The Design, Construction, and Use of an Ice Crystal Counter for Ice Crystal Cloud Studies by Aircraft

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ABSTRACT

An aircraft instrument is described that gives a real-time measurement of the number of ice crystal particles per unit volume in cirriform clouds. Its method of detection is based on the mechanisms of contact electrification, as applied to the collision between a stainless steel wire and an ice crystal. The signal conditioner, which employs a series of integrated circuits, converts the frequency of crystal collisions into a voltage. Several examples of actual flights are shown.

1. Introduction

Very little is known about the macrophysics of ice crystal cirriform clouds. With the increased production of artificial ice crystal clouds by the release, intentionally or inadvertently, of seeding agents (Schaefer, 1968) or water vapor, and the unknown effect of these on the energy budget of the earth, it is becoming increasingly important to study the macrophysics of these clouds. Their mechanism of formation, and such parameters as the number density (number of particles per unit volume) of ice crystals, their size, and mode of growth, are not well known. An investigation of these variables, as well as a comparison of natural and artificial ice crystal clouds, needs to be made. As a step toward these goals, we have been concerned with the problem of determining ice crystal number densities from aircraft.

Ice crystal concentrations in these clouds have normally been estimated by two basic methods. One method is the collection and replication of individual ice crystals, as demonstrated by Schaefer (1941). Weickman in 1945, as cited in Borovikov *et al.* (1961), replicated ice crystals using a cellulose nitrate varnish and subsequently photographed the samples. Similar work has been carried out by Borovikov in 1953 (Borovikov *et al.*, 1961), using the polyvinyl formal technique devised by Schaefer (1941), and by Malkina (Borovikov *et al.*, 1961), using methylmethacrylate. In the United States, MacCready and Todd (1964), Averitt and Ruskin (1967), and Spyers-Duran and Braham (1967) developed instruments that employ polyvinyl formal for continuous replication of ice crystals from aircraft. The main difficulties are the determination of the collection efficiency and crystal shattering on impact.

Another method of determining ice crystal concentrations is by measuring the water content of the cirriform cloud. This is done by collecting the ice particles on filters and subsequently weighing the liquid water. By assuming an average size of ice crystal, one can arrive at an ice crystal concentration from this measurement. Such work was carried out by Zaitseve and Minervin prior to 1957 (Borovikov *et al.*, 1961) and by Tverskoi (1962). The problem with this technique is that the water content of cirriform clouds is so low that long sampling times are required to obtain a measurable quantity of water.

The collection-and-count method suffers from the fact that it is not only laborious, but also does not yield real-time concentrations, while water content methods are useful only for very general studies. Our interest in the structure of these cloud forms necessitated the development of a real-time device for concentration measurements that would be small, lightweight, easily installed on an aircraft, and present as few difficulties as possible in operation and maintenance.

For some years, aerosol particle concentrations and sizes have been measured by using contact electrification. This was first suggested by Guyton (1946), who based his work on the electrostatic charges created by the frictional contact of particles on a nozzle that directed their flow in such a way that the particles impinged on a wire. This technique is now commonly used in Germany in instruments for measuring dust particles. Schütz (1966) describes an instrument using the same principle, but employing, as a detector, an inverted cone in a high velocity air stream.

Stimmel *et al.* (1946), Schaefer (1947) and Dunham (1965), using the same physical principle, have measured the charge delivered by an ice crystal on impact with a metal surface. Based on the work of these

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authors, we decided that ice crystal concentrations could be measured with apparatus similar to those employed in aerosol physics.

2. Principle of operation

As we considered the problem of an ice crystal-wire interaction, it became apparent to us that several mechanisms might be involved. Though they are not vital to the understanding of this instrument, we feel that it would be helpful to include a brief comment on each, as they were considered in the design stage of development.

When ice crystals are charged (Pudovkina and Sedunov, 1963), they will, on striking a wire, give up some of their charge. Since the probe is connected to the aircraft ground through a current measuring device, the resultant impulse of current can be used to trigger a counting circuit. There also exists the likelihood that a charged crystal, passing near the probe, will induce a charge on the wire resulting in a similar current. In fact, in this latter case, both a positive and a negative current will appear. This will lead to double counting for some circuit designs.

When the ice crystals are uncharged, two other mechanisms can deliver charge to the probe. One mechanism is that of charge transfer due to frictional contact (Henry, 1953). This effect between the metal probe and the ice crystal is probably similar to that between two ice surfaces as studied by Reynolds *et al.* (1957). The other mechanism which may be acting results from the fact that there is a difference between the work functions of a metal and a semiconductor (Loeb, 1945; Vick, 1953). If we assume that an ice crystal exhibits the electrical properties of a semiconductor, it might be reasonable to assume, on contact with the probe, that charge transfer will occur.

Due to the multiplicity of mechanisms, certain problems may arise. In the case of inductive charging, the effective sampling volume is probably increased, and thus leads to some uncertainty in the crystal concentration measurement. If an ice crystal interacts with the probe by way of more than one mechanism, the results are superimposed. As already mentioned, contact electrification is not particular to ice; dust particles will also be counted. This could be a considerable problem if it were not for the fact that a 1 μ aerosol particle will result in a much lower imput than a 50 μ ice particle. The presence of a 50 μ aerosol particle at the cirrus cloud level is rather unlikely. In liquid clouds, charged water droplets should also be effective in charge transfer. This may be particularly important when the liquid water content of a cloud is high, as there may be liquid water accumulation on objects upstream from the probe, and the resultant spray from these objects is, more than likely, charged. As the instrument is intended for high-altitude work, where the water content of clouds is quite low, this problem is not very relevant.

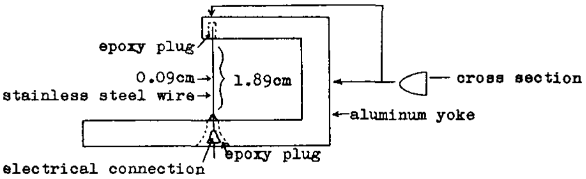

FIG. 1. Cross section of the probe mounted in the yoke.

3. The instrument

Unlike the work in aerosol physics, where a large surface area is used to assist in particle charging, we employed, as a probe, a single exposed wire projecting into the airstream of an aircraft. This is necessary as the ice crystals, unlike most aerosol particles, tend to shatter on impact, and any shattering prior to the sensor would lead to erroneous results. This lack of prior charging is also a reason why small aerosol particles will probably not be detected.

Wires of aluminum, copper, iron and stainless steel were tested for their electrical properties when impacted with ice crystals in a wind tunnel capable of operating at wind velocities up to 36 m sec^{-1}. It was found that there was no significant difference among the metals tested at 36 m sec^{-1} or several lower velocities. Therefore, since a fine probe is preferable to keep the sampling volume small and yet provide the required strength to maintain its form at the high speeds of the aircraft on which the instrument was to be mounted (approximately 200 m sec^{-1}), we decided to use a fine stainless steel wire. The diameter of the wire was 0.09 cm and the exposed length 1.89 cm. This probe was securely mounted in, and electrically insulated from, an aluminum yoke, by epoxy plugs (Fig. 1). A 3-cm mast supported the yoke (Fig. 2) above the boundary layer of the aircraft. A signal input lead ran down through the mast from the probe, to the signal conditioner located inside the aircraft.

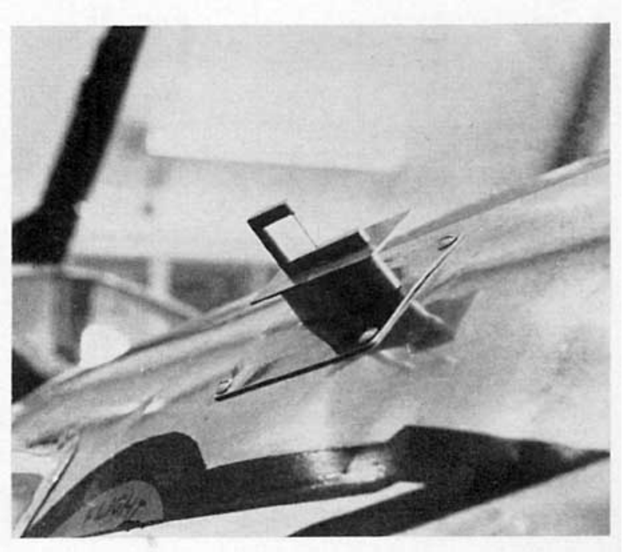

FIG. 2. Mast and yoke installed on the aircraft.

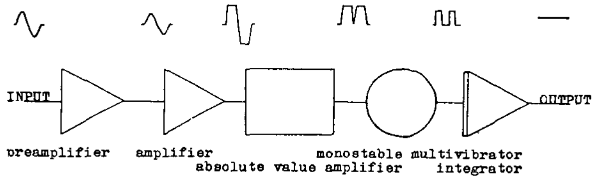

FIG. 3. Block diagram of the signal conditioner showing the output waveform of each stage.

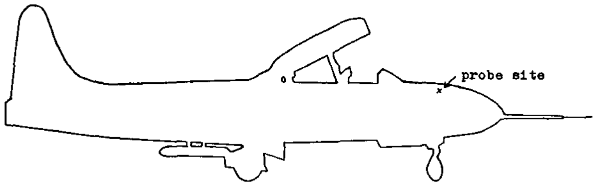

FIG. 4. Profile of the T-33 aircraft showing the location of the probe assembly.

Due to the uncertainty in the magnitude of the pulse current and crystal concentration, the signal conditioner had to meet several design criteria. To give adequate sensitivity with the small currents expected, the input impedance had to be very high. At the same time, it was desirable to handle the widest possible range of pulse heights. Due to the data reported by Pudovkina and Sedunov (1963), we had to take into account the existence of signals of both polarities. Since we also wanted a large dynamic range of counting rates, the circuit response time needed to be short.

To meet these requirements, we designed a signal conditioner composed of a preamplifier, an amplifier, an absolute value amplifier, a monostable multivibrator, and an integrator (Fig. 3). This circuit converts the frequency of the pulses from the ice crystal impaction on the probe, to a dc voltage, which can be measured by any dc voltmeter of sufficient range.

The circuits were all tested for low temperature drift down to −45C. It was found that over the entire range from −45C to +20C, for a constant voltage output, the sampling frequency decreased by 400 Hz. Compensation for this is straightforward. Since the output did not drift appreciably with time, at −45C, the measurements at operating temperatures can be considered to be accurate with respect to one another. If the housing temperature is also known, then an absolute value could be obtained.

4. Installation

We flew this instrument on the National Research Council of Canada's Lockheed Shooting Star (T-33), operated by the Flight Research Section of the National Aeronautical Establishment (Mather, 1967), based at Uplands Airport, Ottawa, Ontario. This aircraft is ideally suited and instrumented for this work. It is equipped for all-weather operation and has a ceiling of approximately 13,000 m. There is 15 V available for transistor circuitry, as well as a well-developed data collection system. The angles of attack and yaw, pitch, yaw and roll rates; normal, lateral and longitudinal accelerations; total differential air temperatures; control surface deflections; static and dynamic pressures; ground speed; and vector infrared temperatures are all available from the aircraft's installations.

The probe assembly is mounted on the starboard flap of the nose compartment, as shown in Figs. 2 and 4. A short cable leads from the probe, through the aircraft skin, to the preamplifier mounted on the reverse side of the flap. The probe assembly is bolted directly to the preamplifier housing on the inside of the aircraft.

We ran a shielded cable from the preamplifier to a predetermined input on the aircraft signal conditioner box. The rest of the circuit is mounted on an 11 cm by 12 cm fiberglass-plastic circuit board, with a 34-pin Elco connector at one end. This mounting is employed as it is compatible with the existing installations. By plugging this board into a predetermined position in the aircraft signal conditioner box, power is supplied to the board, as well as access to the input and output signals.

The dc output of the circuit is suitably transformed and recorded on one channel of a fourteen channel FM tape recorder, which is a permanent installation in the aircraft. For real-time measurements, the signal can be led to an inboard monitor. At the end of a flight, the tape is removed, demodulated, and played back at the National Aeronautical Establishment's Flight Research Section Lab. We are also able to obtain simultaneously from this tape a continuous record of the uncorrected outside temperature for the flight. The air speed is reported on the audio track of the same tape by the pilot or observer on board the aircraft. From our data, it appears as though the pilot was able to keep the aircraft within 5% of the airspeed he indicated.

5. Data

Since the instrument was installed on the aircraft, two basic types of flights have been made with the ice crystal counter operating. A series of runs were made through active cumulonimbus clouds, from which the effects of lightning discharges, precipitation, and high water content clouds can be observed. The other series of runs were made at high levels, above 6000 m and primarily around 9000 m, through cirriform clouds.

The cumulonimbus runs revealed no meaningful information. If we accept the values of rain drop concentrations as given by Houghton (1968), typically 1–10 drops per liter of air, and the cloud particle concentrations, as can be found in Fletcher (1966)—typically hundreds of droplets per cubic centimeter for continental cumuli—then we find it very difficult to explain what is being counted. The output count is too high to be just counting rain drops yet too low to be counting all the cloud particles. One possible explanation is that the water content was high enough in the cloud to result in the significant buildup of water at some leading surface on the aircraft, and the resulting spray from this was being picked up by the counter. These small droplets would probably be charged and thus register on the ice crystal counter. This explanation is particularly appropriate after a shield was installed over the probe support in an attempt to cut down external noise. The securing bolts of this shield run up through a plate just below the yoke, and are screwed into two large capture nuts just to the side of, but upstream from the probe (Fig. 5). Another possible explanation is that the water in the cloud grounded the probe to the aircraft skin, resulting in the aircraft noises getting into the signal conditioner.

The cirrus runs, on the other hand, gave values that agree with previous estimates. Some early runs made in May 1969 were encouraging, but noise was still a problem. As a result of this, we placed another zener diode in the signal conditioner to act as a noise filter. All the data we are considering in this section were gathered after the addition of this filter.

On 13 June 1969, while cruising at 10,900 m, with an outside temperature of -54C, the pilot reported a pass through a cirriform cloud. At the same elevation, but a short time later, the pilot reported going in and out of a similar cloud. The results of each of these passes can be seen in Figs. 6 and 7. Due to the very short time constant of the integrator, and the apparent nonuniformity of the cloud particle distribution, the occurrence of two or more crystals appears as a spike (see Fig. 8). The solid line represents a concentration of 30 crystals liter^{-1}, and is the low-frequency stop on the recorder. This does not represent a zero count as the range of the aircraft system, 100–4000 Hz, is rather limited, as we want to give a reasonable sensitivity to the output. Concentrations <30 are not measurable. A pulse up to two divisions represents a short-term concentration of approximately 110 crystals liter^{-1}. (The crystal concentration is equal to $F/(DLSM)$, where F is the frequency of particle interactions with the probe, D the diameter of the probe, L the exposed length of the probe, S the velocity of sound, and M the mach number).

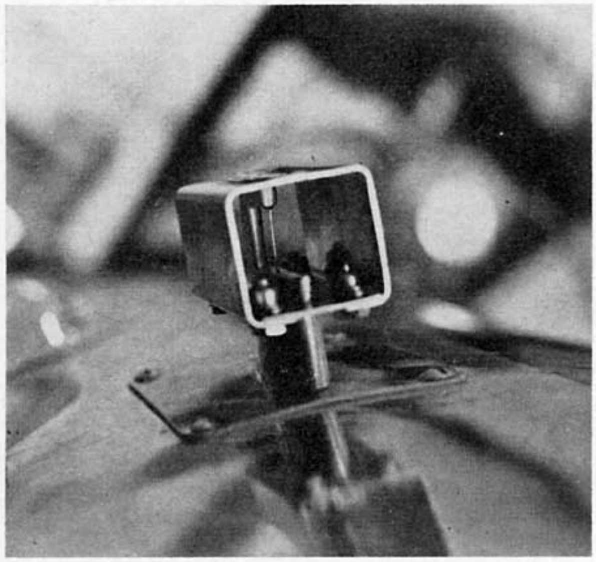

Fig. 5. Probe assembly with the shield installed.

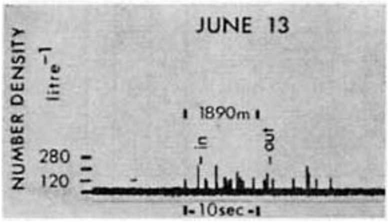

Fig. 6. Recorder output for a pass through a cirriform cloud.

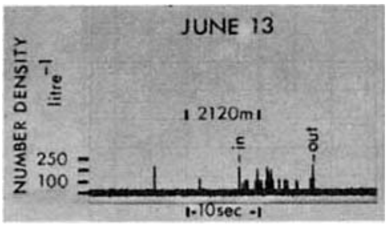

Fig. 7. Recorder output for a pass through a cirriform cloud.

On 18 June 1969, a flight was made at 11,700 m, at an air temperature of -55C, during which the pilot reported that he was making numerous penetrations of scattered very thin cirrus. Two portions of this flight are reproduced in Figs. 9 and 10. Again, the solid line represents a threshold of 30 crystals liter^{-1}. The maximum excursion here indicates a short term concentration of 530 crystals liter^{-1} in Fig. 9, and 500 crystals liter^{-1} in Fig. 10. The lack of apparent difference is due to differences in the air speed.

On 17 June 1969, while the aircraft was climbing out of Uplands Airport at Ottawa, it passed through a layer

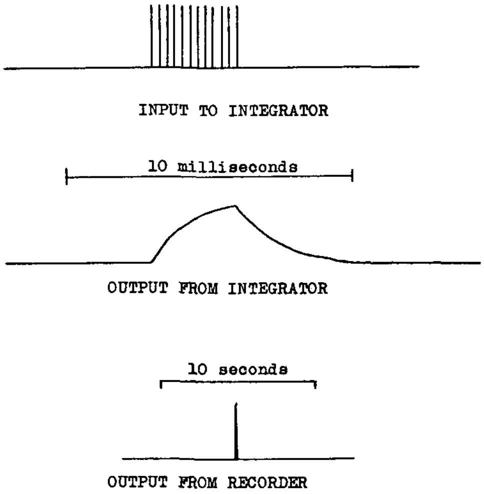

Fig. 8. Explanation for spikes at the recorder output in terms of the input and output of the integrator.

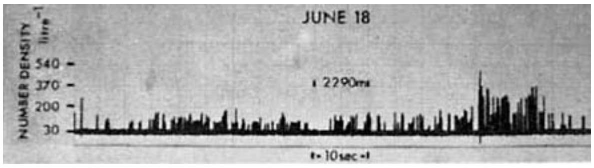

FIG. 9. Recorder output for a pass through scattered cirrus.

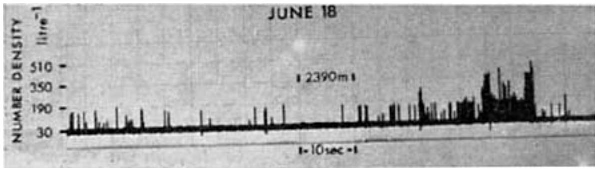

FIG. 10. Recorder output for a pass through scattered cirrus.

of cirrus uncinus. Below the cloud, the ice crystal counter was reporting an average concentration of 120 liter^{-1} (Fig. 11). Just prior to the pilot reporting entry into the cloud, the count drops below the threshold of 30 crystals liter^{-1}. If this cloud were ice, it appears to us to be highly unlikely that the cloud would have a lower crystal concentration than just beneath it. The layer of interest was around 6500 m and the corrected temperature was -29C. These data seem in agreement with the concept of a mixed or supercooled water cloud with ice crystals falling out of it, as mentioned by Ludlam (1948). Even the slight separation of the fall streak and the nonfibrous cloud appears to be evident (Ludlam, 1956).

The crystal concentrations we found, while flying through cirrus clouds, agree with the concentrations found by Braham and Spyers-Duran (1967) using replication, while flying well below cirrus clouds, but do not agree with those determined by Tverskoi (1962) using the water content method, who also made penetrations of cirrus. One reason for this disagreement may be that our values are relatively instantaneous, while Tverskoi's figure of 2 liter^{-1} is an overall average.

We are unable to be more specific as to the genera or species of the particular clouds flown through as it was not possible for us to fly with the aircraft, and the observer was not familiar with the details of cloud classification.

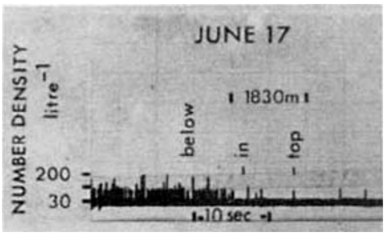

FIG. 11. Recorder output for a pass through cirrus uncinus.

6. Instrumentation problems

Most of the problems we are having with the ice crystal counter, as it now exists, lend themselves to fairly simple solutions.

As can be seen from the data examples, the integration time constant is too short. We suggest that a time constant in the order of 100 msec—a distance constant of 30 m—might be more appropriate and meaningful.

For clouds of the type of concentration exhibited in Figs. 6, 7, 9–11, it appears as though the sampling volume per given aircraft speed should be increased. A possible design for a probe, that appears to us to be most reasonable to give a larger sampling volume, is a flat coil of strong wire. This construction would still keep the collection efficiency high, while not appreciably increasing the supports necessary for the probe. Perhaps several different sampling volume probes could be employed, thus increasing the range of the concentrations detectable.

Other difficulties and suggested solutions primarily concerned with the electronics can be found elsewhere (McTaggart-Cowan, 1969).

7. Conclusion

The ice crystal counter, as we have described it, satisfies the criteria of size, weight, and ease of installation and operation that we initially set for it.

8. Suggestions for future use

Since this instrument is capable of detecting particles, it opens up the possibility of conducting several cloud physics experiments:

1) Measurement of number densities of crystals in ice crystal clouds, both natural and artificial.
    a. Comparison of cirriform clouds and contrails during successive periods of their life times.
    b. Correlation of visibility of crystal clouds both from the air and from the ground, with number densities.
    c. Correlation of radiation effects of crystal clouds with the number density.
    d. Crystal fallout from cirriform clouds and contrails.
2) Detection of the phase of uncharged cloud particles.
3) Measurement of snow flake number densities in the precipitation shaft and at the surface.

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