

A Summary Portfolio
of
ACADEMIC PROGRESS
and
A Research Prospectus

On Interactions of Matter and Energy:

*Progress on Opto-Physical Recognition and Classification of Aerosol and Clouds
in the Terrestrial Atmosphere*

by

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On Interactions of Matter and Energy: Progress on Opto-Physical Recognition and Classification of Aerosol and Clouds in the Terrestrial Atmosphere - A Research Prospectus

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Abstract –

We propose to address some basic questions regarding the terrestrial aerosol – *How much aerosol is detected?* and *What are its opto-physical properties?* We propose strategies making progress toward their answer by two distinct paths. In the first path we make use of sun-tracking photometers available through NASA's AERONET to develop a robust opto-physical aerosol typology, use this typology to compile seasonal aerosol climatologies for each AERONET station in the study, and use these results to crudely map a global time integrated aerosol climatology. The basis states for this first study are the spectral values of the *single scattering albedo (SSA)*, the *extinction Angstrom exponent (EAE)*, the *absorption Angstrom exponent (AAE)*, the *real component of the refractive index (RRI)*, and the *imaginary component of the refractive index (IRI)* – all readily available from the Level 2.0 AERONET database. We propose the possibility of extending this typological aerosol classification scheme to develop *analytic shape functions* for aerosol optical properties and specific aerosol types – an endeavor not yet in the literature. In the second path we propose to make use of the other proven measurement strategy for determining the *diffuse component* of earth received solar irradiance – that of shadowband radiometry. We propose the development of a novel micro-spectrometer based instrument, combining a suite of photodiodes to extend the range from the UV through the visible to the near IR (somewhere from $\sim 280\text{nm}$ to $\sim 2.15\ \mu\text{m}$). Although the far end result would be to apply the existing aerosol opto-typological classification scheme to the data from the microShadowband spectroRadiometer (μSR^{TM}), realistic timetable targets place the immediate output product at instrument refinement, resolution and spectral data analysis comparisons with a UNR located similar high-resolution MFRSR, and comparative studies with the UNR AERONET station. The resulting achievement targets aim to make progress toward a field-portable, environmentally robust, low-power consumption, large spectral range shadowband radiometer for aerosol optical property retrievals.

PREFACE: THE STUDENT'S APPROACH TO THE PROSPECTUS SUBMITTED

As a consideration to the reader we felt it necessary, with the hope of informative direction, to explain the approach taken to this written portion of the examination. As the purpose is to in part, to verify (ascertain) the student's capability to individually propose, and work toward solution of a scientific research problem, the core of this work is the inclusion of two completely self-contained proposals (Parts 2A, 2B). These two proposals are individually purposed to include the research problem, scientific scope, broader impacts, methodology and scope of the work, itemized task targets, further prioritized research beyond the tasks outlined in the original flow of work, timetables and milestones, and the outcome product dissemination strategy. Both proposals were submitted to national agencies, received high scores and were considered fundable. With this in mind, we ask the reader to graciously consider we have done due diligence regarding proposal preparation in restricted page formats.

NOTE: each proposal, PART2A* and PART2B, includes their own figures and references internally – they are submitted herein without further alteration nor with renumbering of figures and references, exactly as they were to the original solicitation. The only redaction has been the of CV, and the proposed budget with the DRI/UNR financials spreadsheet. Individual copies of the statements of originality on our part could be retrieved (if necessary), as they were filed by the student's dissertation advisor at their original submission.

These core proposals proper are wrapped by sections expanding on further details of the background researches, details regarding the development and construction of the instrument to date, and brief statements addressing other specifics requested in the ATMS Graduate Student Guide

NOTE: Figures, tables, and references in the surrounding written sections (specifically excluding Part2A and Part2B), are conventionally numbered in the order they appear in this greater collection of documents. We humbly invoke the readers grace in accommodating this format as presented herein.

We also felt it convenient to construct a look up table, placing some specific aspects as encouraged in the ATMS Graduate Student Guideline, identifying the locations within this document where the specified portions of the requirements are to be found within the proposals.

*A majority of the work for the proposed portion entitled PART 2A has been recently published and found contained in the 2 following documents: **These works are a first-ever published ground-based global aerosol typology and climatology using NASA's AERONET data archive.** [evidence of "originality and "uniqueness"]

Hamill, Patrick., Giordano, Marco., Ward, Caroline., Giles, David., Holbein, Brent. *An AERONET-based Aerosol Classification using the Mahalanobis distance: Atmospheric Environment 140, 213-233, September 2016.*

and its companion, in the supplement of the same volume

Giordano, Marco E., Ward, Caroline S., and Hamill, Patrick. *A Global Compendium of Aerosol types based on Mahalanobis Distances and AERONET data: [An internally hyperlinked compendium of Seasonal Aerosol and Local Aerosol Compositions]: Atmospheric Environment 140, 213-233, September 2016.*

The subsequent data product based upon these works, rendered by D. Giles can be seen in visual display at:

https://aeronet.gsfc.nasa.gov/climo_maps/mplayer_jpg.html

On Interactions of Matter and Energy: Progress on Opto-Physical Recognition and Classification of Aerosol and Clouds in the Terrestrial Atmosphere - A Research Prospectus

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Table of the Prospectus Components

The student feels that it may be informative to the reader of these documents, to make direct reference to where the required components of the prospectus [as specified in the *UNR ATMS program Graduate Student Guide page 6 (revised October 2014)*], are addressed. A guide to the reader is formulated in Table 1 (below) – where in the first column is found the prospectus component, and the second column refers specifically to where in this collection of documents the student has addressed that topic.

Table 1: expected prospectus components and their location within this submitted document.

Research Prospectus Component	Location within this submitted document	
a. Discussion of the research area and how it globally fits into the atmospheric sciences.	Part 1 pages 8-9 Part 2 page 10-11	
b. Discussion of all areas of atmospheric sciences that are impacted by the proposed research, with details of impacts.	Part 1 page 9	
c. Historical Development of the research area.	Part 1 – ¶13,4 page3 Parts 2A - page 12, 14,15 Part 2B – page 23	Oral session
d. Survey of the current state of the art in the research area.	Part 1 page 3	Oral session
e. Discussion of other approaches to the problem that are being pursued elsewhere.	Part 2 pages 12, 14, 15	Oral session
f. Outline for the proposed research topic with milestones to be achieved.	Parts 2A, 2B with specific details in the timetables <i>ibidem</i> . Refer specifically to page 30 in Part4	Oral session
g. Discussion of branches necessary should the research go in unexpected directions.	Part 4 page 31	Oral session
h. Projections of the importance of the research to the future of atmospheric science.	Part 1 page 9 Part 2A §, pages 10-11 Part 2B§ on Scientific Merit – page 24	
i. Discussion of the career goals of the student.	Part 5 page 32	
j. Discussion of the nature of the proposed research from the evolving NSF perspective.	The aspects of “Transformativity” are addressed in Part 1 page 8 and specifically contained as Part 2C on page 27	
k. Discuss who funds the research, why they are interested in funding this research, and what they expect as an outcome of this research as a tangible product.	This material is based upon work supported by the National Aeronautics and Space Administration under Grant No. NNX15AIO2H	

This work is centered about what can be determined from ground-based *passive* remote sensing of the earth's lower atmosphere. In this context, we are interested in the physical presence and nature of Bulk Columnar Aerosol (BCA), and to a lesser extent, the presence of cloud types and their bulk extensive properties. We will not yet be diverted by attempts to ascertain the vertical distributions of those properties.

We will attempt to think in terms of spectroscopic measurements - such that the Sun is our probe, the earth's atmosphere is the experimental chamber, and our spectro-photometric instruments are our sampling/measurement apparatus. It has been considered preferential to orient our ground instrumentation in specific geometries with respect to the Sun, in specific locations geographically, and to sample at specific times throughout the solar day.

The Components of Earth received solar irradiance

The flux density of the Sun's radiated energy impinging upon a unit surface at the earth, will be our "energy" measure [as expressed in W/m^2 incident upon some portion of the earth's surface, or our instrument detector]. This *solar irradiance* enters the top of our chamber [atmosphere] with a relatively well-known and constant value. The decrease in the top-of-atmosphere [TOA] value is directly related to the presence and nature of the "matter" along the path of the *irradiance*. If we, for now, simplistically adopt a *beam* concept parallel to the direction of propagation of this "energy", we can further develop a set of concepts related to the components of the beam, as they are received by our instrument(s). We adopt the conventional nomenclature defining the *Global Horizontal Irradiance* (GHI), as the total amount of energy flux density received at the collecting apparatus located on a horizontal sheet with respect to a specific location on the surface of Earth [see **Figure 1**]; the *Direct Normal Irradiance* (DNI) as the amount of energy density flux arriving along a direct path between the Sun's surface and the point of the collector on the sheet always perpendicular to the beam path; and, the *Diffuse Horizontal Irradiance* (DHI) as the energy flux density arriving at the collector point from all paths, due to all processes, other than direct propagation from Sun to collector. Adding to our conceptual development the notion of the *Solar Zenith Angle* (SZA), which we define as the angle between the normal vector emanating from the horizontal plane of our collecting apparatus, and the direct line from the center of the collecting apparatus through the center of the solar disk.

The received *irradiance* at any instant in time (available to be measured) is a mixture of the magnitudes of these components arriving at the instrument collector through various pathways and physical processes. The relationship between these components, in simplest form, states that the "total" irradiance expressed in the magnitude of the *Global Horizontal Irradiance*, is

PART 1: INTRODUCTION TO THE BROADER TOPIC AREA, BACKGROUND INFORMATION, AND PANORAMIC PERSPECTIVE

equal to the sum of the product of the *Direct Normal Irradiance* and the cosine of the *Solar Zenith Angle*, with the *Diffuse Horizontal Irradiance*. This relationship is expressed below as:

$$\text{GHI} = [\text{COS}(\text{SZA}) \cdot \text{DNI}] + \text{DHI} + \text{GRI (ground reflected irradiance)}.$$

NOTE: often the ground reflected terms are ignored due to their relative low magnitudes with respect to the total. *In complex terrains such is not the common case.*

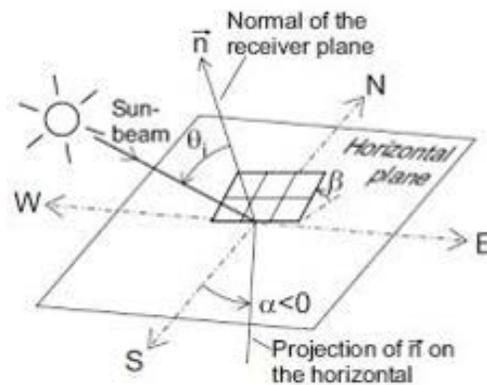


Figure 1: The basic geometry of the irradiance components with respect to a horizontal sheet affixed to a specific point on the surface of earth. [simplified after Duffie and Beckham 2013 figure 1.6.1 pg 13]

These mentioned components of the received solar irradiance are depicted in **Figure 2** below:

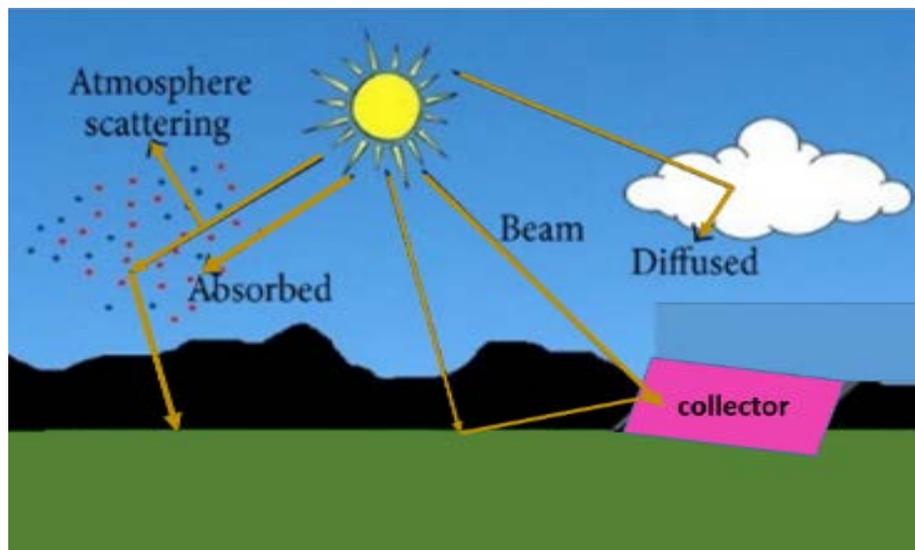


Figure 2: A modified cartoon of the various components of atmospheric radiation. Courtesy of ESRI.

The importance of characterizing the Diffuse Irradiance

“Most of our knowledge about the atmospheres of planets is obtained from an analysis of radiation diffusely reflected by the planetary atmosphere.” V.V. Sobelov (1975)

From the general discussion and geometric considerations, it should be clear that the processes involved in aerosol and cloud scattering (molecular and particulate), absorption, and surface reflection (from clouds and geomorphologic features including the “ground”) comprise the *diffuse* component of solar irradiance. There are what are considered *sub-components* of the DHI (Perez, et al. 1990).

The *Diffuse* Component contains information on which we can make progress on responding to two important questions regarding matter in the Earth’s atmosphere. These are: *How much aerosol is there?* and *What are the opto-physical characteristics of these aerosols?*

Historically a pair of companion instruments have been used to measure two of the three received solar irradiance components - usually via a Sun-pointing heliometric measurement, and a broadband hemispheric radiometric measurement, the third component obtained by differencing (Wesley, 1982; Coulsen, 1975). A common specific combination that proved useful were tracking pyroheliometers, in tandem with broadband radiometers. Many established measurement stations - such as those of ARM Climate Research Facility (Atmospheric Radiation Measurement, run by the U.S. Department of Energy <https://www.arm.gov>), and the Global Radiation Monitoring Division of NOAA’s ESRL (Earth Systems Research Laboratory <https://www.esrl.noaa.gov/gmd/grad/>), including its SURFRAD stations, have been so equipped since the early 1980s (<https://www.esrl.noaa.gov/gmd/grad/surfrad/>).

More recently single instruments have been designed to accomplish this same task. One version of this is by an instrument which can point and track directly at the Sun (Sun-tracking photometer) [obtaining DNI], sweep radially away to obtain the diffuse components at varying angles from the Sun (in the horizontal plane), and point overhead obtaining directional components of the sky diffuse irradiance. Another approach has been to use an instrument which has its sensor head pointing upward from the horizontal plane - to continuously observe the GHI, periodically shading/occluding the solar disk to obtain the DHI component. Each approach measures two of three irradiance components and calculates a third (along with some correction factors). We shall generalize and refer to the former as *sun-photometry*, and the latter as *shadowband radiometry*.

In the sections to follow, we propose research activities that are based in each of these approaches. In the first, we specifically make use of the AERONET data archive of collected retrievals from its global ground-based *sun tracking photometer* network. In the second we

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propose to make progress on the development of a unique version of a *shadowbanding* instrument [which could eventually provide similar data products as to those available through the AERONET archive], but with enhanced field portability, some unique data collection capabilities, and much reduced per unit cost.

Returning to our previously introduced meta-conceptual questions - *How much aerosol is there?* and *What are the opto-physical characteristics of these aerosols?*

In our AERONET work, we are given the answer to the first of these questions in the form of the *extensive* properties - Extinction Optical Depth and Aerosol Optical Depth (as functions of specific visible wavelengths). We then proceed to pose and pursue deeper questions which have a global significance. A set of such questions contains the following:

Can we develop a strategy to opto-physically classify these measured aerosols into robust types?

Can we use our derived classification scheme to develop local seasonal aerosol climatologies?

Can we use our derived classification scheme to develop a historic (time integrated) global aerosol climatology?

Can we extend our classification scheme to develop global seasonal aerosol climatology representations?

To address these questions, we need to obtain information beyond the basic *extensive properties* related to how much of some specific substance is present in an atmospheric column (number concentrations, etc.), but gain access to values of the *intensive properties* of matter (refractive indices, scattering albedos, angstrom exponents, etc.) which provide insight into the nature/composition of the aerosol. Conveniently we have direct access to such a set of variables – as they are provided in the AERONET data retrieval set, as functions of specific wavelengths.

Using the AERONET Global database, and a developed statistical strategy (based in optics), we opto-physically identified five major types of aerosol - based solely upon intensive optical properties of spectral *Single Scattering Albedo* (SSA), spectral *Indices of Refraction* (real – RRI and imaginary - IRI), and two *Angstrom Exponents* (extinction – EAE and absorption - AAE) . These we classified as *Maritime Aerosol*, *Dust Aerosol*, *Urban Industrial Aerosol*, *Biomass Burning Aerosol*, and *Mixed Aerosol*. [These will be discussed in further detail in Part 2 of this prospectus, pages 10-12]. It should be noted that each of these five aerosol types can be further discriminated into specific *aerosol sub-types* by this same classification scheme. One direct use of this information would be for comparison against other aerosol instrumental collection programs; another as input to satellite retrieval correction algorithms [e.g. MODIS]. A near surface use is to consider the classification of aerosols by type might provide environmental insight into their possible source location, or their near-ground origins.

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As a result of our preliminary aerosol typology and *Global AERONET Climatology*, we have produced two publications representing the first-ever AERONET aerosol Global Climatology (based upon a self-consistent robust aerosol classification typology using over 200 long-term AERONET sites), and a Global Compendium of local seasonal aerosol climatologies of the ground sites included. These are found as Hamill, et al. 2016; and Giordano et al. 2016 respectively [*opere citato*].

An example of a direct output of our AERONET aerosol typology scheme can be seen in the work of one of our co-authors (D. Giles) displayed online as an AERONET climatology Map [shown as **Figure 3** below].

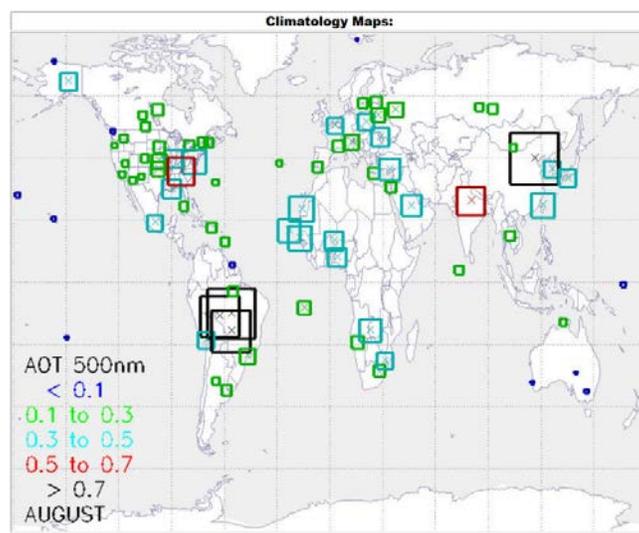


Figure 3: AERONET global climatology representing AOD 500 nm Seasonal averaged AUGUST all years 1993- to date. Courtesy D. Giles available at https://aeronet.gsfc.nasa.gov/climo_maps/mplayer_jpg.html

Further research into the aerosol classification scheme and the potential output products of its results, may be able resolve *shape functions* for specific Bulk Columnar Aerosol opto-physical properties (example specific SSA functions for European BC aerosols and for North American), and *shape functions* for specific seasonal geographical aerosols (e.g. Mexico City or Munich). The potential value of such work might result in simple mathematical input parameters to GCMs or RCMs, or further NASA use in MODIS corrections schemes.

Let us recall that we desire also to obtain information about the interaction of clouds in this passive remote sensing study. Using strictly the data archive available through the AERONET, this is not readily viable – as the data are *cloud screened* prior to public release (as Level 2.0 quality assured). By this we simply mean that algorithms are applied to the raw/ Level 1 data that have rather stringent constraints on the rapid variations in the photometric signal. This strategy

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has been invoked by the NASA AERONET working group for a multiplicity of reasons (Smirnov, et al. 2000). Available courtesy of NASA at https://aeronet.gsfc.nasa.gov/new_web/PDF/RSE.pdf.

To continue, we should briefly mention a few other issues – the sparsity of the AERONET instrumentation grid (and hence database) in the Western Basin and Range province [simply examine the details of **Figure 3** *ibidem*]; the virtual lack of cloud-related spectral radiation information available through the AERONET database; and the increasingly made-public over reporting of the AOD by MODIS for this region [along with lack of ground-truth data to correct satellite retrievals.] We propose to work toward the refined development a high-resolution, field-portable, spectral radiometer that makes use of the other strategy for measuring the components of received solar irradiance - *shadowbanding*.

In the context of obtaining the DHI from a *shadowband* designed instrument, we keep in mind, the non-shadowed measurement retrieves the GHI, the interval when the sensor head is shaded retrieves the DHI portion, and the DNI component is back-calculated. A simple cartoon of a time-series measurement of the total received solar irradiance can be used to illustrate this concept [**Figure 4**]. In the figure below, the segment of the data represented by a magnitude of A is obtained while the band is retracted below the level of the horizontal plane – the total GHI, segment B represents the measured irradiance magnitude when the band occults the Sun, shading the sensor head – it is the diffuse component DHI, and the remainder shown as segment C, is the decrease in the GHI by extinction due to all processes along “direct” paths (obtained by differencing).

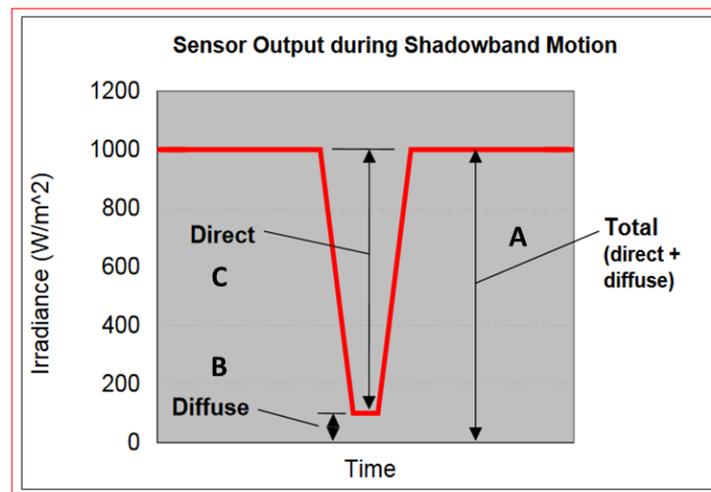


Figure 4: an idealized conceptual diagram of the raw shadowband measurement in time. Segment A is measured with the band retracted, B when the band occults the Solar disk, and segment C is the decrease in irradiance due to extinction.

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The shadowband device herein proposed has had some preliminary development which produced a *demonstration of concept* instrument during the spring of 2017 – the microShadowband Spectroradiometer - μ SR™.

It should be noted that we do not have reason to consider either approach – *shadowbanding* or collimated-beam *sunphotometry* to be inherently more accurate than the other. Technically they measure different aspects of the diffuse irradiance and its sub-components differently. Many shadowband radiometers make use of the same photodiode components as a CIMEL 3-18, so their base component uncertainties must be relatively similar. Where it does make a difference is in the calculating of the Aerosol Optical Depth (AOD). At a wavelength of 440nm or greater, a CIMEL has the AOD uncertainty of $\sim \pm 0.01$ (Eck et al., 1999); however, as the Level 2.0 cloud screening and quality assurance algorithms stop inverting the data to retrieve the optical properties at $AOD < 0.40$ (Smirnov et al., 2000), there are no Single-Scattering Albedo data to be obtained. [this and the asymmetry parameter are crucial to characterization and typological studies.] It is this selected sensitivity by NASA that the shadowband community can exploit, as the cloud-screen criteria can be more robust as the instrument does not point directly at the sun. Typically, AOD can be retrieved at < 0.10 with the same or better levels of uncertainty by shadowband radiometers. As for total column water vapor AERONET CIMELS are barely $\sim \pm 10\%$ (Holben, et al., 2001). AERONET CIMEL sky radiances (sky diffuse sub-component) are measured directionally, having a calibration-related uncertainty of $\pm 5\%$ (Holben et al., 1998). Again, the approach the proposed shadowband instrument is no to be compared to a tracking sun-photometer for many reasons – a mere example of which is the is the mechanical complexity, and software development to accurately position the sensor head.

In a big think notion, the far-field goal would be to make use of a suite of micro Shadowband spectrRadiometers deployed within the Western Basin-range region, the data from which could be imported into the *aerosol typology model* developed, and previously referred to herein (Hamill et al. 2016), resulting in a presently unavailable *regional aerosol climatology* product. Recognizing there exists no connected continental US shadowband network [of any design specific instruments] from which to approach such as goal on the basis of a purely data analytic study, we propose to make strides toward such ends by the development of a novel instrument. Similarly recognizing that producing a commercial research grade instrument is so far beyond the scope of a single dissertation research project, and incorporates far too many engineering and financial/logistical challenges for this time frame, we propose a more modest target. REMEMBER this is a scientific research and not an engineering or economic/marketing campaign; commercial viability, although a tantalizing vision, is the vapor of a hot summer dream.

As a real-world, presently-existing-target, one could be referred to the NASA Ames Airborne Tracking Sunphotometer – a 14 channel photometric instrument that measures direct solar irradiance, and retrieves spectral AOD and optical properties. [Details of the instrument are found in Murphy et al. 2015; and NASA's Airborne Sciences Mission are found at <https://airbornescience.nasa.gov/instrument/AATS-14>]. This instrument has been employed to also calculate Column Water Vapor (CWV) [Livingston et al., 2008]. As the instrument “flies” on airborne missions, the data is used to construct vertical profiles of water vapor density and spectral aerosol extinction. A direct result is the possibility of reliable, in-situ, vertical aerosol optical property profiles. Such results have been used in satellite validation studies to

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improve retrieval algorithms for MODIS and MISR. **NOTE: NASA owns this instrument, and there is presently a single instance of such.**

The proposed micro Shadowband spectroRadiometer is novel (substitute “unique” substitute “original”) in the following contexts:

Intended usage: presently there are not readily field-portable Shadowband Radiometers, due to size and power consumption requirements.

Design specifications: the current standard is a band shadow constructed to occult ~5 degrees of solar angle.*

Data collection: potentially recording the irradiance components continuously throughout the solar day, could provide more detailed information on the geometric positions of clouds with respect to the collector position.

Spectral range: the inclusion of a suite of specific wavelength photodiodes which target a UV channel, specific water vapor at ~ 940 nm, and extension into the near IR at ~ 1.0, 1.5, 2.1 μm respectively. It must be emphasized that in order to be able to compare against, and participate in validation studies of other instruments, the μSR measured wavelengths must match as closely as possible using affordable, available photodiodes. [Figure 5].

Deployment configurations: 1) presently we envision conventional “head-up” horizontal mounting, but can conceive this horizon may be elevated either by balloon or UAS. 2) we have evidence from companion studies at UNR, the instrument may be deployed in an inverted “heads-down” mode from a UAS base to retrieve surface spectral radiances or albedos.

Manufacturing techniques: we believe many structural and shielding components for the instrument’s environmental packaging can be designed, tested, and refined *in-house*, using CAD software as *Solidworks*, and 3-D printing of materials between UNR and DRI facilities. The actual electronic board holding the componentry can be designed online and fabricated by an online specialty board fabricator. The board for the demonstration instrument was fabricated at UNR in the UNR DLM technology center.

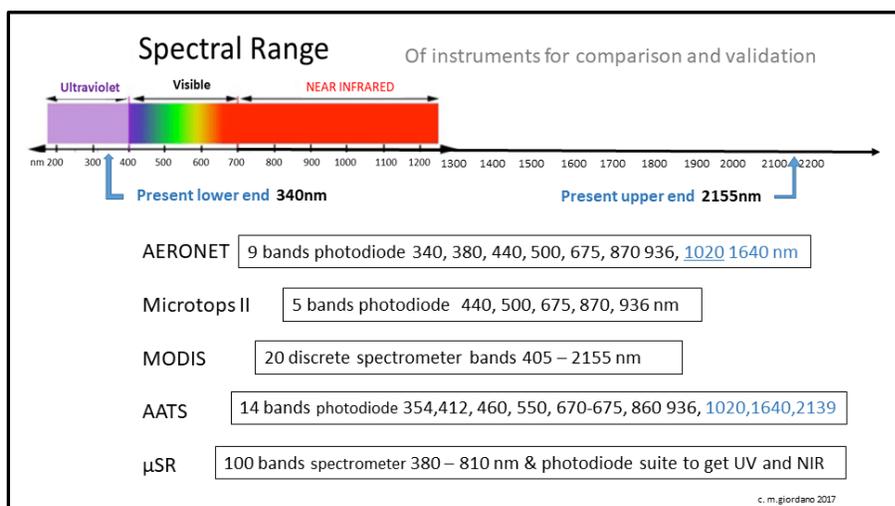


Figure 5: The graphic compares the Spectral ranges of known instruments which can be used to calibrate and compare the newly developing μSR^{TM} during testing, and possibly in further validation studies.

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A summary table of the configuration, capability and component status of the presently existing demonstration unit is found as **Table 4** in **Part 3** of this document.

* Hence the actual position of the sun in the recorded data is instrumentally resolved to $\sim \pm 2.5$ degrees in the solar angle.

Thoughts on a Panoramic Perspective:

The research proposed in Part 2A of the subsequent section is mathematically and statistically important – as all data related physical phenomena studies are at the heart of empirical science development. There can be no claim that extensive aerosol identification has a theoretical basis, as there is no fundamental physical law demanding its presence. However, we could assert that use outcomes resulting from accurate aerosol classification can impact the atmospheric modelling community. In the future, it could be conceived that researchers and students may use global aerosol maps of PM2.5, and speciated aerosols as readily as we now routinely invoke the reanalysis products of ground and sounding observations without considering they themselves are *modeled*. As yet, we can only consider how these Bulk Columnar Studies may not so easily provide information on surface aerosol abundances and identities, nor their precise vertical distributions. It can, in the academic sense, be directly linked between aspects of atmospheric data analysis and atmospheric modeling.

The research proposed in Part 2B of the subsequent section is a bit more wide-ranging in its scope. We consider can the use of off-the-shelf electronics, and the transition from enthusiast usage to emerging research purposes to be in line with the recent societal trend of DIY entrepreneurship. We do not intend nor claim to pursue science aims with that in mind, but the convenience of small-scale in-house fabrication, repurposing of electronic components (perhaps outside the design intent of the original manufacturers) for novel measurement strategies, does have an appeal. An observable paradigm of scientific campaigns based in small instruments deployed near the earth’s surface, in either balloon or UAS configurations, has been establishing itself.

Both projects could have at least tangential *citizen science* components. Student appropriate curricular activities can be constructed to incorporate student use of NASA AERONET data from NASA’s graphical display tools interface, to examine the BCA values of a specific AERONET station, and compare them with the nearest EPA surface Air Quality measurements. If after design cycle, test cycle, and calibration cycle refinements, a portable spectral shadowband radiometer deployable in a small urban array may be as valuable with respect to aerosol classification schemes as a more remote geographic array. Both of these notions should be considered to be well outside the timeline of our proposed research.

On to the proposals

Title: *On the Terrestrial Aerosol: Toward an AERONET-based Global Aerosol Classification Using Generalized Distance Functions.*

Introduction:

Studies of the Earth's climate and its temporal variations require having a detailed knowledge of gases and aerosol particles in the atmosphere, including their optical properties, concentrations, and distributions. Aerosols are short lived, highly heterogeneous, and difficult to characterize on a global or regional scale. It is well known that the effect of aerosols is one of the greatest uncertainties in carrying out climate studies (IPCC AR4, 2007). Since in-situ aerosol measurements are limited in time and space, a great deal of effort has gone into measuring aerosols from orbiting spacecraft. Space-borne instruments that provide information on aerosols as part of NASA's EOS program include CALIPSO (Omar et al. (2009)), MODIS (Remer et al. (2008)), MISR (Levy et al. (2007)), and POLDER (Kacenelenbogen et al. (2006)). These systems yield extensive information about the geographic and temporal aerosol distribution (usually in terms of optical depth). Some systems also measure or derive various optical parameters such as polarization or backscatter ratio, which might be useful in determining aerosol type. The determination of aerosol type by remote sensing is a difficult problem.

The global aerosol is a spatio-temporal varying "field" with both natural and anthropogenic sources and sinks; as such, studies concerned with the construction of a robust typology, leading to a temporal aerosol climatology are well-aligned with the Earth Sciences mission. The emphasis that an opto-physical aerosol typology derived from ground-based measurement may also provide a standard against which satellite modeled retrievals may be compared. This would be compatible with the overall mission objective of the EOS program specifically CloudSat/CALIPSO, and POLDER. It is doubtful that satellite instrument derived aerosol typology can serve as ground-truth checks of their own results.

One of the purposes of this research is to demonstrate that the aerosol type can be reasonably determined using a limited amount of information on the aerosol's optical properties.

The primary source of data for this research is extracted from the ground-based network of sun photometers called AERONET (AEROSOL ROBOTIC NETWORK, Holben et al. (1998)). Previous studies which also used the AERONET optical properties to identify aerosol types generally concentrated on the single scattering albedo (Leahy et al. (2007), Johnson et al. (2009), Muller et al. (2010), Toledano et al. (2011)) and/or the extinction and absorption angstrom exponents (Bergstrom et al. (2007), Russell et al. (2010)).

In this research we propose to investigate the use of a consistent set of retrieved AERONET optical properties to define our data space, and a specific generalized distance – the *Mahalanobis Distance* to identify aerosol types and their seasonal variation for nearly 200 AERONET sites. We also expect to be able to construct regional overviews of aerosol types by continent and eventually a global aerosol climatology. A modified version of this strategy was used by Russell et al. (2014, 2012) who focused primarily on the classification of aerosol types using the Mahalanobis distances and the Wilks' lambda distribution, then compared the aerosol types thus obtained with those determined by POLDER. Our methodology may be constructed similarly, but we intend to compose a different set of "reference clusters" [based upon a variable set contained by a greater number of AERONET sites] applied to a much larger population of the AERONET data set to determine (a) the dominant aerosol type at each location, (b) the seasonal dependence of aerosol type, and (c) the global distribution of aerosol types. We also seek to consider potential problems which may be associated with this technique, as in the mis-identification of aerosol types in some specifically problematic sites such as Bonanza Creek (Alaska), Mexico City, and some South-East Asian cities. We also propose to more robustly determine the essential optical signature to properly identify a verifiable maritime aerosol. Toward that end, we anticipate incorporating a maritime

aerosol into our analysis by using the site-specific relative humidity (obtained from meteorological data) and calculating the expected optical properties of salt solution droplets.

Our objective being to quantify the relative percentage of aerosol types at AERONET sites on a climatological basis, which can potentially be used as initial estimates to compare with, or be used by satellite retrievals and modelling platforms made use of by other NASA EOS mission projects.

An Approach to the study:

It is proposed in this work to extract the necessary information to construct a robust aerosol typology by statistical methods making use of a high-dimensionality of the AERONET data set. In this study we intend to make use of only opto-physical characteristics provided by the passive remote sensing photometers. Naturally these total-column measurements cannot reliably differentiate between the source(s) of any one aerosol within the column from an indigenously generated local aerosol, but should be considered to be capable of well-characterizing the local *bulk columnar aerosol* (BCA) in a time-constrained period corresponding to its directly measured instrumental time stamp. Previously published detailed typological works have not yet incorporated the entirety of the AERONET data set, but have been rather restricted to local, or regional studies. The detailed work of Giles et al. [2012] on the nineteen AERONET sites, and Logan et al. [2013] on four Asian sites are examples of this point. The insistence upon the isolation of the AERONET data to its largest reliably available common set, and perhaps the limitations of the data space we can construct, are to make progress toward using the results in the construction of a global, AERONET-based aerosol climatological map [in the seasonal and annual time domains].

Generalized Distance Functions represent the relationships between “objects” in higher-dimensional data spaces, similarly to the fashion in which a Euclidian distance represents the spatial representation between objects in a right-rectangular Cartesian space. The objects referred to here in the context of higher-dimensional spaces, are to be thought of as the types, clusters, or groups of measurements returning similar values for the measured variables within the data space. Hence these groups of values of the measured properties can be ascribed as representative of the physical “objects” detected by the measurements. Here we will use the terms *class*, *cluster*, *group* or *type* as freely interchangeable in the context of representing the characteristics of the column measured by a set of photometric samplings at AERONET sites. The distance calculated between a class cluster, group or type may be expressed in a few common fashions. One is to measure the separation among classes by the distance between the closest adjacent points of the two separate clusters [representing a minimum distance of separation], another is to measure the separation among classes by the distance between the nearest point of one cluster to the centroid of the adjacent cluster; but a more commonly employed measure, is the centroid-to-centroid distance.

The distance measurement (or calculation) between sets [prescribed or otherwise determined] affects our understanding of the dimensional distribution of the measured data in two important modes: in the first, distances within a group can be characterized by point-to-point criteria, or point-to centroid of commonly measured points criteria [think of a *radius of inclusion* or *exclusion* concept]. In the second, the distances between clusters may be determined by point-to-centroid criteria, or by centroid-to-centroid criteria. Each of these modes of employing a distance measurement for classification has the potential to distort the density ellipse and its contours within a group, and mis-categorize (misclassify) a member of a sample set. It is apparent that it is important to use a well-defined distance measure, and precisely determine the statistical criteria by which data points are considered for inclusion within a group, the mechanism for determining multi-dimensional outliers for the identified clusters, and methods of visualization that provide credence to the overall classification scheme/algorithm.

As a portion of this study we propose to examine closely the mathematical determination of criteria for aerosol class inclusion, the higher-dimensional representations of the measures by which classes may be

reliably separated/identified, and some methods of robustly visualizing the classes so as to “see” the separations that are not easily identified in standard bivariate plots or simple two-dimensional data, or of projections of higher-dimensional density hyper-ellipsoids onto a well-known two-dimensional plane. The use of the *Mahalanobis Distance* (D_M) as a general measure of inclusion and separation will be exploited. The study will incorporate attempts to determine the exact minimum number of AERONET variables which must be included in the data space to incorporate the greatest number of AERONET sites, having the most number of full-retrieval records available. This will hopefully make transitions to a global aerosol climatological map having fewer geospatial voids. Hence the selection of included AERONET variables should be one that incorporates a span covering the greatest amount of variance within the data. A traditional transformation to canonical variable space, and comparing eigenvector magnitudes should help determine whether an eight-variable space or a five-variable space will be sufficient.

The concept of pre-specifying or “seeding” clusters with data from populations which have a strong tendency to reproduce similar data values, is used widely in multi-dimensional statistical analysis [Moussiades and Vakali 2009; Burton 2102, 2013]. The proposed study does not uniquely vary from this approach, and will incorporate data from multiple AERONET sites to form the initial specified reference clusters. Once a reference set of AERONET variables has been properly determined (which will incorporate the greatest number of AERONET sites over a period of data collection having a specific number of complete records), and a reliable set of aerosol types have been statistically determined to be distinctly identifiable, individual data collected from a specific AERONET site can be cast into the data space and individual retrievals classified on the basis of the generalized distance criteria (D_M) with respect to the set of *reference clusters*. A composite analysis based upon the normalized percentage a specific aerosol type occurs at that specific local can be rendered into a pie chart or other visualization tool. Monthly and annual aerosol trends and variations can be depicted for each site in the form of histograms, or bar charts etc. In this fashion

the data required to construct an AERONET global climatology might be compiled for graphical presentation.

Proposed Studies and Experiments:

A. Mathematical and Statistical investigations concerning the method of constructing the pre-selected reference clusters:

- Mathematical and statistical analysis of AERONET variables using Canonical coordinate transformations, *Linear Discriminant Analysis*, and *Quadratic Discriminant Analysis* to properly determine the proper covariance matrices to invoke when calculating the generalized distance value. Further refinement of the set of AERONET variables to include in the typology data space – converging toward completely spanning the sample space should be refined.
- Investigations into the in-class inclusion criteria, and the methodology of determining “outlier” data to be either removed from a reference cluster set, or re-assigned (to an adjacently proximal cluster) for a set of inversion measurements from an individual AERONET site (which are being classified).
- Investigations into refining and more conclusively determining aerosol sub-classes of Flaming biomass-burning BBF, Smoldering biomass-burning BBS, and Boreal biomass-burning BBB [Sano et al. (2011)].
- Investigations into refining and more conclusively determining aerosol sub-classes of Saharan, Arabian, Indo-Gangetic, and Mongolo-Sinese (Gobi) dusts using SSA values as functions of specific wavelengths [Englebrecht, et al. 2015].

B. Investigations concerning the incorporation of Polarization data products into the AERONET variable set:

With the increase in the number of AERONET sites incorporating polarization filter packs into the CIMEL instrument, it is anticipated that more polarization data will be coincident with the aerosol inversion data found in the AERONET database [Holben et al. ICAP 2014]. The direct use of such information might be implemented in two distinct fashions:

- In the first, we would seek to incorporate a variable such as the *Degree of Linear Polarization* (DLP) as a function of scattering angle $DLP(\Theta)$ at some specific AERONET wavelength (670nm or 440nm), as another variable expanding the set space from 5 variables to 6, (or from 8 variables to 9). This has not yet been performed. However it has been anticipated to be useful in determining aerosol microphysical properties [Xu et al. 2015], and to be useful in making AERONET inversion data products viable for cloud optical depth (COD) interpretations [Knobelspeisse et al. 2015]. In the latter example, they are interested in the Q component of the Stokes polarization vector. [As a parallel study to this, we might be able to extract Cirrus cloud ice phase information from the difference between the AERONET level 1 data record and the L2.0 cloud screened set].

- In the second, we will pursue the notion of defining functions composed of $DLP(\Theta)$ at specific wavelengths, as a possible characteristic signature of aerosol types [Piedra 2014, Waquet et al. 2009]. The function $F(DLP(\Theta), \lambda)$ may have a unique “shape” related to the bulk columnar aerosol

composition. It might be anticipated these “functions” could be used as the basis for another form of AERONET aerosol typological analysis.

C: Investigations concerning extracting information from the shape analysis of AERONET aerosol reference clusters:

The shape of the projections of the data hyper-ellipsoids representing the reference aerosol types onto a 2-dimensional plane (bivariate axes), carries detailed information about the nature of the distribution of the data within the class. The orientation of the semi-major axis of the data ellipse with respect to a specific axis of the projection plane, will provide information into the nature of the covariance structure relating the two variables represented on the axes of the plane. This covariance structure relates directly to the method one can use to construct the covariance matrix required in the calculations of a Mahalanobis distance (D_M). So it is expected that this be considered in detail with respect to a further development of a strategy of aerosol classification (based upon discriminating or defining classes by generalized distances).

Apart from the locally projected orientation of the data ellipse, one can mathematically transform the distributions of the data along either the semi-major or semi-minor axis of the data ellipse into a histogram sorted by frequency of occurring values. From these constructed histograms, one can attempt to fit the data with an analytic function representing the property or variable represented along the axis of the plane of projection. For example one can transform the distribution of data in SSA-EAE space from a reference urban industrial site such as GFSC, into two separate histograms of EAE and SSA respectively. These histograms once fitted with an appropriate analytic function [such as a Gamma or Beta function] can be used as descriptions of the measured variable as a continuous function of wavelength. It is anticipated this strategy may have promise as a method to functionally adjust, correct, or compare AERONET data with satellite derived data products [Giordano 2014]. Presently very little has been available to the reader using this approach to determining analytic expressions of aerosol optical properties.

Another area to be explored here is to determine if the data distribution shape (shape of the density ellipse projected into a 2-dimensional plane) be used as a verifier or indicator of aerosol type. [for a visual on the shape concept see Figure 1]. So a research associated question might be: *can we identify an aerosol by the*

shape of the distribution of its data for any single AERONET variable? Can the shape of the EAE distribution, or the AAE distribution be used to differentiate dust from urban industrial carbonaceous aerosol?

D: Improvement upon the determination of the Maritime aerosol, and the incorporation of maritime aerosol network (MAN) data into the classification scheme:

The maritime classification seems to be the most challenging aspect of developing an AERONET typology scheme. One reason is that relatively few AERONET stations are placed where the predominant aerosol would be expected to be categorized as “maritime”, when compared to the more abundant continentally located instruments. Another is that the optical depth for this class of aerosol is often less than 0.4, and the SSA, IRI and sphericity reported in the inversion values may not be reliable in the V2 L2 records (Dubovik and King (2000) and Holben et al.(2006)). [Perhaps this matter has been resolved in the V3 algorithms.]

It is anticipated that the Lanai AERONET site will become the reference standard, as it has many retrievals of AOD less than 0.2 (Sayer, et al. 2012a) with extinction angstrom exponent (EAE) values less than 1.0 (Sayer, et al. 2012a).

There may be some effort made into incorporating the records from *Maritime Aerosol Network* [AERONET man in refs.] into the definition of the reference standard, and as a check into the appropriateness of individual almucantar retrievals which may be classified as maritime in coastal located venues (Sayer et al. 2012b, and Smirnov et al. 2011).

A timetable of project aspects and their estimated work schedule is presented as **Table 1**.

Further Discussion:

Previous works by others:

The work proposed here in this document is by no means to be considered as pioneering. There has been considerable work prior, to determine the suitability of AERONET as a validation of satellite remote sensing data products, as a global laboratory for gaining insight into aerosol photometry, as well as characterization of aerosols at the site locations. Much of this effort has been recorded in the literature of NASA’s GLORY Mission team.

The work of Russell et al. [2014] made use of eight AERONET variables (“parameters”) [EAE_{491,863}, SSA₄₉₁, dSSA (SSA₈₆₃-SSA₄₉₁), RRI₆₇₀, IRI₆₇₀, AAE_{491,863}, Vol_{fine fraction}/Vol_{total}, and % Spheres], which then could be used to create definitions between seven pre-specified clusters. This methodology is rather robust, and is to be considered an integral part of this study for comparative validation. Their work made direct and correlative use of other satellite remote sensed data products to refine algorithms, filter data sets, and gain insight into the global aerosol variability.

On the Use of Pre-selected Reference Aerosol Types:

As mentioned, one technique we will employ will involve determining the Mahalanobis distance of a point from the centroid of a reference aerosol cluster. Each reference cluster should be characteristic of a particular type of aerosol. To obtain a set of reference clusters, we can associate a specific type of aerosol with a given location (as was done by Cattrall et al. (2005)). Thus, one would expect *urban industrial* aerosols in locations such as Washington, D.C., Hamburg, Lille, Moscow, etc. Similarly, aerosols from *biomass burning* are expected at sites in the Amazon and Southern Sahel in Africa. *Dust* is prevalent in Saudi Arabia, and *maritime aerosols* are expected to be found on islands and coastal locations. The aerosols of many cities in Asia do not fit into any of these categories. Cattrall et al. defined a category called “South-

East Asia,” although prevalent in Asia, is expected that aerosols showing similar optical properties will also present at other locations. Consequently, we will refer to it as “*Mixed Aerosol*,” following the nomenclature of Giles et al. (2012). In this work we would anticipate a minimum of five distinct reference clusters, which we can refer to as Urban Industrial, Biomass Burning, Mixed Aerosol, Dust, and Maritime.

There have been numerous attempts to classify aerosols, each using a different definition of aerosol types. For example, the CALIPSO analysis assumes six aerosol types, denoted clean continental, clean marine, dust, polluted continental, polluted dust, and smoke (Omar et al., 2013). The MODIS system (version C5) uses five aerosol models, which are described in detail by Levy et al. (2007), Mielonen et al. (2010), and in the MODIS ATDB by Remer et al. (2004). The models are: continental, dust, non-absorbing, neutral and absorbing. They were modified from the results presented by Dubovik et al. (2002). Currier et al. (2008) indicate that OMI has 24 different aerosol models of which 10 are classified as “weakly absorbing,” 9 are carbonaceous aerosol models, 4 are dust models and 1 is a volcanic ash model. These are differentiated from one another by the values of the geometric mean radii, the standard deviations of the two modes, the number fraction of the second mode, and the indices of refraction. In their analysis of AERONET aerosol measurements, J. Lee et al. (2010) categorized aerosols as dust, black carbon, non-absorbing anthropogenic aerosol (sulfates in the fine mode and sea salt in coarse mode) and mixed aerosol (defined as aerosols whose fine mode fraction is between 0.4 and 0.6). Russell et al. (2010), Giles et al. (2011), and Giles et al. (2012) used AAE and EAE to determine the dominant absorbing aerosol type in the aerosol mixture. Giles et al. (2012) expanded upon Russell et al. (2010) and J. Lee et al. (2010) by using AERONET Version 2, Level 2.0 data to classify dominant aerosol types (i.e., urban industrial, biomass burning, dust and mixed) based on typical aerosol source regions using SSA and AAE as a function of EAE and fine mode fraction of the AOD. Giles et al. (2012) showed that SSA and EAE provide the most distinct reference aerosol type clusters of the 2-D combinations analyzed using Voronoi clustering.

They presented scatter plots of absorption angstrom exponent vs. extinction angstrom exponent and of absorption angstrom exponent vs. fine mode aerosol fraction, showing the distinctions between “Mostly Dust”, “Mostly B.C.” and “Mixed B.C. and Dust.” Burton et al. (2012) used values obtained with an airborne High Spectral Resolution Lidar to define eight aerosol types. The AeroCom model inter-comparison (Kinne et al. (2006)) used five aerosol types having denoted sulfate, organic carbon, black carbon, mineral dust, and sea-salt.

Thus, each attempt to identify aerosol type tends to use a somewhat different way of defining the aerosol type. The choice of parameters, as is only natural, is based on the measurement characteristics of the particular instrument under consideration. Nevertheless, we can appreciate that our classifications will be reasonably in line with what has been chosen by other investigators.

Further discussion on the determination of Aerosol types:

There is valid evidence that the general categories of dust and biomass burning aerosol can be further split into sub-classes or categories by distinctions of two-dimensional projections of the data. There is little argument that there are distinctions in mineralogy between North African Saharan dusts and Arabian dusts [Kim et al. 2011]. There maybe even optically distinguishable characteristics further separating Asian dust sourced from the Indo-Gangetic plain or the southern Chinese desert basin.

Similarly biomass burning may be reliably separated into sub-types of flaming or smoldering depending upon which AERONET sites are seeded into the reference cluster data [Martins et al. (1998), Eck, et al. (2013)]. However it might also be considered that fires resulting in detectable aerosols classified as biomass burning, regardless of source origin, may go through various smoldering and flaming phases during the fire lifetime. It is hoped that high latitude Boreal fires with significant underlying peat beds burning throughout the year, may be photometrically distinguishable from the other two classes. This study would be performed

after the solidification of biomass-burning reference clusters, then making direct comparison to see whether Siberian, and North American sites such as Yakutsk, Ussuriysk, Urkutsk, Tiksi, Barrow, Bonanza Creek, Arm Oliktok, Yellowknife Aurora, and Resolute Bay will be distanced enough within the space to warrant a separate aerosol class.

In preliminary studies using a 5 AERONET variable space ($AAE_{870,440}$, $EAE_{870,440}$, SSA_{440} , RRI_{670} , and IRI_{670}), setting a cluster inclusion criteria of $D_M \leq 2.0$ to retain an individual record contributing to the class, it was found the Russell BB-Dark (the aerosol previously known as “flaming”), and BB-White (the aerosol previously known as “smoldering”) clusters to be separated by cluster-to-cluster Mahalanobis Distance (D_M), value equal to 2.27 (Giordano 2014). Although this is not inconsequential, it does not provide mathematical evidence that the types are well-separated, other than by their initial seeding into separate categories. Similarly, the analysis shows the BB-White class to be overlapped by the lower SSA tail of the Urban Industrial type. To the point, the centroid-to-centroid D_M separating Urban Industrial from BB-W, to be equal to 2.58. Hence for an initial typological scheme, we will propose to consider Biomass Burning as a single category for now, and await the results of a possible High Latitude Boreal forest fires aerosol event analysis, to further refine the class.

On the use of the Mahalanobis Distance:

The technique we use to determine the aerosol type that best fits a particular measurement is based on a statistical quantity developed by Mahalanobis (1936). The dimensionless “Mahalanobis distance” can be used as a measure of how far a particular measurement is from the centroid of a reference cluster. [It may be thought of as similar (but not equivalent) in character to a standard deviation measure]. A particularly useful property of the Mahalanobis distance (D_M) is that there is no limit to the number of variables that can be used to evaluate it. We could use the five variables EAE, AAE, SSA, RRI and IRI to evaluate the D_M , but we could, as Russell et al., make use of eight variables by including sphericity and volume ratio, or functions of the various parameters obtained from the AERONET inversions. However, it is anticipated that fewer sites will contain complete records of these AERONET variables – hence they could not be properly compared against sites having substantially more full retrievals.

The Mahalanobis distance is calculated as follows. Let $\mathbf{x} = (x_1, x_2, \dots, x_N)^T$ represent an N-dimensional vector whose components are the values of N parameters of a “test point” \mathbf{x} . Consider a cluster of values with means given by the vector $\boldsymbol{\mu} = (\mu_1, \mu_2, \dots, \mu_N)^T$. Then the Mahalanobis distance from the test point to the cluster is defined by

$$D_M(\mathbf{x}) = [(\mathbf{x}-\boldsymbol{\mu})^T \mathbf{S}^{-1} (\mathbf{x}-\boldsymbol{\mu})]^{1/2}$$

where $\mathbf{S} = \mathbf{cov}(x_i, x_j)$ is the covariance matrix whose elements are defined by

$$S_{ij} = \mathbf{E}[(x-\mu_i)(x-\mu_j)]^T .$$

Here \mathbf{E} is the “expectation” which in our case is just the mean value (but not restricted to such). The covariance matrix allows one to account for the diffusiveness of a cluster (related to the standard deviations that are the diagonal elements of \mathbf{S}) and cross-correlations among different dimensions of a cluster (the off-diagonal elements of \mathbf{S}). Similarly we may re-construct the Mahalanobis distance (D_M) in its equivalent representation in a probability space.

Care must be taken in the method used to construct the covariance matrix used in the calculation. The use of pooled, joint, or group singular covariance matrices depends upon whether one is calculating evenly weighted data sub-sets, is interested in within-group distances, or group-to-group centroid-to-centroid distances. Different data structures may necessitate the use of differently constructed covariance matrices [Moussaides and Valaki (2009), Russell, et al. (2014)].

Figure 1: a bivariate projection of the 5 dimensional reference hyper-ellipsoids onto the SSA-EAE plane. Indicating an example of aerosol type clusters and their shapes.

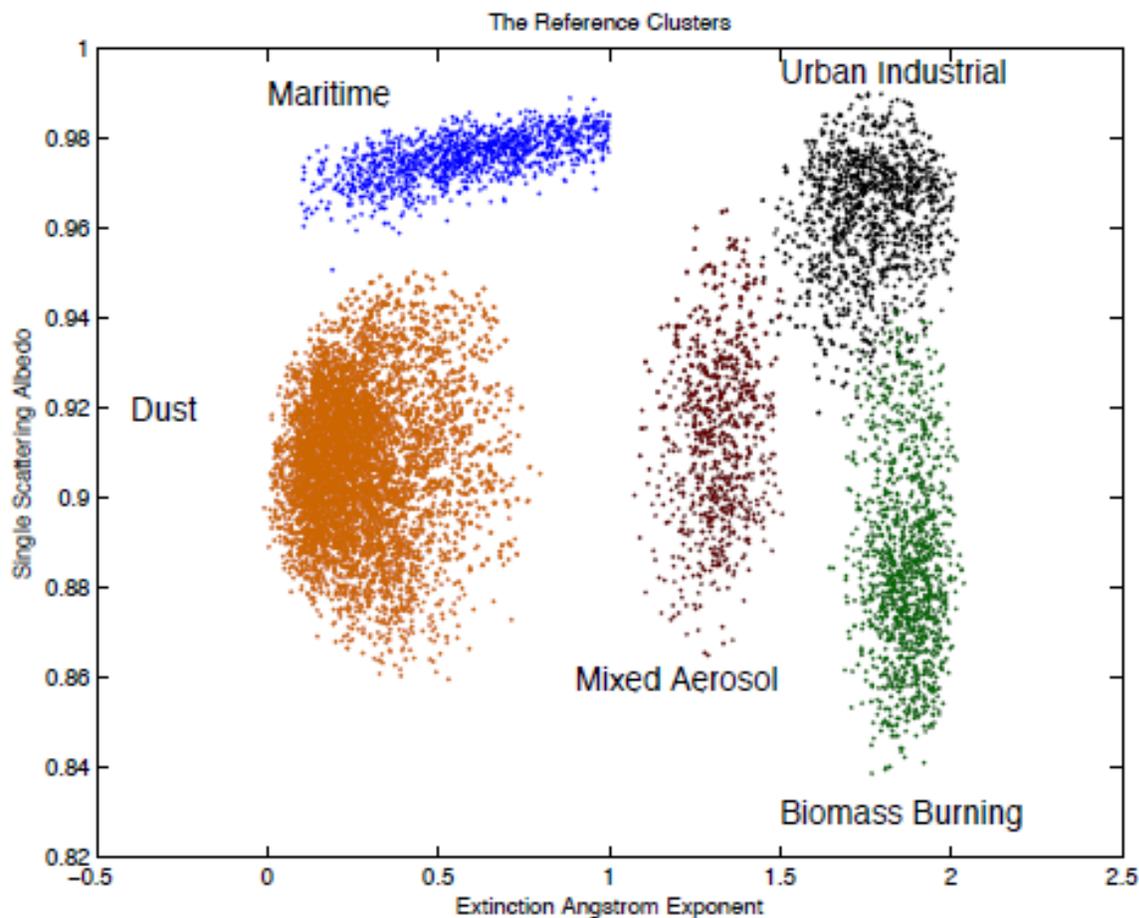


Table 1: The student’s estimated project outlook

Task	Objective/ Milestone	Proposed Dates
A1	Statistical refinement of the variables in the data space	Q I
A2	Investigations into “in-class” criteria and “outlier” definitions	QII
-	<i>Submission of Paper on Preliminary classification Scheme</i>	Q III
A3,4	Steps to refine Aerosol Sub-classes of Biomass Burning and sub classes of Dust aerosols	Q III, IV
-	<i>Submission of paper on Aerosol sub-classification typologies</i>	QIV - V
B1,2	Incorporation of Polarization data into the variable set	QIV - QVI
B2	Attempt to define Aerosol typing functions from $F(DLP(\Theta), \lambda)$	QVII - QVIII
C	Non-Parametric Shape function analysis of variable distributions	QIX - X
-	<i>Submission of Paper on Distribution shape function analysis</i>	QX - QXI
D	Incorporation of Maritime Aerosol Network Data into scheme	QIII , QXII

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AERONET Maritime Aerosol Network

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Title of Project: *Development of a Multi-purpose reconfigurable Multi-Spectral Irradiance Monitor for Rapid Deployment Aerosol Measurement in Complex Terrains.*

Abstract: In this project we aim to further the development of a small, field-portable, instrument for measuring the incoming solar irradiance components (direct and diffuse) at varying sun position angles throughout the day. The device portability will be such that we can locate it during various seasons in venues where other ground-based measurements do not exist [only satellite coverage is available]. The data measured data from this device will be used to make calculations of atmospheric properties [such as *aerosol optical depth* (AOD) or *cloud optical depth* (COD)] at specific locations throughout the Nevada Basin and Range region. Results are to provide local air column information, and serve as a check against NASA satellite derived values.

Background and Introduction: This work touches on two major issues of significance: 1) the importance of accurate characterization of the aerosol and cloud interactions with incoming solar radiation - in a well resolved geographic sense [“good spatial resolution”]; and, 2) the fact although satellites do provide excellent spatial coverage, presently available data in the western US from satellite retrievals of atmospheric properties, is poorly correlated with the ground-sensed data (where it is available). Work toward resolving portions of both of these known problems will be attempted.

The premise: The retrieval of AOD and other column parameters from ground-based optical instrumentation is sparse in the Desert/ Basin and Range West; the values of aerosol optical depth do not correlate well with the calculated and measured values of particulate matter (PM) less than 2.5 micron in aerodynamic diameter (PM_{2.5}) [1]. Satellite-based retrievals from NASA’s Moderate Resolution Imaging Spectroradiometer (MODIS) are for various reasons – including the *Dark Target* and *Deep Blue* surface reflectance algorithms, render rather poorly the AOD values and aerosol types, when compared with ground lidar or sun photometry from the Global Aerosol Robotic Network (AERONET) [2,3]. Despite improvements in the way satellite instruments interpret the various shades, and land features of the earth’s surface below them [known as “target algorithms “] resulting in more realistic characterizations of the backgrounds of light soils, snow, and various terrain features, - accurate ground data to compare and correct against, is still sparse. (Lyapustin et al., MODIS version 6 MAIAC algorithm) [4].

The work: we have begun the development of a highly portable and rather inexpensive solar powered mini-shadowband multispectral radiometer. The device can function in two modes: 1) in upward looking mode, the shadowband will allow direct measurement of the Diffuse Horizontal Irradiance [DHI] and the Global Horizontal Irradiance [GHI] continuously throughout the day for all sun angles; in downward facing mode [with the shadowband removed] the device can be UAV/UAS mounted to measure ground reflectances leading to an angular measure of the reflectance from the surface of earth for the range of visible wavelengths at all incident angles (BRDF). Accurate measurements of the Earth surface reflectance are required to properly determine Earth’s albedo [5].** With this we hope to be able to make inversion algorithms to calculate Aerosol Optical Depths, Cloud optical Depths, possibly Liquid Water Path, and Droplet/ aerosol mean effective radius. The device is based upon using a broadband mini-spectrometer capable of specific wavelength irradiance measurements, and a set of companion photodiodes to measure the wavelengths beyond 800 nm and into the IR (matching those of the Cimel318 at AERONET sites such as UNR Leifson Physics building installation).

The instrument: it is intended to be a rather inexpensive, field-portable unit much smaller than those market-available [ship-borne Fast Shadowbands Radiometers (FSRs), Thin Cloud Shadowband Radiometers (TCSRs) [6]] [see figure 2A, B] at rather low component cost per instrument. It is a combination of a precision spectrometer, and a set of individually wavelength centered photodiodes. Of course the most positive outcome would be making reliable measurements taking into account thin cirrus effects as well as those of aerosols. This instrument is presently referred to as the *micro Shadowband spectroRadiometer μ SR™*.

Project Summary: NASA is deeply invested in satellite use for quantifying atmospheric aerosols for both climate and health applications. There currently are large problems with the data in the western U.S., especially in the Great Basin of Nevada. The immediate goal of this work is to develop a low cost, highly portable, ground-based multi-spectral diffuse and direct irradiance instrument that can be used in NASA sponsored projects to improve the performance of the satellite retrieval of aerosol. This instrument is to be constructed such that it can be a ground-based upward-looking mini-shadowband radiometer; and, with removal of the band, be UAS/UAV mounted in downward-looking mode to retrieve surface reflectance and albedo measurements. The project entails improvement of a recent prototype, being developed through a collaborative group of researchers at NSHE's Desert Research Institute-Reno, The University of Nevada-Reno and NASA's Jet Propulsion Laboratory. The instrument will be designed for easy 3-D printing of the sensor head and integration of a programmable micro controller electronics package. Field testing will occur both at UNR, the Black Rock Desert, Great Basin National Park, and selected high altitude ground stations. The long term vision of this collaboration is to work with NASA toward deployments of a finer grid measurement network, integration on higher altitude UAVs, and extra-terrestrial measurement in extreme environments such as the lunar or Martian atmosphere.

Project Tasks and Research Methods:

Addressing the Research Problem and Preliminary Project Development

The acquisition and analysis of aerosol data is critically important to understanding the Earth's radiation budget with respect to climate changes. Accurate remote sensing of aerosols is important for understanding the interrelationship between solar irradiative forcing and climate change, degradation of atmospheric visibility, and regional and local air quality [7]. The most common and expansive tool for aerosol data acquisition is via satellite remote sensing. However, satellite data must be validated by terrestrial surface measurement as the ground truth baseline. The ground-based atmospheric column sensing network [AERONET] is sparse in the Western States – specifically 3 sites across Nevada. Satellite aerosol data does not match well with the ground based results in the west [2,3]. We propose to directly address the sparse grid issue, and the resolution of satellite results with those of ground instruments by the development of a very inexpensive (<\$500/unit), robust, highly portable, easily reproduced irradiance monitor. The cost factor is important to be able to deploy many instruments placed strategically on a wider spatial network.

Specifically regarding the Western US, recent detailed studies reveal that there is a large discrepancy between the satellite-retrieved AOD data (from MODIS) and the ground-based columnar AOD signals from AERONET [2,3]. The question is why does the satellite retrievals do not match the ground based remote sensing data? The discrepancy is likely due to high surface reflectance of desert regions [3]. The instrument should be capable of being mounted on the underside of a plane or UAV to provide detailed surface reflectance measurements as well.

Scientific Relevance and Merit:

Since aerosol composition and concentration exhibit great variation in space and time (in contrast with the greenhouse gases), global scale capturing of these variations is essential to our understanding. Such global coverage is done only with large terrestrial grid networks [AERONET], and/or satellite remote sensing. Satellite implementations of aerosol remote sensing using multiple optical sensors, can be done using sun-synchronous orbits. Examples of such are Aqua and Terra (orbiting at an altitude of 600 – 800 km, with a period of 96 – 100 min, and an inclination of $\sim 98^\circ$) which are equipped with the Moderate-Resolution Imaging Spectroradiometer (MODIS). These two instruments are perhaps the most important satellite-borne devices used in global observation of aerosol optical depth (AOD)[7]. As a result of the specific orbit parameters of each satellite, both of the daily MODIS records are based in observations of earth's atmosphere at high solar zenith angles over the low and mid-latitudes, then transition into nighttime over the high latitudes. Hence, they tend to observe and record a generally weak aerosol signal against an almost fully sunlit background of the earth's surface or of the top surface of clouds. It is these bright background signals which make AOD determination, and earth albedo measurement very challenging. Common examples of this scenario include terrains dominated by snow and ice cover, as well as those against lighter colored semi-arid regions and desert surfaces. These optically and geographically complex terrains are predominant in the western US, specifically including Nevada. NASA's world-wide land-based grid of high-resolution passive data collecting Sunphotometers [AERONET] is actually very sparse throughout the western US of Nevada and California. To specifically address the sparseness of the land-based data archive, we sought to develop a more cost-effective solution than directly proposing to expand the existing AERONET by increasing the number of instruments and coincidentally strategically placing them at smaller distances of separation. We propose developing a light-weight, robust, rapidly deployable highly transportable monitoring system which can be located in various strategic ground venues for further comparative studies between satellite remote sensing and ground-based measurement. As an intentional design feature, the instrument may also be aerially mounted, and used in a low-altitude, downward-looking configuration. Ultimately one step toward a goal of closing the gap between the MODIS and the AERONET results for the mountainous and desert Nevada regions.

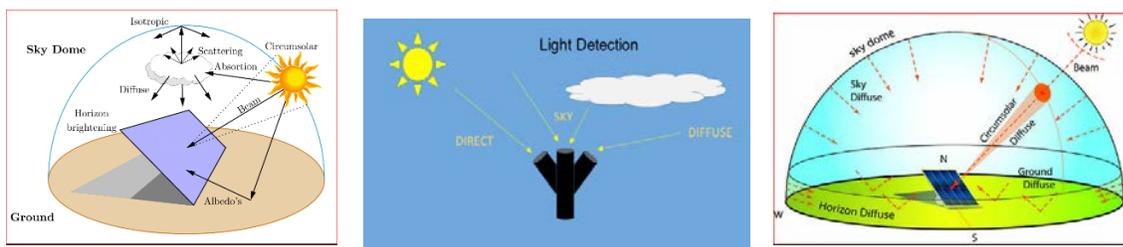


FIGURE 1: Simplified schematics of surface solar Irradiance components courtesy Penn State University <https://www.e-education.psu.edu/eme810/node/543> and m.giordano

TIMETABLE: we hope to have the functioning prototype undergoing bench testing by summer 2017, and companion testing adjacent the UNR MFRSR by fall 2017. It is then anticipated, we would field test the device in the Spring 2018 in such venues as The Black Rock Desert [light, flat background], Great Basin National Park [complex terrain and varying color background], and possibly White Mountain Observatory [free tropospheric calibration]. Beyond that it would greatly depend upon the quality of data collected to being some study of the comparative nature, and verifiable retrievals.

Table 1: The student’s estimated project outlook

Task	Objective/ Milestone	Target Dates by quarter
A1	Design, Component selection of electronics, construction of a Prototype	Q I Fall 2017
A2	Prototype preliminary tests aside adjacent UNR MFRSR on LP rooftop	QII Winter 2017/8
-	<i>Submission of Paper on Preliminary Prototype Design Or Poster Session at conference</i>	Q III Spring 2018
A3,4	Redesign/refinement of Prototype into functioning System	Q III, IV Spring / summer 2018
-	<i>Submission of paper on Preliminary data comparisons with other instruments AERONET cimel-318, YES MFRSR etc,</i>	QIV Summer 2018
B1,2	Further data analysis and comparisons subject to student funding and academic progression through the dissertation	QV -QVI F2018 – Winter 2018/9

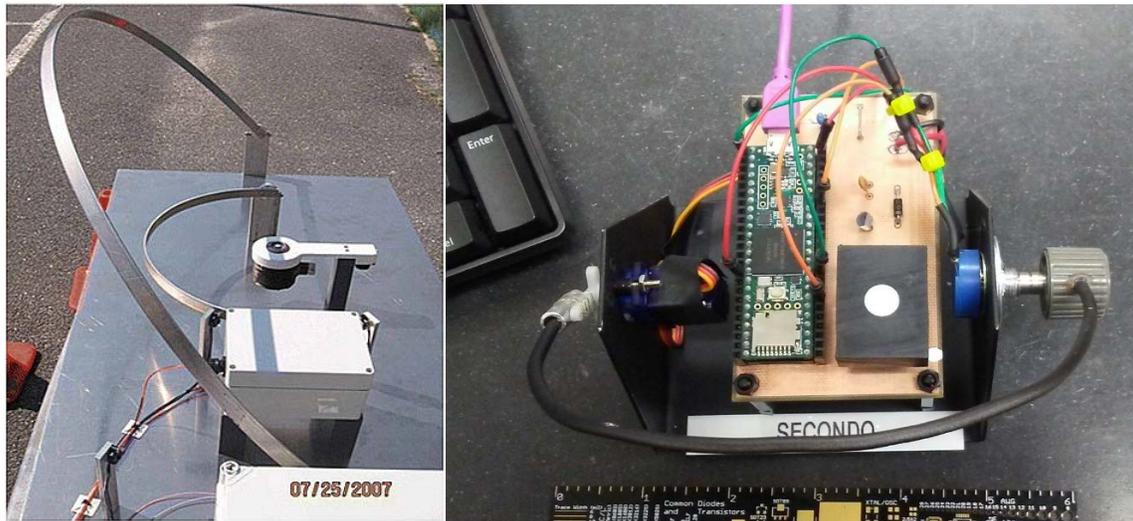


FIGURE 2: A. The Irradiance™ TCSR unit has an outer band of 90 cm diameter. The table shown is ~ 1 meter across. B. A version of an early demonstration prototype [*seconda*] of the μSR™ shown on laboratory table for scale. The μSR™ as shown is ~ 0.14 m across its width.

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The dissemination of the progress, and results of this project will follow two streams: the first would be to peers and scientific colleagues within the Atmospheric Physics / Geosciences community, the second would be targeted to a more general public audience and the K-12 student population.

Stream 1 - Scientific Community: tentatively considering funding and acceptance

The yearly cycle of poster/conference presentation would be as follows for the Academic Year 2017/2018:*

- Fall 2017:*
- 1) UNR Graduate Student Association Research Poster Symposium. This annual event takes place on the UNR campus and is adjudicated by faculty.*
 - 2) American Geophysical Union Fall Meeting In New Orleans, LA (11-15 Dec.). This annual meeting of the AGU has both poster session, and presentation sessions. I would submit for a presentation, and most likely be relegated to a poster at the session moderator's discretion.*
 - 3) American Meteorological Society 98th Annual Meeting Austin, TX (7-11 Jan.). This annual meeting of the AMS has both poster session, and presentation sessions. I would submit for a presentation, and most likely be relegated to a poster at the session moderators discretion.*
- Spring 2018:* 4) NASA Space Grant Consortium Annual Meeting poster session. TBA
- Fall 2018:* The expected cycle is similar to the Fall 2017 events, with the exception the AGU move to Washington D.C., and the AMS is yet TBA.

Publication targets are most likely something from the following Journals:

- For the instrument and its implementation
 - 1) Journal of Atmospheric and Ocean Technology
 - 2) Atmospheric Measurement Techniques
 - 3) Journal of Applied Optics
- For the ensuing Aerosol and cloud study results
 - 1) Journal of Quantitative Spectroscopy and Radiative Transfer
 - 2) Atmospheric Environment
 - 3) Atmospheric Research
 - 4) Atmospheric Chemistry and Physics

Data and figures from the instrument record will be linked to a publically accessible web url, on my portion of an FTP server at: <ftp://pubfiles.dri.edu/pub/MARCO>. Other data such as images from a local skycam reside there.

Stream 2 - General Community at Large: These events and opportunities are highly subject to future scheduling, but may include making myself available through the **Nevada STEM Mentor Network** to train teachers and mentor younger students. Opportunities to engage in local Science Fairs and "Community Days"- such as those by the UC Davis Tahoe Environmental Research Center in Incline Village, and the Lake Tahoe Community College's annual South Lake Tahoe Science Expo [this year 4-7 April 2017].

*Conference participation is dependent upon available travel funds, cost of the event registrations, travel, and lodging.

This sections is merely an outline of topics, details and other aspects related to the development and testing of the developing instrument – the micro Shadowband SpectroRadiometer μ SR™. [The sections contained herein may or may not be contained in further versions of documents pertaining to the proposed dissertation proper. They are presented here to demonstrate our thoughts and serve as placeholders for further investigation.]

On aspects related to the Development of a *Solar Irradiance Measuring Instrument*:

- A. A brief history on the development of sun occulting measurement devices – variations on a theme
- B. Specifics of The *micro-Shadowband Radiometer* - μ SR™
 1. Targeted Instrument Measurement Criteria
 - a. matching AERONET, MODIS, and existing MFRSR capabilities
 - b. light collection and detection
 - 1) diffusing the incoming signal
 - a) the nature of a *Lambertian* surface
 - b) Diffusivity as a material property
 - c) Materials with high Transmittance, high *Diffusivity* and low *Absorptance*
Teflon/PTFE, Spectralon, AVIAN B,D
 - 2) collimating and / or Integrating the received *Diffused* signal
 - a) History & conceptual development of an *Integrating Sphere*
 - b) Design considerations of an *Integrating Sphere*
 2. Targeted Instrument Design Criteria
 - a. Band and sky angle criteria
 - b. Electronics and components considerations
 - c. Environmental and Production considerations
 3. The Present configuration of the existing prototype
 4. Associated challenges and aspects of a Shadowband Instrument
 - Correcting the *Diffuse Irradiance* for the shadowband
 - Approaches to band correction schemes
 - Instrumental limitations and *Uncertainty* estimates

PART 3: PATHS AND EXPLORATIONS RELATED TO THE DEVELOPMENT OF A SOLAR IRRADIANCE MEASURING INSTRUMENT

- C. An Operational Methodology for The *micro-Shadowband Radiometer* - μSR^{TM}
- D. A simplistic Measurement Strategy for The *micro-Shadowband Radiometer* - μSR^{TM}
- E. Toward a Data Analysis strategy for The *micro-Shadowband Radiometer* - μSR^{TM}
 - 1. Langley Plots to Calibrate and obtain an AOD(λ)
 - 2. Strategies to obtain SSA, RRI, IRI, AAE, EAE from the diffuse component

A summary of the present status / configuration of the working demonstration device - μSR^{TM}

Some of the basic properties and attributes of the existing demonstration instrument are summarized in tabular form, and presented in **Table 4** below.

Dimension	140 mm across the band	110 mm across the base	215 mm maximum vertical dimension
Shadowband	Arc diameter 110 mm	~ 1.0 degree of angular sky resolution (shading)	Sweep at 1 degree angular intervals
Band control	270° rotation range 6 volt servomotor	High resolution potentiometer external position feedback control	Doubly redundant band control(internal to servo, and external potentiometer)
Spectral range	380 nm – 810 nm in 100 discrete bands	Resolution: 15nm at half max FWHM	Micro Spectrometer Hammamatsu C12660MA/C12880MA
Expanded Spectral range(s)~280nm – 2.15 μm Targeted	UV photodiode suite Near IR Photodiode suite	As available to match CIMEL 318 8 band MODIS suite UNR MFRSR And AATS 14 band ranges	TBD Intor, or Hammamatsu or Vishay
Diffuser	3-D printable, machinable PTFE	Not as perfect as SPECTRALON but available	
Instrument housing	3-D printable plastics	Present design and fabrication in house	Collaboration between UNR and DRI
Configurations	Upward ground-based	May be carried aloft – balloon or UAS	May be inverted for ground reflectance/albedo collection
Processor/controller	32 bit ARM processor ~ 180MHz – cortex M4	Programmable through micro USB port	Teensy 3.6 available through PJRC https://www.pjrc.com/teensy/
Measurement capability	Interval single degree Shading	Potential of DHI measurement for every single sun position angle	Can be used to determine cloud presences and properties: LWP, COD, and $R_{\text{effective}}$ Implications for predawn and below horizon diffuse measurement
Per unit component cost	Targeted at \$1500-\$2000 USD	To be determined as of now	

To summarize what has been presented:

In this document we have proposed two aspects of the same notion – attempt to robustly classify aerosols through information acquired from aspects of the diffuse component of the surface received solar irradiance. Use our classification scheme to construct local, regional, and global aerosol climatology products. In the one aspect we use AERONET database values gained by *sunphotometric* means, in the other – we propose to make progress in developing a small instrument specifically designed to acquire data via a *shadowband spectro-Radiometric* means.

Concerning projected timing and milestone criteria:

Our timetables were presented in the sections directly in Part 2. In the one table on page 17 we presented times are relative by academic term and calendar quarter. This was done on the conditional nature of the start of such tasks specified in the section titled *Proposed Studies and Experiments A-D* on pages 12-14. In the other table we aligned tasks with the UNR academic calendar as it seemed appropriate. This table is found in Part 2B on page 25. Both are redundantly inserted below.

Proposed timetable of the further AERONET typological research

Task	Objective/ Milestone	Proposed Dates
A1	Statistical refinement of the variables in the data space	Q I
A2	Investigations into “in-class” criteria and “outlier” definitions	QII
-	<i>Submission of Paper on Preliminary classification Scheme</i>	Q III
A3,4	Steps to refine Aerosol Sub-classes of Biomass Burning and sub classes of Dust aerosols	Q III, IV
-	<i>Submission of paper on Aerosol sub-classification typologies</i>	QIV - V
B1,2	Incorporation of Polarization data into the variable set	QIV - QVI
B2	Attempt to define Aerosol typing functions from $F(DLP(\Theta),\lambda)$	QVII - QVIII
C	Non-Parametric Shape function analysis of variable distributions	QIX -X
-	<i>Submission of Paper on Distribution shape function analysis</i>	QX - QXI
D	Incorporation of Maritime Aerosol Network Data into scheme	QIII , QXII

Proposed timetable of the instrument development of the μ SR™

Task	Objective/ Milestone	Target Dates by quarter
A1	Design, Component selection of electronics, construction of a Prototype	Q I Fall 2017/W2018
A2	Prototype preliminary tests aside adjacent UNR MFRSR on LP rooftop	QII Spring 2018
-	<i>Submission of Paper on Preliminary Prototype Design Or Poster Session at conference</i>	Q III Spring 2018 into summer 2018
A3,4	Redesign/refinement of Prototype into functioning System	Q III, IV Spring / summer 2018
-	<i>Submission of paper on Preliminary data comparisons with other instruments AERONET cimel-318, YES MFRSR etc,</i>	QIV FALL 2018
B1,2	Further data analysis and comparisons subject to student funding and academic progression through the dissertation	QV -QVI F2018 – Spr/sum 2019

Expectations of divergent events and aiming for a closure:

Given the present logistical considerations of resources accessible at the Desert Research Institute, it does seem imperative that we establish well-functioning relations with UNR Department of Physics personnel to procure access to UNR-only resources. Such resources might include machining [either by the student or professionally performed in the UNR Physics Machining facility housed in the basement of LP], as well as access to the LP Physics Atmospheric Instrumentation Laboratory. We do not presently anticipate difficulties on the UNR portion. We would be grateful to any direct guidance provided by Professor Arnott as he is a pre-eminent instrumentalist.

Some form of publishable result on the data collected while developing the instrument from display piece into genuine prototype should be possible by Fall 2018. Depending upon progress on the instrument, we anticipate a completion of the preliminary phase of this study either Spring term 2019, or Fall 2019. Progress on a patentable research-grade produced instrument may be the direction of a Post-Doctoral Research position should time and funding opportunity permit.

CAVIAT: THIS EXPRESSION, LIKE LIFE ITSELF IS TO BE CONSIDERED A WORK IN PROGRESS

Having been part of two physics-based Silicon Valley start-ups, performed scientific research pro-bono (not part of this discussion), and been available to see both my parents depart this life, i have considered this UNR experience an enormous blessing - opportunity to complete a Ph.D. in the Physical Sciences. i appreciate the further work to establish a habit of scientific research.

My personal goals and my societal goals have become convergent over the years. i will say this as having spent years already serving my community as a public school Physics instructor in *the International Baccalaureate System* within a generally underperforming public High School, and as a university lecturer. The direct plan is to manage the transferring of that Physics experience to the university level after completion of my doctorate.

My original academic and educational target beyond the Ph.D. was to pursue the higher doctorate of DSc. i would prefer to complete my PhD in the USA, and continue on in the UK or EU system to achieve the DSc. Since it is generally only available to those who have an affiliation with a university that grants such an honor, my path would be to establish an affiliation with one of those institutions via study abroad, and the co-tutelle option. Appropriately targeted universities through which the research in atmospheres, is done within the Department of Physics, are Oxford, Imperial College London, and St. Andrews in Scotland. My plan is to apply to them directly [prior to completing the degree, and having no platform to work from]; then to spend at least one year of solid research in such an institution. This could be a formal Post-doctoral researcher position, or some other designation. So far i have made no progress in that direction. i would prefer to target directly a professorship post.

My career desire, (and societal ambition) is to pursue university research and teaching - educating, influencing and encouraging another generation of physical scientists. As such, i desire to maintain the connection to teacher training, curriculum development, and societal scientific literacy in the STEM disciplines. Here at DRI we have a direct connection to the local public schools through the Green Power Initiative program. i have been recruited to serve as an *ad hoc* contributor to the design of hands-on investigative experiences and interactive in-class activities – implementing my prior instructional and curriculum development professional experience. In this regard it would not be outside my sight to target a position here within the UNR/DRI physics community, desiring to obtain a permanent departmental chair.

i have always desired to make my work scenario into a collaborative environment where faculty have interactions that positively contribute to their professional development, as well as the development of pathways to student achievement. i have begun to consider a few projects that extend beyond the traditional classroom environment. This is an attempt at collaboration across small academic communities. This interest is in developing high-level physical science programs that will link the traditional secondary school science experience with the university-level science education. This concept might involve either an after-school format, or a more in-vogue summer bridge program for students intending to pursue a university education. It is likely to be an augmentation to the existing K-12 format. It might involve some aspects of developing transportable experimental laboratories or make use of existing university resources. The aim is to improve STEM student experiences, and the curriculum in the local area, such that it develops a positive benefit of student confidence and success for incoming first-year students in college and university systems. There is much to be thought out here.

None of this is to be a redirection away from pure scientific research related to atmospheric physics. My interests in that area are diverse. Some are related to atmospheric optics and EM interactions, optics of granular and complex media (snows, ices, etc.); others are large-scale planetary wave structure, turbulence theoretical development, geophysical-scale convection models, planetary-scale driving forces, and atmospheric manifestations of *Macroscopic Quantum Phenomena* (MQP).

On the general nature of light, its propagation, conceptualizations and mathematical formalism

For more detail on the physical nature of this radiation emanating from the sun, the reader is referred to an original works by Max von Planck in 1900 and 1901 [1,2]. For more physical insight into how this energy may be propagated through space [in a form consistent with the Heaviside formulation of the Maxwellian EM notions] from the Sun toward Earth, the reader is referred to early works on light by Albert Einstein from 1905, and 1910 [3,4,5,6]. Those interested in further development of the notions of propagating rays and ray bundles are referred to Landau and Lifschitz [7] (1951, specifically chapter 7). We will follow the naming conventions of *The International Organization for Standardization* (ISO) and the *International Union of Pure and Applied Physics* (IUPAP) conventions in symbols and nomenclature. [a review of these with specific regard to *radiative transfer* is found in Grainger 2009 [8].

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