N71-18950

NASA CONTRACTOR REPORT

NASA CR-61339

BALLOON-BORNE HUMIDITY AND AEROSOL SENSORS

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February 16, 1971

Prepared for

NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER
Marshall Space Flight Center, Alabama 35812

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. NASA CR-61339	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE BALLOON-BORNE HUMIDITY AND AEROSOL SENSORS		5. REPORT DATE February 16, 1971
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) D. G. Murcray and D. B. Barker		8. PERFORMING ORGANIZATION REPORT #
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Physics, University of Denver, Denver, Colorado 80210		10. WORK UNIT NO.
		11. CONTRACT OR GRANT NO. NAS8-30179
12. SPONSORING AGENCY NAME AND ADDRESS NASA, Washington, D. C.		13. TYPE OF REPORT & PERIOD COVERED CONTRACTOR
		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES Contract Monitor: D. W. Camp, Aerospace Environment Division, Aero-Astrodynamics Laboratory, Marshall Space Flight Center.

16. ABSTRACT

A state-of-the-art survey of humidity and aerosol sensors emphasized those techniques and instruments that could possibly be used with nonrecoverable rawinsonde balloon type packages to explore the first 20 km of the atmosphere. A literature search plus discussions with investigators active in this field provided background data for a study of promising techniques. Theoretical and experimental analyses established the feasibility of sensing atmospheric humidity through IR emission.

17. KEY WORDS Water Vapor Concentration; IR Emission; Humidity and Aerosol Sensors	18. DISTRIBUTION STATEMENT FOR PUBLIC RELEASE: E. D. Geissler, Director, Aero-Astrodynamics Laboratory

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
UNCLASSIFIED	UNCLASSIFIED	42	$3.00

MSFC - Form 3292 (May 1969)

FOREWORD

Current atmospheric studies of interest to the meteorological and aerospace communities have indicated the need for more detailed information than is currently available with regard to water vapor concentration and aerosol sizes and concentrations in the lower 20 km of the atmosphere. A program to measure these quantities over a significantly wide range of spatial and temporal variables would not be economically feasible without accurate, inexpensive sensors that could be flown and monitored by telemetry on small rawinsonde type balloons. The objectives of the program described in this report were to 1) Survey existing (and previously developed) instrumentation which is capable of detecting particulate matter and humidity in the first 20 km of the atmosphere, 2) Assess the potential of each technique for yielding a lightweight, remote sensor that could be developed with sufficient accuracy and reliability and produced economically, 3) From the current research and development activity project sensor availability in the near future, 4) In discussions with the sponsor determine if any particular sensor concept should be studied in more detail for contractor development, and 5) If it is so determined, proceed with study, development and analysis.

During the course of this study a number of persons in our laboratory contributed to the success of various portions of the program: John Williams participated in discussions of IR capabilities; Aharon Goldman and John Van Allen assisted in theoretical calculations and data reduction; John Kosters and Troy Dow were responsible for many of the details of the balloon flight program.

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BALLOON-BORNE HUMIDITY AND AEROSOL SENSORS

Recent widespread interest in atmospheric phenomena related to meteorology, pollution and aviation has emphasized the need for more complete and accurate data on temperature, humidity, density, winds, turbulence, composition and other parameters of the atmosphere. Two limited aspects of this broad field were dealt with in the study being reported: instrumentation to detect and measure humidity and aerosols. Emphasis was placed on expendable, light-weight rawinsonde-type instruments for probing the lower 20 km of the atmosphere.

The study began with a state-of-the-art survey which was primarily a literature search, although discussions were held with a limited number of other investigators active in these fields. The literature survey was initiated with a Retrospective Search performed by the Technology Application Center at the University of New Mexico. Obvious gaps in coverage of their report were then filled in with a standard library search using abstract sources and by working back in time from literature references in current articles. The study was carried back to about 1925 on the assumption that a technique which was investigated but not found feasible earlier might be feasible with current technology. From the abstracts and available reviews, articles and reports that appeared to be pertinent were selected and copies obtained for a more detailed analysis.

Several of the techniques being investigated, some of them extensively, show promise, and useful remote sensors of aerosols and humidity may be developed from the current research. Other techniques which appear feasible have received little attention. One of these, the detection of water vapor by infrared emission, has significant merit and was chosen for further theoretical and experimental investigation, since it is compatible with available laboratory facilities and the investigators' experience.

I. HUMIDITY SENSING

The volume of literature in the area of humidity detection is staggering. Bibliographies with thousands of entries could easily be compiled. Although many articles deal with industrial processes and air conditioning, much of the literature applies directly to atmospheric measurements because of the extensive research and development in radiosonde sensors. Fortunately, much of the available knowledge has been brought together and distilled in the four-volume report, Humidity and Moisture, of the First International Symposium on Humidity and Moisture held in Washington, D. C. in 1963. Our literature search concentrated mainly on the subsequent period although in some areas earlier references are significant.

Another valuable source of information was the conference on "Water Measurement Techniques for Mars" held at the Jet Propulsion Laboratory on 21 May 1969 which one of the authors (DGM) attended. The major objective of the Viking soft landing planned for 1974 will be to measure the water vapor on Mars. The conference was called to consider all possible techniques for making these measurements; hence, many of the people who are currently working on water vapor measuring instruments were present. The informative discussions centered around the capabilities of each technique to make the desired measurements. A point of interest was the lack of any new techniques for measuring water vapor.

A. STATE OF THE ART

Of the many schemes and techniques that have been proposed for humidity sensing, four basic processes with specific forms of implementation appear to have the required sensitivity and other characteristics for the balloon application under consideration.

1. Sorption

Aluminum Oxide - The electrical properties of a layer of Al_2O_3 depend very strongly on the amount of water vapor adsorbed on the layer, which in turn depends on the vapor pressure of the water in the air surrounding the surface. The use of this property to measure atmospheric humidity has been investigated by a number of groups in the United States, England and Japan. It is currently being manufactured as a unit by Panametrics.* The manufacturer claims the unit is capable of measuring frost points well below -100 C. The accuracy of measurements made has been the subject of considerable controversy. Investigators who have attempted to use the unit have found the results obtained depended on many factors, a number of which could not be controlled during field use. The manufacturer on the other hand claims that the inconsistencies in the results obtained by the users has been due to faulty experimental techniques. If the problems associated with using the units can be solved, this method would be suitable for use as a balloon-borne hygrometer system.

Piezoelectric Sorption Detector - The resonant frequency of a quartz crystal is basically a function of crystal parameters and physical dimensions. However, certain crystalline orientations are particularly sensitive to any material added to the surface. This property has been used as a means of developing an ultrasensitive mass detector. By coating the crystal surface with a material that absorbs a particular molecule, the system can be used as a selective detector. This property has been used to make a hygrometer by coating a quartz crystal with a strongly hygroscopic material. The instrument can be made fairly sensitive; however, sensitivity is achieved with a loss in speed of response and it is doubtful whether the unit could be made to work in the stratosphere without increasing the frost point of the sampled air by pumping. This possibility should not be ruled out since the accuracy of most techniques could be improved by increasing the absolute humidity of the sample.

Cobalt Oxide - On the basis of patent claims (1967, assigned to IBM), the CoO unit should be considered for further development. The CoO crystalline surface appears to adsorb water vapor causing

*Panametrics, Inc., Waltham, Mass. See Chleck, Appendix A, p. 28

the electrical resistance to vary exponentially (4 or 5 orders of magnitude from 0% to 100% RH). Further claims include low temperature coefficient, negligible hysteresis and immunity to air pollutants. We have, however, been unable to obtain any more information about the device either in the literature or from inquiries to IBM.

2. Frost Point

This technique was first developed by Dobson and Brewer in the early 1940's. It consists of measuring the temperature of a mirror surface that is maintained at the frost point. In the Dobson-Brewer instrument this was done manually and the measurements were limited to the altitudes which could be reached by aircraft. Barrett and coworkers in the early 1950's designed a small unit where the mirror was maintained at the frost point by means of a servomechanism. This unit was small enough to be carried aloft by small balloons and several ascents were made. This type of frost point measuring device has continued to receive considerable attention since that time. Various techniques have been used for sensing frost on the measuring surface and providing the signal required for control of its temperature; however, the units that are currently in production in the United States and in Japan still employ the optical head which relies on scattering by the frost layer for sensing its presence. These units as used by various investigators appear to work at least occasionally. Some ascents give anomalous results and it is subject to local contamination as are all point measuring instruments. The Japanese version of this unit is relatively inexpensive and suitable for use on a small balloon. It is built to be flown as a standard rawinsonde unit. The accuracy and reliability of the current unit are not known. The early units quite often gave very high humidity readings in the lower stratosphere and appear questionable in light of the results obtained by other investigators. The current version may fulfill the requirements of this program. The frost point instrument has the additional advantage that it is an absolute instrument and if it is operating properly, should give a measurement of the atmospheric humidity directly without going through a calibration procedure.

3. Radiant Absorption and Emission

Ultraviolet Absorption - Water vapor has strong absorption features at wavelengths short of 3000Å. The major atmospheric constituents as well as the minor constituents also have strong absorption features in the same wavelength regions. This has limited the use of this wavelength region for water vapor measurement. In addition the strong atmospheric absorptions by various molecules at the high altitudes preclude the use of the sun as a radiation source and hence limit this technique to short atmospheric paths achieved with internal sources which in turn has limited the sensitivity.

Infrared Techniques - Water vapor has a number of very strong absorption bands in the infrared region of the spectrum, whereas the major atmospheric constituents (O_2, N_2) do not. These water vapor bands have been used by a number of investigators to determine the amount of humidity present at the higher altitudes. The techniques that have been used separate logically, from the standpoint of interpretation and experimental procedure, into absorption and emission systems. In the first, the absorption by water vapor as the radiation traverses a path from a source to a spectrally sensitive detector (filter radiometer, spectrometer, etc.) is measured. In most cases reported in the literature, the sun has been used as the radiation source for this type of measurement in the stratosphere. Attempts have been made to fly a source along with the detector and to detect the absorption over a short path close to the balloon; however, this technique has not had sufficient sensitivity for use in the stratosphere. The use of the sun as the source seriously limits the absorption technique.

Water vapor also emits strongly in those wavelength regions where it absorbs strongly. The emission, however, depends not only on the amount of absorption but also on the temperature. In order to use this technique, it is necessary to measure the temperature profile as well as the emission profile. While this technique has a number of shortcomings, it has been demonstrated to have the sensitivity required to make the measurement and it is possible to build the unit into a sonde type of device.

4. Mass Flow

In the phosphorous pentoxide sensor, the highly hygroscopic P_2O_5 is deposited between the electrodes of an electrolytic cell. Water vapor in the gas flowing through the cell is absorbed by the P_2O_5 and disassociated by an applied voltage. The resulting charge flow in the circuit is a direct measure of the mass of H_2O entering the cell. Although basically simple in concept and adequately sensitive for low humidities, the technique has a number of limitations: gas flow control is required to prevent saturation at high humidities; detailed mechanisms of cell operation are not known; ionic conduction causes electrode plating and shorting; time constants are long at lower temperatures; and recombinations of the gaseous dissociations products cause some uncertainties. However, for short term sonde applications, some of these problems are less significant, and the development of a simple pumped or diffusion flow control could yield a sensitive, absolute instrument.

B. INFRARED EMISSION STUDIES

Most of the potentially useful humidity sensors are being explored or developed by several laboratory groups or industrial concerns. However, the area of IR emission has received less support. It appeared that in terms of laboratory experience and facilities we were equipped to make a unique contribution to the development of this technique: a filter radiometer was available for use with minor modifications; calibration facilities were available; and several large balloon flights were scheduled for another project on which the radiometer could be piggy-backed thus eliminating a major expense. In conference with the sponsor it was decided that a more detailed analysis of the IR emission profile plus several flights to assess the feasibility of the technique for small packages could make a significant contribution to the field of humidity sensing.

1. Theoretical Considerations

Consider the atmosphere above the balloon to consist of a number of layers where each layer is considered to be isothermal and the water vapor is uniformly mixed in the layer. The radiation emitted by the i^{th} layer will be given by

$$N_i(\lambda) = \epsilon_i(\lambda)\beta(\lambda T_i)$$

where ϵ_i is the emissivity of the layer at wavelength λ and $\beta(\lambda T_i)$ is the radiance of a black body at wavelength λ and temperature T_i. The radiation emitted by the i^{th} layer must traverse the layers between the balloon and the i^{th} layer hence radiation observed at the balloon from the i^{th} layer is given by

$$N_{oi}(\lambda) = \epsilon_i(\lambda)\beta(\lambda T_i)\tau_i(\lambda)$$

where τ_i is the atmospheric transmission between the balloon and the i^{th} layer. The observed radiance will be given by

$$N(\lambda) = \sum_{i=1}^{n} N_{oi}(\lambda) = \sum_{i=1}^{n} \epsilon_i(\lambda)\beta(\lambda T_i)\tau_i(\lambda)$$

as the balloon ascends the radiance will change and at the time the balloon has traversed the first layer the radiance will be given by

$$N(\lambda) = \sum_{i=2}^{n} N_{oi}(\lambda) = \sum_{i=2}^{n} \epsilon_i(\lambda)\beta(\lambda T_i)\tau_i(\lambda)$$

hence the change in radiance is

$$\Delta N(\lambda) = \epsilon_1(\lambda)\beta(\lambda T_1)\tau_1 = \epsilon_1(\lambda)\beta(\lambda T_1)$$

$$\text{since } \tau_1 = 1 \quad .$$

In practice the experimental data are obtained with an instrument that passes a band of wavelengths; hence, the quantity observed is given by

$$\Delta N = \int_{\lambda_1}^{\lambda_2} \Delta N(\lambda)d\lambda = \int_{\lambda_1}^{\lambda_2} \epsilon_1(\lambda)\beta(\lambda T_1)d\lambda$$

where λ_1 and λ_2 are the limits of the wavelength passed by the filter. Several factors had to be considered in choosing the wavelength interval to be used in the balloon radiometers. These included the characteristics of black body radiation at the temperature encountered in the upper troposphere and lower stratosphere, the absorption spectrum of water vapor, the availability and cost of filters, detectors, etc., for the various wavelength regions where water vapor absorbs strongly. The system chosen represented a compromise which it was felt would yield data concerning the feasibility of the techniques without being too expensive.

2. Experimental Program

In the modified filter radiometer (Figure 1) the incoming atmospheric radiation was focused by a 10 cm mirror onto a Reeder thermocouple detector with a KBr window. The focused beam was chopped by a segmented mirror chopper which on alternate half cycles imaged a temperature-monitored reference black body onto the detector. The thermocouple output, which thus represented the differential emission between the black body and the atmosphere, was amplified, synchronously rectified, and filtered to provide a voltage signal at a convenient monitoring level. A timing circuit alternately inserted into the optical path of one of two available stock filters (Figure 2). The filter centered close to 15μm was chosen as a system performance check since it passed radiation centered in the strong absorption due to the CO_2 and could give data on the atmospheric temperature close to the balloon-borne package. The other filter was chosen to lie in the wavelength region containing many strong absorptions due to the rotational water vapor band. This choice of filter was not optimal as will be discussed in more detail below.

A mounting for the radiometer was added to an existing research instrument gondola which also supplied the necessary power and the signal processing required for telemetry and on-board recording of the reference black body temperature and radiometer output. Balloon flights were made from Holloman Air Force Base, New Mexico, with typical ascent rates of 3 m/s up to float altitude of 30 km. The radiometer had a look angle of 5° above horizontal.

After several test flights in which problems of variable amplifier gain and mirror orientation were discovered and corrected, useful data was obtained during flights on 13 June and 11 July 1970. Figures 3 and 4 show the CO_2 temperature data compared with air temperature data from radiosondes flown at approximately the same time and location. Figures 5 and 6 show the total radiance from the water vapor.

In Section I.B.1. it was shown that the change in radiance with altitude was given by

$$\Delta N = \int_{\lambda_1}^{\lambda} \epsilon(\lambda)\beta(\lambda T)d\lambda$$

where $\epsilon(\lambda)$ is the emissivity of the water vapor in the layer traversed by the balloon, $\beta(\lambda T)$ is the Planck black body function and λ_1 and λ_2 are the limiting wavelengths passed by the filter. The function $\epsilon(\lambda)$ is a rapidly varying complex function of the wavelength and a completely accurate inversion of the integral to obtain the amount of water vapor present in the layer would require an elaborate computation on a digital computer. In the altitude region above 9 km, where the amount of water vapor is small, the absorptions due to water vapor are weak enough to fall in the so-called "linear region" and the emissivity can be fairly closely approximated by

$$\epsilon(\lambda) = f(\lambda)u$$

where u is the amount of water vapor present in the layer and $f(\lambda)$ is a function which can be determined from the theoretical and laboratory studies of the absorption of radiation by water vapor. Using this expression and the Rayleigh-Jeans approximation for the radiance of a black body,one obtains

$$\Delta N = [\int_{\lambda_1}^{\lambda_2} f(\lambda) \left(\frac{8\pi k}{\lambda^4}\right) d\lambda] \; uT$$

where k is Boltzman's constant. Under the conditions for which these assumptions are valid,the quantity in brackets can be evaluated by numerical methods and the determination of the water vapor mixing ratio from the observed ΔN and temperature becomes straightforward (Figures 7 and 8).

C. FUTURE WORK

The results of the experimental phase of this program have demonstrated conclusively that it is possible to measure the small amount of water vapor present in the upper troposphere and lower stratosphere by measuring the infrared emissions in the 20 to 35μm region. This technique has the advantage over a number of the other techniques in that there is no question of the time constant involved in the measurement. These feasibility studies were made with a relatively large and heavy package which certainly would not be suitable for sonde operation. The next step in a program aimed at developing a hygrometer for use in conjunction with a small balloon would be to design and construct small prototype instruments that would be light enough to be carried on a small balloon and inexpensive enough so that they could be used as throwaway packages. A series of test flights would be required to make sure they performed according to design. On the basis of the costs of the various components used in this study, it is evident that such a system could be built such that the cost in quantities as small as 10 could be kept to less than $600.00 per unit. These units would be designed to operate in conjunction with a standard rawinsonde transmitter. The only major operational difficulty appears to be the problem of making sure that the unit is nominally pointing at the desired look angle. Thus the large oscillations which are normally associated with rawinsonde balloon package would have to be greatly reduced. Aside from this problem the design and operation of such units would be routine.

Toward the end of this program the problem was posed as to whether or not it would be possible to determine the distribution of water vapor in the atmosphere from ground based measurements. An instrument of this sort was constructed by Foster, Volz and Foskett in the early 1960's. This instrument utilized the observed absorption in the infrared solar spectrum in the relatively weak ρ band of H_2O at 0.96μm. The system was calibrated by comparison with rawinsonde ascents, and although there was considerable scatter in the calibration data, it appeared to give reasonable results. This technique has the disadvantage that data can only be taken when the sun is up and not obscured by clouds. Another possible technique would be to use the emitted atmospheric radiation to determine the amount of water vapor present. As in Section I.B.1., the atmosphere above the observing point would be assumed to be in n layers. The radiance as observed at wavelength λ would be given by

$$N(\lambda) = \sum_{i=1}^{n} \epsilon_i(\lambda)\beta(\lambda T_i)\tau_i(\lambda)$$

where as before $\epsilon_i(\lambda)$ is the emissivity of the i^{th} layer which will be a function of the amount of water vapor in the i^{th} layer, $\beta(\lambda T_i)$ is black body radiance at wavelength λ for temperature T_i and $\tau_i(\lambda)$ is the atmospheric transmission between the i^{th} layer and the observing point which depends on the wavelength and the amount of water vapor present between the i^{th} layer and the ground. Assuming that the atmospheric temperature versus altitude profile is known, this expression can be written as

$$N(\lambda) = \beta(\lambda T_1)\ f_1(\lambda) + \beta(\lambda T_2)\ f_2(\lambda) + \cdot\cdot\cdot + \beta(\lambda T_n)\ f_n(\lambda)$$

where $f_1(\lambda) \cdot\cdot\cdot f_n(\lambda)$ depend on the water vapor distribution. The functions $f_1(\lambda) \cdot\cdot\cdot f_n(\lambda)$ are rapidly varying functions of λ. By using a spectral radiometer one could measure the atmospheric radiance at any number of wavelengths. Thus one would have a set of observations

$$N(\lambda_j) = \sum_i \beta(\lambda_i T_i)\ f_i(\lambda_j)\ . \qquad j = 1 \cdot\cdot\cdot k \quad \text{where } k>n\ .$$

If the wavelengths of observation are properly chosen, it is, in principle, possible to determine uniquely the distribution of water vapor in the n layers which gives rise to the observed $N(\lambda_j)$. This problem is one of considerable meteorological interest particularly in satellite inversion techniques. As a result the problem has received considerable attention over the last few years and the computational procedures have been well developed. Observationally, the problem treated here of determining the water vapor amount from observed downward radiance is considerably more difficult than the problem treated for the satellite situation where the data are obtained from above the atmosphere. This is due to the fact that the temperature and water vapor amounts are decreasing with altitude. As a result the major portion of the observed radiance comes from the lower layers and the contribution from the cold, dry upper layers is quite small. Thus the radiance must be accurately measured or the contribution from the upper layers will be lost. While the uncertainty in the measurement will limit the altitude to which the water vapor content can be determined, in most cases it appears that water vapor amount can be inferred up to the 4.5 to 6 km level.

II. AEROSOL SENSING

Many instruments have been developed to study various aspects of aerosol distributions and properties: integrated mass concentration, particle size spectrum, optical properties, chemical composition, physical properties, volatility and water droplet nucleating characteristics. A number of available commercial instruments and laboratory techniques depend upon filter, impact or electrostatic collection of samples which are later examined by optical or electron microscopy, by liquid suspension counters or weighed with sensitive microbalances; others utilize various optical scattering techniques.

The bibliography that was compiled falls far short of being all inclusive. Rather an attempt was made to include significant papers in the historic development of aerosol research, general background discussions, reviews and representative reports on the current state of the art of various methods of detection. Emphasis was placed on those techniques which may be applicable to rawinsonde type measurements.

A. STATE OF THE ART

No instruments which adequately meet the requirements of this program seem to be currently available. The developmental or prototype devices which show some potential can be categorized according to the measurement principle involved.

1. Optical Scattering

Two general techniques have been used. The dark-field microscope (and its optical inverse) monitor the light scattered from individual particles as they drift through a very small sampling volume. From Mie scattering theory plus calibrations with known, uniform aerosol suspension, the particle size distribution can be inferred from the light pulse distribution. Such an instrument developed by Sinclair will count particles in the diameter range 0.3-17 μm although variations in refractive index in unknown aerosols can cause uncertainties of at least a factor of 2. Rosen has made balloon flights with a simplified version of this concept with two channels counting particles in the range 0.2-0.7 μm and >0.7 μm. Two photomultiplier detectors in coincidence were used to attain low background counting rates. Sampling problems restricted the upper size limit to about 1.0 μm and the measurable concentrations to 0.05-200/cm^3.

The integrating nephelometer described by Ahlquist and Charlson and the laser scatterer of Proctor examined a larger optical volume and monitored the total light scattered. The derived scattering coefficient can be related to visibility or meteorological range. One adaptation of the nephelometer with a one second time constant has been flown in aircraft to 1500 m to obtain low altitude vertical profiles.

All of these instruments used pumps or blowers and ducting to deliver sampled air to the optical region. This was required primarily to shield the detectors from ambient light but, for balloon flights, would also improve the sampling statistics in low concentration regions. The atmosphere sampled was thus a very restricted volume near the instrument which has caused some questions to be raised concerning contamination from the package and balloon. Rosen flew the dark-field microscopes suspended 90m feet below the balloon and took data both during ascent and during descent by parachute following balloon release. He indicated that no evidence of balloon contamination was observed.

These optical units have been more highly developed in instrument design and theoretical understanding of the basic principles involved than any of the other techniques to be discussed. With some restrictions on accuracy and detectable size, they could probably all be adapted to a rawinsonde size package. If the sampling of a larger volume was desirable, a low-powered version of the optical radar utilizing a laser pointed horizontally could probably integrate backscattered radiation from a significant distance from the package.

2. Electrostatic

Guyton used triboelectricity (friction electricity) in the construction of a simple aerosol counter. A glass duct was terminated in a 45° cone section which had a small opening at the vertex. A vacuum pump drew the air sample through the duct, and the aerosol impinged on a fine detector wire placed across the opening. The charge deposited on the wire triggered a counter through a high gain amplifier. The electrostatic charges appeared to come from frictional encounters as the aerosols passed through the duct and orifice, and in some cases the magnitude of the charge could be related to the surface area of the particles. For other particulate materials there was little correlation and little understanding of how the charge originated. Three μm was the lower limit of detectability of the original research, but with modern electronic developments, this could probably be lowered to 1 μm. While the basic design is simple and could be made quite compact, the uncertainties about the principles involved, and the peculiarities of high gain charge amplifiers make this approach seem doubtful without much more study and development. Liu has used corona charging of aerosols followed by electrostatic deflection to deposit samples on grids for microscopic examination. He is also studying the charge transfer mechanism which may improve the theoretical understanding of electrostatic techniques.

3. Acoustic

Research in this area was begun only recently, but it was included because it offers the potential of a small, light device. Langer used a glass duct which gradually tapered down to a long, thin capillary section with an abrupt transition to a larger exit section. A sensitive microphone at the exit detected acoustic pulses as particles left the capillary section. In the initial studies there was very little size discrimination, and particles smaller than 10 μm were not detected even at high flow rates. Research is continuing at NCAR.

4. Mass

The use of sensitive microbalances to weigh particles trapped in graduated filters has been used extensively in laboratory studies of aerosols and their size distribution. One form of microbalance may be applicable to rawinsonde applications. As was discussed in the section on humidity sensors, the resonant frequency of an oscillating quartz crystal can be shifted linearly by the mass deposited on the active area of the crystal face. If a suitable active adhesive could be applied to the crystal face so that all impinging particles would be trapped, then the shifting oscillator frequency would represent the mass accumulating during balloon ascent. In well regulated laboratory environments a deposit of 10^{-12}g has been detected; 10^{-9} - 10^{-10}g is probably a realistic value for a practical field instrument. A water droplet 1 μm in diameter weights approximately $5(10^{-10})$g. This technique holds the greatest promise for this program; development effort would be required in the areas of crystal mounting, adsorbant coating and miniaturized, stable electronic readout. In principle, the crystal could be operated in the open to directly sample the atmosphere; however, pumped flow might be necessary for adequate sensitivity in regions of low aerosol concentration.

Hot-wire anemometers have been used to detect volatile aerosols. The cooling of the wire as the droplet vaporized produced an output pulse whose area is proportional to the mass and heat capacity of the aerosol. Burgess and Reist using a 5 μm wire heated to 130C detected water droplets in the 1 μm range. Flow velocity and wire temperature changes were found to cause significant variations in sensitivity however.

5. Impact

This area is speculative; our literature search turned up no direct aerosol applications. As with the acoustic detector, it was included because of the potential for this problem. A piezoelectric crystal gives an electrical output in response to any energy input that produces a crystalline lattice distortion. NASA has sponsored many projects in micrometeorite detection; some of these have investigated piezoelectrics. A detector studied at Toronto University could detect an impulse of $<10^{-2}$ dyne-sec. A 1 μm water droplet with a velocity of 1 m/sec would have a momentum of $5(10^{-8})$g-cm/sec which would give an inelastic impulse of $5(10^{-8})$ dyne-sec. This energy gap may be too large to bridge; however, NASA-Ames was reported to have developed a transducer much too sensitive for the micrometeorite application.

B. PROJECTIONS

The cost and complexity of a balloon-borne aerosol detector would appear to vary at least linearly, but probably to some higher power, with the degree of particle characterization desired. The simplest and least expensive unit would respond to total or time-integrated mass collected. A more elaborate unit could give in addition a particle count. Still more complex optical scattering devices could add an indication of particle size although more study is needed on the effects of particle shape and refractive index. Chemical composition and structure information would require elaborate techniques such as gas chromatography, mass spectrometry and neutron activation analysis or their combination.

For simple counting and mass determinations, the piezoelectrics should receive further study. For more detailed analyses, some form of optical scattering instrument is probably a workable compromise; the electronics can be relatively simple, the cost moderate and information about particle concentrations and sizes may be obtained. Numerous new sensor configurations of this type will become feasible in the immediate future because of the current rapid advances being made in the development of electro-optical devices: small, high efficiency solid-state light emitters and room-temperature, solid-state lasers; high-transmission, narrow-band interference filters; sensitive room-temperature detectors, both photoemissive and solid-state. Most of the current developments are in the red and infrared regions of the spectrum, while blue or ultraviolet would be more desirable for the detection of small particles. However, research is being done on frequency converters and other devices for the shorter wavelength regions.

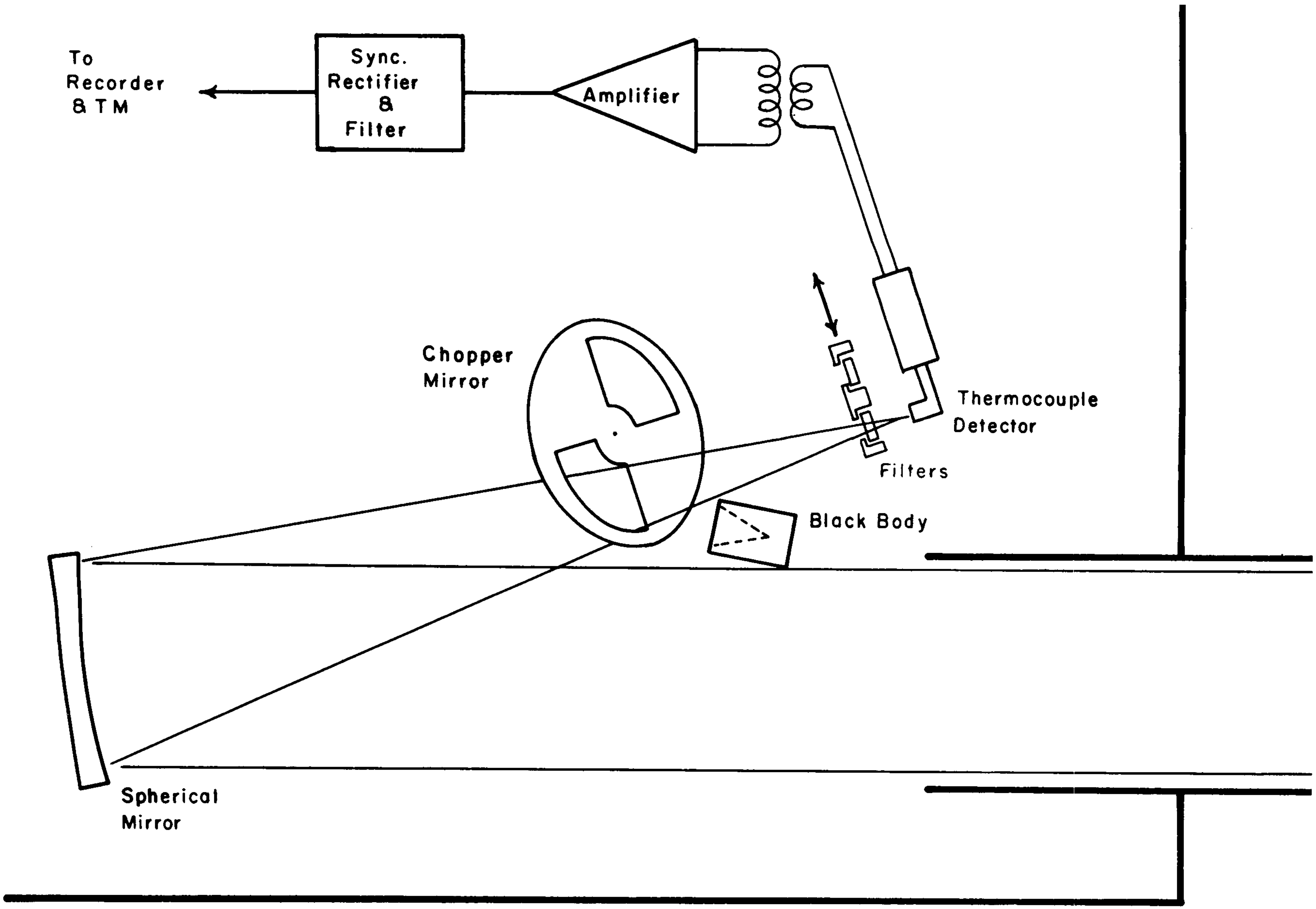

Figure 1. Filter radiometer.

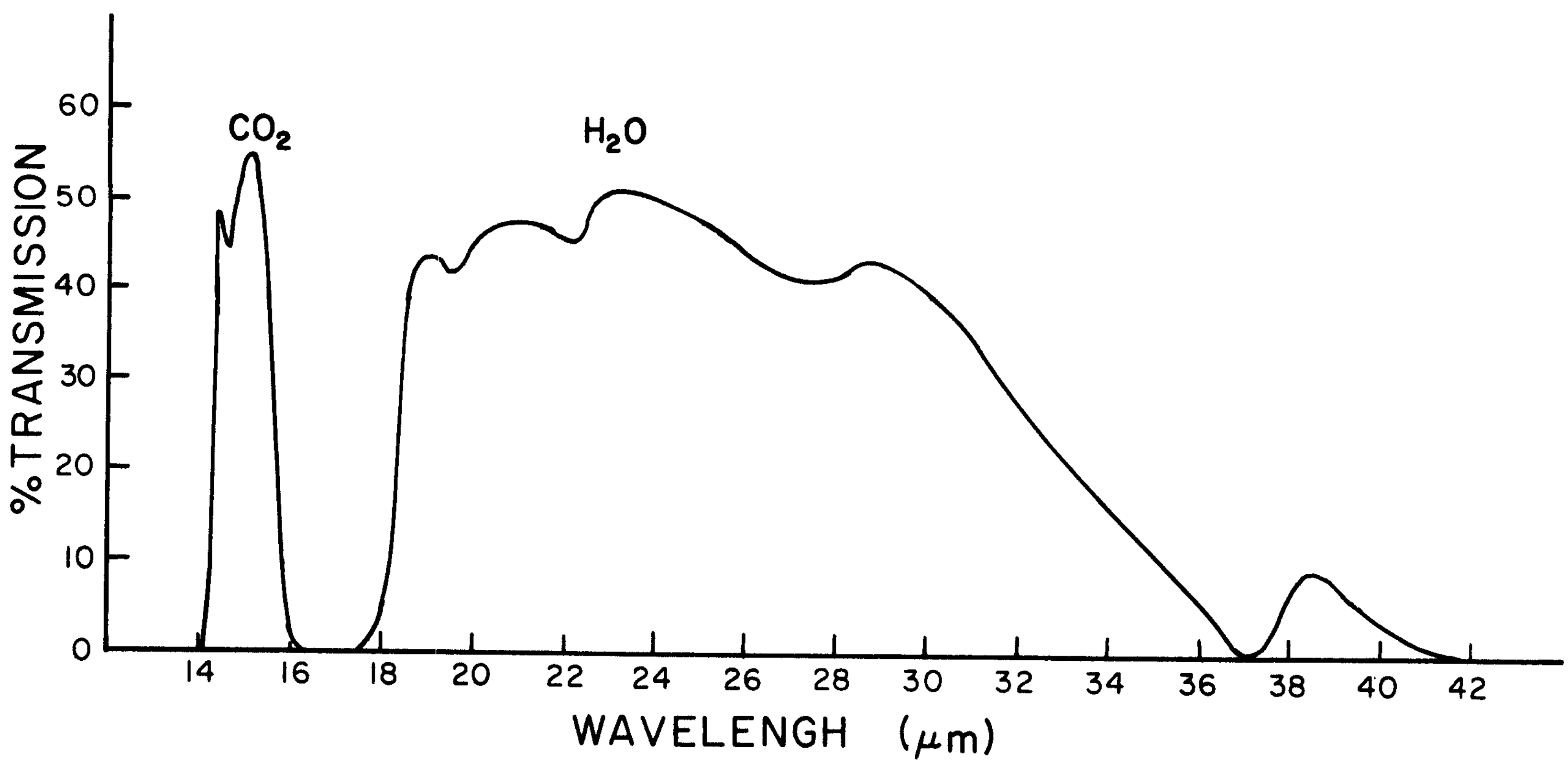

Figure 2. Bandpass filter characteristics.

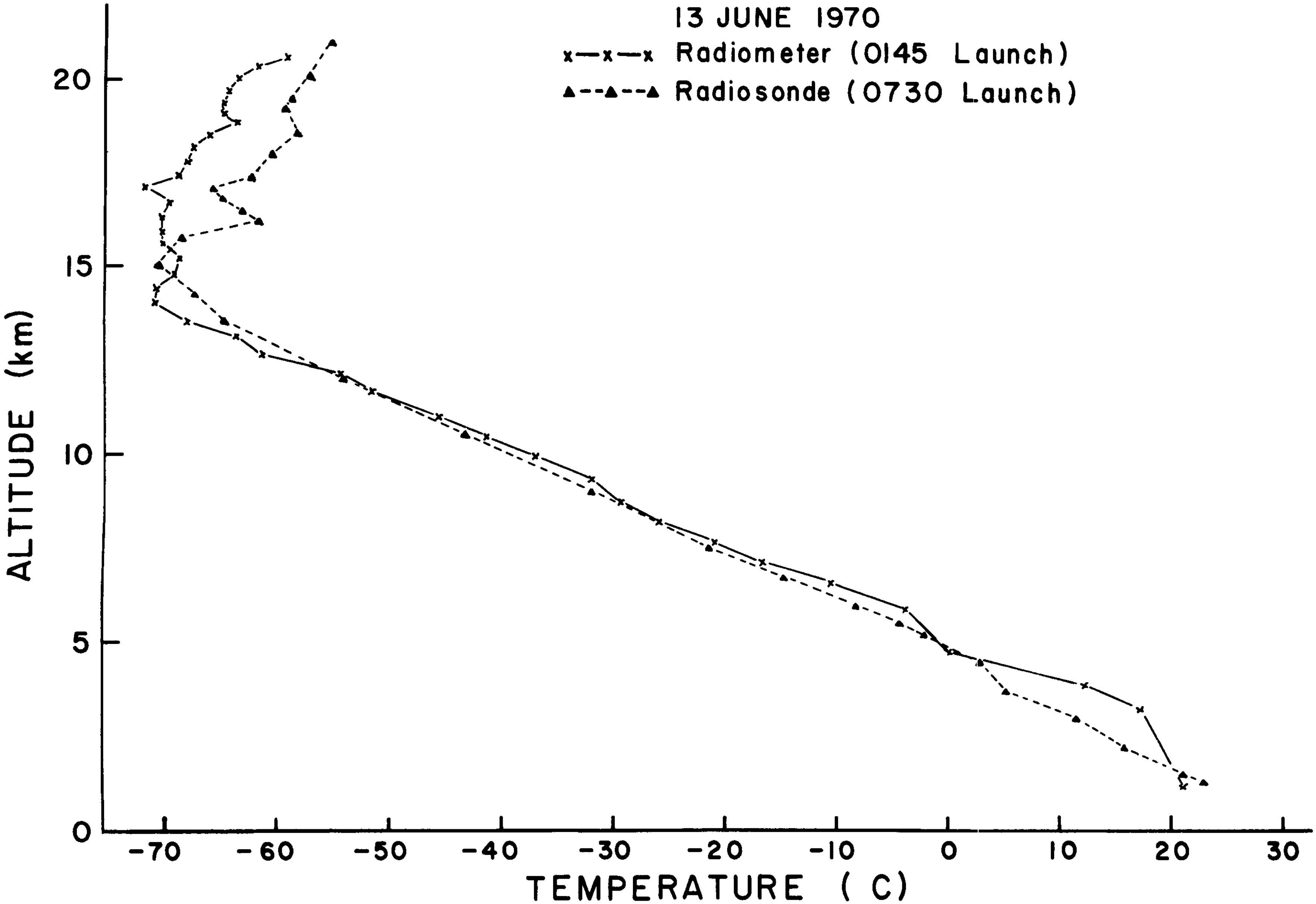

Figure 3. Air temperature calculated from radiometer data compared with radiosonde measurements on 13 June 1970.

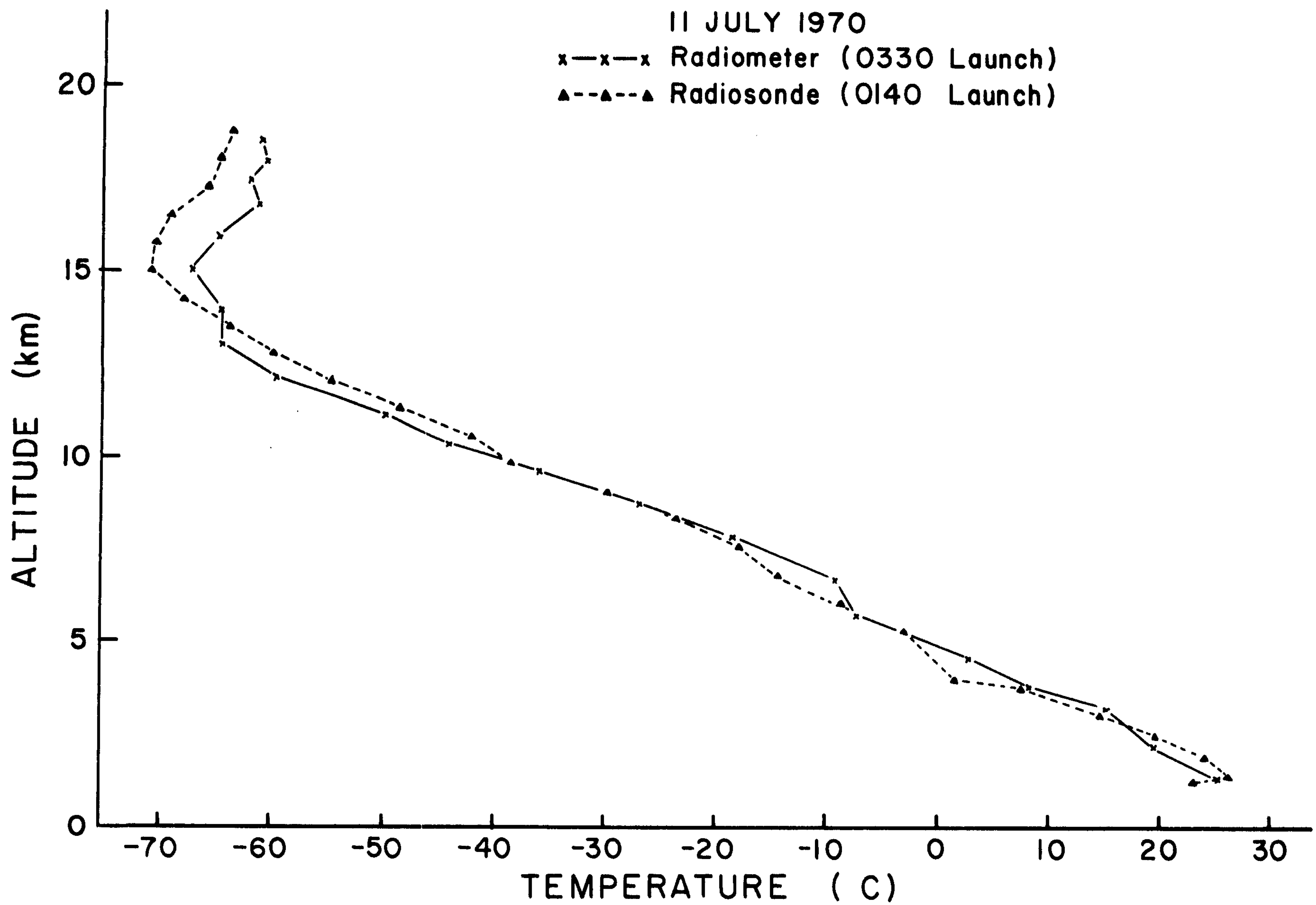

Figure 4. Air temperature calculated from radiometer data compared with radiosonde measurements on 11 July 1970.

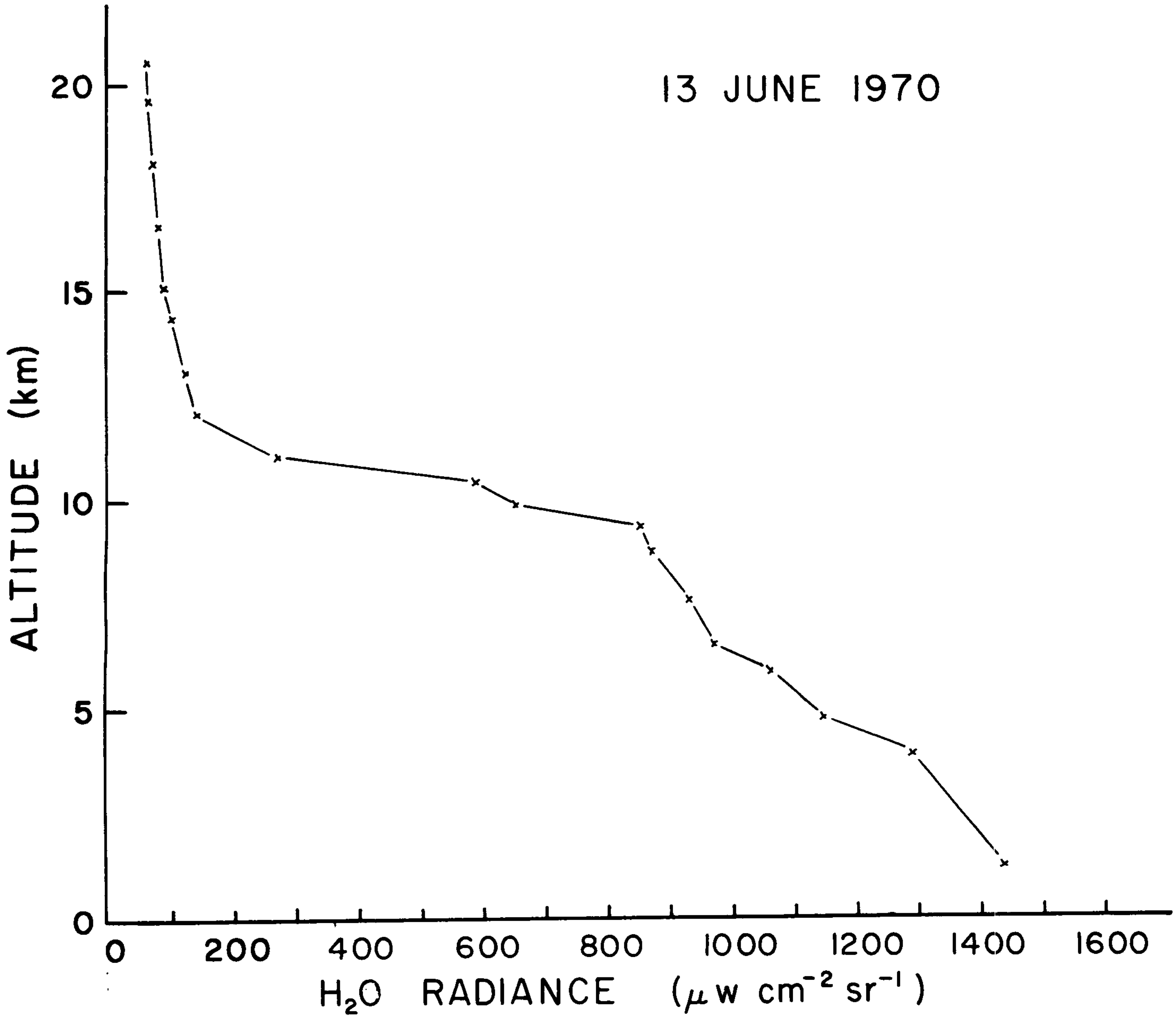

Figure 5. Water vapor radiance calculated from radiometer data for 13 June 1970.

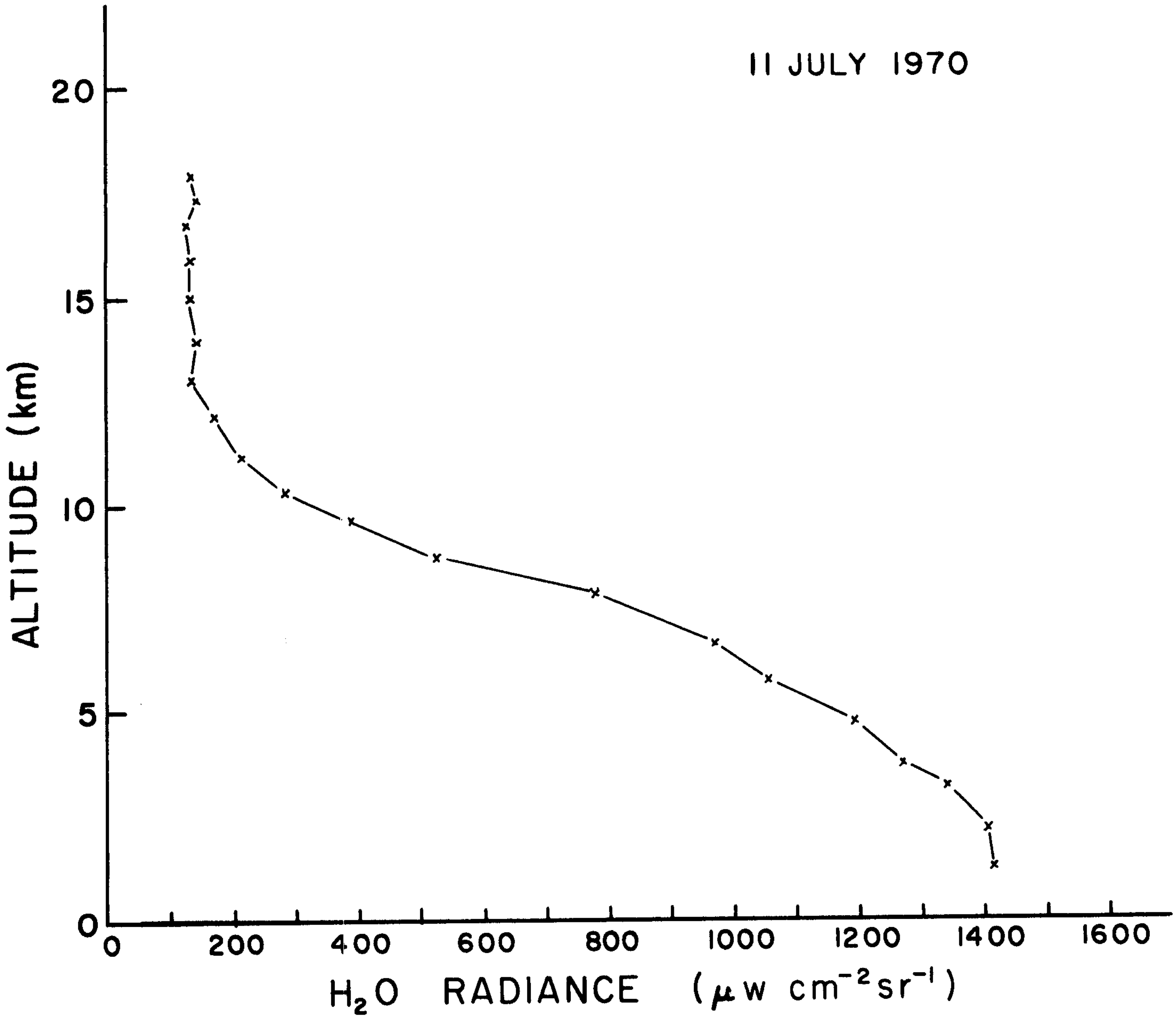

Figure 6. Water vapor radiance calculated from radiometer data for 11 July 1970.

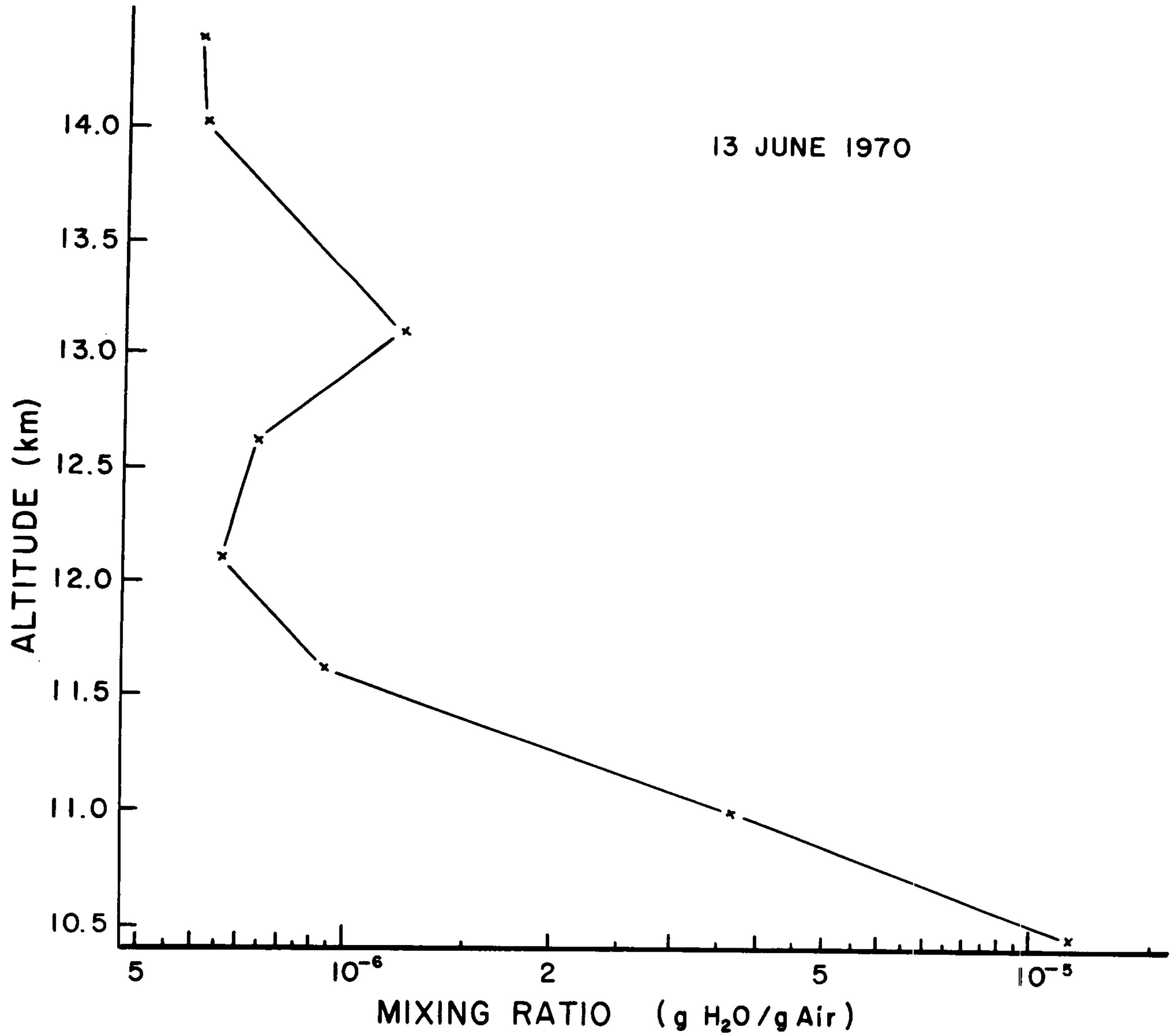

Figure 7. Water vapor mixing ratio calculated from radiometer data using a linear approximation. 13 June 1970.

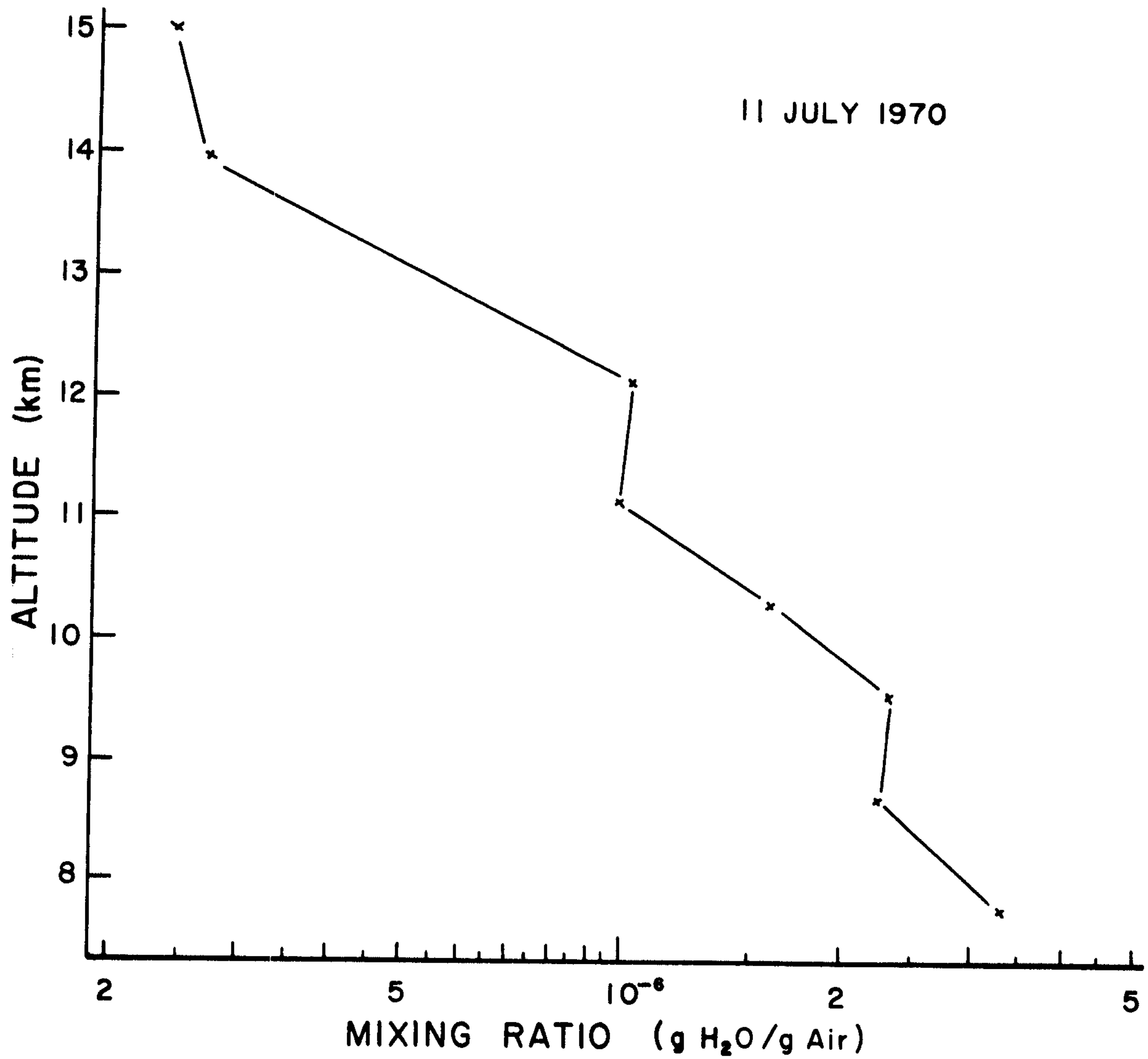

Figure 8. Water vapor mixing ratio calculated from radiometer data using a linear approximation. 11 July 1970.

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APPENDIX B

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