FINAL REPORT

on

Inversion of Canopy Reflectance Models for Estimation of Vegetation Parameters

for

NASA Goddard Space Flight Center
Greenbelt, Maryland 20771

by

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Overall Objectives

One of the keys to successful remote sensing of vegetation is to be able to estimate important agronomic parameters like leaf area index (LAI) and biomass (BM) from the bidirectional canopy reflectance (CR) data obtained by a space-shuttle or satellite borne sensor. One approach for such an estimation is through inversion of CR models which relate these parameters to CR. The feasibility of this approach has been shown by the principal investigator and his associates (Goel and Thompson, 1985).

The overall objective of the research carried out during the tenure of this contract was to address heretofore uninvestigated but important fundamental issues, develop the inversion technique further and delineate its strengths and limitations.

Technical Approach

The following is a summary of technical approach, adapted from the research proposal which led to this contract.

The technical approach will consist of inverting first one-dimensional CR models, using field measured data for a variety of vegetations (natural and planted), to determine if the field measured biophysical parameters can be estimated using the CR data alone. It is expected that some of the existing models will be deficient in representing the relationship between canopy parameters and the CR. If so, these models will ~~to~~ be modified to include effects like specular reflectance, angular dependence of leaf reflectance and transmittance, and shadowing effects. During the analysis, an assessment will be made of the following aspects: advantages and disadvantages of using CR data in many wavelengths or spectral bands; use of linear and non-linear transforms of CRs for various solar/view angles and various spectral bands, optimal solar/view angles for LAI and leaf angle distribution (LAD) estimation.

One dimensional CR models are attractive for initial investigations because of their simplicity and comprehensibility. However, they are not expected to represent well the reflectance of many vegetation canopies such as crops planted in rows and forest stands. To include such vegetations, we will investigate the inversion of two- and three- dimensional models, and modify them if necessary.

The above mentioned investigations neglect the effects of atmospheric scattering. This effect is obviously relevant to remote sensing. Following these investigations, we plan to include the atmospheric scattering effects and study the inversion of CR models when such effects are present.

Finally, we plan to carry out some activities on the temporal variation of canopy reflectance which may improve on the capabilities of temporal profile modeling approach in vegetation characteristics identification and productivity assessment. These activities will use time-independent CR models to construct time dependent behavior of spectral and angle transforms of CRs.

In summary, these activities and approaches are designed to cover all the important dimensions (wavelength, angle and time) of remote sensing in the visible and near infrared regions.

Research Activities and Results

In this nine month period of research we carried out mainly the following two activities.

(1) Development and Inversion of a CR Model for Vegetation with Three-dimensional Inhomogeneities.

(2) Analysis of Simple Models for Atmospheric Scattering.

Since the development of models for canopies with three-dimensional inhomogeneities which could also be inverted was expected to be a big challenge, the emphasis of our work was on the first activity. The details of the first activity and results obtained have been given in a 72 pages long report (Goel and Grier, 1987) in the form of a research paper which has been submitted for publication. Here, we will only highlight the main aspects of this activity and present key results. The second activity has not yet led to publishable results; we will only give a progress report and present interim results.

(1) Development and Inversion of a CR Model for Vegetation with Three-dimensional (3-D) Inhomogeneities

We started our activities by looking into existing CR models for 3-D canopies which explicitly take into account the interactions of radiation with the vegetation elements. There are two main models which have been proposed.

The conceptual framework of the model due to Kimes and Kirchner (1982, Kimes, Newcomb, Nelson and Schutt, 1986) is a rectangular solid of any dimension that is subdivided into cubical cells of unit dimensions. Each cell is identified by its x, y, and z coordinates and is associated with information about the scene component within the cell (type of component - leaves, stems, soil, etc.; component area indices-leaf area index, branch index, etc.; the angular and spatial distributions of components; and optical properties of components). A complex computer program is written which follows the solar radiation as it moves from cell to cell. In any cell, part of the solar flux is either absorbed, transmitted, or scattered (into a finite number of directions). Multiple directional scattering between the cells is simulated interactively until all the flux is absorbed, escaped from the canopy, or reaches a small prespecified threshold.

Norman and Wells (1983) designed their Bidirectional General

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Array (BIGAR) model with vegetation canopies in mind. They approximate the canopy by an array of subcanopies in the shape of ellipsoids that may be equally spaced, randomly spaced, or spaced in any manner desired. All of the foliage is contained in these ellipsoids and can be positioned randomly or in a non-random fashion (e.g., different foliage density in the interior of the figure than on its periphery). This density distribution within each subcanopy is chosen to represent the foliage distribution of a real canopy. Each ellipsoid is characterized by its dimensional parameters, location of its centroid, and distribution of foliage inside it. Ellipsoids are allowed to overlap so that the model can be used to simulate 1-D and 2-D vegetation canopies. To calculate the radiation transfer within the canopy, each ellipsoidal subcanopy is divided into a grid of cubical cells.

After assessing the two models, we decided to investigate further the BIGAR model, especially its invertiblity. Dr. John Norman of the University of Nebraska kindly provided us the computer software in which the model was implemented. We developed the software for inverting the model. We tested this model to estimate the canopy parameters for soybean and corn canopies, using the data sets collected and provided to us by investigators at Purdue University. The model seems to allow quite an accurate estimation of important parameters like LAI and percentage of ground cover from canopy reflectance data.

We then tested the model with the data on simulated balsam fir canopies, again collected and provided to us by investigators at Purdue (Ranson, Daughtry, and Biehl, 1986). We modified the BIGAR model software to simulate the spatial locations of subcanopies used during the data collection. Inspite of considerable effort, we failed to fit the model to the data. We could not determine whether deficiencies/errors are in the data or in the model.

The use of BIGAR model to estimate the canopy parameters through its inversion has two shortcomings: (1) Excessive computer time. On a mainframe computer (IBM 4381, model 1), it took several hours of CPU time for a typical inversion. Also, the computer time increases quite rapidly (at least linearly) with the number of cells or grid points used to divide each of the ellipsoidal subcanopies. (2) Discreteness and local trapping. In the iterative inversion process, the canopy architectural parameters are changed in a continuous fashion. However, in BIGAR, because of the discrete grid structure, the canopy reflectance may not change for small changes in the canopy architectural parameters. Since the inversion procedure is based on the gradient of reflectance as a function of canopy parameters, one may erroneously conclude that one has obtained the optimal value of the canopy parameters. In other words, the inversion procedure may get locally trapped.

We, therefore, decided to develop a CR model for 3-D inhomogeneous canopies which can be inverted, using a reasonable amount of computer time, without getting locally trapped.

We have succeeded in developing such a model, dubbed as TRIM, for Three-dimensional Radiation Interaction Model. It is an extension of our model for row-canopies (Goel and Grier, 1986a,b). The details of the model are given in Goel and Grier(1987).

Following, Norman and Welles (1983), in this model, we divide the ground plane in a grid structure, with each cell containing one or more elliptical subcanopies. All the foliage is contained in these subcanopies. By varying the two parameters J and D which represent the two axes of the ellipse (in the horizontal plane), we could represent various staged of growth of the canopy (Fig. 1), including a row-planted vegetation canopy (Fig. 2).

For a one layer canopy, divided into a rectangular grid, the model uses twelve canopy parameters; 7 parameters (leaf hemispherical reflectance ρ , leaf hemispherical transmittance τ, LAI, leaf angle distribution parameters μ and ν defining a beta distribution (Goel and Strebel, 1984), soil hemispherical reflectance ρ_s, and fraction of diffused skylight, SKYL) for the homogeneous (one-dimensional) canopy model, two parameters P and Q defining the grid cell size, two parameters J and D defining the two axes of the ellipsoidal subcanopy and ROAZ, azimuth direction of one of the axes (corresponding to P) of the grid.

In Fig. 3 are given the bidirectional reflectance surfaces generated by TRIM for an early stage of growth (corresponding to Fig. 1(a), LAI = 1.0), at an intermediate stage of growth with (corresponding to Fig. 2, LAI = 3.0), and for a fully covered canopy (corresponding to Fig. 1(d), LAI = 5.0).

We also tested the model to determine its mathematical invertiblity. That is, whether one can obtain all the canopy parameters from the bidirectional canopy reflectance data alone. For this purpose, we chose a set of canopy parameters and used the model to calculate the canopy reflectances for 25 viewing directions. The model was inverted using these reflectances to estimate the canopy parameters. These estimated values were found to be same as those used in generating the CR data, suggesting (though not mathematically proving) the invertiblity of the model.

We also carried out the error analysis of the model, i.e., the errors in the estimation of canopy parameters if the canopy reflectances are randomly changed by a few percent. The overall conclusion of this analysis is that the addition of two canopy architectural parameters (Q and D) in the present model over the row model did not significantly change the accuracy with which one can estimate the LAI and the percentage of ground cover through inversion of TRIM.

We inverted the model using field measured canopy reflectance data on partially covered and fully covered canopies and on a naturally growing shinnery oak canopy (the data was kindly provided to us by Dr. Donald Deering of NASA-GSFC).

We measure the success of TRIM and the inversion technique using two criteria: (1) How well do the estimates of the canopy parameters compare with the corresponding measured values? (2) How well do the calculated CRs (using TRIM with the estimated values of canopy parameters) compare with measured values? On both scores, the model and the inversion technique passed very well. In Figs. 3, 4, and 5 are given the measured and calculated bidirectional reflectance surfaces for partially covered corn, fully covered corn, and shinnery oak canopy. As can be seen from these figures, the calculated reflectances compare very well with the measured ones.

(2) Simple Models for Atmospheric Scattering-Status Report

We initiated the investigation of the atmospheric scattering.

For this purpose, we chose the model recently developed by Verhoef(1985). We chose this model because it is very similar to the SAIL model for canopy reflectance which we have been using in our studies. Further, this model had the potential of inclusion of canopy reflectance in a simple way.

This model is a coupled atmospheric-vegetation canopy radiative transfer model which uses the same four-stream approximation to the radiative transfer equation as used in the SAIL model, both for the canopy and atmospheric scattering. Mr. Verhoef kindly made available to us a computer implementation of the model.

In its present form, the model approximates the atmosphere by two layers. The upper layer (stratosphere) is assumed to contain only ozone. The wavelength dependent optical thickness of ozone is taken from published tables (for an arbitrary wavelength not in the table, piecewise linear interpolation scheme is used). The second layer (troposphere) is assumed to consist of Rayleigh scatterers, aerosols and water vapor. The optical thickness for water vapor absorption is assumed to be proportional to the aerosol optical thickness. For a given aerosol haze, the phase function for aerosol scattering is taken from published tables (for an arbitrary wavelength not in the table, piecewise linear interpolation scheme is used and for a scattering angle not in the table cubic spline interpolation scheme is used). Optical depths for molecular and aerosol scattering are taken from standard tables for the U.S. Standard Atmosphere for several wavelengths, altitudes and visibilities.

Our initial approach was to modify the model to minimize or eliminate altogether the use of tables. For this purpose, we replace the tables-read aerosol scattering phase function by the following two-parameter phase function.

$$p(\theta) = 4\alpha g(1-g^2)^{2\alpha}[(1+g)^{2\alpha}-(1-g)^{2\alpha}]^{-1}(1+g^2-2g\cos\ )^{-(\alpha+1)}$$

Here g is the asymmetry parameter, θ is the scattering angle, and α is another parameter. Using Verhoef's model and the tables of aerosol phase functions for medium haze conditions, we calculated the bidirectional radiance through the atmosphere, for a set of view zenith and azimuth angles and for two solar zenith angles. Using these calculated values, the model, with the above noted analytical phase function, was then inverted. The model fitted the data quite well if the viewing angles are such that solar aureole is excluded (relative azimuth between sun and view directions more than 30^0) and the scattering angles do not include forward scattering ($\theta > 30^0$).

In order to fit the model better, we modified the analytical phase function. We added a term for the forward scattering which is highly peaked at the scattering angle of zero and then drops rapidly. We also made the backscattering coefficient as a parameter. It gave an excellent fit for scattering angles upto 10^0.

We also compared the model against the widely used LOWTRAN model for atmospheric scattering. Dr. Donald Strebel of SAR at NASA-GSFC kindly provided us with atmospheric radiances as calculated from this model for three atmospheric conditions (rural, visibility V = 23 km; rural, visibility V = 5 km; urban, visibility V = 5 km) and three wavelengths (0.5, 0.7 and 1.0 μm). These radiances were used as input into our atmospheric model to determine how close our model represents the LOWTRAN model. The following table summarizes the degree of fit, in terms of percentage difference between the atmospheric radiances as calculated by our model and by the LOWTRAN model.

Atmosph. Condition	Wavelength (in μm) 0.5	0.7	1.0
Rural, V = 23 km	17.2%	6.4%	5.0%
Rural, V = 5 km	39.1%	29.3%	25.4%
Urban, V = 5 km	90.8%	44.6%	41.0%

This table shows that the our model fits the LOWTRAN model better for clearer atmospheric conditions than for the dirtier one, and for a given atmospheric condition, the fit is better in the near-infrared region than in the visible one. This trend is consistent with the physics of scattering; LOWTRAN model includes only single scattering which is a good approximation only for clearer sky conditions and in the near-infrared region.

Significance and Future Activities

The three-dimensional canopy reflectance model, TRIM, which we have developed, and its use in estimating LAI and growth stage of the canopy through its inversion should make any one feel optimistic about the eventual estimability of these parameters from CR data alone, even for naturally growing vegetations. Such an estimation, of course, is the goal of remote sensing. Accurate estimations of these parameters should help in better estimations of water balance and vegetation dynamics, being pursued under the ISLISCP Program, sponsored by NASA.

The atmospheric model, when completed, should enable one to correct for atmospheric scattering, when estimating vegetation characterstics from the remotely sensed data.

We plan to carry out the following activities during the coming year.

(1) Further Development of TRIM

We have validated the model and its use in estimating parameters through its inversion with field measured data only for corn and shinnery oak canopies. We plan to validate it for other canopies, with true 3-dimensional inhomogeneities, such as those found in orchards and sparsely covered forests, assuming that the CR and canopy parameter data for such canopies will become available to us. We anticipate extending the model to allow for random distributions of subcanopies (i.e., make the model stochastic). Other areas which warrant further research are the incorporation of bidirectional properties of soil reflectance, non-lambertian behavior of the vegetation elements, and the "hot spot" phenomenon. Inclusion of these effects, however, will have its price in terms of increasing the number of unknowns in the model, making the process of inversion harder and either increasing the requirements on the number of CR observations or requiring a priori knowledge of some of the ancillary canopy parameters.

(2) Further Investigation into Atmospheric Scattering

We plan to continue development of the simple atmospheric model, by comparing the values for radiances given by this model against those calculated by using other more completed models, such as Dave's model, Gerstl's model, and Diner's model. Using these comparisons, we will make the necessary modifications in the model. At this time, we are unable to specify the exact nature of modifications but we anticipate modification of the phase function.

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Goel, N. S. and Grier, T. (1986b). Estimation of Canopy Parameters for Inhomogeneous Vegetation Canopies from Reflectance Data II. Estimation of Leaf Area Index and Percentage of Ground Cover for Row Canopies. Int. J. Remote Sens., 7:1263-1286.

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INVERSION OF CANOPY REFLECTANCE MODELS FOR ESTIMATION OF VEGETATION PARAMETERS - Narendra S. Goel

Research Papers Published

1. Goel, N. S. and Grier, T. (1986a). Estimation of Canopy Parameters for Inhomogeneous Vegetation Canopies from Reflectance Data I. Two-Dimensional Row Canopy. Int. J. Remote Sens., 7: 665-681.

2. Goel, N. S. and Grier, T. (1986b). Estimation of Canopy Parameters for Inhomogeneous Vegetation Canopies from Reflectance Data II. Estimation of Leaf Area Index and Percentage of Ground Cover for Row Canopies. Int. J. Remote Sens., 7:1263-1286.

3. Goel, N. S. and Grier, T. (1987). Estimation of Canopy Parameters of Row Planted Vegetation Canopies using Reflectance Data for only four View Directions. Remote Sens. Environ., 21:37-51.

Research Paper Submitted for Publication

1. Goel, N. S. and Grier, T. "Estimation of Canopy Parameters for Inhomogeneous Vegetation Canopies from Reflectance Data III. TRIM: A Model for Radiative Transfer in Heterogenous Three-Dimensional Canopies." Remote Sens. Environ. (submitted).

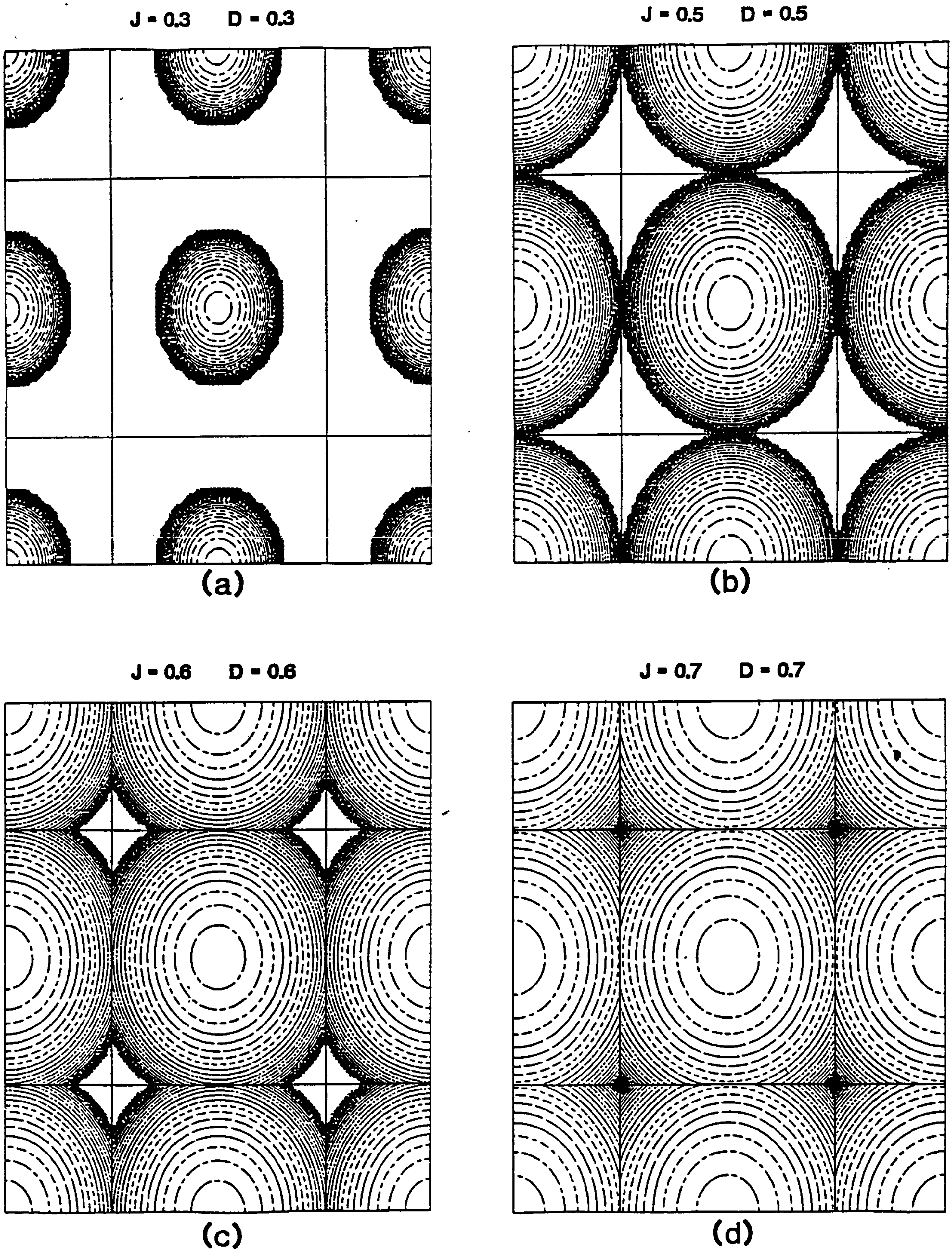


Fig.1

J = 0.3 D = 0.7

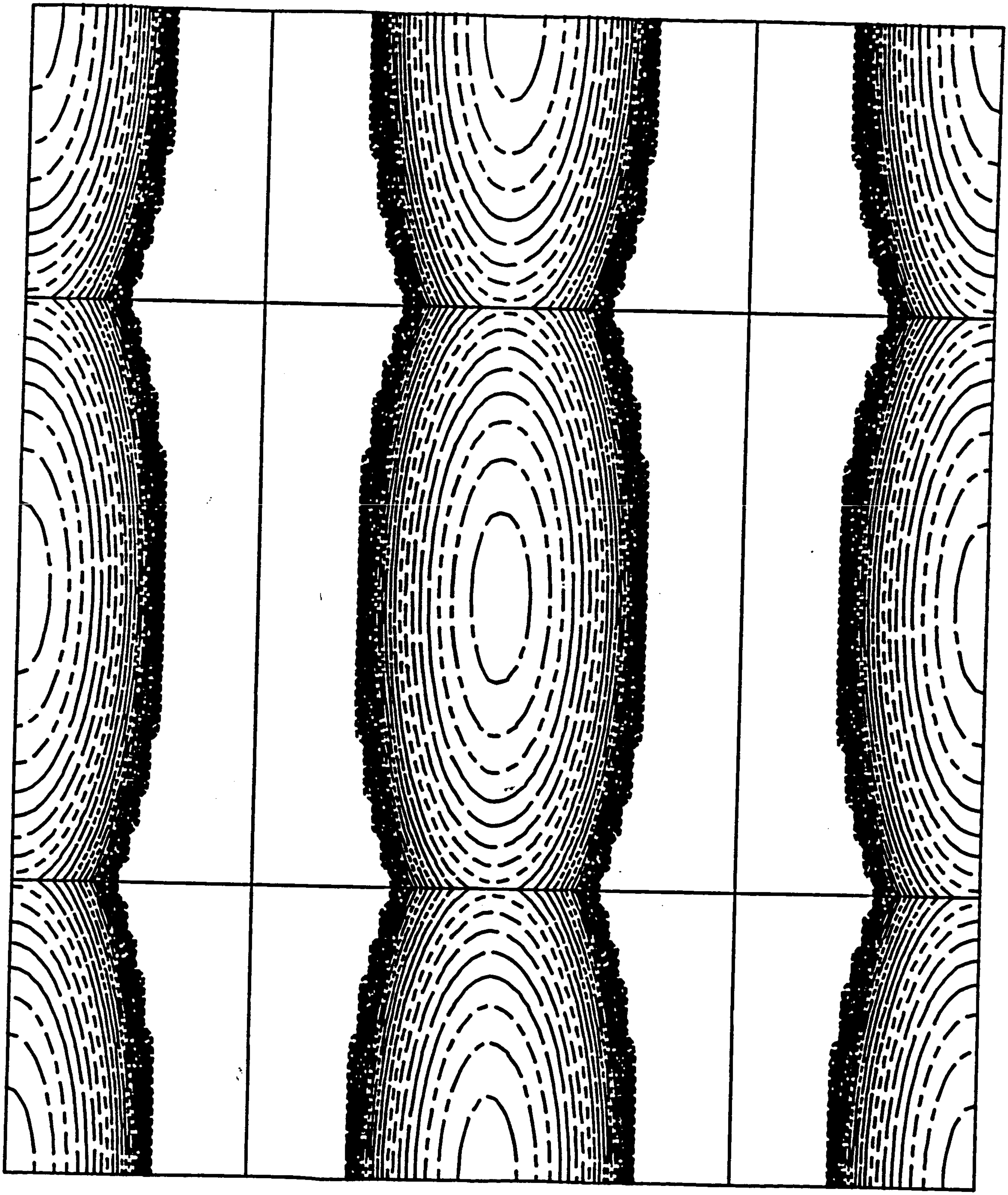
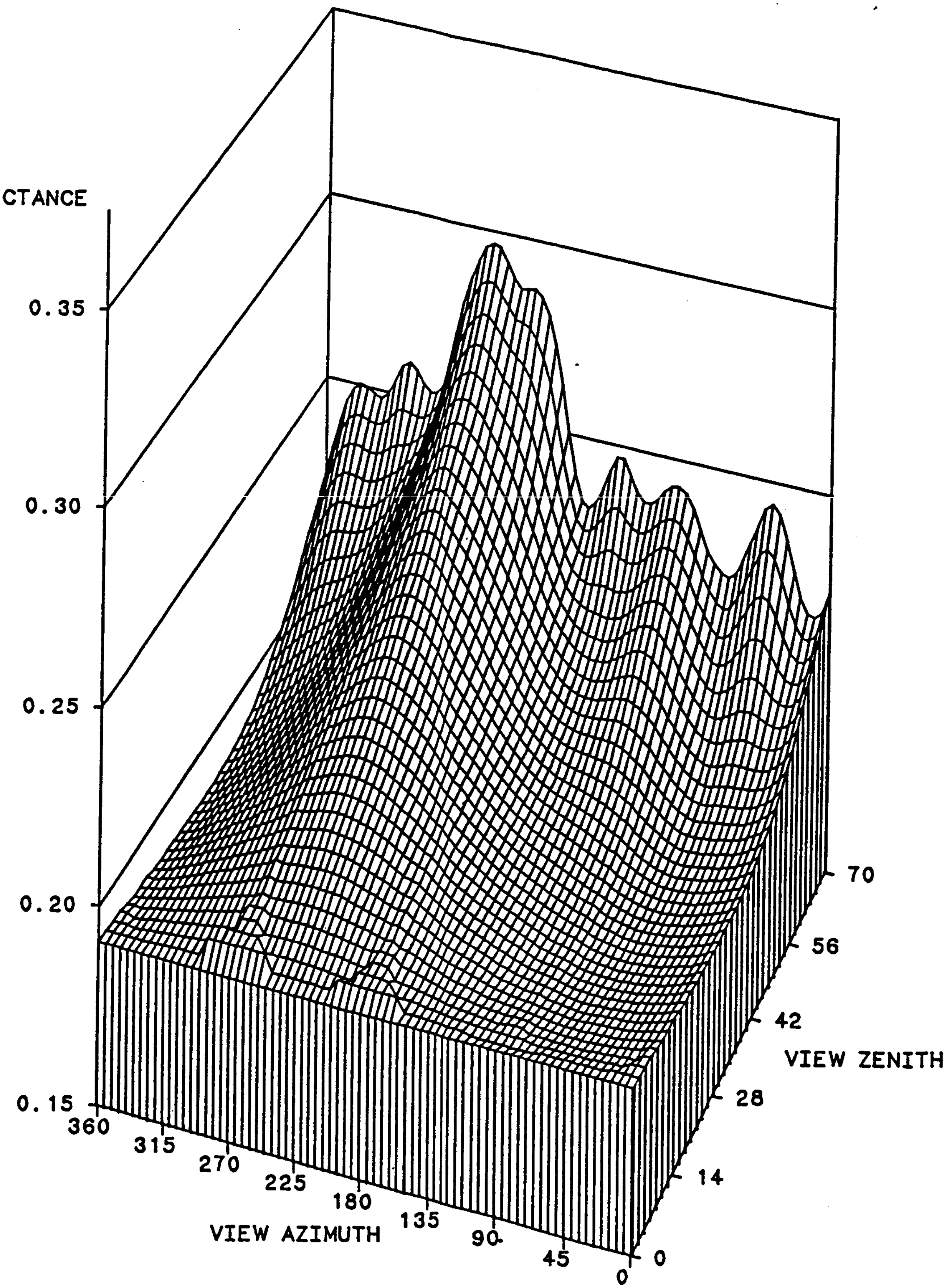


Fig.2

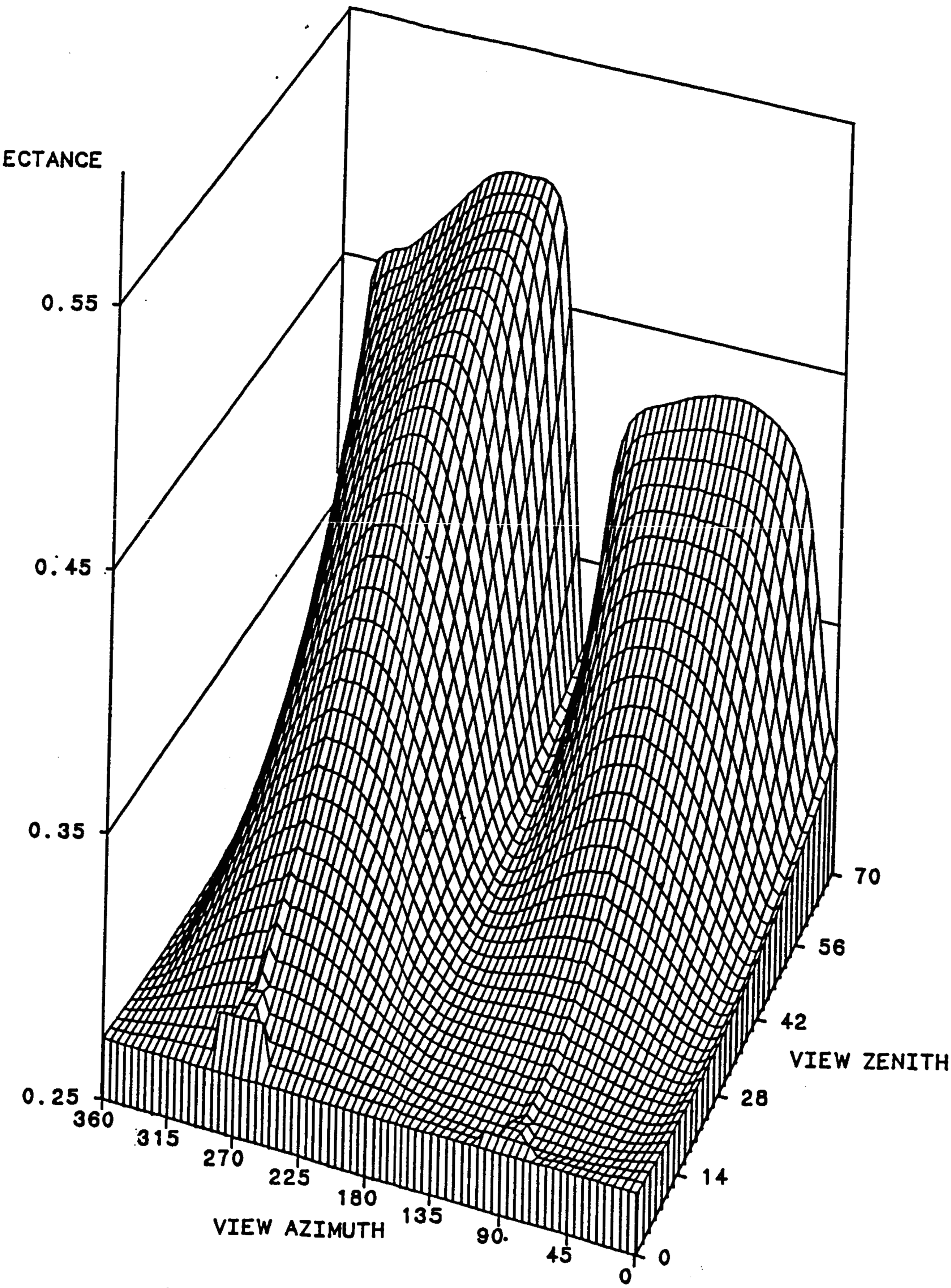
TRIM



SUN ZENITH = 45 DEG.; SUN AZIMUTH = 240 DEG.

Fig.3(a)

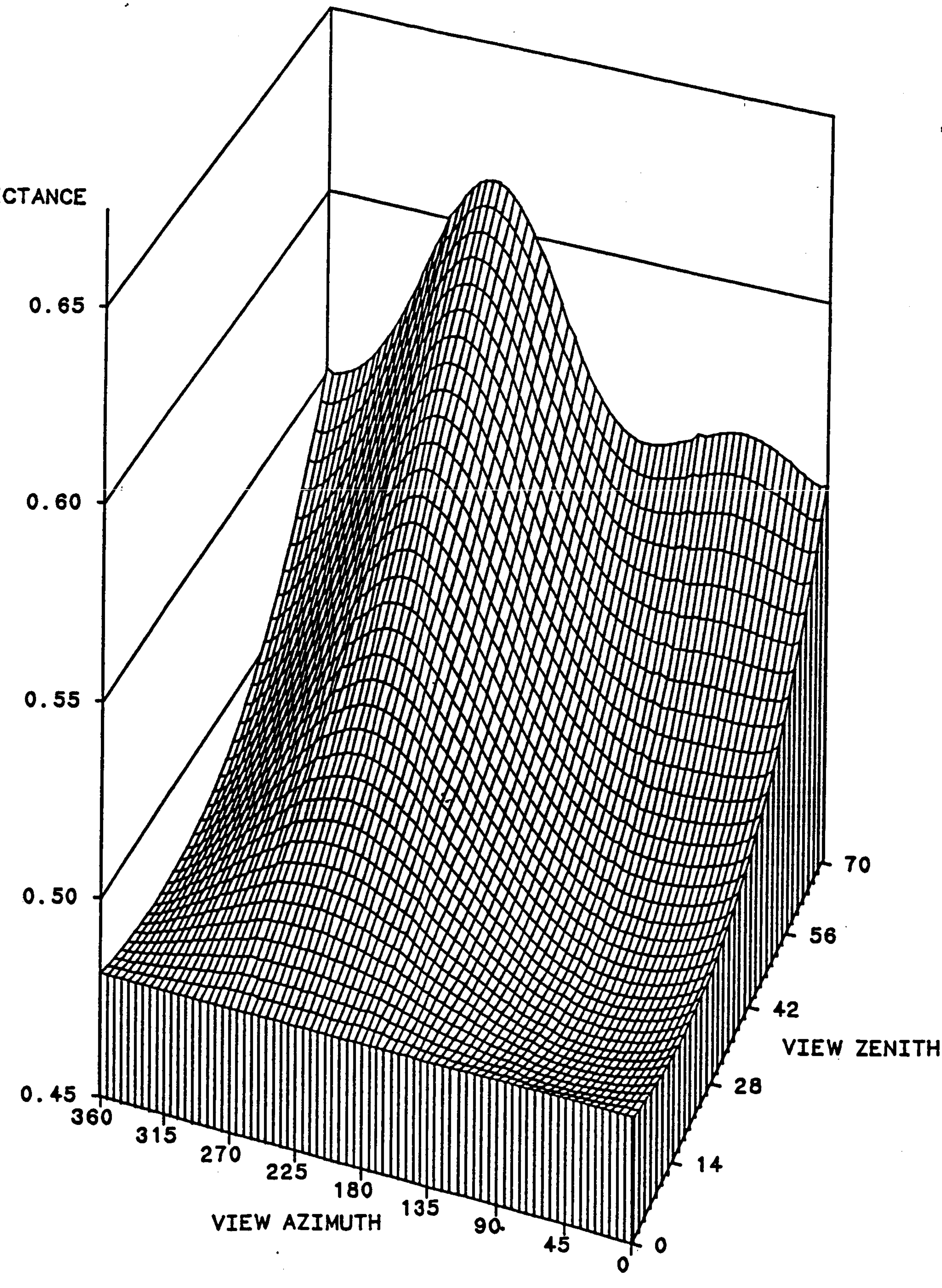
TRIM



SUN ZENITH = 45 DEG.; SUN AZIMUTH = 240 DEG.

Fig. 3(b)

TRIM



SUN ZENITH = 45 DEG.; SUN AZIMUTH = 240 DEG.

Fig. 3(c)

Measured CR

CORN JUNE 24

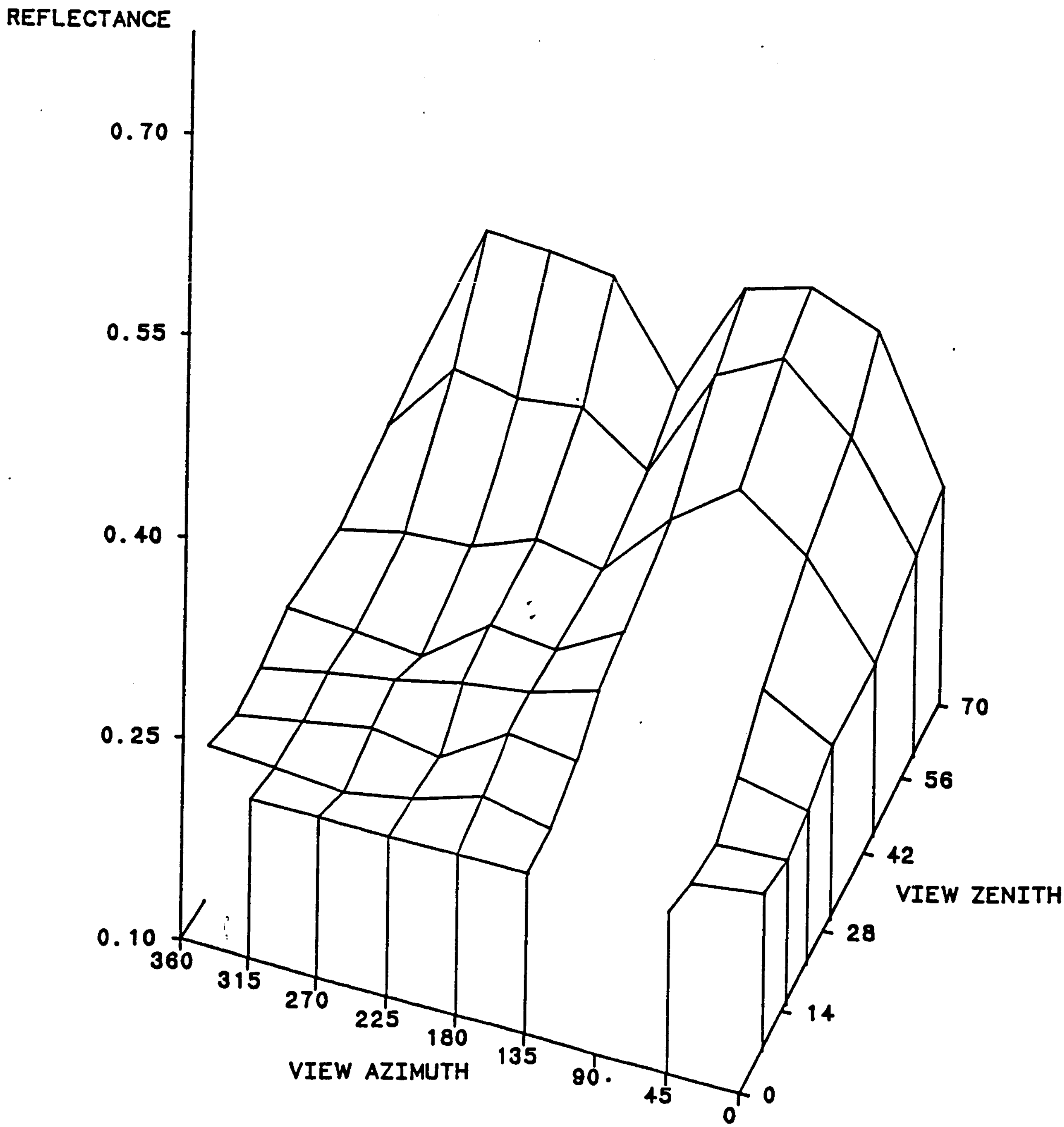


Fig.4(a

SUN ZENITH = 47 DEG.; SUN AZIMUTH = 95 DEG.

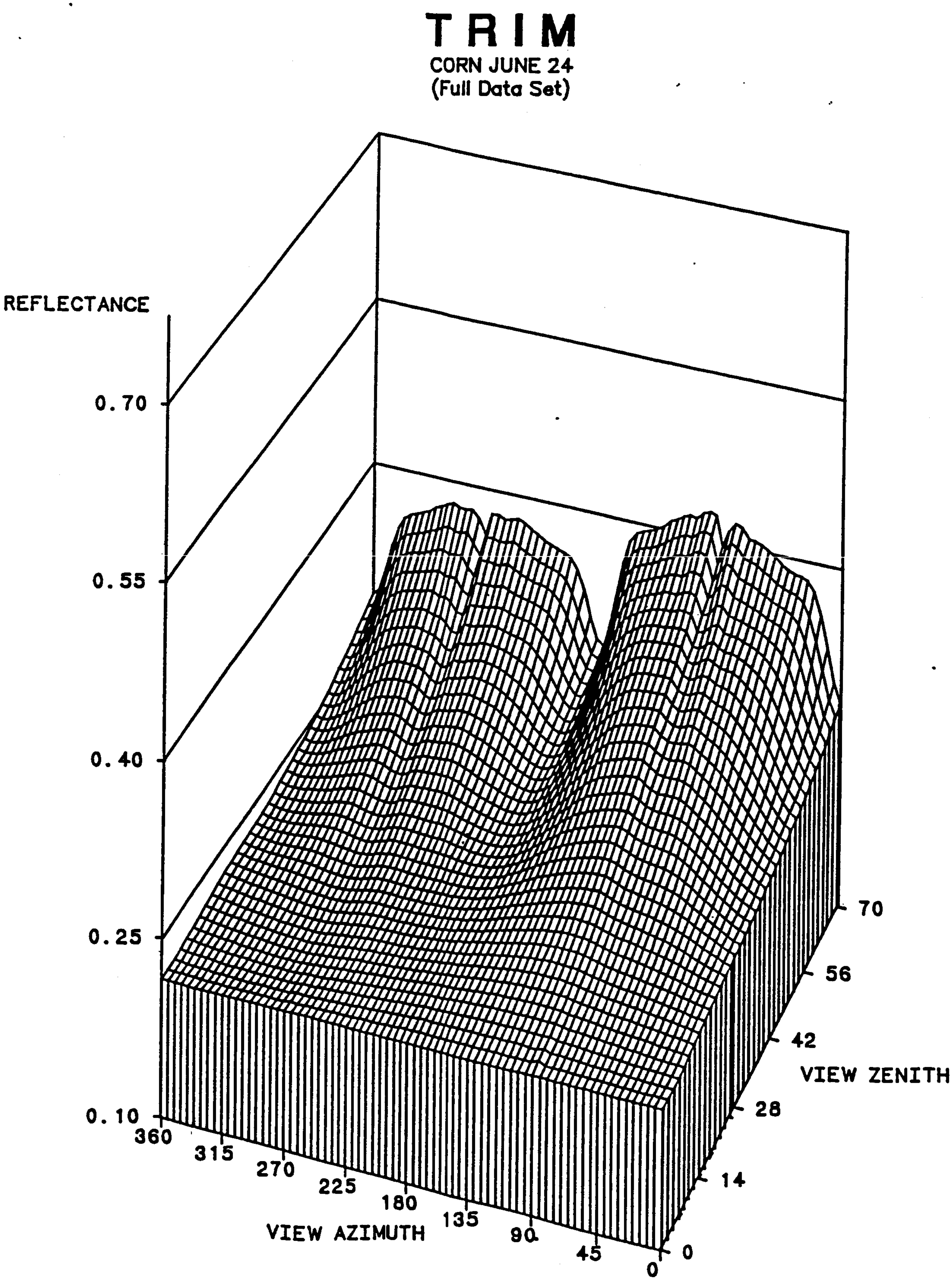


Fig.4(b)

SUN ZENITH = 47 DEG.; SUN AZIMUTH = 95 DEG.

Measured CR

CORN JULY 23

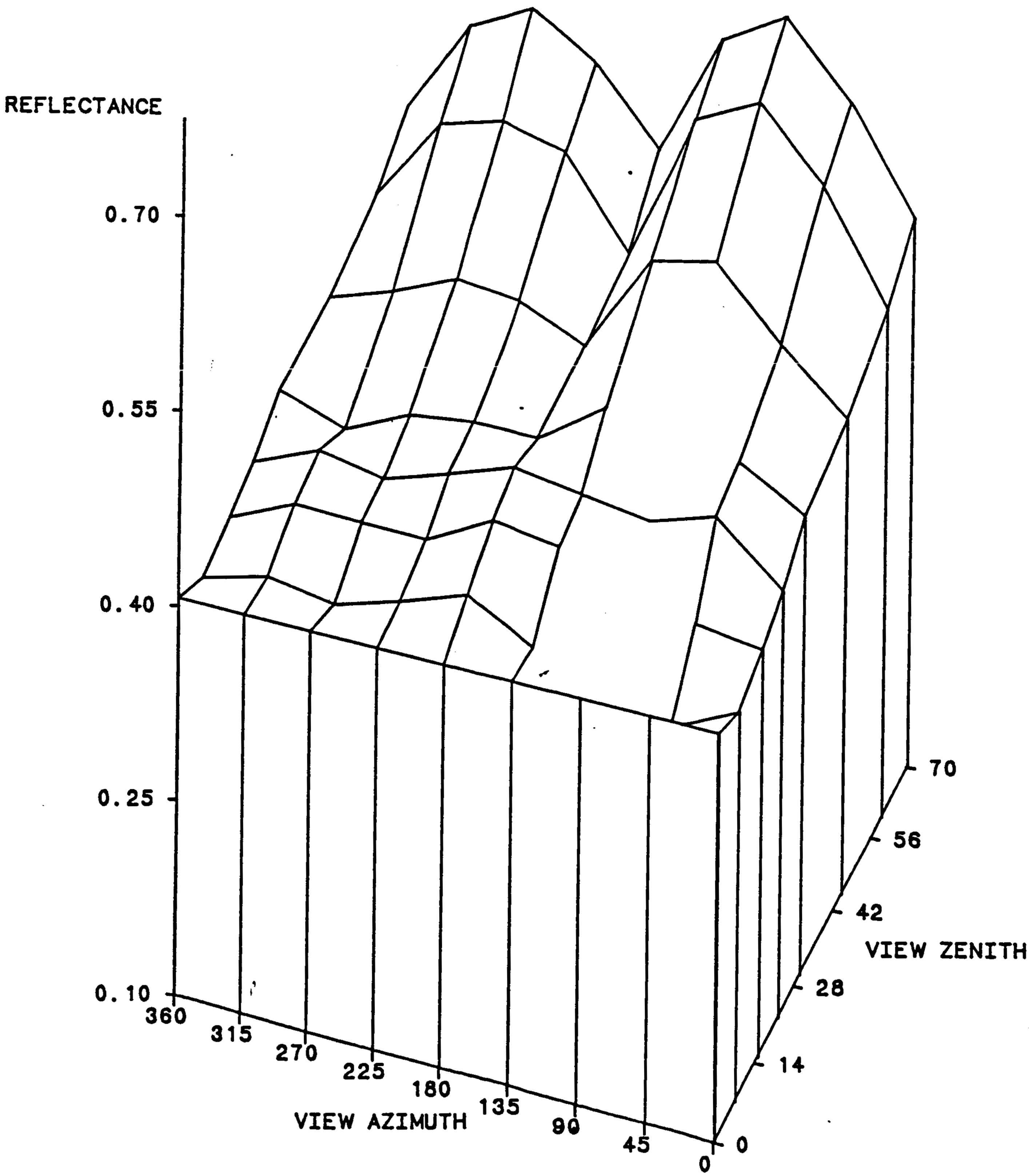


Fig.5(a)

SUN ZENITH = 48 DEG.; SUN AZIMUTH = 99 DEG.

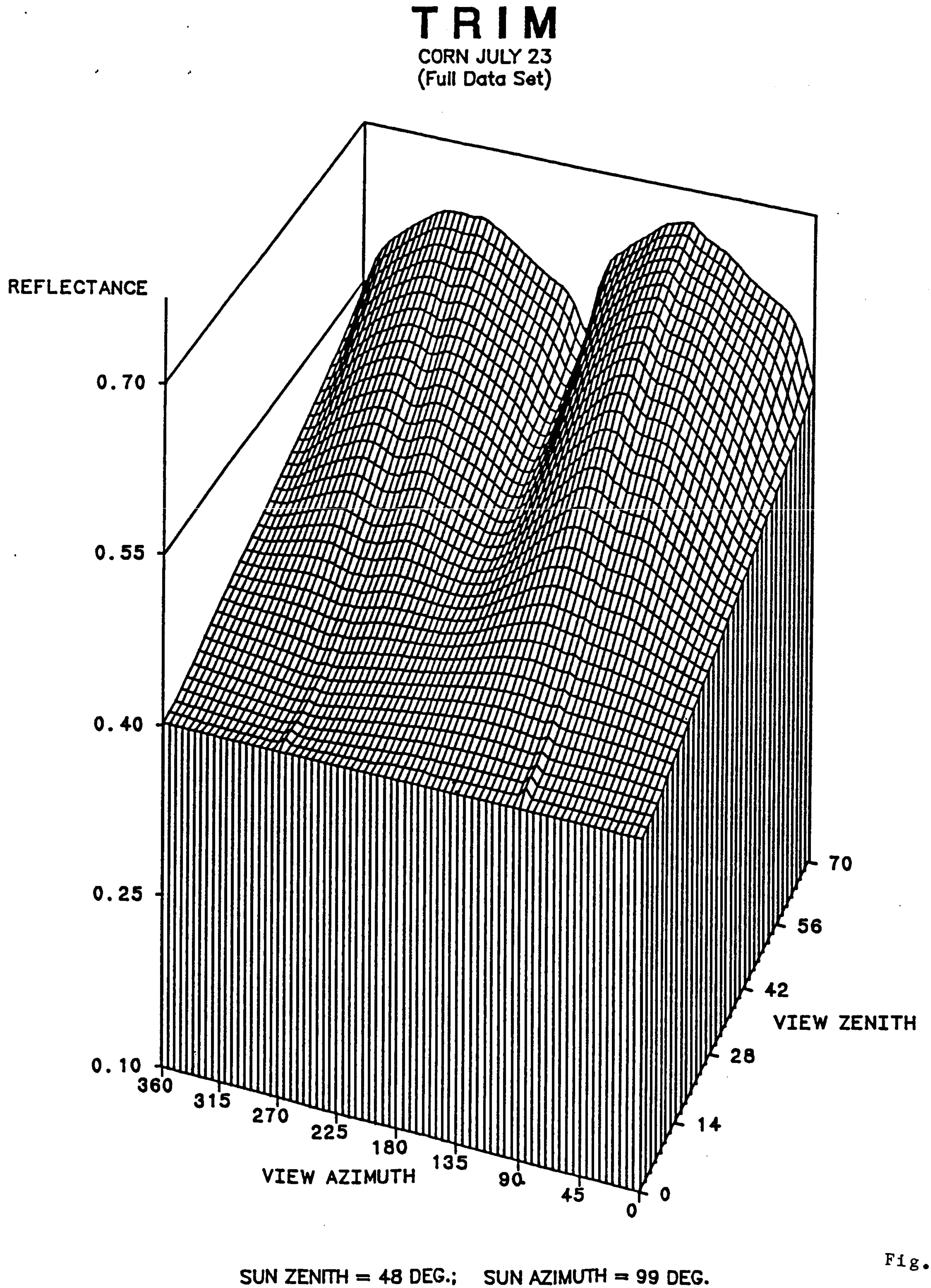
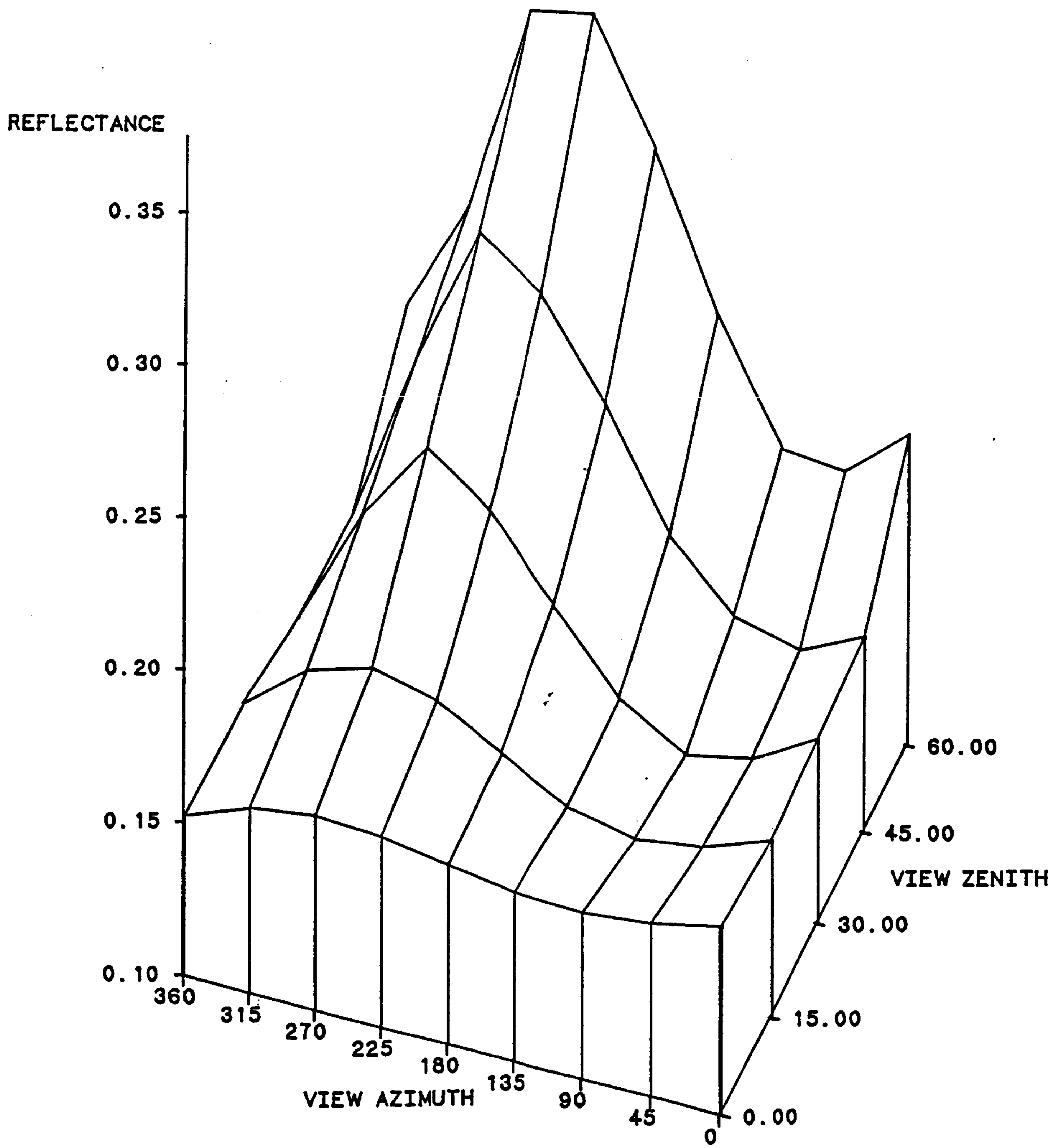

TRIM
CORN JULY 23
(Full Data Set)
REFLECTANCE
0.70
0.55
0.40
0.25
0.10
360
315
270
225
180
135
90
45
0
VIEW AZIMUTH
70
56
42
VIEW ZENITH
28
14
0
SUN ZENITH = 48 DEG.; SUN AZIMUTH = 99 DEG.

Fig.5(b)

Measured CR

Spline Interpolated
SHINNERY OAK JUNE 6

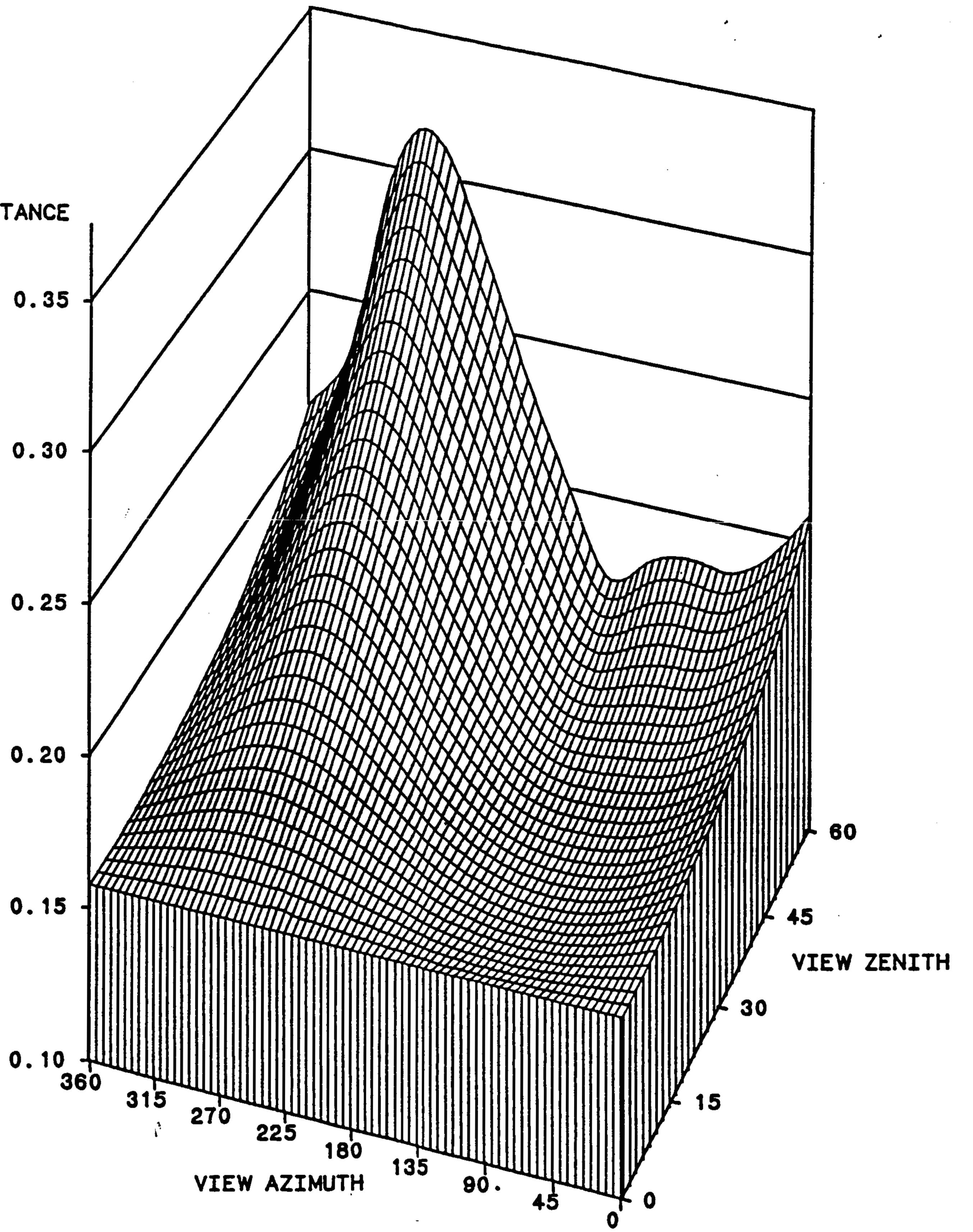


SUN ZENITH = 51 DEG. SUN AZIMUTH = 273 DEG.

Fig. 6a

TRIM

Three-dimensional Form
SHINNERY OAK JUNE 6



SUN ZENITH = 51 DEG.; SUN AZIMUTH = 273 DEG.

Fig. 61