Societal Benefits of Spaceborne Composition-Resolved Particulate Matter Monitoring for Assessing Health Impacts Associated with Specific Pollution Sources

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1. Key Earth System Science challenge

Airborne particulate matter (PM) poses a serious health risk for much of the Earth's population, and is a well-known cause of heart disease, stroke, cardiovascular and respiratory illness, low birth weight, and lung cancer (Newby et al., 2015; Atkinson et al., 2015; Mehta et al., 2013; Loomis et al., 2013; Brook et al., 2010). The 2013 Global Burden of Disease Study (Forouzanfar et al., 2015) ranks ambient PM as the top environmental risk factor worldwide, responsible for nearly 3 million premature deaths per year.

> Although there is a scientific consensus that exposure to PM increases the risks of death and disease, the relative toxicity of specific PM *types*—components having different size and chemical composition—is poorly understood (Bell et al., 2007). According to the US Environmental Protection Agency, "[T]he evidence is not yet sufficient to allow differentiation of those constituents or sources that may be more closely related to specific health outcomes" (EPA, 2013a). Moreover, there is currently very little monitoring of PM species outside of the US (Health Effects Institute, 2010).

The National Research Council (NRC, 2004), European Commission (EC, 2004), and World Health Organization (WHO, 2013) have stressed the importance of filling the gap in understanding of the associations between specific particle types and health impacts. **Understanding the associations between specific particle types and health impacts is critical because different types of particles originate from a variety of sources, and intervention and emission control strategies need to be prioritized to maximize protection of human health.** Meeting this challenge requires implementing the vision put forth in the 2007 Earth Science Decadal Survey, namely that "developing a reliable observational and predictive capacity, based on remote-sensing data used in the context of human health risk, should be a goal of future space mission decisions and agency responsibilities" (NRC, 2007).

Anticipated scientific and societal benefits: Identifying the toxic constituents of PM has far-reaching implications for safeguarding public health and prioritizing intervention and control strategies. Improved knowledge of particle type-health outcome relationships can also help prioritize research on the biological mechanism for PM toxicity (NRC, 2004). The US Office of Management and Budget (OMB) emphasizes that "the large estimated benefits of EPA rules are mostly attributable to the reduction in public exposure to a single air pollutant: fine particulate matter" (OMB, 2011). Because these controls are also associated with roughly half of all regulatory costs (proposed at $66.8 billion in FY16), discriminating health outcomes by source-specific PM type and identifying the most toxic sources and components—as opposed to the current assumption of equivalent toxicity—will help to identify vulnerable populations for specific intervention strategies, and lead to more targeted regulations and significant cost savings.

Science communities that would be involved: The scientific challenge requires an interdisciplinary effort comprised of researchers and policy specialists with expertise in remote sensing, aerosol science, atmospheric chemistry, air quality, computer science, epidemiology, and public health, along with biologists responsible for studying the mechanisms of PM toxicity to establish connections between the satellite-based retrievals and adverse health outcomes.

2. Why is it timely to address this challenge now?

According to the UN, world population is expected to grow by 33% from 2000 to 2030, with major population increases in urban centers in less developed countries. The current projections are that if business-as-usual is maintained, <u>the rate of premature mortality due to PM could exceed 6 million deaths per year by 2050, double the current amount</u> (Lelieveld et al., 2015; Jerrett, 2015; Apte et al., 2015). Evidence that health effects depend jointly on PM size and composition was presented in some recent studies (Eeftens et al., 2014; Liu et al., 2015). The significant health hazards and associated uncertainties as to which particle types and sources are the most injurious makes it is imperative that Earth science assets be applied to improving our understanding of their association with human health impacts, providing the necessary information to enable targeting societal resources toward the most effective means of protecting public health.

NASA investments during the last decade, primarily through the Earth Science Technology Office's Instrument Incubator Program, have brought polarimetric and lidar technologies required for particle speciation monitoring to a high level of technological maturity. These technologies are ready to be transitioned to space.

3. Why are space-based observations fundamental to addressing this challenge?

Surface PM monitors alone cannot meet the challenge of understanding of the associations between specific particle types and health impacts because they are too sparsely distributed, expensive to install and maintain, and non-existent in many parts of the world where air pollution health impacts are greatest. The distribution of monitors in even well instrumented areas requires the assumption that everyone living within a 20–50 km radius experiences identical PM exposure. In reality, aerosol concentrations vary over spatial scales smaller than the distances between monitors, so such assumptions lead to inaccurate exposure estimates (Ross et al., 2013).

The US EPA's surface $PM_{2.5}$ network, which measures particles with aerodynamic diameter <2.5 μm, has an annual cost of over $60M (South Coast Air Quality Management District, 2013), and given the cost per station, dense measurements at neighborhood scale (a few km) even for limited geographic areas would be impractical and cost prohibitive. The EPA recommends urban PM monitoring at this scale as it represents conditions where people commonly live and work (EPA, 2013b). EPA $PM_{2.5}$ speciation measurements are even more spatially and temporally limited than the total $PM_{2.5}$ network, with ~200 in the US, a few dozen in Europe, and virtually none elsewhere. Existing deterministic chemical transport modeling (e.g., CMAQ) used by EPA has limited capabilities due to biases in prediction of PM loadings and limited observational constraints. Space-based observations offer the only practical and cost-effective approach to measuring total and speciated PM concentrations with sufficient density and coverage to determine PM composition variability at spatial-scales relevant for human health worldwide.

Existing and Planned US and International Programs: Currently, global estimates of $PM_{2.5}$ are derived from a combination of aerosol data from NASA satellite instruments such as MISR, MODIS, and CALIPSO (van Donkelaar et al., 2010; 2013; 2015), and the resulting products have been used in a variety of health impact studies, including the Global Burden of Disease Study (Brauer et al., 2012). However, these instruments, as well as VIIRS on Suomi/NPP and CATS on the International Space Station, either do not contain all of the required capabilities needed to partition PM into specific types, or do not provide sufficient spatial coverage or resolution. Current and planned passive instruments that provide adequate coverage and partial capabilities for particle speciation, such as OMI (ultraviolet), POLDER (polarimetry), and future sensors based on these instruments (e.g., EVI-1 TEMPO and EUMETSAT's 3MI) are unable to address this challenge either because of their inability to provide sufficiently accurate aerosol data or because their spatial resolution is too coarse.

Additional investments needed relative to existing and planned U.S. and international programs: The capabilities required to meet the identified science challenge include: (a) spatially-resolved aerosol absorption, particle size, and refractive index, (b) sub-kilometer footprints to resolve the neighborhood scale, and (c) vertically-resolved aerosol microphysical characterization to accurately constrain the transformation of the passively-determined column integrated quantities to near-surface speciated PM. A combination of next-generation passive and active polarimetric instruments provides this suite of capabilities. Passive multiangle radiometry from the ultraviolet, visible, near-infrared, and shortwave infrared with high-accuracy polarimetry at sub-km resolution will provide column integrated optical, microphysical, and macrophysical aerosol properties, including abundance, particle size distribution, single scattering albedo, real refractive index, and particle shape with wide areal coverage (Waquet et al., 2009; Xu and Wang, 2015; Xu et al., 2015). Simultaneous retrievals using high spectral resolution lidar measurements provide vertical profiles of aerosol backscatter and extinction and layer-wise estimates of aerosol concentrations, effective radius, and complex index of refraction (Müller et al., 2014) need to accurately constrain the transformation of the passively-determined column integrated aerosol properties to near-surface speciated PM.

Linkage of space-based observations with other observations to increase the value of data for addressing key scientific questions and societal needs: Advanced satellite observational capabilities are, by themselves, not sufficient to address the challenge of extending the scientific understanding of the optical properties and chemical composition of aerosol species hazardous to human health from localized to regional and, eventually, global scales. The linkages between aerosol optical properties retrieved by remote sensing techniques and aerosol chemical composition measured *in situ* must first be well established with an integrated satellite/surface-level data and modeling strategy (IWGEO, 2004). The approach requires four principal elements: (1) A chemical transport model that provides initial estimates of the abundances of different aerosol types for selected geographical areas where PM pollution is a significant air-quality issue and where PM surface monitoring is limited. (2) Spaceborne instrumentation consisting of multi-angle, multispectral radiometric and polarimetric imaging in conjunction with high spectral resolution lidar. (3) Geostatistical models derived using collocated surface PM monitors to "calibrate" the satellite retrievals, thereby providing maps of near-surface concentrations of major PM sources with dense sampling and wide coverage. This element will benefit from measurements of $PM_{2.5}$ composition being implemented by the Surface PARTiculate mAtter Network (SPARTAN) (Snider et al. 2015). (4) Geocoded birth, death, and hospital records and epidemiological analyses that associate exposure to PM types from particular sources with health outcomes. The PM type-exposure statistics and health associations, made available to decision makers worldwide, would be used then to prioritize intervention and emission control strategies.

In summary, the space-based observations would yield immense societal benefit by offering unprecedented information on PM composition.

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