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ATMOSPHERIC EFFECT ON REMOTE SENSING OF THE EARTH'S SURFACE

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1. INTRODUCTION

The Earth's atmosphere has a significant bearing on the quality of images of the Earth's surface as observed from space by reflected sunlight. This atmospheric effect is caused by absorption and scattering of sunlight by molecules and aerosols. The molecular effects can be accounted for, but the aerosol effects are variable and poorly known during satellite observations. The optical parameters used to compute the atmospheric effects are: its optical depth to determine the extinction of light; the single scattering albedo, which is the fraction of light scattered from total extinction; and the scattering phase function giving the probability of scattering in a particular direction.

The atmosphere tends to make dark surfaces appear brighter and bright surfaces darker, but the resultant effect depends on the surface reflectance pattern itself. Atmospheric scattering diffuses the boundaries between adjacent fields. This effect, called the adjacency effect, is due to light reflected from the ground surrounding a sensor's field-of-view and then scattered into the field-of-view. The adjacency effect depends on the above mentioned optical parameters and on the depth of the aerosol layer.

Theoretical analyses of atmospheric effects, ground-based measurements of atmospheric parameters, and analysis of satellite data are reported on here. This work occurred during the period 1982-4.

2. JUSTIFICATION, OBJECTIVES, AND APPROACH

2.1. Justification

Recently developed theoretical models of radiative transfer in the atmosphere can be used to perform atmospheric corrections for known aerosol characteristics. The development of correction algorithms requires testing the models against measurements to investigate the main atmospheric characteristics that affect certain remote sensing techniques, and to develop methods to measure these characteristics from ground and from space.

2.2. Objectives

To study the atmospheric effect on remote sensing by theoretical modeling and to measure this effect. To relate the effects of the atmosphere to the aerosol characteristics in order to determine which are the main characteristics that affect a given remote sensing function. The specific goals are:

a. Laboratory simulation and analysis of field measurement of the atmospheric effect to study the effect and to validate theoretical models.

b. Development of a theoretical model that can simulate the atmospheric effect over any variable surface.

c. Study the atmospheric effect on the spatial resolution of satellite images of the surface and on classification of surface features.

d. Analyze the relative importance of aerosol scattering and absorption on remote sensing of the surface in order to determine if atmospheric corrections based on the optical thickness alone are feasible.

e. To measure the atmospheric characteristics that are important for atmospheric corrections: optical thickness, path radiance, scattering phase function, and single scattering albedo, and find the relations between them in order to establish the minimum information required for atmospheric corrections.

2.3 Approach

a. In order to measure the atmospheric effect and test theoretical models, a field and controlled laboratory experiments are performed in the presence of nonuniform surface reflectance.

b. The simulation of the atmospheric effect over a general varying surface reflectance is performed by the calculation of the atmospheric Modulation Transfer Function (MTF) and application of two-dimensional Fourier Transforms for the calculation.

c. Analyze the aerosol effect on spatial reduction and classification by means of the atmospheric MTF and application of the 2-D Fourier Transform technique.

d. Radiative transfer computations are used to derive the relative importance of aerosol scattering and absorption on remote sensing of the surface albedo, vegetation index, and classification.

e. A system is developed to measure simultaneously from the ground the optical thickness, the path radiance, the scattering phase function, and the single scattering albedo. The covariance between these parameters is studied. Inversion procedures are developed to derive from the observations the aerosol optical-thickness, scattering phase function, and absorption.

3. RESEARCH RESULTS

3.1. Measurement of the atmospheric effect

A laboratory experiment [6] was conducted in which a half white, half black plate represented the nonuniform surface and a dish with hydrosol of latex spheres represented the hazy atmosphere. A solar simulator irradiated the dish and a detector scanned the upward radiance across a line perpendicular to the border between the white and black area. Fig. 1A shows an example of the measured radiance and the theoretical fit [1] as a function of the distance from the boundary X (normalized by the hydrosol height H). In this experiment the adjacency effect (the effect of a bright object on the radiance above a nearby dark object) was measured as a function of hydrosol optical thicknesses for nadir and off nadir observation directions. Good agreement was found between theory and experiment. The measured adjacency effect had an amplitude 20% higher than the theoretical one, and a range 25% shorter than in theory.

A field experiment was also conducted [8] in which the upward radiance above and below the haze layer was measured simultaneously with ground and airborne measurements of the atmospheric characteristics. Fig. 1B shows an example of the upward radiance from the nadir below and above the base. The radiances are measured over the dark water as a function of the distance from the bright vegetated land (the wavelength is 773 nm). The reflectance of the vegetated surface was approximately 0.35. A comparison with theory shows similar good agreement as in the laboratory study, with the adjacency effect somewhat stronger and narrower than in theory (as was found in the laboratory study). This difference can be due to the approximations in the theory and due to errors in accounting for very large particles.

3.2. Resolution and classification

The experimental verification of the radiative transfer theory and the application of Fourier Transform [7] to generalize the theory so that the upward radiance can be simulated for any 2-D varying surface, enables the application of the theory to study the atmospheric effect on spatial resolution and classification of surface features [3], [5] and [7]. It was found (see Fig. 1C) that the atmospheric effect reduces the spatial resolution substantially. For the Thematic Mapper (TM) the spatial resolution of 30m (defined for Modulation transfer value of 0.35) is reduced to 100m by a hazy atmosphere (aerosol optical thickness = 0.5, $\lambda = 550$nm). An atmospheric correction that ignores the adjacency effect can correct the resolution to 50m. Similarly, significant effects were found on classification of surface features [3] and on separability between field classes [7].

3.3 Scattering versus absorption

A theoretical study was conducted [9, 12] to test the common hypothesis that the atmospheric effect depends mainly on one atmospheric parameter—the optical thickness (τ_A). An increase in the amount of aerosol tends to brighten dark surfaces and darken bright surfaces (see Fig. 2A). In the brightening process aerosol scattering has a dominant effect and absorption is of secondary importance; but in the darkening process the absorption has an important role. For a given bright surface the atmospheric effect can be of brightening or darkening depending on the ratio of aerosol scattering and extinction optical thicknesses (ω_0). A reliable estimate of such effects can not be made until more is known about atmospheric absorption and its variability. However, Fig. 2B shows that remote sensing of contrast such as vegetation index is weakly affected by absorption, but still affected by changes in the optical thickness. The vegetation index is a function of the slope of a line in this figure and thus does not change appreciably with absorption (from model 1 to 2 and from model 3 to 4). Figure 2B also shows how the reflectance of the earth-atmosphere system is altered by the atmosphere.

3.4 Ground-based experiment

In order to learn about the optical characteristics of the atmopshere as they affect remote sensing, a ground experiment is being performed in order to collect and analyze a substantial data base. Simultaneous measurements in the visible and near infrared spectrum are made of the solar transmission, the sky radiance in the direction of the North Star and also in the almucantar through the sun and the degree of polarization of the skylight. The aerosol optical thickness is derived from the solar transmission. The path radiance is measured in the direction of the North Star in order to minimize geometric effects and observe changes associated with aerosols. During a day the angle between the observer, sun, and North Star is essentially constant.

Attempts have been made to relate atmospheric corrections to only one parameter—namely the aerosol optical thickness, in only one spectral band. Figure 3A shows the strong correlation between path radiance (at 870nm) and optical thickness (at 610nm). 94 percent of the radiance variance is associated with optical thickness variance for these wavelengths. The correlation between the radiance at 870nm and the optical thickness at 610nm was bigger than the correlation with optical thickness at 870nm. This is due to a different size dependence of the radiance and the optical thickness. The correlation between path radiances in two spectral bands (Fig. 3B) shows the accuracy of estimating the path radiance in one band from that in another band. The radiance at 870nm can explain 74 percent of the radiance variance at 480nm, and 62 percent of the radiance variance at 1670nm.

The aerosol scattering phase function is derived from the radiance of the skylight in the solar almucantar. The inversion proceeds by an iterative method to account for molecular and multiple scattering. An inversion of radiances computed for a model atmosphere is shown in Fig. 3C. The true aerosol phase function of scattering angle is given by P_4. P would be the estimated phase function derived from the radiance, if only molecular scattering was accounted for. P_o is the first guess of the aerosol phase function, which is used to estimate the radiance of multiple scattering. This value is subtracted from the measured value to obtain the P_1-estimate of the aerosol phase function. The procedure is repeated with this new value of the phase function (P_1). After two more such iterations, the curve P_3 is obtained, and it is nearly identical to the true value (P_4). Although the simulated radiances are free of errors, an analysis of the error budget has been made. This inversion method has been applied to measured radiances. Eventually, these functions will be compared with those derived from solar transmission data.

5. CONCLUSION

Radiative transfer theory (RT) for an atmosphere with a nonuniform surface is the basis for understanding and correcting for the atmospheric effect on remote sensing of surface properties. In the present work the theory was generalized and tested successfully against laboratory and field measurements. There is still a need to generalize the RT approximation for off-nadir directions and to take into account anisotropic reflectance at the surface.

The adjacency effect results in a significant modification of spectral signatures of the surface, and therefore results in modification of classifications, of separability of field classes, and of spatial resolution. For example, the 30m resolution of the Thematic Mapper is reduced to 100m by a hazy atmosphere. The adjacency effect depends on several optical parameters of aerosols: optical thickness, depth of aerosol layer, scattering phase function, and absorption. Remote sensing in general depends on these parameter, not just adjacency effects, but they are not known well enough for making accurate atmospheric corrections. It is important to establish methods for estimating these parameters in order to develop correction methods for atmospheric effects. Such estimations can be based on climatological data, which are not available yet, correlations between the optical parameters and meteorological data, and the same satellite measurements of radiances that are used for estimating surface properties. Our knowledge about the atmospheric parameters important for remote sensing is being enlarged with current measurements of them.

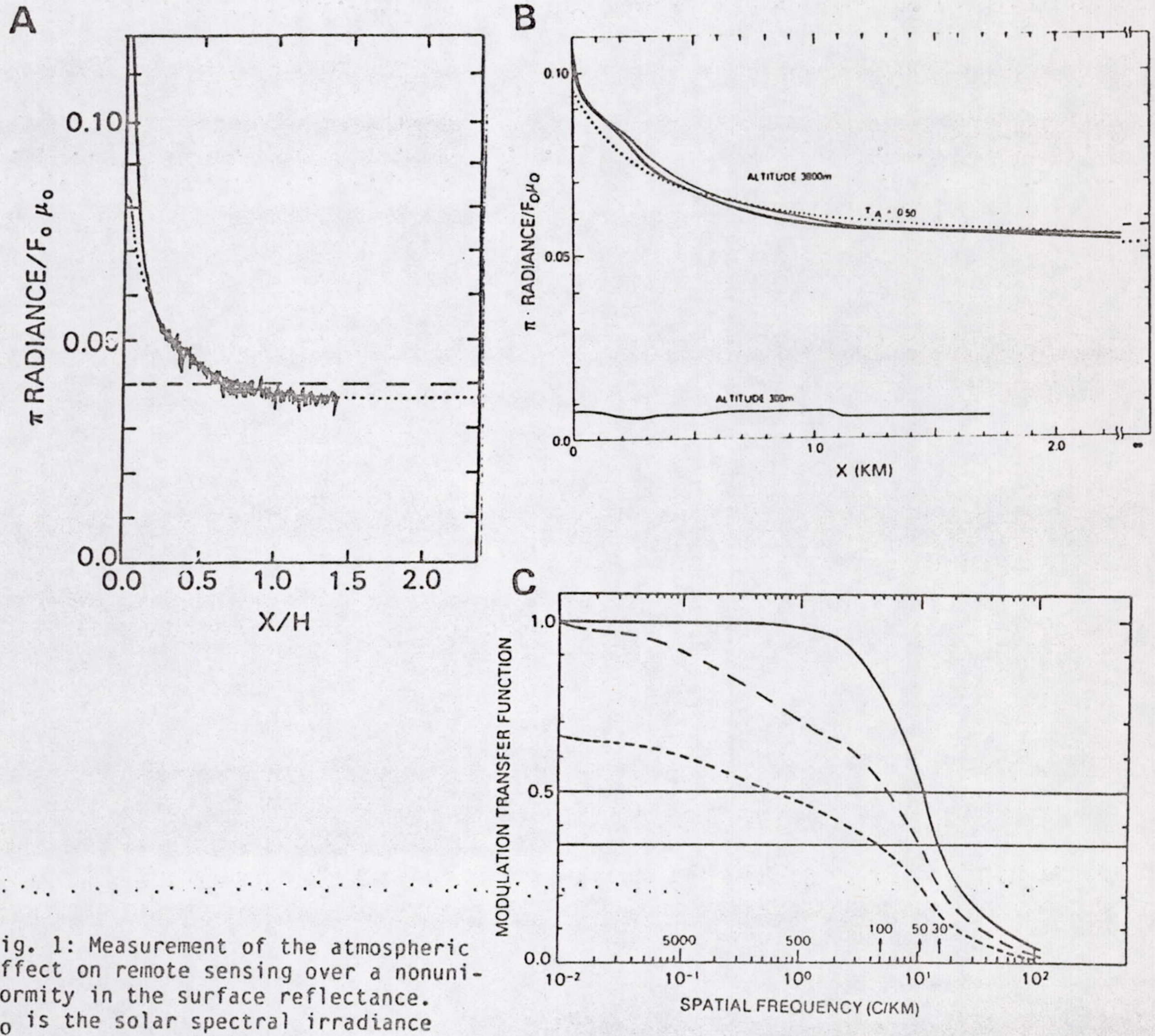

Fig. 1: Measurement of the atmospheric effect on remote sensing over a nonuniformity in the surface reflectance. F_0 is the solar spectral irradiance and θ_0=arccosine(μ_0), the solar zenith angle.

A - Laboratory simulation for optical thickness 0.3, nadir observation. The theoretical fit (....) and the surface reflectance (- - -) are indicated. X is the distance from the bright area and H the hight of the scattering medium.

B - Field measurements for aerosol optical thickness 0.5. The aircraft measurements (——) and theory (....) are indicated.

C - The atmospheric effect on spatial resolution of the Landsat Thematic Mapper (TM). The modulation transfer functions for the TM(——) alone, with atmospheric effect (....) and with correction that ignores the adjacency effect (- - -) are shown. The original resolution (30m) is reduced to 50m by the adjacency effect and to 100m by the total atmospheric effect.

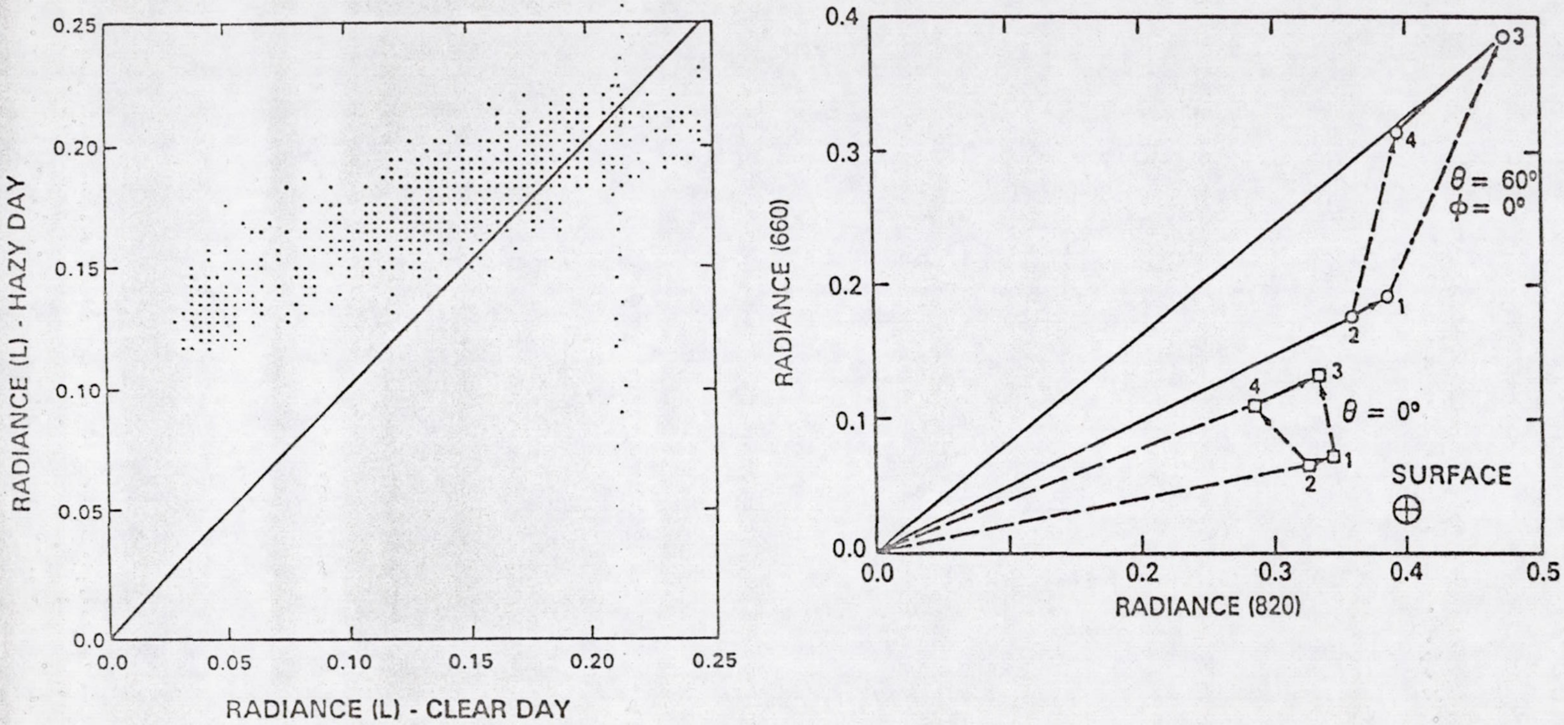

Fig. 2: A - Scatter diagram of the radiance from a Landsat image on a hazy day as a function of the radiance on a clear day taken over Washington, DC; for 700-800nm band. The radiance is normalized to reflectance units.

B - Radiance of models of the earth-atmosphere system. The surface consists of dense alfalfa. The solar zenith angle is 50°; the direction of observation is given by the polar angle θ, and azimuth ϕ from the direction of propagation of incident sunlight. The number besides the plotted points refer to the aerosol models:

MODEL	ω_0	τ_A60nm)	τ_A(820nm)
1	0.96	0.287	0.200
2	0.88	0.287	0.200
3	0.96	0.861	0.600
4	0.88	0.861	0.600

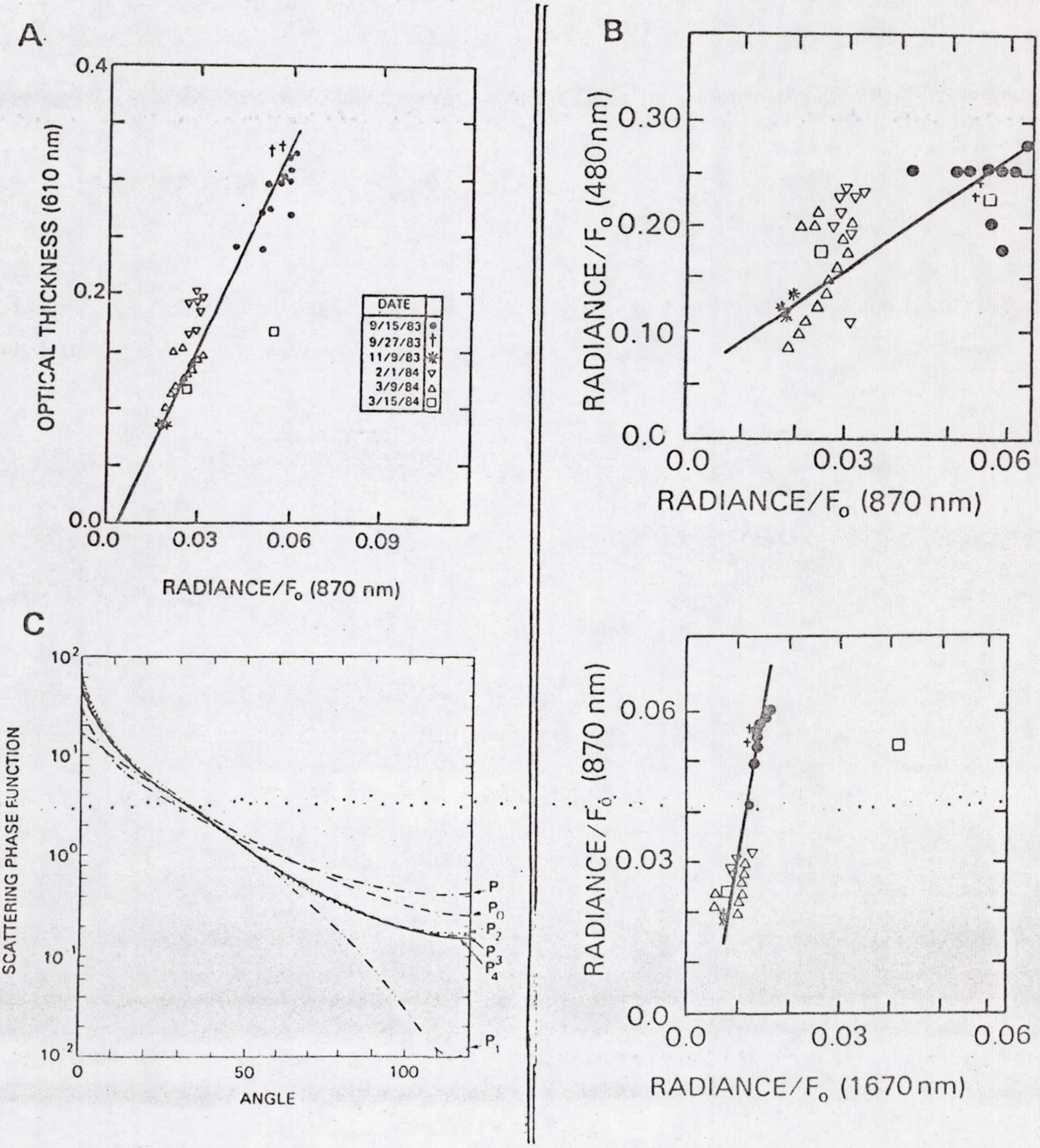

Fig. 3: Example of analysis of ground measurements of the sky radiance.
A - The relation between the optical thickness τ_a at (610nm) and the sky radiance (at 870nm) in the direction of the North star. Each symbol represents a different observation day.
B - The correlation between the sky radiance at 480nm and 870nm; and 870nm and 1670nm.
C An example of inversion of the almucantar simulated radiances for the aerosol scattering phase function.