Development of Airborne Hemispheric Spectrometer

New Dimension of Hyperspectral Sensing

Reno K.-Y. Choi and Edward J. Milton

Geography and Environment, University of Southampton, SO17 1BJ, UK

NATURAL ENVIRONMENT RESEARCH COUNCIL

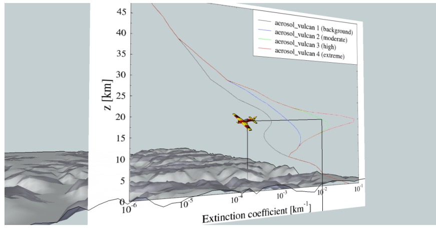
UNIVERSITY OF Southampton

Abstract

A new concept of hyperspectral instrument is presented. Novel design of hyperspectral skydome allows retrieval of atmospheric constituents and properties from a snapshot of spectral solar radiation over entire sky, regardless of platform motion either on ground or aircraft. Design and description of subsystems of the instrument are given followed by preliminary tolerance analysis, whose results are to be added in the retrieval algorithm along with hardware specifications. Extended application of the hyperspectral skydome is being carried out filling in the gap in the imaging spectrometry.

Introduction

Properties in lower part of atmosphere, i.e. troposphere and stratosphere, are an important topic in wide range of science community, such as weather, air pollution and global warming. Aerosol and trace gas studies are key to understanding the Earth's atmosphere and therefore the sustainable environment of the Earth. Generation and transport of anthropogenic (and natural) constituents are thought to be implicated in climate changes and affect human health in the form of air pollution. Since decades, complicated nature in the region has been studied 1) for net fluxes between lower and upper layers of atmosphere and 2) to understand its dynamics (Holben, et al. 1998; King et al, 1999). Various monitoring techniques have been used, such as active systems like CALIPSO, ground-based lidar, and passive systems such as sun/sky photometers. Although those approaches have its own unique capabilities and limitations, synergystic use of different approaches has been the key to improvements in radiative transfer models and retrieval algorithms (e.g. Ricchiazzi et al. 2006). Such technique on airborne platform yields unique capability, in the interest of validation of spaceborne retrievals of stratospheric and tropospheric constituents and consistency with other monitoring means for horizontal and vertical distributions of gas and aerosol properties. Next generation airborne sunphotometer is being undertaken at NASA for gases and aerosols extending beyond its predecessor (Schmid et al, 2010).



Such information is also arguably essential for airborne imaging spectrometers (IS), due to 1) nonequivalent path lengths in viewing geometry, requiring additional atmospheric information at sensor altitude, 2) its normal flight altitudes around the edge of planetary boundary layer below which still plays an important role in radiative forcing sensitive to the ground reflected spectral signature, e.g. Ozone, aerosol and water vapour, and 3) high spatial and temporal atmospheric variability under the sensor altitude. Downwelling irradiation synchronised with airborne IS, e.g. ILS for Itres instrument CASI and FODIS for Specim instrument AISA, is supposed to give at-sensor spectral reflectance. This simple device needs assimilation of navigation and empirical sky radiance model to suppress aircraft motion from the irradiance at tilted surface and to retrieve basic atmospheric parameters, i.e. direct-to-diffuse ratio and skyradiance distribution at horizontal level (Choi and Milton, 2001).

The UK Natural Environment Research Council's (NERC) Strategy "Next Generation Science for Planet Earth" identified the support of the development of new and innovative technologies for environmental science, under which the Technology Proof of Concept (TPoC) programme initiated a study for the definition of an airborne hyperspectral skydome. It aims to carry out theoretical studies and to develop a prototype instrument that extends far beyond the conventional systems. To achieve the goal, the noble design with an imaging spectrometer enables to avoid complicate moving parts, like ground-based sunphotometers, which 1) quicken sky scanning, 2) increase reliability, and 3) lower the maintenance cost.

Concept

When the Sun light enters Earth's atmosphere, scattering and absorption interfere with atmospheric constituents. Mie and Rayleigh scattering defines characteristics of scattering by relative difference between wavelength and particle size. The light observed is therefore the result of countless interaction with atmosphere (and some from ground). It is simply divided into direct and diffused components, each of which is considered as an important spectral signature of atmospheric constitutes (**Figure 2**). Spectral transmission of direct-mean spectral solar radiance with respect to that of top-of-the-atmosphere (TOA) is directly related to the aerosol density, water and ozone, while angular distribution from diffused radiation represents geometric information of aerosol and cloud properties.

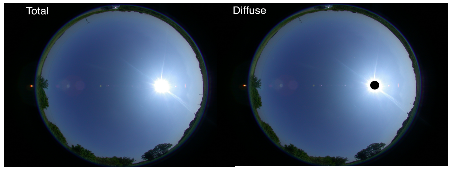


Figure 2. True RGB photo shot of sky with fisheye lens. Direct component of solar radiation is masked with black disc, representing diffused radiation.

All secondary reflection and absorption in the atmospheric constituents appears as diffused component of solar radiation,

$$E_{diff} = \int_{\Omega} L(\theta, \phi) d\omega$$

In other words, total solar irradiance is sum of direct and diffuse components (**Figure 3**),

$$E_{total} = E_{diff} + E_{dir}$$

Since the hyperspectral skydome spectrometer takes direct measurements of total irradiance (E_{total}) and diffuse radiation (E_{diff}) by integral of NAP readings (Equation 1), direct component of solar radiation (E_{dir}) can be indirectly retrieved by Equation 2. Pagnutti et al (2006) successfully demonstrated that such indirect derivation of direct-beam solar radiation has potential for alternative sunphotometer.

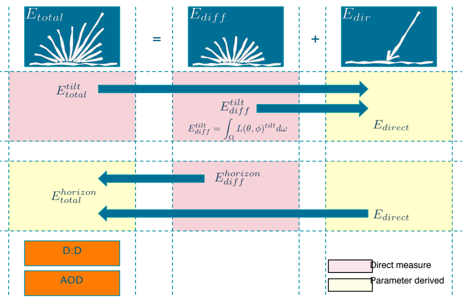


Figure 3. Schematic diagram of data processing chain for HemiSpec. Sections are divided by types of radiation vs. sensor position. Final product yields D:D (Direct-to-Diffuse ratio) and AOD (Aerosol Optical Depth)

Hemispheric Spectrometer

Outline of skydome design is depicted in Figure 1. The fundamental of the design is to acquire both spectral irradiance and radiance over sky. While a cosine corrector covers 180° FOV for irradiance measurement (wide angle probe; WAP), total of 143 radiance probes (<5° FOV; narrow angle probe; NAP) are evenly distributed over the similar coverage of irradiance. All optical probes have unique fixed view angle on a skydome structure (DOM). Optical fibre bundle (OFB) transfers the light in the optical probes into a multi-channel spectrometer (SPEC), projecting them onto a single 2D CCD. The operation of SPEC is supported by CDHU (Command & Data Handling Unit) and power unit (PSU). A miniature AHRS (Attitude & Heading Reference Sensor) is mounted at the skydome for position of the sensor head.

Figure 4. 3D model of HemiSpec skydome. There are x143 Narrow Angle Probe (NAP) and x1 Wide Angle Probe (WAP) mounted on the structure.

Skydome (DOM)

The dome is an aluminium structure with 208×180 mm that maintains view angles of all optical probes (**Figure 4**). The spherical curvature of the dome is extended 20° below horizon. Hence, the radiance probes in skydome maintains downwelling irradiance at horizontal level even if the dome is tilted up to 20°.

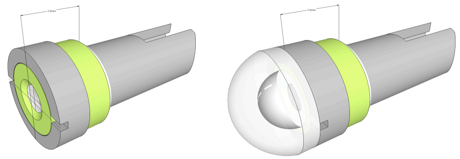


Figure 5. CAD design of NAP (left) and WAP (right).

Narrow & Wide Angle Probe (NAP & WAP)

NAP is a miniature fore-optics with ±2.5° FOV, i.e. receives light from pre-determined area of interest as well as protecting optical fibres from dust or moist in the air (**Figure 5**). Ray tracing analysis shows that FOV of NAP is secure with wavelengths. While NAP is securely attached with a standard LC fibre connector, the unit is to hold its position in skydome. This customised triplet system minimises chromatic aberration between 400 and 1000 nm, while straylight is expected to be minimal by <1%.

WAP is a cosine corrector with <180° FOV. It uses the same optical component as NAP since it has good chromatic aberration. Wide FOV is achieved by an additional PTFE at front aperture (**Figure 5**). Optimal shape of the diffuser is to be found by stochastic photon transfer analysis for best performance.

Figure 6. PPO instrument multichannel spectrometer (left) and VPH transmission grating.

Spectrometer (SPEC)

P&P Optica Inc offers a multichannel spectrometer, whose module takes up to 144 optical fibres (**Figure 6**). This portable instrument (320×120×100 mm) uses a volume phase holographic (VPH) transmission grating (470-915 nm) that enables compact system with minimal straylight. The modular system allows replacing conventional imaging fore-optics to a multi-branch fibre optic coupler in front of the entrance slit. Spatial domain of the data is effectively no longer limited by optical FOV, while maintaining the identical spectral range. For maximum number of fibres, the optical fibre is customised with 85μm diameter with 60μm core. The other end of the spectrometer has Hamamatsu camera (C10151) with 2068×512 pixels of CCD. As nominal integration time is 1 second with a mechanical shutter, lights from all fibres are simultaneously recorded.

Conclusion

Novel design of airborne hyperspectral skydome is introduced as a replacement of conventional sunphotometers. While with no moving part, the new skydome is capable of snapshot of sky radiation and aircraft motion can be compensated. Successful demonstration of the prototype instrument will be followed by operation of the skydome on the aircraft in early 2012.

Applications of hyperspectral skydome are not restricted for airborne operation. It is a spectrometer with extended geometric flexibility. Many operational issues from imaging spectrometry are often from unknowns in 3D interaction of solar radiation field that is beyond the imager's limited FOV, such as BRDF. For example, the down-looking hyperspectral skydome on aircraft, i.e. moving platform, provides broader geometric ranges of BRDF samples. Study of the potential applications is taking place in parallel with developing prototype instrument

References

CHOI K.Y. and MILTON E.J., 2001, A model-based approach to correcting spectral irradiance data using an upward-looking airborne sensor (CASI ILS). In, RSPS2001: Geomatics, Earth Observation and the Information Society. 1st Annual Meeting of the Remote Sensing and Photogrammetry Society. Nottingham, UK, Remote Sensing and Photogrammetry Society, 64-75.

HOLBEN, B.N., T.F. ECK, I. SLUTSKER, D. TANRÉ, J.P. BUIS, A. SETZER, E. VERMOTE, J.A. REAGAN, Y.J. KAUFMAN, T. NAKAJIMA, F. LAYENU, I. JANKOWIAK, and A. SMIRNOV, 1998, AERONET-A Federated Instrument Network and Data Archive for Aerosol Characterization - An Overview, Remote Sensing of Environment, 66(1), 1-16.

KING, M., KAUFMAN, Y., TANRÉ, D., NAKAJIMA, T., 1999, Remote Sensing of Tropospheric Aerosols from Space: Past, Present, and Future, Bulletin of the American Meteorological Society, 80(11), 2229-2260.

PAGNUTTI, M., Robert E. RYAN, Kara HOLEKAMP, Gary HARRINGTON, and Troy FRISBIE, 2006, Novel Hyperspectral Sun Photometer for Satellite Remote Sensing Data Radiometric Calibration and Atmospheric Aerosol Studies, NASA Stennis Space Center, Report no. SSTI-2220-0063, 48p.

RICCHIAZZI, P., GAUTIER, C., OGREN, J.A., SCHMID, B., 2006, A comparison of aerosol optical properties obtained from in situ measurements and retrieved from Sun and sky radiance observations during the May 2003 ARM Aerosol Intensive Observation Period, J. Geophys. Re., Vol. 111, 13p.

SCHMID, B., FLYNN, C., DUNAGAN, S., JOHNSON, R., RUSSELL, P.B., ZAVALETA, J., REDEMANN, J., KLUZEK, C., HOLBEN, B., 2010, 4STAR Spectrometer for Sky-scanning Sun-tracking Atmospheric Research: Development and Results from First Test-flights, American Geophysical Union, Fall Meeting 2010, abstract #A11I-03.

SCHOPFER, J., Stefan DANGEL, Mathias KNEUBÜHLER and Klaus I. ITTEN, 2008, The Improved Dual-view Field Goniometer System FIGOS, Sensors, 8, 5120-5140.

THUILLER, G., SABATINO Sofia, and Margit HABERREITER, 2005, Past, present and future measurements of the solar diameter, Advances in Space Research, 35, 329-340.

YERSHOVA, A., Steven M. LAVALLE, and Julie C. MITCHELL, 2009, Generating Uniform Incremental Grids on SO(3) Using the Hopf Fibration, International Journal of Robotics Research, 29, 9, 18p.