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DOUBLE BOLOMETER MEASUREMENTS OF THE EFFECTS OF ATMOSPHERIC RADIATORS

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The University of Wisconsin
Department of Meteorology
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P. M. Kuhn,[1] R. A. Ragotzkie,[2] V. K. Menon[2]

ABSTRACT

The feasibility and testing of an air-borne, double bolometer (radiometer) technique for deriving atmospheric water vapor profiles at modest cost is illustrated. To achieve these results with "shelf" equipment, the radiative transfer equations are solved for the water vapor transmissivity at aircraft holding levels using observed upward irradiances as input data. The transfer solutions are obtained from computer programs developed specifically for this purpose.

Results indicate an accuracy at least as good as that of the standard sounding electrical hygrometer but with measurements obtained at levels much higher than those at which hygrometer observations are possible. The implications for use on high-flying jet or special purpose aircraft or on rockets are presented.

INTRODUCTION

The equation of radiative power transfer may be subjected to an iterative solution to produce atmospheric water vapor distributions as a function of remote radiant power measurements over different infrared spectral ranges (Möller, 1962). The purpose of this research is to study such a solution employing remote aircraft measurements of radiant power, but made primarily in one spectral region. A balloon technique was proposed by Kuhn (1966). These techniques are different from those of satellite instrumentation researchers (Houghton, 1961; Wark, 1961; Möller, 1962; King, 1964, 1965). Their efforts are limited, necessarily, to irradiance observations from the fixed satellite orbit employing sensors receptive to radiant power in two or more different spectral intervals.

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The procedure to be described requires observations of temperature, height and spectral irradiance at a number of aircraft holding levels. Two "shelf-type" radiometers sensitive over different spectral intervals constitute the sensor capability. One radiometer monitors the air-surface interface temperature while the other measures the spectral component of upward irradiance as a function of height.

COMPUTATION OF RADIANT POWER

Temperature and irradiance data are input to a transfer solution for spectral irradiance passing upward through a plane parallel gaseous atmosphere. This may be written for a gas as,

$$F = -\int_{\nu_1}^{\nu_2}\int_{z_1}^{z_2} B_\nu \left| \frac{\partial \tau_\nu(z)}{\partial z} \right| dz\, d\nu + \int_{\nu_1}^{\nu_2} B_{\nu_0} \left[\int_{z_1}^{z_2} \left| \frac{\partial \tau_\nu(z)}{\partial z} \right| dz \right] d\nu \ [\mathrm{w/m^2}] \quad [1]$$

The subscript "o" indicates surface conditions.

The iteration procedure requires insertion of a progressive series of trial values for $\tau_\nu(z)$ in Eq. 1 until the component spectral irradiance calculated is equal to the measured component of the upward irradiance. Of course, one begins with a trial value of W (mixing ratio in grams of moisture per gram of dry air) since $\tau_\nu(z) = \tau(w)$. The iteration will converge to a last value which is assumed to be the actual mixing ratio at that observation level. Effects of other aerosols will be discussed in a subsequent section. By using broad band and fine (window) band chopper bolometers the aircraft does not have to make any surface landings for surface temperature observation. It requires only a vertical sounding. Direct application of this technique to rocket-borne radiometers will also be discussed in the next section.

To solve Eq. 1 for water vapor it is necessary to measure the component of upward irradiance, F coming from a cone of reception with a solid angle opening $\Delta W = 2\pi \cos\theta \sin\theta\ \Delta\theta$. θ is the nadir angle of a downward looking radiometer. $\Delta\theta$ defines the half beam width of the radiometer.

MEASURED IRRADIANCE EVALUATION

The curves for the filter transmissivities are shown in Fig. 1, curves "a" and "b", the former for the interface monitor and the latter for the broad band radiometer, similar to TIROS III, Channel 4.

Curve "1a" covers the transmissivity of the infrared "window," temperature monitoring radiometer (hereafter designated IRW). Curve "1b" covers the transmissivity of the infrared irradiance or flux density radiometer (hereafter designated IRF). (Spectral sensitivities, ϕ_ν', of the IRW and IRF are not given as they are a function of the particular manufacturer's radiometers.) Möller (1963) has shown that "because of different spectral transmissivities of the radiometer filter, lenses, and prism and of different spectral reflectivity of the chopper, the radiometer has an effective spectral sensitivity, ϕ'." The measured irradiance ($\bar{F}'\Big]_{\nu_1}^{\nu_2}$) may then be expressed by,

$$\bar{F}'\Big]_{\nu_1}^{\nu_2} = \Delta W \int_{\nu_1}^{\nu_2} I_\nu \phi_\nu \, d\nu \qquad [W/m^2] \qquad [2]$$

The IRW and IRF radiometers were calibrated against an assumed hemispherically symmetrical black source. We then have,

$$\bar{F}\Big]_{\nu_1}^{\nu_2} = \int_{\nu_1}^{\nu_2} B_\nu(T_{eq}) \phi_\nu \, d\nu \qquad [W/m^2] \qquad [3]$$

When required, the equivalent black body temperature ($T_{eq.}$) can be determined from Eq. 3 (Möller, op. cit.).

B_ν ($T_{eq.}$) is the spectral black body irradiance illuminating either the IRW or IRF apertures. The IRW and IRF radiometers employed in this research had solid opening angles of 3 degrees.

MODEL COMPUTER CALIBRATION OF RADIOMETERS

Assuming the prism transmissivity to be 1.0 for all ν, (wave number) and the chopper reflectivity to be 1.0 for all ν, the sensitivity calibration of the IRW and IRF units were evaluated with the equation of radiative power transfer (Eq. 1) with a spectral filter transmissivity term, $\tau(\phi)_\nu$, and aperture, ΔW, added. They define the radiant power illuminating the radiometer sensor system, but behind the filter.

This calibration sensitivity will be reduced by the prism transmissivity and chopper reflectivity. However, in choosing filter calibration sensitivity this illuminating power is important to the manufacturers. Eq. 1, including $\tau(\phi)_\nu$, becomes,

$$F = -\int_{\nu_1}^{\nu_2} \int_{z_1}^{z_2} \tau(\phi)_\nu B_\nu \left| \frac{\partial \tau_\nu(z)}{\partial z} \right| dz + \int_{\nu_1}^{\nu_2} \tau(\phi)_\nu B_{\nu_0} \left[\int_{z_1}^{z_2} \left| \frac{\partial \tau_\nu(z)}{\partial z} \right| dz \right] d\nu \quad [W/m^2] \qquad [4]$$

The IRW and IRF radiometers were "calibrated" by a computer solution to Eq. 3 in the CDC-3600. The calibrations yielded curves of $\mu W/cm^2$ versus assumed hemispherical black source temperatures as "seen" through a solid angle aperture of ΔW equal to $2\pi \sin\theta \cos\theta \Delta\theta$ steradian. These curves are displayed by Fig. 2.

IRW ALTITUDE CORRECTIONS, CALCULATED AND OBSERVED

A referral to Fig. 1 clearly shows the considerable overlap of the water vapor absorption band with the pass area 1050 to 1400 cm^{-1}. To illustrate these effects transfer equation solutions for received power (Eq.3) were run for 12 mean monthly soundings for Sault Ste. Marie, Michigan, from sea level to 18,000 feet. Figs. 3 and 4 illustrate the extremes encountered over the 12 months. The March sounding requires a 6.0°C correction at 10,000 feet. The influence of water vapor absorption in the 1050--1400 cm^{-1} pass band of the filter is very important. A Kodak IRTRAN 6 filter appears much more suitable than the Indium Antimonide cell. This, of course, is not a new idea. Fig. 5 is an example of the altitude correction required when the 7.4-13.2 filter is used. The sharp cut on and cut off at 10μ and 12μ, respectively, resulting in a narrower pass band, produces a somewhat weaker signal at the plane of the sensor system. But, it is essentially free of water vapor absorption. Laboratory tests of such a filter are being made.

Fig. 6 illustrates an actual aircraft calibration over Lake Superior near Duluth from the surface to 6,000 feet. The displayed data closely resemble the computer solution for altitude correction in Fig. 5.

The effects of a total optical mass of 0.1 and 1.0 gram/cm^2, respectively, at an average temperature of 10.0°C through an altitude of 3,000 feet can be seen in Fig. 7. The overlap between 7.3 and 9.4microns and 12.0 and 13.6 microns is clear. This is not a particularly wet sounding. One might suggest a 10-12 micron filter but problems of resolution and sensitivity then become important in a cost consideration. This is quite true of "shelf" hardware.

DETERMINATION OF ATMOSPHERIC WATER VAPOR

In view of problems in the accurate, and relatively low cost, measurements of atmospheric water vapor distribution by aircraft and balloon borne dew point sensors, we are testing the feasibility of an iterative solution of the radiative power transfer equation. Our end product will be the moisture distribution in parts by mass/1000.

Input to the transfer equation in solving for atmospheric moisture are the aircraft sensor (or ballon sensor) measured pressure (altitude), air temperature, and IRW and IRF radiation profiles. A fourth parameter required in the solution of Eq. 4, the radiative transfer equation, is an assumed profile of the mixing ratio of water vapor (grams/kilogram). A good first approximation will be the mean monthly mixing ratio sounding for the nearest upwind radiosonde station.

In essence we solve Eq. 4 for the emitted water vapor and transmitted window water vapor radiation terms. This is shown symbolically in Fig. 8. This solution, for various levels, is then compared with the observed IRW component of measured upward irradiance evaluated by Eq. 3. If the agreement is within a set convergence limit for all levels the solution is complete. If the convergence limit is not reached at a given level this is "noted" by the computer and we move on to the succeeding levels, following the same procedure. Adjustment of the water vapor profile is then made on the entire sounding and the iteration procedure repeats. Average computer solution time is 15 seconds (CDC-3600) for a 10 level solution, over the spectral range 4.39 to 20.83 microns (560--1480 cm^{-1}). The convergence limit chosen is 1.0 w/m^2 (100$\mu W/cm^2$). This is beyond the minimum resolution quoted by manufacturers of such equipment.

AIRCRAFT INSTRUMENTATION

The NCAR Queenaire Beechcraft aircraft was made available to this project by Dr. D. R. Rex, Director of flight facilities at NCAR. Without his cooperation the modification of the aircraft and ascents could not have been made. Ports with shock mountings supported the two (IRW and IRF) radiometers. Data were recorded by the standard aircraft data collection system. Simultaneous measurements of IRW and IRF upward irradiance, altitude and air temperature were made coincidentally with visual observations of the surface.

AIRCRAFT RADIOMETRIC SOUNDING

An aircraft sounding with the IRW and IRF was made, under visually determined cloudless conditions on 14 July 1965. The area surveyed was over Lake Superior, twenty miles east of Duluth, Minnesota, covering the period 2245 CDT through 2331 CDT. Flow aloft under a subsiding Canadian High, to the northwest, was west-northwesterly at all levels. Table 1 gives the observed pressure, height, air temperature, IRW estimate of surface temperature and IRF observed upward flux. In addition it displays the iterative calculations of upward irradiance with the corresponding input mixing ratio.

TABLE 1

OBSERVED AND CALCULATED SOUNDING DATA

					1st Iteration		2nd		3rd	
PRESS	HT(FT)	T_{AIR}	IRW	IRF_O	F_c	W(g/kg)	F_c	W	F_c	W
1012	0	12.5	12.5	( )	11.41	9.2	11.41	8.3	11.6	2.0
1003	300	19.4	12.3	11.00	10.04	9.2	10.04	8.3	10.4	2.0
920	2600	16.3	12.1	11.50	10.17	8.1	10.17	7.3	10.4	0.6
886	3600	13.3	12.0	10.80	9.93	7.5	9.94	6.8	10.2	0.6
825	5600	7.9	11.7	10.30	9.55	6.4	9.56	5.8	9.9	0.5
794	6600	5.4	11.5	10.10	9.25	6.0	9.27	5.4	9.7	0.5
763	7600	3.8	11.4	9.90	9.07	5.2	9.09	4.7	9.7	0.3
735	8600	1.8	11.2	9.40	8.92	4.7	8.94	4.2	9.5	0.2
710	9600									
682	10600	0.3	11.0	9.34	8.74	3.5	8.77	3.1	9.4	0.1

(Temperature in ^{o}C; pressure in millibars; height in feet; irradiance in watts/meter^2; mixing ratio in grams/kilogram.)

It is clear from the columns headed 2nd and 3rd iteration, that the temperature profile, necessarily, is most important in determining the convergence of the observed irradiance (IRF) and the calculated irradiance, F_C. But, with relatively accurate temperature measurements the iteration on mixing ratio will converge quite rapidly, in this case in three iterations. The constraint imposed on the solution is present in the observed (fixed) temperature profile. This, then results in a unique solution for the moisture. The reduction in moisture in this instance reached a maximum of 30% to result in convergence. One should bear in mind that we are applying a systematic reduction, or where required, increase in the profile of the mixing ratio. Smith (1966) at Wisconsin has suggested a "power law" generation of the profile of moisture based on the observed surface temperature and humidity. In summary, Fig. 9 gives the sequence of moisture soundings vs. altitude and pressure to final convergence. The observed special Duluth sounding, which carried over Lake Superior, is included for reference. The agreement is obvious.

The minimum resolution of the nominal 2μ - 20μ IRF unit (Barnes Engineering Company) is 0.7 W/m^2 or approximately 0.2°C. This resolution is indicated by the minimum resolution bar limits to either side of the observed irradiance values at 1003, 825, and 686 millibars in Fig. 9. This is nearly four times the resolution of standard IRW units (Barnes Engineering Company). Both the increased transmissivity of the germanium lens (flat) and the larger spectral pass band of the IRF contribute to the greater sensitivity of this bolometer over the IRW.

While nine aircraft holding levels were used in the 14 July 1965 ascent and moisture computation, it is presumed clear that the same accuracy in water vapor computations could be attained with but three irradiance observations. More dense vertical measurements are not warranted by the minimum sensitivity of the instrument.

One can note that our best estimates of water vapor mixing ratios will be for values in that part of the water vapor transmissivity curve between a mixing ratio of .01 and 1.0 grams/kilogram.

CLOUD OR AEROSOL EFFECTS

A previous experiment using a window radiometer (IRW) and a 4.5 to 5.6μ (1780-2220 cm^{-1}) radiometer to determine a gross size distribution of atmospheric aerosols was attempted. This failed due to the lack of sensitivity of the bolometer in the restricted spectral operating range of from 4.5 to 5.6μ.

However, the IRW and IRF radiometers appear to have more of a capability along these lines. In an aircraft ascent on 25 July 1965 over Lake Superior, east of Duluth, passage 1100 feet above a layer of tenuous fog (10μ or larger aerosol), the IRW signal decayed very sharply. The IRF, though showing some decay in signal response, was much less affected. On the other hand, passage of both radiometers in the near saturation, pre-fog conditions resulted in a very rapid decay in the signal output of the IRF but, in much less attenuation in the IRW. In clouds both units decay abruptly. Thus, it appears that double bolometers of the pass bands described will have value in determining, qualitatively, the distribution of certain types of atmospheric radiators.

CONCLUSIONS

Aircraft Operations

Admittedly, relatively expensive dew point devices are available for aircraft observations of humidity. However, their accuracy may be considerably less than the radiometric technique for determining atmospheric moisture that we have discussed. If this is so, then applications to remote sensing of the atmospheric moisture structure in remote areas without recourse to any surface observations may well be feasible.

Balloons

It appears quite clear that one of the major uses of low cost infrared radiometric detectors lies in the realm of balloon soundings. Of course we would now have to forego the chopper bolometers, described, and refer to the conventional radiometersonde (Kuhn and Suomi, 1965). Without discussing this device, let us generalize by saying that a suitable, selectively sensitized detector to duplicate the transmissivity of the IRW is possible and under search. When this is realized one may be able to sound atmospheric moisture and particulate layers to altitudes above 100,000 feet with much greater reliability than can be achieved with the present electrical hygrometer. Tests have been conducted using powdered talc on one sensor (IRW) and standard blackening agent on the IRF. While still not satisfactory they indicate continued research. We are speaking of a total additional cost of twenty-five dollars, including computer reduction of data, over a standard Weather Bureau radiosonde ascent.

One should also note that our greatest resolution occurs in that part of the water vapor spectrum between .01 and 0.5 gm/cm^2 of water vapor. This is evident from an examination of the slope of the transmissivity of water vapor versus optical mass. This, then, prompts a question on the use of rockets or high level balloons.

Rockets

With a sufficiently high resolution (relatively low in cost in keeping with the vein of this study) one could monitor the downward component of spectral irradiance against a background of "zero" radiant power. Certainly this is not a new idea, but appears worth investigation. The results could augment high flying frost point equipment for stratospheric water vapor profiles.

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TABLE OF SYMBOLS

F: Irradiance (watts/meter^2 or microwatts/centimeter^2)

ν: Wave number (reciprocal centimeters)

z: Height (feet)

B: Blackbody irradiance

τ_ν: Spectral transmissivity

w: mixing ratio for H_2O vapor (grams/kilogram)

ϕ_ν: Spectral sensitivity

$\tau(\phi)_\nu$: Spectral filter transmissivity

μW: Microwatts

IRW: Infrared window Radiometer (watts/meter^2)

IRF: Infrared irradiance Radiometer (watts/meter^2)

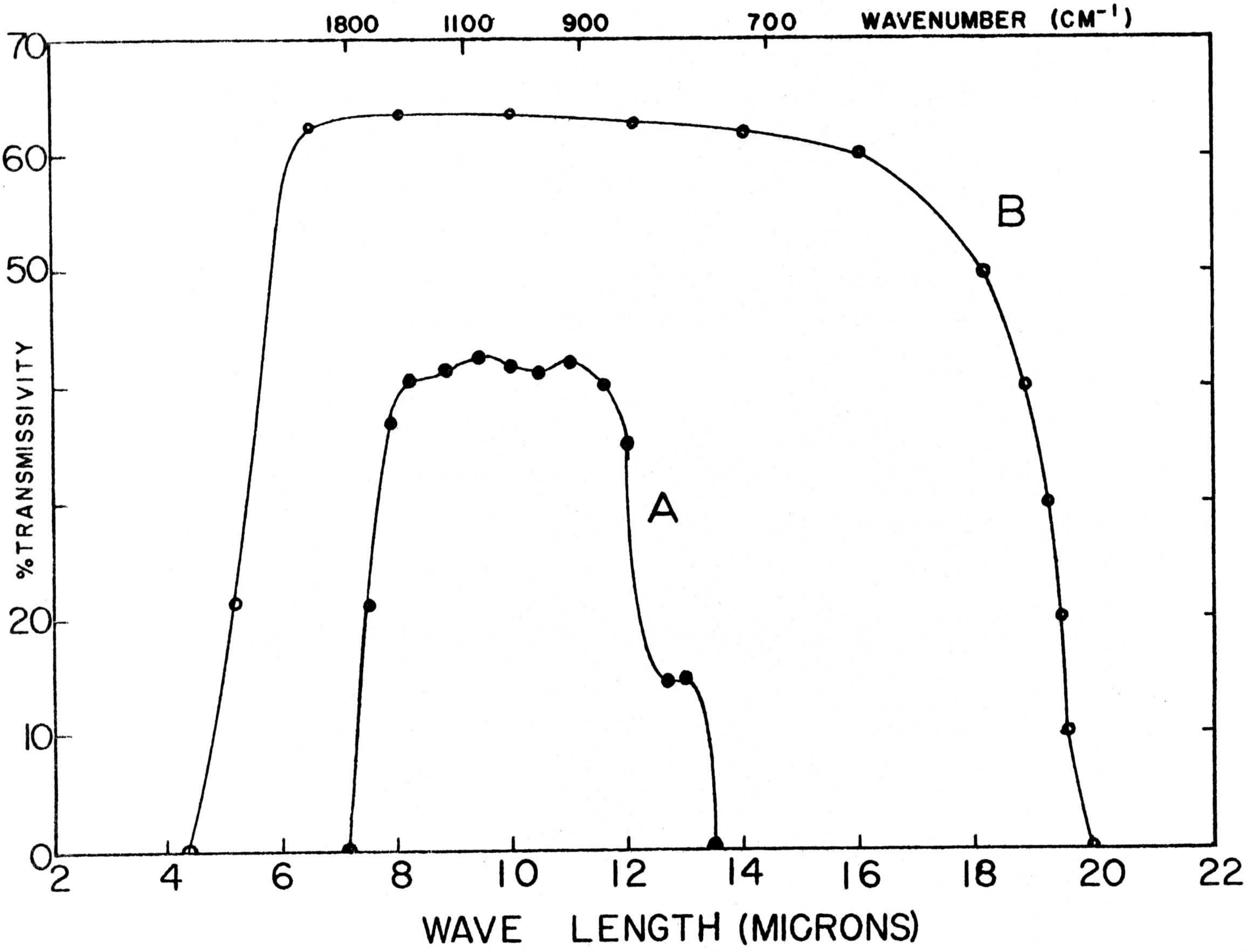
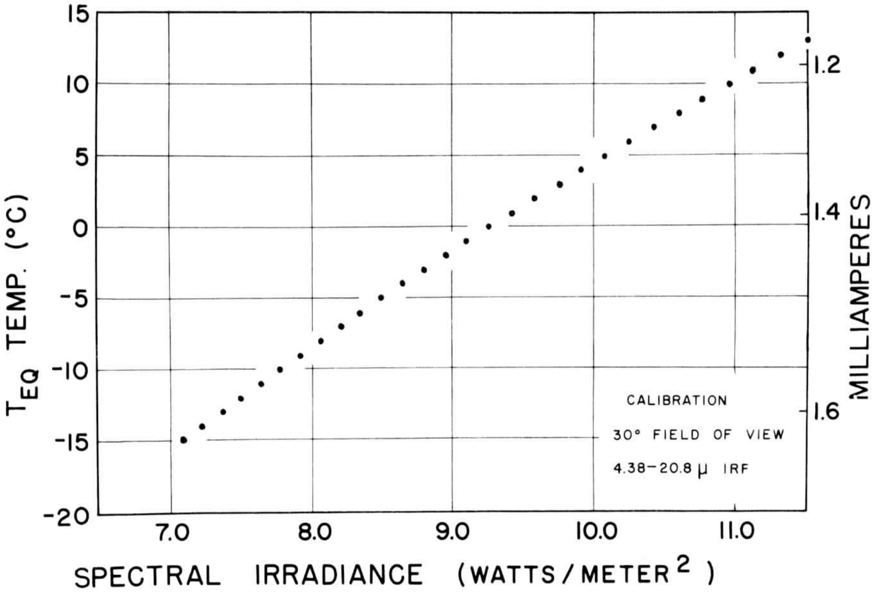


Figure 1. Filter transmissivities for the interface monitor (A) and the broad band radiometer (B).



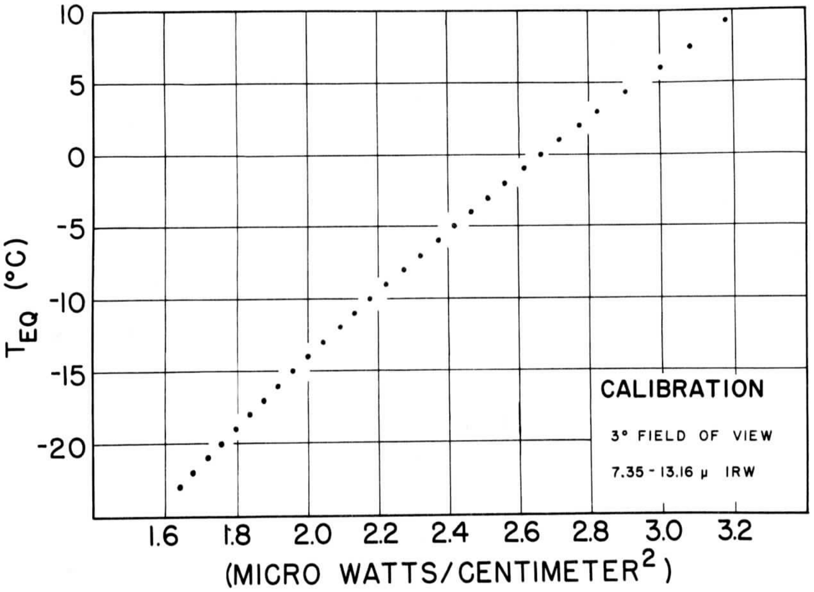


Figure 2. Computer model calibrations, IRW and IRF.

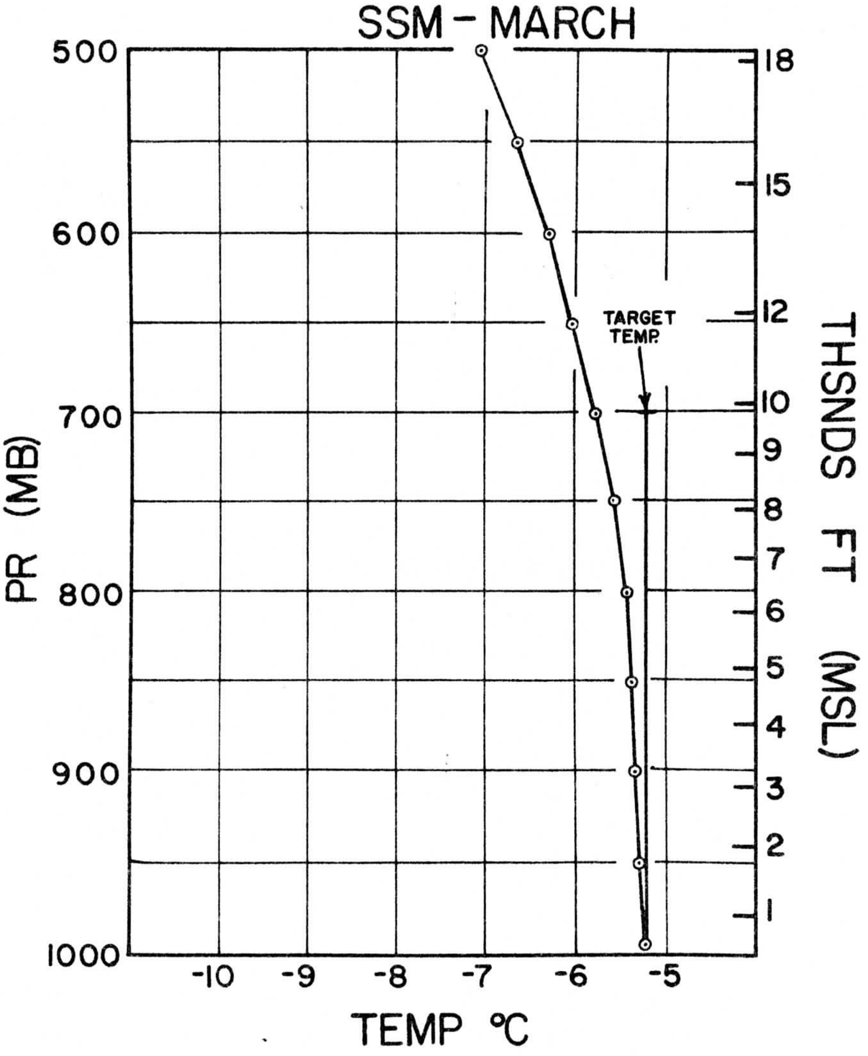


Figure 3. IRW altitude calibration effects, March, Sault Ste. Marie (SSM).

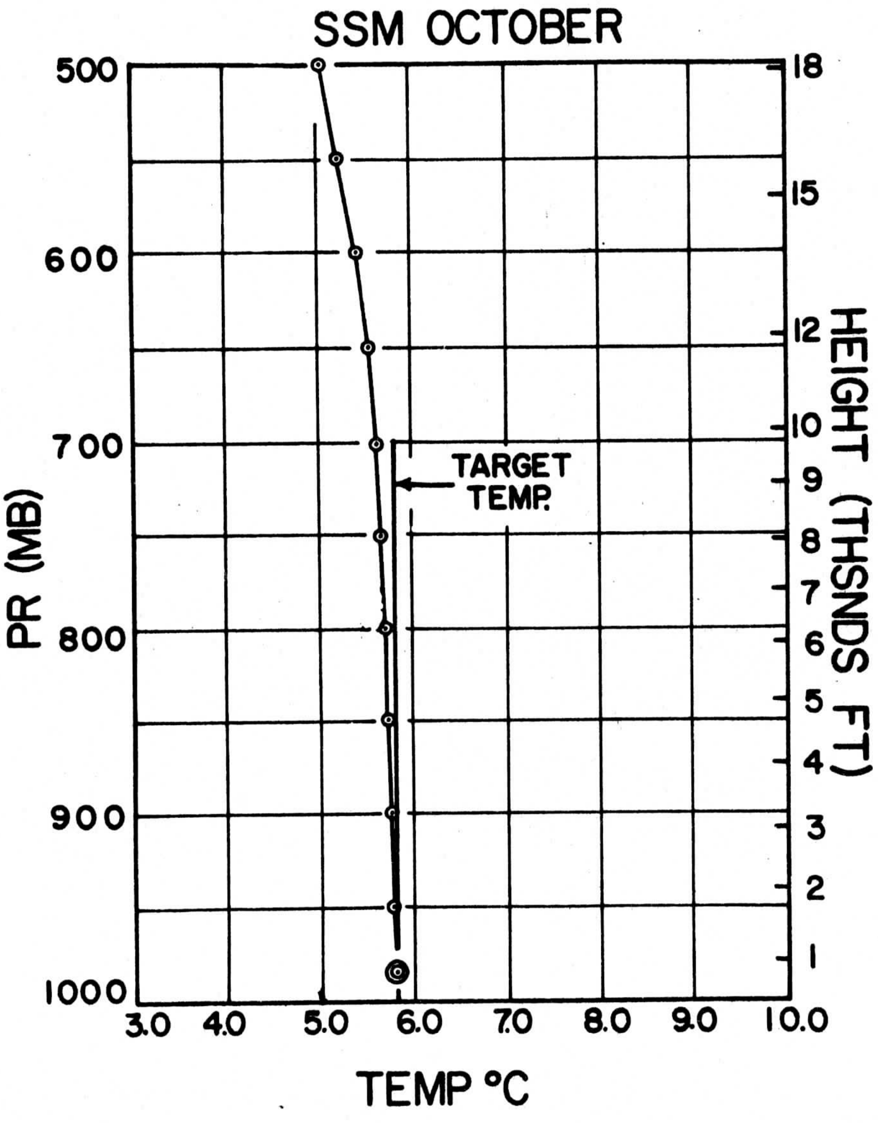


Figure 4. IRW altitude calibration effects, October, Sault Ste. Marie (SSM).

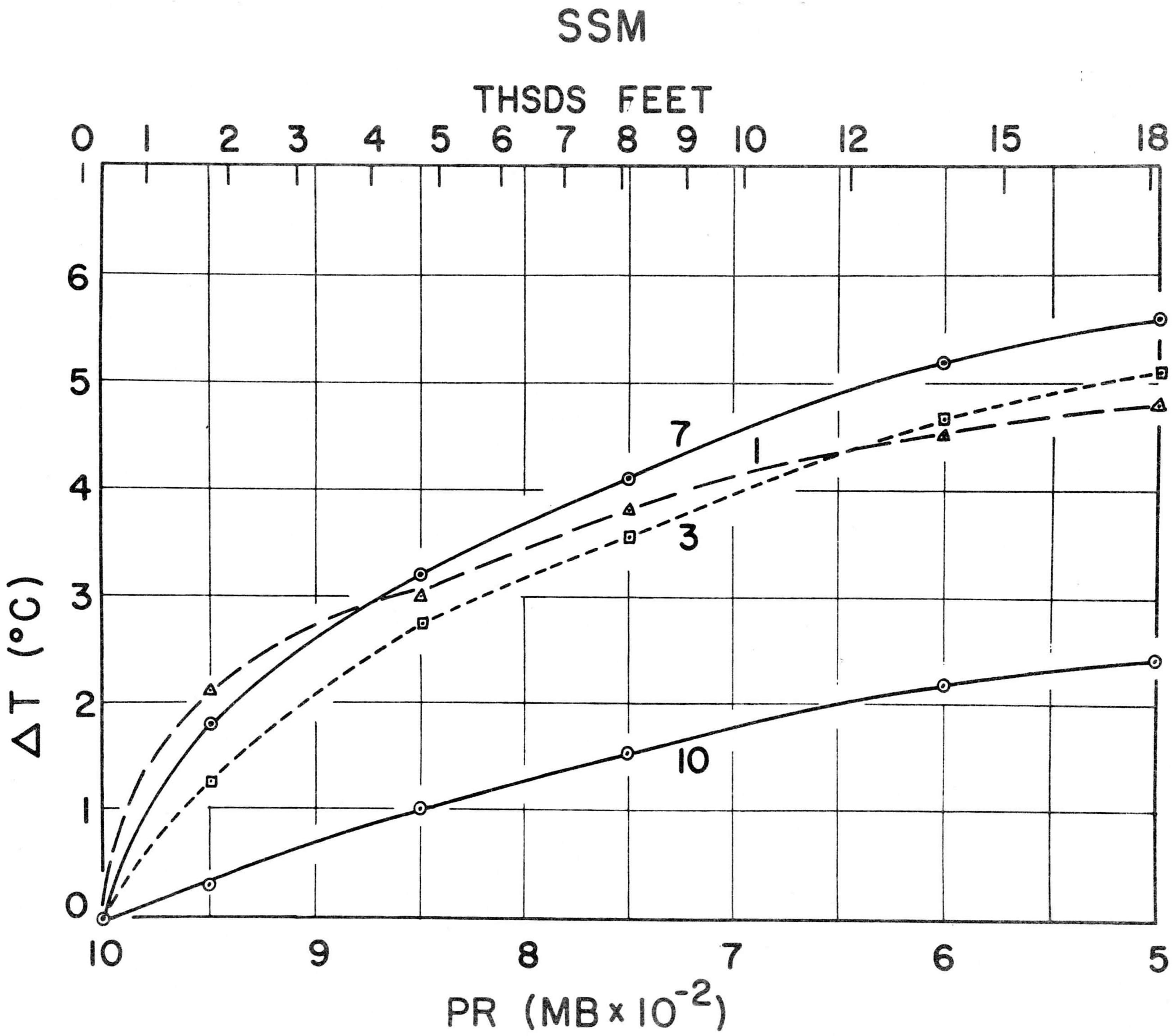


Figure 5. Computed altitude corrections, IRW, Sault Ste. Marie (SSM).

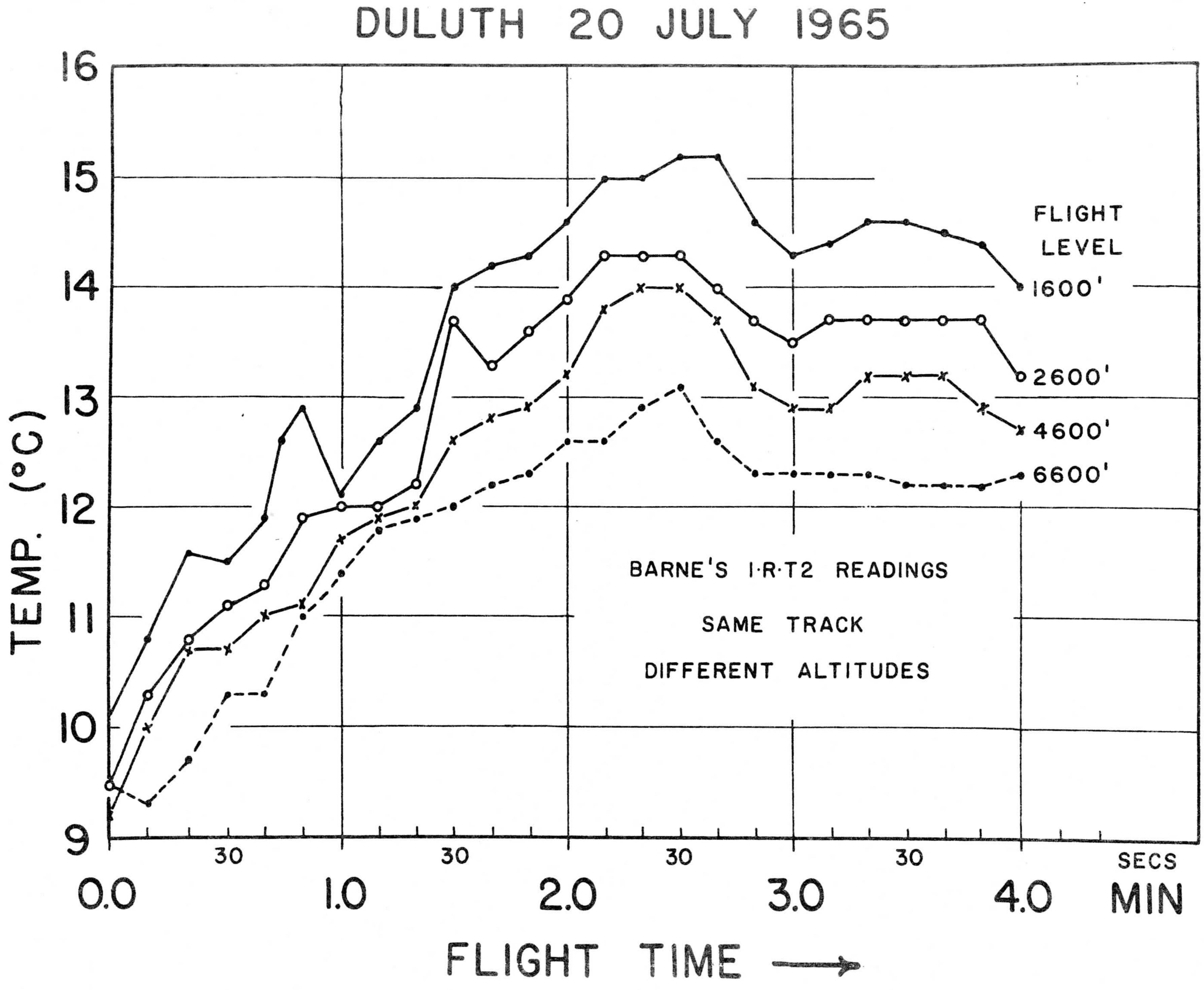


Figure 6. Observed altitude corrections, IRW, Duluth (DLH).

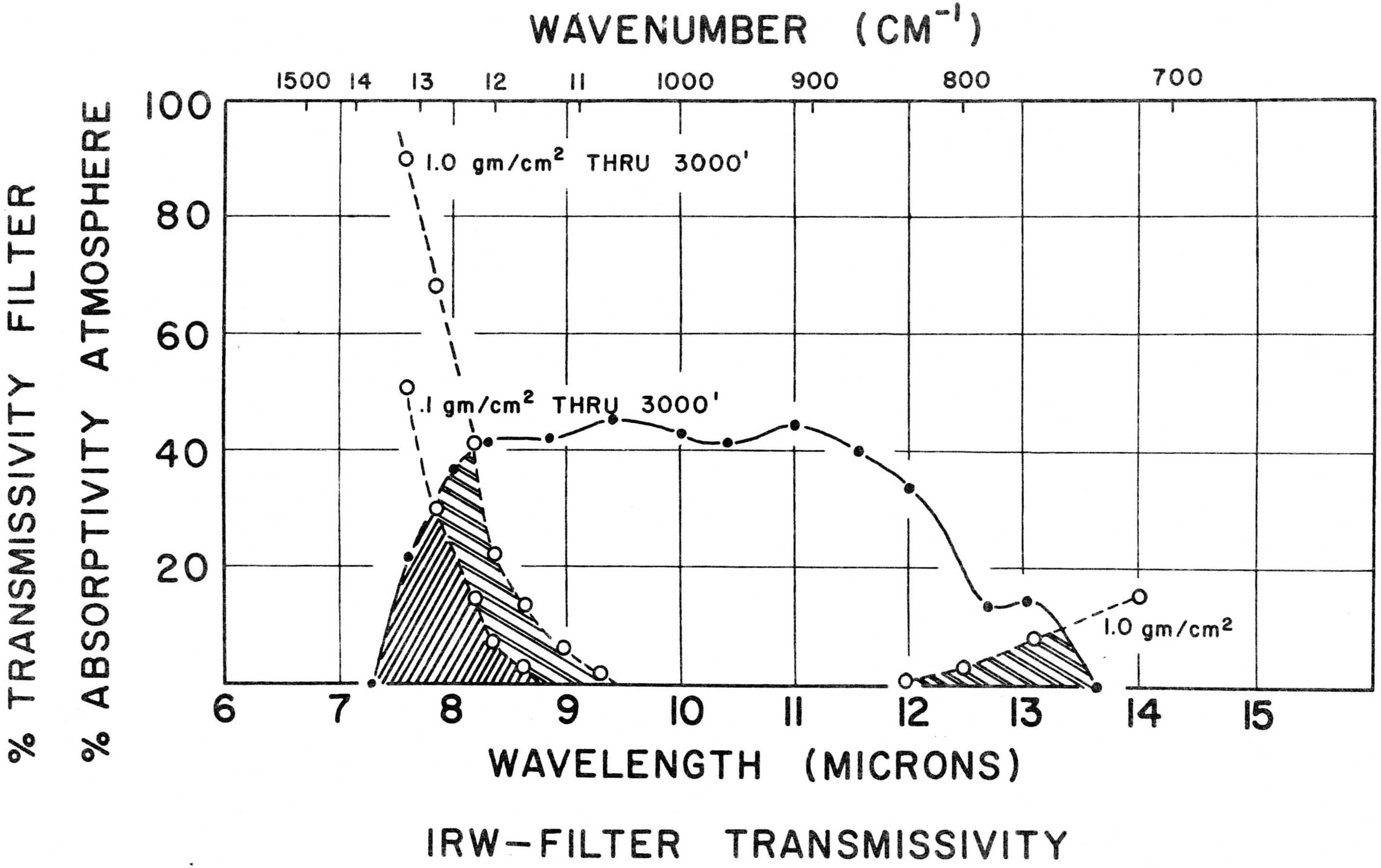


Figure 7. Atmospheric effects on IRW filter.

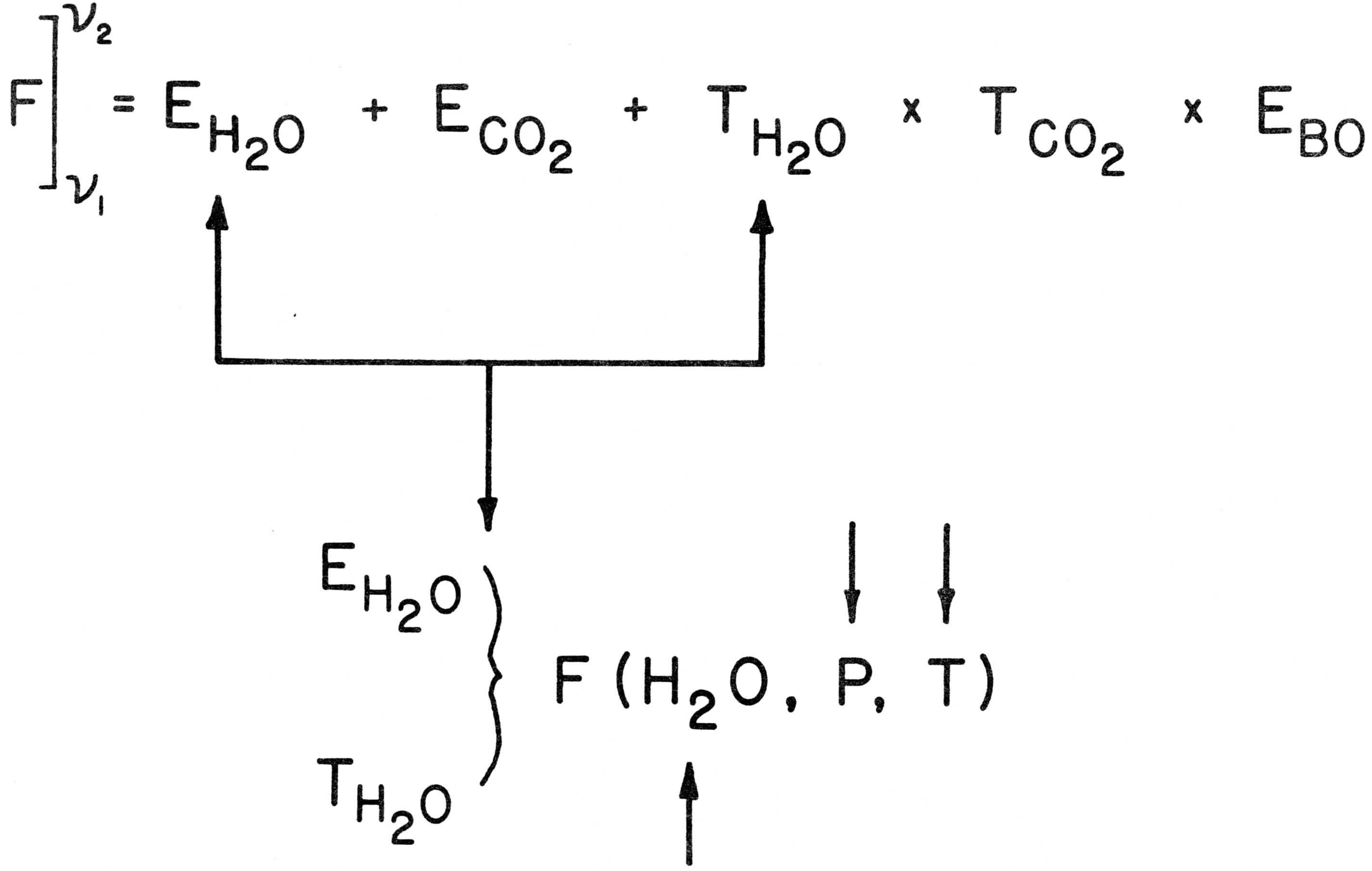


Figure 8. Symbolic form of radiant power transfer solution.

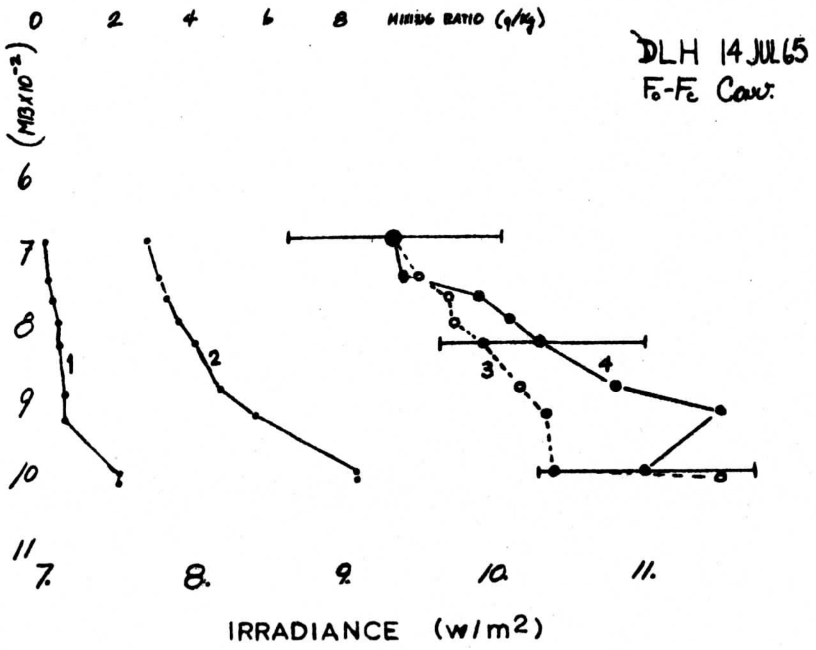


Figure 9. Convergence of iterative transfer solution.

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13. ABSTRACT

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Results indicate an accuracy at least as good as that of the standard sounding electrical hygrometer but with measurements obtained at levels much higher than those at which hygrometer observations are possible. The implications for use on high-flying jet or special purpose aircraft or on rockets are presented. (U)

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