FINAL REPORT

Analytical Tools for Cloudscope Ice Measurement

IN-47
011387

By

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NASA CONTRACT NAG 2-1104

PERIOD: January 1, 1997 - December 31, 1998.

DECEMBER 1998

ABSTRACT

The cloudscope is a ground or aircraft instrument for viewing ice crystals impacted on a sapphire window. It is essentially a simple optical microscope with an attached compact CCD video camera whose output is recorded on a Hi-8 8mm video cassette recorder equipped with digital time and date recording capability. In aircraft operation the window is at a stagnation point of the flow so adiabatic compression heats the window to sublimate the ice crystals so that later impacting crystals can be imaged as well. A film heater is used for ground based operation to provide sublimation, and it can also be used to provide extra heat for aircraft operation. The compact video camera can be focused manually by the operator, and a beam splitter - miniature bulb combination provide illumination for night operation. Several shutter speeds are available to accommodate daytime illumination conditions by direct sunlight.

The video images can be directly used to qualitatively assess the crystal content of cirrus clouds and contrails. Quantitative size spectra are obtained with the tools described in this report. Selected portions of the video images are digitized using a PCI bus frame grabber to form a short movie segment or stack using NIH (National Institute of Health) Image software with custom macros developed at DRI. The stack can be Fourier transform filtered with custom, easy to design filters to reduce most objectionable video artifacts. Particle quantification of each slice of the stack is performed using digital image analysis. Data recorded for each particle include particle number and centroid, frame number in the stack, particle area, perimeter, equivalent ellipse maximum and minimum radii, ellipse angle, and pixel number. Each valid particle in the stack is stamped with a unique number. This output can be used to obtain a semiquantitative appreciation of the crystal content. The particle information becomes the raw input for a subsequent program (FORTRAN) that synthesizes each slice and separates the new from the sublimating particles. The new particle information is used to generate quantitative particle concentration, area, and mass size spectra along with total concentration, solar extinction coefficient, and ice water content. This program directly creates output in html format for viewing with a web browser.

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Analytical Tools for Cloudscope Ice Measurement

INTRODUCTION.

The cloudscope is an wing mountable instrument for imaging cloud hydrometeors and large aerosol that impact upon the sapphire window. Figure 1 is a schematic representation of the cloudscope.
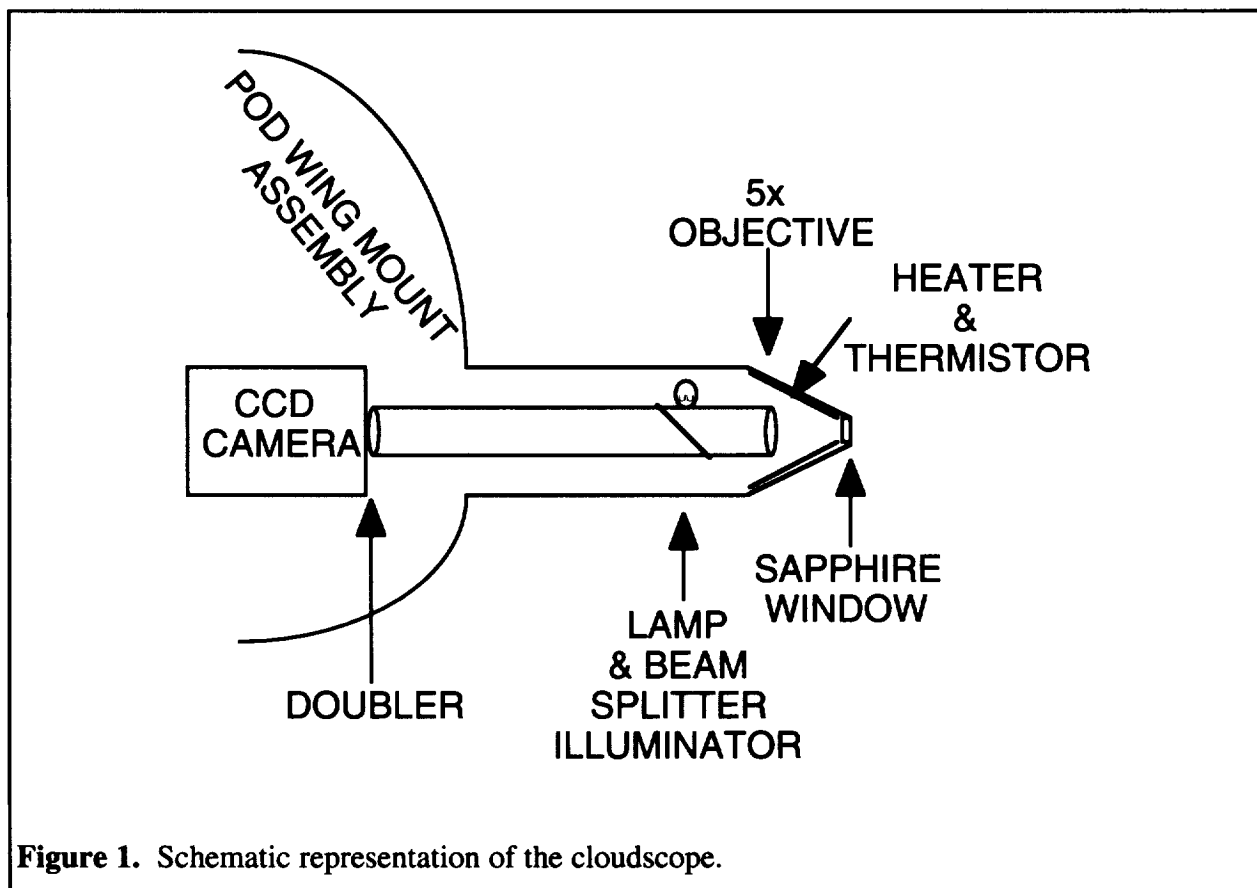
Figure 1. Schematic representation of the cloudscope.

This report will concentrate on the application of the cloudscope to ice crystals in cirrus clouds and contrails. In aircraft operation the cloudscope is mounted on a wing pod (i.e. 'PMS' pod) with the controls at the station in the aircraft. Ice crystals impact on the sapphire window and are imaged onto the CCD array of the camera with the combination of objective and doubler. The relative distance between the camera and the objective can be adjusted during flight for optimal focus. The nose cone of the objective can be heated to encourage sublimation, or when off, the sapphire window is adiabatically heated as it is a stagnation point of the flow. In the absence of nose cone

heating, the window typically arrives at the total temperature. The total temperature is simply the air temperature plus a term proportional to the square of the flow velocity (conversion of kinetic energy to heat). For night time operation a beam splitter is used to direct the illumination from a built in lamp onto the sapphire window.

An image of the cloudscope mounted on a meteorological aircraft is shown in Fig. 2.

Figure 2. Cloudscope mounted on the outer pod of the UND Citation.

The cloudscope is on the outer pod while the forward scattering spectrometer probe is mounted on the inner pod. The flight direction is toward the left.

Let us work through an example to illustrate the cloudscope data products and the steps involved in the analysis. First one selects a segment of video tape to analyze. It is best to work with segments that have minimal overlap of crystals, implying that crystals are neither too large nor too numerous. These conditions are best met in high altitude cirrus near cloud top and in young contrail. Typically we use a Sony CVD1000 VCR that can display the crystal images and an

overlaid time stamp on a monitor while simultaneously displaying the crystal images on the computer screen through use of the on board computer frame grabber (computer details will be given later). We are interested in evaluating an 18 second flight segment (from cloudscope data on the hurricane Nora outflow over the DOE SGP CART site on 26 Sept. 97, UND Citation aircraft platform) and will set the computer to grab frames at 10 frames per second. The VCR records at a nominal rate of 30 frames per second. The combination of computer memory and frame grabber memory determine the maximum number of frames that can be grabbed and the maximum frame rate. The user triggers the computer with the mouse to start capturing frames when the desired time arrives, and the computer obtains a digitized movie.

The frame grabber captures gray scale images at a size of 640x480 pixels using the NIH Image application (let's simply call it NIH). A montage of these images is shown in Fig. 3, where for size reference, the horizontal distance across one frame is approximately 420 μm, and is equal to 640 pixels. Every 10th frame is shown. Note that old crystals sublimate on higher frame numbers and that a new crystal has impacted on frame 111.

Some images have excess noise in them from video noise or scratches on the window. These can be removed or reduced by using Fourier transform filtering. The Fourier transform of one frame of the montage in Fig. 3 is shown in Fig. 4. Most of the crystal image information appears near the center of the Fourier transform. Several dark spikes are out in the middle of each quadrant, and these correspond to video imperfections like faint diagonal lines in the images. Sometimes these lines cause problems on the analysis as they are recorded as particles. Our macros written for NIH allow one to interactively design a filter for removing undesirable spatial frequency components. Figure 5 shows a filter designed with a wide wand tool in NIH (10 points brush width). One simply waves the white wand over those frequency components to be removed, directly on the FFT image. Note that the filter doesn't have to be that precise to be effective. When finished, the macro converts the filter to a binary image as needed for the filter and inverse transform operation that occurs next. All images in the movie (also called a stack) are Fourier transformed and filtered using the filter. The resulting montage of images upon filtering is

shown in Fig. 6. The improvement in image quality can be quite dramatic for certain images, though the example here already started with a relatively clean stack.
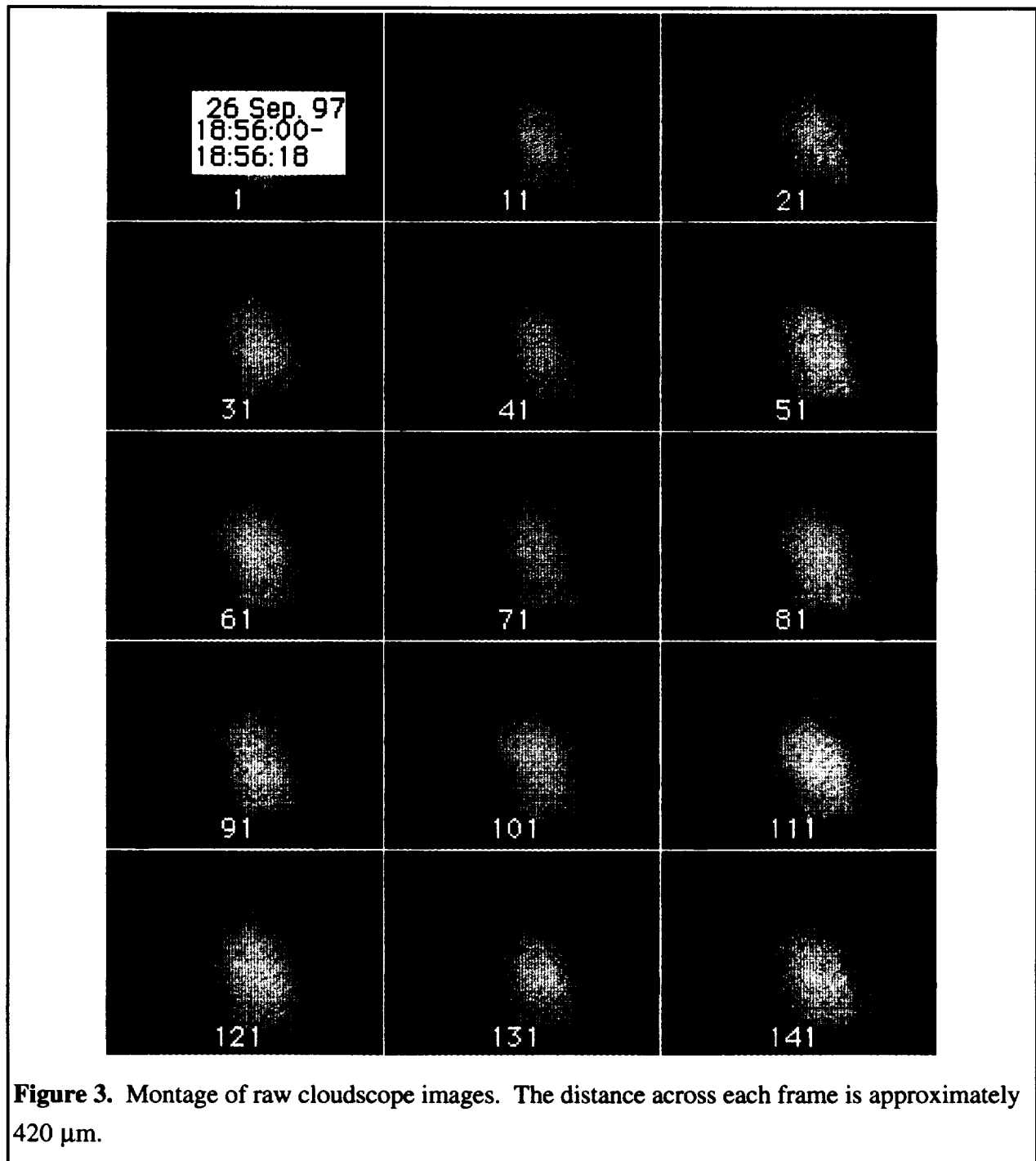
Either the raw stack of Fig. 3 or the filtered stack of Fig. 6 can be used for the next step. Our NIH macro produces quantitative measures for the particles in each slice of the stack by performing particle sizing and quantification using digital image analysis. NIH produces both a analyzed stack and a spread sheet of values of particle properties. The analyzed stack is very useful because each particle detected by NIH is given a number as shown in Fig. 7. One can then play the original stack side by side with the analyzed stack to ensure that the algorithm is working correctly. Once the spread sheet of values is confirmed and correct, it can be used to produce semiquantitative plots of the crystal character in the cirrus cloud, as shown in Fig. 8. Figure 8 is somewhat complex so let's consider each part in some detail. One horizontal axis is the pixel number or crystal position. Now, each pixel in the 640x480 grid is given a unique number assigned by ascending row and column. The crystal position is then determined by NIH as the centroid of the particle. The other horizontal axis is frame number, and is a measure of time. The time between frame numbers is dependent on the frame digitization rate. The third axis (z axis) is the crystal area given in pixels, and is the area reported by NIH for the particle. Particle sublimation is easily observed on these kinds of graphs. Each 'ski slope' corresponds to a sublimating particle. Note that some particles never sublimate at all. These are either imperfections on the ccd array of the camera or are non-aqueous particles (large aerosol). They can easily be discerned from the sublimating particles. One can qualitatively compare the sublimation rate of different particles using this kind of graph. Note that the sublimation rate is habit dependent to a large degree (fluffy particles sublimate fast), and probably also substance or impurity dependent as well, though the decoupling of fluffiness and impurity is non trivial if not impossible.
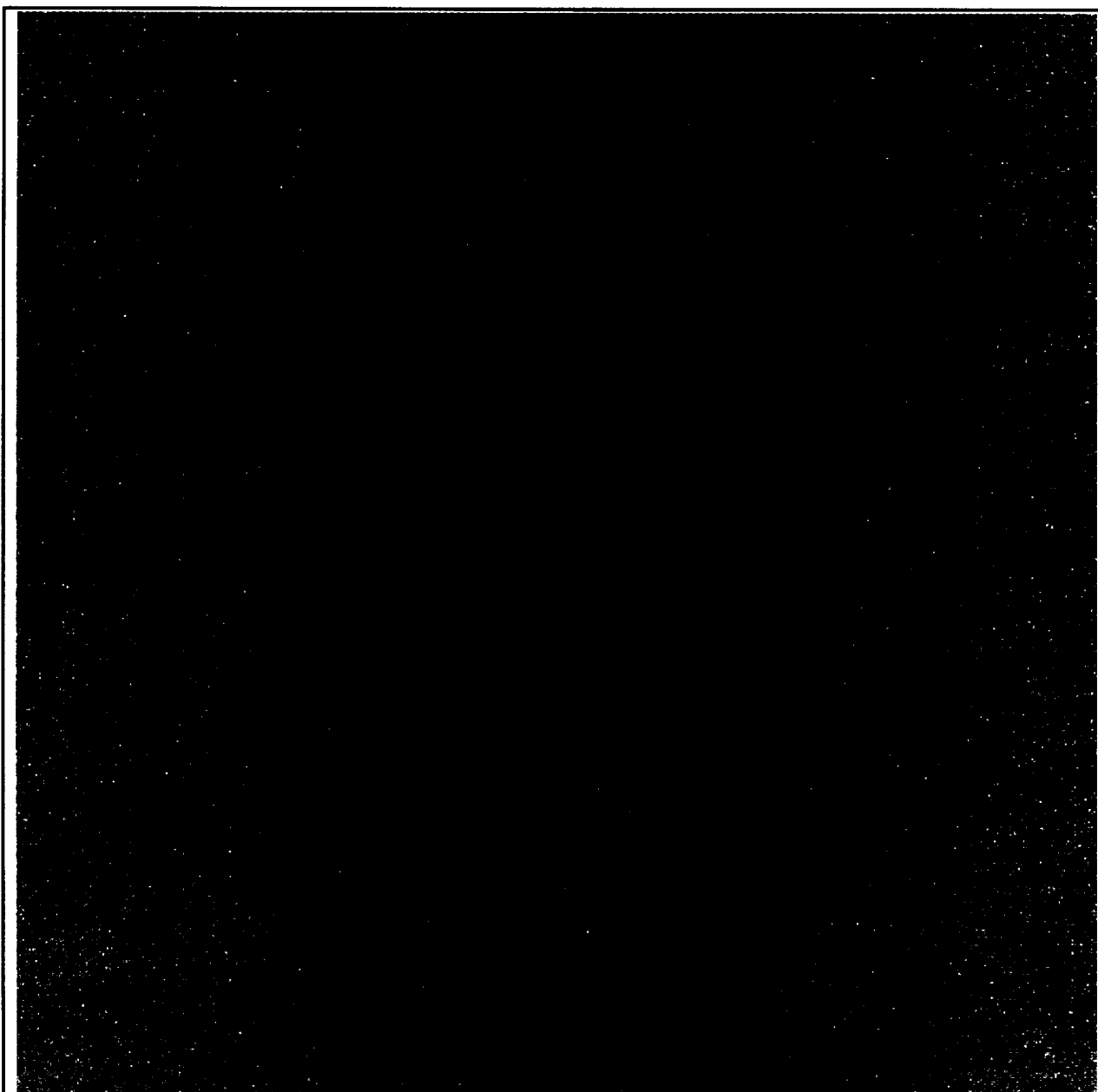
Once NIH is through with the stack, the spread sheet is read into a FORTRAN program to compute particle size spectra, normalized by flight speed, field of view, and the time between slices in the stack. The FORTRAN program computes a synthetic image where particles are conceived of as ellipses having aspect ratios and orientation as determined by NIH. NIH conserves the particle
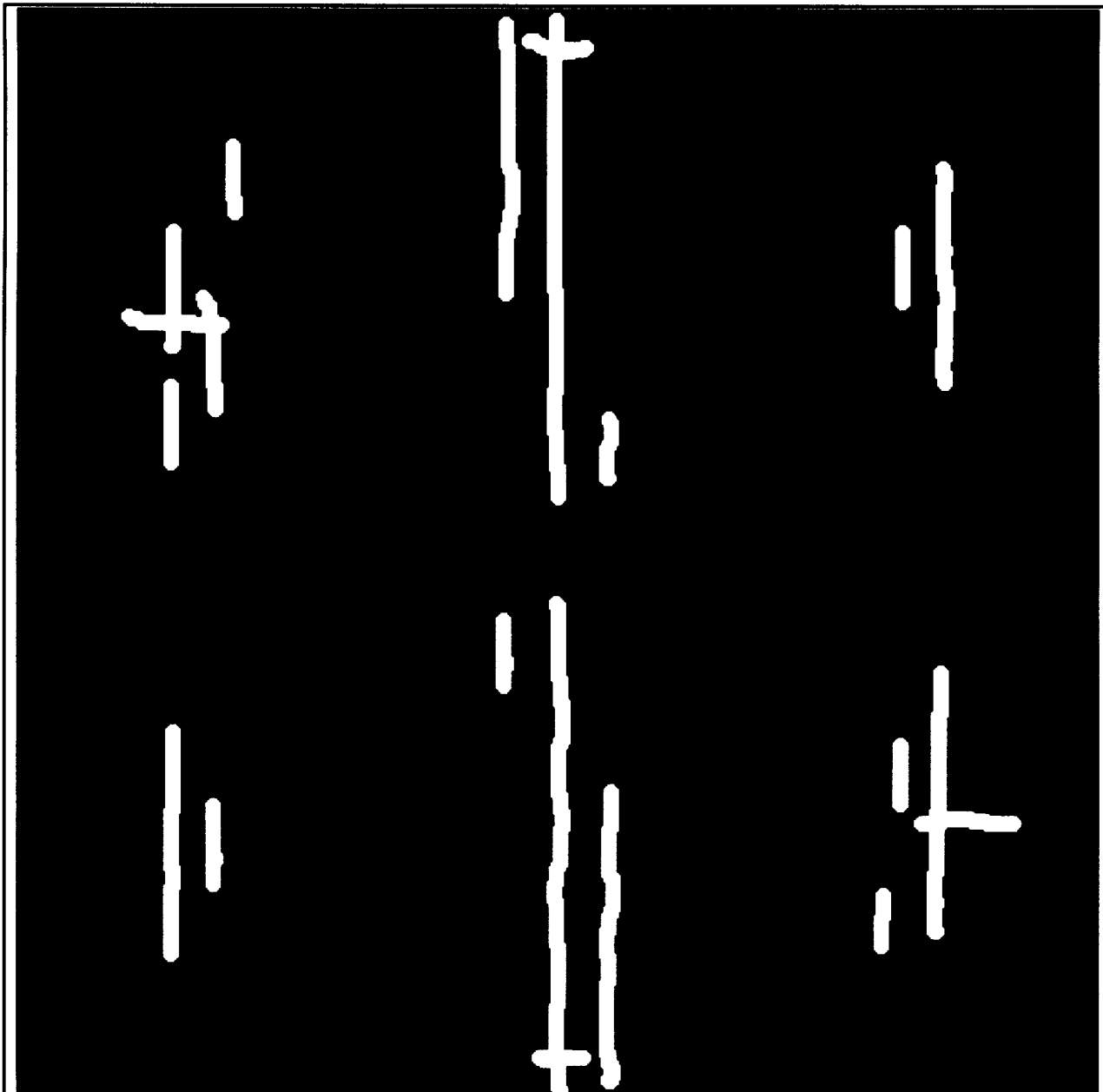
area in fitting an ellipses to a random particle, and also computes a particle perimeter. The FORTRAN program simply compares the present synthetic slice with the previous one to see if the particle in question overlaps with one on the previous slice. If it does not overlap, it is likely a new particle, and so is added to the number concentration bin that corresponds to its maximum ellipse dimension. The area is also saved and binned, and added to the running sum of computed optical depth. The mass is estimated from mass dimensional relationships at this point, but the sublimation rate versus time is also a computed quantity if desired.

Figure 9 is an example from another time interval from the same flight as the data from Figs. 3-8. Figure 9 compares the number concentration observed by 4 distinct probes. The FSSP probe is calibrated to measure the size of spherical water droplets equivalent to an amount of light scattered into a cone of angle 3-10 degrees, and has not been properly qualified for use in cirrus. The problem with cirrus and contrails is the small crystal content - the standard 2DC imaging array probes do not have the resolution or sample rate to do a great job on the small particle end of the spectrum. Note that the FSSP and cloudscope reckoning of particle size spectra are in reasonable agreement, that the replicator and 2DC spectra agree well, and that the replicator response apparently rolls off with decreasing particle size likely due to collection efficiency problems. This is a very interesting piece of hard fought data. The analysis was quite careful in obtaining these spectra. It is the first time that direct evidence of FSSP efficacy has been evaluated with a probe capable of measuring in the same size range, and is also direct evidence that the fuselage replicator often operated on the Citation aircraft does have a roll off issue in some circumstances of operation. (The wing mounted replicator is not likely to have these collection efficiency issues due to a major difference of design. In the fuselage replicator, flow is forced out the entrance slit to evaporate the chloroform. In the pod replicator, no such outflow exists.)

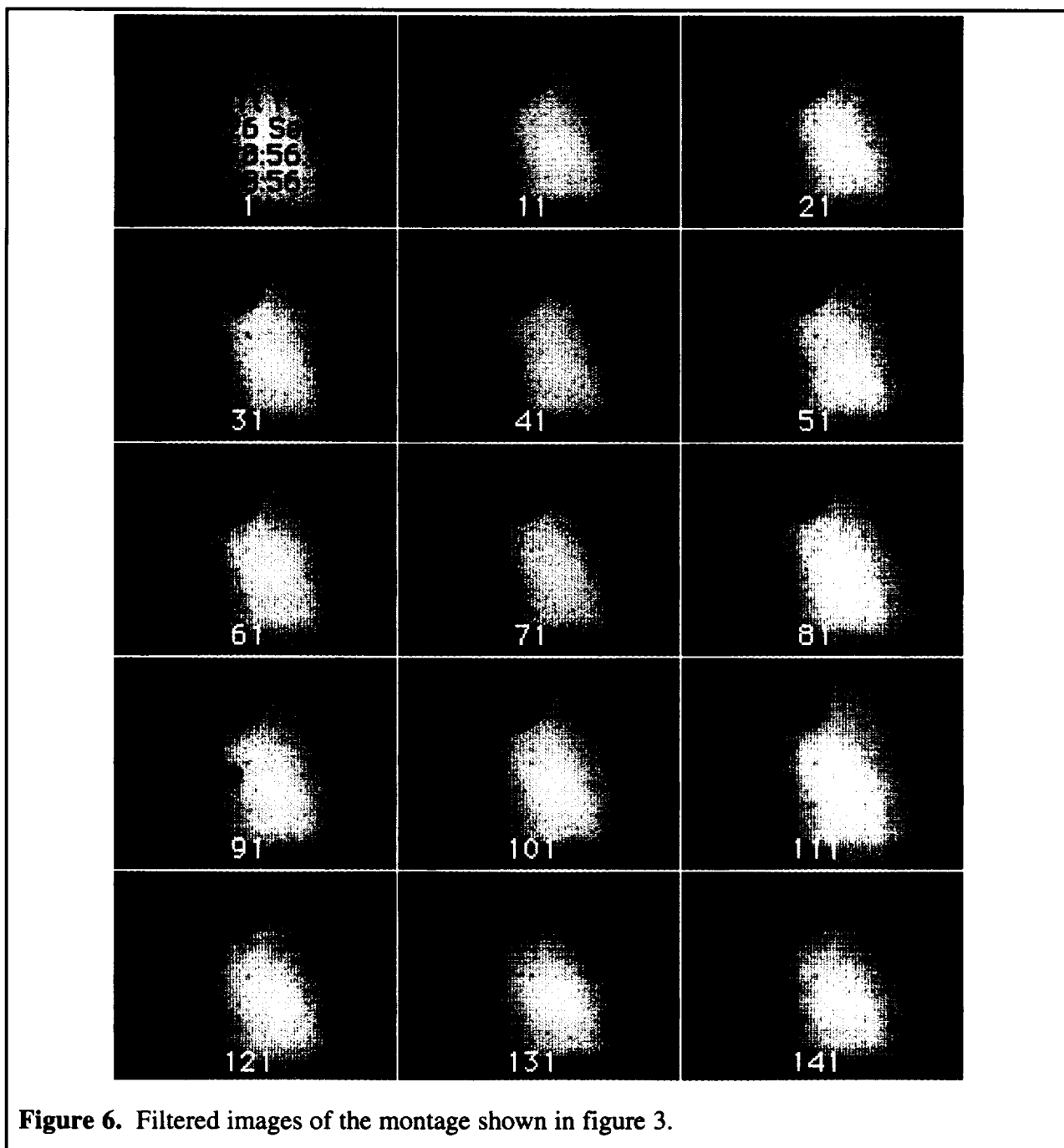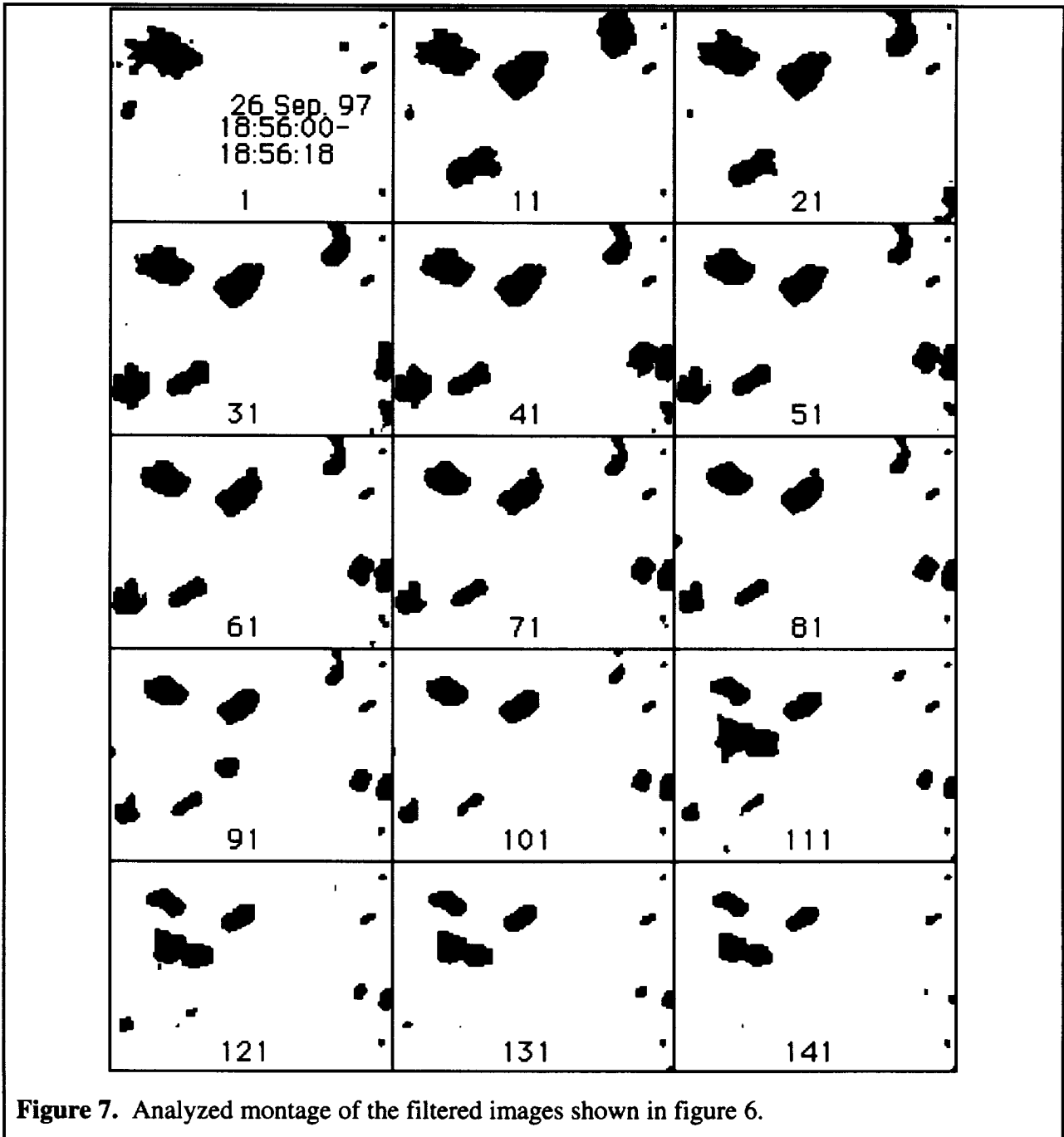**Figure 3.** Montage of raw cloudscope images. The distance across each frame is approximately 420 μm.

Figure 4. Fast Hartley transform of one slice of the montage in Figure 3.

Figure 5. Binary mask used to block undesired spatial frequency components in figure 4.

Figure 6. Filtered images of the montage shown in figure 3.

Figure 7. Analyzed montage of the filtered images shown in figure 6.
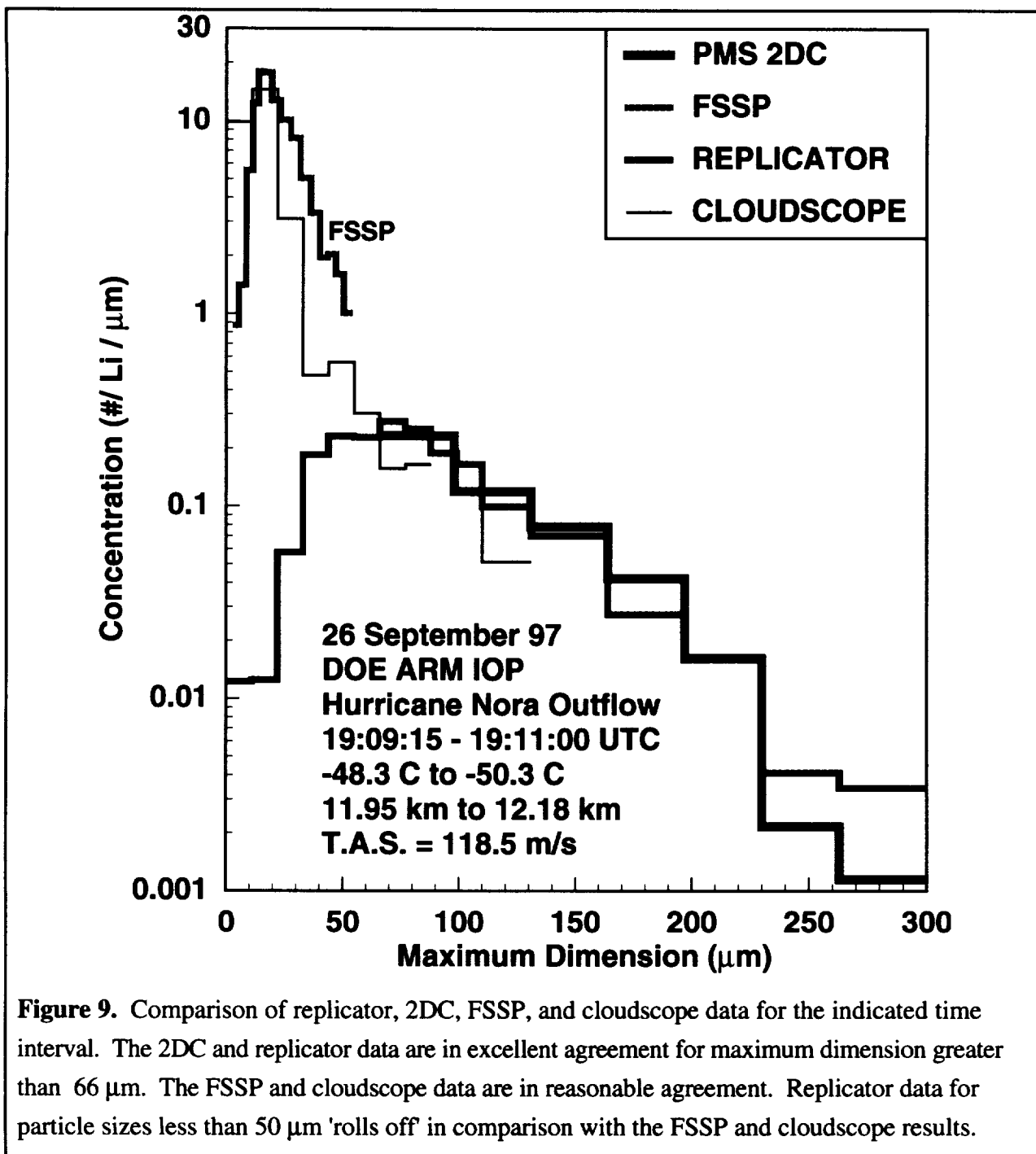
**CLOUDSCOPE CIRRUS DATA FROM DOE ARM 97 IOP: 26 September
18:56:00-18   Air Temperature = -46 C, ambient pressure = 226 mb
30 frames / second capture, 10 frames / second analysis, 1.524 pixels/μm**
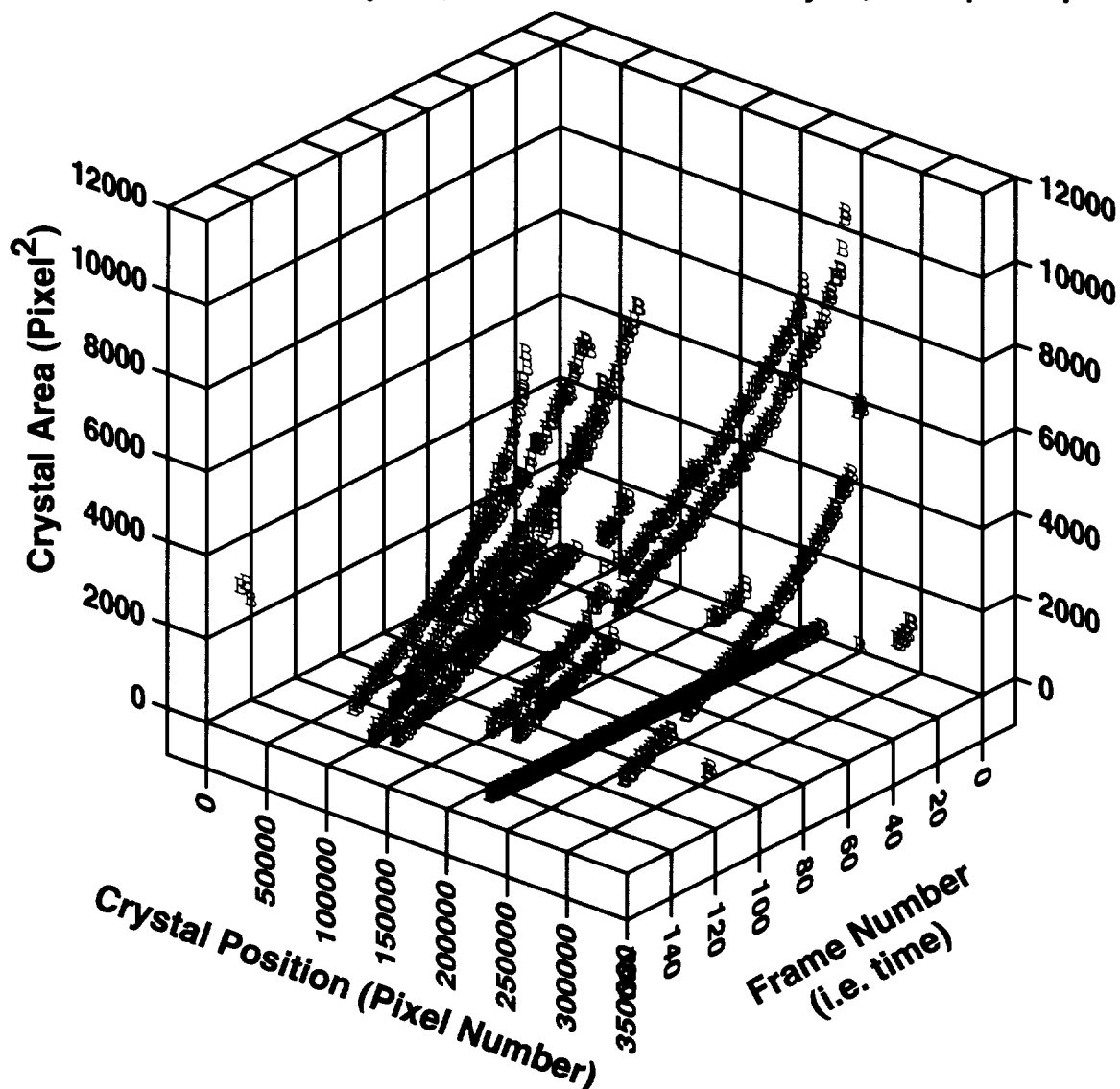
Figure 8. Time evolution of crystal area. Each 'ski slope' corresponds to a sublimating crystal.

Figure 9. Comparison of replicator, 2DC, FSSP, and cloudscope data for the indicated time interval. The 2DC and replicator data are in excellent agreement for maximum dimension greater than 66 μm. The FSSP and cloudscope data are in reasonable agreement. Replicator data for particle sizes less than 50 μm 'rolls off' in comparison with the FSSP and cloudscope results.

A. Another example

Another example of the power of Fourier transform filtering is considered along with a

discussion of the limitations of the analysis program. Figure 10a shows an image of contrail

particles obtained during SUCCESS on the 05/12/97 flight near 11:22:20. Note the high aspect

ratio particle in the second quadrant of the image. There is a lot of noise in this image, both in the

form of vertical lines on the left, video interference throughout, and darkness on the right. In

addition, the partial lines on the left half of the image are actually scratches on the cloudscope

window and appear on every frame. We would like to use Fourier transform filtering to remove

the noise. The Fourier transform filtered image is shown in Fig. 10b. Note the image

improvement and the total absence of the vertical lines on the left. These vertical lines would have

been a major difficulty for the particle counting algorithm within NIH.

The Fourier transform of Fig. 10a is shown in Fig. 11a. The vertical lines in Fig. 10a

show up as a horizontal frequency spectra on the center of the image, and the spatial frequency

spectra associated with the scratches are the tell tale lines near the origin, at an angle of about 10

degrees (the Fourier components are at 90 degrees orientation difference from regular image

features like the scratches). The Fourier transform filter shown in Fig. 11b was coarsely designed

and implemented to clean up the image. The dark regions of the filter are passed and the white

regions are stopped (set to zero).

Even with Fourier transform filtering, the image in Fig. 10b is still noisy in the sense that

the dark regions on the right hand side are still dark. From frame to frame, this darkness is

different, and even breaks up at times, mimicking particles. The great variability of this darkness

causes the FORTRAN program to pick up many false particles.
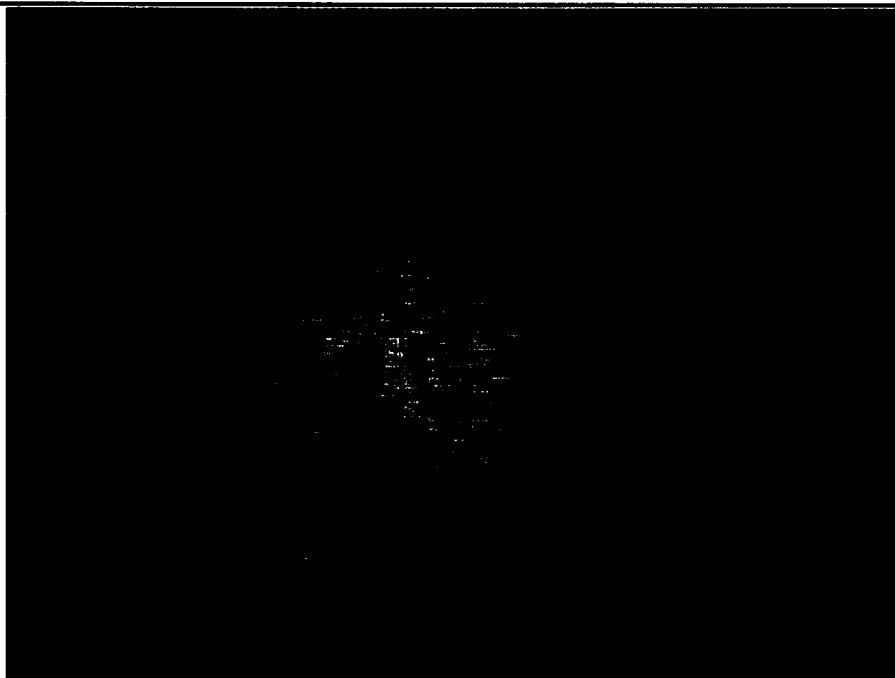
Figure 10a. Raw slice of an image from contrail particles on 5/12/98 during SUCCESS. Note the vertical lines on the left and the slashes due to video interference.
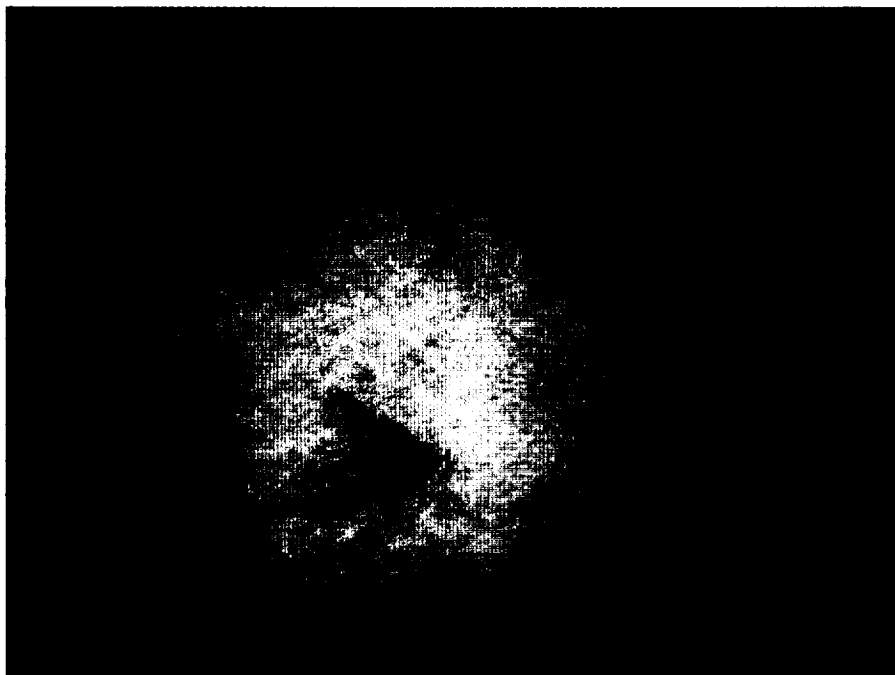
Figure 10b. Same slice as in 10a, though now cleaned up with Fourier transform filtering. Note that the right boundary remains dark. This boundary is recorded as a variable background, and thus is very difficult to distinguish from particles.
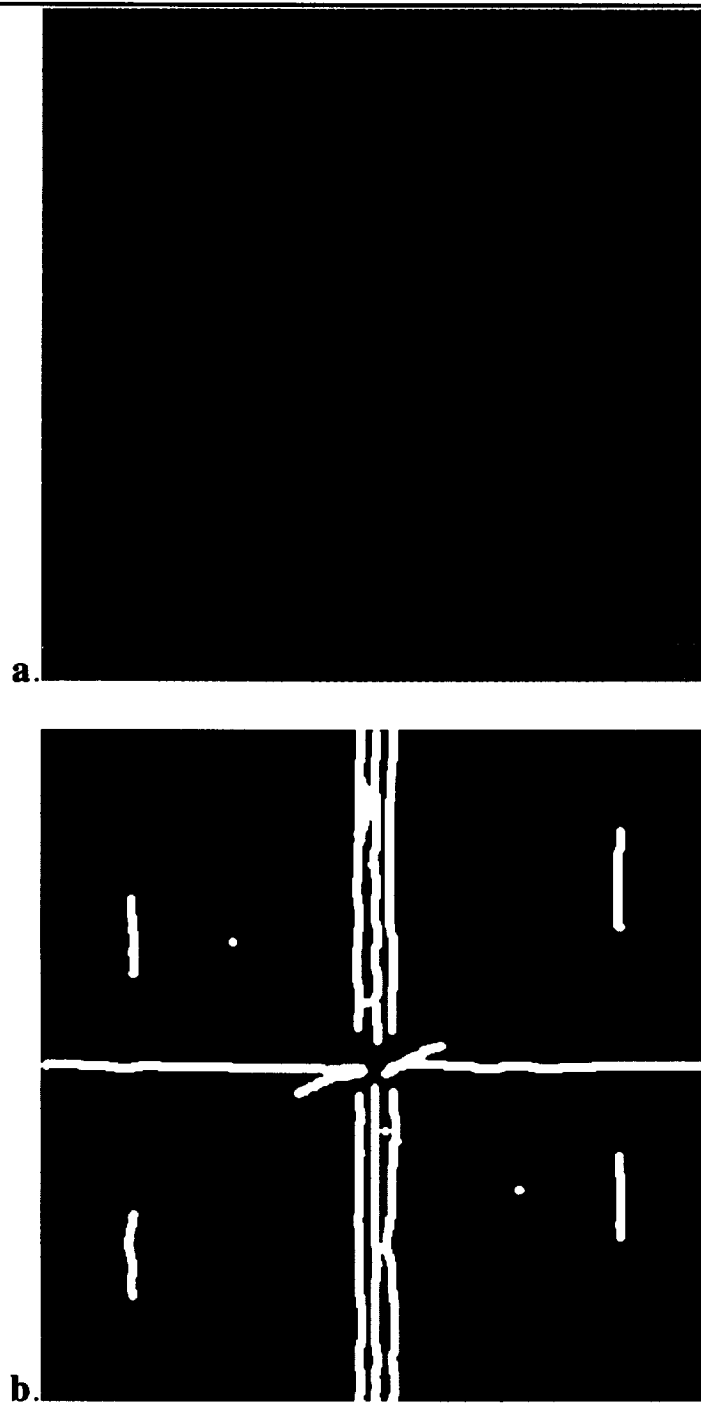
Figure 11. a. Fourier transform of image in Fig. 10a, and b, the filter used. White regions in b are stop bands.

TECHNICAL DETAILS OF HARDWARE, SOFTWARE, AND OF OPERATION

A. *Hardware*

The hardware used is as follows:

- PCI bus Power Macintosh computer (G3 for example), with at least 256 MB RAM.

- Scion LG3 frame grabber with 64 MB of RAM, PCI bus model.

- Sony CVD-1000 VCR recommended, though any VCR or even raw video is acceptable.

The hardware choices were based on the standardization of the PCI bus, and the availability of the Scion frame grabber card for the PC interface as well.

B. *Software*

- NIH Image version 1.62b71 (public domain) available from the NIH Image Web site:

  http://rsb.info.nih.gov/nih-image/.

- Custom NIH Image macro written at DRI, and available from Pat Arnott.

- Custom FORTRAN program available from Pat Arnott of DRI.

The NIH image program has been ported to the PC platform by the Scion corporation (http://www.scioncorp.com/), and the FORTRAN program can be compiled on this platform. The commands were largely based on FORTRAN 77 for compatibility.

C. *Operation summary.*

The macro commands for counting and sizing particles will be discussed first. The reader may find access to the well-written NIH operation manual to be useful. The objective of the NIH Image macros is to first set up the frame grabber, grab a movie or stack as it is called in the NIH Image parlance, clean up the stack if necessary to remove noise, and to count and size all of the particles on each slice of the stack. The FORTRAN program is then used to reduce the counted slice data to number concentration.

- The only setup option needed for NIH Image is to set go into the "Analyze" menu item, "Options", and set the max measurements to 8000 (the maximum number of particles that can be counted by NIH Image at one time.).

- Using the "Special" menu item, "Load Macros ..." and load the DRI macro entitled CloudscopeAutoV2. The macros are all given in Fig. 12. The user performs one function in each block of commands.

- First the frame grabber gain and offset is set. Try the "Set Video... " command first, and view the histogram. A desirable histogram example is shown in Fig. 13.

Figure 12. Macros for digital image analysis and particle counting. Each block of commands performs one function in the process. Comments are given in {blue} and do not appear in the NIH program.

Figure 13. Histogram.
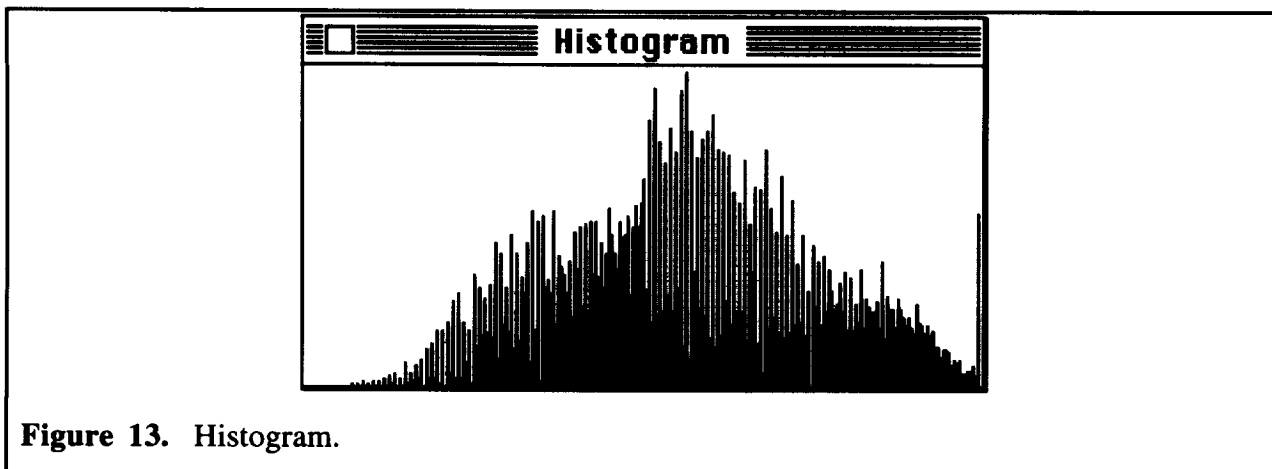
- Next grab a movie from one of the preset macros or from the more general one, "Movie User Select ...". Save this stack as a raw stack.

- Use the next block of commands to move around in the stack or to break it up into short substacks, each with a unique number for a name.

- The filter commands can be used to clean up noisy images. Some knowledge of Fourier spatial frequency analysis would be useful here. Just follow the steps indicated. When finished and with a clean stack, save it as a filtered stack under a new name. Stacks can be saved either as quicktime or TIFF images.

- Finally the user will analyze the stack using the command "ANALYZE STACK with cleaning. Save the analyzed stack. A text file is created that contains the obtained particle information. To save this particle information, press the option key, and under the "FILE" menu, choose export. Pressing the option key will save a header in the text file that describes each column.

- Now the user runs the FORTRAN program. The FORTRAN program can be compiled using the ABSOFT compiler (http://www.absoft.com). The text file created in the previous step is the input to the program. Output from the program is a condensed version of the text file that only contains the new particles found, a file containing the size, area, and mass distributions in ASCII format, and a similar file in the html format that can be easily read with a web browser.

- A transcript of a run of the FORTRAN program is given here.

OPEN THE FILE CONTAINING RESULTS

(dialog box appears)

OPEN THE NEW PARTICLE REPORT FILE

(dialog box appears)

OPEN THE SIZE DISTRIBUTION FILE

(dialog box appears)

ENTER TIME DATA WAS OBTAINED as hh:mm:ss

11:22:20

ENTER DATE DATA WAS OBTAINED as mm_dd_yy

05_12_97

ENTER THE CLOUDSCOPE USED FROM THE FOLLOWING

 a = Standard Aircraft Cloudscope (default)

 b = Large Format Cloudscope

 c = Lab Cloudscope

 d = Medium Format Cloudscope

a

ENTER THE SETTING FROM THE FOLLOWING

 a = aircraft operation (default)

 b = ground or lab operation

a

TO READ AIRCRAFT INFO FROM FILE ENTER a (default)

n

ENTER THE AIRCRAFT TRUE AIR SPEED in m/s

220.

ENTER THE AIR PRESSURE in mb

200

ENTER THE AIRCRAFT ALTITUDE IN km

10

ENTER THE AIRCRAFT LATITUDE IN DEG xx.xxx

99.999

ENTER THE AIRCRAFT LONGITUDE IN DEG xxx.xxx

99.999

ENTER THE AIR TEMPERATURE in Celsius

-60

ENTER THE WINDOW TEMPERATURE FROM...

 c = compute the total temperature (default)

 d = known measured temperature

c

ENTER THE FRAMES PER SECOND DURING DIGITIZATION
10
 Enter the NUMBER OF FRAMES digitized in the stack
127

Sample volume in Liters .369646

****
**** Working ....
****

ENTER y TO EVALUATE ANOTHER FILE

CALCULATION OF THE CLOUDSCOPE SAMPLE VOLUME FOR AIRCRAFT OPERATION

The cloudscope samples a thin pencil of cloud. The pencil cross section is defined by the 640 x 480 pixel stack. The 640 x 480 pixel stack maps into a physical area of 420 μm x 315 μm. Denote the physical area by symbol A. The sample volume, V, is thus

$$V = A_c * TAS * nf / fps \quad , \tag{1}$$

where TAS is the aircraft true air speed, nf is the number of frames digitized, and fps is the digitization rate in frames per second used to obtain the stack. Note that nf/fps is simply the physical time represented by the stack. The symbol A_c refers to a corrected sample area where $A_c \leq A$. The sample area must be corrected because larger particles have a larger probability of touching the boundaries of the 640 x 480 pixel region, and boundary particles are not counted since their true size can not be apriori known for the general case of nonspherical particles.

Consider an area defined by taking a small circle of diameter D around the inside perimeter of the 420 μm x 315 μm region. Any particle of diameter D that falls within this defined area certainly will not touch any edge; however, a particle of diameter D landing in this area will touch the outer boundary half of the time thus will be ignored, and the other half of the time it will touch the inner boundary and be counted. Thus the corrected area is reduced from A by 1/2 that of the area so defined.

JOURNAL ARTICLES THAT DO OR WILL ACKNOWLEDGE SUPPORT FROM THIS CONTRACT.

1. infrared **Emission (500-2000 cm-1) of Laboratory Ice Clouds.** Carl G. Schmitt, and W. Patrick Arnott, 1998, accepted to the Journal of Quantitative Spectroscopy and Radiative Transfer.

2. **Forward Scattering Spectrometer Probe and Cloudscope Size Spectra of Laboratory Ice Clouds.** Carl. G. Schmitt, W. Patrick Arnott, Douglas Lowenthal, and Jane Niehauss-Brooks, to be submitted to J. Ocean. and Atmos. Tech.

3. **A Video Impactor for Cirrus Cloud Characterization: Principles and Instrument Comparisons.** W. Patrick Arnott, Mike Poellot, John Hallett, Jane Niehauss-Brooks, and Kenneth DePaoli, to be submitted to J. Ocean. and Atmos. Tech.

MASTER THESIS PROJECT BASED ON SUPPORT FROM THIS CONTRACT.

Jane Niehauss-Brooks obtained a master degree in computer science from the University of Nevada, Reno. She used this topic in her project paper for a non-thesis masters degree. Her overall contributions to the software development and data analysis were substantial, and are gratefully acknowledged.