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SHIP TRAIL/CLOUD DYNAMIC EFFECTS FROM APOLLO-SOYUZ PHOTOGRAPH JULY 16,1975

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1. INTRODUCTION

Since the original study by Conover (1966) and more recent work by Coakley *et al.* (1987), Twomey *et al.* (1984), and Scorer (1987), ship trails have been looked upon as the possible Rosetta Stone connecting the possible effects of increasing aerosol over the ocean and cloud albedo effects on climate. However, as the Rosetta Stone was useless for translating Egyptian hieroglyphs without understanding ancient Greek, much more needs to be understood about ship trails before the climate connection can be quantified. We describe in this paper the results of a preliminary analysis of a ship trail photograph (Fig. 1) taken by the Apollo-Soyuz crew at 22:21 GMT on 16 July 1975. The photograph was taken from an altitude of 174 km (approximate location 30N 123W) and shows three separate ship trails with two of the trails intersecting (El Baz and Mitchell, 1976). Because these photographs were taken from a non-geosynchronous satellite with a high resolution camera, the quality of the photograph provides more detail than is usually obtained from meteorological satellites (minimum spatial resolution 14 m compared to 57 m from Landsat). The photograph not only shows enhanced detail of the ship trails themselves, but also cloud free bands generated by the ship trails. The ship trails have maximum photographed widths of 3-6 km. These cloud free bands are an obvious indication of the importance of ship trail cloud dynamics to ship trail development. These cloud dynamical effects are driven both by the initial energy release of the ship's power plant (100-200 MW for average six boiler ship; Conover, 1966) and by latent heat release from the aerosol nucleation process. Since the aerosol nucleation process is the key to understanding ocean aerosol/cloud interactions, it is important to partition these two processes in the ship trail development. We will describe in this paper preliminary numerical modeling efforts to simulate the ship trails in Fig. 1 using only the energy release from the ship and thereby give an indication of how much more energy input may be required from the nucleation process.

2. DATA DESCRIPTION

The primary data source for this work is the Apollo-Soyuz photograph described by Black (1979). Five sets of negatives were obtained from the Johnson Space Center Photographic Laboratories which included calibration step wedges. Each negative represented a quantified development range in red and blue. This was necessary in order to quantify the relative cloud albedo increase in the ship trail accounting for the nonlinearity of the film response function. Sea surface temperatures and meteorological parameters have been obtained from the Fleet Numerical Weather Center for times and locations close to location of the ship trails. We have requested, but not yet obtained, geostationary satellite images to better pinpoint the exact locations of the ships and hopefully identify the ships in the picture and their power plant characteristics.

The principal visual features of the Apollo-Soyuz photograph include the following:

1. Trails widening to 3 6 km over 40 km long paths. This is slightly smaller spreading than any of the points listed by Gifford (1985) which included north sea data by Crabtree (1982) (a ship speed of 10 knots is assumed). This implies either extreme stability or a scale of cloud formation different from pollutant plume spreading or the ship speeds have been slightly underestimated.

2. Both the ship trails and the cloud free regions grow in size at about the same rate,

3. Intersecting trails show that the point of intersection is no brighter than either ship trail alone,

4. Internal structure of the trails tend to mirror the spatial frequency and orientation of background clouds, (the fractal dimension of the ship trail perimeter is about 1.1 compared to 1.35 for large scale clouds [Lovejoy, 1982] which shows the relative simplicity of the ship trail clouds).

5. Magnification of the region of the beginning of the nonintersecting ship trail shows that the trail effects first appear as a brightening of the background clouds (Fig. 2).

An example of the results of image analysis of the digitized photograph is shown in Figs. 3. Figure 3a shows the pixel intensity levels down a line crossing the lower of the two intersecting ship trails to the right of the intersection and nonintersecting trail. Figure 3b is the digitized film response of the calibrated step wedge and shows the near linearity of the film over the range shown in Fig. 3a. Figure 3 shows that the brightest part of the ship trail was almost twice as bright as the brightest background cloud for the nonintersecting trail and only 20% brighter for the intersecting ship trail. For the case of the intersecting ship trail, the overall albedo change caused by the ship (including the cloud free regions) is very small. This implies that, at least in this one case, disregarding the cloud free region surrounding the ship trail would lead to a serious overestimate of the ship trail albedo effect.

The digitized intensity data were also used to determine percentage of background clouds near the ship trails. Figure 4 (lower left) shows the histogram of intensities used to bifurcate cloud and noncloud regions. The minimum in the histogram to the left of the maximum was used to separate cloud from non-cloud and the reconstructed cloud/no cloud field is also shown in Fig. 4. This leads to cloud percentage of 63%. When this percentage is multiplied by the area of the cloud free region and by an assumed liquid water content taken for Pacific stratocumulous clouds by Boers and Betts (1988) yields an absence of 8.5×10^8 g of liquid water. If a mean speed of the ship is assumed to be 10 knots this implies a direct power input of about 230 MWatts would be required if the cloud free regions were simply a result of evaporated background clouds. This implies that either the two intersecting ships are extremely large (about 13 times the average six boiler ship assuming 10% of available energy goes to heating the air) or, more likely, the existence of a triggered atmospheric instability. This instability could be triggered by a combination of dynamic buoyant forcing of the ship plume and latent heat released by aerosol condensation processes.

3. NUMERICAL MODEL RESULTS

As a preliminary effort to better understand the possibility of an instability in marine cloud layer development we have applied a numerical hydrodynamic model. This model is described in detail by Yamada and Kao (1986) where they showed how 3 dimensional cloud patches can develop within an ensemble mean mesoscale atmospheric model with scales which are similar to the background clouds observed in the satellite photograph. The code has been used to simulate cloud development during GATE as well as over the North Sea (Kao and Yamada 1988). These applications bound the observed air/sea interface temperature of 16°C near the ship trails (20°C for GATE and 9°C for the North Sea). The code uses second order turbulence closure and produces cloud probability fields. The code is also hydrostatic which limits the ability of the code to simulate the initial ship plume scale buoyant processes. The ship scale size plume is averaged over a 500×500 m^2 horizontal grid which represents the smallest resolution compatible with the hydrostatic assumption. The model also includes no aerosol microphysics. With these limitations we are only able to bound but not specify precisely the potential for meteorological instability driven ship trail development. Also, until more is known about the ship's exhaust plume, we cannot partition the direct buoyant effects of the ship's plume and aerosol microphysical energy release effects. With these qualifications in mind, much can still be learned about the potential for ship trail and surrounding cloud-free region development given a range of input conditions.

Figures 5 and 6 show the modeling results 1 hour after a short duration heat release for the liquid water content and vertical velocity, respectively. This preliminary calculation does not simulate a moving ship directly, rather it shows the development of one heated grid cell. A heat source is put at the center grid over a 10 m-thick layer for 90 s (3 internal time steps in the model). This time frame is determined from the ship speed (assumed 10 knots) and the grid size. The strength of the heat source increases from 0 to 1.2°C during the heating time. This quantity is determined from the temperature and outflow rates of exhaust gases corresponding to about a 30 MW point heat release evenly distributed over the grid. The assumed meteorological conditions corresponded in most cases to observed conditions near the ship trail observations. These include a surface air temperature and relative humidity of 16°C and 95%, respectively. The model assumes a mixed layer of 500 m with constant potential temperature and relative humidity of 85% above the surface. Above the mixed layer a change of potential temperature change of 4°K/km was assumed. The model assumed near calm winds, however, whereas the observed wind speeds varied from 5 to 10 knots. Since we do not as yet know the directions of the ship trails, the effect of winds will be modeled at a later time.

Though Figs. 5 and 6 do not appear very much like a cloud (a result of the graphical interpolation), both show the development and persistence of a high liquid water content and updraft region about a kilometer wide after one hour with maximum values of 2.6×10^{-2} g/kg and 1.65 cm/s, respectively. Surrounding this cloud is a region of low liquid water content and downdrafts of 2×10^{-3} g/kg and 0.7 cm/s, respectively. When the model input was less than 1 MW compared to about 30 MW a very slight increase in liquid water content was observed at the center with no resolvable decrease or downdraft surrounding it.

4. CONCLUSIONS

Without specific data on the power plant and ship trajectory, we have been able to combine image analysis and numerical model results to bound the potential importance of cloud dynamic effects triggered by marine cloud instability and the buoyancy effect of the ship's plume. Much more specific information about the ship is necessary to partition the relative importance of direct plume heating and latent heat release from cloud nucleation due to plume aerosols.

The major results of this analysis include the following:

1. The high resolution available from the Apollo-Soyuz photograph (14 m) showed that early development of the ship trail appears as a brightening of background clouds rather than an independent cloud.

2. Cloud free regions and low relative brightness associated with the intersection of the two ship trails argue against a simple relationship between cloud albedo and aerosol condensation nuclei from the ship.

3. Numerical model simulation of the ship trail and marine cloud instability show that the direct bouyancy input from the ship may be as important as the energy release due to nucleation processes.

Acknowledgments

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Figure Captions

Fig. 1. Ship trail photograph from Apollo-Soyuz off the coast of southern California, July 16, 1975 at 22:30 GMT.

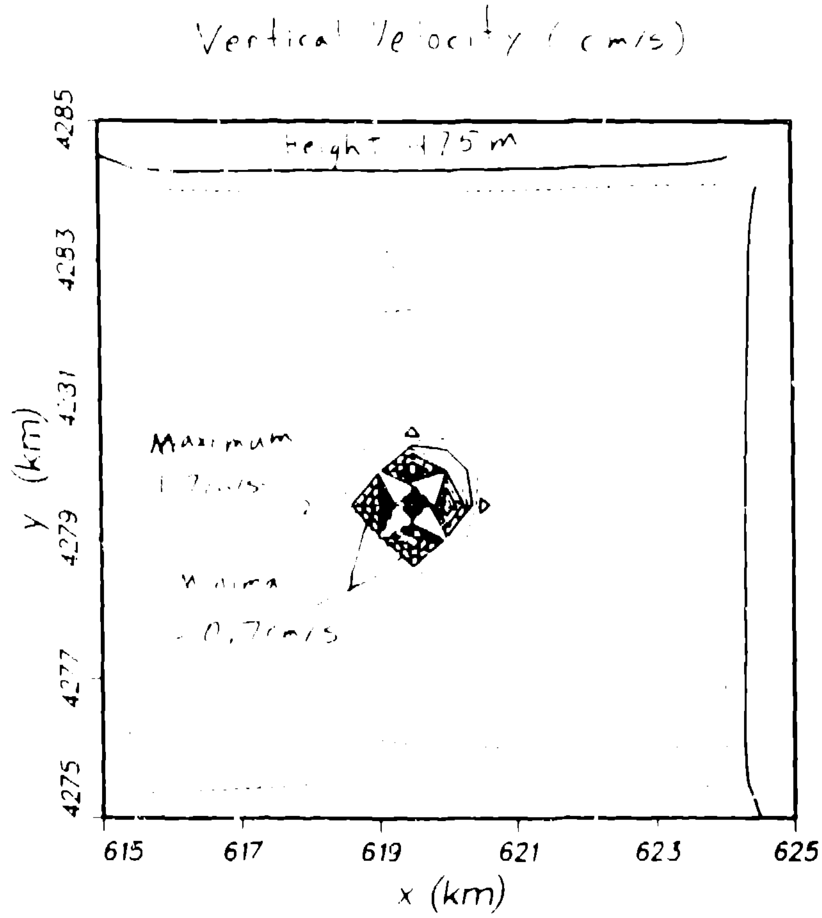
Fig. 2. Magnification of origin of lower ship trail in Fig. 1.

Fig. 3. Digitized pixel intensities down a line intersecting the lower of the two intersecting ship trails and the ship trail in Fig. 2 to the right of the intersection a) and the step wedge calibration for the film b).

Fig. 4. Histogram of cloud intensities (lower left) used to separate cloud and noncloud in a region between and to the right of the intersecting ship trails and the results of the bifurcation. (The satellite background cloud picture is on the upper left with cloud/no cloud representation on upper right. The lower right graph shows two lines corresponding to the number of points above and below separation implying 63% cloudiness.)

Fig. 5. Numerical model calculations of the development of cloud liquid water from heating within a central grid point equivalent to 30 MW for a duration of 90 s (the time a ship would reside within a grid cell assuming a 10 knot ship speed). Outside contours show the development of a cloud-free region.

Fig. 6. Same as Fig. 5 for vertical winds in the region of the heated grid and associated down drafts.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x (km)
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617
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623
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4279
4283
4285

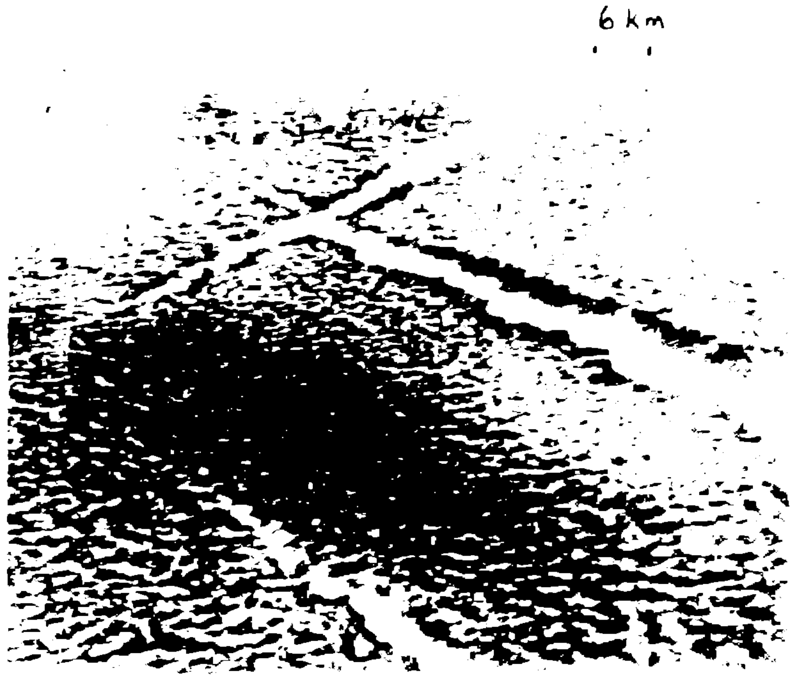


Fig 1

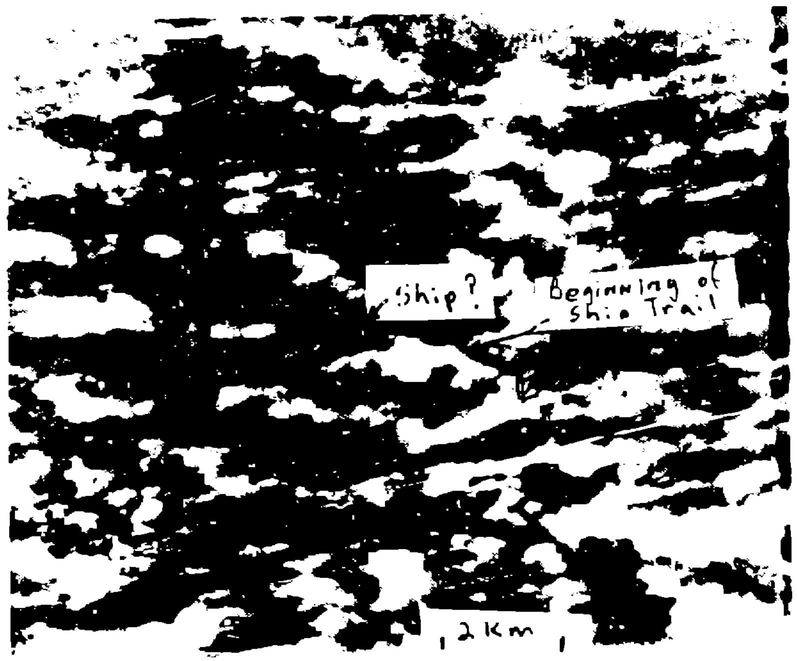
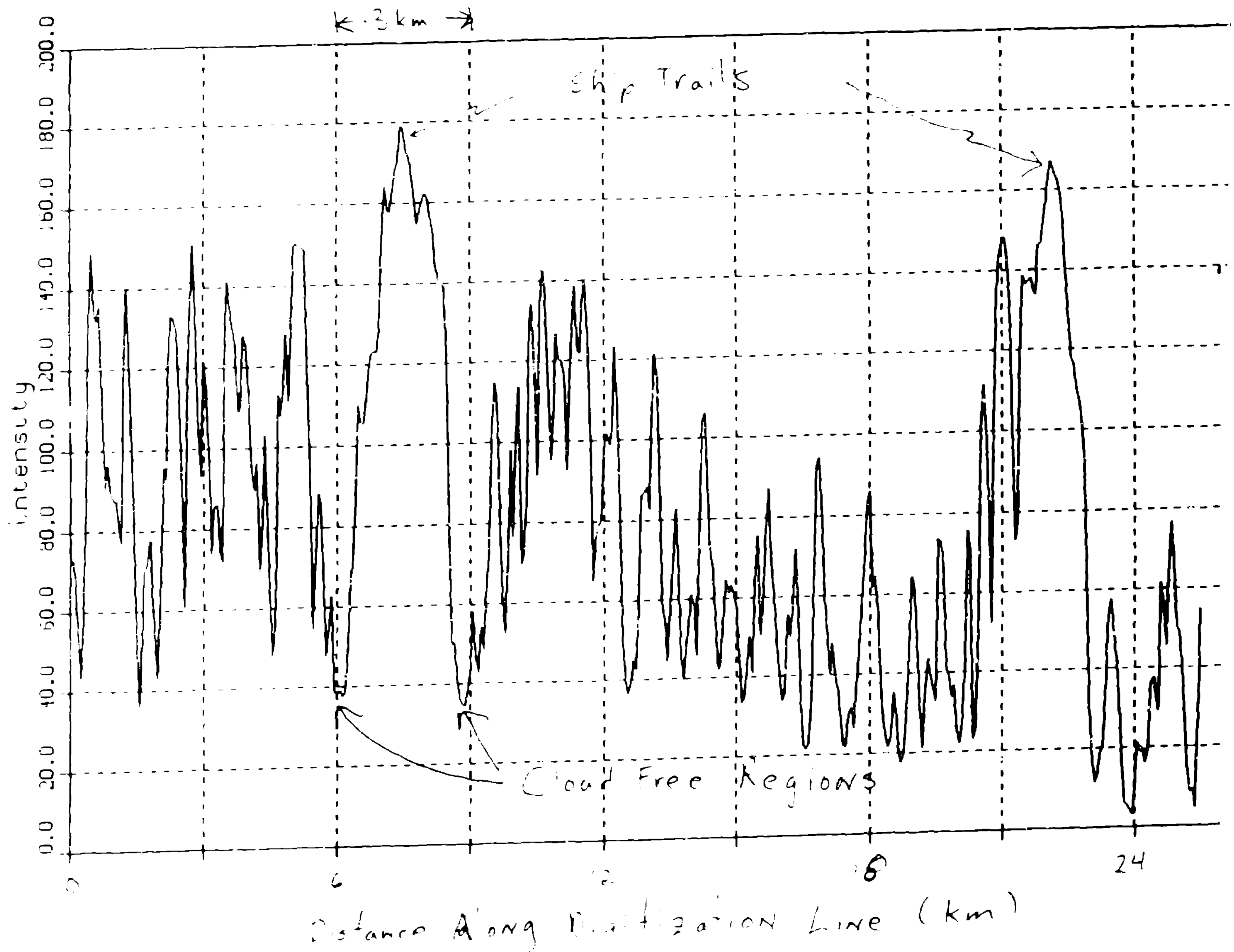
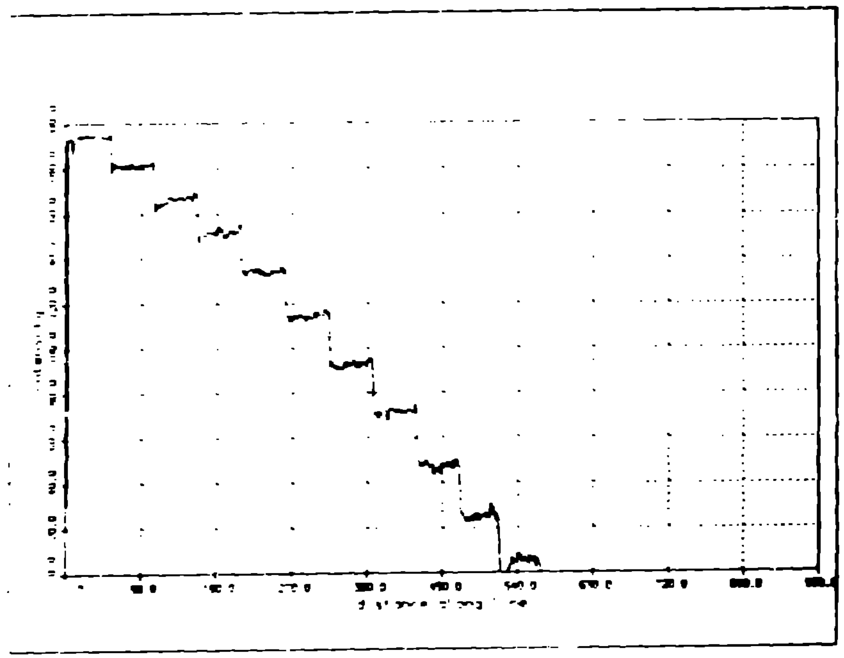


Fig 2



←3 km→
Ship Trails
Cloud Free Regions
Intensity
200.0
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
0
6
12
18
24
Distance Along Digitization Line (km)



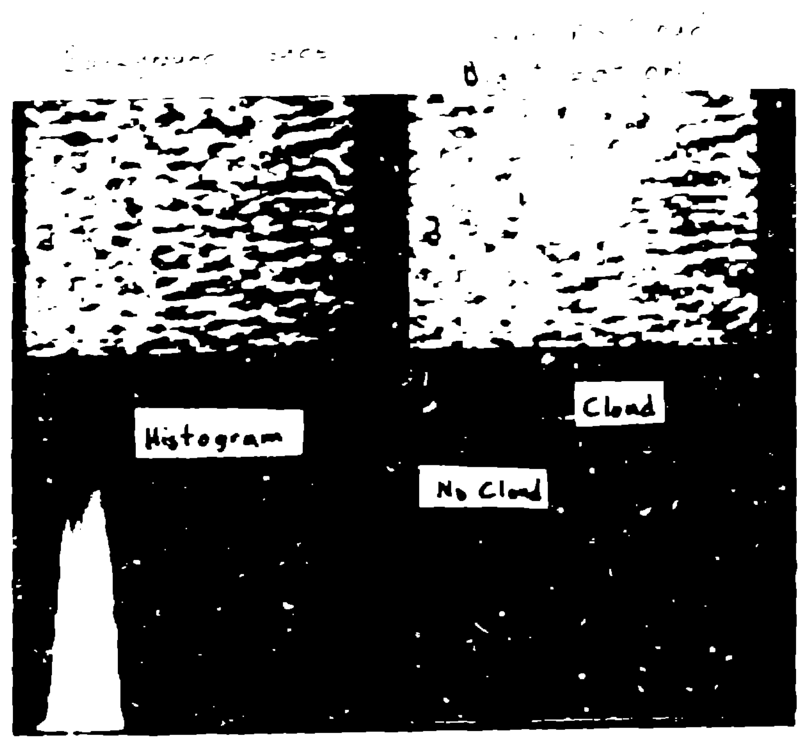
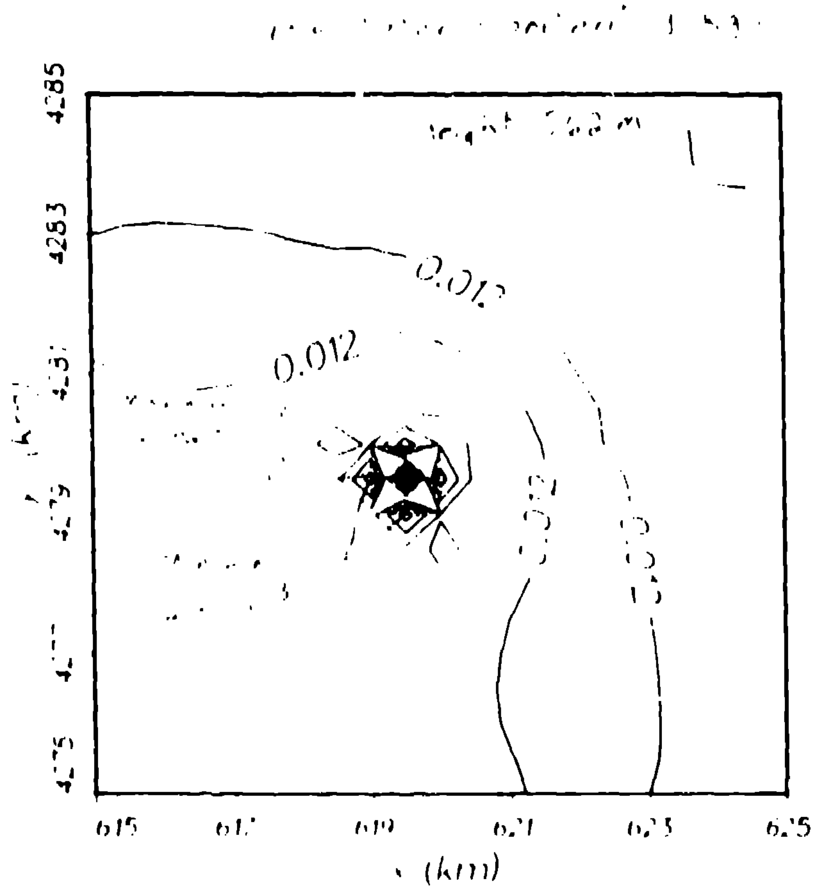


Fig 7



0.012
0.012
x (km)