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THESIS

APPLICATIONS FOR THREE-DIMENSIONAL COMPUTER GRAPHIC CLOUD REPRESENTATIONS PRODUCED FROM SATELLITE IMAGERY

Submitted by

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Department of Atmospheric Science

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In partial fulfillment of the requirements

for the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Spring, 1985

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY Arthur C. Meade ENTITLED Applications for Three-Dimensional Computer Graphic Cloud Representations Produced from Satellite Imagery BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF Master of Science

Committee on Graduate Work

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ABSTRACT OF THESIS

Applications for Three-Dimensional Computer
Graphic Cloud Representations
Produced from Satellite Imagery

This research focuses on applications for three-dimensional cloud representations which are displayed above a topographic surface. The computer graphic cloud-topography displays are produced using actual GOES satellite data, Defense Mapping Agency topography data, and rawinsonde upper air data. Data from these three sources is used to generate three-dimensional models which mathematically define cloud cover and topography for a given area. By applying computer graphics techniques, these three-dimensional models can be displayed as continuous tone images or perspective line drawings. Satellite data and topography data, displayed in this manner, produces a realistic depiction of cloud cover displayed above a topographic surface. As for applications, these displays can be used for cloud studies, briefing aids, and flight simulations.

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Spring, 1985

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CHAPTER 1

Introduction

In recent years, computer driven image processing systems have been developed which combine computer technology with graphics technology to produce systems capable of displaying a wide variety of digital imagery. As a result, many graphics software packages have been designed to support these systems. Some of the more advanced graphics software packages are capable of displaying three-dimensional (3-D), mathematically defined models as continuous tone images or perspective line drawings. In the work covered by this thesis, computer graphics technology is applied to produce integrated cloud-topography displays from actual GOES satellite data and topography data. In order to do this, clouds and topography have to be mathematically defined in three dimensions.

In this research process, two-dimensional (2-D) satellite images and 2-D topographic images are used to produce 3-D, mathematically defined, cloud-topography models. High resolution (512 x 512), topographic images are produced which represent the earth's terrain over a 4.27 x 4.27 degree area. These topographic images, mapped in a Mercator projection, can be produced for all areas in the continental United States. GOES infrared and visible images, remapped into a

Mercator projection, are produced which represent cloud cover data over the same 4.27 x 4.27 degree area. These Mercator projection images accurately overlay each other. By displaying these images in succession using an image processing system, cloud cover and cloud features can easily be associated with effects from underlying topographic features. More importantly, by having these images accurately overlay each other, cloud cover information can be obtained with respect to topography. Information, contained in the above Mercator projection images, plus rawinsonde upper air data is used to mathematically define 3-D cloud-topography models for sub-areas within the 4.27 x 4.27 degree areas. These 3-D cloud-topography models represent the cloud cover and topography within the given sub-area and can be displayed using MOVIE.BYU software.

MOVIE.BYU is a graphics software package which was developed at Brigham Young University. It is used in this research to manipulate, rotate, illuminate, and display these mathematical models using the VAX 11/780 computer and the COMTAL image processing system. MOVIE displays these 3-D models on the COMTAL as either continuous tone images or perspective line drawings.

Three-dimensional cloud-topography models, displayed by MOVIE, create a realistic depiction of cloud cover above a topographic surface. Because of the display's enhanced information content and visual appeal, this thesis focuses on applications for satellite data displayed in this manner. Applications described in this thesis include: cloud studies, briefing aids, and flight simulations. The following five chapters discuss the data, recources, software, and methodology used to create the 3-D cloud-topography model. Chapter 7 describes the applications for these models. Included are examples which illustrate how the cloud-topography model can be used. Finally, Chapter 8 contains a summary of work covered by this research. Suggestions for improvement are included along with suggestions for future work in this area.

CHAPTER 2

Data

Three data sources are used to create the 3-D cloud-topography models. These include: Defense Mapping Agency topography data, rawinsonde upper air data, and GOES satellite data. These data sources along with data acquisition procedures are described in the following sections.

A. Topography Data

The Defense Mapping Agency (DMA) read elevation data from 1:250,000 scale topographic maps for every 30 seconds of latitude and longitude in the continental United States, parts of southern Canada, and parts of northern Mexico. Individual elevations within this data set were read in feet, to the nearest increment of 20. These values represent elevations at specific geographical points and are not average values.

The magnetic tape containing this data was obtained from the National Center for Atmospheric Research (NCAR). The tape consists of 1099 tape blocks, each of which, contains all the elevation data for a 1 x 1 degree square. Data is included for a region from 23°N to 51°N and from 130°W to 60°W. The tape blocks are organized starting in the southwest corner of the region, scan eastward to the eastern boundary, then 1 degree north from the start and eastward again. A total of 28 of these west-east scans are made. Tape blocks which only contain sea level data are omitted. Figure 2-1 shows regions where topography data is available.

Each tape block contains a latitude and longtiude followed by 14641 consecutive elevations. The latitude and longitude specify the geographical location of the 1 x 1 degree squares. The elevations contained in a tape block are organized starting in the southwest corner of the 1 x 1 degree square, scan eastward to the eastern boundary of the 1 x 1 degree square, then move 30 seconds north from the start and eastward again. A total of 121 west-east scans are made. Boundary values in each 1 x 1 degree square are repeated in adjacent 1 x 1 degree squares (Joseph, 1982).

B. Rawinsonde Data

The National Weather Service (NWS) maintains a network of rawinsonde stations which send rawinsondes aloft twice daily at 0000 GMT and 1200 GMT. These rawinsondes contain an instrument package and a radio transmitter. The instrument package contains instruments which measure temperature, pressure, and humidity throughout the troposphere and lower stratosphere. As the rawinsonde ascends through the atmosphere, the radio transmits these measurements back to the station where the measurements are recorded, encoded, and transmitted to users. Rawinsonde data, collected in this manner, is divided into two types: mandatory level data and significant level data.

Mandatory level reports contain observations from ten specific atmospheric pressure levels: 1000, 850, 700, 500, 400, 300, 250, 200,

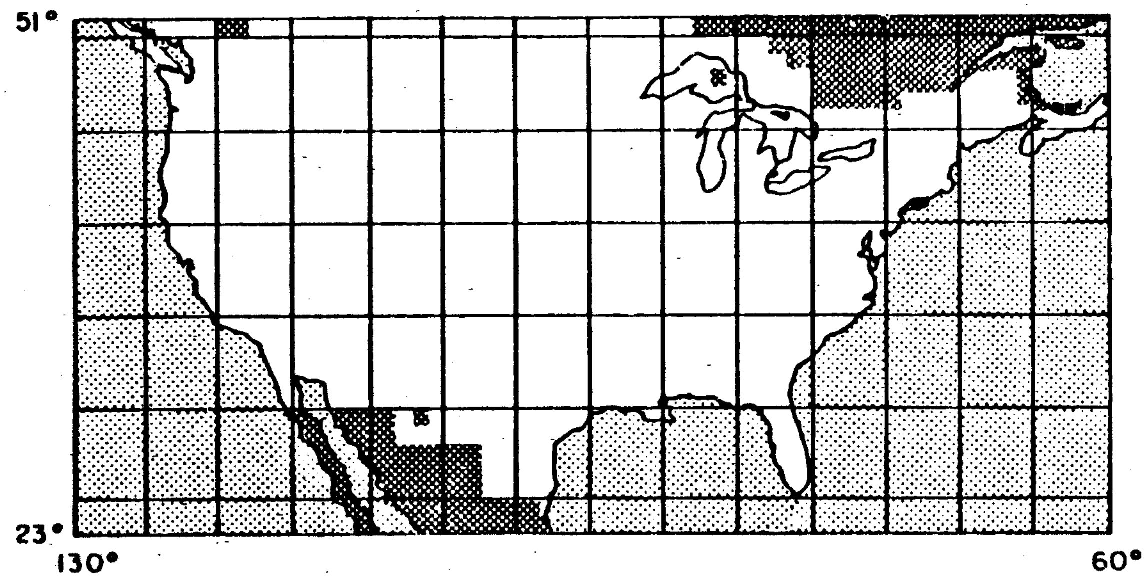

Figure 2-1
Available topographic data
(adapted from Joseph, 1982)

150, and 100 mb. For each level, temperature, wind direction and speed, dew point depression, and height of the pressure surface are reported. In addition, surface information and tropopause information are included in the reports.

Significant level reports contain data for any level where important changes in the temperature, humidity, and wind profiles occur. This report contains two sections, one for reporting temperature and humidity, and the other for reporting wind profiles.

The CSU Atmospheric Science Department receives this data from the FAA604 weather circuit. The data is received via a three-meter antenna, processed by the VAX 11/780 computer, and stored on disk. In this research, only mandatory level data is used.

C. Satellite Data

The National Oceanographic and Atmospheric Administration (NOAA) operates two geostationary meteorological satellites (GOES) which orbit the earth at an altitude of 35000 kilometers above the earth's equator. Since the satellites orbital period is synchronous with the earth's rotation rate, the satellites remain stationary relative to fixed locations on earth. One satellite is positioned near 75°W longitude and given the designation of GOES-East. The other is positioned near 135°W longitude and designated as GOES-West (Epstein et al., 1984). Currently, GOES-East is not operational and GOES-West is positioned near 110°W longitude.

The instrument flown aboard the GOES satellite is the Visible Infrared Spin Scan Radiometer (VISSR). The VISSR consists of a mirror that is stepped to provide north-south viewing of the earth while satellite rotation provides west-east scanning. The mirror is stepped one notch following a west-east scan. A total of 1821 of these west-east scans make up a full frame image of the earth. Normally, a complete full frame image is scanned every 30 minutes, 24 hours a day, seven days a week.

Radiation received by the mirror is reflected into a 16-inch diameter telescope. A fiber optics bundle is used to couple the telescope to eight visible band detectors sensitive to visible radiation (.54 - .70 μm). Germanium relay lenses are used to pass infrared radiation through optical filters, providing a 10.5 - 12.6 μm band pass, to the infrared detector.

The visible detector has a nominal resolution of about one kilometer while the infrared detector has a resolution of only about eight kilometers. The infrared data is oversampled in the west-east scan. As a result, the sampling resolution is four kilometers in the west-east direction. Therefore, at the sub-satellite point, visible data has a one kilometer ground resolution and infrared data has a 8 x 4 kilometer ground resolution (Hord, 1982). Ground resolution decreases away from the sub-satellite point due to the curvature of the earth.

Output from the infrared and visibile detectors is digitized on the satellite and transmitted to a satellite ground station at Wallops Island, Virginia. There, navigation parameters are added. The data is formatted, calibrated, and retransmitted back to the satellite for relay to other users.

As the data is relayed, the CSU Atmospheric Science Department's Direct Satellite Readout Ground Station (DSRGS) collects, processes, and stores this data. The DRSGS basically consists of the following components: two dish antennas to receive the data, two PDP 11/34 computers to process the data, and three disks to store the data. A ten-meter dish antenna is positioned to receive data from the GOES-West satellite and a five-meter dish antenna is positioned to receive data from the GOES-East satellite. In normal operational mode, only one DEC PDP 11/34 computer is needed to process this data since GOES-East data is transmitted on the hour and half hour, while the GOES-West data is transmitted at 15 minutes past the hour and 45 minutes past the hour. The other DEC PDP 11/34 is used as a backup to insure data collection continues if one of the components within the system fails or needs maintenance. Data received by DRSGS can be stored on disk, 9-track magnetic tape, or transferred to the IRIS system where the data can be displayed (Laybe, 1983). A block diagram of the DRSGS/IRIS system is shown in Figure 2-2.

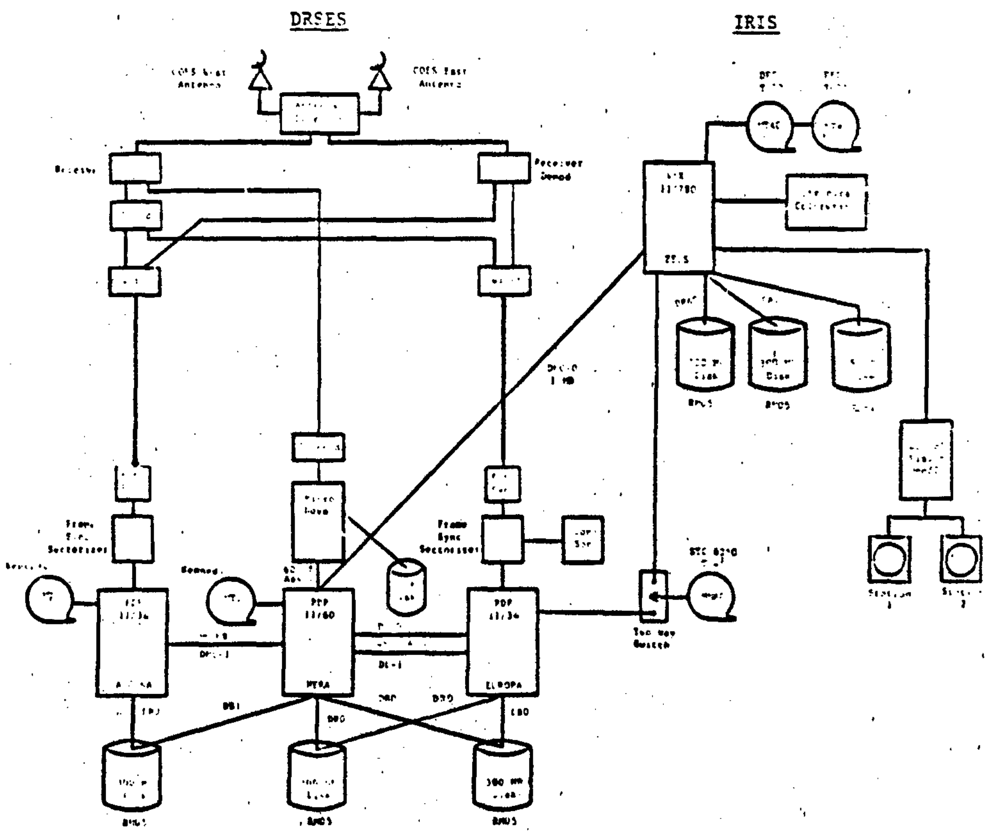

Figure 2-2
Block diagram for DRSGS/IRIS system

CHAPTER 3

Interactive Research Imaging System (IRIS)

The Interactive Research Imaging System provides the data manipulation capability and the image processing capability to create and display 3-D cloud-topography models. The Interactive Research Imaging System consists of two main components, the VAX 11/780 computer and the COMTAL Vision One/20 image processing system. Since these two resources were used extensively in the research process, they warrant further explanation. In addition, a description is included on how these resources are used to display the 3-D cloud-topography models.

A. VAX 11/780 Computer

At the heart of the Interactive Research Imaging System (IRIS) is the DEC VAX 11/780 computer. This mid-size computer features a 32-bit processor which possesses sufficient computing speed for many meterological and image processing applications. Perhaps the VAX 11/780's most attractive feature is the VAX/VMS Operating System. This operating system allows very large programs to run efficiently by using a virtual memory system. With this system, the VAX 11/780 uses disk storage to extend main memory onto disk. To the user, it appears the systems main memory is unlimited in size (Staff, Digital Equipment Corporation, 1982).

The CSU Atmospheric Science Department's VAX 11/780 is configured with 3 megabytes of main memory along with 1.1 gigabytes of disk storage capacity. Two DEC TU77 tape drives provide additional storage capacity in the form of a 9-track magnetic tape and provide a medium to enter data onto the system. A communication link from the VAX 11/780 to the DRSGS's PDP 11/60 provides a means by which satellite data, collected by DRSGS, can be transferred to IRIS. Another link from the VAX to the COMTAL Vision One/20 image processing system provides a means to display data received from the DRSGS. One additional link from the VAX to the Colowrite C-4300 (Optronics) provides a means to obtain hard copy, high resolution, color transparencies of imagery displayed on the COMTAL monitor. A block diagram of the DRSGS/IRIS system is shown in Figure 2-2.

The CSU VAX 11/780 supports two high level languages, VAX FORTRAN and VAX PASCAL, and one assembly level language, VAX-11 Macro. All software used to create and display the 3-D cloud-topography model is supported by VAX FORTRAN.

B. COMTAL Vision One/20

Another key component of the IRIS system is the COMTAL Vision One/20 image processing system. This system produces high resolution (512 x 512) imagery over a full range of brightness values in shades of grey or pseudocolor. Although the COMTAL Vision one/20 is a standalone system which performs a multitude of image processing operations by itself, it can be interfaced with the VAX 11/7C0 as host. This feature gives the COMTAL/VAX configuration exceptional image processing and display capability.

Digital imagery (i.e. imagery which is obtained by partitioning the area of one image into a finite two-dimensional array of small, uniformly shaped, mutually exclusive regions called pixels) can be created and displayed on the COMTAL monitor using an image plane (512 x 512 x 8 bits). By assigning 8 bits to each pixel in an image plane, 256 (2^8) grey shades are possible. These images can be displayed on the COMTAL monitor as monochrome images or as pseudocolor images.

Monochrome images, defined by eight pixels, can show 256 levels of greyness. Each pixel making up the image can be black (pixel value = 0), white (pixel value = 255), or any level of greyness in between.

Pseudocolor images are obtained by arbitrarily adding color to the monochrome images. These pseudocolor images are produced by the COMTAL's pseudocolor processor. This processor accesses a red, green, and blue pseudocolor memory which, when activated, produces signals to the red, green, and blue guns in the color monitor. Each of the pseudocolor memories contain 256 8 bit locations which correspond to a level of greyness in the monochrome image. Each location in a pseudo-color memory contains a value from 0-255 specifying the intensity of the color produced by the gun. When the memories are activated by the pseudocolor processor, the values of pixels making up the monochrome image are indexed into the red, green, and blue pseudocolor memories. Then, the red, green, and blue guns are each fired at the specified intensity creating a pseudocolor image by exciting a combination of red, green, and blue phosphors on the screen.

A digital image can also be represented by a graphics plane (512 x 512 x 1 bits). Since each pixel is specified by only one bit, two

(2^1) grey shades are possible. A pixel represented in this way appears either black (pixel value = 1) or white (pixel value = 0). Digital images which are defined in this manner are termed "COMTAL graphics" or "graphics". These graphics often contain line drawings, grid lines, or labels. Since the COMTAL stores a color attribute for the graphic as a whole, an entire graphic can be set to any of 16 colors. Another COMTAL feature allows the user to overlay a graphic on a monochrome or pseudocolor image. This capability gives the user the ability to label and grid monochrome and pseudocolor images without destroying any of the images original information content (Staff, COMTAL Corporation, 1982).

C. Display Methods

The VAX/COMTAL systems are used to display the 2-D Mercator projection imagery and the 3-D cloud-topography models. This section describes how the two systems are used to produce these displays.

Mercator projection images are created on the VAX 11/780 computer and displayed on the COMTAL as a monochrome images. In this thesis, these images often appear with one or more COMTAL graphics overlaid onto the monochrome image. These graphics contain either labels, state boundaries, or other representations.

Cloud-topography models are created on the VAX 11/780 computer and displayed on the COMTAL as pseudocolor images, COMTAL graphics, or a combination of both. A 3-D model displayed as a pseudocolor image contains a continuous tone representation of the model. A 3-D model displayed as a COMTAL graphic contains a contour line respresentation of the model. Most of the cloud-topography displays appearing in this thesis were displayed on the COMTAL monitor as a pseudocolor image overlaid by one or more COMTAL graphics. When displayed as a pseudocolor image, topographic bases are colored green and cloud representations are colored white. To increase the display's perspective, contour lines, which are written to a COMTAL graphic, are overlaid onto the pseudocolor image. The COMTAL graphic overlaying the clouds is colored white, while the COMTAL graphic overlaying the base is colored green. This display method increases the display's perspective and visual appeal, plus adds a grid to the topographic base for quantitative scaling.

CHAPTER 4

Software

An extensive amount of software was used in the process of creating and displaying the 3-D cloud-topography models. Software falls into three main groups: IRIS Software, MOVIE.BYU Graphics Software, and User Software which was written by the author. The major programs within each group are discussed with respect to purpose and function.

A. IRIS Software

IRIS applications programs are designed to process, manipulate, and display satellite data received by the Direct Readout Satellite Ground Station (DRSGS). These programs are executed using the Transportable Applications Executive (TAE). TAE is a set of executive programs which interact with the user to manage the execution of applications programs. The main advantage of TAE is that it provides a menu driven, user friendly means to run applications programs. TAE is also interfaced with an IRIS data base. This data base is used by the applications programs to store satellite image navigation parameters, image file attributes, and other information describing satellite data sets. In this research, IRIS applications programs are used: 1) to create digital images from raw satellite data, 2) to display the digital images on the COMTAL, 3) to create IRIS data base entrys defining image attributes, and 5) to plot geopolitical boundaries on COMTAL graphics. Applications programs performing these functions are described below.

CSUGOES

Raw GOES satellite data, which has been received by the DRSGS, is read from either disk or magnetic tape and processed by the CSUGOES program. This program produces image files which can be displayed on the COMTAL monitor. With each image file, automatic navigation parameters are also read into the IRIS data base.

WINDOW

Data processed by CSUGOES can be displayed on the COMTAL by the WINDOW program. WINDOW creates a sub-image by extracting a subset of data from an exisiting image. The program modifies the apparent resolution of the data to make the sub-image fit exactly into a 512 x 512 image plane. If the original image was smaller than 512 x 512 pixels, WINDOW can be used to expand the image to fit into the 512 x 512 image plane. If the original image is larger than 512 x 512 pixels, WINDOW shrinks the image to fit into the 512 x 512 image plane. The resulting sub-image is displayed on the COMTAL monitor.

REMAP

Satellite data which has been processed through CSUGOES can be remapped into various projections using the REMAP program. In this research, REMAP is used to remap satellite data into Mercator projection images covering a 4.27 x 4.27 degree area. These remapped Mercator projection images can be displayed on the COMTAL monitor by using WINDOW.

DEFSCT

DEFSCT is used to define output image file attributes for the REMAP program. Parameters entered into the DEFSCT program define the location of the 4.27 x 4.27 degree area for the output image file. Other parameters define the projection of the output file. These parameters are stored in the IRIS data base.

GPPLOT

Images which are displayed on the COMTAL can be gridded by plotting geopolitical boundaries on them using the GPPLOT program. These boundaries are usually written to a COMTAL graphic.

B. MOVIE.BYU Software

MOVIE.BYU is a general purpose graphics package used to create, manipulate, and display 3-D mathematical models. The software package consists of a total of seven programs, of which, only DISPLAY was used in this research. DISPLAY is the largest and most sophisticated program in the package and, as the name implies, is used to display the 3-D cloud-topography models.

DISPLAY

The particular version of DISPLAY used in this research was obtained from the CSU Electrical Engineering Department. This version was originally configured to interface with the RAMTEK 9050 graphics device. Since no RAMTEK devices were available at the CSU Atmospheric Science Department and no COMTAL interfaces were commercially available, DISPLAY was modified to interface with the COMTAL.

Three-dimensional, mathematically defined models can be manipulated and displayed using the DISPLAY program. Models are made up of a series of three and four sided polygonal elements which are used to define model surfaces. Each element consists of three or four nodes which represent intersection points where the sides of the elements meet. To define a model, the X, Y, and Z coordinates of each node in the model must be defined and stored in a coordinate array. To complete the model description, the exact sequence in which nodes are to be connected to form polygons must be specified and stored in a connectivity array. A model can further be broken down into parts. Parts may be defined by grouping contiguous polygonal elements. These groups are specfied and stored in a parts array. The coordinate array, the connectivity array, and the parts array completely describe the model mathematically and are stored in a geometry file.

Models described in the above manner can be viewed on the COMTAL monitor using DISPLAY. When displayed, models appear as either continuous tone images or perspective line drawings. A total of 39 interactive commands are available to the user to specify how the model is to be displayed. The SCOPE command is used to specify the output device and to specify whether the model is to be displayed as a continuous tone image or perspective line drawing. The PARTS command allows the user to withhold model parts from the display. Other commands are available to manipulate the model. The ROTATION, TRANSLATION, FIELD, and DISTANCE commands allow the user to view the model from virtually any position. Still other commands allow the selection of color and shading for continuous tone imagery. The COLOR command is used to specify colors by part along with background color. Colors are specified as mixtures of the three primary colors, red, green, and blue. Model illumination can be specified by the LIGHT command. Up to four light sources can be arbitrarily defined in space. The VIEW command is used to display the model on the COMTAL color monitor (Christianson and Stephenson, 1981).

C. User Software

A total of eight user programs are used in this research. Seven of them are used to create the 3-D cloud-topography models. The other program is used to illustrate an application for the cloud-topography model. User software is compatable with both the MOVIE.BYU Graphics Software and the COMTAL image processing system. These eight programs are described briefly below.

DMA512

DMA512 is a user interactive program used to create 2-D, Mercator topographic images. These images represent the earth's terrain and cover a 4.27 x 4.27 degree area. The exact location of the area covered by the topographic image is specified by entering a reference latitude and longitude which defines the northwest corner of the 4.27 x 4.27 degree area. After the reference latitude and longitude is specified, DMA512 extracts the appropriate elevation data from the DMA data tape, scales the data, and formats the data as a 512 x 512 COMTAL image. This COMTAL image is written to an output file. Scaling parameters are also written to this file. Information contained in this image file is later used by another program to mathematically define 3-D topography models.

SHIFTR

After the REMAP program is used to create a Mercator satellite image, the resulting image may not exactly overlay the Mercator topographic image. If a better fit is desired, SHIFTR can be used to shift or translate a satellite image left or right, up or down, a specified number of pixels. The left-right shift is specified by a number, X. A positive value for X shifts the image to the right X pixels while a negative value shifts the image left. Similarly, the up-down shift is specified by a number, Y. A positive value for Y shifts the image up Y pixels while a negative value shifts the image left. The resulting image is shifted the specified number of pixels.

DEFINE

DEFINE is a user interactive program which is used in the process of generating a 3-D cloud-topography model. DEFINE is used: 1) to display Mercator images on the COMTAL monitor, 2) to specify input and output file names used in the process, and 3) to specify parameters which define a sub-area of a Mercator image to be transformed into three dimensions. DEFINE writes these file names and parameters to an output file. By having this data in a file, it can be accessed by other programs which are used in the process. This alleviates the need to enter file names and parameters more than once.

INTCLD

INTCLD is a user interactive program designed to produce cloud layer files. These files contain cloud top height information and cloud base information which defines cloud cover for the specified sub-area of a Mercator satellite image. INTCLD is used: 1) to determine cloudy and clear pixels within a sub-area of a Mercator satellite image, 2) to determine cloud top heights for cloudy pixels, and 3) to determine cloud base heights for cloudy pixels. INTCLD produces three cloud layer files, each of which, represents cloud cover for a layer in the atmosphere. Information contained in these files is later used by another program to mathematically define 3-D cloud models.

TOPGEN

TOPGEN is a user interactive program designed to produce 3-D topography models. These models mathematically define the topography for a sub-area of a Mercator topographic image. TOPGEN extracts the appropriate elevation data from the topographic image, scales the elevation data, and produces a geometry file which contains a topography model. This geometry file is written in a MOVIE.BYU readable format and can be displayed on the COMTAL using the DISPLAY program.

CLDGEN

CLDGEN is a program designed to produce 3-D cloud models. These models mathematically define cloud cover for a sub-area of a Mercator satellite image. CLDGEN reads the three cloud layer files produced by INTCLD. For each cloud contained in these files, the program produces a geometry file which contains a 3-D cloud model. Up to 26 geometry files can be produced. These files are written in a MOVIE.BYU readable format and can be displayed on the COMTAL using the DISPLAY program.

MERGER

MERGER is designed to produce a 3-D cloud-topography model. This model mathematically defines cloud cover and topography for a sub-area of the Mercator images. MERGER produces this model by combining the 3-D topography model (TOPGEN) and the 3-D cloud models (CLDGEN). MERGER writes the mathematical description of the 3-D cloud-topography model to a geometry file. This file is written in a MOVIE.BYU readable format and can be displayed on the COMTAL using the DISPLAY program.

FLTRAK

FLTRAK is used to plot a flight track on the 3-D cloud-topography model. These flight tracks mathematically define, in 3-D, an aircraft's path from take-off to landing. This program is discussed further in Chapter 7.

CHAPTER 5

2-D Image Generation

The process of creating a 3-D cloud-topography model begins by generating a set of three Mercator projection images. These three images contain topography data from the DMA data set, infrared data from GOES infrared satellite imagery, and visible data from the GOES visible satellite imagery. Data contained in these images is used to define terrain and cloud cover for a 4.27 x 4.27 degree area of the earth. It is the main concern here that the three images accurately overlay each other since it is from these images that the 3-D models will be generated.

At this point, it must be emphasized that the visible satellite image is not absolutely necessary to generate 3-D cloud-topography models. The main function of the visible image is to aid cloud interpretation and image navigation. Therefore, the process of generating a 3-D model will work equally well using only the topographic image and the infrared image. However, without the visible image, the accuracy of cloud interpretation and image navigation may suffer. The remaining part of this chapter explains how the Mercator images are generated and navigated.

A. Mercator Topographic Images

The generation process begins by the selection of a 4.27 x 4.27 degree area to be transformed into a 2-D Mercator topographic image. Once the area of interest is selected, the DMA512 program is used to create the topographic image. To specify the area of interest, the latitude and longitude of the northwest corner of this area is entered into the DMA512 program. Once the area is defined, a 512 x 512 array of elevations is extracted from the DMA data tape. These elevations are converted to meters and a scale factor is calculated by dividing the highest elevation in the array by 255. The scale factor is used to scale each elevation in the array from 0 to 255. Once scaling is complete, the data is formatted as a COMTAL image and is written to an output file. The scaling factor and the reference latitude and longitude are also saved in the file for later use.

A Mercator topographic image is shown in Figure 5-1. This image represents the terrain for an area covering southeast Wyoming, southwest Nebraska and northern Colorado. A COMTAL graphic containing state boundaries has been overlaid onto the image. To show the resolution of the image, several geographical features have been labeled.

Each elevation in the image is scaled 0 to 255 and is represented by a pixel grey shade. Data is scaled such that elevation is proportional to grey shade. Lighter grey shades represent higher elevations and darker grey shades represent lower elevations. Each grey shade increment in Figure 5-1 represents a 17.68 meter change in elevation. Individual elevations in the image can be calculated by multiplying the pixel grey shade value by the scale factor (17.68 meters).

Figure 5-1
Mercator topographic image

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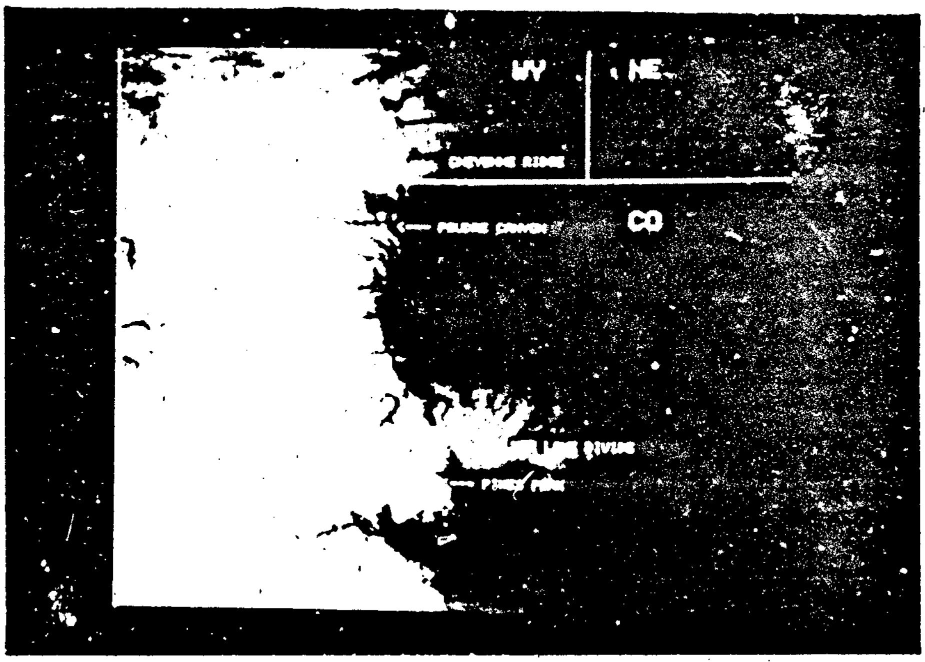
WY
NE
CO

Each pixel in the image represents an elevation which is separated by 30 seconds of latitude in the north-south direction and 30 seconds of longitude in the east-west direction. Since the latitude and longitude of the pixel in the northwest corner of the image is known, the latitude and longitude of each pixel in the image can be calculated by referencing the pixel's X and Y screen coordinates. The pixel in the northwest corner of the image is referenced by screen coordinates X = 0 and Y = 0. X screen coordinates increase to the east (right) and Y screen coordinates increase to the south (down). Since each pixel is separated by 30 seconds of latitude in the north-south direction, the latitude of a pixel can be calculated by multiplying its Y screen coordinate by 30 seconds of latitude and subtracting the resulting number from the reference latitude. Likewise, the longitude of a pixel can be calculated by multiplying its X screen coordinate by 30 seconds of longitude and subtracting the resulting number from the reference longitude.

Since the elevation and geographical location can be calculated for each pixel in the image, the image contains all the information needed to define a topographic surface in three dimensions. Data contained in this image will later be used to define a topographic base for the 3-D cloud-topography model.

B. Mercator Satellite Images

Now that the topographic image has been generated for a 4.27 x 4.27 degree area, GOES satellite imagery can be collected for this region. Figures 5-2 and 5-3 show infrared and visible satellite

Figure 5-2
Infrared GOES satellite image for 2132 GMT,
31 October 1984

Figure 5-3
Visible GOES satellite image for 2132 GMT,
31 Ocotber 1984

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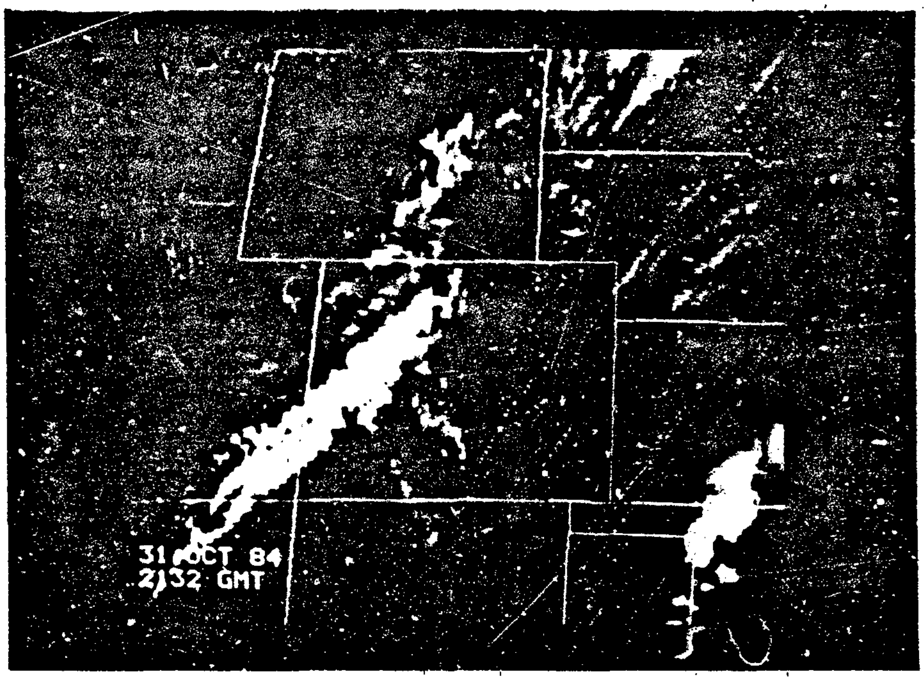
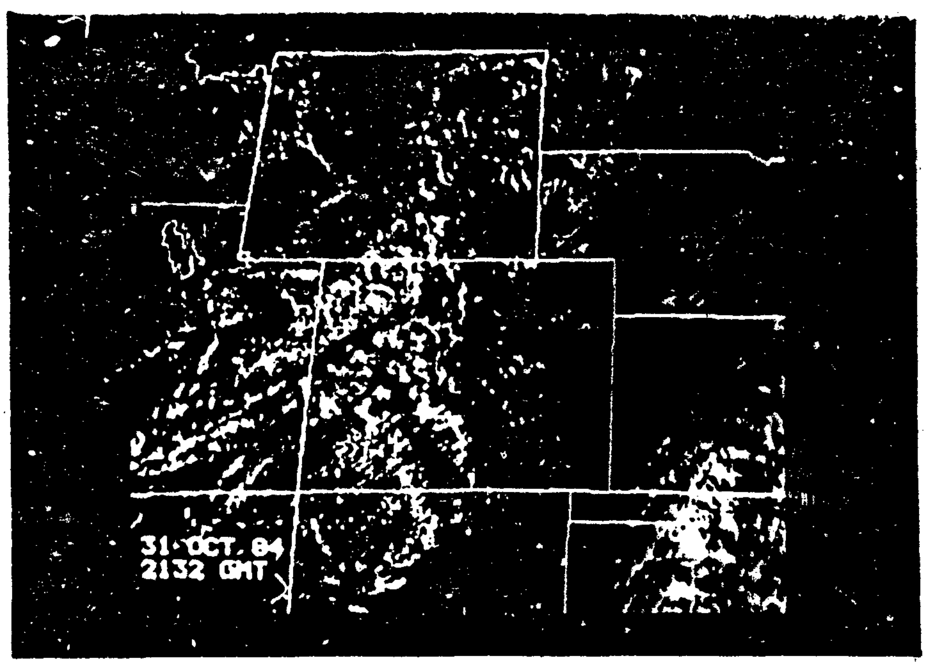

31 OCT 84
2132 GMT


31 OCT. 84
2132 GMT

imagery for 2132 GMT, 31 October 84. This data was collected by the DRSGS, processed using CSUGOES, and displayed using WINDOW. This imagery covers a portion of the western United Sates including the area covered by the topographic image shown in Figure 5-1.

The next step in the process is to remap the data contained in these images (Figures 5-2 and 5-3) into a Mercator projection that will accurately overlay the topographic image (Figure 5-1). This is accomplished using the REMAP program. Figures 5-4 and 5-5 show the resulting infrared and visible images after the remapping process. These images were displayed using WINDOW and gridded with state boundaries using the GPPLOT program. By comparing the topographic image (Figuare 5-1) with the visible image (Figure 5-5), it can be seen that the images closely overlay each other.

To show how closely they actually do match, elevations greater than 3589 meters have been blacked out in Figure 5-6. The black area has been made into a COMTAL graphic which can be used as a template to overlay onto the visible image. When this template is overlaid onto the image, the orographically induced clouds covering the mountain ranges should coincide closely with the template. Figure 5-7 shows the visible image after the template is overlaid. From Figure 5-7, it can be seen that the images overlay each other to within several pixels after the remapping process.

Many times, the remapping process is not as accurate as the above example shows. Figure 5-8 is a visible image which has been remapped into a Mercator projection. In this case, mountain ranges are plainly visible. By overlaying the template onto this image, it is apparent

Figure 5-4
Mercator infrared image for 2132 GMT
31 October 1984

Figure 5-5
Mercator visible image for 2132 GMT
31 October 1984

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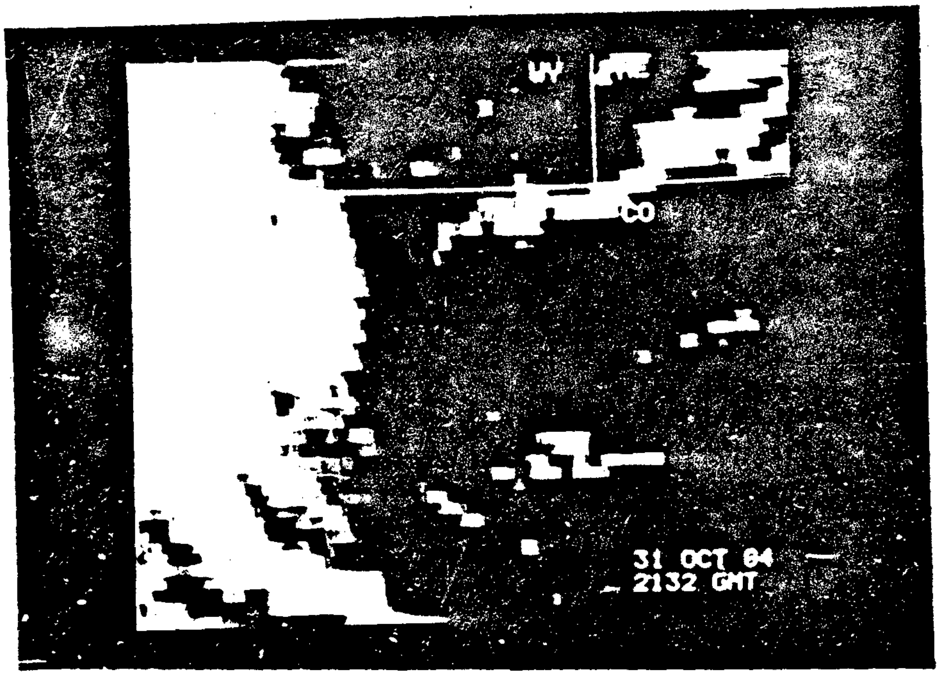
WV
CO
31 OCT 84
2132 GMT

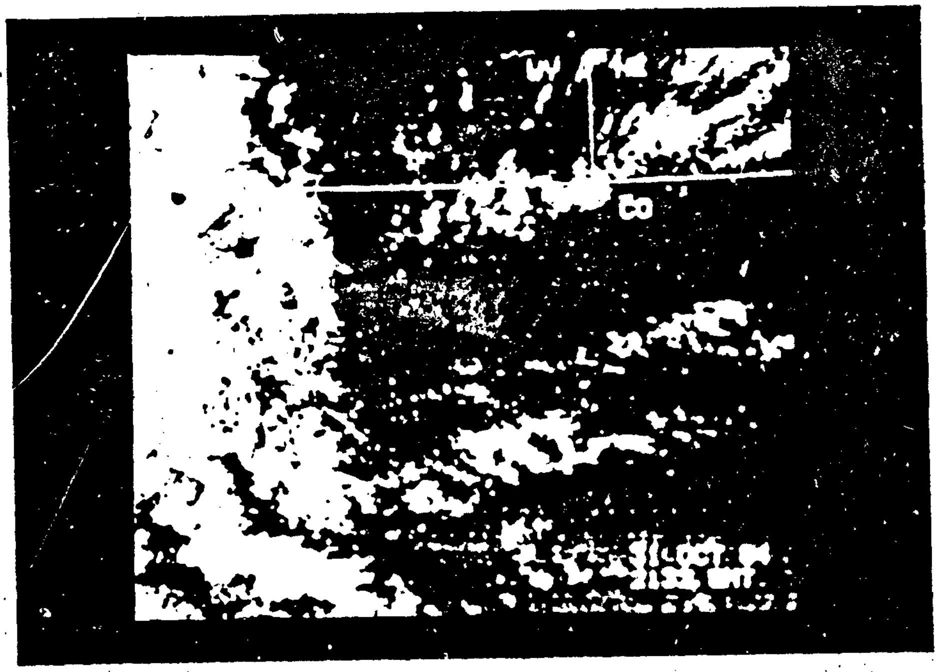
WV
CO

Figure 5-6
Mercator topographic image with template overlaid representing elevations above 3571 meters.

Figure 5-7
Mercator visible image with 3571 meter template overlaid.

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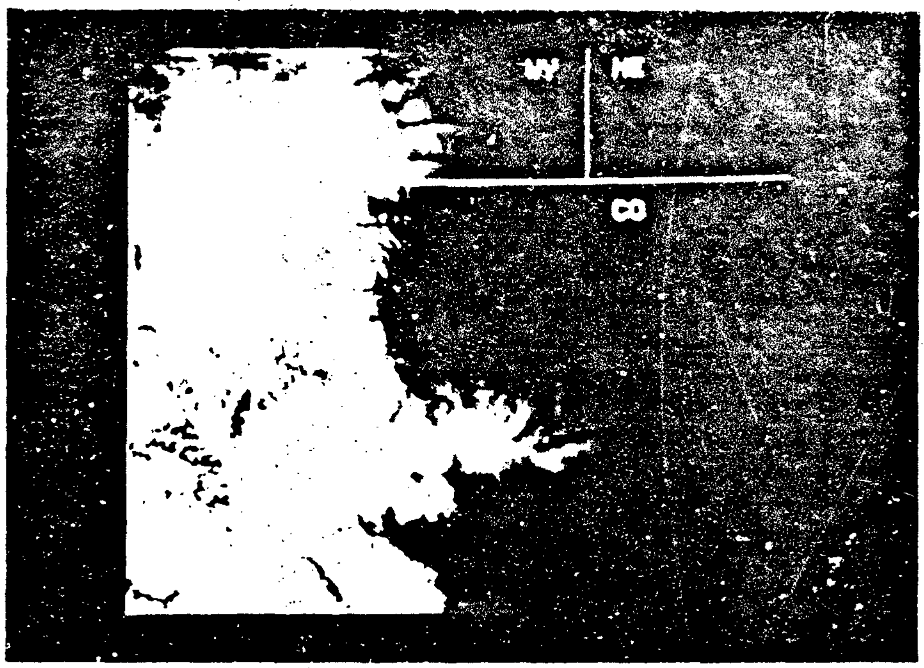

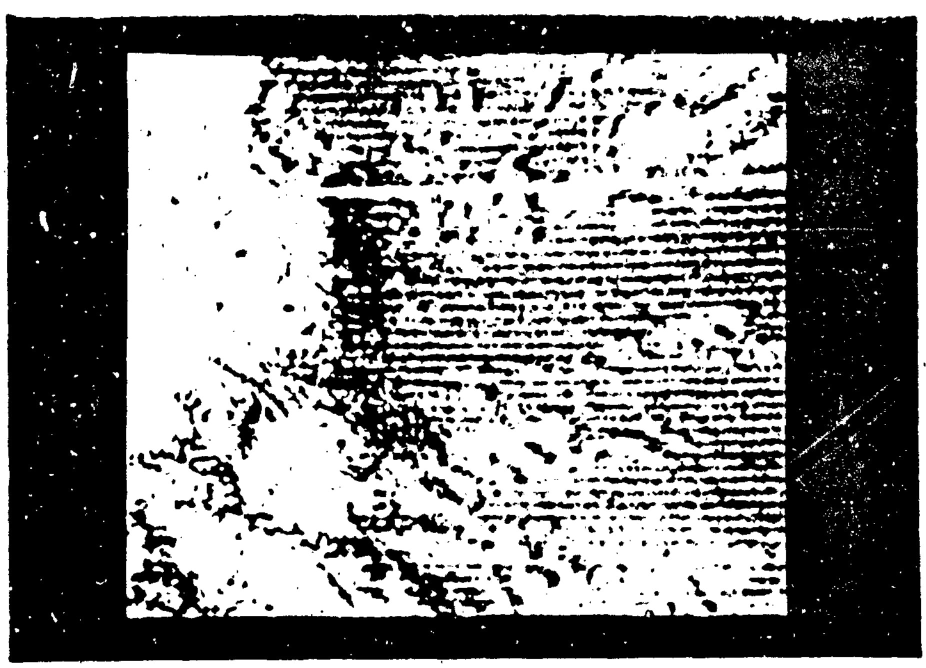

Figure 5-8
Mercator visible image for 1930 GMT, 23 January 85
with 3571 meter template overlaid.

Figure 5-9
Mercator visible image for 1930 GMT, 23 January 85
showing 3571 meter template overlaid after correcting
navigation error.

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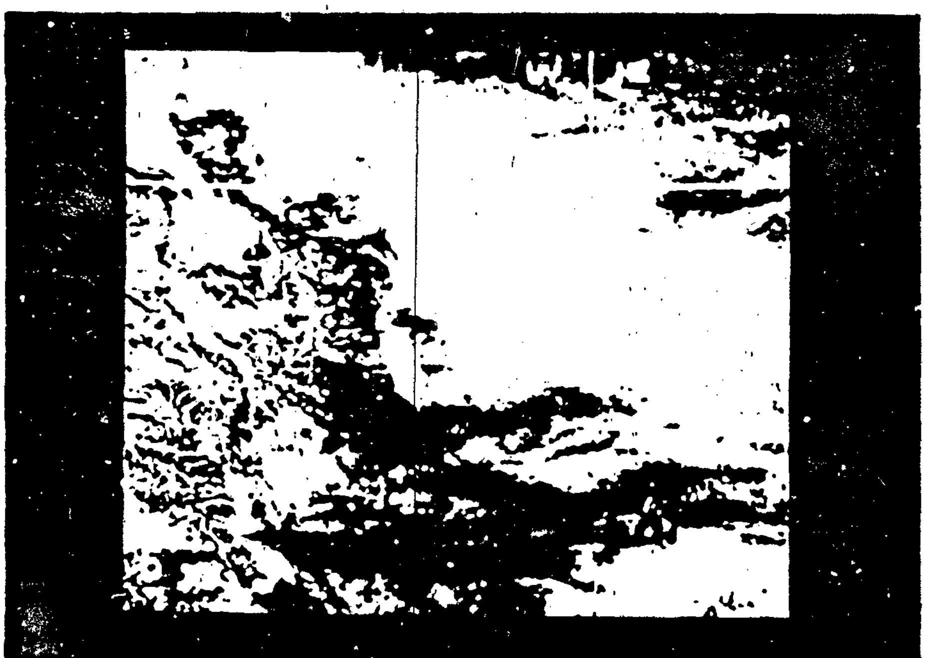

that the image does not overlay the topographic image. To correct the descrepancy, the SHIFTR program can be used to insure a more accurate fit. Figure 5-9 shows the same visible image with the black template after the visible image has been shifted two pixels to the left and nineteen pixels down. This image accurately overlays the topographic image.

Since the satellite images accurately overlay the topographic image, cloud cover data can be obtained with respect to topography. Data contained in the Mercator infrared image will later be used to define the cloud representations that will be displayed above the topographic base.

CHAPTER 6

3-D Model Generation

The previous chapter explained how a set of Mercator projection images is produced. This chapter explains how these images are used to produce 3-D cloud-topography models.

A. Sub-Area Selection

The generation process begins with the selection of a sub-area that is to be transformed into three dimensions. This sub-area can be defined using any of the three Mercator projection images. If the user is interested in a cloud formation, the sub-area may be defined on a satellite image. If the user is interested in the cloud cover over a particular area, the sub-area may be defined on the topographic image. The process for selecting a sub-area is the same.

A sub-area can be selected for essentially any area covered by a Mercator projection image. The sub-area can include any 16 x 16, 32 x 32, 64 x 64, 128 x 128, 256 x 256, or 512 x 512 pixel area within the Mercator image; however, the sub-area must remain within the bounds of the image. The location of this area can be defined using the program, DEFINE, which first displays the desired images on the COMTAL. The location of the sub-area is defined by specifying an X and Y screen coordinate for the northwest corner of the sub-area and a side length. The X and Y screen coordinates can be determined using the cursor control device. By placing the cursor over the northwest corner of the desired sub-area, the cursor control device will return the X and Y screen coordinates of the cursor position. The side length for the sub-area is specified by the number of pixels along one side of the sub-area. Choices are 16, 32, 64, 128, 256, and 512. Once the X and Y screen coordinates and the side length are entered into DEFINE, a box is drawn around the selected sub-area. If the displayed sub-area is not acceptable, another one can be defined. Figure 6-1 shows a sub-area displayed on the Mercator infrared image (Figure 5-4). In this case, the sub-area encompasses the entire image. Parameters defining the sub-area are: X screen coordinate = 0, Y screen coordinate = 0, and side length = 512.

Since MOVIE.BYU software is only configured to display sub-areas up to and including 64 x 64 pixels, any sub-areas which are larger than 64 x 64 pixels must be reduced to a smaller array size. This is done by specifying a reduction factor which defines the amount by which the original array is to be reduced. For example, in Figure 6-1, the defined sub-area is 512 x 512 pixels. A reduction factor of 16 averages each 16 x 16 square in the sub-area to a single smoothed pixel. The result is that the entire 512 x 512 pixel sub-area is reduced to a 32 x 32 array of pixels. If the defined sub-area is 32 x 32 pixels or 64 x 64 pixels, a reduction factor can optionally be selected. The final result of data reduction is that the data

Figure 6-1
Mercator infrared image for 2132 GMT, 31 October 84
with white box showing defined sub-area.

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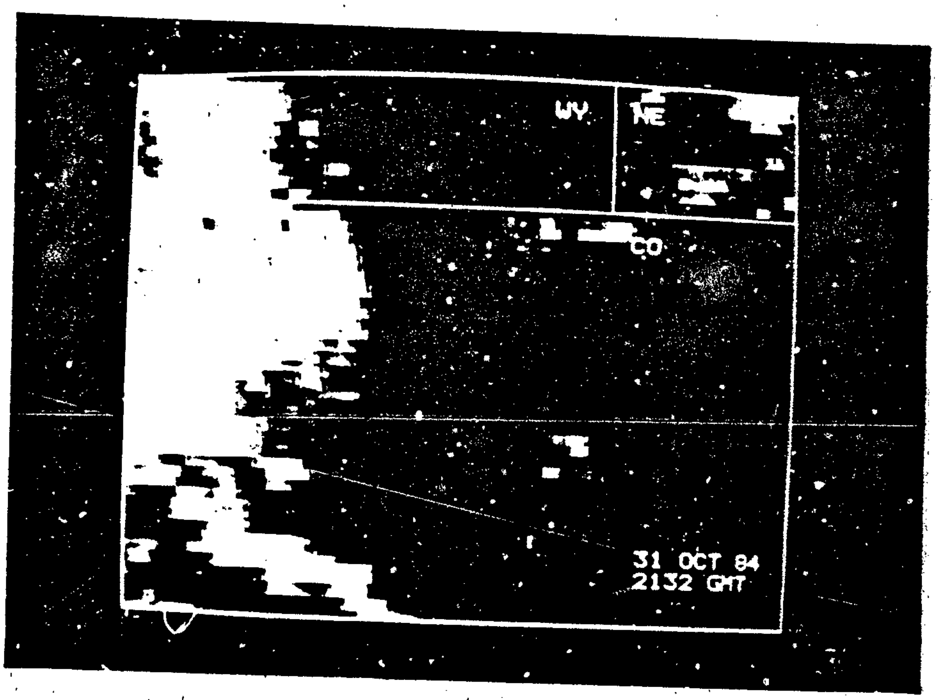
WY
NE
CO
31 OCT 84
2132 GMT

contained in every sub-area is reduced to a 16 x 16, 32 x 32, or 64 x 64 array of pixels.

The reduction factor is specified at the time the sub-area is defined using the DEFINE program. The DEFINE program allows the user to only enter a reduction factor that results in a 16 x 16, 32 x 32, or 64 x 64 array of pixels. After the reduction factor is entered, DEFINE stores the X and Y screen coordinates, the side length, and reduction factor in a file where the data can be accessed by other programs used to create the 3-D cloud-topography model.

B. Cloud/No Cloud Threshold Selection

After the sub-area is defined, cloud cover for this area is defined by determining which pixels are cloudy. Cloud/no cloud determinations are based on a simple threshold technique. This technique involves using either a threshold radiance count from the infrared image or a threshold brightness count from the visible image to make the cloud/no cloud determination. Pixels with radiance counts (brightness counts) greater than or equal to the threshold are considered cloudy. Pixels with radiance counts (brightness counts) less than the threshold are considered cloud free.

The cloud/no cloud threshold is specified by using the INTCLD program. INTCLD begins by letting the user display the desired images on the COMTAL. Once the images are displayed, the user inspects the imagery and interprets what is cloud and what is not. The cursor control device can be used as an aid to determine the cloud/no cloud threshold. By placing the cursor over the threshold radiance grey shade (brightness grey shade) the cursor control device will return the value of the radiance count (brightness count) at the cursor position. This value is entered into the INTCLD program.

After the cloud/no cloud threshold is entered, INTCLD extracts the visible and infrared data from the sub-area defined on the Mercator satellite images. If a reduction factor greater than one was specified, the data within the defined sub-area must be reduced in size. Recall that the reduction factor specifies the amount of by which the original sub-area is to be reduced. Thus, if a reduction factor of 16 is specified, every 16 x 16 square in the sub-area is averaged to a single smoothed pixel. For satellite data, data reduction is done by averaging the individual pixels within a square using the following scheme: If fifty percent or more of the individual pixels in a square are equal to or greater than the cloud/no cloud threshold, the resulting smoothed pixel is considered cloudy. The radiance count (brightness count) for this cloudy pixel is calculated by averaging the radiance counts (brightness counts) of those individual pixels equal to or greater than the cloud/no cloud threshold. If less than fifty percent of the individual pixels within a square is equal to or greater than the cloud/no cloud threshold, the resulting smoothed pixel is considered clear. The radiance count (brightness count) for this clear pixel is calculated by averaging all of the pixels within a square.

After all the data in the sub-area is reduced in the above manner, the result is a 16 x 16, 32 x 32, or 64 x 64 array of smoothed pixels. This array can be displayed on the COMTAL as a reduced image. Figure 6-2 shows the reduced infrared image for the sub-area shown in

Figure 6-2
Reduced infrared image for 2132 GMT, 31 October 84.

Figure 6-3
Reduced infrared image for 2132 GMT, 31 October 84
with cloud/no cloud threshold applied.

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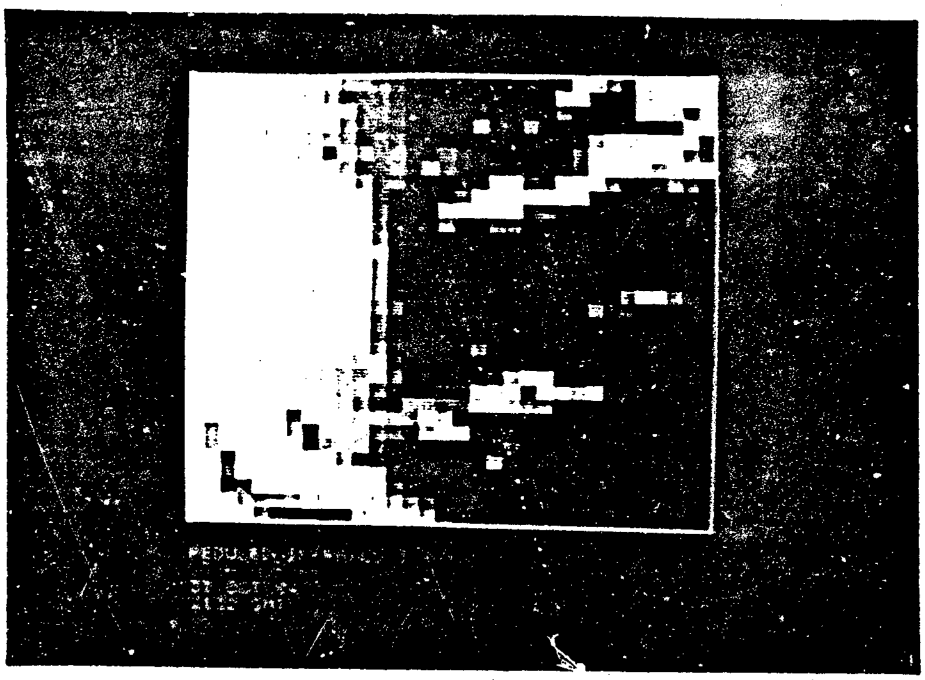

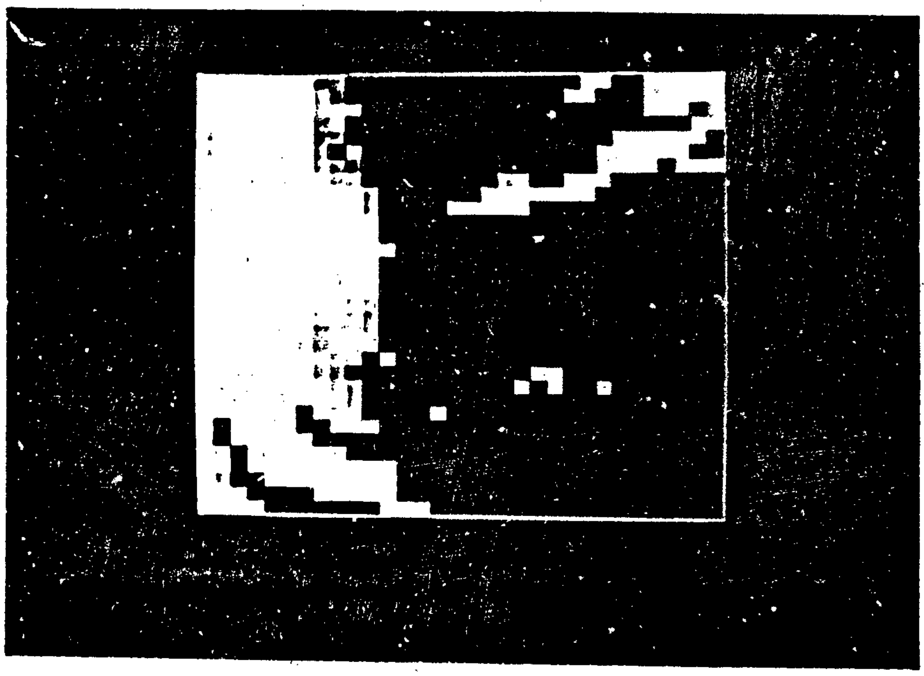

Figure 6-1. Individual pixels within the reduced 32 x 32 array have been duplicated by a factor of 8 (i.e. each pixel in the 32 x 32 array is duplicated to an 8 x 8 pixel array, thus producing a 256 x 256 pixel image). This is done only to enlarge the viewing area.

The final step in the cloud/no cloud determination process is to apply the cloud/no cloud threshold to the reduced infrared image. Figure 6-3 shows the same reduced infrared image in Figure 6-2 after the cloud/no cloud threshold is applied. In Figure 6-3, all smoothed pixels in the reduced infrared image that are below the cloud/no cloud threshold have been set equal to 0 and appear black. Radiance counts associated with each cloudy pixel in the reduced infrared image are later related to temperature and are used to determine cloud top heights.

C. Cloud Top and Base Height Calculations

The next step in the process of creating a 3-D cloud-topography model is to determine cloud top heights and cloud base heights for each of the cloudy pixels within the reduced infrared image (Figure 6-3). This is done by relating pixel radiance counts to temperature. The resulting temperatures are then related to height using rawinsonde sounding data.

The radiance counts associated with a GOES infrared image correspond to a defined set of equivalent black body temperatures. This information is summarized in a calibration table which contains a range of radiance counts and their corresponding black body temperatures. Table 6-1 shows the standard infrared calibration table used in this research. The accuracy of these temperatures is limited to two to four degrees Kelvin (K), generally, nearer two degrees K in winter and four degrees K in summer (Hord, 1982). The INTCLD program uses data contained in Table 6-1 to calculate cloud top temperatures for each cloudy pixel in the reduced infrared image.

After all the cloud top temperatures are determined, the next step is to relate these temperatures to heights using an atmospheric profile of temperature versus height. Atmospheric profiles of temperature versus height are obtained from rawinsonde upper air data. Here, a sounding is selected that is both near in proximity to the area of interest and close to the valid time for the satellite image. Once the sounding is selected, it is retrieved from a disk file on the VAX and the mandatory level data is manually decoded. Decoded data is entered into a file which is read by the INTCLD program. INTCLD processes this sounding data to eliminate surface inversions and other inversions that may occur in the troposphere. Missing levels are also eliminated in the process. The resulting sounding has a negative lapse rate throughout the depth of the troposphere. This insures that only one cloud top height can be assigned for a given cloud top temperature.

Figure 6-4 shows a temperature versus height profile. This profile was selected for determining cloud top heights for the sub-area shown in Figure 6-1. This profile was created from a Denver, Colorado rawinsonde sounding valid for 1200 GMT, 31 October 84. Figure 6-5 shows the same Denver sounding after having been processed by INTCLD. Notice that the surface inversion has been eliminated.

Table 6-1
Standard infrared calibration table (from Clark, D. J., 1983)

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COUNT VALUE	KELVIN	CENTIGRADE	FAHRENHEIT
000	330.0	56.8	134.3
001	329.5	56.3	133.4
002	329.0	55.8	132.5
003	328.5	55.3	131.6
004	328.0	54.8	130.7
005	327.5	54.3	129.8
006	327.0	53.8	128.9
007	326.5	53.3	128.0
008	326.0	52.8	127.1
009	325.5	52.3	126.2
010	325.0	51.8	125.3
011	324.5	51.3	124.4
012	324.0	50.8	123.5
013	323.5	50.3	122.6
014	323.0	49.8	121.7
015	322.5	49.3	120.8
016	322.0	48.8	119.9
017	321.5	48.3	119.0
018	321.0	47.8	118.1
019	320.5	47.3	117.2
020	320.0	46.8	116.3
021	319.5	46.3	115.4
022	319.0	45.8	114.5
023	318.5	45.3	113.6
024	318.0	44.8	112.7
025	317.5	44.3	111.8
026	317.0	43.8	110.9
027	316.5	43.3	110.0
028	316.0	42.8	109.1
029	315.5	42.3	108.2
030	315.0	41.8	107.3
031	314.5	41.3	106.4
032	314.0	40.8	105.5
033	313.5	40.3	104.6
034	313.0	39.8	103.7
035	312.5	39.3	102.8
036	312.0	38.8	101.9
037	311.5	38.3	101.0
038	311.0	37.8	100.1
039	310.5	37.3	99.2
040	310.0	36.8	98.3
041	309.5	36.3	97.4
042	309.0	35.8	96.5
043	308.5	35.3	95.6
044	308.0	34.8	94.7
045	307.5	34.3	93.8
046	307.0	33.8	92.9
047	306.5	33.3	92.0
048	306.0	32.8	91.1
049	305.5	32.3	90.2
050	305.0	31.8	89.3

COUNT VALUE	KELVIN	CENTIGRADE	FAHRENHEIT
051	304.5	31.3	88.4
052	304.0	30.8	87.5
053	303.5	30.3	86.6
054	303.0	29.8	85.7
055	302.5	29.3	84.8
056	302.0	28.8	83.9
057	301.5	28.3	83.0
058	301.0	27.8	82.1
059	300.5	27.3	81.2
060	300.0	26.8	80.3
061	299.5	26.3	79.4
062	299.0	25.8	78.5
063	298.5	25.3	77.6
064	298.0	24.8	76.7
065	297.5	24.3	75.8
066	297.0	23.8	74.9
067	296.5	23.3	74.0
068	296.0	22.8	73.1
069	295.5	22.3	72.2
070	295.0	21.8	71.3
071	294.5	21.3	70.4
072	294.0	20.8	69.5
073	293.5	20.3	68.6
074	293.0	19.8	67.7
075	292.5	19.3	66.8
076	292.0	18.8	65.9
077	291.5	18.3	65.0
078	291.0	17.8	64.1
079	290.5	17.3	63.2
080	290.0	16.8	62.3
081	289.5	16.3	61.4
082	289.0	15.8	60.5
083	288.5	15.3	59.6
084	288.0	14.8	58.7
085	287.5	14.3	57.8
086	287.0	13.8	56.9
087	286.5	13.3	56.0
088	286.0	12.8	55.1
089	285.5	12.3	54.2
090	285.0	11.8	53.3
091	284.5	11.3	52.4
092	284.0	10.8	51.5
093	283.5	10.3	50.6
094	283.0	9.8	49.7
095	282.5	9.3	48.8
096	282.0	8.8	47.9
097	281.5	8.3	47.0
098	281.0	7.8	46.1
099	280.5	7.3	45.2
100	280.0	6.8	44.3
101	279.5	6.3	43.4

COUNT VALUE	KELVIN	CENTIGRADE	FAHRENHEIT
102	279.0	5.8	42.5
103	278.5	5.3	41.6
104	278.0	4.8	40.7
105	277.5	4.3	39.8
106	277.0	3.8	38.9
107	276.5	3.3	38.0
108	276.0	2.8	37.1
109	275.5	2.3	36.2
110	275.0	1.8	35.3
111	274.5	1.3	34.4
112	274.0	.8	33.5
113	273.5	.3	32.6
114	273.0	-.2	31.7
115	272.5	-.7	30.8
116	272.0	-1.2	29.9
117	271.5	-1.7	29.0
118	271.0	-2.2	28.1
119	270.5	-2.7	27.2
120	270.0	-3.2	26.3
121	269.5	-3.7	25.4
122	269.0	-4.2	24.5
123	268.5	-4.7	23.6
124	268.0	-5.2	22.7
125	267.5	-5.7	21.8
126	267.0	-6.2	20.9
127	266.5	-6.7	20.0
128	266.0	-7.2	19.1
129	265.5	-7.7	18.2
130	265.0	-8.2	17.3
131	264.5	-8.7	16.4
132	264.0	-9.2	15.5
133	263.5	-9.7	14.6
134	263.0	-10.2	13.7
135	262.5	-10.7	12.8
136	262.0	-11.2	11.9
137	261.5	-11.7	11.0
138	261.0	-12.2	10.1
139	260.5	-12.7	9.2
140	260.0	-13.2	8.3
141	259.5	-13.7	7.4
142	259.0	-14.2	6.5
143	258.5	-14.7	5.6
144	258.0	-15.2	4.7
145	257.5	-15.7	3.8
146	257.0	-16.2	2.9
147	256.5	-16.7	2.0
148	256.0	-17.2	1.1
149	255.5	-17.7	.2
150	255.0	-18.2	-.7
151	254.5	-18.7	-1.6
152	254.0	-19.2	-2.5

COUNT VALUE	KELVIN	CENTIGRADE	FAHRENHEIT
153	253.5	-19.7	-3.4
154	253.0	-20.2	-4.3
155	252.5	-20.7	-5.2
156	252.0	-21.2	-6.1
157	251.5	-21.7	-7.0
158	251.0	-22.2	-7.9
159	250.5	-22.7	-8.8
160	250.0	-23.2	-9.7
161	249.5	-23.7	-10.6
162	249.0	-24.2	-11.5
163	248.5	-24.7	-12.4
164	248.0	-25.2	-13.3
165	247.5	-25.7	-14.2
166	247.0	-26.2	-15.1
167	246.5	-26.7	-16.0
168	246.0	-27.2	-16.9
169	245.5	-27.7	-17.8
170	245.0	-28.2	-18.7
171	244.5	-28.7	-19.6
172	244.0	-29.2	-20.5
173	243.5	-29.7	-21.4
174	243.0	-30.2	-22.3
175	242.5	-30.7	-23.2
176	242.0	-31.2	-24.1
177	241.0	-32.2	-25.9
178	240.0	-33.2	-27.7
179	239.0	-34.2	-29.5
180	238.0	-35.2	-31.3
181	237.0	-36.2	-33.1
182	236.0	-37.2	-34.9
183	235.0	-38.2	-36.7
184	234.0	-39.2	-38.5
185	233.0	-40.2	-40.3
186	232.0	-41.2	-42.1
187	231.0	-42.2	-43.9
188	230.0	-43.2	-45.7
189	229.0	-44.2	-47.5
190	228.0	-45.2	-49.3
191	227.0	-46.2	-51.1
192	226.0	-47.2	-52.9
193	225.0	-48.2	-54.7
194	224.0	-49.2	-56.5
195	223.0	-50.2	-58.3
196	222.0	-51.2	-60.1
197	221.0	-52.2	-61.9
198	220.0	-53.2	-63.7
199	219.0	-54.2	-65.5
200	218.0	-55.2	-67.3
201	217.0	-56.2	-69.1
202	216.0	-57.2	-70.9
203	215.0	-58.2	-72.7

COUNT VALUE	KELVIN	CENTIGRADE	FAHRENHEIT
204	214.0	-59.2	-74.5
205	213.0	-60.2	-76.3
206	212.0	-61.2	-78.1
207	211.0	-62.2	-79.9
208	210.0	-63.2	-81.7
209	209.0	-64.2	-83.5
210	208.0	-65.2	-85.3
211	207.0	-66.2	-87.1
212	206.0	-67.2	-88.9
213	205.0	-68.2	-90.7
214	204.0	-69.2	-92.5
215	203.0	-70.2	-94.3
216	202.0	-71.2	-96.1
217	201.0	-72.2	-97.9
218	200.0	-73.2	-99.7
219	199.0	-74.2	-101.5
220	198.0	-75.2	-103.3
221	197.0	-76.2	-105.1
222	196.0	-77.2	-106.9
223	195.0	-78.2	-108.7
224	194.0	-79.2	-110.5
225	193.0	-80.2	-112.3
226	192.0	-81.2	-114.1
227	191.0	-82.2	-115.9
228	190.0	-83.2	-117.7
229	189.0	-84.2	-119.5
230	188.0	-85.2	-121.3
231	187.0	-86.2	-123.1
232	186.0	-87.2	-124.9
233	185.0	-88.2	-126.7
234	184.0	-89.2	-128.5
235	183.0	-90.2	-130.3
236	182.0	-91.2	-132.1
237	181.0	-92.2	-133.9
238	180.0	-93.2	-135.7
239	179.0	-94.2	-137.5
240	178.0	-95.2	-139.3
241	177.0	-96.2	-141.1
242	176.0	-97.2	-142.9
243	175.0	-98.2	-144.7
244	174.0	-99.2	-146.5
245	173.0	-100.2	-148.3
246	172.0	-101.2	-150.1
247	171.0	-102.2	-151.9
248	170.0	-103.2	-153.7
249	169.0	-104.2	-155.5
250	168.0	-105.2	-157.3
251	167.0	-106.2	-159.1
252	166.0	-107.2	-160.9
253	165.0	-108.2	-162.7
254	164.0	-109.2	-164.5
255	163.0	-110.2	-166.3

STANDARD IR CALIBRATION

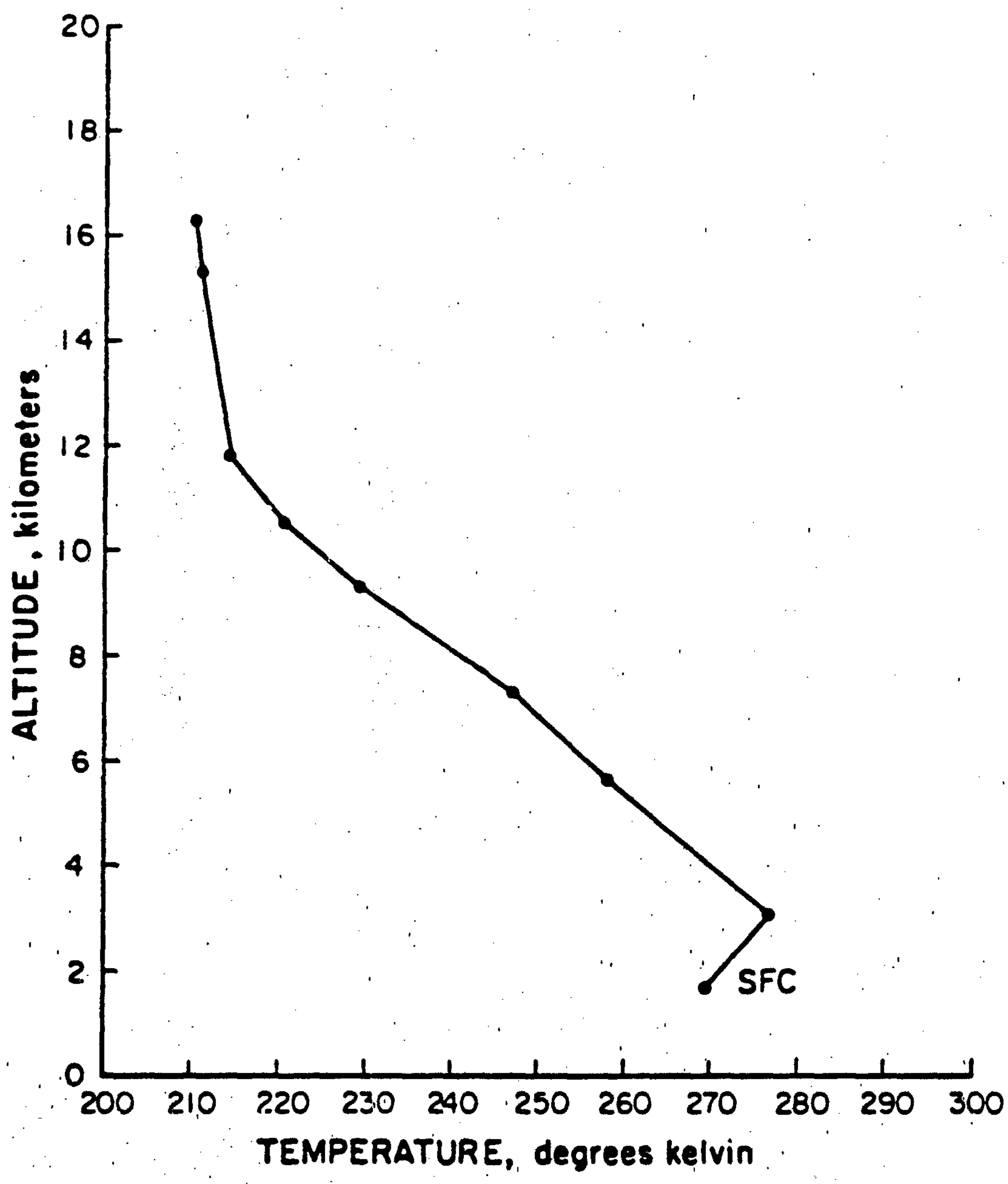

Figure 6-4
Temperature versus height profile for Denver, Colorado, 1200 GMT, 31 October 84.

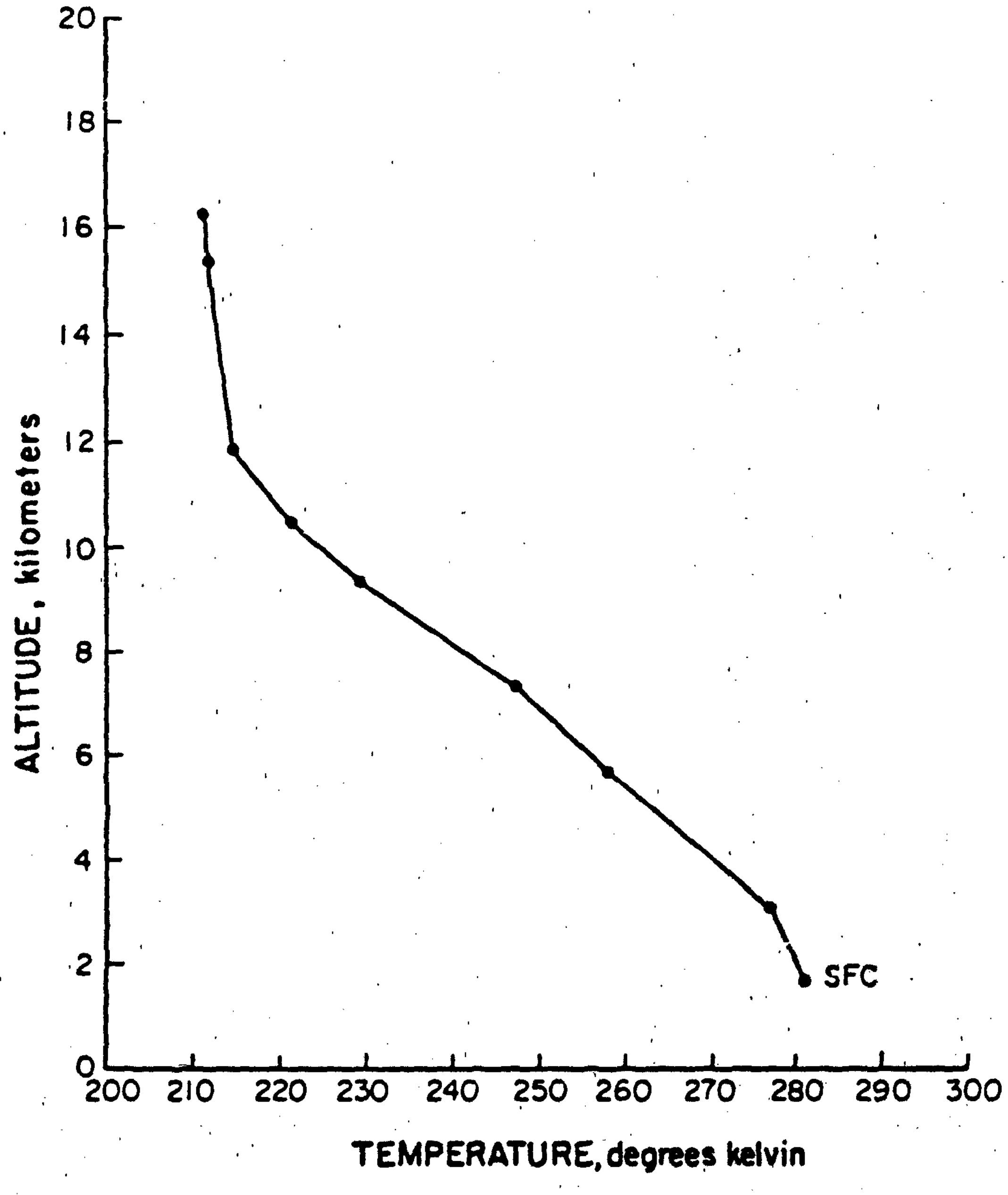

Figure 6-5
Temperature versus height profile for Denver, Colorado, 1200 GMT, 31 October 84 after inversion has been eliminated.

After the sounding is processed, INTCLD creates a table which contains an entry for each temperature interval in the sounding. Each entry in the table contains: the temperature (T_B) at the bottom of the layer, the temperature (T_T) at the top of the layer, the height (H_B) at the bottom of the layer, and the lapse rate for the entire layer. Table 6-2 shows the table created from the sounding data shown in Figure 6-5. INTCLD uses data in this table to calculate cloud top heights. For each temperature associated with a cloudy pixel, INTCLD finds the interval where the temperature falls. Using the lapse rate for this layer, INTCLD interpolates the height difference from the bottom of the layer. This height difference is added to the height (H_B) at the bottom of the layer. The resulting height is assumed to be the cloud top height for the cloudy pixel. Cloud top heights are calculated for all cloudy pixels in the reduced infrared image.

After all cloud top heights are calculated, the minimum cloud top height is calculated. This minimum cloud top height is assumed to be the maximum allowable cloud base height for all the clouds within the reduced infrared image. This height is displayed on the user terminal and the user determines a reasonable base height for the clouds in the sub-area. This value is entered into the program. As long as the value is below the maximum allowable base height it is accepted by INTCLD.

Finally, after the cloud base height is entered, INTCLD creates three cloud layer files. These files contain data which define cloud cover and contain a cloud top height and cloud base height for each

Table 6-2
Interval table produced from temperature versus height profile shown in Figure 6-5.

LEVEL	TEMPERATURE (T_B)°K	TEMPERATURE(T_T)°K	LAPSE RATE °K / km	HEIGHT (H_B) km
1	281.6	276.7	-3.60	1.65
2	276.7	258.0	-7.11	3.01
3	258.0	246.8	-6.75	5.64
4	246.8	229.4	-8.70	7.30
5	229.4	220.6	-7.33	9.30
6	220.6	214.2	-4.51	10.50
7	214.2	211.2	- .87	11.92
8	211.2	210.2	-1.20	15.37

cloudy pixel in the infrared image. Information contained in these cloud layer files is later used to create 3-D cloud representations that will be displayed above the topographic base.

D. 3-D Topography Models

At this point, a 3-D topography model is created using data contained in the Mercator topographic image. This model mathematically defines the base for the 3-D cloud-topography model and is created using the TOPGEN program.

The process of generating a 3-D topography model begins by reading the data contained within a sub-area of the Mercator topographic image. To find the location of this sub-area, TOPGEN reads the file which was created by the DEFINE program. This file contains a reduction factor and the parameters which define the sub-area. Next, each pixel value contained within the defined sub-area is read and converted to an elevation using the scale factor that was calculated when the topographic image was created. If a reduction factor greater than one was specified, the elevations contained within the sub-area are averaged. The final result is that a 16 x 16, 32 x 32, or 64 x 64 array of elevations is created representing the topography for the specified sub-area.

To define the topography model, elevation data contained in the above array must be scaled horizontally and vertically. Horizontal scaling involves transforming the location of each elevation in the array to a model X and Y coordinate. Vertical scaling involves transforming each elevation in the array to a model Z coordinate. Model X and Y coordinates are calculated as follows: One is subtracted from each absolute array location and mutiplied by a resolution factor. Thus, a resolution factor of 4 would scale a 32 x 32 array of elevations from 0 to 124 in each direction. The elevation in the southwest corner of the sub-area would have an X and Y coordinate corresponding to (0, 0). The next elevation to the east would have an X and Y coordinate corresponding to (4, 0) while the first elevation to the north would have an X and Y coordinate corresponding to (0, 4) etc. After model X and Y coordinates are calculated, the actual distances respresented by each side of the model are calculated. North-south and east-west distances are averaged and this average distance is divided by the number of units along one side of the model. The result is a model scale factor which specifies the number of meters represented by one model unit. Model Z coordinates are calculated by dividing each elevation in the array by the model scale factor. After all the model Z coordinates are calculated, the resulting model X, Y, and Z coordinates are stored in a coordinate array.

Each model X, Y, and Z coordinate is referred to as a node. To complete the description of the topography model, the exact sequence for connecting each node is specified. This sequence is stored in a connectivity array. The result is that the topographic surface is defined by a series of four sided polygons.

Usually, the horizontal distance represented by a model is much larger than the vertical distance. As a result, a scale model would appear very flat. To bring out topographic features, a vertical scale factor can be specified. This vertical scale factor is used to exaggerate the model's vertical scale. To aid the selection of a vertical scale factor, TOPGEN calculates a model height to width ratio and displays this ratio on the user terminal. If the user decides to exaggerate the vertical scale, a vertical scale factor is entered. Then, a new model height to width ratio is calculated and displayed. If the new ratio is not satisfactory, a new scale factor can be entered. After the desired height to width ratio is obtained, each model Z coordinate in the coordinate array is multiplied by this factor.

Finally, a model base is added to give the surface a solid appearance and a parts array is specified. The resulting coordinate array, connectivity array, and parts array is written to a geometry file. This file contains the complete mathematical description for the 3-D topography model. The file is written in a MOVIE.BYU readable format and can be displayed using the DISPLAY program. Another file is also written which contains scaling data used to create the model. Data in this file will be used later to scale 3-D cloud models.

The 3-D topography model can be viewed on the COMTAL monitor using the DISPLAY program. Figure 6-6 shows a topography model as it appears on the COMTAL monitor. The model is displayed as a continuous tone image superimposed with a graphic which contains model contour lines. No rotations have been applied and the resulting view of the model is from the top of the model. This model represents the topography for the entire area shown in Figure 5-1. The vertical scale has been exaggerated by a factor of 15; however, with this view,

Figure 6-6
Top view of 3-D topography model.

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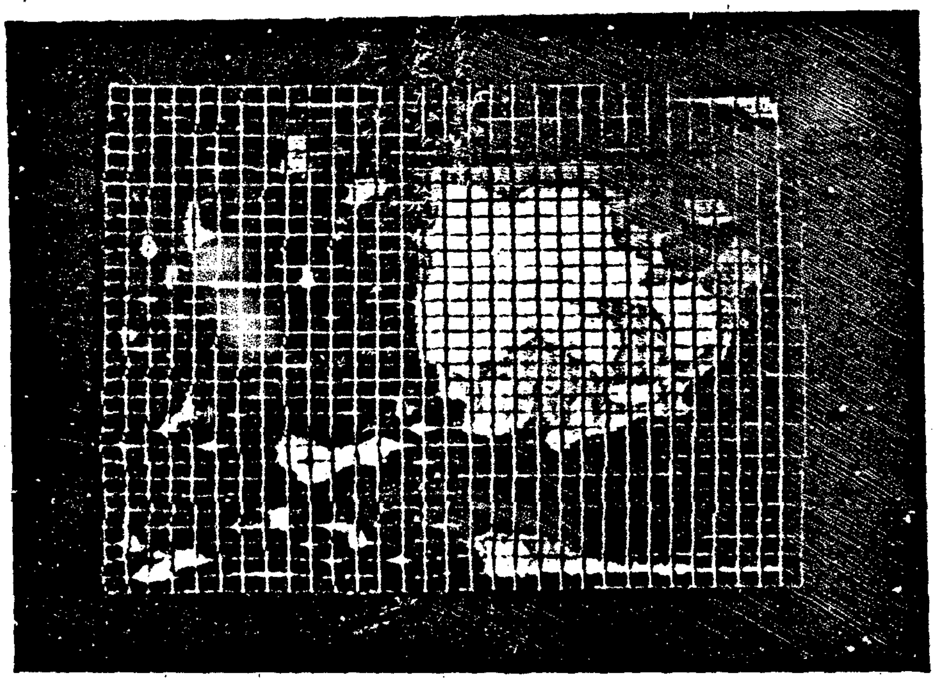

topographic features are not readily noticable. Normally, the 3-D topography model is not displayed and is done here for illustrative purposes.

E. 3-D Cloud Models

The previous section explained how the topographic base is created for the 3-D cloud-topography model. This section explains how the cloud representations are created.

The cloud representations are created using the CLDGEN program. CLDGEN begins by reading the cloud layer files which were produced by the INTCLD program. After a file is read, a "cloud" is extracted from the cloud layer file. Here, a "cloud" is defined as a group of cloudy pixels which touch each other in either the east-west direction or north-south direction. Information defining a cloud is transformed into X, Y, and Z coordinates using scaling information which was produced by TOPGEN. Further data manipulation produces a coordinate array, connectivity array, and parts array. These arrays, which mathematically define a cloud, are written to a geometry file. This process continues until all clouds have been extracted from the cloud layer file. After a cloud layer file is depleted of clouds, the second and third cloud layer files are processed in the same manner. Final output for this process is a series of up to 26 geometry files each of which contains a single 3-D cloud model.

The 3-D cloud models which were produced for the data shown in Figure 6-3 can be viewed on the COMTAL monitor using the DISPLAY program. Figure 6-7 shows the 3-D cloud models as they appear on the

Figure 6-7
Top ew of 3-D cloud models for 2132 GMT,
31 October 84

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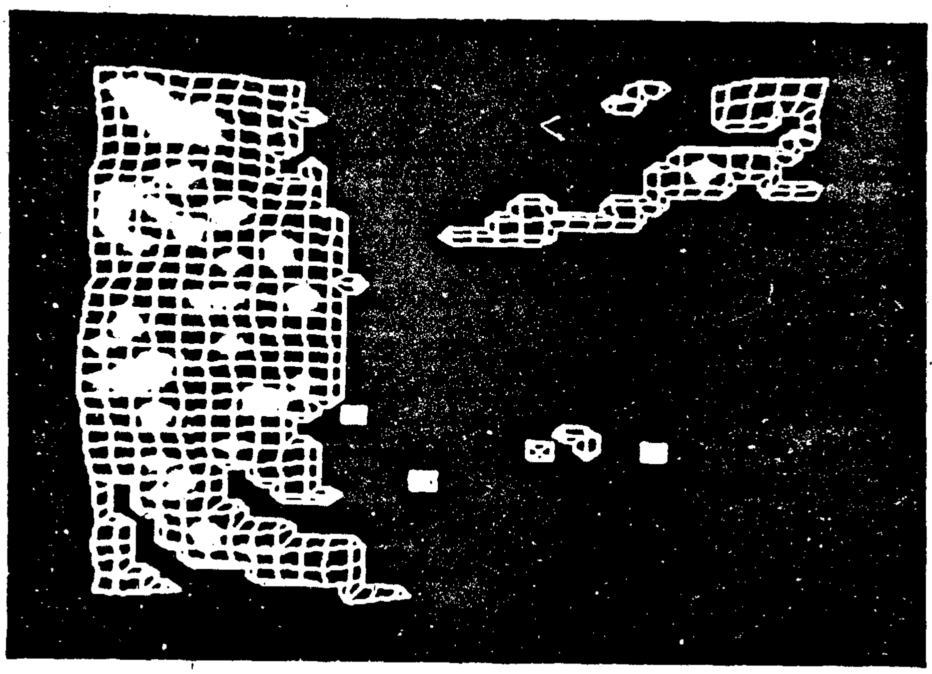

COMTAL. These models have been displayed as a pseudocolor image overlaid by a graphic which contains model contour lines. Again, no rotations have been applied and the resulting view is from the top of the model. The vertical scale is exaggerated by a factor of 15. This figure depicts the cloud cover over the entire region shown in Figure 6-1. Notice the similarity between Figure 6-7 and Figure 6-3. Again, these 3-D models are not normally displayed and are shown here for illustrative purposes.

F. 3-D Cloud-Topography Models

The final step in the process is to combine the 3-D topography model with the 3-D cloud models to produce the 3-D cloud-topography model. Geometry files containing these models are combined using the MERGER program. Final ouput from this program is a geometry file which contains the 3-D cloud-topography model.

The 3-D cloud-topography model, which was produced by combining the cloud models shown in Figure 6-7 and the topography model shown in Figure 6-6, can be viewed on the COMTAL monitor using the DISPLAY program. Figure 6-8 shows the 3-D cloud-topography model as it appears on the COMTAL. Again, no rotations have been applied. Figure 6-8 graphically illustrates how the topograpny model (Figure 6-6) and the cloud models (Figure 6-7) are combined. Figure 6-8 represents the topography and cloud cover for the areas covered by Figures 5-1 and 6-1, respectively.

Figure 6-9 is the same cloud-topography model as shown in Figure 6-8 after rotations have been applied. The resulting view is from

Figure 6-8
Top view of 3-D cloud-topography model for 2132 GMT, 31 October 84.

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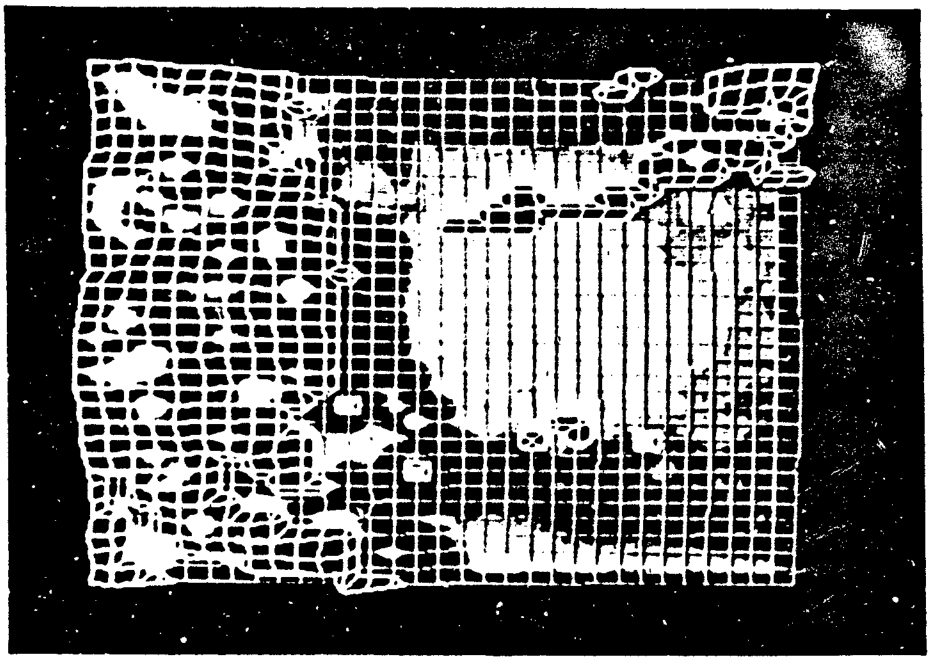

Figure 6-9
Rotated view of 3-D cloud-topography model for
2132 GMT, 31 October 84.

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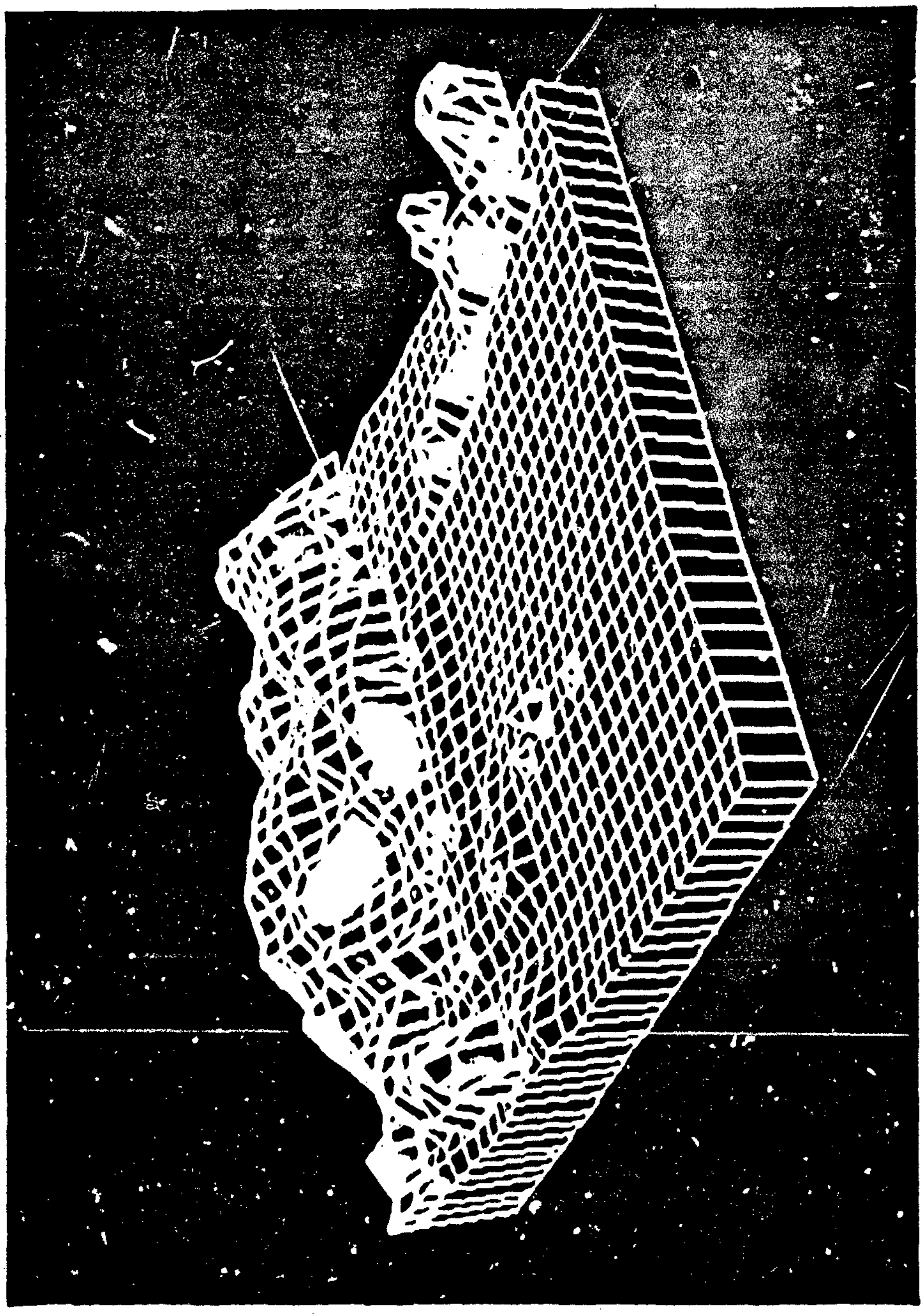

the southeast looking northwest. A portion of the Rocky Mountains is visible on the upper left hand side of the model. This view shows the vertical structure of both the terrain and the clouds.

CHAPTER 7

Applications

The aim of the previous four chapters was to explain data, resources, software, and methodology used to create the 3-D cloud-topography model. This chapter illustrates how the 3-D model can be used for cloud studies, briefing aids, and flight simulations.

A. Cloud Studies

GOES satellite data, displayed as digital imagery, is represented by a regularly spaced array of pixels. Each pixel in the array is assigned a specific grey shade based on the numerical value of the pixel. The resulting picture or image is flat scene representation that varies to grey shade from pixel to pixel. Satellite data which is displayed in this manner is commonly used by meteorologists to study vertical cloud structure and cloud development.

To study vertical cloud structure, infrared images are often enhanced. Image enhancement involves altering the image in some way to facilitate the interpretation of its information content. One method of image enhancement involves increasing or decreasing contrast over a range of pixel values. Using this method, enhancement curves are defined which assign lighter or darker grey shades to specified pixel values. Another method of image enhancement involves the use of color to show detail in the imagery. Using this method, pseudocolor enhancement curves are defined which assign mixtures of the three primary colors (red, green, and blue) to specified pixel values. Both methods are used effectively to show vertical cloud structure.

A time series of satellite images is often used to study cloud development. Normally, a time series consists of two or more satellite images separated by a time step ranging from minutes to hours. Cloud development can be studied by comparing these images in the time series and observing changes in the cloud field. Alternatively, cloud development can be studied by creating a movie loop from the time series of satellite images. Here, satellite images are displayed in rapid succession on an image processing system. The result is a time lapse display of clouds and weather systems which produces the illusion of continuous cloud growth.

The same concepts can be applied using the 3-D cloud-topography model. Displays are produced from the cloud-topography model using MOVIE.BYU software. These displays can be used to study vertical cloud structure and cloud development in a similar fashion to those methods discussed for 2-D satellite imagery.

Three-dimensional cloud-topography models can be used to study vertical cloud structure. To bring out detail, the model's vertical scale is exaggerated. Vertical model scaling is similar to image enhancement in the sense that it facilitates the interpretation of the model's information content. By exaggerating the vertical scale, small height differences are amplified allowing relatively minor cloud features to be seen. When the model is displayed, these cloud features can be viewed and studied from virtually any angle or perspective. In addition, the satellite data is scaled vertically proportional to actual height rather than to temperature.

Three-dimensional cloud-topography models can be used to study cloud development. Here, a time series of cloud models is used instead of a time series of satellite images. The time series of models can be displayed on the COMTAL monitor using the DISPLAY program. Cloud development and growth can be studied by comparing the models. Alternatively, cloud development can be observed by creating and displaying movie loops using the time series of 3-D models.

Figures 7-1, 7-3, and 7-5 show a time series of GOES infrared images as they appear on the COMTAL monitor. Individual images are separated by a time interval of approximately 15 minutes. The series shows the development of cumulus convective activity in north-central Kansas from 2215 GMT to 2245 GMT on 21 June 1984. Figures 7-2, 7-4, and 7-6 show the corresponding 3-D cloud-topography displays for the boxed sub-area on the 2-D infrared images. The vertical scale has been exaggerated by a factor of five to show the vertical cloud structure. Topographic features cannot be seen since the terrain within the boxed sub-area is relatively flat. However, the displays show a realistic depiction of a growing cumulus cloud above the corresponding topography. Figure 7-2 shows initial development. Figure 7-4 shows a cumulus tower developing out of the cumulus cloud.

Figure 7-1
Mercator infrared image for 2115 GMT, 21 June 84.

Figure 7-2
3-D cloud-topography model for boxed sub-area
in Figure 7-1.

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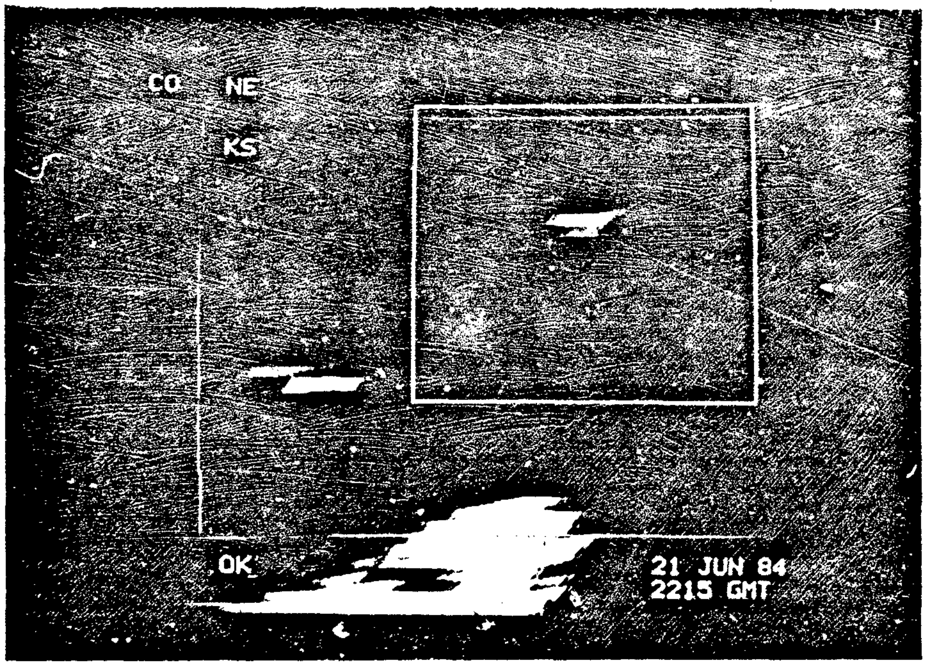
CO
NE
KS
OK
21 JUN 84
2215 GMT

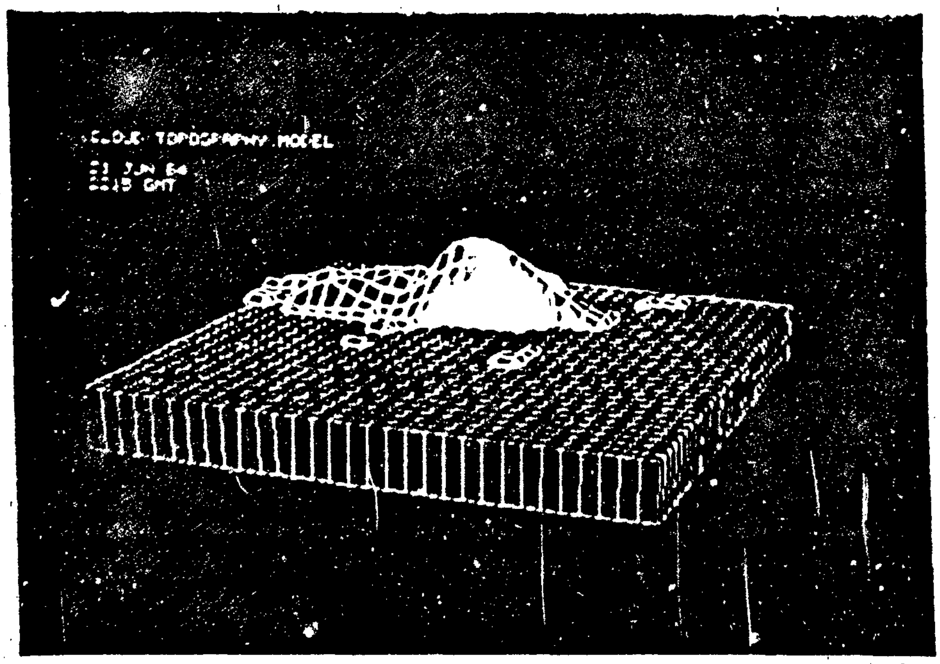
TOPOGRAPHY MODEL

Figure 7-3
Mercator infrared image for 2229 GMT, 21 June 84.

Figure 7-4
3-D cloud-topography model for boxed sub-area
in Figure 7-3.

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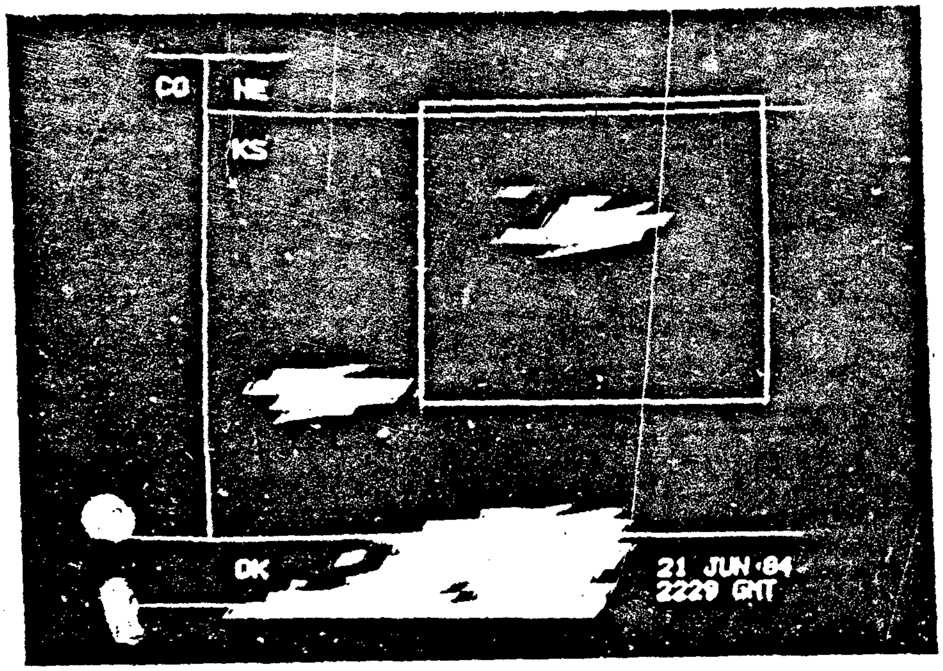
CO
NE
KS
OK
21 JUN 84
2229 GMT

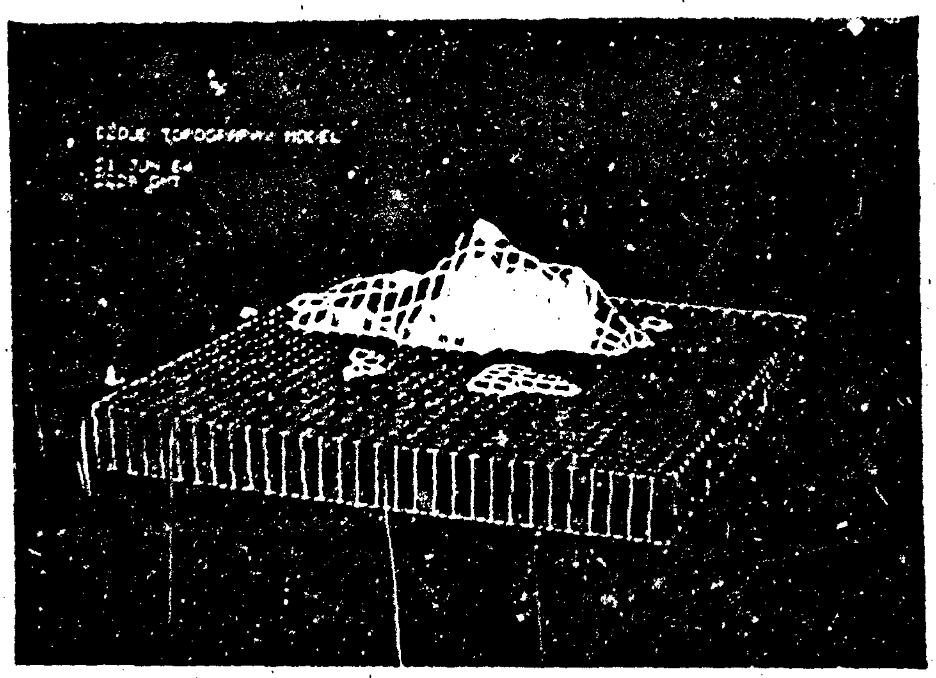

Figure 7-5
Mercator infrared image for 2245 GMT, 21 June 84.

Figure 7-6
3-D cloud-topography model for boxed sub-area in Figure 7-5.

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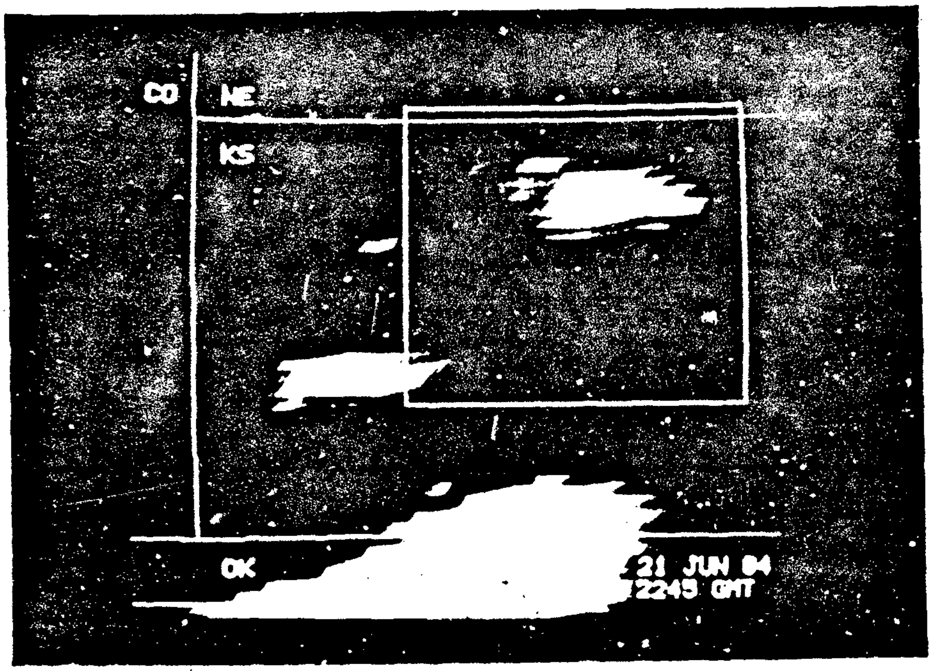
CO
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KS
OK
21 JUN 84
2245 GMT

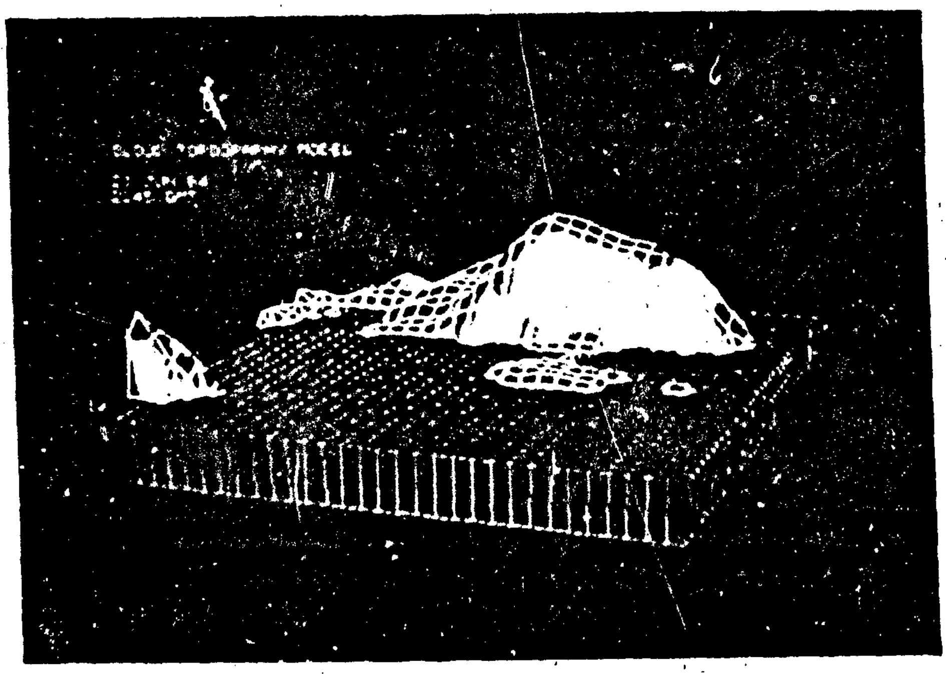

Figure 7-6 shows further development of the cumulus tower and significant development to the east. The entire sequence shows the development of a small isolated thunderstorm which is propogating to the east. Clearing is seen behind the storm. Figures 7-2, 7-4, and 7-6 were part of a four frame movie loop which showed this development in 3-D perspective.

In cloud studies, displays similar to those shown in Figures 7-2, 7-4, and 7-6 can be used to study vertical cloud structure and cloud development. Displays such as these graphically show cloud development in a realistic manner. When used in conjunction with 2-D flat satellite imagery, greater image understanding is realized.

B. Briefing Aids

Displays produced from the 3-D cloud-topography model contain information on cloud cover and weather systems which is of interest to pilots. In addition, these displays effectively present satellite data in such a way that the information can be easily understood and comprehended. As a result, these displays can be used as an aid to brief pilots on weather. However, to make the display more meaningful to a pilot and to enhance the displays information content, flight tracks can be plotted on the 3-D model. These flight tracks mathematically define, in 3-D, the path of an aircraft from take-off to landing. When displayed with the 3-D model, flight tracks enable the pilot to visualize atmospheric conditions along the planned route.

Flight tracks can be plotted on the 3-D cloud-topography model using the FLTRAK program. FLTRAK accepts five parameters which are needed to mathematically define the 3-D track. These parameters include the aircraft's take-off location, average ascent angle, average cruising altitude, average descent angle, and landing location. The take-off and landing locations are specified by entering each locations respective latitude and longitude. Average ascent angle is specified by entering the aircraft's climb angle from the point of take-off to the point where the aircraft reaches its cruising altitude. Similarly, average descent angle is specified by entering the aircraft's descent angle from the point where the aircraft departs from cruising altitude to the point where the aircraft lands. Cruising altitude is specified by entering the aircraft's average altitude, between ascent and descent, in meters. Once all parameters are entered, FLTRAK uses this data to scale a model part defining the aircraft's flight path. This model part is then merged to the specified 3-D cloud-topography model.

Figure 7-7 shows a Mercator infrared image for 2132 GMT, 31 October 84. This figure shows the cloud cover for a portion of southern Colorado and northern New Mexico. A line is shown depicting a flight path from Pueblo, Colorado (PUB) to Durango, Colorado (DRO). Figure 7-8 shows that this route crosses two mountain ranges, the Sangre de Cristo Mountains to the east and the San Juan Mountains to the west. These two ranges are separated by the relatively flat San Luis Valley. Figure 7-7 shows orographically induced clouds formed over these two mountain ranges.

Figure 7-9 shows the corresponding cloud-topography display for the data shown in Figures 7-7 and 7-8. In this figure, the 3-D

Figure 7-7
Mercator infrared image for 3132 GMT, 31 October 84
with flight path plotted.

Figure 7-8
Mercator topographic image with flight
path plotted.

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PUB
CO
NM
31 OCT 84
2132 GMT

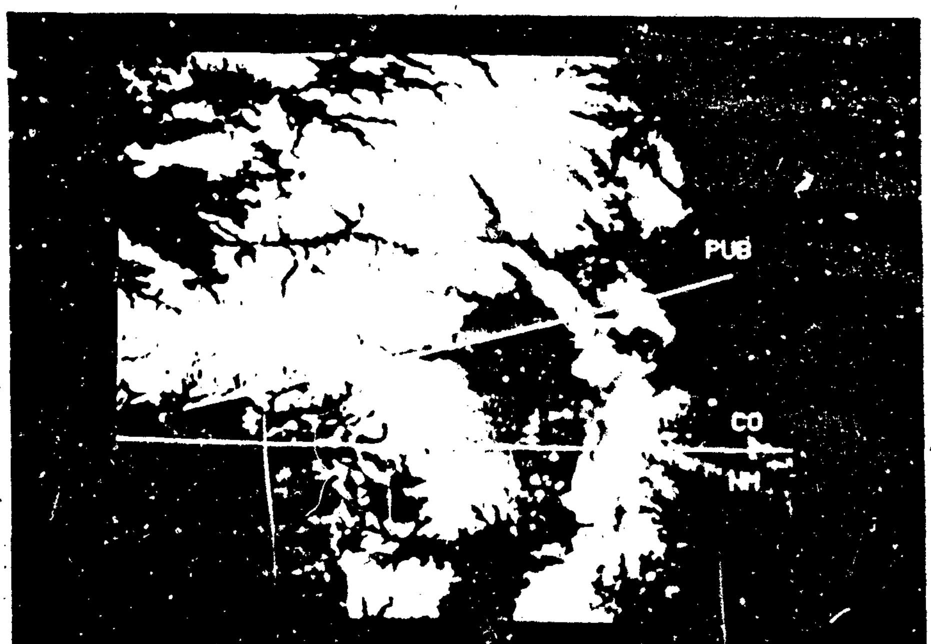
PUB
CO
NM

Figure 7-9
3-D cloud-topography model for data shown in
Figures 7-7 and 7-8 with flight track plotted.

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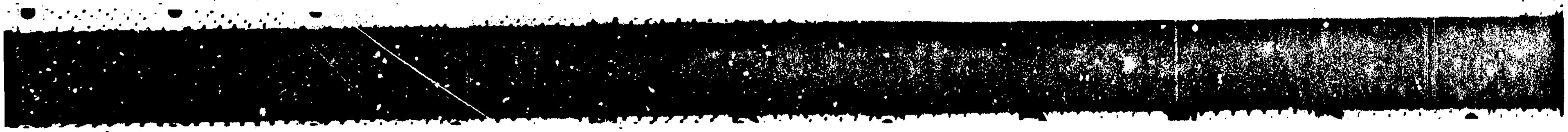

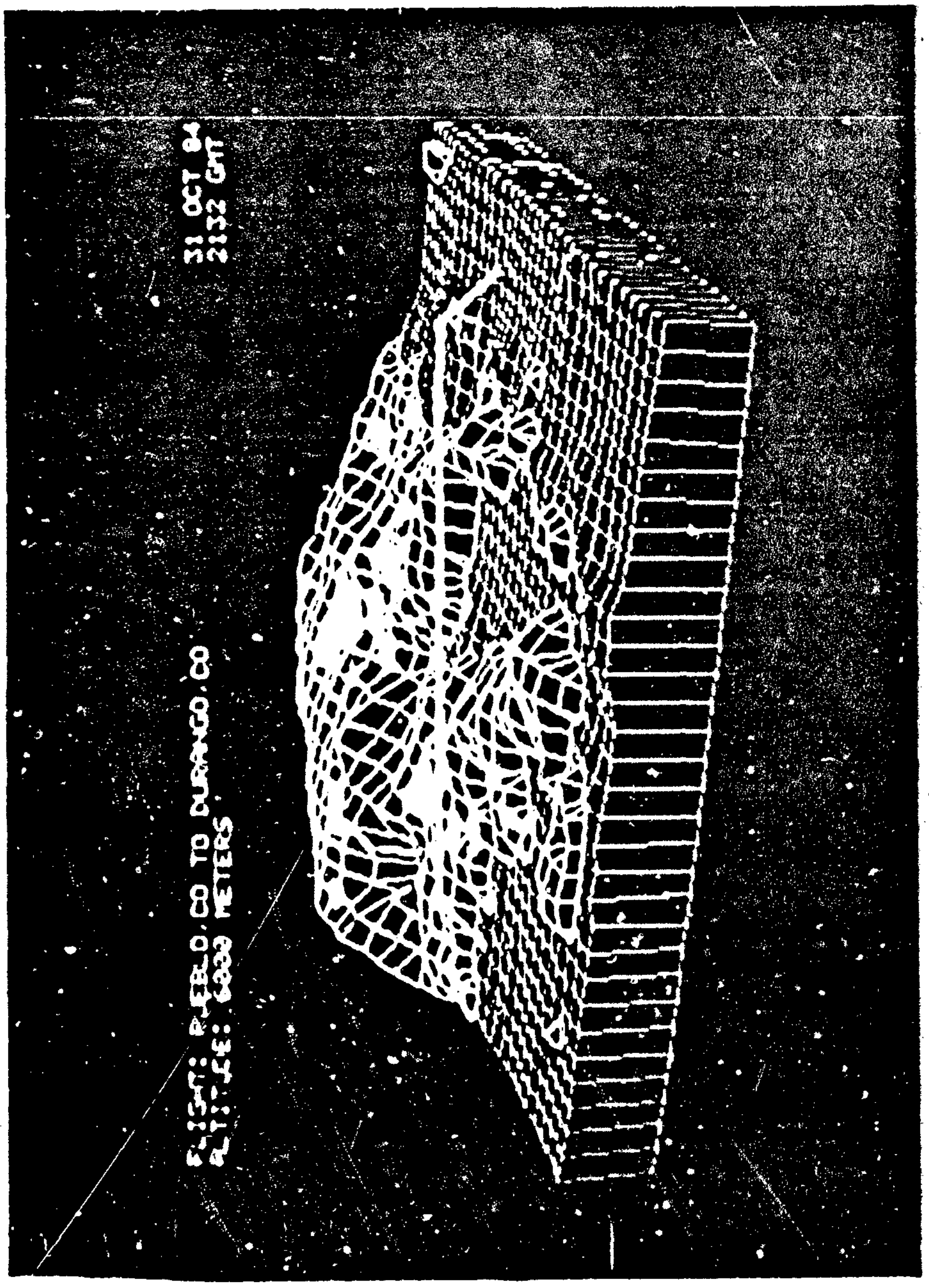
FLIGHT: PUEBLO,CO TO DURANGO,CO
31 OCT 84
2132 GMT

cloud-topography model is viewed from the southeast. A flight track is shown depicting the route from Pueblo, Colorado to Durango, Colorado. The track has been defined by a cruising altitude of 6000 meters and ascent and descent angles of 8 degrees. In this display, ascent and descent angles appear greater than 8 degrees because the vertical scale of the 3-D cloud-topography model has been exaggerated by a factor of 10. From Figure 7-9, it is obvious that a pilot flying this route would encounter orographically induced clouds over the mountain ranges. However, at an altitude of 6000 meters, the pilot should be flying well above the cloud tops. In addition, the display shows that the pilot could expect clear conditions for take-off and landing. Clear skies could also be expected over the San Luis Valley.

As a briefing aid, displays similar to Figure 7-9 could be shown to pilots to brief them on weather. In this type of display, topography data and satellite data are presented in such a way that the information can be quickly and effectively comprehended. Data presented in this manner lets the pilot visualize conditions along the intended route.

C. Flight Simulations

An alternate way of presenting cloud and topography data is from the same perspective that a pilot might see the actual clouds and topography. This display method uses MOVIE.BYU software to manipulate and display the 3-D model in such a way that simulates flight.

Figure 7-10 shows a Mercator visible image valid for 2132 GMT, 31 October 84. This image covers the same geographical area shown in

Figures 7-7 and 7-8. Data is also valid for the same time period. A line defining the flight path from Pueblo, Colorado to Durango, Colorado is also shown in Figure 7-10. A box drawn in the center of the image defines a sub-area that is to be transformed into a 3-D cloud-topography model. Inside the boxed-off area, two bands of orographically induced clouds can be seen which have formed over the Sangre de Cristo Mountains to the east and San Juan Mountains to the west.

The 3-D cloud-topography model created for the sub-area in Figure 7-10 is shown in Figure 7-11. Figure 7-11 graphically shows the view the pilot would see while flying at an altitude of 6000 meters (MSL) and looking west along the line shown in Figure 7-10. This view is valid for point A (labeled in Figure 7-10). In Figure 7-11, a portion of the Sangre de Cristo Mountains is seen in the foreground and the first band of clouds formed above these mountains is visible. Off in the distance, a portion of the cloud free San Luis Valley is seen. On the horizon, the second band of clouds which are formed over the San Juan Mountains is visible.

Figure 7-12 shows the view the pilot might see at point B (labeled in Figure 7-10). In the foreground, cloud tops are visible. More of the San Luis Valley is visible and the orographic clouds on the horizon appear a bit closer.

Figure 7-13 shows the view the pilot might see at point C (labeled in Figure 7-10). Here, the first band of clouds is no longer visible. The cloud free San Luis Valley is seen in the foreground and the second band of clouds is seen on the horizon.

Figure 7-10
Mercator visible image for 2132 GMT, 31 October 84
with flight path plotted.

Figure 7-11
View of 3-D cloud-topography model for boxed
sub-area in Figure 7-10 at point A.

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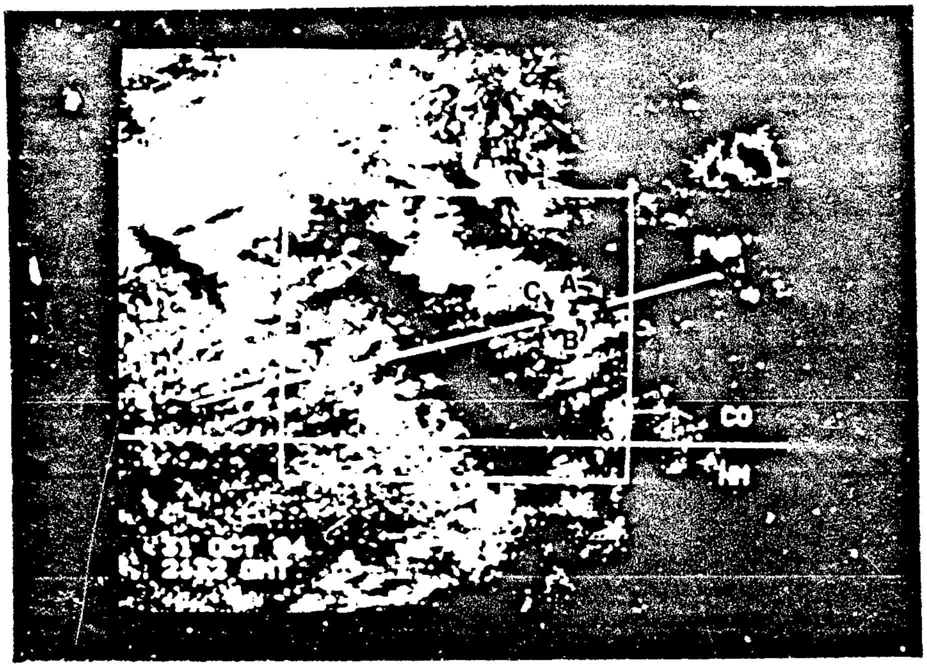
C
A
B
CO
NH

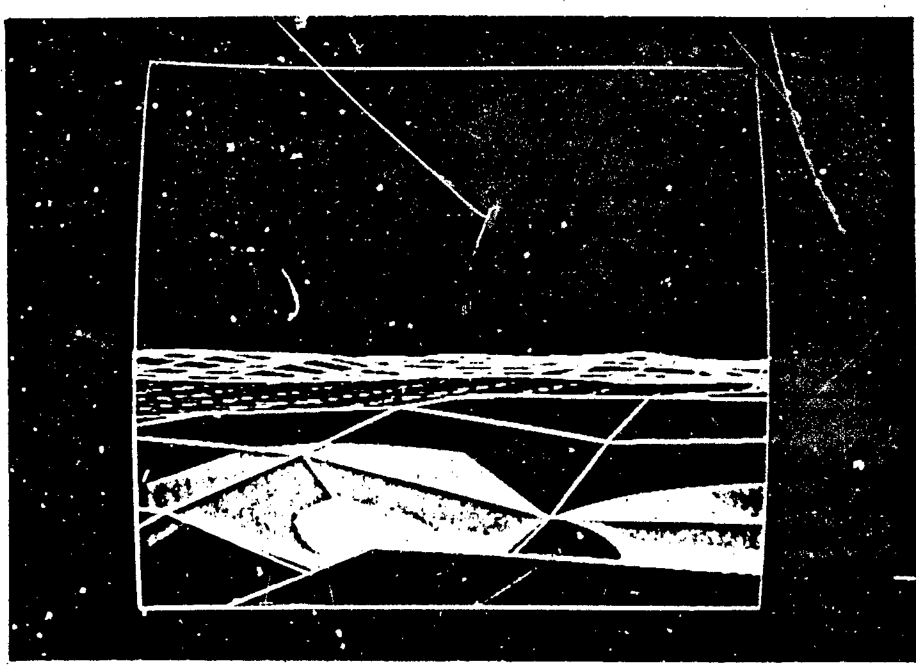

Figure 7-12
View of 3-D cloud-topography model for boxed sub-area in Figure 7-10 at pcint B.

Figure 7-13
View of 3-D cloud-topography model for boxed sub-area in Figure 7-10 at point C.

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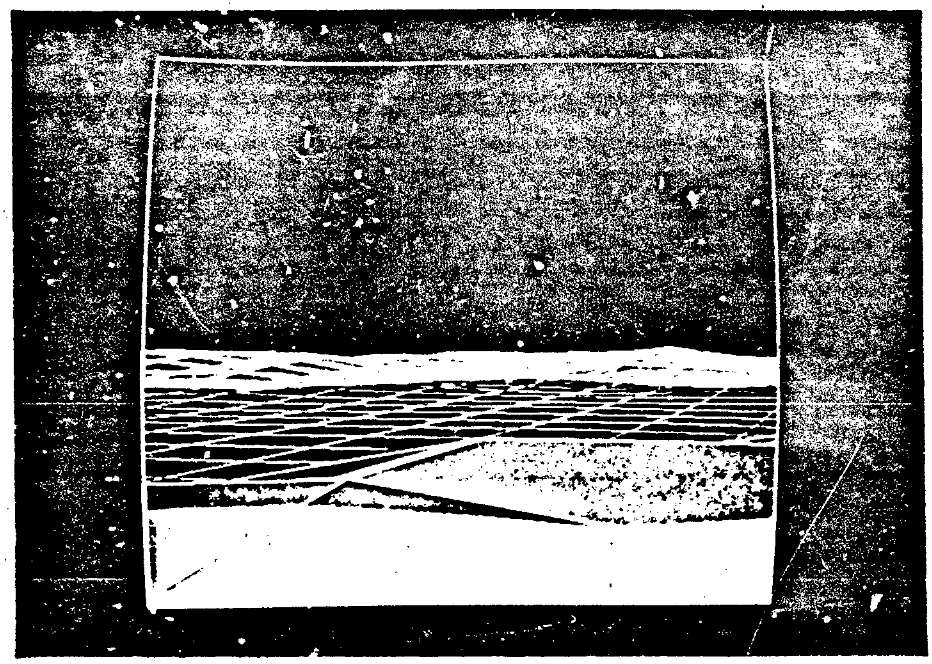

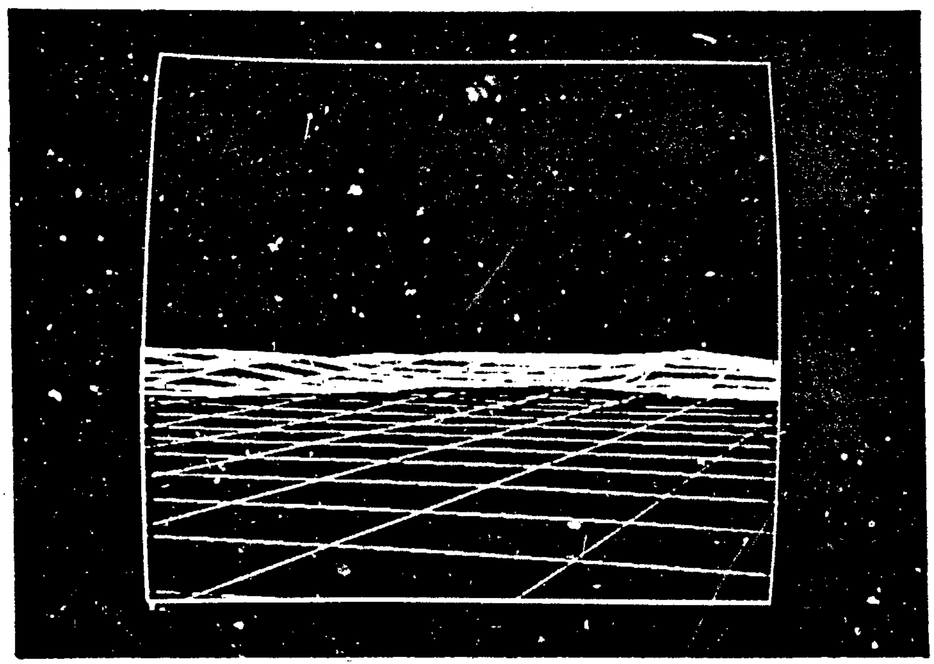

The sequence (Figures 7-11, 7-12, and 7-13) graphically shows what a pilot might see at several points along the hypothetical flight path. It must be emphasized that these displays are created using actual satellite data versus simulated data. Data displayed in this way, or perhaps movie loops showing such a sequence, could be shown to pilots to inform them on weather conditions along a flight route.

The next sequence of figures compares an actual photograph of clouds to a computer graphic display of clouds. The photograph was taken from a commerical airliner on approach to Stapleton International Airport in Denver, Colorado on 2 December 84. The computer graphic display of cloud cover is valid for 2132 GMT, 31 October 84 for the area shown in Figure 6-1. It is important to note that the valid times of the graphic display and the photograph do not match. However, the meteorological situation is similar in that orographically induced clouds are formed over the Front Range of the Rocky Mountains.

Figure 7-14 shows a scale model of the cloud cover and topography shown in Figures 6-1 and 5-1. The area covered by this model includes most of central Colorado including the Denver area and the Front Range.

Figure 7-15 shows a view of the above cloud-topography model from the same perspective a pilot might see clouds and topography on an approach to Stapleton International Airport. This view shows the orographically induced clouds over the Front Range.

Figure 7-16 is a photograph of orographically induced cloud cover over the Front Range. This photograph was taken looking west and slightly north, approximately 100 kilometers from the Front Range using a 28 millimeter, wide angle lens.

Figure 7-14
3-D cloud-topography model for 2132 GMT, 31 October 84
drawn to scale.

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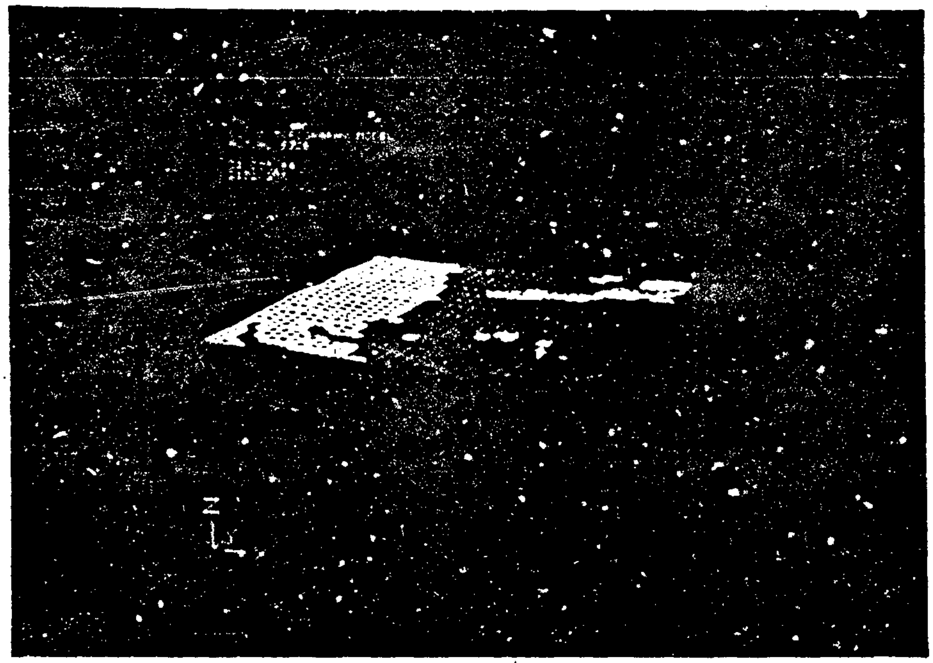

Figure 7-15
3-D cloud-topography model for 2132 GMT, 31 October 84, showing orographically induced clouds over the Front Range.

Figure 7-16
Photograph of orographically induced clouds over the Front Range taken from a commerical airliner on 2 December 84.

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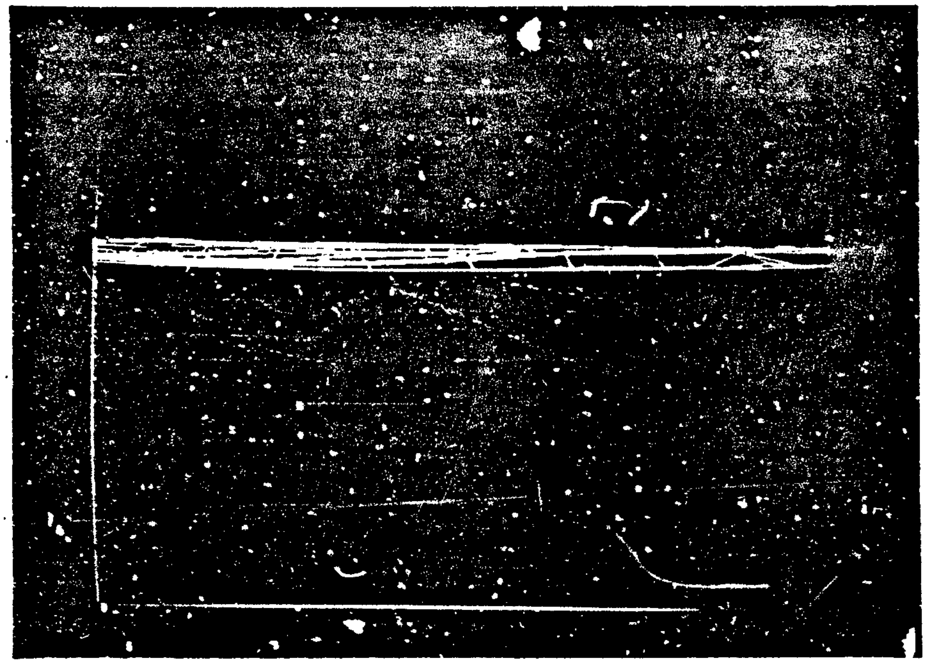

By comparing Figures 7-15 and 7-16, the graphic representation of the orographic clouds is similar to the actual photograph of the orographic clouds. This last sequence of figures shows that graphically produced cloud representations can be used for flight simulations.

CHAPTER 8

Conclusion

A. Summary

In this research, GOES satellite data and topography data have been mapped into high resolution, Mercator images which accurately overlay each other. As a result, cloud cover information can be obtained with respect to topography. Using a matching set of Mercator images, a sub-area can be specified which defines the portion of the images to be transformed into a 3-D, mathematically defined model. To determine cloud cover for this sub-area, a cloud/no cloud threshold is specified for the infrared image. Pixels with radiance counts greater than or equal to the cloud/no cloud threshold are considered cloudy. Cloud top heights are determined for cloudy pixels by relating the pixels radiance count to temperature. The resulting temperatures are then related to height using an atmospheric profile of temperature versus height. Cloud base heights are determined for cloudy pixels by manually estimating the base height. This estimation is based partly on guidance from data contained in the infrared image and partly on meteorological experience. Information contained in the Mercator topographic image is used to produce a 3-D topography model for the defined sub-area. Cloud top height information, cloud base height information, and cloud cover information is used to produce 3-D cloud models for the defined sub-area. The resulting 3-D topography model and the 3-D cloud models are combined to produce the 3-D cloud-topography model.

Three-dimensional cloud-topography models can be rotated, manipulated, illuminated, and displayed using MOVIE.BYU software. The resulting displays produce a realistic depiction of cloud cover above a topographic surface. Due to the display's visual appeal and enhanced information content, these cloud-topography displays are well suited for cloud studies, briefing aids, and flight simulations.

For cloud studies, 3-D cloud-topography models can be used to study vertical cloud structure and cloud development using methods similar to those currently used for 2-D flat imagery. When used in conjunction with 2-D satellite imagery, the displays produced from the 3-D model enable greater image understanding.

For pilot briefing, 3-D cloud-topography models can be modified to show an aircraft's flight track. As a briefing aid, the displays produced from the modified 3-D model enable the pilot to visualize atmospheric conditions along the planned flight route. When presented in this manner, satellite data and topography data can be quickly and effectively comprehended.

For flight simulation, 3-D cloud-topography models can be rotated and manipulated in such a way that cloud cover and topography can be viewed from the same perspective a pilot might see the actual cloud cover and topography. Data viewed in this manner can also be used to brief pilots, or could be used in flight simulations.

B. Future Work

One area for future work would focus on improving the 3-D cloud-topography model. Currently, the cloud-topogaphy model contains only one layer of clouds. Although the software is set up to handle up to three layers, current methods for cloud determination can only descriminate one layer of clouds in the satellite image. The addition of the capability to descriminate multiple cloud layers would make the 3-D model more realistic. Another model improvement would incorporate a quantitative vertical scale into the model. Mackinen (1984) describes two excellent methods for scaling cloud data which could be adapted to the 3-D cloud-topography model. The capabililty to display a quantitative vertical scale would allow the user to better estimate the vertical extent of clouds. Another model improvement would incorporate an option to scale the topographic data in such a manner that would allow topographic features to be seen in areas where terrain is relatively flat. For example, the cloud-topography displays shown in Figures 7-2, 7-4, and 7-6 show the development of a thunderstorm over northern Kansas. However, topographic features in this area cannot be seen. The incorporation of advanced vertical scaling techniques would show topographic features without distorting the clouds which are displayed above the topographic surface. One final improvement would incorporate more advanced techniques to: 1) descriminate cloudy and clear regions in infrared satellite image, 2) determine cloud top heights, and 3) determine cloud base heights. These improvements would increase the accuracy of the data being displayed.

Another area for future work would focus on decreasing the amount of time required to create and display a 3-D cloud-topography model. Currently, it takes approximately five minutes to create a 3-D model, and fifteen minutes to display the 3-D model. Thus, most of the time is spent displaying the 3-D model. To significantly reduce this time, more efficient algorithms are needed to display the 3-D model. To speed up the process, the general purpose MOVIE.BYU software could be abandoned in favor of new software which is specifically designed for the display of meteorological data. This new software would use more efficient algorithms to perform the coordinate transformations needed to display the model. Another approach to this problem would utilize a hardware/sofware combination to perform these coordinate transformations. This approach could result in systems that perform the coordinate transformation function and the model display function in real time (approximately 1/30 of a second). A real time system would be ideal for applications such as flight simulation where actual movement during flight could be simulated.

Still another interesting area for future work would compare actual photographs of clouds to computer graphic cloud representations produced from the 3-D cloud-topography model. Here, aircraft flights could be made and photographs of clouds could be taken. At the same time the photographs are taken, satellite data could be collected. Computer graphic representations of clouds could be produced from the satellite data and compared to the actual photogaphs taken from the aircraft. Such comparisons would be valuable for cloud studies, model improvements, and other research activities.

One last area for future work would explore additional applications for the 3-D cloud-topography model. Three applications for the 3-D cloud-topography model are discussed in this thesis. Other applications could be developed which would take advantage of the MOVIE.BYU software display capabilities. One possible application would incorporate radar data into the 3-D cloud-topography model. Using this idea, cloud cover and radar echo regions could be displayed to show precipitation areas in clouds. Another possible application would incorporate other meteorological data into the 3-D cloud-topography model. Displays could be produced showing cloud cover and isentropic surfaces, cloud cover and pressure surfaces, or cloud cover and any other meteorological parameter which could be adequately described as a surface. Another possible application would use the 3-D cloud-topography model for spatial cloud studies. Here, 3-D clouds could be projected onto a surface and percent cloud free line of sight could be calculated as a function of angle and distance. These are but a few potential applications which could be developed using the 3-D cloud-topography model. Undoubtedly, there are many more.

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