4STAR Spectrometer for Sky-Scanning Sun-Tracking Atmospheric Research: Instrument Technology Development

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Abstract – The 4STAR (Spectrometer for Sky-Scanning, Sun-Tracking Atmospheric Research) combines airborne sun tracking and sky scanning with diffraction spectroscopy, to improve knowledge of atmospheric constituents and their links to climate. Direct beam spectral measurement of optical depth improves retrievals of gas constituents and determination of aerosol properties. Sky scanning enhances retrievals of aerosol type and size distribution. 4STAR measurements will tighten the closure between satellite and ground-based measurements.

The design builds on previous sun tracking instruments that have provided critical measurements in more than a dozen field campaigns. 4STAR incorporates a modular sun-tracking/ sky-scanning optical head with fiber optic signal transmission to rack mounted spectrometers, permitting miniaturization of the external optical head, and future detector evolution. Technical challenges include compact optical collector design, radiometric dynamic range and stability, and broad spectral coverage. Preliminary calibration and engineering flight tests are discussed.

Keywords: atmosphere, climate, pollution, radiometry, technology

1. INTRODUCTION

Since 1985 NASA Ames airborne tracking sunphotometers (AATS-6 and -14) have made extensive measurements of atmospheric constituents via their effect on the Sun's direct-beam transmission through the atmosphere. Constituents measured to date include O_3 (e.g, Livingston, 2005), H_2O, (e.g., Schmid, 2000); and aerosols (e.g., Russell, 2007). AATS measurements are used extensively to validate and supplement satellite retrievals of stratospheric and tropospheric constituents (e.g. Russell, 2007), validate airborne and ground-based lidar data products, characterize horizontal and vertical distributions of gas and aerosol properties, study closure (consistency) with in situ samplers aboard many aircraft, test chemical-transport models, and study the radiative effects of atmospheric constituents and Earth surfaces that are important to both climate and remote measurements. AATS measurements and analyses are described in more than 100 publications since 1987.

The NASA Ames Sunphotometer-Satellite Group and the Department of Energy (DOE) Pacific Northwest National Labs (PNL) Climate Physics Group have collaborated on development of a new airborne sunphotometry instrument that will provide information on gases and aerosols extending far beyond what can be derived from discrete-channel direct-beam measurements, while preserving or enhancing many of the desirable AATS features (e.g., compactness, versatility, automation, reliability). The enhanced instrument combines the sun-tracking ability of the current 14-Channel NASA Ames AATS-14 with the sky-scanning ability of the ground-based AERONET Sun/sky photometers, while extending both AATS-14 and AERONET capabilities by providing full spectral information from the UV (350 nm) to the SWIR (1700 nm).

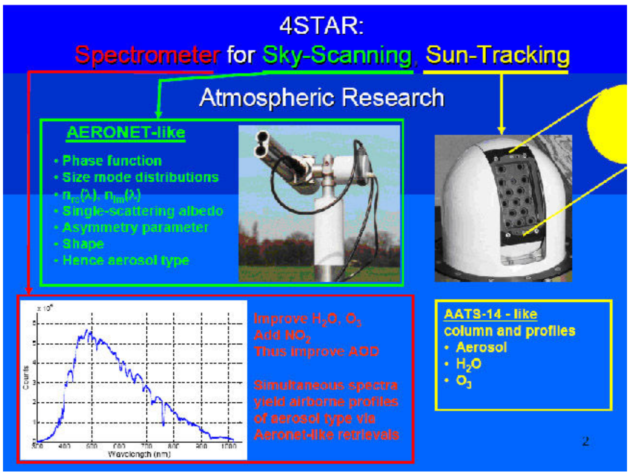

Figure 1. Essential features of 4STAR as related to AATS-14 and AERONET

2. INSTRUMENT DESCRIPTION

Previous AATS designs were based on a number of opto-electronic modules comprising a spectral-band interference filter covering a photodiode detector, with amplifier, and digitizer circuitry interfaced to a data acquisition system, all built into the instrument body. A 2-axis motion control system with analog feedback control and DC servomotor actuators provided tracking of the solar disk to permit very stable radiometric measurements with negligible variability from tracking error. 4STAR retains similar sun tracking requirements but represents a major departure from this design for nearly all instrument subsystems.

The most fundamental improvement derives from the science requirement for higher spectral resolution to resolve gas absorption features, and provide detailed continuous measurements across the spectrum. Advances in diffraction spectrometer designs have made it possible to specify commercial spectrograph and detector combinations that will meet 4STAR requirements for resolution and dynamic range. Two spectrometers are required for the full 350 to 1700 nm spectral domain.

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**We gratefully acknowledge the support of NASA's Radiation Sciences Program and The DOE Battelle Memorial Institute

Fiber optic bundle fore-optics are commonly implemented with field spectrometers, and represent a straightforward choice for the 4STAR light collection system. A flexible bundle can be easily manipulated to track the sun or scan the sky, and the small input aperture is easily adapted to miniaturized baffle tubes that properly limit the instrument field of view.

Recent improvements in industrial grade motion control equipment permit the specification of packaged stepping-motor/driver and feedback sensors that can meet the high pointing accuracy and modest dynamic response requirements for the instrument. Finally, digital controller and data acquisition elements permit replacement of virtually all analog circuitry in the system with PC-based hardware that is readily programmed from a graphical user interface. The single element in the 4STAR that persists from earlier AATS designs is the quadrant photodiode detector that provides the differential analog signal to track the sun.

2.1 Requirements

4STAR functional requirements to meet the scientific goals for the instrument are summarized in table 1.

Table 1. Summary of Requirements

Spectral	range	resolution
visible/near infrared (VNIR)	350 to 1015 nm	2-3 nm
short wave infrared (SWIR)	900 to 1700 nm	5-10 nm
Angular sampling	range	FOV
Direct solar beam	full hemisphere	1.25 deg
sky light	full hemisphere	2 deg
Pointing control	range	accuracy
elevation	0 to 180 degrees	0.2 deg
azimuth	many revolutions	0.2 deg
Operational		
space (time)* to acquire direct beam data		100 m
space (time)* to acquire sky scan data		10000 m
aircraft pitch, roll, and yaw rate tracking limits		6 deg/sec
aircraft climb and bank angle limits		25 deg
altitude ceiling		12500 m
*space divided by airspeed provides time requirement		

2.2 Technical Challenges

Several key questions arise in considering the transition to the new technology solutions outlined above:

1. Are the CCD (quantum) detector elements capable of meeting the radiometric accuracy and stability required?
2. Does the combination of small aperture fiber optics and aggressive spectral dispersion within the spectrograph permit adequate light collection to meet the signal-to-noise ratio (SNR) requirement? Can we sample fast enough to get useful sky scan measurements within an acceptably small spatial domain?
3. Are stray light artifacts internal to the spectrometers adequately controlled (or deterministically correctable)?
4. Will a fiber optic bundle and fiber optic rotary joint (FORJ) provide consistent radiometric transmission through the full range of motion?
5. Can the optical collectors be fitted with windows that will stay clean during flight experiments?
6. Can the mechanical motion axes be properly sealed across the aircraft pressure barrier without limiting tracking response?

2.3 Prototypes

These technical challenges have been addressed through the development and testing of several prototype instruments. An initial ground-based proof-of concept design was developed to test questions related to spectrometer, fiber optic, and baffle tube performance. A Zeiss MCS series spectrograph with Hamamatsu CCD detector and Tec5 interface electronics was interfaced to a customized "Y" fiber bundle to permit light collection from either of 2 baffle tubes optimized for either direct solar beam or scattered sky light collection. An altitude/azimuthal pointing system was designed and fabricated, driven by identical Oriental motor precision-grade harmonic planetary-geared stepping motors with integrated resolver feedback systems on each axis. National Instruments digitization and motion controller cards were interfaced to a rack-mount industrial PC system with Intel processor, Microsoft Windows XP operating system, and National Instruments LabView graphical data acquisition and control programming software.

This ground prototype system performed remarkably well and most of the elements were adopted for the flight instrument design. The modular configuration permits the spectrometer, data system, and power supplies to be rack mounted and the scanning head (motors, fiber, and baffle tubes) to be quite compact. Furthermore, the custom scanning head frame components can accommodate a variety of collection optics and fiber bundle configurations, and can be interfaced to a variety of spectrometer and detector elements that can be readily added as rack mount components.

An important finding of preliminary work with this system was that the sky light collection task is a significant optical design driver. Scattered light flux is far weaker than the direct solar beam, and the sky light baffle tube must effectively reject the very bright direct beam radiation when the instrument is attempting to measure scattered light in the critical zone within ~5 degrees of the solar direction. Additionally, the time required to scan through a reasonable set of directional measurements along the principal plane and almucantar (perhaps 20 measurements in each dimension) is critical. Low signal levels are generally accommodated by longer integration times, but in this case both scans must be completed within ~100 seconds to stay within the atmospheric "cell" dimension of 10000 meters specified in section 2.1 (for a nominal airspeed of 100 m/sec).

The light collecting ability of a fiber optical system is limited by the fiber cross-sectional area and numerical aperture (NA), which defines the acceptance angle over which incident light will undergo total internal reflection at the core/cladding interface and be captured in the wave guide. A customized fiber bundle comprising 19 100-micron hexagonal-packed fibers was designed with all but one fiber utilized for sky light collection (maximizing cross sectional area). A Cassegrain mirror fore-optic was added to the sky light baffle tube to fill the numerical aperture of all fibers in the bundle. Test data indicate that filling the fiber NA and mode structure with a diffuser at the fiber face also helps to fill the diffraction grating aperture in the spectrometer and improves the stability of individual spectral channel measurements. This treatment resulted in ~50x improved signal levels, but added direct beam cross-talk into the measurement within ~10 degrees of the solar direction owing to scattering from Cassegrain mirror surfaces. A "mini baffle stack" was devised to minimize this scattering, at the cost of a ~60% reduction in signal levels.

Additional baffle tube and shutter prototypes were built to support the compact flight instrument design. A pitch-roll-spiral-climb tilt table was designed and built to simulate the types of motion to be expected in flight and evaluate the ability of the tracking system to meet the tracking specification. Considerable work was done with these prototypes, particularly the sky light baffle tube, to achieve the best possible signal levels. A useful baseline capability has been achieved, but it is expected that further refinements to the sky light tube and fiber optic bundle may be required before the flight instrument can address the most challenging clear-sky and near-sun measurements.

2.4 Flight Instrument

The design of the flight instrument depicted in Figure 1 began in January 2010. The NASA design methodology and airworthiness certification process were adopted to ensure that the instrument can be used productively in the NASA Airborne Science Program and collaborating DOE flight experiments. In addition to the measurement requirements described in section 2.1, design objectives included minimal intrusion into the air stream and reliable performance in a broad range of moisture, thermal, vibrational, and pressure environments. Initial certification, integration and flight testing was planned for the DOE Gulfstream G-1 aircraft based at Pasco WA.

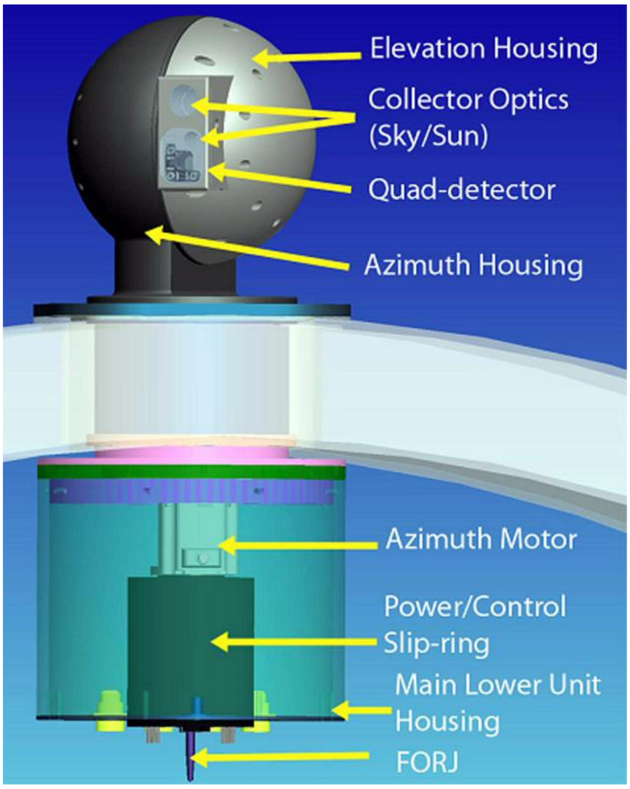

Figure 2. 4STAR components

With the baffle tube and fiber optics elements from prototype development in hand, the flight instrument design problem was essentially one of integrating several commercially available subsystems into the smallest and most robust package (in keeping with schedule and budget constraints). A split-sphere design was selected, with minimal protrusion of optical components into the air stream, to avoid high variability in air loads resulting from a non-symmetrical shape scanning through the full altitude-azimuthal range of motion.

The 180° elevation axis range of motion can be achieved using a flexible coil for both the electrical and optical signals connecting to baffle tube, shutter, and quadrant detector components. The principal constraint on this coil geometry is the allowable bend radius for the fiber optic light guide, which scales linearly with the fiber core diameter. This is one important reason for using a bundle of smaller fibers rather than one large fiber. The bend radius limitation for doped-silica-clad synthetic-fused-silica fibers having the best spectral transmission properties for this application is ~40 mm. A radial coil geometry was selected with the inner end of the coil rotating with the elevation housing shaft and the outer end connected to the azimuth housing. This coil assembly is termed the "clockspring" because of its similar appearance, and fits compactly around the elevation planetary gearmotor drive (not shown) in the azimuth housing. The instrument comprises 4 axially stacked clockspring elements; one for the fiber optic bundle and 3 for electrical conductors.

The flight instrument requires continuous-rotation light and electrical conductors on the azimuth axis to enable spiral climb and descent maneuvers as required for vertical profile measurements. An Oriental motor helical ring drive rotary actuator was specified to provide a large on-axis region to route these conductors. A stock 48-channel Moog fiber-brush slipring was specified for the electrical conductors. A solid-core fiber optic rotary joint (FORJ) was designed to match the fiber bundle geometry.

The instrument head must be sealed against rainwater intrusion. Even water vapor in the head can be problematic if it causes fogging or frosting of optical tube elements that add scattered-light noise into the measurement. Furthermore, the instrument head penetrates the pressure shell of the aircraft and must be sealed to maintain cabin pressure to ensure airworthiness. The seal design borrowed heavily from AATS heritage, using Teflon lip seals on the elevation and azimuth shafts and synthetic fused silica windows to seal the baffle tubes. Window cleanliness is a challenge, and the instrument is fitted with a quick-lock mount to permit pre-flight cleaning from inside the cabin, as well as a sealed parking block (not shown) to protect the windows from heavy rain and cloud condensation during flight. All non-rotating assembly interfaces are sealed with low-temperature silicone o-rings. A dry-gas purge system was included to provide a constant low-pressure (~10 kPa) differential between the inside of the head and the static pressure outside the aircraft. This system required considerable airworthiness analysis to accommodate safe use of the compressed gas energy source as well as the more complex pressure regulation scheme required to regulate against the external static reference pressure.

3. CALIBRATION

The NASA Ames Sunphotometer-Satellite group has invested considerable effort in developing the most effective calibration procedures for direct beam sunphotometry in the study aerosols (Schmid, 1998). The scientific productivity of the AATS instruments relies on the Langley calibration technique, typically applied from a high mountain location in the cleanest possible air. A preliminary Langley calibration was performed in 2008 on the first 4STAR prototype; this calibration will be repeated with the flight configuration prior to and following all science flight experiments. Several additional measures of performance are important to verify instrument performance.

Primary is the field of view (FOV) scan where the baffle tube input aperture is scanned cross a nearly collimated source (typically the sun) to verify that radiometric throughput is constant with scan angle, i.e. that angle-dependent scattered light is not contaminating the signal. Figure 3 presents FOV scans for the direct solar and sky light measurements. It is critical that the direct solar FOV scan provide a flat plateau over the region where the (0.57°) sun completely fills the (1.25°) aperture of the direct beam baffle. AATS experience indicates that 2% per degree variability in this plateau is a practical limit, and provides adequate SNR to support scientific analysis.

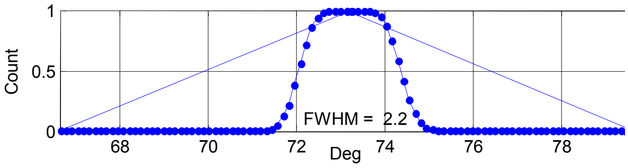

Figure 3. FOV for direct solar beam

The sky light FOV measurement is concerned not with the plateau but rather with the regions just adjacent to it, indicating the ability of the optical system to measure only sky-scattered light and not spurious direct beam light scattered or reflected by baffle tube components (primarily the power optics that are required to fill the fiber NA). AATS provides no heritage for this design; rather the Cimel instruments used extensively in the AERONET grid are the standard. The Cimel design utilizes power optics as well as rather long (~300 mm) baffle tubes, and has the option to integrate as long as required to achieve adequate signal strength. 4STAR is challenged to miniaturize equivalent performance into the ~200 mm diameter split sphere, with adequate photon flux to the detectors to meet the 100 second sky-scan requirement. Figure 4 shows that 4STAR response matches Cimel response over the range (≥3°) used for AERONET retrievals. Quite recent implementation of a new baffle configuration has significantly reduced the scattered light evident below 3°.

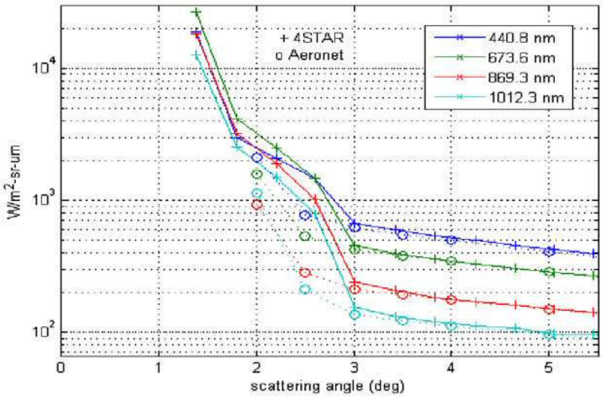

Figure 4. Direct beam contamination of sky light signal close to the sun.

4. TEST FLIGHTS

Three Test Flights were completed in September 2010. The certified instrument (shown in Figure 5) was installed on the DOE Gulfstream G1 aircraft as shown in Figure 6 and flown for a total of 5.3 hours at altitudes up to ~6000 m. Test objectives centered on airworthiness certification and the functional demonstration of tracking and direct beam measurement capability. The instrument met all test objectives for sun tracking measurement and provided considerable data to evaluate performance. A series of additional test flights are scheduled for the G1 to test sky light data acquisition and develop the operational protocols that will lead to a science qualified instrument.

5. FUTURE WORK

Several instrument enhancements are considered in addition to the tuning that will accompany upcoming engineering flights. Scientists on the sunphotometer team are interested in scattering measurements in and around cloud edges, and for some modes


Figure 5. 4STAR flight instrument

of operation, bright scattering poses a significant challenge to the quadrant detector approach to pointing and tracking. A sun tracker based on CCD array technology is under consideration, that would better discriminate the solar disk from other glint or bright scattering sources that contaminate the quadrant detector signal. Additionally, the CCD radiometric measurements would be of value in spatially mapping cloud edge scattering.

Polarization is generally recognized as an important dimension of measurement capability to maximize remotely sensed information about aerosols. Attention has been given in the 4STAR design to accommodate future incorporation of polarization elements into the sky light collector.


Figure 6. 4STAR mounted in DOE Gulfstream G1 (atop aircraft just ahead of propeller)

Finally, it is recognized that a field calibration standard would be quite valuable to complement the Langley calibration method, particularly as the fiber optic light path must be disconnected and reconnected several times during the course of deployments. Recent developments of light emitting diode (LED) sources, spectrally mixed to more closely resemble the solar spectrum and interfaced to appropriate integrating sphere or diffuser stack optical elements (Fryc, 2005) may provide a useful field- and perhaps even flight-calibration capability.

Close collaboration with experts within NASA, DOE, and NIST is planned on this development.

6. SUMMARY

A new airborne sunphotometer has been designed, fabricated, and tested by the NASA Ames Sunphotometer-Satellite Team working in collaboration with the DOE Climate Physics Group at PNL. The instrument builds on the heritage of previous NASA instruments but incorporates new and different technology for most of the major subsystems. Improved measurement capabilities include many more spectral channels, with fine enough spectral resolution to study gas constituent absorption as well as aerosols. Furthermore, a separate baffle tube collector has been added to permit sky scattered light collection over the full principal plane and almucantar angular domain. This capability permits the extension of the ground-based AERONET measurement strategy to include vertical profiling from aircraft.

The new instrument has been engineered, fabricated, and certified for flight. A series of additional flights are planned to bring the instrument to full scientific mission readiness, to support NASA and DOE Airborne Science missions as well as the calibration and validation of earth observing systems that measure the effects of aerosol and molecular absorption on the Earth's radiation budget.

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