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AIRCRAFT MEASUREMENTS RELATED TO THE DETERMINATION OF SEA SURFACE TEMPERATURE FROM METEOSAT

by

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1. Introduction

There are several difficulties in deriving sea surface temperature (SST) from the upwelling radiance measured by a satellite. The problem of calibrating the satellite radiometer is one. For a spin-scan radiometer of the type on Meteosat, the lack of a facility for placing a calibration target in front of the complete optical system adds to the problem [1]. Although the radiance measurements are made in spectral regions over which the atmosphere is fairly transparent, such as the 11 μm "window", it is always necessary to apply corrections for atmospheric absorption and emission. Given a knowledge of the temperature and humidity distributions, models can be used to calculate the atmospheric correction. The models themselves are sources of error and require validation.

The work described here was designed to tackle these difficulties as they apply to the Meteosat 11 μm channel. It is recognised, however, that other problems exist, such as uncertainties in temperature and humidity distributions under operational conditions, isolation of sea surface radiances in partially cloudy conditions and differences between radiative and "ships' buckets" SSTs.

2. Observational programme

In November-December 1978, Met Research Flight performed an exercise to produce data from which an absolute calibration for the 11 μm channel of the Meteosat radiometer could be derived. It was intended that the calculations involved should provide estimates of the errors in the derivation of SSTs from Meteosat radiances. This study also entailed consideration of certain problems in processing 11 μm observations from other sources.

The aircraft instruments provided measurements of the temperature and humidity profiles and the radiative SST. These have been used in conjunction with an atmospheric transmission model and knowledge of the Meteosat radiometer spectral response to calculate the radiation emitted from the top of the atmosphere along a slant path. The theoretical radiances can be compared with the Meteosat signals to provide a calibration for the radiometer. Also the radiance calculations themselves provide an estimate of the temperature deficit - the difference between the radiative SST and the brightness temperature measured at the top of the atmosphere. In this spectral region the deficit is caused mainly by atmospheric water vapour. A useful comparison is only possible if the aircraft measurements are made in cloud-free conditions. Similarly, areas in which significant layers of haze or dust are present are avoided.

In addition the Barnes radiometer on the aircraft provided measurements of upwelling radiation at different pressure levels which have been compared with theoretically computed values to assess the self-consistency of the measured radiances, the measured atmospheric profile and the radiative transmission model used.

3. Aircraft data

The plan for the aircraft measurements is specified elsewhere [2]. Briefly, it consists of a series of horizontal "L"-shaped flight patterns (of side ~30 km) at different pressure levels between the surface and 600 mb over the same area of ocean. Along each "L"-shaped run, measurements are made of temperature, humidity and upwelling infra-red radiation (using the Barnes radiometer). In addition measurements of temperature and humidity are made during a descent at 1000 ft/min from about 600 mb to the surface over the same area of ocean, and also during a similar ascent. These yield further information on the shape of the temperature and humidity profiles. The flight plan specifies that all these measurements are to be made under cloud-free conditions so that the Meteosat radiances can be identified unambiguously as those emitted from a cloud-free column of atmosphere.

The aircraft measurements of temperature and humidity up to 600 mb, supplemented by data obtained from nearby radiosonde ascents, were used to obtain profiles of temperature and humidity throughout the troposphere. In the upper troposphere lack of data created large uncertainties, particularly in the humidity profile, but since the absolute humidities are so low at these heights the Meteosat radiances were affected comparatively little by errors in the profile.

During this exercise, two flights were made to measure the temperature and humidity profiles in the lower troposphere - on 30 November and 5 December 1978. The flights took place out of Gibraltar over the eastern Atlantic.

Pressure and temperature were measured and recorded automatically at a high sampling rate (eg 20 per sec for temperature), as was humidity using a Cambridge hygrometer. These data were subsequently processed to provide mean values for each constant level run. The Barnes radiometer readings were also recorded automatically and the instrument calibrated by in-flight observation of internal black body targets. Two major calibration sequences of 15 minutes duration were performed at the beginning and end of the measurement programme, and a short calibration sequence (to correct for instrumental drift) was made during the turn at the middle of each "L"-shaped run. In addition, during horizontal runs, humidity was measured and recorded manually using a Dobson-Brewer hygrometer. On average, about 5 measurements were obtained on each "L"-shaped run. In general the manual readings gave more accurate absolute measurements of humidity, particularly at higher levels, and the automatic measurements of humidity profile recorded during ascent and descent were mainly used to confirm the interpolation of the profile shape between the levels at which manual measurements were available.

4. Satellite data

The radiometer signals are digitized on board the satellite and transmitted to earth. Even after ground processing the radiances are still expressed in digital "counts"; a calibration process is required to convert "counts" into units of radiance or temperature. The end product of our satellite data analysis is a number of instrument "counts" which can be said to be equivalent to the brightness temperature at the top of the atmosphere calculated from the atmospheric profile data. This is derived by considering a histogram of radiance counts for an area including that over which the aircraft was operating. A 32 x 32 array of picture elements (pixels) from the IR image was considered; this is also the sample size used by ESA's Meteorological Information Extraction Centre (MIEC) in deriving SSTs [3]. In deciding which 32 x 32 array of pixels corresponded to the appropriate geographical area, it was assumed that the location of pixels was that which they would have in the Meteosat "reference image" [4]. This assumption was tested by checking that the coastlines, where visible, were in the expected places. On this basis it was estimated that the location error was ~5 pixels, varying from image to image on any one day. This is thought to contribute insignificantly to the total error in the calibration.

Estimating from the histogram the mean count corresponding to the cloud-free radiance is not in general a trivial exercise. Therefore, in the results reported below the complete histograms are given in addition to the value at which the peak counts occurs.

5. 30 November 1978 flight

5.1 Aircraft measurements

The aircraft measurements over the selected area were made between 0900Z and 1520Z, and the average co-ordinates of the measurements were 32.9°N, 11.35°W. All measurements of temperature and humidity described in section 3 were analysed and plotted on a TØ-gram, together with data from a radiosonde at 32.7°N, 16.8°W and 1200Z (08521, Madeira). The "best" estimate of the representative profile with associated errors was obtained from the available data as follows:

a. Temperature, surface to 750 mb - the mean values for the constant pressure level runs were used. They were in good agreement with the ascent and descent profiles.

b. Temperature, 750 to 400 mb - the mean values of the ascent and descent profiles were used. In general the two agreed to within 1K.

c. Temperature, above 400 mb - the radiosonde profile was used and large tolerances allowed. Although the difference in locations of the aircraft measurements and the radiosonde makes this tie-on suspect, the effect on the calculated Meteosat radiances of temperatures at these levels was found to be negligible. Above 100 mb the US standard atmosphere (1976) was used, though again the effects of these layers are negligible.

d. Humidity, surface to 400 mb - the means of the manually-recorded values taken on the constant pressure level runs were used. Below 500 mb the shape of the automatically-recorded profile was used to interpolate between the manual values (although the absolute values of the automatic measurements were in error by several degrees).

e. Humidity, above 400 mb - no data were available. A typical stratospheric value of 3×10^{-6} for the humidity mass mixing ratio was assumed above 100 mb and a reasonable interpolation was used between 400 and 100 mb. Large tolerances were allowed, but these contributed negligibly to the error in the calculated radiances, since the absolute humidities at these heights are so low.

The best estimate of the whole profile is given in table 1. The surface pressure was derived from the height amsl and pressure measured on the lowest constant level run. The means and standard deviations of the calibrated Barnes radiances for each constant pressure level run are given in table 2.

5.2 Meteosat data

The appropriate 32 x 32 array of pixels from the IR image was selected as described in section 4: for this day the array consisted of lines 1966-1997 and pixels 1451-1482. Figures 1, 2 and 3 show the radiance histograms for the images at times 1155Z, 1255Z and 1455Z respectively. The peak count on all three is at 153. The secondary peak at a lower count for times 1255Z and 1455Z corresponds to some cumulus cloud which was noted during the flight. For the 1255Z image, the eight 32 x 32 arrays surrounding the chosen array were also analysed. All the histograms had peaks in the low 150s (although in some the peak was not as clearly defined as in figures 1, 2 and 3) and from these peaks the spatial gradient in the cloud-free radiance was estimated to be about 0.5 counts over a distance ~150 km.

The peak radiance of 153 counts was converted to a brightness temperature using two different calibration methods suggested by ESA:

a. MIEC method as outlined in section 3.1 of the Meteosat Calibration Report, Issue 4 [5], correcting for the drift of the "black body counts" with time using data given in the Meteosat Calibration Report, Issue 3 [6]:

$$153 \text{ counts} \longrightarrow 19.9^{\circ}\text{C}$$

b. "Engineering" method [1]:

$$153 \text{ counts} \longrightarrow 22.1^{\circ}\text{C}$$

(It has been noted that the engineering method was anomalously poor for a period during November-December 1978 [7]).

5.3 Calculation of Meteosat brightness temperature

The widely used atmospheric transmission model LOWTRAN 3B [8] was employed to calculate transmissions along paths through an atmospheric profile defined by table 1 at a zenith angle appropriate to Meteosat and the location of the aircraft measurements, ie 40.2° (the small variation in zenith angle of about $\pm 0.15^{\circ}$ over the measurement area being neglected). LOWTRAN calculates mean transmissions over intervals of 20 cm^{-1}. Consequently transmissions were calculated at 20 cm^{-1} intervals. Using these values, the radiative transfer equation was integrated along the path to find a radiance at the top of the atmosphere for each 20 cm^{-1} interval across the range of the radiometer response. These radiances were then convolved with the spectral response of the instrument (obtained from [6]) and the result expressed as a brightness temperature.

The above procedure was performed for the full atmospheric profile and also for the atmosphere truncated at each level in table 1 such that the calculated brightness temperature represented what the satellite would measure if there were no atmosphere above that level. The calculations were performed for 5 different profiles:

1) The "best" profile (as specified in table 1) with surface brightness temperature, T_o.

2) "Wet" profile - as (1) but humidity profile increased by the errors in table 1.

3) "Dry" profile - as (1) but humidity profile decreased by the errors in table 1.

4) High SST - as (1) but with surface brightness temperature, (T_o + σ_o).

5) "Hot" profile - as (1) but with temperature profile increased by the errors in table 1.

In this way the effects of various sources of error were investigated.

T_o was chosen to be 19.20°C as a result of the analysis described in section 5.5. σ_0 was chosen slightly arbitrarily as 0.40 (typical of the standard deviation of the Barnes radiometer measured brightness temperatures).

The resulting brightness temperatures for each profile truncating at each level are given in table 3, which also defines how the errors in the brightness temperature caused by the various sources can be assessed. The conclusion from this table is that, if we accept the accuracy of the transmission model (see section 5.5), then the cloud-free brightness temperature measured by Meteosat on this occasion was 15.0 ± 0.7°C.

The use of profiles 1 to 5 to estimate in this way the error in the brightness temperature is open to criticism, since the errors at all levels are applied in the same direction. This would correctly take account of any bias error in the profiles, but in this case the bias errors are probably much smaller than the random errors. Therefore this method of error analysis will tend to produce an over-estimate of the brightness temperature error. However, the use in the transmission model of linear interpolation between the levels at which the profiles are specified does not account for the uncertainty in the profiles between the levels and so will tend to lead to a counteracting under-estimate of error. Moreover, since the estimates of the errors at each level are largely subjective, a more detailed error analysis was not thought worthwhile.

All these calculations were performed using a US standard atmosphere ozone profile. The effects of ozone were investigated by repeating the calculations for profile (1) but with no ozone. A difference of only 0.02 degrees was found. Therefore errors caused by uncertainties in ozone profile may be neglected. In general, LOWTRAN calculates transmissions for water vapour, ozone and uniformly mixed gases. However, in the spectral region for which the Meteosat IR channel has significant response, only water vapour is important.

The calculation of brightness temperature has been repeated at ESA with the profile given in table 1 but using ESA's transmission model [9]. It gave a result of 14.9°C which compares favourably with our estimate. However, this agreement probably indicates that the two models are based on the same absorption coefficients and leaves open the question of whether those coefficients are accurate.

5.4 Calculation of Barnes radiometer brightness temperatures

These were derived in a similar way, the calculations differing from those for Meteosat only in the following respects. Firstly, a spectral response profile appropriate to the Barnes radiometer was used. This response is much wider than that of the Meteosat IR channel: they have significant responses over the following spectral regions:

Meteosat IR channel : 750- 990 cm^{-1}
Barnes radiometer : 620-1340 cm^{-1}

Secondly, a zenith angle of zero degrees was used since the Barnes radiometer operated viewing vertically downwards.

The resulting brightness temperatures for each of the 5 profiles specified in section 5.4 are given in table 4. For the "best" estimate profile they are plotted in figure 4. The error bars shown are the values of σ_A as defined in table 3. Also shown in figure 4 are the measured Barnes radiances and their standard deviations as given in table 2. The large differences shown in table 4 between 300 mb and 0 mb (of table 3) are caused by the greater effects of ozone and carbon dioxide for the instrument with the wider pass-band.

5.5 Comparison of measurement with calculation for the Barnes radiometer

It can be seen from figure 4 that, although the measurement error bars overlap those for the calculations, there is a strong indication that the calculation is underestimating the temperature deficit. This may be caused by errors in LOWTRAN, since there is still considerable uncertainty in the absorption coefficients of water vapour in the 11 μm "window" region. The following analysis is an attempt to estimate from the Barnes measurements the difference between the measured and calculated temperature deficits which may be caused by inaccuracies in the parameters of the transmission model.

Let us assume, as a first approximation, the model causes the calculated temperature deficit to differ from the measured deficit by a constant factor, α. A second reason for possible discrepancy between measurement and calculation is the assumption in the calculation of a surface brightness temperature, T_o. Let us assume that this is in error by an amount, δ, and that this causes an error, $\beta\delta$, in the brightness temperature calculated for pressure level, p. It can be shown that $\beta = \sigma_S/(\sigma_S)_o$, where σ_S is defined in table 3 and $(\sigma_S)_o$ is the value of σ_S at the surface. If we allow a random error, ϵ, in the measurement brightness temperature, T_m, then T_m is related to the calculated temperature, T_c, (plotted in figure 4) as follows:

$$T_m + \epsilon = T_o - \alpha(T_o - T_c) + \beta\delta,$$

$$\therefore \quad \epsilon = (T_o - T_m) - \alpha(T_o - T_c) + \beta\delta.$$

Using a least squares fit technique and weighting each measurement, T_m, by its standard deviation, σ_m, the best fit is obtained by minimising $\sum \epsilon^2/\sigma_m^2$ with respect to α and δ, where the summation is over all measurements of T_m. Obtaining T_m and σ_m from table 2, T_c from figure 4, β by interpolation from the data in table 4 and using $T_o = 19.20°C$, this technique yielded the following best estimates for α and δ:

$$\alpha = 1.16 \quad \text{and} \quad \delta = -0.08.$$

The significance of these results may be summarised as follows:

a. An estimate of the difference between the measured and calculated temperature deficit, possibly caused by errors in LOWTRAN, is 16%. However, it can be seen from figure 4 that the errors in the temperature and humidity profiles cause an uncertainty in this value of the same order. Also, even if exact, it would not be directly applicable to the Meteosat temperature deficits as the spectral responses of the instruments are quite different. However, the results do imply that LOWTRAN must be used with reservations for calculations in the 11 μm "window" region.

b. An estimate of the radiative SST is

$$19.20 - 0.08 = 19.12°C$$

This correction does not materially affect the result of section 5.3, since the correction is small. Because of atmospheric attenuation, its effect on the Meteosat brightness temperature is even smaller ($\simeq -0.05$ deg), and this is very much less than the total error in brightness temperature calculated in section 5.3.

5.6 Ship observations

These were analysed for the period, 26 November to 4 December 1978. Only one measurement was reported within 100 km of the aircraft flight area - a value of 20°C. Within the surrounding area, 31-35°N and 9-14°W, there were 20 reports during this period. All ranged between 19°C and 21°C with a mean of 19.8°C. The best estimate of the radiative SST given above is consistent with a true SST of 19.8°C; it corresponds to an emissivity of about 0.99. However, it is recognised that this degree of consistency is probably fortuitous since "ships' buckets" observations cannot be relied upon to give results of this accuracy, and one might also anticipate the surface temperature being slightly different from the bulk water temperature, depending on insolation, air temperature, wind speed, etc.

6. 5 December 1978 flight

The aircraft and satellite data were analysed in a similar way to those of the previous flight. The best estimate of the temperature and humidity profile is given in table 5 and the Barnes radiometer measurements in table 6. However, for the following reasons the data failed to yield any useful comparisons:

a. The coincident Meteosat radiances for the measurement area (lines 2040-2071, pixels 1463-1494) were seriously cloud-contaminated for all the images analysed - at times 1055Z, 1255Z and 1455Z. The histogram for 1055Z is shown in figure 5 and illustrates that no cloud-free radiance is identifiable.

b. The comparison between Barnes radiometer measurements and calculations was attempted, but the combined effects of a large scatter on the measured values and a small range in their heights (only from the surface to 850 mb) made an analysis similar to that in section 5.5 unprofitable.

7. Summary of results

Assuming that the peak radiance from the histograms can be equated with the cloud-free radiance, these results provide the following calibration point for the Meteosat IR channel: on 30 November 1978, <u>153 counts</u> corresponded to a brightness temperature of <u>15.0 ± 0.7°C</u>. The error in the calculated brightness temperature is caused mainly by uncertainties in the temperature and humidity profiles. It is noted that this calibration is at variance with those derived in section 5.2. Also, if the suggestion that LOWTRAN causes an underestimate of the temperature deficit is correct, then the difference between our calibration and the others will be greater.

The best estimate of the temperature deficit appropriate to the Meteosat spectral response for the profile measured on 30 November 1978 is 4.2 ± 0.7 deg. Of this deficit, the layer above 500 mb is responsible for about 0.3 deg and that above 400 mb for about 0.2 deg.

The comparison of the Barnes radiometer measurements with theoretical calculation suggests that LOWTRAN may be in error for this spectral region. However the results are not conclusive.

In September 1979 further flights were performed by MRF. The objectives were the same as for the previous flights but measurements were obtained over the tropical Atlantic off Dakar. The data have not yet been analysed but it is hoped that they will provide further calibration points for the Meteosat 11 μm channel and estimates of SST for warmer oceans where the correction for atmospheric attenuation is high.

Acknowledgements

I am indebted to Mr R W Lunnon for most of the preliminary work involved in organising this project and in the initial data analysis, and to Mr D Offiler for processing the aircraft data. I should also like to thank the staff and aircrew at MRF for their efforts in making the aircraft measurements, and the staff at ESOC, Darmstadt, for providing the Meteosat data.

References

[1] ESA Technical Note, Calibration of the Meteosat IR channel, M Reynolds, 21 September 1978.

[2] MRF Trials Instruction No 32 - Meteosat Calibrations.

[3] Introduction to the Meteosat system, Chapter 5.

[4] Introduction to the Meteosat system, Chapter 6.

[5] Meteosat 1, Calibration Report, Issue 4, Jan-Mar 1979.

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[7] Wilkinson G G, Dept of Atmospheric Physics, Oxford, private communication, July 1979.

[8] Selby J E A, Shettle E P, McClatchey R A, AFGL-TR-76-0258, Env Res Pap 587, Atmospheric transmittance from 0.25 to 28.5 µm: Supplement LOWTRAN 3B (1976).

[9] Lunnon R W, ESA/ESOC, private communication, August 1979.

Note:

References [1], [3], [4], [5], [6] are available from ESOC/MDMD (Robert Bosch Strasse 5, 6100 Darmstadt, W Germany).

Table 1

Atmospheric profile 30 November 1978

Pressure mb	Temperature °C	Dew point °C	Humidity mixing ratio Kg/Kg
1023 (surface)	18.3 ± 0.5	9.2 ± 0.5	
1000	16.5 ± 0.5	9.2 ± 0.5	
950	12.5 ± 0.5	8.5 ± 1	
900	9.7 ± 0.5	6.0 ± 2	
850	8.0 ± 0.5	5.0 ± 1	
800	5.7 ± 0.5	4.0 ± 2	
750	3.2 ± 0.5	-3.4 ± 2	
700	1.0 ± 1	-10.0 ± 2	
650	-2.0 ± 0.5	-24.0 ± 5	
600	-6.5 ± 0.5	-35.0 ± 5	
500	-16.5 ± 1	-35.0 ± 5	
400	-29.5 ± 1	-50.0 ± 5	
300	-43.3 ± 2	-58.0 ± 10	
200	-63.3 ± 2	-71.0 ± 5	
100	-62.9 ± 2		$3 \pm 2 \times 10^{-6}$

Table 2

Barnes radiometer measurements 30 November 1978

Pressure mb	Mean Barnes temp °C	Standard deviation of Barnes temp °C	Mean time of measurements GMT
1018.1	19.34	0.39	1017
1007.8	19.41	0.46	1337
1007.5	18.64	0.49	1034
983.8	18.73	0.40	1051
974.7	18.77	0.31	1320
958.0	18.39	0.46	1108
951.3	18.26	0.29	1303
899.9	17.01	0.67	1246
899.8	17.36	0.28	1127
850.3	16.66	0.43	1143
750.3	15.13	0.34	1200
609.0	13.86	0.44	1225

Table 3

Calculated brightness temperatures   Meteosat IR channel   30 November 1978

Pressure mb	T_1 °C	T_2 °C	T_3 °C	T_4 °C	T_5 °C
1023 (surface)	19.20	19.20	19.20	19.60	19.20
1000	19.10	19.10	19.10	19.48	19.13
950	18.61	18.58	18.65	18.96	18.69
900	17.94	17.80	18.06	18.25	18.05
850	17.25	17.01	17.46	17.55	17.39
800	16.52	16.18	16.82	16.79	16.68
750	15.93	15.48	16.33	16.20	16.12
700	15.60	15.08	16.05	15.86	15.80
650	15.45	14.88	15.93	15.71	15.65
600	15.38	14.78	15.88	15.64	15.58
500	15.25	14.61	15.79	15.51	15.46
400	15.14	14.45	15.70	15.40	15.35
300	15.07	14.36	15.64	15.33	15.28
0	14.96	14.22	15.53	15.21	15.16

T_n is the brightness temperature for the nth atmospheric profile described in the text.

Terms describing sources of error in the brightness temperatures are defined as follows:

Error from temperature profile, $\sigma_T = T_5 - T_1$

Error from humidity profile, $\sigma_H = \frac{1}{2}(T_3 - T_2)$

Error from surface temperature, $\sigma_S = T_4 - T_1$

Error from atmospheric profile, $\sigma_A = (\sigma_T{}^2 + \sigma_H{}^2)^{\frac{1}{2}}$

Total error, $\sigma = (\sigma_A{}^2 + \sigma_S{}^2)^{\frac{1}{2}}$

Table 4

Calculated brightness temperature   Barnes radiometer   30 November 1979

Pressure mb	T_1 °C	T_2 °C	T_3 °C	T_4 °C	T_5 °C
1023 (surface)	19.20	19.20	19.20	19.60	19.20
1000	19.05	19.04	19.05	19.41	19.09
950	18.48	18.45	18.50	18.81	18.57
900	17.73	17.63	17.81	18.04	17.84
850	17.02	16.86	17.17	17.32	17.16
800	16.31	16.08	16.51	16.59	16.47
750	15.68	15.36	15.95	15.95	15.85
700	15.22	14.86	15.53	15.49	15.42
650	14.88	14.48	15.21	15.14	15.08
600	14.54	14.13	14.89	14.81	14.74
500	13.82	13.36	14.19	14.08	14.02
400	12.89	12.40	13.29	13.15	13.11
300	11.87	11.35	12.28	12.14	12.11
0	7.75	7.23	8.16	8.00	7.96

Table 5

Atmospheric profile 5 December 1978

Pressure mb	Temperature °C	Dew point °C	Humidity mixing ratio Kg/Kg
1021 (surface)	18.5 ± 0.5	16.5 ± 1	
1000	17.5 ± 0.5	15.5 ± 1	
950	14.5 ± 0.5	11.0 ± 1	
900	12.2 ± 0.5	9.0 ± 2	
850	10.0 ± 1	6.5 ± 2	
800	7.5 ± 1	4.5 ± 1.5	
750	5.5 ± 0.5	-1.0 ± 3	
700	2.0 ± 0.5	-3.0 ± 2	
650	-1.5 ± 0.5	-7.0 ± 2	
600	-6.0 ± 0.5	-11.0 ± 2	
500	-14.5 ± 2	-27.0 ± 5	
400	-27.0 ± 2	-44.0 ± 5	
300	-41.5 ± 2	-54.0 ± 10	
200	-61.0 ± 2	-70.0 ± 5	
100	-67.0 ± 3		$3 \pm 2 \times 10^{-6}$

Mean co-ordinates of measurement area = 36.8°N, 12.3°W

Table 6

Barnes radiometer measurements 5 December 1978

Pressure mb	Mean Barnes temperature °C	Standard deviation of Barnes temperature °C	Mean time of measurements GMT
1014.7	17.74	0.40	1220
1004.4	16.93	0.98	1243
980.1	17.45	0.23	1301
954.3	17.14	0.27	1320
899.6	15.92	0.48	1338
850.8	15.75	0.32	1357

Figure 1. Histogram for 30 November 1978 at 1155Z.

Lines 1966-1997, pixels 1451-1482 from IR image

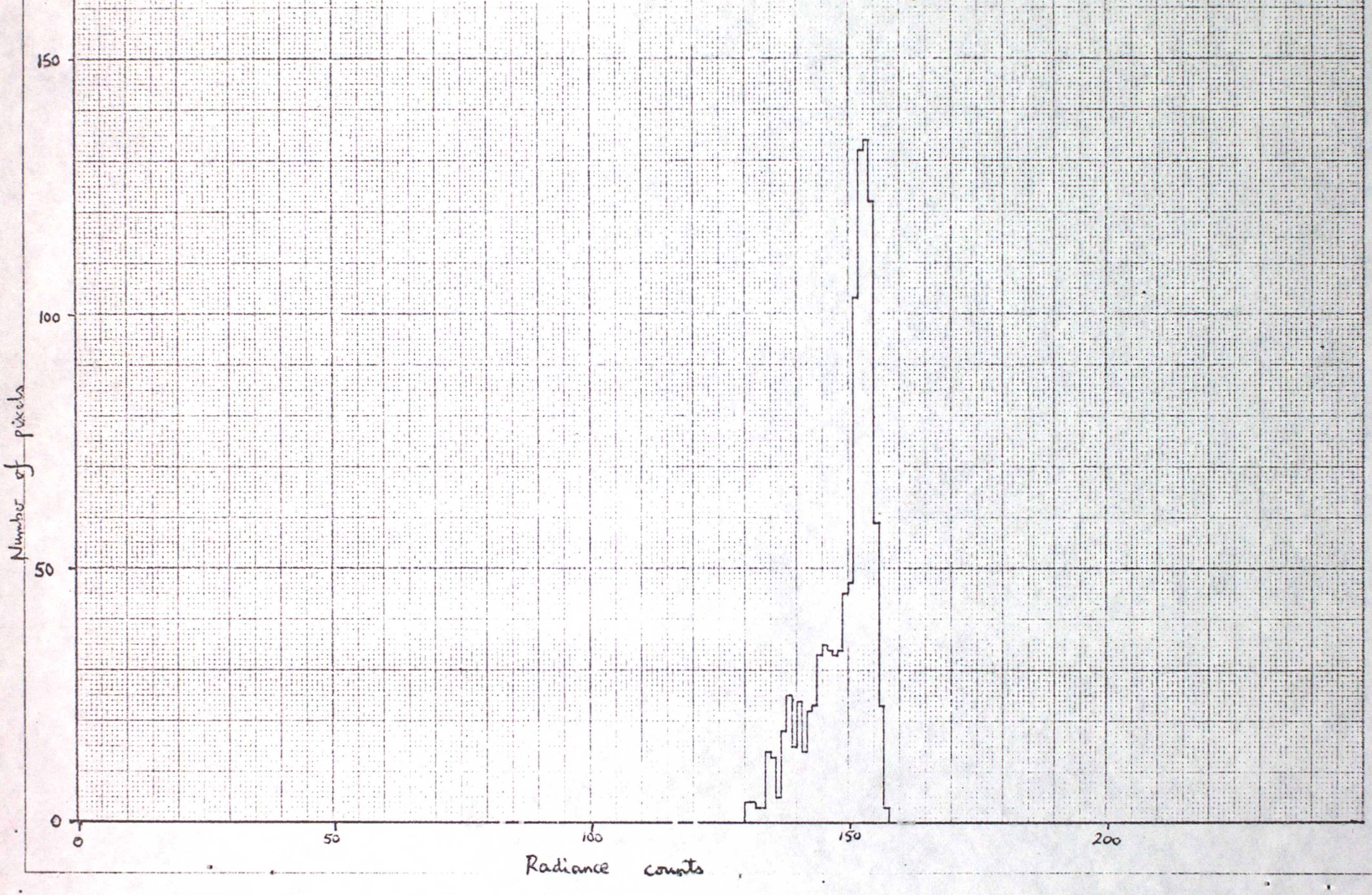

Figure 2 Histogram for 30 November 1978 at 1255 Z

Lines 1966-1997, pixels 1451-1482 from IR image

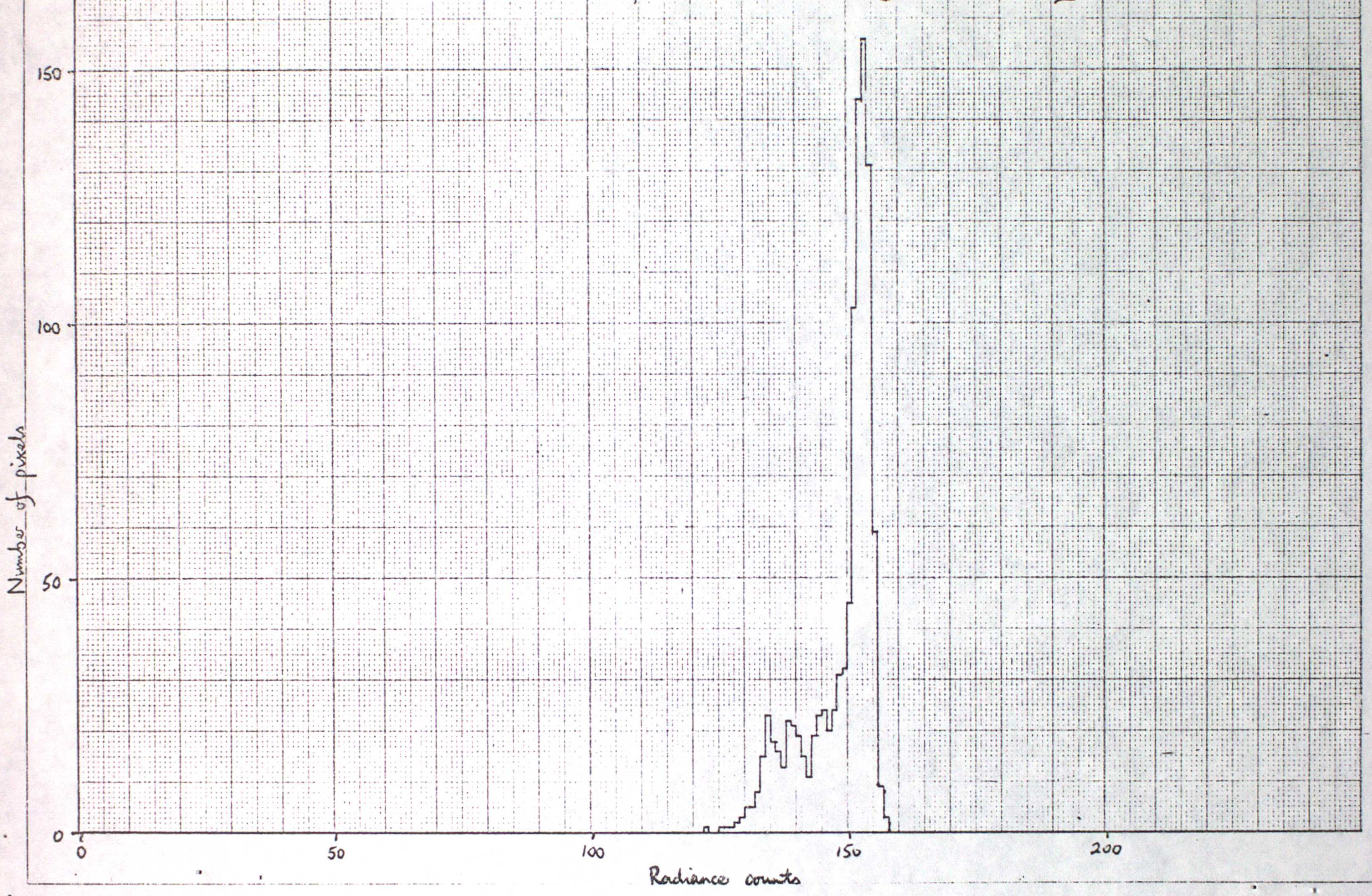

Figure 3

Histogram for 30 November 1978 at 1455 Z
Lines 1966-1997, pixels 1451 - 1482
from IR image

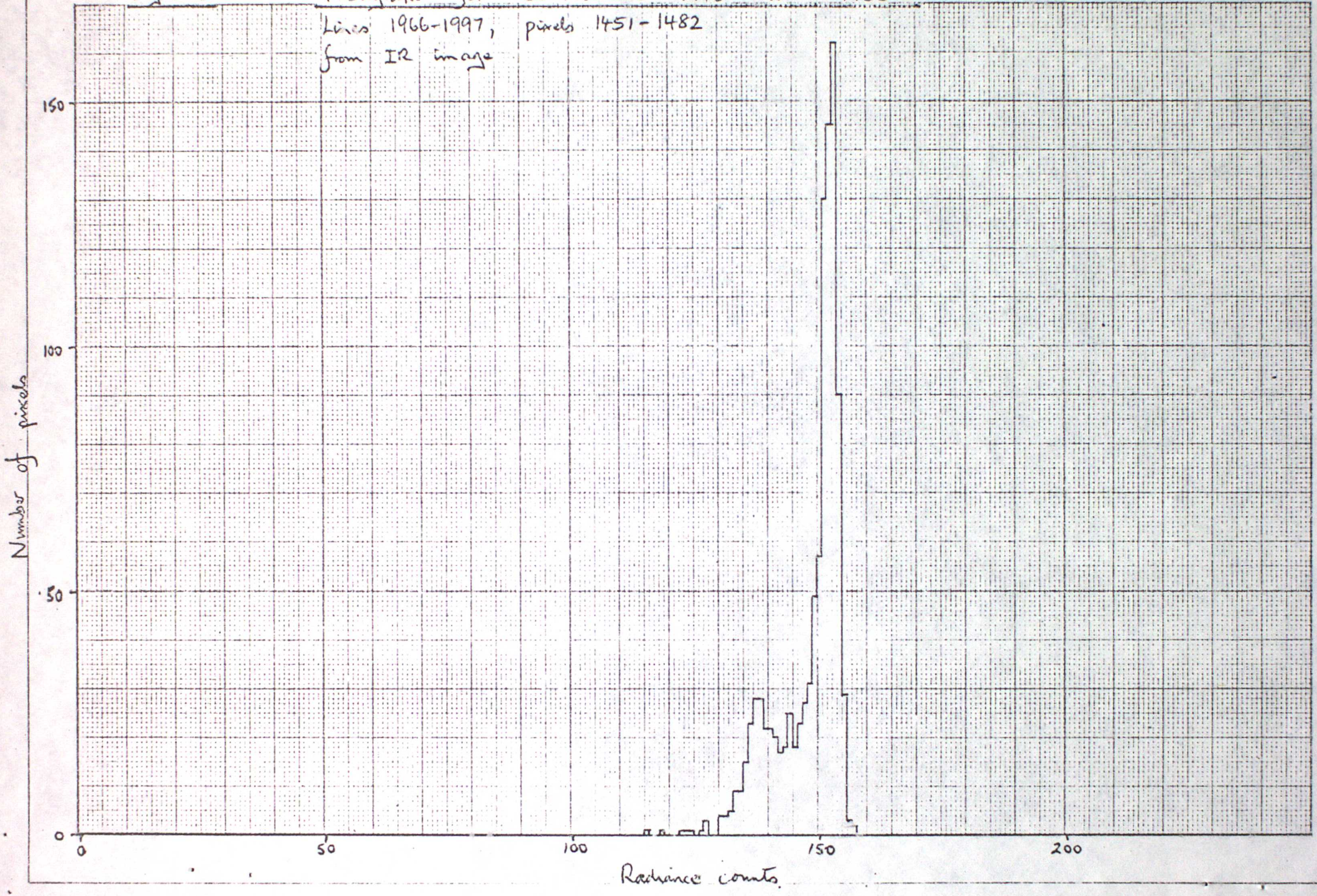

Figure 4

Comparison of measured and calculated brightness temperatures for the Barnes radiometer

30 November 1978

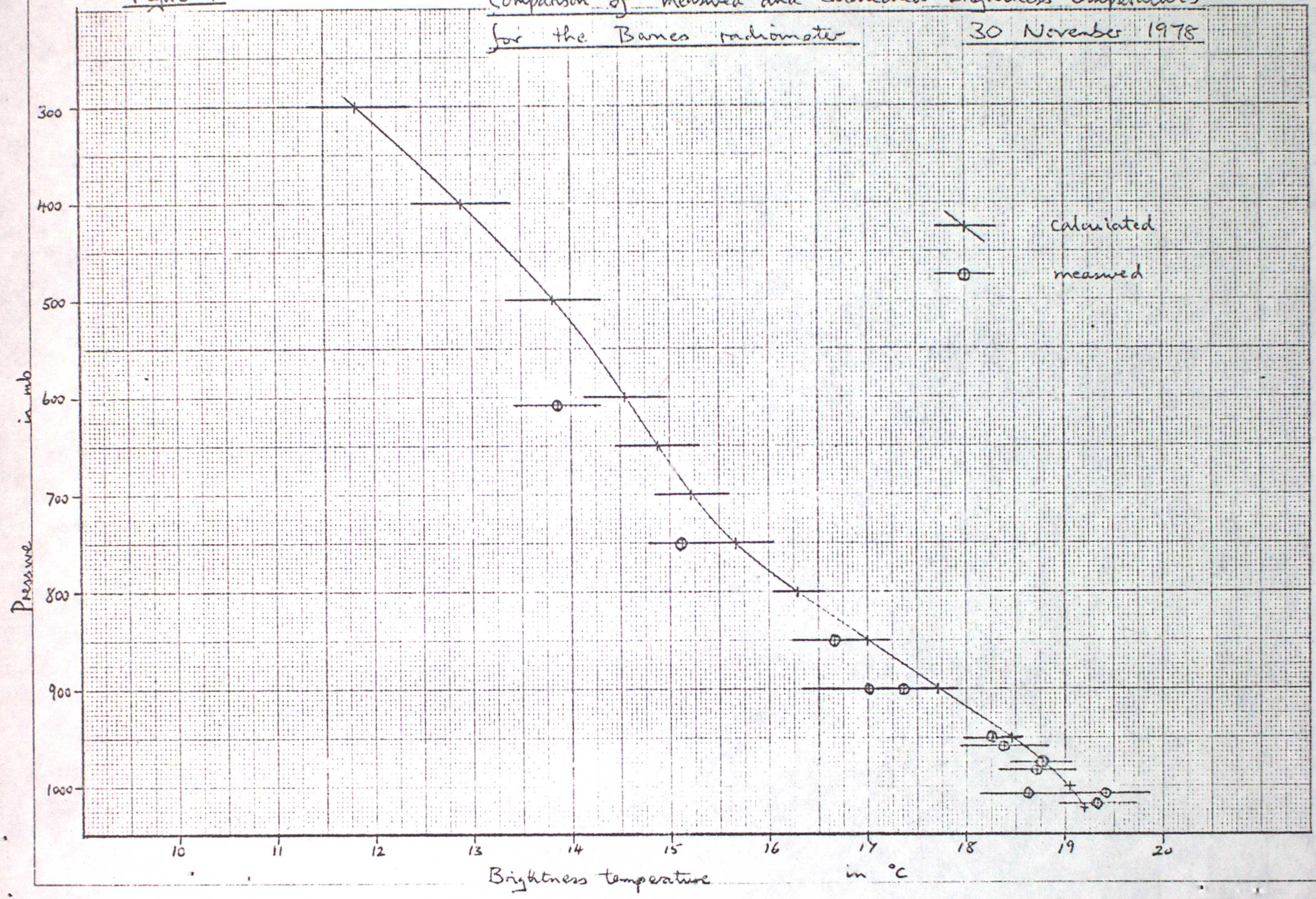

Figure 5

Histogram for 5 December 1978 at 1055Z

Lines 2040 - 2071, pixels 1463 - 1494 from IR image