

**1. PI and Co-I Names and Affiliations**

PI: Robert F. Cahalan (NASA/Goddard Space Flight Center)

Consultant: Professor Harshvardhan, Head, Earth and Atmospheric Sciences, Purdue University

DOE Patent Clearance Granted

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Office of Intellectual Property Law  
DOE Chicago Operations OfficeJuly 10, 2003  
Date**2. Title of Research Grant**

Landsat Observations in Support of ARM

**3. Scientific Goal(s) of Research Grant (Maximum of 200-300 words)**

The goal of this proposal is to compare results from state-of-the-art 3D radiative transfer techniques on a variety of input cloud fields with a wide degree of complexity. This effort will complement ongoing cloud-related efforts of the GCSS working groups, and DoE-ARM Single Column Modeling and Cloud working groups. The intercomparison will be beneficial in delineating the limits and merits of the various approaches currently used to treat 3D radiative transfer theory and will create a broader consensus on what are the most serious remote sensing errors due to 3D effects. Realistic cloud water distributions used as input for many of the experiments will come directly from the ARM archive or from ARM-related modeling activities (such as those in progress as part of GCSS).

Many areas of atmospheric remote sensing and climate modeling are impacted by the 3D scattering of electromagnetic radiation in clouds. This subject is increasingly important in remote sensing because precision aircraft measurements are affected by radiation from cloud sides, and because new high spatial resolution instruments (Landsat's ETM+, EO-1's Hyperion, and others) resolve in-cloud photon mean-free-paths on the order of 100 m. These 3D effects must be simulated in detail for full understanding of such measurements. 3D radiation is also important to climate, because the 3D structure of clouds impacts large-scale radiative fluxes, through so-called "plane-parallel biases". Often those may be computed using the IPA (Independent Pixel Approximation) but determining the accuracy of IPA estimates requires 3D simulations. The whole discipline of the earth and planetary remote sensing relies largely on plane-parallel models of radiation scattered by clouds, and it is important to delineate the limits of accuracy using full 3D simulations.

The 3D scattering of light by clouds has been studied at least since the mid 1960's. However, the rapid development of computers, improved Monte Carlo and related numerical methods, and improved observations and simulations of cloud 3D structures, especially in the 1990's, have resulted in major advances in this field and in remote sensing and climate applications which have not yet been systematically presented and summarized at a major workshop. Therefore, NASA Goddard's Laboratory for Atmospheres, with U. Arizona's Cooperative Center for Atmospheric Science and Technology, is organizing a series of conferences on "Intercomparison of 3-dimensional Radiation Codes" which will bring together 3D radiation practitioners, as well as those interested in practical applications.

**4. Accomplishments in "Bulletized Form". Just a sentence or two description of specially significant results obtained in the previous twelve months.**

- *I3RC International Workshops Proceedings*. Papers and abstracts reporting results from the First and Second International Workshops on the Intercomparison of 3D Radiation Codes were published in a book with ISBN 0-9709609-0-5
- *I3RC graphics tool*. Output from the I3RC phases 1 and 2 studies can now be plotted and compared using a Java-Swing interface that allows selection of plotted fields, and full panning and zooming. This is accessible on the web at <http://i3rc.gsfc.nasa.gov>. Agreement among exact 3d methods is remarkable. Disagreements are documented for 3D approximations such as diffusion and discrete angle scattering.
- *"Open Source" Working Group*. Several participants are contributing code to an open source library that will be able to solve all the baseline cases. The code is in Fortran 90, and structure of the code is being designed by Robert Pincus and Frank Evans, both at U. Colorado.

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- *New 3D Working Group under International Radiation Commission.* Robert Cahalan will chair a new 3D working group which has been approved by the International Radiation Commission at their 2001 meeting in Innsbruck, Austria. Main focus will be a continuation of I3RC, but with representation also from the land surface modeling community.
- *Polarstratiform clouds.* Variability of polar stratiform clouds based on data from ARM/SHEBA found that variability and bias is smaller than that of subtropical stratocumulus, and primarily associated with surface inhomogeneities such as those due to leads in sea ice.
- *Absorption of Solar Radiation Observed in ARESE 2.* Analyzed data from the ARESE 2 experiment, and reported on findings in 2 ARESE Team Meetings, represented by Lazaros Oreopoulos. Publication is now being submitted to *JGR-Atmos*.

**5. Progress and accomplishments during last twelve months (or from beginning of the current effort whichever is shorter). Expectation here is no less than one page and no more than 5 pages double spaced not counting figures/graphics.**

- *Web-based development.*

The I3RC web site continues to improve, with a more attractive interface, more flexible plotting, and increased overall content. Part of this work involved the creation of programs using the interactive data language (IDL) to generate statistical plots of all the output from the various models. These routines were written in such a way as to make the entire task as automated as possible and thus both updates and future plots (results from I3RC phases II and III) can be done without much additional effort.

The I3RC linux server provides a common platform for the members of the I3RC, to facilitate timing comparisons of the various codes, and to provide a platform for open source development.

A java applet is being designed to use the path radiance technique to derive atmospheric aerosol optical thicknesses from any Landsat scene. Optical thicknesses are input to a radiative transfer model (e.g., 6s, Second Simulation of the Satellite Signal in the Solar Spectrum) and based upon the users' input apparent reflectances generate a lookup table, used to perform an atmospheric correction on a user selected Landsat TM image.

The program includes options to display x-y plots of the lookup table values, scatter plots of bands 1, 3 and 7 from the Landsat data used in the path radiance technique, histograms of the before and after image correction, and plots of the before and after image correction data which will display the actual reflectance values when the user presses a mouse button. The program will allow anyone to run do atmospheric correction through a web browser and it will access Landsat image data from the user's local machine (the client) rather than from the server.

- *Retrieval of cloud optical depth.*

Figure 3 shows wavenumber spectra for both IPA and 3D cloud nadir radiance fields simulated by MC method. The IPA radiance fields have the same power-law spectra as the optical depth. The spectra of the 3D radiance fields bend away from this power law below a few hundred meters. This scale-break occurs at the so-called radiative smoothing scale which is where the IPA breaks down. Equation (1) provides a good estimate of these scale breaks:

The results of our theoretical study were applied to Landsat TM observations. We found that TM power spectra are strongly affected by photon horizontal transport. We were able to understand (and simulate) a variety of shapes not shown or explained in previous observational studies.

- *Retrieval of cloud optical depth.*

We proposed a new satellite or aircraft cloud optical depth retrieval technique that accounts for cloud side illumination and shadowing effects present at high solar zenith angles. We believe this may prove important in testing radar retrievals of cloud optical depth in broken cloud fields. The technique uses the normalized difference of nadir reflectivities (NDNR) at a conservative and an absorbing wavelength. It can be further combined with our inverse Nonlocal Independent Pixel Approximation (NIPA) that corrects for radiative smoothing, thus providing a retrieval framework where all 3D cloud effects can

potentially be accounted for. The effectiveness of the new technique was demonstrated using MC simulations. Real world application is shown to be feasible using Landsat-5 Thematic Mapper (TM) radiance observations over the ARM SGP site. The results of retrieval are compared with the LWP inferred from the surface MWR.

- *Radar/microwave radiometer cloud retrieval*

We performed vertical cloud property retrievals for three months of Nauru data (12/98 - 1/99 and 6/15 - 7/15/99) and three months of SGP data (12/97 - 2/98). We compared several different cloud property retrieval methods, and found that some were very sensitive to uncertainties in the observed liquid water path or radar reflectivity; often leading to unrealistic retrieved number concentrations. We developed our own vertically integrated retrieval method based on Bayes' theorem, which uses prior knowledge about cloud microphysics from in situ cloud probes and accounts for uncertainties in the observed data. Figure 4 shows that the Bayes method gives more credible results than the Frisch method in this difficult case. The Bayes method combines the MWR and MMCR data in a more optimal way and remains consistent with known microphysics

- *Impact of sub-grid scale variability on prognostic cloud schemes*

The representation of clouds in large scale atmospheric models has become substantially more realistic in the past decade with the introduction of prognostic cloud schemes. These schemes explicitly compute the average concentrations of water and ice in the cloudy portion of each grid cell as a time-evolving balance between sources and sinks. The schemes are formulated in terms of average values within the grid cell. In nature, though, concentrations  $q$  of cloud water and ice vary at spatial scales down to centimeters. Variability in  $q$  generally increases with spatial scale, and at the grid spacings typical of climate models (250 km) the neglected variability can be a substantial fraction of the mean value.

6. **As appropriate attach one or so electronic figures with paragraph discussions highlighting current research. Label with PI name, affiliation, and year. We will use these in presentation materials.**
7. **List all *refereed* publications either submitted or published during the *current* grant FY that acknowledge DOE ARM support. Two copies of all submitted papers should accompany the progress report. (Two reprints of all published papers should be submitted to the ARM Science Director when reprints are received. If this wasn't done at the time please include reprints with the progress report.\*)**

### **ARM-related publications (2001-2002)**

#### **JOURNAL PAPERS (JP)**

- [1] Cahalan, R. F., Oreopoulos, L., Wen, G., Marshak, A., Tsay, S.-C., and DeFelice, T., 2001. Cloud Characterization and Clear Sky Correction from Landsat 7. *Remote Sens. Environ*, **78**, 83-98.
- [2] Wen, G., R. Cahalan., Tsay, S.-C., and L. Oreopoulos, 2001. Impact of cumulus cloud spacing on Landsat atmospheric Correction and Aerosol Retrieval. *J. Geophys. Res.-Atmos.*, **106**, 12,129-12,138.
- [3] Oreopoulos, L., A. Marshak, R. Cahalan, 2002. Consistency of ARESE II cloud absorption estimates and sampling issues, submitted to *J. Geophys. Res. (Atmos.)*

8. **List all published (either paper or web-based) extended abstracts in the current FY that acknowledge DOE ARM support. Two copies of each should accompany the progress report.**

#### **CONFERENCE PAPERS (CP)**

1. Oreopoulos, L., R. F. Cahalan, A. Marshak, Cloud absorptance estimates from three ARESE II days, *11<sup>th</sup> ARM Science Team Meeting*, March 19-23, 2001, Atlanta, GA.

2. Oreopoulos, L., R. F. Cahalan, G. Wen, A. Marshak, and D. Kratz, Cloud retrievals from Landsat-7 during ARESE II, 11<sup>th</sup> ARM Science Team Meeting, March 19-23, 2001, Atlanta, GA.  
[http://www.arm.gov/docs/documents/technical/conf\\_0103/oreopoulos-l.pdf](http://www.arm.gov/docs/documents/technical/conf_0103/oreopoulos-l.pdf).

**9. Please update us on the status of submitted referred publications from the previous FY progress report. (If none, note "NONE").**

- [1] "Offbeam Lidar: an emerging technique in cloud remote sensing based on radiative Green function theory in the diffusion domain," A. Davis, R. F. Cahalan, J. D. Spinhirne, M. J. McGill, and S. P. Love, *Phys. Chem. Earth*, **B 24**, 177-185, 1999.
- [2] "Horizontal Radiative Fluxes in Clouds and the Accuracy of the Independent Pixel Approximation at Absorbing Wavelengths," A. Marshak, L. Oreopoulos, A. Davis, W. Wiscombe, and R. Cahalan, *Geophys. Res. Lett.*, **11**, 1585-1588, 1999.
- [3] "On the Removal of the Effect of Horizontal Fluxes in Two-aircraft Measurements of Cloud Absorption," A. Marshak, W. Wiscombe, A. Davis, L. Oreopoulos and R. Cahalan, *Quart. J. Roy. Meteor. Soc.*, **125**, 2153-2170, 1999.
- [4] "Path Radiance Technique for Retrieving Aerosol Optical Thickness Over Land," G. Wen, S.-C. Tsay, R. Cahalan, and L. Oreopoulos, *J. Geophys. Res. - Atmospheres*, **104**, 31,321—31,332, 1999.
- [5] "Cloud 3D Effects Evidenced in Landsat Spatial Power Spectra and Autocorrelation Functions," L. Oreopoulos, A. Marshak, R. Cahalan and G. Wen, *J. Geophys. Res.*, **105**, 14,777-, 2000.
- [6] "Landsat 7 reveals more than just surface features in remote areas of the globe," T. P. DeFelice, D. J. Meyer, G. Xian, and R. Cahalan, *Bull. Amer. Meteor. Soc.*, includes cover photo, **81**, 1047-1049, 2000.
- [7] "A New Normalized Difference Cloud Retrieval Technique Applied to Landsat Radiances over the Oklahoma ARM Site," L. Oreopoulos, R. Cahalan, A. Marshak, and G. Wen, *J. Appl. Meteorol*, **39**, 2305-2321, 2000.
- [8] "Cloud Characterization and Clear Sky Correction from Landsat 7," R. F. Cahalan, L. Oreopoulos, T.-S. Tsay, G. Wen and T. DeFelice, *Rem. Sens. Environ.*, **78**, 83-98, 2001.
- [9] "Impact of Cumulus Cloud Spacing on Landsat Atmospheric Correction and Aerosol Retrieval," G. Wen, R. F. Cahalan, T.-S. Tsay, and L. Oreopoulos,, *J. Geophys. Res. - Atmospheres.*, **106**, 12,129-12,138, 2001.