A Small, Radio-Controlled Aircraft As A Platform For Meteorological Sensors

T. G. Konrad

M. L. Hill

J. R. Rowland

and

J. H. Meyer

Meteorological research has long felt the need for a simple, relatively economical, controllable, and recoverable platform to carry meterological sensors and instrumentation for in situ measurement of atmospheric parameters. Platforms presently in use, such as free-flying or tethered balloons, towers, and full-sized aircraft have certain limitations which restrict their use or make them inappropriate in particular applications. The development and performance capability of a small, radio-controlled aircraft as a versatile measurement platform along with the required radio control and meteorological sensing instrumentation is described. Experience with the system in several extended field tests has shown that controlled soundings to 4000 feet are possible with the unaided eye. For flights above this altitude, simple optical aids have been developed and soundings to 10,000 feet have been made.

THE SPATIAL AND TEMPORAL STRUCTURE OF THE ATMOSPHERE is of interest both in the study of the atmospheric processes themselves and in the study of their effects on electromagnetic wave propagation. Some studies require very sophisticated sensing and recording equipment for fine-scale, fast-response measurements, while others are less demanding. For example, programs to study the dynamics of the convective process in the clear air have shown the need for repeated, fine-time-scale sounding of the atmospheric parameters. In this case the mean properties of the air are of interest, and relatively simple, unsophisticated sensors and instrumentation may be used. On the other hand, experiments relating to the scattering of electromagnetic energy from small-scale refractive index fluctuations due to turbulent mixing require fast response instrumentation and high-frequency recording for fine-scale measurement of the atmospheric properties.

These differences in the technical requirements along with differences in operational requirements and economic constraints are reflected, in turn, in the choice of a platform for the meteorological equipment. The sensing and recording instrumentation along with the platform represent an interdependent system which should be tailored to the particular application.

At present the most commonly used platforms for *in situ* atmospheric sensing are towers, balloons (either tethered or free-flying), and full-scale aircraft. However, each of these platforms has certain limitations which restrict its use or make it inappropriate in particular applications. Tethered balloons are limited in altitude capability by the necessity for lifting their own tether. As the altitude capability increases, the size of the balloon and associated equipment and the operational difficulties also increase. Free-flying balloons, such as are used in radiosondes, cannot be controlled or recovered after release, while the use of full-sized aircraft often represents a prohibitive and unnecessary expense. Thus, there is a need for a simple, economical, controllable, and recoverable platform to carry meteorological sensors and instrumentation having modest accuracy and response characteristics. Small, radio-controlled airplanes and hobby equipment have been used in technical projects such as glide testing of reentry vehicles.[1] However, the authors know of only one previous attempt to use them for meteorological sensing.[2] This was done about 1961 and met with limited success. At that time, the hobby-type radio control equipment and servo systems had limited capability and reliability. The presently available multiple-channel radio equipment, however, provides fully proportional control and is highly reliable. Further, the development of integrated circuits has permitted a reduction in the size and weight requirements of the meteorological sensing instrumentation and telemetry.

This paper describes the development of a small radio-controlled aircraft as a measuring platform along with the performance capability and operating procedures. The system has been used in field experiments and sample test data are included here.

Design Criteria and Performance Objectives

The design criteria and objectives for the aircraft described below were established based on the atmospheric process to be studied, namely, the convective process in clear air. As such, the resulting performance capabilities do not reflect the ultimate capability or applicability of this type platform. Previous studies of convection in clear air using high-power, high-resolution radars have shown that the convective field grows in altitude quite rapidly once the surface inversion is destroyed.[3] In order to study convective development, fine-time-scale soundings are required about every 30 minutes. Clear air convective growth is limited by one of two things: an elevated temperature inversion may exist which stops the convective activity before condensation occurs, or a condensation point may be reached and clouds are formed. Experience has shown that one of these two limits typically is reached below 10,000 feet.

Parameters to be measured were pressure, temperature, humidity, aircraft vertical velocity, and airspeed. All data were to be telemetered to the ground. The payload weight requirement using solid-state electronic circuitry was estimated at 3 to 5 pounds. This included the sensors, electronics, batteries, and telemetry but did not include aircraft fuel.

The above operational requirements, then, determined the aircraft performance objectives for altitude (10,000 feet), payload (3 to 5 pounds) and rate of climb (500 to 1000 ft/min). Aircraft speed was to be held to a minimum, around 20 to 40 mph. Since the conditions at a constant altitude are also of interest both in the study of convection and other atmospheric processes, the aircraft was expected to have an endurance capability at altitude of several hours.

One of the advantages of the system is that it is mobile, and sounding measurements can be made in whatever location the convective activity is occurring. This advantage, however, implies that the system must be simple and highly reliable for use at remote sites where elaborate support equipment is unavailable. In keeping with this requirement, then, only well-proven, off-the-shelf, commercially available equipment used by modelers and radio control hobbyists such as transmitters, receivers, servos, engines etc., was considered in the aircraft platform design.

Aircraft Design and Performance

The basic aircraft design was developed by one of us (Hill) for use in obtaining World Record performances as prescribed in the Aviation Sporting Code of the Federation Aeronautique International. These sporting regulations, which restrict the takeoff weight (including fuel) to 11 pounds (5 kg), place a premium on weight saving in the structure. Aircraft of this size and configuration used for record assaults have typically weighed 4½ to 5 pounds (without fuel, but including engine and radio control unit). Considerable experience with respect to aerodynamics, payload capacity, engine performance, structures, etc., was therefore in hand prior to the start of this project. However, special considerations with respect to structural strength were applied to this particular aircraft because of the anticipated heavier takeoff weight and more severe operating

[1] R. D. Reed, "Flight Testing of Advanced Spacecraft Recovery Concepts Using the Aeromodellers Approach," *Proc. 2nd Flight Test Conference, Los Angeles,* AIAA paper, 1968, 68-242.

[2] W. A. Good, Applied Physics Laboratory, private communication.

[3] T. G. Konrad, "The Dynamics of the Convective Process in Clear Air as Seen by Radar," *J. Atmos. Sci.* **27,** Nov. 1970, 1138–1147.

environment (i.e., higher gust and landing loads), plus the requirements of reliable repetitive operation as compared to an all-out effort to achieve a single strenuous performance.

A three-view sketch of the aircraft is shown in Fig. 1 and a photograph in Fig. 2. The wing is a composite structure consisting of a polystyrene foam core covered with 1/16-inch sheet balsa. A layer of fiber glass cloth-epoxy resin was inserted between the balsa and foam core. This method of construction has been described elsewhere[4] and is in wide use by hobbyists because of the high strength-to-weight ratio. The SR-2 airfoil profile was employed.[5] This is a high lift section that utilizes a partially laminar boundary layer to achieve low drag. Its profile is flat on the bottom surface, and this feature is useful in avoiding warps during construction.

[4] M. L. Hill, "Channel Chatter," *Flying Models,* No. 382, Jan. 1969, 22–23.

[5] M. L. Hill, "Hill SR-2 Airfoil," *Flying Models,* No. 395, Feb. 1970, 50–51.

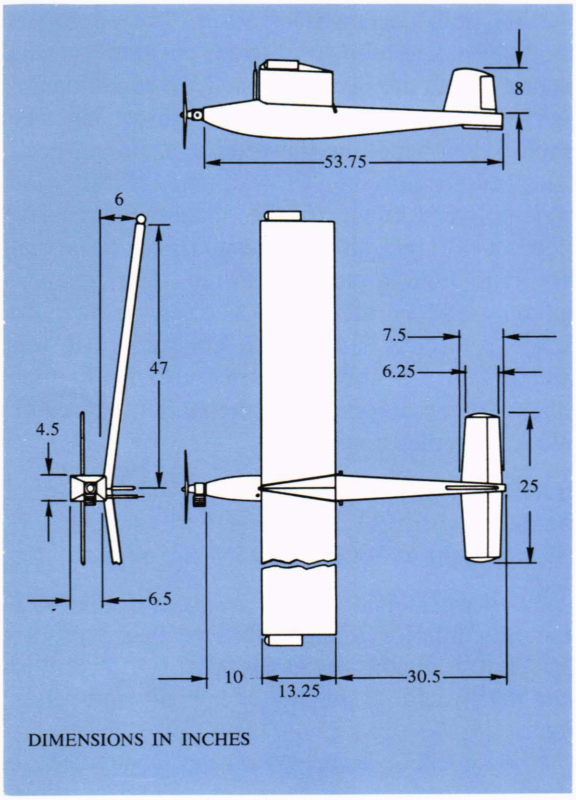

Fig. 1—Three-view sketch of basic aircraft configuration.

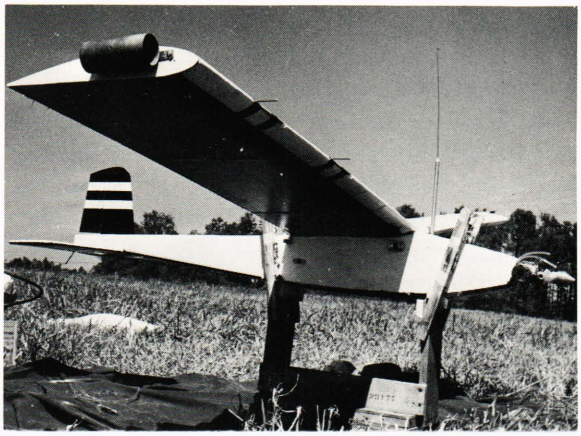

Fig. 2—Photograph of aircraft held in simple jig for checkout prior to launch. Note telemetry antenna, pitot-static tubes on leading edge of wing, sensor pods, and switches on side of fuselage.

The fuselage is a conventional "bridge-truss" box structure using 3/8-inch-square balsa longerons as described previously.[6] The body is covered with 1/16-inch sheet balsa and coated with fiber-glass-resin to resist impact loads on landing. The underside of the fuselage is covered with extra layers of fiber glass to withstand belly landings as discussed below. The horizontal and vertical stabilizers are conventional balsa spar and rib structures, covered with Supermonokote (a mylar film with heat sensitive adhesive on one side). The wing and horizontal stabilizer are removable for easy transport and were attached for flight by means of heavy rubber bands passing longitudinally across their centerlines to hooks anchored in the fuselage. This method of attachment is more than adequate to withstand flight loads and is used to prevent damage during hard landings by virtue of its ability to flex on impact.

A standard hobby-type two-cycle engine* of 10 cc capacity is used to turn a 12-inch-diameter, 5-inch-pitch propeller, which has been found to be the most suitable size for flying to high altitude. The fuel consists of a mixture of 70% methanol, 5% nitromethane, and 25% castor oil. At full power, the engine turns 12,000 rpm, produces about 0.9 hp, and consumes about three pounds of fuel per hour. The engine is fitted with a rotating barrel carburetor which can be used to

[6] M. L. Hill, "Old Faithful—World Endurance Record Radioplane," *APL Technical Digest,* **4,** No. 5, May-June 1965, 17–22.

* The engine called "Super Tigre" by the manufacturer is available from World Engines, 8906 Rossash Avenue, Cincinnati, Ohio, at a cost of about $45.

reduce power to about 10% of full power for cruising or descending. Minimum fuel consumption is about ½-pound per hour.

The radio equipment employed was a standard off-the-shelf set† for use by hobbyists. It includes a portable transmitter, a receiver, servos, and rechargeable power supplies. The transmitter operates on a frequency of 75.64 MHz, a frequency allocated by the Federal Communications Commission for citizens-licensed control of model aircraft. Transmitter output is about 300 mW, and this provides a range of about three miles when the aircraft is flown at elevation angles in excess of 20 degrees. Range is diminished at very low angles and is only ¼-mile when both receiver and transmitter are on the ground. The complete airborne system, which provides for six channels of simultaneous proportional control, weighs about 18 ounces and occupies about 50 cubic inches of volume.

Only three channels of the six available were employed for control of the aircraft. One channel was used for throttle control, another for pitch control via the elevator, and the third for yaw control by means of the vertical rudder. Normally, movable ailerons would be used to provide roll control. These are unnecessary on this design since dihedral is used to provide "hands off" stability of the aircraft. More than ample roll control results from the inherent aerodynamic coupling of the dihedral to the yaw control.

The weight of the basic, dry aircraft (fuselage, wing, horizontal and vertical stabilizers, engine, radio receiver, and servos) is 7 pounds 3 ounces. The electronic instrument package, batteries, and sensors weigh three pounds. The design and performance of this equipment is discussed in a separate section below. Fuel weight is dependent on the type of mission, e.g., sounding vs. constant-altitude-time-history, but can range from a half pound to two pounds. Thus, the all-up flight configuration weighs roughly 11 to 12 pounds.

Based on the experience discussed above concerning this type of aircraft design, some important performance figures were known prior to construction. These were: (a) a minimum of 0.16 hp is required to sustain flight at sea level at an all-up weight of 11 pounds, this value having been established in flights of duration models; (b) a climb rate of 2500 feet per minute can be achieved at sea level at an all-up weight of 7 pounds, and a climb rate of 1000 feet per minute is still available at 20,000 feet altitude; these two figures have been established in altitude record flights; and (c) the maximum value for L/D, the lift-to-drag ratio, is about 14 to 1 and occurs at about 26 mph. Using these values along with extrapolation of performance relationships for full-scale aircraft, estimates were made of the performance of the aircraft at an all-up weight of 12½ pounds. The resulting predictions were:

Time of flight to 10,000 feet	14 minutes
Maximum climb rate (sea level)	850 ft/min
Absolute ceiling	18,500 feet
Stall speed	20 mph
Minimum sinking speed (unpowered)	1.5 ft/sec
Maximum level cruising speed	60 mph
Minimum level cruising speed	26 mph

It should be pointed out that in practice these values can not be achieved in conditions of high winds. The useful, or practical, ceiling and climb rate are both decreased by wind. The aircraft is normally flown above a fixed position on the ground where the pilot is located. In conditions of high wind, some of the available thrust must be employed to penetrate the wind to maintain position. In the extreme, for example, if the wind velocity were equal to the maximum cruising speed of 60 mph, all thrust would have to be employed to hold a steady position. The practical ceiling would be zero feet. Needless to say, the device is useless under such conditions. It was desired that the aircraft be operable in 40 mph winds. At these conditions, the ceiling and climb rate was predicted to be:

Practical ceiling	6500 feet
Maximum practical climb rate	350 ft/min
Time of flight to 5000 feet	22 minutes

These performance figures are seen to be substantially inferior to the calm weather performance, but were considered adequate for the limited data that would be sought under high wind conditions.

A number of tests have been conducted to establish actual aircraft performance under various conditions of loading and to test various operational procedures. The results of these tests are discussed below. Certain of the estimated per-

† Manufactured by Kraft Systems, Inc., 450 California Avenue, Vista, California. The cost of this type of equipment is about $400.

formance predictions, however, have not been checked, for example the absolute ceiling of 18,500 feet or the time to 10,000 feet for the fully loaded configuration.

Meteorological Sensors and Electronics Instrumentation

The instrumentation for the drone was designed with certain constraints imposed by the physical characteristics of the drone (space available), by the payload capability, and by the operating environment. The total weight of the payload, i.e., instrumentation including sensors, telemetry, and batteries, was held to three pounds. Available space was 3.5 by 3.5 by 7.5 inches. Figure 3 shows the electronics package and battery pack, and Fig. 4 shows the package installed in the aircraft fuselage directly under the wing. A detailed description of the sensors, electronic circuitry, telemetry, power, calibrations, etc., has been published[7,8,9] and will not be attempted herein. Briefly, the drone is instrumented to measure pressure, altitude, dry bulb temperature, wet bulb temperature, relative humidity, airspeed, and aircraft vertical velocity. Table 1 lists the various sensors. Figure 5 shows the wing tip pods which house the temperature and humidity sensors. Note the fiber glass screening over the front of the pod. This is to prevent grass, weeds, rocks, etc. from damaging sensors during landing. The wiring to connect the sensors with the electronics runs along a hole inside the foam core of the wing. The pitot-static tubes for airspeed and vertical velocity are located on the leading edge of the right wing as shown in Fig. 2.

The telemetry system described in the above references involves frequency multiplexing the signals from the various sensors. It is fairly sophisticated, expensive equipment and has high per-

TABLE 1

MEASURED PARAMETERS AND SENSORS

Parameter	*Sensor*
Dry Bulb Temperature	Thermistor
Wet Bulb Temperature	Thermistor with wick
Relative Humidity	Carbon film on glass
Pressure	Pressure sensitive potentiometer
Air Speed	Pitot-static tube and two thermistor mass flow sensors[7,9]
Vertical Velocity	Pitot-static tube and two thermistor mass flow sensors[9]

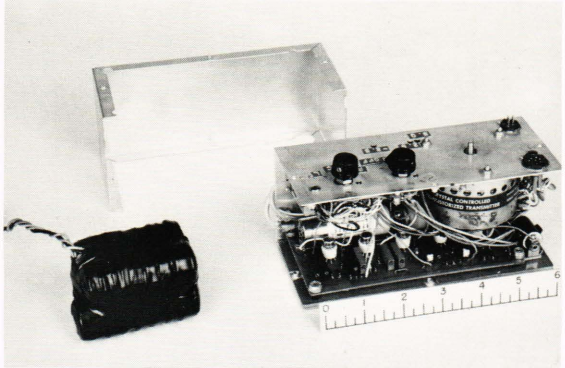

Fig. 3—Basic electronics package and battery pack. Electronics package includes transmitter and multiplexing equipment. Scale is in inches.

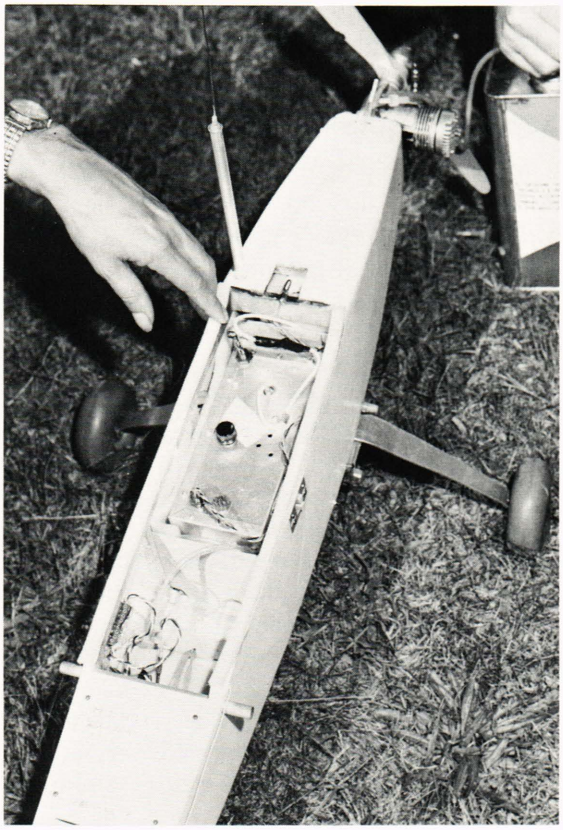

Fig. 4—Electronics package mounted in aircraft fuselage. Battery pack is located forward of package and cannot be seen.

[7] J. R. Rowland, "Electronic Instrumentation for the Small, Drone Aircraft," BPD70U-6, The Johns Hopkins University, Applied Physics Laboratory, Mar. 1970.

[8] J. R. Rowland, "Updated Instrumentation for the Small Drone Aircraft," BPD70U-36, The Johns Hopkins University, Applied Physics Laboratory, Nov. 1970.

[9] J. R. Rowland, "The Application of an Electronic Mass Flow Rate Sensor to an Instrument for the Measurement of Aircraft Vertical Velocity," BPD70U-5, The Johns Hopkins University, Applied Physics Laboratory, Mar. 1970.

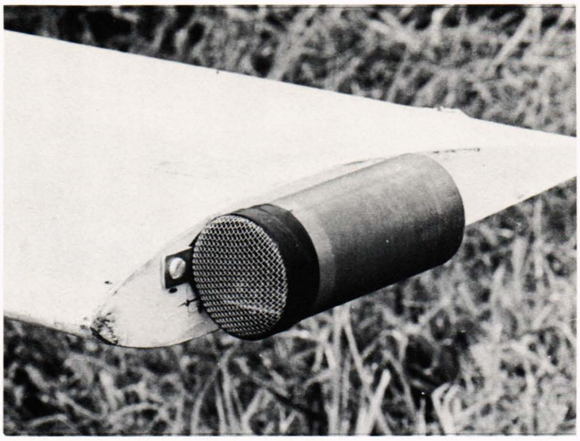

Fig. 5—Sensor pod mounted on the wing tip. Note fiber glass screen over pod.

formance capability. It was used for reasons of availability only and simpler, more economical equipment could be used in this and most other applications. Figure 2 shows the telemetry antenna located just forward of the wing. In order to preserve battery power, external switches for the telemetry and sensor electronics are provided on the side of the fuselage just below the wing. These are shown in Figs. 2 and 4.

Support Equipment

Most observers can spot an 8-foot radio-controlled aircraft at 5000 to 6000 feet slant range with the naked eye, but the practical limit for maintaining control is lower than this figure. The reason is that it is necessary that the pilot be able to discern attitude and direction of flight in order to apply the correct controls. Experience has shown that 3500 to 4000 feet is about the maximum altitude at which the wing, tail, and fuselage profiles can be adequately seen to maintain control without optical aids. Since the objective was to provide a capability to 10,000 feet, it was necessary to develop some optical support equipment to allow flights to these higher altitudes.

Test flights were made with elaborate servo-driven, optical trackers with 20 and 50 power binoculars and also with closed circuit television displays. These devices provide a capability of higher altitude flights, but they are very cumbersome, trailer-mounted devices that require towing vehicles and external electrical power. As a result, they are incompatible with the objective of providing a simple system that could easily be put into operation at remote sites. It was demonstrated that a pilot can maintain control when viewing the aircraft through a closed-circuit television monitor. Difficulties in orientation were encountered by the pilot when the monitor was held stationary. No difficulty, however, was experienced when the TV monitor was pointed synchronously with the optical or radar tracker at the aircraft.

A simple optical system was built which consisted of two pairs of 7-power binoculars mounted with a common boresight on the swivel at the top of a standard camera tripod. This device is shown in Fig. 6. It requires an operator who uses a handle to point the binoculars and track the aircraft. The pilot observes the aircraft through the second pair of binoculars and has both hands free to operate the control transmitter. Both the tracker and pilot are in a standing position during flight. The pilot has sufficient side vision to sense the horizon and heading and there are no problems related to orientation. Many flights have been made and numerous trackers and pilots have used the device, all adapting to it very easily and naturally. There is one disadvantage to the device and that is that both pilot and tracker must assume awkward positions that cause neck fatigue during flight at high elevation angles (above 60 degrees).

To overcome the fatigue problem, an alternate, simpler system was developed. It consists of a small pair of 6-power, wide-angle binoculars mounted in a pair of machinists safety goggles. The pilot can slip these over his eyes whenever needed. In normal operations, we have found it wise to have two pilots available and fitted with such glasses. This provides redundancy in the tracking and pilot operation and permits easy re-

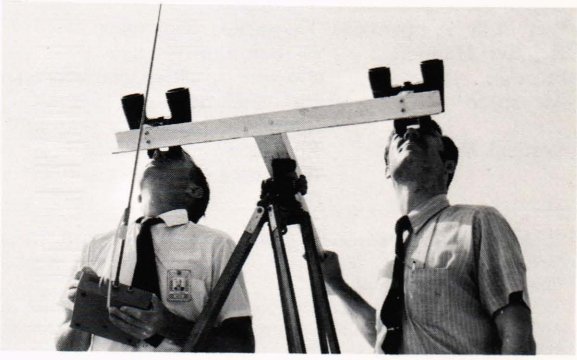

Fig. 6—Simple optical tracker mounted on camera tripod. Pilot is at left and tracker is at right holding handle.

lief of pilots by transfer of the transmitter from one to the other.

Aside from the optical aids described above, no special support equipment is needed. The aircraft and all necessary equipment for flight operations from remote locations such as fuel, spare parts, and tools can be easily transported in a station wagon.

Operational Procedures

One of the operating design criteria was that the platform be capable of operation from remote, unimproved sites such as open fields or pastures. Under these conditions, landing gears are impractical. They are easily caught in high grass or weeds during take-off and landing causing the aircraft to nose over abruptly. This might result in structural damage. The aircraft is simply hand launched and is belly landed. In general, experience has shown that these procedures are quite satisfactory and little or no damage results when landing on grass, plowed fields, or crops. Where a smooth surface is available, such as a runway or a road, a landing gear may be used and more than ample power is available to fly the aircraft off the ground. Figure 4 shows the fuselage with a landing gear attached.

Figure 7 shows the aircraft being readied for a flight at a typical remote operating site. Note the high grass and the plowed field and trees in the background. A simple jig mounted on a tool box is used to hold the aircraft during checkout and calibrations. During certain experiments the aircraft is tracked by radar. In order to provide a distinctive radar signature and aid in radar acquisition, a metallized mylar streamer, 2 inches wide and 20 feet long is attached to the tail skid as shown in Fig. 7. The streamer causes a scintillation in the radar signal which is easily recognizable. Figure 8 shows the aircraft in flight. Again note the condition of the field.

For repeated fine-time-scale soundings the aircraft climbs under power to altitude where the engine is shut off. The controls are then set for a slow, gliding descent in either a spiral or a straight line, up-and-down wind pattern. For sampling at constant altitude, the aircraft can often be pointed into the wind and the throttle setting adjusted so that the aircraft airspeed matches the wind speed at altitude. In this condition, the aircraft remains motionless with respect to the ground. This technique is limited, of course, to those wind speeds within the minimum and maximum cruising speeds for the aircraft, discussed in an earlier section. At any wind velocity up to and including 40 mph, it is possible to apply power and travel about one-half mile laterally in any direction from the operator with no optical aids. Further horizontal distances require binoculars as discussed above.

Fig. 7—Aircraft being readied for flight at a remote site.

Test Results

Preliminary tests of the aircraft and optical tracker were first performed without meteorological electronics on board. Flights to 10,000 feet altitude (12,500 feet slant range) were made where flight altitudes were confirmed by radar tracks of the aircraft. During these initial tests the potentially hazardous effects of haze and partial cloud cover were noted. In the case of haze or smog, the safe visibility range is significantly re-

Fig. 8—Aircraft in flight at remote operating site during July 1970 experiment.

duced when the aircraft is flown at low elevation angles as compared to nearly vertical. The loss of visibility, however, is fairly gradual and can be recognized by the pilot and tracker in time to prevent the loss of visual contact.

When a low-level cloud drifts across the line of sight, visual contact, of course, is completely lost and the aircraft must be reacquired. This is particularly hazardous in conditions of high winds since the rapid horizontal drift of the aircraft greatly reduces the time for reacquisition and the aircraft may be lost. We have flown the aircraft well above the cloud base in conditions of 2 to 3 tenths cumulus cloud cover. Under these circumstances, a "cloud spotter" is useful to advise the tracker and pilot concerning the proximity of clouds.

The need for increased structural integrity over that typically used by modelers was graphically and painfully illustrated during one of the first flights with all the instrumentation installed. At that time, the wing being used was a standard balsa wood spar and rib structure covered with the mylar film. It had been designed and tested for a loading of 5 g with an anticipated all-up aircraft weight of 10 pounds. Take-off weight was actually 11 pounds. A climb to roughly 7000 feet was made in 8 minutes and the engine was throttled back for a constant altitude cruise. Shortly thereafter the aircraft was placed in roughly a 45 degree dive to descend to 5000 feet. There was considerable clear-air convective activity to about 6000 feet as seen by the Joint Air Force-NASA (JAFNA) radar facility located at Wallops Island, Virginia, and by the flight characteristics of the aircraft. During the descent from 7000 feet the aircraft reached an overspeed condition, and when it entered the convective region it apparently encountered a severe updraft which caused it to pitch up sharply. The wing failed by complete fracture at the center span and tore away from the fuselage. This experience led to the construction of the foam core wing described earlier which was stressed and tested for a 10 g loading at the 11 pound flying weight.

During a week-long experiment in October 1969, twenty flights, including soundings and constant altitude probes, were made from a remote site approximately 14 miles north of the JAFNA radars. The flights were typically of fifteen minutes to one-half hour duration. Ground weather conditions ranged from near calm to winds of 25 knots. Flights were made to 4000 feet on days when winds of 40 knots were reported for that altitude. In these high winds, the time of flight to 4000 feet was roughly ten minutes. The telemetered pressure altitude data showed an initial climb rate of 450 ft/min which decreased to 250 ft/min at 4000 feet. In calm weather, the initial climb rate was found to be 900 feet per minute and the aircraft reached 5000 feet in about 7 minutes. These results confirmed the initial predictions of aircraft performance and the effect of wind on climb rate.

In July 1970 the aircraft was used in another week-long experiment designed to probe convective development during the initial formation and growth stages. Soundings roughly every one-half hour to forty-five minutes were made for extended periods of time on several days. To illustrate the type of operation and data which can be obtained, sample data taken during this experiment are shown in Fig. 9.

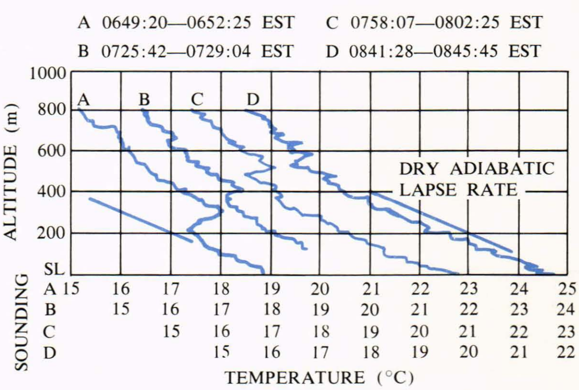

Fig. 9—Example of fine-time-scale temperature soundings made early in the development of convective activity on July 17, 1970. Note lifting and dissipation of inversion by convection.

The temperature soundings shown were the first four of a total of ten soundings made on July 17, 1970. Note that the temperature scale in Fig. 9 is shifted for successive soundings. The steps in the altitude (pressure) trace are the result of mechanical "stiction" in the sensor. Surface readings were taken with the aircraft on the ground for two-minute intervals prior to and following each flight. Of interest is the lifting and final destruction of the elevated inversion by the convective activity. The JAFNA radar facility documented the convective development with Range Height Indicator and Plan Position Indicator photographs. These data are then correlated and compared with the meteorological measurements.

Conclusions

The feasibility and usefulness of a small, radio-controlled aircraft as a platform for meteorological sensing equipment has been demonstrated. The system is simple and relatively inexpensive, using commercially available radio-control components. Being controllable and recoverable, it can make repeated fine-time-scale soundings or sample the atmospheric properties at constant altitude in selected, remote locations, for extended periods of time. The platform is quite versatile and should be useful in a wide variety of meteorological studies where current platforms are limited or inappropriate.

The operating volume is limited by winds and optical problems more than by performance of the aircraft and control systems. Experience with the system has shown that the aircraft can be controlled using the unaided eye up to about 4000 feet. Above this altitude some simple optical assistance is necessary. Although the present aircraft has been successfully launched and flown in high winds, control of the aircraft under these conditions is difficult and should be avoided. The system described was developed for a fairly specific meteorological application but increased payload, altitude capability, and speed are certainly possible with a modest increase in system complexity and cost.

Acknowledgment

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