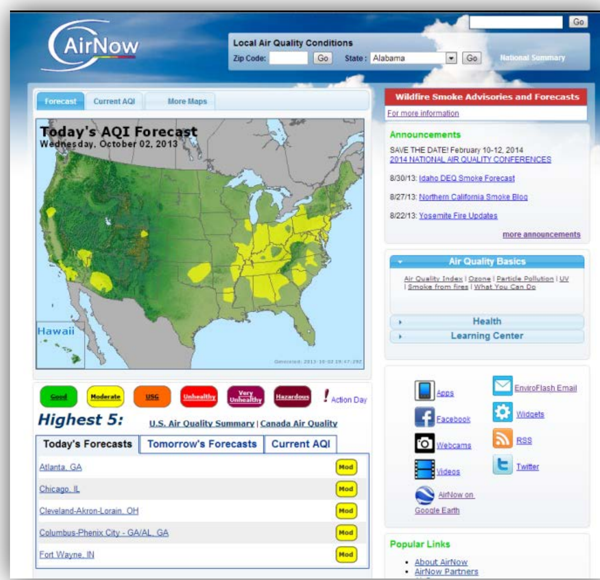

Figure 5. Screen capture of AirNow.gov.

The AirNow program obtains its data from the same state-operated monitoring networks used for regulatory compliance with the NAAQS. The regulatory data go through a painstaking and time-consuming quality assurance. However, while accuracy is the most critical feature of the data for compliance purposes, timeliness is equally important for the purposes of AirNow. Consequently, the AirNow program applies a less extensive quality control process (handling missing data, grossly out-of-range readings, etc.) in order to provide hourly updates on ozone and $PM_{2.5}$. These hourly reports support daily pollution forecasts to the media and other stakeholders and are intended to be timely enough to influence individual behavior. For example, declaration of community-level action or awareness days based on air quality forecasts triggers voluntary programs, such as carpooling, to reduce pollution and improve local air quality. The same forecasts coupled with public health messages help individuals avoid or limit their exposure, especially those with high sensitivity to pollution, such as asthmatics or young children.

AirNow also maintains an informational website (AirNow.gov, Figure 5) where near-real-time ozone and $PM_{2.5}$ maps and city air quality forecasts are posted for public access. In addition, the AirNow program offers a password-protected website, called AirNow-Tech, which gives the organizations that contribute data direct access to the full national database for research, analysis, and planning. States use this same daily data, either through AirNow-Tech or directly from their own EPA-approved monitoring networks, for similar but more localized forecasting, analysis, and public reporting.

1.2 Existing Sensor Networks

The ground sensors and the data they collect about ambient air quality are governed by federal regulations in 40 CFR Part 58. These regulations establish data standards such as timeliness and validation, as well as requirements for the scientific precision of the instruments that collect the data, and specifications for quality assurance processes to assure data quality. Monitoring stations in the networks may house single or multiple sensors specialized for measuring different pollutants (**Figure 6**). The networks are designed and operated by the states (and some tribal and local agencies and federal installations) with the advice and approval of EPA.

Figure 6. A surface monitoring site. (Source: EPA)

The placement of sensors in the state monitoring networks follows a set of complex design criteria that specify detailed factors for each type of pollutant, with special consideration for measuring exposure in large population centers. The federal regulations further require an annual monitoring network plan and periodic network assessment to continually consider updates that respond to changing conditions. Subject to public comment and EPA approval, states may move, add, or decommission monitoring stations or sensors in response to changing needs.

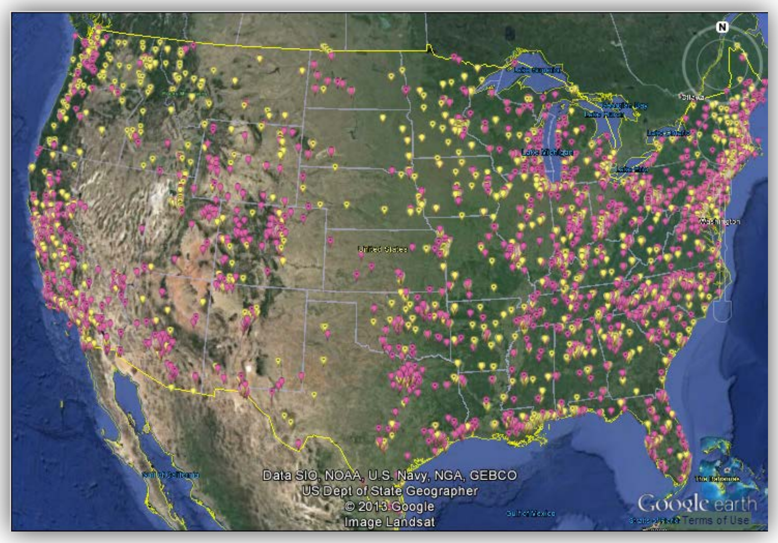

Figure 7. Ozone (pink balloons) and $PM_{2.5}$ (yellow balloons) monitor locations, obtained from EPA, September 2013.

As illustrated on a national map of ozone and $PM_{2.5}$ monitors (**Figure 7**), networks that meet these extensive regulatory requirements do not necessarily provide full geographic coverage due to the expense of siting, installing, and maintaining monitors of exacting scientific quality. Rough estimates of the costs are around $100,000 to deploy a monitoring station, and about $50,000 per year to maintain one, although the costs can vary widely according to the complexity of the monitoring station, the specific pollutants measured, travel distance from the home base of the organization that maintains it, and other factors. As a result, sensors are deployed as strategically as possible and their actual readings are used to demonstrate compliance with the NAAQS. When reported to AirNow, however, the monitoring data are interpolated using complex algorithms to estimate conditions in surrounding geographic areas in order to provide forecasts for most communities. In some areas, no reasonable estimates are possible due to distance, topography, and other factors, so AirNow does not report conditions for these areas.

The ASDP system was developed to partially compensate for these gaps in the ground sensor network for $PM_{2.5}$. The blending or fusing of surface $PM_{2.5}$ measurements and satellite-estimated $PM_{2.5}$ concentrations in the ASDP provides additional spatial air quality information to AirNow in areas without existing surface monitoring networks. The ASDP system uses satellite-estimated $PM_{2.5}$; however, the system was designed to implement a wider range of remote sensing capabilities for additional pollutants. Data are available from two daily satellite passes over the United States at mid-morning and early afternoon. The satellites gather data within a 4-km grid for all areas in the United States where atmospheric and

The blending or fusing of surface $PM_{2.5}$ measurements and satellite-estimated $PM_{2.5}$ concentrations in the ASDP provides additional spatial air quality information to AirNow in areas without existing surface monitoring networks.

other conditions allow. Dense cloud cover, snow cover, and desert landscapes prevent the satellites from taking readings in areas with those conditions.

1.3 Rationale for this Study

NASA's recent report, *Measuring Socioeconomic Impacts of Earth Observations*, urges government managers and decision makers to look for new ways to quantify the socioeconomic benefits of projects and programs (National Aeronautics and Space Administration, 2013). In the area of air quality, this need to quantify benefits applies not only to federal government agencies, but is equally important to state and local governments and to non-profit organizations that are all challenged by budget cuts and increased demands for service. The NASA report highlights a number of "impact assessment approaches" to help quantify the value of earth science data.

This study evaluated the socioeconomic and economic benefits of adding NASA satellite data to AirNow. The benefits were evaluated using two approaches:

1. Face-to-face interviews in three case study locations (Denver, Colorado; Atlanta, Georgia; and Kansas City, Missouri) to assess the public value or community-level benefits.
2. Analysis of the cost savings of using satellite data instead of installing new monitors to provide air quality information for public health decisions to populations in currently unmonitored locations.

1.4 Document Organization

This document summarizes findings from analyzing the socioeconomic and economic benefits of adding NASA satellite data to AirNow. The Center for Technology in Government at the State University of New York at Albany/SUNY (CTG) completed the socioeconomic analysis, and STI completed the economic analysis.

Section 2 describes the methodology and results from the socioeconomic analysis.

Section 3 describes the methodology and results for the economic analysis.

Section 4 summarizes the users' recommendations to realize the socioeconomic value of satellite data.

The following appendices provide additional details:

- Appendix A: Case Summaries
- Appendix B: List of Interviewees
- Appendix C: Economic Analysis of Adding NASA Satellite Data to AirNow

2. Socioeconomic Analysis

This section describes the methodology and results used to evaluate the socioeconomic benefits of adding satellite data to AirNow.

2.1 Community-Level Analysis of Air Quality Data Use, Limitations, and Value Potential

CTG assessed the socioeconomic benefits of air quality data at a community level through three case studies in the Denver, Atlanta, and Kansas City regions. The study was designed to contribute to efforts to improve estimation of the socioeconomic benefits derived from Earth observation data in policy and management decisions.

The data analysis focused on the ways in which current AirNow source data and data products contribute to socioeconomic benefits today and how satellite-enhanced data might contribute to different or greater benefits in the future. We organized the analysis according to a public value framework that assesses the impact of existing AirNow source data and data products along several dimensions, including financial, social, strategic, political, quality of life, stewardship, and mission impacts.

The study was designed to contribute to efforts to improve estimation of the socioeconomic benefits derived from Earth observation data in policy and management decisions.

To understand the potential benefits of satellite-enhanced AirNow products, we traced air quality data use within local, state, and regional contexts, including the flow of monitoring data and associated products among different stakeholders. We took these contexts into consideration to address the following questions:

- Who are stakeholders in air quality information, and what are their needs and capabilities?
- Who uses AirNow source data and data products now, and how do they use it?
- What techniques or strategies seem to have the most positive effect on public awareness and behavior, and what evidence is available on these effects?
- What gaps or weaknesses in current data reduce its usability and usefulness for different kinds of users?

- To what extent could NASA satellite data ameliorate these problems or provide for new or expanded uses?
- What other activities, information, or capabilities would enhance the usability and usefulness of AirNow data for informing and educating the public about air quality and its effects on health and quality of life and for furthering the goals of the Clean Air Act?

The three case studies involved a total of 23 face-to-face and three telephone interviews with responsible officials and leaders in these communities, representing EPA, state agencies, local public health authorities, regional planning and outreach organizations, university researchers, and relevant others. The interviews covered existing uses of air quality information and the potential value of incorporating NASA satellite data to support and enhance the missions and impact of these organizations. Interviews were transcribed and coded to identify factors associated with each of the research questions and the various indicators of public value. The study data also include regulatory documents, news media, local and state websites and reports, and previous research studies in these three sites.

Three Case Studies

The case studies involved a total of 23 face-to-face and three telephone interviews with responsible officials and leaders in these communities, representing EPA, state agencies, local public health authorities, regional planning and outreach organizations, university researchers, and relevant others.

The research conducted during this project shows that choosing and using approaches recommended by NASA (National Aeronautics and Space Administration, 2013) can be significantly aided by a more thorough and fine-grained understanding of the potential uses of satellite-enhanced data by specific users with specific needs and capabilities. Our project shows that satellite-enhanced data are not equally useful or usable or valuable to everyone. We applied the Public Value Framework (Cresswell et al., 2006) to show how different types of value could emerge for different stakeholder groups. Once the value types are identified and goals are set, measures can be specified and quantitative assessment (and achievement) becomes more feasible. The salient value types in this study are

- Financial — impacts on current or anticipated income, asset values, liabilities, entitlements, and other aspects of wealth, or risks to any of the above.
- Mission — impacts on the ability of a public agency to achieve its core mission and goals.
- Strategic — impacts on economic or political advantage, or opportunities, goals, and resources for innovation or planning.
- Political — impacts on personal or corporate influence on government actions or policy, role in political affairs, or influence in political parties or prospects for current or future public office.
- Social — impacts on family or community relationships, social mobility, status, and identity.

- Stewardship — impacts on the public's view of government officials as faithful stewards or guardians of the value of the government itself in terms of public trust, integrity, and legitimacy.

2.2 Summary of Case Findings: Different Contexts, Similar Practices and Concerns

As recounted in the case summaries in Appendix A, these three communities represent widely different physical characteristics, demographic patterns, and economies. They have different historical air pollution problems and somewhat different arrangements among government institutions and community organizations. Local government agencies and state field staff play different roles in each case, with different combinations of activities, such as facility permits and supervision, burn permits, or routine maintenance of local monitoring sites in the sensor network. Consultants perform the forecasting function in Missouri and maintain most of the monitoring sites in Colorado. A consensus forecasting process in Georgia involves both state agency experts and local university researchers in daily pollution forecasts. In Colorado, forecasting is performed solely by the state air quality agency.

The cases also have important commonalities. For all, ozone is the predominant air quality challenge, and although all three states have achieved significant absolute reductions in ozone (and other pollutants), they struggle to meet the ever-tightening requirements of the NAAQS. In all three states, mobile sources and burning are major contributors to air pollution, and every state expressed concern about interstate pollution transport as a contributing factor to attainment of the standards.

In all three cases, the state agency actively maintains its own database drawn from its monitoring network in addition to reporting that data to the EPA Air Quality System and to AirNow. All three states prefer to use, and encourage others to use, their state databases and state-operated or state-sponsored websites for air quality information and public health messaging. Little direct use is made of the AirNow public website at the state or local level, although the underlying purpose of AirNow, namely daily forecasts and related public health messages, motivates the states' own forecasts and messaging strategies. By contrast, all state air quality agencies use AirNow-Tech for analytical purposes.

None of the states has funding from federal environmental or health agencies to support public health programs related to air quality. Instead, they all rely on the funding available through the Federal Highway Administration's (FHWA) Congestion Mitigation and Air Quality Improvement (CMAQ) Program for public education and outreach. As a consequence, the content of most public messaging is shaped by transportation considerations rather than public health directly. Because of this focus, the messages are mostly geared toward the general public rather than sensitive groups, and they tend to be quite general in content and not targeted to the specific information needs of those who face elevated health risks.

In all three case studies, an intermediary organization is a significant or primary provider of public information, education, and outreach. In Denver, this is the Regional Air Quality Council (RAQC), which also develops and oversees implementation of the State Implementation Plan (SIP) to reduce ozone for the Denver metropolitan region. The Mid-America Regional Council performs similar responsibilities in Kansas City and the surrounding bi-state region. In Atlanta, the Clean Air Campaign handles public messaging and offers a variety of awareness and education programs to residents, employers, schools, and others.

2.3 Users, Uses, and Sources of Existing Air Quality Data

Since satellite data are not precise enough to be used in determining attainment of the NAAQS, the additional information provided by satellites is primarily suitable for research or for public education and outreach through programs like AirNow. The case studies shed light on the extent to which current and satellite-enhanced AirNow data can generate community-level benefits in terms of better network design, state-level environmental programs, public health initiatives, and education and research uses.

> The additional information provided by satellites is primarily suitable for research or for public education and outreach through programs like AirNow.

The community-level benefits generated from using current and satellite-enhanced AirNow data can result in many kinds of individual, organizational, and public value, but research has established that the existence of data does not automatically generate value. Instead, value is a function of information use and users (Dawes and Helbig, 2010). The extent to which information is usable and useful depends on its fitness for a given user's particular needs. Wang and Strong (1996) adopted the concept of "fitness for use," taking into consideration both subjective perceptions and objective assessments of data quality which have a bearing on the extent to which users are willing and able to use information. The four factors of fitness for use are as follows:

- **Intrinsic quality** most closely matches traditional notions of information quality. It includes accuracy and objectivity, but also involves believability and the reputation of the data source.
- **Contextual quality** refers to the context of the task for which the data will be used. It includes considerations of timeliness, relevancy, completeness, and sufficiency, and of value added to the user. Often there are trade-offs among these characteristics; for example, between timeliness and completeness (Ballou and Tayi, 1999).
- **Representational quality** relates to meaning and format. It requires that data be not only concise and consistent in format, but also interpretable and easy to understand.

- **Accessibility** comprises ease and means of access as well as access security.

All four factors are relevant to air quality data and to the variety of users and uses the data can support. When users, uses, and data characteristics match well, more value is generated. When they are not well-aligned, value declines accordingly.

For the potential value to be realized, the satellite data need to be well-defined and well-managed, but also accessible, understood, appropriate, and usable by different kinds of users for different purposes (Dawes, 2010). Much can be learned from the experiences of state agencies and other air quality data users that will help assure the realization of economic, social, and other types of public value. The Denver, Atlanta, and Kansas City case studies documented many combinations of users, uses, and value as well as a variety of ways in which value can be increased.

2.3.1 Data Uses and Users

Table 1 presents the patterns of data use identified by the different data users in the cases. Three main categories of use were evident:

- Regulatory uses related to the Clean Air Act and companion state-level regulatory and enforcement programs;
- Public outreach and education, including daily pollution forecasts and health messaging; and
- Planning and research uses both within government and by independent researchers mainly in universities.

Of the different users, state air quality agencies use monitoring data for the largest number and widest range of purposes, from designing the monitoring networks, to executing SIPs, to daily forecasting, to planning for future activities or policies. Public outreach and education accounts for the greatest variety of uses; every kind of user engages in this activity to some extent. The preponderance of public outreach and education is carried out by quasi-governmental organizations and Non-Governmental Organizations (NGOs) on behalf of government. In these cases, such organizations were essential to the public information function; without them, it would barely exist.

Table 1. Uses and users of air quality data in the case studies.

Uses of air quality monitoring data in the cases	Type of User						
	EPA Regions	State air quality agencies	Regional and special-purpose state agencies	Local governments	Quasi-governmental agencies and NGOs	Academic researchers	Consultants
Regulatory Uses							
Network design and approval	X	X					
Non-attainment designations	X	X					
Exceptional event justification	X	X					
State Implementation Plan (SIP) preparation	X	X	X		X		
State-level regulatory programs		X		X			
Regional monitoring	X						
Public Outreach and Education Uses							
Daily pollution forecasting		X				X	X
Public health messaging		X	X	X	X		
"Spare the air" messaging		X	X	X	X		
Employer & commuter programs					X		
Internal government conservation programs				X			
School programs					X		
Public inquiry or local educational events	X	X	X	X	X		
Planning and Research Uses							
Atmospheric and other modeling	X	X				X	
Public health research						X	
Public policy research	X	X				X	

2.3.2 Data Uses and Data Sources

Table 2 summarizes the usual data sources that support the different uses of air quality data described in the cases.

Table 2. Current uses of air quality data in the cases by usual data sources.

Uses of air quality monitoring data in the cases	Data Sources						
	AirNow Website	AirNow-Tech	State monitoring database	State public website	Existing NASA & NOAA satellite products	Independently collected data	Other data sources (e.g., census data)
Regulatory Uses							
Network design and approval			X		X		X
Non-attainment designations			X				
Exceptional event cases			X		X	X	
State Implementation Plan (SIP) preparation			X			X	X
State-level regulatory programs			X			X	X
Regional monitoring	X	X					
Public Outreach and Education Uses							
Daily pollution forecasting		X	X		X		
Public health messaging			X		X		
"Spare the air" messaging			X				
Employer & commuter programs			X				X
Internal government conservation programs			X			X	X
School programs			X	X			X
Individual public inquiry or local educational events	X			X			X
Research Uses							
Atmospheric & other modeling		X	X		X	X	
Public health research		X	X			X	X
Public policy research		X	X			X	X

The state monitoring databases and public websites are the most frequently used data sources. Together, these two sources are associated with every data use identified by the interviewees. By contrast, the AirNow public website is used mainly for two purposes: to monitor multi-state trends, and to respond to individual public inquiries or prepare material for local outreach events, such as community forums. EPA regional offices use a mix of AirNow, AQS, and AirNow-Tech data to monitor conditions in their respective regions to evaluate, summarize, and report the previous day's air quality to EPA management or to track unusual events. In Atlanta, for example, EPA Region 4 used AirNow for near-real-time monitoring and reporting of multi-state air quality impacts during the 2010 Deepwater Horizon oil spill in the Gulf of Mexico. In addition, most organizations we interviewed said they use AirNow when fielding calls from the public related to air quality concerns, and they refer callers directly to AirNow for accessible, easy-to-digest information. AirNow is also similarly helpful in educational and outreach events in local communities.

Forecasting calls for very sophisticated data use. In Colorado, forecasters use computer weather models, AirNow-Tech, and a number of satellite products, including NASA's MODIS (Moderate Resolution Imaging Spectroradiometer) Terra and Aqua satellite imagery, GOES (Geostationary Operational Environmental Satellite) imagery, AIRS (Atmospheric Infrared Sounder) data, NOAA's GOES Aerosol/Smoke Product (GASP), among others. In Georgia, in addition to the reports from the monitoring stations, a team of forecasters from the state and Georgia Institute of Technology (Georgia Tech) use a variety of other data sources to develop daily pollution forecasts. These include National Weather Service national forecast models; computer weather models; AirNow-Tech; NASA satellite products; NOAA's air quality forecast model; and hydrology, linear regression, and 3D models developed by scientists at Georgia Tech.

The OzoneAware program in Denver, the anti-idling campaign in Atlanta, and Take Care of our Air in Kansas City are examples of public outreach uses of air quality data. These programs do not use the underlying monitoring data or other primary sources. Instead they rely on the states' daily forecasts and AQI codes, as well as state agency notifications about events such as wildfires that affect air quality. They use these products to issue advisories or alerts or to craft education campaigns that raise general awareness of air quality issues and actions individuals can take to protect their health or reduce emissions. Some local health departments perform similar activities, also drawing their information from the state website or from state-sponsored social media alerts and related messages.

For public health and public policy researchers, primary data from state monitoring networks or AirNow-Tech are often combined with other data sources to conduct exposure studies, policy evaluations, investigations to better measurement techniques, and other kinds of research studies that contribute to a better scientific understanding of air quality issues and effects.

2.4 User-Identified Limitations of Existing Air Quality Data

Despite the many and varied uses of existing air quality data, interviewees identified gaps and weaknesses that limit their ability to use the data to its fullest potential.

2.4.1 Gaps in the Monitoring Network

The most obvious and important gap in existing air quality data is a consequence of the monitoring network itself. For example, in Colorado, large portions of the state are long distances from the ground-based monitors in the regulatory network, which is concentrated on the narrow urban corridor along the front range of the Rocky Mountains extending from Fort Collins to Colorado Springs. In Georgia, monitors are concentrated around Atlanta and a few other cities, while large portions of the state are not directly covered by the network. Similarly, extensive portions of Missouri are far from the ground-based monitors in the regulatory network, which is concentrated around the four largest population areas of St. Louis, Kansas City, Springfield, and Columbia.

A primary reason for these gaps is the regulatory requirements for placement of the monitors. For $PM_{2.5}$ in particular, the minimum monitoring requirements do not require monitoring locations to be based on spatial coverage; instead, they are placed to account for exposure risk. This approach emphasizes population density, so the monitors tend to be clustered around cities.

The monitoring gaps limit the overall ability of states to provide timely and accurate air quality information to all areas, but it is neither economically nor politically feasible to place enough monitoring stations to eliminate these gaps. These gaps results in information that is inadequate for fully understanding both current conditions and longer-term trends. In addition, the state-based monitoring networks impose an artificial boundary (state lines) around the data that makes it difficult to track and understand the effects of interstate transport of pollutants.

2.4.2 Interpolation of Ground Monitor Data to Describe Larger Geographic Areas

AirNow uses mathematical interpolation of the ground sensor readings to estimate pollution concentrations in surrounding areas. For some areas within the United States, this is a reasonably good way to fill the data gap. However, for a variety of reasons, these estimates are unreliable for local use in many places. For example, in Colorado, extreme changes in terrain create microclimates that are ignored by the interpolation algorithms, leading to false readings, especially in mountainous areas. In Georgia, large areas without monitors, plus complex meteorology, can make forecasts unreliable because conditions are continually changing. Around Kansas City, estimates do not account for large areas of unmonitored activity, especially in agriculture, that can produce significant amounts of pollution in sparsely populated areas.

2.4.3 Missed Opportunities for Use of Air Quality Data by State and Local Health and Environmental Programs

The data gaps and difficult-to-use formats of air quality monitoring data prevent potential use by non-scientists for a variety of governmental responsibilities. For example, local government representatives expressed strong interest in doing more with air quality information. However, they were often unaware of AirNow, and especially AirNow-Tech, as resources they could use. Moreover, staffing and other resource constraints, coupled with lack of training to use these data sources, limit or prevent them from taking advantage of these resources for their own program goals.

Existing sources of air quality data might provide useful historical or other context for the hundreds of routine facility inspections conducted annually by state and local field staff. However, these resources are not well-understood and are seldom consulted. Field staff rely mainly on immediate onsite observation of compliance with the provisions of state-issued permits and the records each facility is required to maintain. In Georgia, thousands of burn permits are issued each year by both state and local authorities without making use of air quality monitoring data that might inform their day-to-day decisions to limit smoke and other pollutants. One field supervisor noted that the available air quality monitoring data are not easy to use or understand, and that some education about the variety of data sources, analyses, uses, and limitations would be necessary for them to take advantage of the monitoring data in their daily work. One field representative in Denver summed up the problem. "We might have the data we already would need or want, but just knowing how to use it, how to access it, how to make it useful for us [is a barrier]. . . I'm sure there's a ton of information there and if it was displayed a little bit differently it might tell us a completely different story and then we could use it in a much different way. So I think a lot of that stuff probably exists, we just don't even know how to make it helpful."

2.4.4 Challenges for Public Health Messaging and Programming

Federal government funding is no longer available for environmental health outreach or education programs. Some funding is available through the FHWA's CMAQ Program, but it cannot be used to advise directly about human health effects. Despite creative use of these limited resources, including partnerships with EnviroFlash (**EnviroFlash.info)** and the National Weather Service (**Weather.gov**), interviewees expressed serious concerns that the lack of fine-grained data jeopardizes the ability of state and local governments to address environmental health concerns directly.

One challenge is to find ways to target appropriate messages to different groups and to send useful information to people living in all areas of a state. The behavioral recommendations associated with AirNow (and the state-sponsored forecasts and websites) are mostly intended to inform sensitive groups to limit their exposure. However, the messages themselves are simplistic and they are broadcast widely rather than targeted directly to the groups or individuals who care about and could benefit from them.

Another concern has to do with environmental justice. Kansas City public health officials expressed serious concerns that the lack of fine-grained data and program funding is jeopardizing the ability of state and local governments to address environmental health concerns directly. They view this gap as especially detrimental to poor and minority communities who tend to live and work in areas of the city that are likely to be more polluted but are not well-monitored.

2.4.5 Unmet Public Expectations for Air Quality Information

Availability and promotion of public air quality information has stimulated rising public expectations that states cannot meet due to limited staffing, funding, and gaps in network coverage. For example, local governments and regional associations rarely use air quality data directly. Instead they typically rely on the states to gather and analyze the reports from the monitors, to prepare or contract for forecasts, and to issue alerts when needed. Some localities would prefer to operate their own monitors or to have the state add monitors to the statewide network, but these are both unlikely to happen for reasons of reliability and compatibility in the first instance, and cost in the second.

In addition, reporting air quality conditions in a way that makes sense to lay people immersed in very specific local situations remains a major challenge. For example, a state website may indicate "good" air quality for a local area while a local resident complains they cannot see their neighbor's house because of smoke. This mismatch occurs because the website is reporting a 24-hour average, while the caller is looking at the immediate situation. Some work is being done on new algorithms to reduce these discrepancies, but the underlying mismatch remains a problem for public communication.

Public interest in consumer-oriented monitoring tools presents new kinds of challenges regarding data validity and consistency. Government experts need to engage these individuals in a detailed discussion about different data sources, monitoring instruments, and measures in a way that holds their interest but does not oversimplify the science or the data.

2.4.6 Limitations of the Data for Research Purposes

Few of the research studies we learned about need near-real-time air quality data, but access to detailed historical information that reports hourly readings for small geographic units would be very useful for public health studies and policy analysis. AirNow already makes data available for research; however, it is not well-publicized or readily accessible to social scientists who could make extensive use of the data.

2.5 Public Value of Satellite-Enhanced Air Quality Information

During each interview, we presented examples of the satellite and satellite-enhanced AirNow products produced by the ASDP. Each example was drawn from past dates selected to highlight different daily conditions and the capabilities and limitations of the ASDP. We asked the interviewees to consider how they might use these products in light of their intimate knowledge of the case study region and to suggest the value of these products in their jobs or for the stakeholders they serve. The rest of this section describes the main benefits identified.

2.5.1 Fill Gaps in the Ground Sensor Network (*Financial, Mission, Strategic, and Stewardship Value*)

A consistent theme across all of the interviews was that satellite data could be used by local and state governments to supplement the existing ground-based network. Interviewees agreed that both the satellite data and the fused product could fill coverage gaps in the existing network to support routine forecasts and advisories to the public. They could also be used to identify potential air quality hot spots that warrant additional attention from a planning or regulatory perspective. In Kansas City, for instance, one interviewee explained, "we're missing a better understanding of how much emissions in rural areas and upwind transport impact largely urban non-attainment areas."

Gaps in the monitoring network are addressed as far as possible by AirNow by estimating or extrapolating air quality measurements from sensors at the monitoring sites to areas farther away. However, as described in the previous discussion of gaps and weaknesses, distance from the monitor and topographic and meteorological conditions can make these estimates inaccurate. In these instances, the satellite data could supplement the monitoring data. The accuracy of the satellite measurements is affected by local conditions, such as cloud cover, so this supplementation would not always be possible, but in many instances the satellite data could add considerable granularity by providing direct local measurements for forecasting and public information purposes. This would be especially useful in Colorado, where knowledge of the region's topography and geography is crucial to understanding where satellite data could be most useful. An expert in the EPA regional office pointed out how the mathematical interpolation of sensor readings assumes the same conditions spread out over a larger area, but in reality, "it just smears out and that probably is not reality, so the satellite [data] and the fusion may help resolve some of those issues."

2.5.2 Support Design and Deployment of the Regulatory Monitoring Network *(Financial and Mission Value)*

Due to a combination of economic, geographic, and political factors, states cannot place ground sensors in all the places needed to provide complete coverage. However, states constantly evaluate their networks against current and emerging air quality conditions in an effort to optimize the network they do have. They occasionally place monitors in new locations, sometimes as part of the regulatory network and sometimes as exploratory efforts to better understand the conditions in a certain location. Interviewees agreed that satellite data could help identify those areas in the state where the expensive investment in an additional monitor could provide the greatest value.

Colorado, for example, uses other air quality information such as "non-state" and "non-reference"[1] monitors to help identify some of these areas, but the satellite products could be an important additional information source, especially in those areas without ground monitoring of any kind. In Atlanta, an EPA expert described the value of being able to compare ground sensor and satellite data over time to identify persistent maximum concentrations and assess where in the air column they are occurring and what might be the cause. In Missouri, satellite information could provide a cost-effective strategy for state regulators to learn more about the potential impact of agriculturally-generated sources of air pollution and the impact that agriculture has on air quality in rural areas.

2.5.3 Improve Regional and Local Analysis of Air Quality Conditions, from Microscale Environments to Interstate Pollution Transport *(Mission, Social, and Stewardship Value)*

All the experts we interviewed recognized the potential value satellite data could provide to analysis of both regional and localized air quality conditions. For example, while the satellite data is not part of the regulatory network and cannot be used to demonstrate compliance with the NAAQS, it would be valuable to refine daily pollution forecasts because it provides a different kind and granularity of information. Satellite data could increase confidence in the coverage, accuracy, and timeliness of the information that state and local governments use for many routine responsibilities ranging from air quality forecasting, to advisories due to special events such as smoke from fires, to routine regulatory activities such as issuance of burn permits. Moreover, it could greatly refine the monitoring in microscale environments, such as the high mountain valleys of Colorado, where frequent and extreme changes in terrain make the interpolation of ground sensor data especially unreliable. Georgia officials described how satellite data could help them understand pollution effects from inversions that create large areas of stagnant air over the center of the state, where the coverage of ground monitors is the sparsest.

From a regional perspective, several interviewees discussed the potential for satellite data to help them understand transport of air pollution across long distances within and across states. Identifying the source and impact of interstate air pollution has become an increasingly important issue nationwide. Missouri air quality, for example, is strongly affected by the annual burning of two million

[1] "Non-state" monitors refers to federal agency monitors such as Forestry Service or other monitors owned and maintained by local governments or communities. "Non-reference" monitors refers to those monitors not certified by EPA for providing regulatory quality data.

acres of prairie in the Flint Hills of Kansas. Moreover, experts in the Kansas City case estimate as much as one-third of their ambient ground-level ozone is imported from other states.

From a more localized perspective, interviewees questioned exactly how granular the current 4-km resolution of the satellite data would be for local analysis, but they agreed it would be an improvement from the current network coverage. The Georgia Department of Natural Resources pointed out how complex weather patterns push pollutants around the state or create areas of temporary stagnation that may be far from a monitor. Satellite data could increase awareness of air quality issues and potential health effects in these areas.

In Atlanta, representatives of the Clean Air Campaign discussed how satellite data could provide localized analysis of air quality conditions for a variety of stakeholders, such as employers interested in identifying areas where a large number of employees are commuting, local health departments interested in better information about the air quality of their specific county or area of responsibility, industries interested in how their usual practices contribute to both their operating costs and working conditions, and local communities concerned with industrial development.

2.5.4 Improve Understanding of the Potential Impact of Industrial Development and Unregulated Activities *(Mission, Strategic, Political, and Stewardship Value)*

In all three cases, emerging and growing industries outside the main population centers have generated air quality concerns. In the Kansas City region, a new Burlington Northern Santa Fe (BNSF) intermodal transport facility will open in late 2013. While the modern capabilities of the new BNSF facility will help reduce overall air pollution in the metropolitan area, pollution will increase around the facility itself because there will be "less congestion, less idling…electric cranes versus diesel cranes and a lot of improvements in both process and technology." However, the site of the facility is "pristine nature…they are not building on a brown field." Satellite monitoring could track the effects of this development in more detail.

Air quality impacts of agriculture in Missouri and Georgia occur in areas that are sparsely monitored. Satellite data could help monitor and assess local impacts and health effects. Oil and gas exploration are increasing both in Colorado and Missouri, with attendant local concerns for air quality and other types of pollution. One local government expert noted that satellite data might provide an early warning of local impact by identifying emerging air quality issues early and helping the state determine whether ground monitors should be placed in the area. In Georgia, frequent and massive vegetative burning by federal facilities is not regulated by the state. Satellite data could help them understand the full air quality impact of and advocate for changes in current burning practices.

2.5.5 Support State-Level Air Quality Programs and Longer Range Planning and Priority Setting *(Mission Value*)

Satellite data could be used to assist in documenting exceptional events, developing and promoting active adoption of state implementation plans, setting priorities, and providing broader context for state-level regulation and enforcement activities. In the context of state implementation planning, a RAQC official in Denver described how having place-specific data in "almost real-time" would be useful in convincing residents and business interests located some distance from monitoring stations that activities and conditions in their locales do contribute to air quality problems in the area and that they could take actions to help mitigate them.

Satellite data could support permitting and enforcement activities as well as complaint investigations. While the field services staff we interviewed said they rarely use air quality monitoring data in their day to day work, they recognized that satellite data could provide a broader context for their work, making it possible for them to look at various regions retrospectively to identify patterns or "hot spots" of air quality concerns that could then be used to prioritize inspections. They could also potentially use the satellite data to identify historical correlations between air quality conditions and specific complaints.

Southern Georgia near the Florida border is a large area of frequent prescribed burning. In that region, only two monitors (Albany and Valdosta) support the ability of counties to look at air quality as a determining factor in deciding the number and scope of burn permits to issue. "Every one of these counties has an office that permits for that county. I mean, if they had data for their county and [could know] 'Well, what's the air quality data?' If they had that feedback, they might decide, 'Well, I'm only going to issue a couple thousand acres this day instead of 20,000!'"

Planning often involves modeling to predict the dispersion of air pollution and to assess both the impact of pollution sources and potential control strategies. Satellite data would provide additional detailed data with greater geographic coverage for use in these models. The modelers we interviewed all commented that "more data, from more sources" would be welcome in their work. In Georgia, for instance, planners said, "you can't ever have enough data… right now they're trying to project 20 counties from 11 data points."

2.5.6 Support State and Local Public Health Programs (*Mission, Social, and Stewardship Value*)

Satellite data could help support the public health mission of local governments. The satellite products could provide an important information resource that the agency or researchers could use to investigate the link between air quality and health effects. A representative from the Clean Air Campaign in Atlanta observed, "We are starting to work with some of the departments of health in the districts too, or in the counties, so I'm thinking, gosh, Fulton County has this whole health promotion action coalition that just started and they don't have any of this data. They have an actual separate asthma coalition for the county. This would be really helpful for some of the work that they're doing."

The deputy director of the Kansas City Health Department summarized the agency's main focus as it relates to air quality: "We're looking at the health outcomes that could be attributed to poor air quality, such as rates of chronic obstructive pulmonary disease, other respiratory disease, and asthma particularly."

Interviewees stated that the satellite products could provide an important information resource for investigating the link between poor air quality and health effects. More specifically, "what I hope can come from [the satellite products] is the ability to look at more data analysis to allow us to anticipate health impacts, particularly as it relates to emergency room visits, doctor visits, provider visits, related to asthma and upper respiratory illness" and to the impacts on poor and minority neighborhoods that are more exposed to pollution.

2.5.7 Enhance Public Health and Policy Research *(Mission Value, Stewardship Value)*

Researchers identified two main types of potential value from satellite data: improving the granularity, spatial coverage, and validity of air quality data for public health research and policy analysis; and providing data to extend this kind of research beyond urban centers to rural and agricultural areas. A number of policy-relevant research questions could be addressed in large regions or nationally by using the AirNow data base with satellite enhancements. Moreover, the granularity of the satellite data is valuable in understanding the differential effects of pollution on specific neighborhoods, transportation corridors, and public facilities such as schools.

One researcher we interviewed discussed how improved air quality data in rural agricultural areas could support research on how various air quality conditions impact the health and productivity of farm workers – studies that would have both public health and economic value. For example, satellite data might enable studies to associate levels of productivity with ambient air quality in small scale areas, with findings that might inform both public policies and business practices.

2.5.8 Support Science Education and Workforce Development *(Social Value, Mission Value, Political Value)*

Many opportunities exist for using satellite products with school-age children in the classroom, including incorporating actual satellite products in the K-12 science curriculum; increasing student interest in science, technology, engineering, and math by highlighting NASA and EPA as organizations that develop and use these products; and encouraging students to consider the types of careers these organizations offer.

The satellite products could provide school-age children with a learning tool for using and understanding maps and spatial relationships, and exploring how scientific information like air quality data is collected, managed, and used. Most importantly, satellite products could be used to teach them about air quality conditions not only for their state but for their own communities and help them "place themselves within the data." The person in charge of Atlanta's Clean Air Campaign school programs added, "Curriculum directors for the districts would, I think, really be excited to be able to provide this to their students." And the data need not be real time or necessarily complete; for these purposes, selected historical information sets would be sufficient.

3. Economic Analysis of Satellite Enhancements to the Monitoring Network for $PM_{2.5}$

This section describes an economic analysis STI performed comparing the cost savings of using NASA satellite data to provide air quality information in currently unmonitored locations instead of installing additional monitors in those locations. The complete report is in Appendix C.

Studies at regional and local scales indicate that $PM_{2.5}$ concentrations vary significantly spatially and temporally (Martuzevicius et al., 2004; Kim et al., 2000; 2005; Krudysz et al., 2008; Moore et al., 2010; Wilson et al., 2005; Pinto et al., 2004). We used two statistical measures, the Pearson's correlation coefficient squared (R^2) and coefficient of divergence (COD) (Pinto et al., 2004; Kim et al., 2005; Krudysz et al., 2008; Moore et al., 2010; Wilson et al., 2005), to investigate the spatial variability of $PM_{2.5}$ for the contiguous United States.

The goal of this analysis was to answer the following questions:

- **What gaps in coverage area exist in the current $PM_{2.5}$ monitoring network?** This question was investigated by determining the spatial coverage of the existing $PM_{2.5}$ ground monitoring network in the contiguous United States using statistical analysis of the spatial variability of $PM_{2.5}$.
- **What is the population in the unmonitored areas?** This question was investigated by estimating the population outside the current $PM_{2.5}$ network.
- **How many additional monitors would be needed to cover the population within the gaps?** This question was investigated by determining the cost savings of using the NASA satellite data in lieu of adding $PM_{2.5}$ monitors to provide coverage in areas outside the current network.

3.1 Capital Cost Savings Provided by NASA Satellite Data

The capital cost savings were calculated by

1. Determining the spatial coverage of out-of-network populated places using a buffer radius around monitors in the monitoring network and comparing that spatial coverage to the spatial coverage of the satellite data. Only areas with satellite coverage were used for the comparisons.
2. Adding monitors to the centroids of populated places to fill the out-of-network populated places gaps. An analysis was conducted on the cost of expanding the monitoring network's coverage area by placing hypothetical monitors in the centroids of out-of-network populated

places with populations greater than 25,000 and greater than 50,000.

3. Calculating the cost to purchase, install, and operate the additional monitors for five years using cost estimates CTG obtained from state and local officials.
4. Assuming that the costs of using satellite $PM_{2.5}$ is zero. We made this assumption because the satellite data are collected for many purposes and the daily $PM_{2.5}$ from satellite AOD retrievals are a standard product. Although the actual costs are not zero, they are negligible in comparison to the cost of new monitoring stations.

3.2 Results

The $PM_{2.5}$ ground monitoring network coverage area is illustrated in **Figure 8**. The areas shaded in gray are informed by the existing ground network. The other areas, which include most of Maine, Minnesota, Nebraska, South Dakota, North Dakota, Colorado, Wyoming, Montana, Idaho, Utah, Oregon, Nevada, and Arizona, lack representative ground-based monitoring observations. According to the 2010 census data, the population of the contiguous 48 states is nearly 303 million people, with 226.5 million people residing in populated places. The $PM_{2.5}$ network is estimated to provide coverage for 208.3 million people residing in populated places.

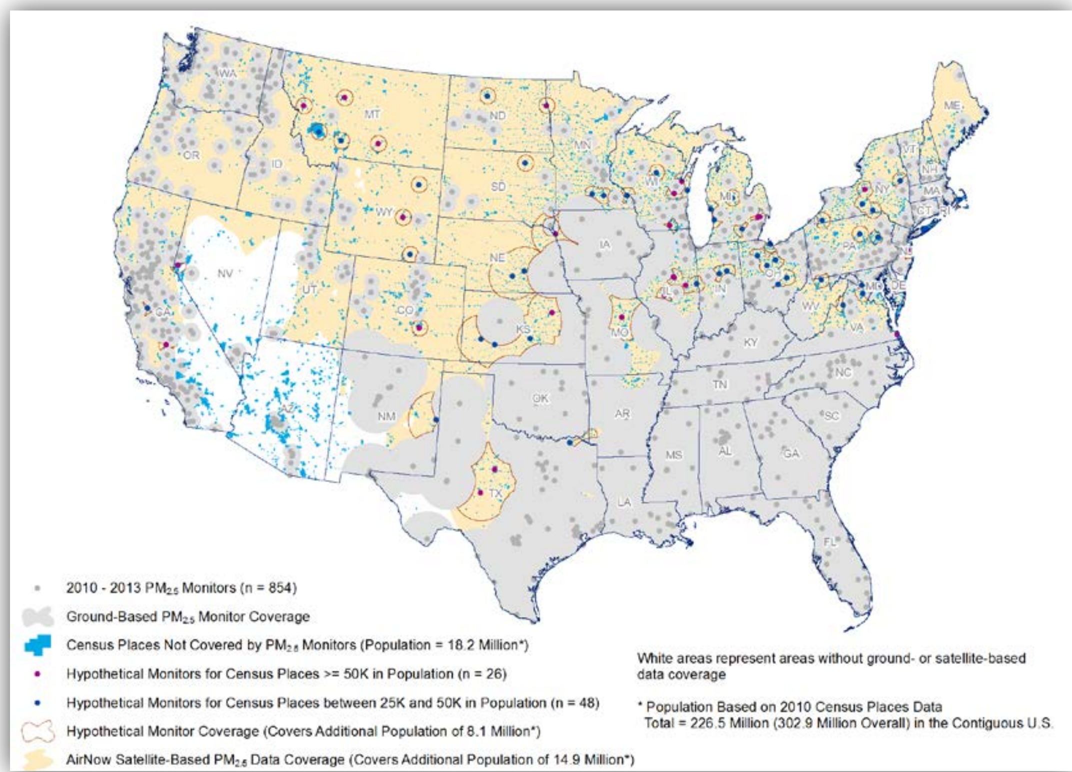

Figure 8. Map of $PM_{2.5}$ data coverage in the contiguous U.S. using EPA-Region-specific buffer radii.

3.3 Economic Benefits of the ASDP Products

The out-of-network population is approximately 18.2 million people. Satellite data could provide daily $PM_{2.5}$ information to 82% of these people (14.9 million). The fusion of NASA satellite data with ground measurements could make daily $PM_{2.5}$ data available to 98.5% (223.2/226.5 million) of people living in populated places.

If $PM_{2.5}$ monitors were added to Census Places not completely within the existing network coverage but inside satellite data coverage and with a minimum population of 25,000, 74 additional monitors would be required at an estimated cost of $25.9 million USD for purchase, installation, and operation for five years. However, the additional monitors would only extend coverage to 44% of the people residing out-of-network (8.1 million).

Additionally, we evaluated the largest (140-km) and smallest (40-km) buffer radius for all sites in the existing network to create a range of capital cost savings provided by satellite data. The benefits of incorporating satellite data are summarized in **Table 3**, and **Figures 9 and 10** illustrate the data coverage map for each scenario.

Table 3. Economic benefits of ASDP products by $PM_{2.5}$ monitor representative radius. Population is in millions of people and cost is in millions of USD.

	Monitor Representative Area		
	40-km Uniform Radius	EPA Region-Specific Radii	140-km Uniform Radius
Out-of-Network Population (millions)	42.5	18.2	2.7
Number of Additional Monitors			
Total	186	74	12
For Census Places ≥ 50K	67	26	6
For Census Places ≥ 25K < 50K	119	48	6
Population Coverage (millions/%)			
Addition of Monitors	19.1/45%	8.1/44%	1.5/56%
Satellite Data	39/92%	14.9/82%	2.2/82%
Installation and Five-Year Operations Costs of Additional Monitors (millions of USD)			
Total	$65.1	$25.9	$4.2
For Census Places ≥ 50K	$23.5	$9.1	$2.1
For Census Places ≥ 25K ≤ 50K	$41.7	$16.8	$2.1

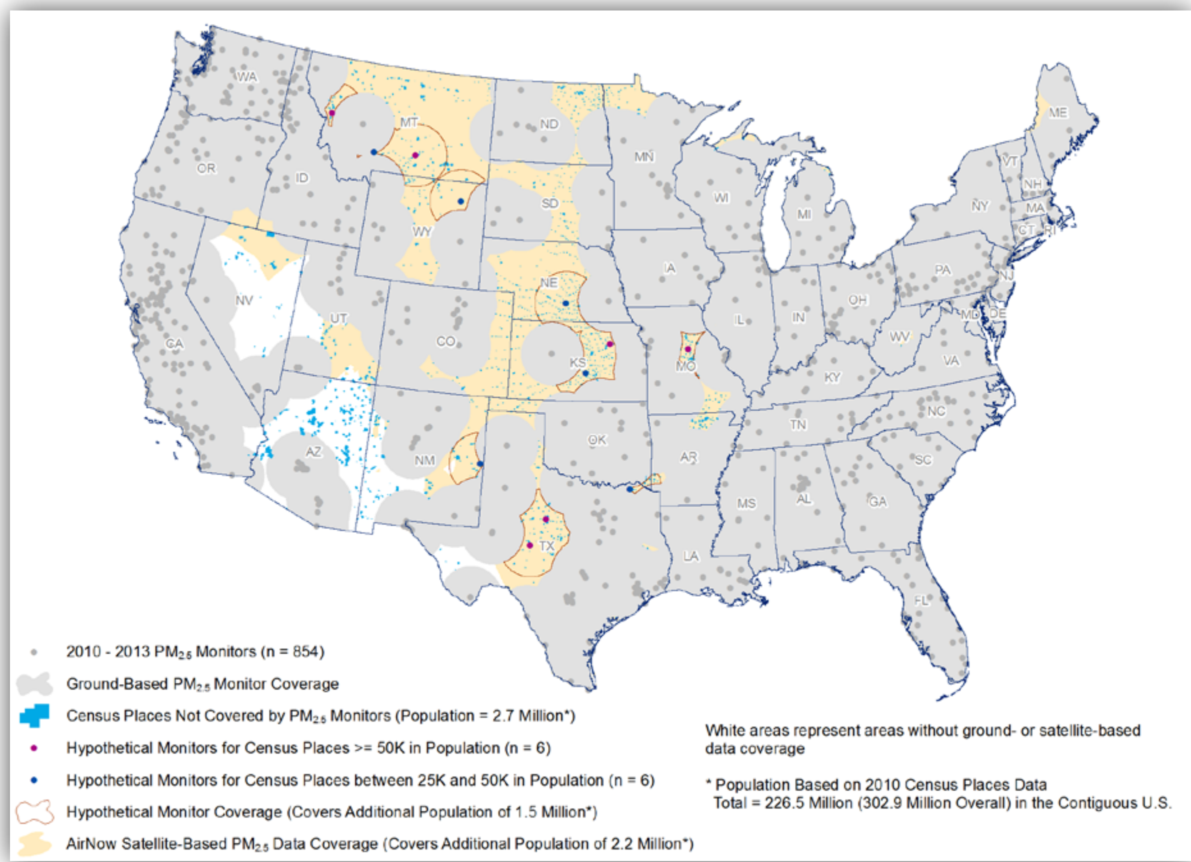

Figure 9. Map of the largest $PM_{2.5}$ data coverage in the contiguous U.S. using a monitor representative radius of 140 km for all monitors.

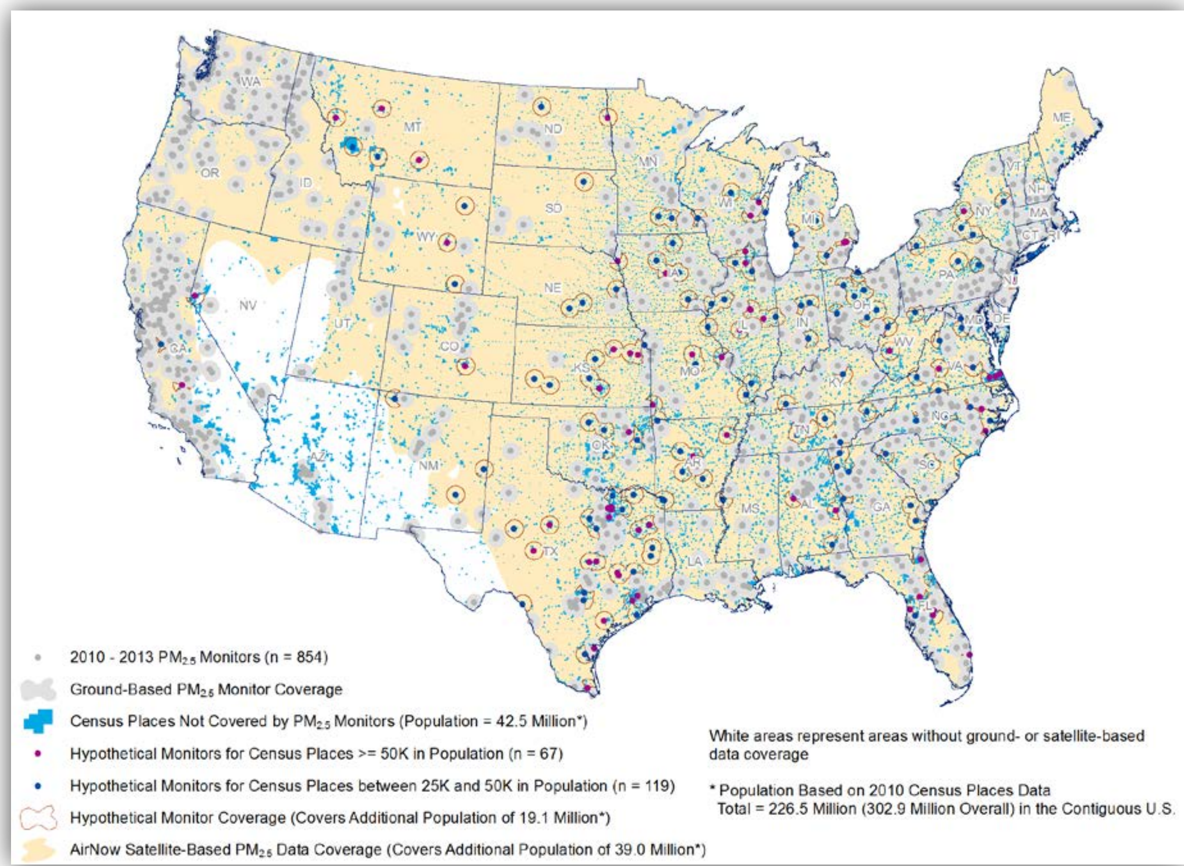

Figure 10. Map of the smallest $PM_{2.5}$ data coverage in the contiguous U.S. using a representative radius of 40 km for all monitors.

3.4 Conclusions

Based on the results of this analysis, including satellite data in AirNow not only extends $PM_{2.5}$ air quality information to millions more United States residents, but also has the potential of saving millions of dollars—the amount that would be needed to expand the existing ground monitoring network to cover the same population. This analysis used a minimum population of 25,000; however, if this analysis were repeated to cover less-populated areas, the cost savings could be in the hundreds of millions of dollars.

Satellite data are a valuable data source. Because of the global coverage of some satellites, satellite data could be used to provide additional air quality information throughout the world, especially in regions with severe air quality problems such as countries in the developing world. The use of satellite data to estimate surface-based pollution is a recent scientific application. Additional research is needed to continue to improve the relationship of satellite data to surface pollution for future satellites, in more locations, and at higher temporal resolutions.

4. Users' Recommendations toward Realizing the Socioeconomic Value of Satellite Data

This section summarizes the interviewee recommendations obtained by CTG. Interviewees represented different stakeholder groups and consequently offered different kinds of recommendations regarding the future development and use of satellite data and fused data products.

The interviews revealed a clear tension between the interviewees' desire for more information that is useful but not of regulatory quality, and their desire for accuracy and consistency across data sources to demonstrate compliance and avoid unwarranted actions or mixed messages to the public, businesses, or local communities. Some of the recommendations therefore focus on the regulatory environment and the need for precise data to demonstrate attainment and progress toward attainment of the NAAQS. Other recommendations reflect scientific and technical viewpoints about how more or different data can inform analysis, forecasting, planning, policy making, or enforcement. A third set of recommendations addresses public health and education concerns about how scientific information and health "messages" can best be communicated to the lay public. However, since each of the three categories of recommendations is intertwined, an ungrouped list can be found below.

> Precise data are needed to inform analysis, forecasting, planning, policy making, and enforcement and address public health and education concerns.

4.1 Compare Satellite Data to Monitor Data to Verify and Improve Quality and Credibility

Satellite data would be a new source for most users of air quality information. Because of this, data quality and reliability need to be assured. One way to assure data quality would be to periodically compare time-matched ground sensor readings on clear days to satellite readings on the same days in the small grid area surrounding each sensor. If the readings are substantially the same, the two sources could be considered to be of equivalent quality for many purposes, and therefore satellite readings in areas more distant from the sensors could be considered valid.

Another approach would be to test satellite readings in remote areas against readings from good-quality mobile ground sensors in the same locations.

A third approach would be to substitute satellite readings for a subset of ground sensor readings, and then compare the combined results to the results from the full set of ground sensors.

All of these approaches would help to establish the validity of satellite data and document its limitations relative to both sensor readings and interpolated results. According to one state expert, "The extent to which the satellite data agrees with monitored data relatively close to the monitors is a good thing."

4.2 Invest in Technologies that Allow Data from Ground Sensors and from Satellite Sensing To Be Gathered, Compared, and Fused for the Same Time Periods

Nearly all interviewees noted that the potential benefits of satellite data, and especially of a fused product, depend on finding a way to synchronize the data from the ground and satellite sources. For example, one air quality expert commented that the current two passes of the satellite that occur in late morning and early afternoon do not capture certain pollutant peaks that occur throughout the day, such as rush hour and high processing times at factories and other facilities. Ideally, the readings from both sources would be recorded frequently so that information could be compared, fused, or adjusted using measurements from both sources taken at the same time of day. Investments in geosynchronous satellites or other technologies that collect data throughout a 24-hour period seemed far preferable to algorithms that attempt to compensate mathematically for missing data and widely different time frames.

4.3 Provide Meteorological Data to Complement the Satellite Data

Forecasters told us the value of satellite data would be greatly enhanced if time-matched meteorological information were also provided. The combination of pollution measures and weather patterns would help them produce better pollution forecasts and help them better understand the transport of pollutants across distances.

4.4 Provide Satellite Imagery and Data Separately from a Fused ASDP Product

The fused ASDP product has potential value as an eventual replacement or point of comparison for current AirNow products. However, simpler approaches, such as making better use of satellite photo imagery, are available now and would be very useful. Some interviewees noted that looking at the separate map representations of the satellite data and the AirNow data was more helpful than looking at the fused product because they could readily see the difference (or agreement) in the readings and interpret their implications. The separate stories can often tell a more complete or complex story than the fusion. In its current form, the fused product not only masks differences in granularity and time scale, it also makes certain standard assumptions about which data source is more reliable—assumptions that may not be appropriate in all circumstances. In other words, "the mismatch can tell more of a story" than the fusion.

4.5 Support Research in Satellite Sensing Technologies that Permit Measurement of Other Pollutants, Especially Ozone

Both $PM_{2.5}$ and ozone are serious health hazards, especially with long-term exposure. Interviewees could see the definite benefits of satellite data for filling in the gaps and improving the granularity of $PM_{2.5}$ data gathered in the sensor network. Some pointed out it would be especially useful to have data on ozone because it is more insidious as a health risk. $PM_{2.5}$ is often accompanied by visible dust, smoke, or haze, as well as eye and respiratory irritation. Ozone is invisible and less likely to prompt individuals to change their behavior absent public health information and outreach.

4.6 Provide Training and Technical Support to both Scientific and Administrative Users of Ground Sensor Data, Satellite Data, and Fusion Products

Data users need information and training about the nature and limitations of the satellite data in order to make informed judgments about whether and how to use it. One question raised several times during the interviews focused on learning how the ASDP integrates the reading from the two passes of the satellites with the $PM_{2.5}$ standard, which is a 24-hour reading. A standard description of this process would help a technical user understand how the fusion is done and whether the result would be relevant or useful in any given application. Administrative users suggested webinars or other training programs to introduce them to the full range of air quality data available, data pros and cons, and suggestions about how data can be applied to support different responsibilities including outreach, research, and environmental justice studies.

4.7 Design Different Kinds of Products to Meet the Needs and Capabilities of Different Users

Because of the complexity and limitations of satellite data, most interviewees were cautious about making the satellite data directly available to the public, noting that interpretation demands more than a layperson's knowledge of and appreciation for the data and what it represents. Interviewees expressed concerns about how the public would react to multiple and different sources of information that can be inconsistent and sometimes contradictory. Overall, interviewees saw the potential value to the public, but cautioned that satellite products would need to be accompanied by outreach and education to help people understand what they were seeing. Several compared the satellite products to mobile and handheld monitors that are emerging in local communities around the United States. Some of these monitors do not meet EPA standards for instrument and data quality and can provide readings that are substantially different from what the public sees on AirNow or official state or local websites, causing confusion and conflict about air quality in their localities.

On the other hand, some argued that investment in a well-designed, tested, and explained fusion product might be a solution to the obvious gaps in the public version of AirNow. One said, "I think we all agree it's incredibly important to be transparent and give the public the information, but if you're not helping to interpret that information, I'm not sure what the value is." Given resource constraints for public outreach and education, this kind of assistance will most likely need to be built into the product itself. An EPA expert suggested one strategy could be to present satellite data side-by-side with the AirNow data on a single web page, with an explanation of the differences. This approach could make the satellite data more understandable and useful to members of the public as an additional source of information.

There was strong agreement that satellite data and data products could enhance the work of various kinds of experts for forecasting, permitting, compliance reviews, and other functions. However, as noted below, different kinds of experts will need different kinds of products or different sorts of technical assistance to use the data effectively. One interviewee added that agency experts need to be encouraged to use a consistent set of data sources in compatible ways because their work and their constituencies overlap. "I would see the most value of these products if my health department, the state health department, and our other nearby health departments were all using the same information and were on the same page. I would hate for one person to be doing satellite, one doing AirNow."

4.8 Improve the Organization and Usability of the AirNow.gov Website

Several interviewees outside the air quality agencies were not fully aware of the range of information and links on AirNow.gov, and others noted that the site is very data-driven and therefore suitable for expert users, but not accessible and useful for general users. While the information the site provides is diverse and valuable, information is often not easy to find, or the site is not easy to use. One interviewee commented that the accessibility, usability, and value of the current AirNow website could be improved for public consumption by an expert evaluation from someone who specializes in user experience.

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Appendix A: Case Summaries

This appendix contains executive summaries for the Atlanta, Georgia (Section A.1); Denver, Colorado (Section A.2); and Kansas City, Missouri (Section A.3) regions. The complete case study reports are provided in the following documents:

- **Atlanta Region Case Study.** Dawes S.S., Burke G.B., and Davis-Alteri A. (2013) Air quality data use, issues, and value in Georgia. Report by the Center for Technology in Government, University at Albany/SUNY, Albany, NY, October.
- **Denver Region Case Study.** Dawes S.S., Burke G.B., and Davis-Alteri A. (2013) Air quality data use, issues, and value in Colorado. Report by the Center for Technology in Government, University at Albany/SUNY, Albany, NY, October.
- **Kansas City Region Case Study.** Dawes S.S., Burke G.B., and Davis-Alteri A. (2013) Air quality data use, issues, and value in Missouri. Report by the Center for Technology in Government, University at Albany/SUNY, Albany, NY, October.

A.1. Atlanta Region Case Study Executive Summary

Georgia Air Quality Characteristics and Data

Over the past 40 years, Georgia has faced problems with various pollutants, including ozone, particulate matter, lead, and sulfur dioxide. Air quality problems are especially prevalent in the Atlanta metropolitan area, which has experienced rapid population growth and business development, with associated increases in emissions from vehicle usage and industrial sources.

In the late 1990s, state rules and determinations associated with emission control technologies for stationary sources produced significant improvements in air quality. In the mid-2000s, the state adopted rules for electric utility generation that continued the downward trend in emissions. At the same time, ongoing improvements in vehicle engine technology and frequent turnover in vehicles in Georgia further reduced emissions. Local outreach campaigns suggesting voluntary actions (and frequent yellow, orange, and red AQI days) have successfully raised public awareness of air quality concerns.

Despite these achievements, the combination of population growth and expanding highway travel with Georgia's warm, dry, and sunny summers produces frequent ozone problems and elevated amounts of $PM_{2.5}$. Atlanta and 20 surrounding or nearby counties do not meet either the annual standard for $PM_{2.5}$ or the 8-hour standard for ozone, or both. Today, the emission sources yet to be controlled are diffuse and more difficult to address because they involve convincing millions of individuals and small businesses to each contribute small improvements through changes in behavior, processes, and technology. The primary contributor to ozone pollution now comes from mobile sources, mainly vehicle traffic, while stationary sources and burning in rural areas are the main contributors to particle pollution.

Georgia's air quality monitoring network comprises 53 stations, including 28 that measure $PM_{2.5}$ and 20 that measure ozone. The remaining stations monitor other pollutants. Meteorological stations are also part of the network. The vast majority of monitors are located in the Atlanta metropolitan region. The continuous monitors in the network transmit data hourly after an initial validation has been performed. The hourly data is then used for daily consensus pollution forecasts and is also reported to AirNow. The daily forecasts are communicated to the public via websites, news outlets, community organizations, and social media to protect public health. Other government and community groups use the forecasts and the monitoring data for varied purposes, including permitting and preparation and execution of state implementation plans to address non-attainment areas, and for environmental and public health research, outreach, and education.

Gaps and Weakness in Existing Monitoring Data

Existing air quality data are extensive, but incomplete and imperfect. Interviewees discussed the following gaps and weaknesses that affect their work:

- **Gaps in the monitoring network.** The most obvious and important gap in existing air quality data are a consequence of the monitoring network itself. Monitors are concentrated around Atlanta and a few other cities, while large portions of Georgia are not directly covered by the network.
- **Interpolation of ground monitor data to describe larger geographic areas.** AirNow uses mathematical interpolation of the ground sensor readings to estimate pollution concentrations in surrounding areas. For some areas of the state, this is a reasonably good way to fill the data gap. However, large areas without monitors, plus complex meteorology, make these estimates unreliable for local use in many places.
- **Targeting and content of public outreach messages.** The challenge is to target appropriate messages to different groups and to send useful information to people all over the state. The main goal of AirNow is to inform sensitive groups to limit their exposure, but often information is too simplistic and not targeted directly to the groups or individuals who could benefit from air quality information.
- **Limitations of the data for research purposes.** Few of the research studies we learned about need near-real-time air quality data, but access to detailed historical information that reports hourly readings for small geographic units would be very useful for public health studies and policy analysis.

Potential Value of Satellite-Enhanced Data

Satellite data and related products that record particulate pollution in a 4-km grid are becoming available for regular use. If fully exploited, this new data resource could potentially deliver the following benefits:

- **Fill gaps in the ground sensor network.** Satellite data products could fill coverage gaps in the existing network to support routine forecasts and advisories to the public.
- **Support design and deployment of the regulatory monitoring network.** While satellite data and fusion products are not intended for regulatory decisions, they ultimately might improve performance of the state's regulatory mission by helping them optimize their network design.
- **Support state-level air quality modeling for longer range planning and priority setting.** Modeling is used to predict the dispersion of air pollution and assess both the impact of pollution sources and potential control strategies. Satellite data would provide additional detailed data with greater geographic coverage for use in these models and for model evaluation.
- **Improving understanding of air quality under stagnant meteorological conditions.** The lack of monitors in rural areas makes it difficult to assess the full impact of some point source pollutants from industry sites or military bases. Meteorological conditions can cause stagnation and local re-circulation of these air-borne pollutants under light and variable or calm winds. Except in cloudy conditions, satellite data could supplement the ground monitors to provide a more complete picture of these situations.
- **Improve regional and local analysis of air quality conditions.** Satellite data could provide localized analysis of air quality conditions for a variety of stakeholders, ranging from employers interested in identifying areas where a large number of employees are commuting, to local health departments interested in better information about the air quality of their specific county or area of responsibility, to certain industries interested in how their usual practices contribute to their operating and healthcare costs and working conditions.
- **Improve data for state and local government functions.** Satellite data could increase confidence in the coverage, accuracy, and timeliness of the information state and local governments use for many routine responsibilities ranging from air quality forecasting, to advisories due to special events such as smoke from fires, to the issuance of burn permits.
- **Enhancing public health and policy research.** Researchers identified two main types of potential value from satellite data: improving the granularity, spatial coverage, and validity of air quality data for public health research and policy analysis; and providing data to extend this kind of research beyond urban centers to rural and agricultural areas.
- **Supporting science education and workforce development.** Several opportunities exist for using satellite products with school age children in the classroom, including incorporating actual satellite products in the K-12 science curriculum and increasing student interest in

science, technology, engineering, and math by highlighting the organizations that develop and use these products and encouraging students to consider the types of careers they offer.

Stakeholder Recommendations for Further Developing Satellite Data Products

Interviewees represented different stakeholder groups and consequently offered different kinds of recommendations regarding the future development and use of satellite data and fused data products. Substantial differences are associated with different users and uses of the data, which together indicate its versatility and value for different purposes. Some of the recommendations focus on the regulatory environment and the need for precise data to demonstrate attainment and progress toward attainment of the NAAQS. Others reflect scientific and technical viewpoints about how more or different data can inform analysis, forecasting, planning, policy making, or enforcement.

- Use satellite data to "ground truth" the monitors and vice-versa to assure data quality and credibility.
- Provide meteorological data to complement the satellite data, accompanied by information accounting for the uncertainties introduced by frontal systems and other conditions that affect satellite readings.
- Invest in technologies that allow data from ground sensors and from satellite sensing to be gathered, compared, and fused for the same time periods.
- Support research in satellite sensing technologies that permit measurement of other pollutants, especially ozone.
- Provide training and technical support to scientific, administrative, and research users of ground sensor data, satellite data, and fusion products.
- Provide satellite imagery and data separately from a fused ASDP product.
- Give priority to developing satellite data products for experts rather than for direct public use.

A.2 Denver Region Case Study Executive Summary

Colorado Air Quality Characteristics and Data

Colorado presents complex topography and meteorology, and extreme variations in population density, urban-rural character, and economic activity that all make the state vulnerable to a variety of air quality issues. Today, ozone is the primary air pollution problem. The Denver metropolitan area has been out of attainment of the National Ambient Air Quality Standards for ozone since 2007. Vehicle usage, coal-fired power plants, and oil and gas drilling are large contributors to ground-level ozone, especially in the heavily populated areas along the Front Range urban corridor. A corrective State Implementation Plan (SIP) is in place to address the non-attainment areas. Extensive oil and gas exploration in other parts of the state are emerging as additional contributors to air pollution. In addition, unique topography and weather patterns bring additional air quality problems in the form of particulates from smoke and blowing dust, as well as high levels of winter ozone in the large, high mountain valley known as the Uintah Basin.

The State of Colorado operates air quality monitors at 57 locations around the state. Additional monitors are operated by federal government installations and some local governments. Most of these report data to AirNow, the national repository of near real time air quality information for public information and research users; others monitor local conditions only. State government meteorologists prepare daily air pollution forecasts that are communicated to the public via websites, news outlets, community organizations, and social media. Other government and community groups use air quality data for a variety of purposes including permitting, inspections, complaint investigations, preparation and execution of SIPs to address non-attainment areas, and environmental and public health outreach and education.

Gaps and Weakness in Existing Monitoring Data

Existing air quality data are extensive, but incomplete and imperfect. Interviewees discussed the following gaps and weaknesses that affect their work:

- **Gaps in the monitoring network.** The most obvious and important gap in existing air quality data are a consequence of the monitoring network itself: large portions of Colorado are long distances from the ground-based monitors in the regulatory network.
- **Interpolation of ground monitor data to describe larger geographic areas.** AirNow uses mathematical interpolation of the ground sensor readings to estimate pollution concentrations in surrounding areas. For some areas of the state, this is a reasonably good way to fill the data gap. However, long distances and, more importantly, extreme changes in terrain make these estimates unreliable for local use in many places.
- **Inconsistent terminology in public health messages.** Public health messages often use different terms to convey information about the same conditions. The choice of “action day,” “advisory,” or “alert” generally reflects either the language of legacy programs or local choices about the content of public health messages rather than real differences in air quality conditions.
- **Rising expectations but lack of resources for more data coverage and public health messaging.** The availability and promotion of public air quality information has stimulated rising expectations and demand for accurate localized data, simultaneously creating potential credibility problems when the state cannot meet the demand due to limited staffing, funding, and gaps in network coverage.

- **Missed opportunities for use of air quality data by state regulators.** The data gaps and difficult-to-use formats of existing air quality monitoring data prevent potential use by non-scientists for a variety of governmental responsibilities.

Potential Value of Satellite-Enhanced Data

Satellite data and related products that record particulate pollution in a 4-km grid are becoming available for regular use. If fully applied to air quality responsibilities, this new data resource could potentially deliver the following benefits:

- **Fill gaps in the ground sensor network.** Both satellite data products could fill coverage gaps in the existing network to support routine forecasts and advisories to the public.
- **Support design and deployment of the monitoring network.** Satellite data can help the state optimize the future placement of monitors in the ground sensor network by providing more information about parts of the state which currently fall in the gaps.
- **Support state-level air quality programs and longer range planning and priority setting.** Satellite data could assist in documenting exceptional events, developing and promoting active adoption of state implementation plans, setting priorities, and providing broader context for state-level regulation and enforcement activities.
- **Improve understanding of micro scale environments.** The rather unique geographic and topographic characteristics of the state create many different air quality situations that can be better understood with good quality, detailed satellite data.
- **Enhance forecasting, daily advisories, and public awareness.** While the satellite data are not part of the regulatory network and cannot be used to demonstrate compliance with the NAAQS, it would be valuable to refine daily pollution forecasts because it provides a different kind and granularity of information.

Stakeholder Recommendations for Further Developing Satellite Data Products

Interviewees represented different stakeholder groups and consequently offered different kinds of recommendations regarding the future development and use of satellite data and fused data products. Some focus on the regulatory environment and the need for precise data to demonstrate attainment and progress toward attainment of the NAAQS. Some reflect scientific and technical viewpoints about how more or different data can inform analysis, forecasting, planning, policy making, or enforcement. Others address public health and education concerns about how scientific information and health messages can best be communicated to the lay public.

- Compare satellite data to monitor data to verify and improve quality and credibility.
- Invest in technologies that allow data from ground sensors and from satellite sensing to be gathered, compared, and fused for the same time periods.
- Support research in satellite sensing technologies that permit measurement of other pollutants, especially ozone.
- Design different kinds of products to meet the needs and capabilities of different users.
- Provide training and technical support to both scientific and administrative users of ground sensor data, satellite data, and fusion products.
- Provide satellite imagery and data separately from a fused ASDP product.

A.3 Kansas City, Missouri Region Case Study Executive Summary

Missouri Air Quality Characteristics and Data

The State of Missouri has been monitoring air quality statewide since the mid-1960s. Today, the Air Pollution Control Program of the Missouri Department of Natural Resources (MDNR) operates monitors at 52 locations. Stations are concentrated around the four largest population areas of St. Louis, Kansas City, Springfield, and Columbia. Extensive rural and agricultural areas of the state are not covered by the monitoring network. The five-county Kansas City metropolitan area spans both Missouri and Kansas and was one of the earliest non-attainment areas for ozone, designated in the 1980s. The area is still operating a 20-year improvement and maintenance plan, and has been in attainment for most of that period. Today, Kansas City maintains good air quality for $PM_{2.5}$ and falls just within the NAAQS standard for ozone. However, ongoing emissions from both industry and vehicles, plus periodic tightening of the NAAQS, put the Kansas City region at risk for non-attainment of ozone in the future. The St. Louis area is out of attainment for both $PM_{2.5}$ and ozone. Specific local sites are out of attainment for sulfur dioxide and lead. Oil and gas exploration in southwestern Kansas may further contribute to increased levels of ozone and particulate matter. Agricultural dust from grain processing and farm operations is another source of particle pollution, although there are few monitoring sites in agricultural regions to assess the extent of the problem. Environmental justice concerns pertain to neighborhoods that border highways and rail lines regarding both ozone precursors and particles.

Air quality monitoring data are used in several different ways in Missouri and the Kansas City region. MDNR maintains a public website that reports actual pollutant concentrations and near real-time ambient air monitoring data. The department also does pollution forecasting for internal management information and planning, but does not produce daily pollution forecasts or public alerts. Instead, MDNR relies on community-based organizations like the Mid-American Regional Council (MARC), the American Lung Association, or local governments like the Kansas City

Department of Health for these activities. In addition, MARC and EPA Region 7 conduct a variety of public education and outreach activities using the web, social media, TV and radio, community meetings, corporate challenges, and other strategies.

Gaps and Weaknesses in Existing Monitoring Data

Existing air quality data are extensive, meet applicable EPA monitoring requirements, but result in spatial gaps that affect the ability to report air quality data in some areas. Interviewees discussed the following gaps and weaknesses that affect their work:

- **Gaps in the monitoring network.** The most obvious and important gap in existing air quality data are a consequence of the monitoring network itself: large portions of Missouri are long distances from the ground-based monitors in the regulatory network.
- **Interpolation of ground monitor data to describe larger geographic areas.** AirNow uses mathematical interpolation of the ground sensor readings to estimate pollution concentrations in surrounding areas. Because the region has relatively simple topography, this can often be a reasonably good way to fill the data gap. However, long distances and unmonitored activities, especially in agricultural areas, can make these estimates unreliable for local use.
- **Inability to target special audiences with public health messages.** Federal government funding is no longer available for environmental health outreach or education programs. Some funding is available through the Federal Highway Administration's Congestion Mitigation and Air Quality Improvement (CMAQ) Program, but that funding cannot be used to advise about human health effects. Despite creative use of these limited resources, interviewees expressed serious concerns that the lack of fine-grained data jeopardizes the ability of state and local governments to address environmental health concerns directly.
- **Competing data sources and interpretations.** The availability and promotion of public air quality information such as AirNow has stimulated public interest in consumer-oriented monitoring tools that present new kinds of challenges regarding data validity and consistency. Government experts need to engage these individuals in a detailed discussion about different data sources, monitoring instruments, and measures in a way that holds their interest but does not oversimplify the science or the data.

Potential Value of Satellite-Enhanced Data

Satellite data and related products that record particulate pollution in a 4 km grid are becoming available for regular use. If fully exploited, this new data resource could potentially deliver the following benefits:

- **Filling gaps in the ground sensor network.** Satellite data products could fill coverage gaps in the existing network to support routine forecasts and advisories to the public. They could also be used to identify potential air quality hot spots that warrant additional attention from a planning or regulatory perspective.

- **Supporting design and deployment of the regulatory monitoring network.** While satellite data and fusion products are not intended for regulatory decisions, they ultimately might improve performance of the state's regulatory mission by optimizing network design.
- **Improving understanding of the potential impact of new industrial development.** In the Kansas City region, Burlington Northern Santa Fe (BNSF) is building a new intermodal facility to open in late 2013. While this move and the associated modern capabilities of the new facility will help reduce overall air pollution in the metropolitan area, pollution will increase around the facility itself. Satellite data could help monitor and assess the local impact.
- **Improving regional and local analysis of air quality conditions.** Satellite data could provide localized analysis of air quality conditions for a variety of stakeholders, ranging from local health departments interested in better information about the air quality of their specific county or area of responsibility, to local communities concerned with industrial development. Where modeling is used to predict the dispersion of air pollution and to assess its impact and potential control strategies, satellite data would provide additional detail with greater geographic coverage for use in these models.
- **Improving data for local public health functions.** Satellite data could help support the public health mission of local governments. The satellite products could potentially provide an important information resource that could be used by the agency or by researchers to investigate the link between poor air quality and health effects.

Stakeholder Recommendations for Further Developing Satellite Data Products

Interviewees represented different stakeholder groups and consequently offered different kinds of recommendations regarding the future development and use of satellite data and fused data products. Substantial differences are associated with different users and uses of the data, which together indicate its versatility and value for different purposes. Some of the recommendations focus on the regulatory environment and the need for precise data to demonstrate attainment and progress toward attainment of the NAAQS. Others reflect scientific and technical viewpoints about how more or different data can inform analysis, forecasting, planning, policy making, or enforcement. The recommendations include

- Use satellite data to "ground truth" the monitors and vice-versa to assure data quality and credibility.
- Invest in technologies that allow data from ground sensors and from satellite sensing to be gathered, compared, and fused for the same time periods.
- Support research in satellite sensing technologies that permit measurement of other pollutants, especially ozone.

- Provide training and technical support to both scientific and administrative users of ground sensor data, satellite data, and fusion products.
- Take special care in designing satellite products for non-experts.
- Improve the organization and usability of the existing AirNow.gov website.

Appendix B: List of Interviewees

B.1 Denver Region

Environmental Protection Agency, Region 8

- Richard Payton, Air Quality Monitoring

Colorado Department of Public Health and Environment

- Marley Bain, Unit Supervisor, Field Services
- Paul Carr, Unit Supervisor, Field Services
- Christopher Dann, Public Information Officer, Air Pollution Control Division
- Greg Harshfield, Gaseous Monitoring Supervisor, Technical Services
- Patrick McGraw, Particulate Monitoring Supervisor, Technical Services
- Shannon McMillan, Field Services Program Manager, Field Services
- Gordon Pierce, Technical Services Program Manager, Technical Services
- Patrick Reddy, Senior Air Quality Meteorologist

Regional Air Quality Council (RAQC)

- Meg Alderton, Communications Manager
- Gerald Dilley, Air Quality Engineer

El Paso County Public Health

- Tom Gonzales, Director, Environmental Health Division

Pikes Peak Area Council of Governments

- Richard Muzzy, Environmental Planning Manager

B.2 Atlanta Region

U.S. Environmental Protection Agency, Region 4, Air, Pesticides, and Toxics Management Division; Air Toxics and Monitoring Branch, Monitoring and Technical Support Section

- Ryan Brown, Environmental Scientist
- Daniel Garver, Environmental Scientist
- Darren Palmer, Environmental Scientist

Georgia Department of Natural Resources, Environmental Protection Division, Air Protection Branch

- Jim Kelly, Program Manager, Planning and Regulatory Development Unit, Planning and Support Program
- Bill Murphey, Unit Manager, Meteorology Unit
- Susan Zimmer-Dauphinee, Program Manager, Ambient Monitoring Program

Georgia Department of Transportation, Air Quality and Technical Resource Branch

- Habte Kassa, Planning Engineer III
- Patti Schropp, Senior Transportation Planner at ATKINS Global

The Clean Air Campaign

- Brian Carr, Director of Communications
- Lesley Carter, School Communications Manager
- Gretchen Gigley, Director of Education
- Jenny Schultz, Communications Specialist
- Mike Williams, Director of Employer Services

Rollin School of Public Health, Emory University

- Jeremy Sarnat, Associate Professor, Department of Environmental Health

- Matthew Strickland, Assistant Professor, Departments of Environmental Health and Epidemiology

Indiana University (formerly of School of Public Policy, Georgia Institute of Technology)

- Douglas Noonan, Associate Professor School of Public and Environmental Affairs

B.3 Kansas City, Missouri, Region

Missouri Department of Natural Resources, Air Pollution Control Program

- Stephen Hall, Monitoring Unit Chief

Environmental Protection Agency, Region 7

- Andy Hawkins, Environmental Scientist
- Amy Bhesania, Missouri State PM Coordinator

Mid-America Regional Council

- Doug Norsby, Air Quality Manager
- Amanda Graor, Air Quality Program Manager

Kansas City Missouri Health Department

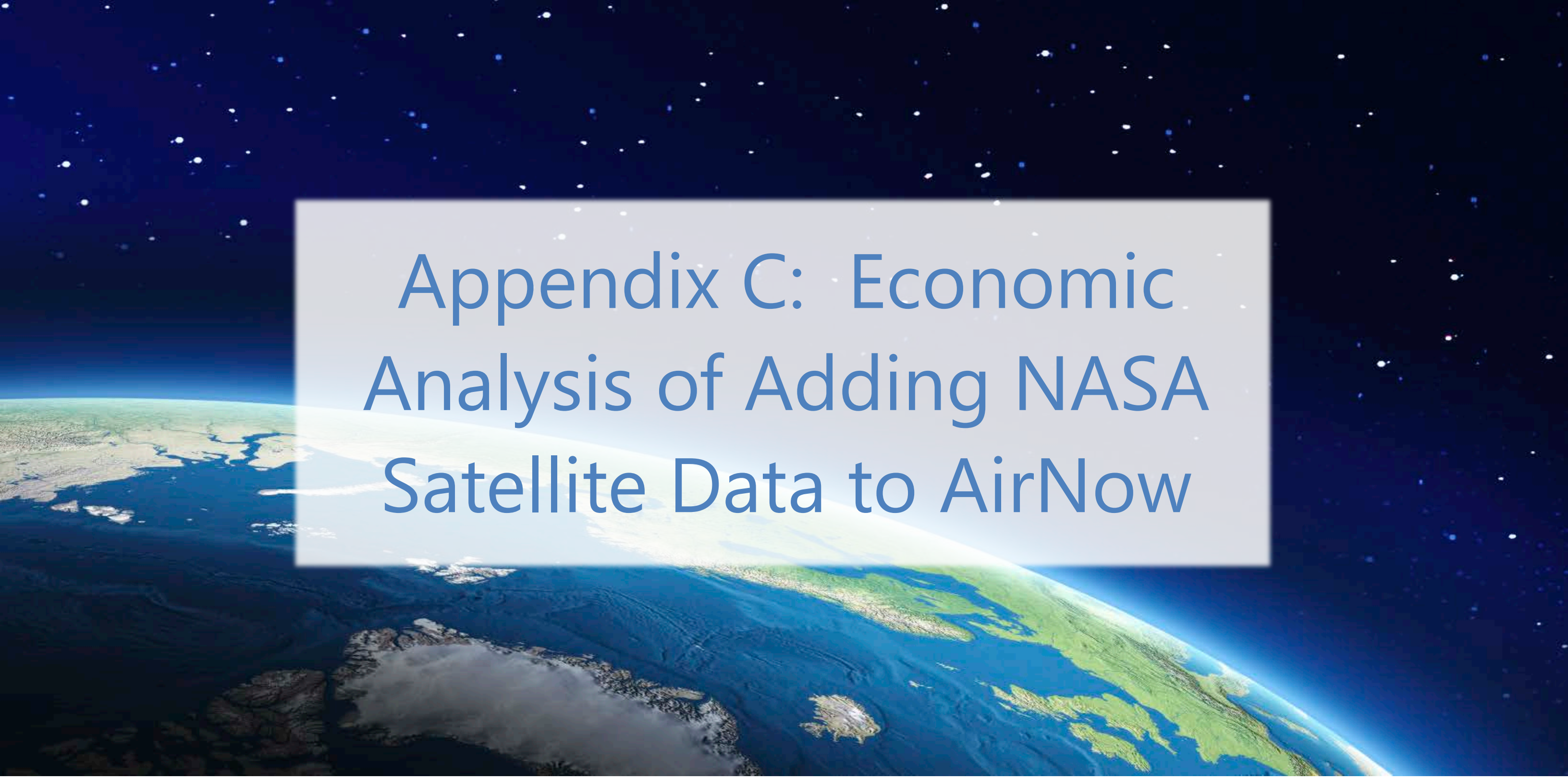
- Bert Malone, Deputy Director
- Catherine Reid, Air Quality Engineer
- Naser Jouhari, Director of Environmental Services

Kansas City Missouri Office of the Mayor

- Dennis Murphey, Chief Environmental Officer, Office of Environmental Quality

Appendix C: Economic Analysis of Adding NASA Satellite Data to AirNow

This appendix contains a full report on the economic analysis performed by STI, which used a statistical approach to determine the spatial variability of $PM_{2.5}$ measurements throughout the United States and to estimate the capital cost savings if the NASA satellite data were used instead of adding new monitors in the unmonitored areas.



Appendix C: Economic Analysis of Adding NASA Satellite Data to AirNow

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STI-910404-5789

October 4, 2013

Exposure to elevated ambient fine particulate matter ($PM_{2.5}$) concentrations is associated with adverse cardiovascular and respiratory health effects. The real-time ambient air monitoring network that is used to inform the public about adverse air quality conditions does not cover all regions in the continental United States. More than 42 million people reside in populated places farther than 40 km from the nearest $PM_{2.5}$ monitor; therefore, those people have no information or likely inaccurate information on real-time exposure to $PM_{2.5}$. From a public health perspective, people who take protective action to avoid exposure to high outdoor $PM_{2.5}$ concentrations will experience substantial health benefits.

One way to provide additional $PM_{2.5}$ information for these unmonitored areas is to use $PM_{2.5}$ estimated from satellite aerosol optical depth data to fill the monitoring gaps. A recent NASA-funded project, AirNow Satellite Data Processor (ASDP), developed a system for the U.S. Environmental Protection Agency (EPA) to routinely estimate surface $PM_{2.5}$ concentrations from satellite data and then fuse these estimates with routine surface $PM_{2.5}$ monitor observations in the AirNow system.

This study evaluated the economic benefits of adding NASA satellite data to AirNow through ASDP products. The benefits were evaluated by determining the spatial coverage and cost savings provided by the ASDP products compared to the costs of installing and operating additional $PM_{2.5}$ monitors. A prerequisite to this analysis was characterization of the spatial coverage of the existing $PM_{2.5}$ monitoring network. This analysis is part of the work done for the ASDP project.

Studies at regional and local scales indicate that $PM_{2.5}$ concentrations vary significantly spatially and temporally (Martuzevicius et al., 2004; Kim et al., 2000; 2005; Krudysz et al., 2008; Moore et al., 2010; Wilson et al., 2005; Pinto et al., 2004). We used two statistical measures, the Pearson's correlation coefficient squared (R^2) and the coefficient of divergence (COD) (Pinto et al., 2004; Kim et al., 2005; Krudysz et al., 2008; Moore et al., 2010; Wilson et al., 2005), to investigate the spatial variability of $PM_{2.5}$ for the contiguous United States.

The goal of this analysis was to answer the following questions:

- **What gaps in coverage area exist in the current $PM_{2.5}$ monitoring network?** This question was investigated by determining the spatial coverage of the existing $PM_{2.5}$ ground monitoring network in the contiguous United States using statistical analysis of the spatial variability of $PM_{2.5}$.
- **What is the population in the unmonitored areas?** This question was investigated by estimating the population outside the current $PM_{2.5}$.
- **How many additional monitors would be needed to cover the population within the gaps?** This question was investigated by determining the cost saving of using the NASA satellite in lieu of adding $PM_{2.5}$ monitors to provide coverage in areas outside the current network.

C.1 Data Acquisition and Processing

This section describes the air quality, population, and cost data used in the analysis.

Air Quality Data

The ambient air quality data used in the analysis were acquired from the national continuous $PM_{2.5}$ monitoring network. The 24-hour averages of the 1-hour continuous $PM_{2.5}$ mass data from AirNow were used because these are the data used to inform the general public of air quality on a real-time (daily) basis. It is important to note that these data are considered preliminary and are subject to additional data validation before the data are considered final and can be used for research or for regulatory decisions. The data selected were defined as the data approved for public reporting by state and local air quality agencies, and are the data found in current AirNow (AirNow.gov) products. Data from January 2010 through June 2012 were obtained from AirNow for all sites approved for public reporting and defined as principle (parameter and POC combination) in the contiguous United States. Data were then required to meet the following data completeness criteria for inclusion in the analysis:

- At least 68 daily averages per quarter (i.e., 75% data completeness) and at least three complete quarters per year for 2010 and 2011, and two complete quarters for 2012.
- At least two complete years, or if 2012 data, complete through June.[1]

Population Data

The most recent population data available were the 2010 U.S. Census Places data from ArcGIS 10.1. The Bureau of Census defines a place as a concentration of population; a place may or may not have legally prescribed limits, powers, or functions. The concentration of population must have a name, be locally recognized, and not be part of any other place. Not everyone resides in a named place; in 2010, approximately 76.5 million people (25%) in the United States lived outside of a named place, either in rural areas or in the densely settled fringes of large cities in areas that were built up, but not identifiable as places (U.S. Census Bureau, 2010). The Census Places data includes census designated places, consolidated cities, and incorporated places (U.S. Census Bureau, 1994).

Cost Data

Estimated costs for purchase, installation, and labor, as well as operation and maintenance costs per year for a new $PM_{2.5}$ monitor, were obtained through interviews conducted as part of the

[1] In late 2012, a major upgrade was performed on the AirNow database, which stores all air quality information at EPA. This upgrade fundamentally changed the way data were stored. As a result, agencies were required to change the format used to submit data. As agencies worked to implement the new format, data gaps resulted, which have since been corrected.

socioeconomic analysis by the Center for Technology in Government (CTG). The estimated cost to purchase and install a new continuous $PM_{2.5}$ monitor was approximately $100,000 USD, with an additional cost of $50,000 USD per year for operations and maintenance.

C.2 Methodology

This section describes the methodology used to determine the spatial variability of $PM_{2.5}$ throughout the United States, define the existing $PM_{2.5}$ monitor network spatial area, and estimate the capital cost savings if the NASA satellite data were used instead of new monitors in the unmonitored areas.

Spatial Variability and Coverage of Ambient $PM_{2.5}$ Monitoring Network

The concentration differences between pairs of nearby $PM_{2.5}$ monitors were used to characterize the spatial variability and extent of spatial coverage of the current ambient $PM_{2.5}$ monitoring network. A coverage radius, representing the zone of influence of a monitor, was assigned based on the spatial variability information.

The spatial variability of $PM_{2.5}$ concentrations in the United States was determined by calculating the coefficient of divergence (COD) and the coefficient of determination (R^2, or the Pearson correlation coefficient squared). The COD and R^2 were calculated for all site pairs within 200 kilometers of each other and grouped by 20-kilometer distance bins up to 200 kilometers for all unique site pairs for all sites in the United States and also by EPA Region.

The COD is defined as

$$COD = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{x_i - y_i}{x_i + y_i}\right)^2} \qquad \text{Eq. 1}$$

where n is the number of pairs of samples, x_i is the daily concentration measured on the i^{th} day at one site, and y_i is the daily concentration measured on the i^{th} day at the other site.

COD is a measure of dispersion of data and ranges from 0 to 1, with values at or near 0 representing two sites that are similar (or have no difference) and values at or near 1 representing sites that are highly different.

For this analysis, we used a COD threshold of 0.20 to identify sites with similar concentrations. There is no universally accepted criteria, however, three recent studies defined sites with COD values less than or equal to 0.2 as spatially homogeneous (Krudysz et al., 2008; Moore et al., 2010; Wilson et al., 2005).

The Pearson correlation coefficient R is defined as

$$R = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2}} \quad \text{Eq. 2}$$

where n, x_i, and y_i are defined as indicated above. R^2 indicates the proportion of variability in one data set that may be explained by the other. An R^2 value of 0.5 or greater was used as the criterion to indicate that two data sets trend together reasonably well in this study.

A cutoff distance for COD threshold was determined as the higher end of the largest distance bin in which the median COD fell below 0.2. The cutoff distance for R^2 was the higher end of the largest distance bin in which the median R^2 stayed above 0.5. The cutoff distances for COD and for R^2 were compared and, conservatively, the lower value was chosen as the representative radius for monitors within each EPA region. For example, if the distance bin for the COD ≤ 0.2 was 20 to 40 km and $R^2 \geq 0.5$ was 60 to 80 km, 40 km was chosen. We explored using narrower distance bins (e.g., 10-km bins) but found the trends in COD and R^2 were less consistent and more difficult to interpret than the 20-km bin values.

In order to have the most up-to-date snapshot of the existing monitoring network in the contiguous United States, sites that reported $PM_{2.5}$ data to AirNow in 2013 that were not among the sites that had complete data during 2010 to June 2012 were added to the pool of sites. Using ArcMap, a buffer (circle) was drawn around each monitor according to the representative radius of the sites in each EPA region. The data were merged and a single polygon that represented the coverage area of each $PM_{2.5}$ ground monitor was defined.

Capital Cost-Savings Provided by NASA Satellite Data

The capital cost savings was calculated by

1. Determining the out-of-network populated places based on the spatial coverage of the current monitoring network, and comparing to the spatial coverage of the satellite data. Only areas with satellite coverage were used for the comparisons.
2. Adding monitors to the centroids of populated places to fill in the out-of-network populated places gaps. An analysis was conducted to expand the current monitoring network's coverage area by placing hypothetical monitors in the centroids of out-of-network populated places with populations greater than 25,000 and greater than 50,000.
3. Calculating the cost to purchase, install, and operate the additional monitors for five years using cost estimates CTG obtained from state and local officials.
4. Assuming that the costs of using satellite $PM_{2.5}$ is zero. We made this assumption because the satellite data are collected for many purposes and the daily $PM_{2.5}$ from satellite AOD

retrievals are a standard product. Although the actual costs are not zero, they are negligible in comparison to the cost of new monitoring stations.

C.3 Results

Spatial Variability and Coverage of the Ambient $PM_{2.5}$ Monitoring Network

680 $PM_{2.5}$ monitors met the data completeness criteria (**Figure C-1**). These sites were paired, and their CODs and R^2s were calculated (**Figures C-2** and **C-3**). As expected, the results showed that COD increased with distance between sites, while R^2 decreased (Figure C-2). Nationally, the upper bound of spatial homogeneity (median COD ≤ 0.2) for ambient $PM_{2.5}$ concentrations is 40 km. The median R^2 of $PM_{2.5}$ data between sites dropped below 0.5 when the site pairs were more than 100 km apart.

The spatial variability of $PM_{2.5}$ by EPA Region is shown in Figure C-3. The regions exhibiting the greatest $PM_{2.5}$ spatial homogeneity are Regions 4 and 7 (central Midwest and the Southeast), both of which had a median COD below 0.2. Regions 1, 2, 3, 5, and 6 also had a more homogeneous $PM_{2.5}$ spatial distribution in comparison to Regions 8, 9, and 10. The higher spatial variability in Regions 8, 9, and 10 may be explained by the larger geographic area, rougher terrain, more complex meteorology, and, in some cases, fewer monitors in several states in the western regions than the eastern and southern regions. R^2 values in Regions 8, 9, and 10 revealed significantly lower (< 0.50) association in the data than the rest of the regions. These results confirmed that $PM_{2.5}$ monitor representative area could be customized by EPA Region because the spatial variability of $PM_{2.5}$ concentrations varies greatly between regions.

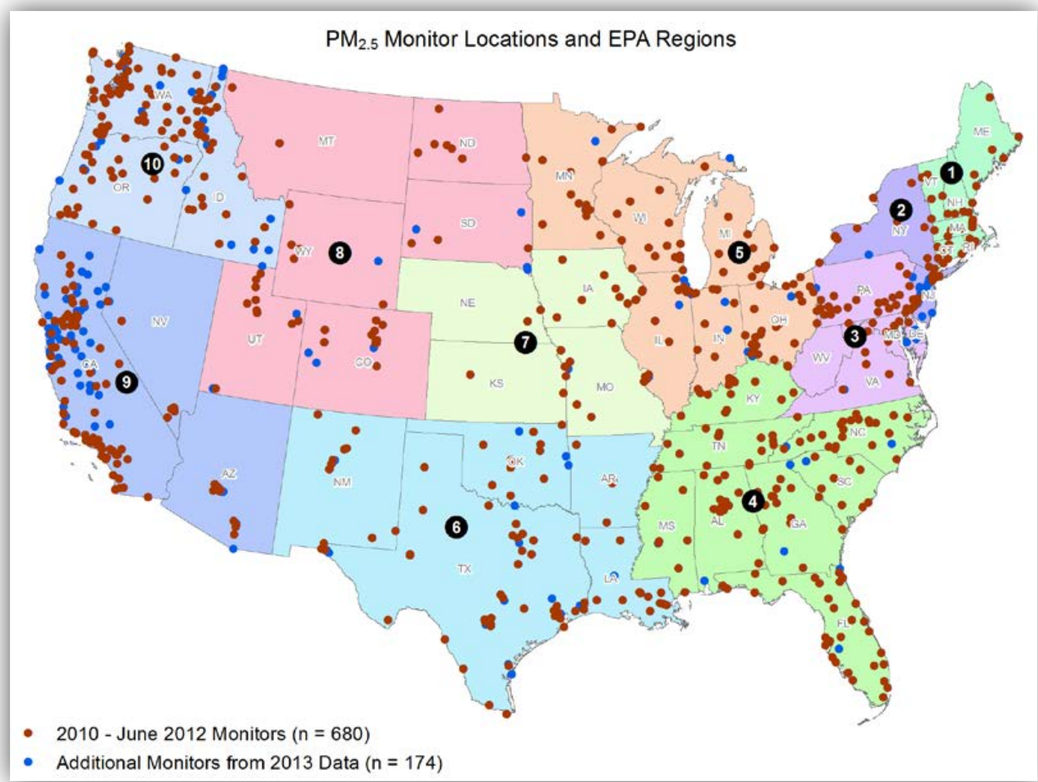

Figure C-1. Map of $PM_{2.5}$ monitor locations by EPA Regions in the contiguous U.S. A total of 854 sites are present on the map. The COD and R^2 statistics were based on 680 sites that met the data completeness criteria (red dots). An additional 174 sites reporting data in 2013 (blue dots) were included in creating the ground monitoring network coverage area.

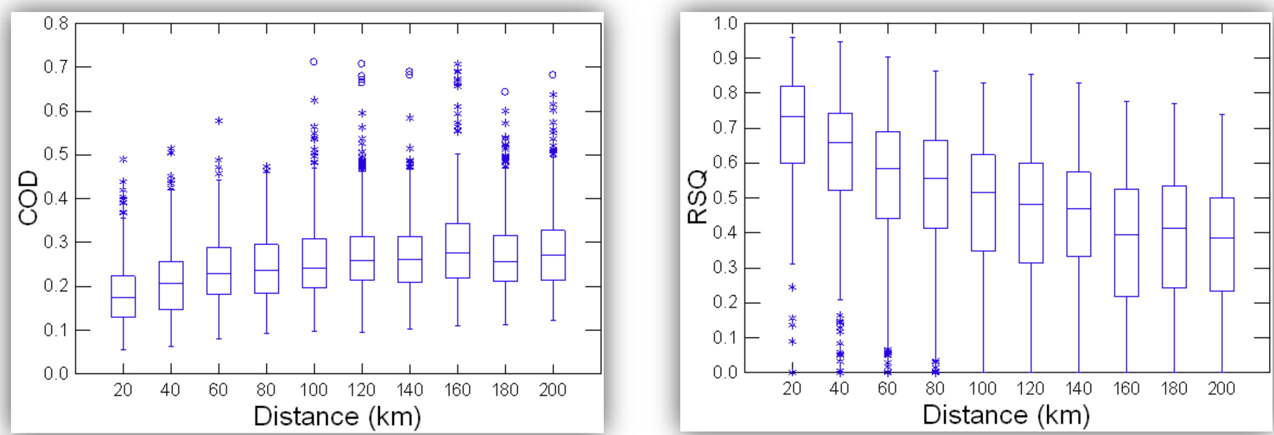

Figure C-2. Box plots of COD (left) and R^2 (RSQ, right) of unique site pairs in the contiguous U.S. in 20-km distance-apart bins. The total site pair count is 5,615. The distance labels represent the upper bounds of the bins. For example, the box-whisker aligned to 40 km contains data for site pairs that are between 20 and 40 km apart.

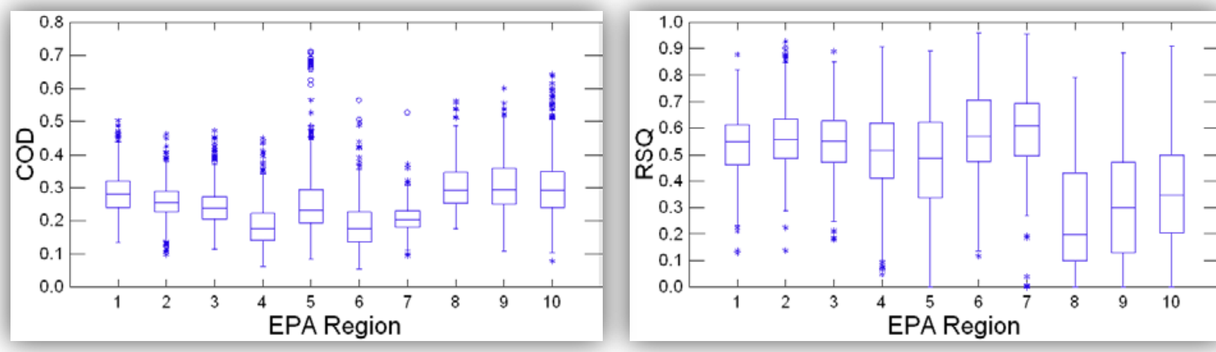

Figure C-3. Box plots of COD (left) and R^2 (RSQ, right) of unique site pairs in the contiguous U.S. by EPA Region.

Existing $PM_{2.5}$ Monitoring Network Coverage Area

The coverage area is defined by a representativeness radius for monitors in each EPA region. The radii were assigned based on the median COD and R^2 within the 20-km distance bins. Specifically, the radius in each region was selected as the upper limit of the smallest distance bin for which either the median COD was less than 0.2 or the R^2 was greater than 0.5. The final representative radii for each region are listed in Table C-1. The radii for Regions 2, 4, 5, 6, and 7 were the smaller of the COD and R^2 cutoff distances. The site pairs for Regions 1, 3, 8, 9, and 10 did not yield a median COD ≤ 0.2 in any of the distance bins; however, the R^2 cutoff distance of four of the five regions was greater than 40 km. Therefore, the COD cutoff distance of 40 km based on national data (Figure C-2) was used as the representative radius for these regions.

Table C-1. The final representative radius of each monitor, distance at which median COD ≤ 0.2 and median R^2 ≥ 0.5, and total unique site pairs used in the analysis by EPA Region.

EPA Region	Representative Radius	COD Cutoff Distance (km)	R^2 Cutoff Distance (km)	Site Pair Count
1	40[a]	NA	180	490
2	40	40	200	364
3	40[a]	NA	180	673
4	140[b]	200	140	906
5	40	40	100	771
6	140	140	160	316
7	120	120	200	285
8	40[a]	NA	20	122
9	40[a]	NA	40	800
10	40[a]	NA	60	1463

[a] National COD cutoff distance used.
[b] R^2 cutoff distance used because COD cutoff distance exceeds R^2 cutoff distance.

The $PM_{2.5}$ ground monitoring network coverage area is illustrated in **Figure C-4**. The areas shaded in gray are informed by the existing ground network. The other areas, which include most of Maine, Minnesota, Nebraska, South Dakota, North Dakota, Colorado, Wyoming, Montana, Idaho, Utah, Oregon, Nevada, and Arizona, lack representative ground based monitoring observations. According to the 2010 Census data, the population of the contiguous 48 states is nearly 303 million people, with 226.5 million people residing in populated places. The current $PM_{2.5}$ network is estimated to provide coverage for 208.3 million people residing in populated places.

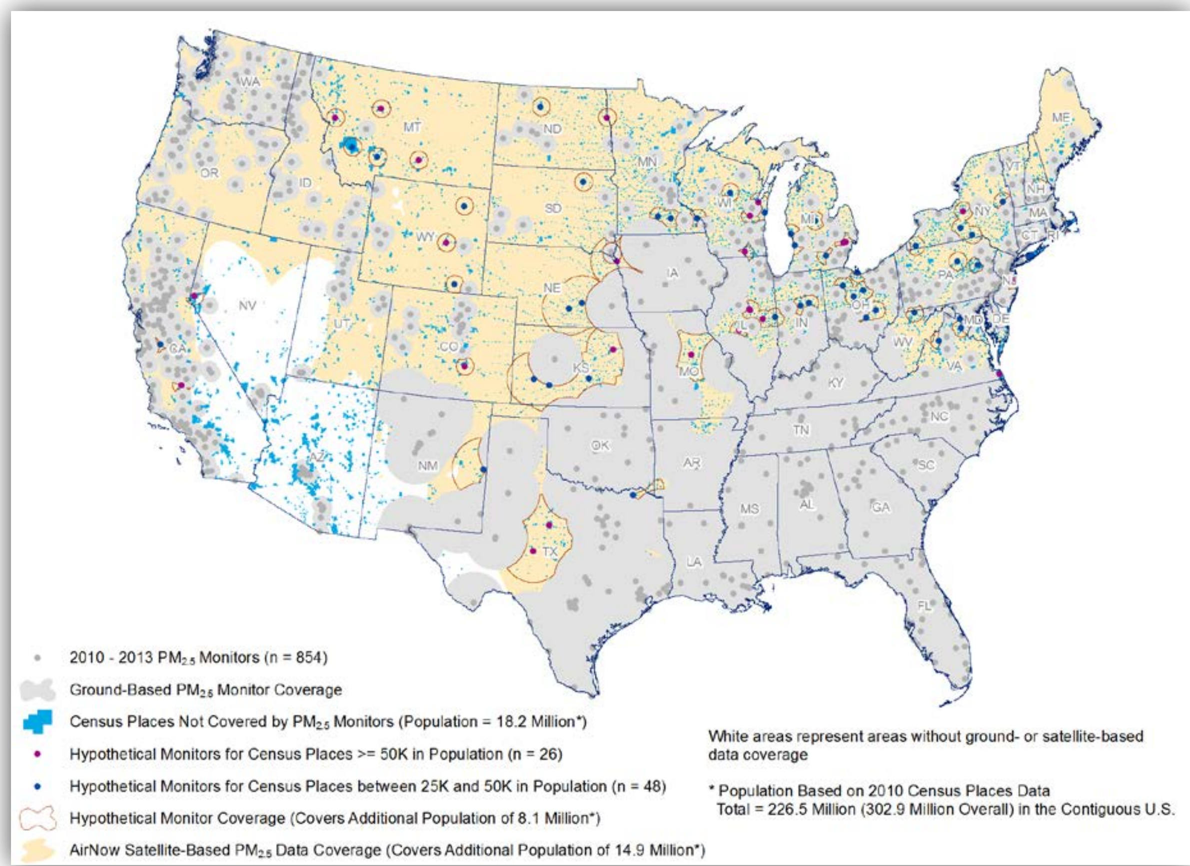

Figure C-4. Map of $PM_{2.5}$ data coverage in the contiguous U.S. using EPA Region-specific buffer radii.

Economic Benefits of ASDP Products

The out-of-network population with satellite data coverage is approximately 18.2 million people. Satellite data could provide daily $PM_{2.5}$ information to 14.9 million of these 18.2 million people (82%). The fusion of NASA satellite data with ground measurements could make daily $PM_{2.5}$ data available to 98.5% (223.2/226.5 million) of people living in populated places.

If additional $PM_{2.5}$ monitors were added to Census Places not completely within the existing network coverage but inside satellite data coverage and with a minimum population of 25,000, 74 additional monitors would be required at a cost of $25.9 million USD for purchase, installation, and operation for five years. The additional monitors would extend coverage to 8.1 million people, or 44% of the population residing out-of-network.

Additionally, we evaluated the largest (140-km) and smallest (40-km) buffer radius for all sites in the existing network to create a range of capital cost savings provided by satellite data. The benefits of incorporating satellite data are summarized in Table C-2, and Figures C-5 and C-6 illustrate the data coverage map for each scenario.

Table C-2. Economic benefits of ASDP product by $PM_{2.5}$ monitor representative radius. Population is in millions of people and cost in millions of USD.

	Monitor Representative Area		
	40-km Uniform Radius	EPA Region-Specific Radii	140-km Uniform Radius
Out-of-Network Population (millions)	42.5	18.2	2.7
Number of Additional Monitors			
Total	186	74	12
For Census Places ≥ 50K	67	26	6
For Census Places ≥ 25K < 50K	119	48	6
Population Coverage (millions/%)			
Addition of Monitors	19.1/45%	8.1/44%	1.5/56%
Satellite Data	39/92%	14.9/82%	2.2/82%
Installation and Five-Year Operations Costs of Additional Monitors (millions of USD)			
Total	$65.1	$25.9	$4.2
For Census Places ≥ 50K	$23.5	$9.1	$2.1
For Census Places ≥ 25K ≤ 50K	$41.7	$16.8	$2.1

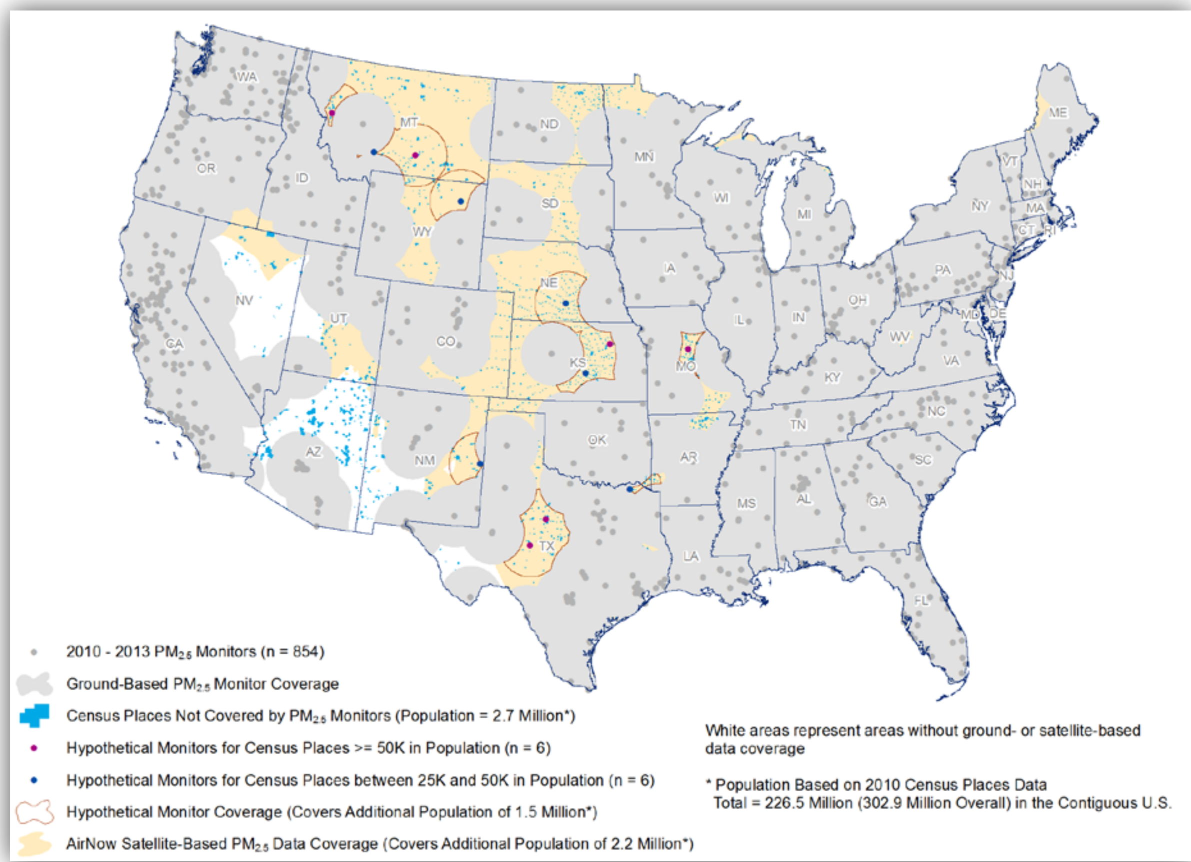

Figure C-5. Map of the largest $PM_{2.5}$ data coverage in the contiguous U.S. using a monitor representative radius of 140 km for all monitors.

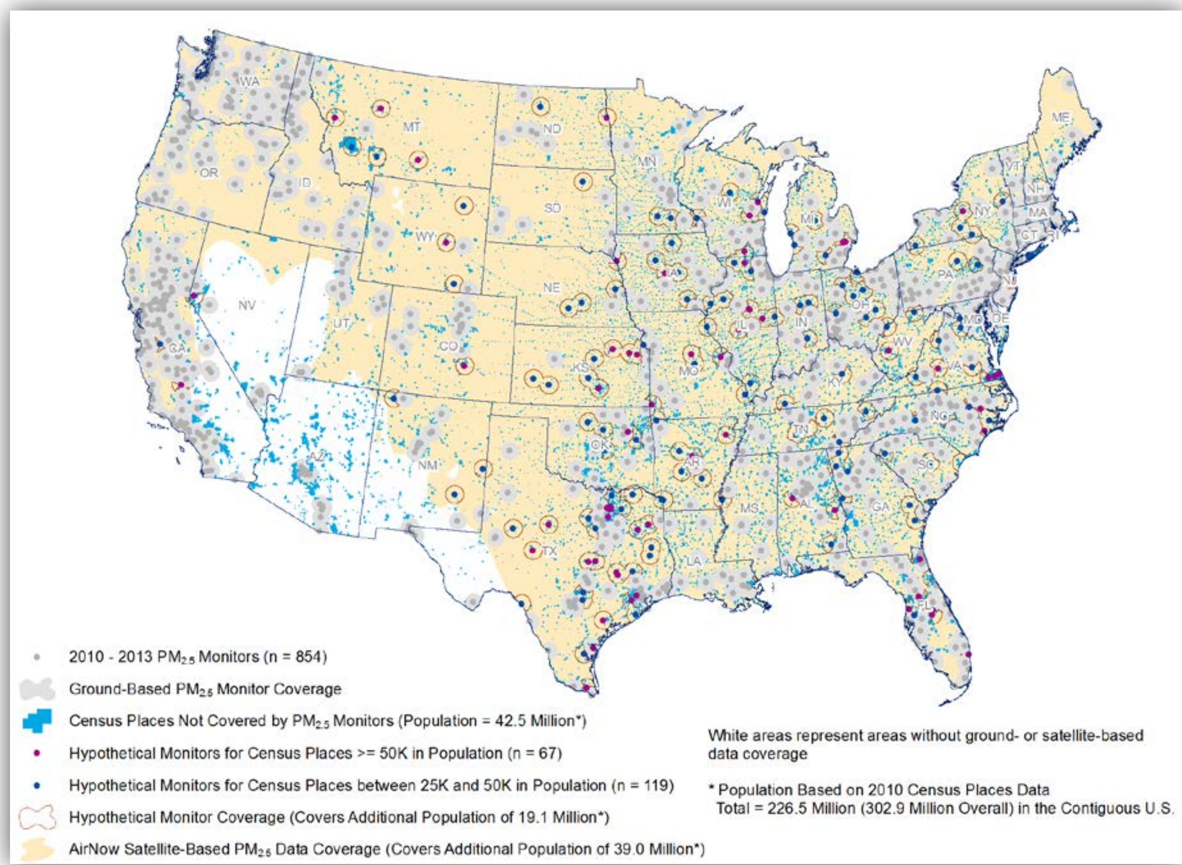

Figure C-6. Map of the smallest $PM_{2.5}$ data coverage in the contiguous U.S. using a representative radius of 40 km for all monitors.

C.4 Conclusions

Based on the results of this analysis, including satellite data in AirNow not only extends $PM_{2.5}$ air quality information to millions more United States residents, but also has the potential of saving millions of dollars—the amount that would be needed to expand the existing ground monitoring network to cover the same population. This analysis used a minimum population of 25,000; however, if this analysis were repeated to cover less-populated areas, the cost savings could be in the hundreds of millions of dollars.

Satellite data are a valuable data source. Because of the global coverage of some satellites, satellite data could be used to provide additional air quality information throughout the world, especially in regions with severe air quality problems such as countries in the developing world. The use of satellite data to estimate surface-based pollution is a recent scientific application. Additional research is needed to continue to improve the relationship of satellite data to surface pollution for future satellites, in more locations, and at higher temporal resolutions.

C.5 References

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