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# Preliminary results from the use of VTPR radiances

B R May

# PRELIMINARY RESULTS FROM THE USE OF VTPR RADIANCES

By B R May

## 1. Introduction

For some years now satellite-borne radiometers have been observing the thermal radiation emitted by the Earth's atmosphere for the purpose of determining the vertical and horizontal temperature structure. The High Atmosphere Branch have obtained a small amount of radiance data from the Vertical Temperature Profile Radiometer (VTPR) on the NOAA2 spacecraft, which has been used to determine the horizontal variation of temperature and thickness above cloud level (300-30 mb) over Europe at 09Z on 18 July 1973.

## 2. The VTPR Instrument

The VTPR, of which there are two in the NOAA2 spacecraft was designed by NESS (National Environmental Satellite Service) of the USA. The NOAA2 spacecraft is in a 1500 km high sun-synchronous polar orbit which enables the VTPRs to make observations of the atmosphere twice per day at latitudes greater than 50° and the remainder of the atmosphere once per day. Near the equator and at mid-latitudes the VTPR observations are made at about 09 and 21 hours local time.

The VTPR is a multi-channel radiometer observing the Earth's atmosphere and surface in eight narrow bands in the infra-red spectrum. Six of the bands ("channels") are in the 15$\mu$ $CO_2$ molecular spectrum, one is in the water vapour spectrum near 20$\mu$ and the remaining one is in the atmospheric "window" near 11$\mu$. In the work described here only radiances from the $CO_2$ channels are used to deduce the atmospheric temperature and thickness profile. The radiances observed in the $CO_2$ channels are not emitted by single levels of the atmosphere but by broad overlapping bands defined by the weighting functions (in figure 1) which are centred at levels from 40 mb (for channel 1) to the surface (for channel 6). The breadth of the weighting functions results in a poor vertical resolving power so that the radiation observed in the channels whose functions peak in the troposphere (channels 4, 5 and 6) consist of radiation from the surface and clouds as well as from the atmosphere itself. The radiance in channels 1 and 2 appears to be unaffected by cloud while channel 3 is occasionally affected. In this work only the radiances in channels 1, 2 and 3 are used to determine the atmospheric temperature and thickness profile above cloud level, from 300 to 30 mb.

In order to increase the geographical coverage the VTPR scans the atmosphere making 23 observations each of an area of about 60 x 60 km across the track of the spacecraft. The successive scans are adjacent and for the purpose of analysis the radiances from eight scans are arranged in boxes, an inner box of 7 x 8 observations, and two outer boxes of 8 x 8 observations. To reduce the amount of data to be handled the temperature and thicknesses are calculated from the mean radiances within the boxes and these are located at their centres, which are about 500 km apart.

The radiance observed in channels 1, 2 or 3 of the VTPR is given by the Radiation Transfer Equation:-

$$R = \int_{\tau=0.0}^{\tau=1.0} B(T_{atm}, \bar{\nu}) \frac{d\tau}{dz} . dz$$

where $B(T, \bar{\nu})$ is the Planck function

$$B(T, \nu) = \frac{c_1 \bar{\nu}^3}{\exp\left(\frac{c_2 \bar{\nu}}{T}\right) - 1.0} \quad \text{.........} \quad (1)$$

( $C_1$ and $C_2$ are constants), $\tau$ is the transmission coefficient from a particular level to the "top" of the atmosphere, and z is a function of pressure. $d\tau/dz$ is the weighting function which is shown in figure 1 for the three channels. The units of R and B are $mW(m^2.sr.cm^{-1})^{-1}$ (called R units for short). For computational purposes the RTE is most easily handled as a finite sum of products:-

$$R_i = \sum^{j=1,J} B(T_j, \bar{\nu}_i) . W_{ij} \quad \text{.............} \quad (2)$$

for the i channels 1 to 3, and for J levels of the atmosphere. Here J = 50 and the levels are equally spaced in - $\log_e(p)$, from p = 1013.246 mb to 0.056 mb. The wave numbers of the channels are $\bar{\nu}_1 = 668$, $\bar{\nu}_2 = 678$ and $\bar{\nu}_3 = 695\,cm^{-1}$. The $\tau$'s and hence the W's are slightly dependent upon the atmospheric temperature and the angle from the vertical at which the radiometer is looking (this affects the path length of $CO_2$). The dependence on temperature was neglected but the dependence upon angle was allowed for. The weighting functions in figure 1 are based on transmission coefficients from ref 1 which were calculated for the 1962 US Standard Atmospheric temperature profile.

The results described here are derived from radiances measured by the VTPR instrument no 2 during two south-going passages of the NOAA2 spacecraft over Europe at about 08 and 10Z on 18 July 1973. Three methods of deducing the 300-30 mb temperature profile and thickness from the radiances have been used which are described in the next section.

## 3. Retrieval Methods

Because of the breadth of the weighting functions no unique temperature profile can be found from a set of the three radiances. Some extra conditions have to be imposed in order to find a temperature profile satisfying the observed radiances and these three methods differ in these conditions. All of these methods are described in greater detail in ref 2.

### Method 1 - Full Statistical Inverse Matrix Solution

In this method the Planck function at level j is expressed as a linear function of three radiances $R_i(\overline{\nu}_{st})$, ($i$ = 1, 2, 3) by

$$B(T_j, \overline{\nu}_{st}) = \sum_i a_{ij} . R_i(\overline{\nu}_{st}) + a_{4j}$$

where $\overline{\nu}_{st}$ is a reference wavenumber close to $\overline{\nu}_1, \overline{\nu}_2$ and $\overline{\nu}_3$. Samples of temperature profiles are used to calculate the $B(T_j, \overline{\nu}_{st})$ from equation 1 and $R_i(\overline{\nu}_i)$ using equation 2: Equation 1 is then used to find the equivalent black-body temperature for each $R_i(\overline{\nu}_i)$ and hence the corresponding $R_i(\overline{\nu}_{st})$; this frequency normalisation is not exact but is adequately accurate if $\overline{\nu}_{st}$ is close to $\overline{\nu}_1, \overline{\nu}_2$ and $\overline{\nu}_3$, and can be used on observed values of $R_i(\overline{\nu}_i)$. The a's are then determined from the calculated values of $B(T_j, \overline{\nu}_{st})$ and $R_i(\overline{\nu}_{st})$ by least square linear regression. This method is identical to Rodgers' "maximum probability" method (ref 3). The samples of temperature profiles that were used were for the latitude bands 0°-30°, 30°-50°, 50°-70° and 70°-90° for summer conditions, to correspond to the epoch of the VTPR data.

Method 2 - Chahine's Direct method

The the previous method there is no limit to the number of levels in the atmosphere at which the temperature is represented even though the number of "observations" is limited to the number of weighting functions. It has been suggested by Chahine that the profile can be represented by the temperature at the same number of levels as there are observations where the levels are chosen to be close to the peaks of the weighting functions, if between these levels and elsewhere suitable variations of temperature are adopted. The method is iterative and is described by the equations (for the $n^{th}$ iteration):-

$$R^{(n)}(\bar{\nu}_i) = \sum^{j=1,J} B(T_j^{(n)}, \bar{\nu}_i) . W_{ij}$$

$$B(T_i^{(n+1)}, \bar{\nu}_i) = B(T_i^{(n)}, \bar{\nu}_i) . R(\bar{\nu}_i)_{ob} / R^{(n)}(\bar{\nu}_i)$$

$$T_j^{(n+1)} = f(T_i^{(n+1)})$$

The three levels that were used were 41 mb for channel 1, 62 mb for channel 2 and 137 mb for channel 3; above 41 mb and below 137 mb temperature profiles of a constant shape were adopted based on the mean profiles calculated during the use of method 1, with interpolation in latitude to the location of the observation. Between the three levels a linear variation of temperature was used as suggested by Chahine.

This method has been criticised on the grounds that an expected small-scale feature of the temperature (such as the well-defined tropopause or low latitudes) cannot be represented if it lies between two levels. The results described in a later section show that it is also capable of producing solutions containing improbable-looking features.

Method 3 - Smith's modification of Chahine's method

This method is similar to Chahine's but the radiances are used to determine the profile at all levels, not just a limited number of levels. It is an iterative method which changes the overall shape of the profile in accordance with the radiance information but preserves the features of the profile which are small compared with the breadth of the weighting functions such as a sharply defined tropopause. The method is described (for the $n^{th}$ iteration) by the equations:-

$$R^{(n)}(\bar{\nu}_i) = \sum^{j=1,J} B(T_j^{(n)}, \bar{\nu}_i) . W_{ij}$$

$$B(T_{ij}^{(n+1)}, \bar{\nu}_i) = B(T_j^{(n)}, \bar{\nu}_i) + [R(\bar{\nu}_i)_{obs} - R^{(n)}(\bar{\nu}_i)]$$

$$T_j^{(n+1)} = \frac{\sum^{i} T_{ij}^{(n)} . W_{ij}}{\sum^{i} W_{ij}}$$

The starting solutions used in method 3 are the mean temperature profiles for the latitude bands used in method 1 interpolated to the location of the observation.

Methods 2 and 3 (the "direct" methods) have an advantage over method 1 in that they do not require temperature statistics from samples of profiles and that the first guess profile required to start the iterative procedure can also be used to calculate the appropriate weighting functions if required.

4. Results

Before going on to describe the results obtained by the use of these three methods of retrieval, it is useful to look at the VTPR radiances from which the temperatures and thicknesses were retrieved, which are plotted in figures 2a, b and c. The arrangement of the radiances in lines of three across the sub-spacecraft track can be clearly seen, where the first North-to-South pass over eastern Europe took place at about 08Z and the second over the UK at about 10Z. Where the radiances are near coincident for the two passes, they are generally in good agreement (bearing in mind the two-hour delay) which indicates that over this time scale, at least, the VTPR is an encouragingly stable instrument. For comparison the r.m.s. instrumental noise of the mean radiances is reported to be about 0.05 R units for channel 1 and 0.025 R units for channels 2 & 3 respectively (ref 1). At all locations $R_1 > R_2 > R_3$ which is consistent with the positive temperature gradient above the tropopause and the heights of the weighting functions in figure 1. All the channels show a gradual increase of radiance with latitude with a trough of smaller radiances extending north-south from Greece to Northern Russia and a ridge of larger radiance from the western Mediterranean to Scandinavia.

It is fortunate that we have also been able to obtain the "SIRS" soundings calculated from VTPR data used here. The SIRS soundings are temperature and thickness profiles produced operationally by NESS from the VTPR radiances using the "minimum information" method (ref 1). This is a modification of Method 1 in which the effects of the correlation between the temperature at different levels of the atmosphere in determining the solution profile are suppressed. The SIRS soundings extend from 10 mb to the surface but only for sea areas, so that only a few comparisons could be made between them and the results obtained by the methods described previously.

The centre of one box of observations was very close (within 70 km) to Stornoway upper-air station so that a spot comparison could be made of the temperatures and thicknesses obtained by various methods from the radiances and the radio-sonde ascent. The temperature profiles are plotted in figure 3 for 09Z, in which the radio-sonde profile is an interpolation between the 00Z and 12 Z ascents. From 100 to 30 mb the temperatures obtained by methods 1 and 2 average about two degrees warmer than the sonde temperatures while the SIRS temperatures average about three degrees colder. From 100 to 250 mb the temperatures from method 1 are closest to the sonde temperatures. Chahine's method (no 2) gives a temperature profile in complete disagreement with the profiles obtained by all other methods and the sonde ascent, showing a peak temperature of $-27^{\circ}$C at 63 mb. Thus, as mentioned previously, not only is Chahine's method incapable of representing an expected small-scale feature of the temperature profile, it also appears capable of producing an unexpected one. The 300-30 mb thickness from the sonde ascent is 1516 gpdm compared with the values of 1507 from the SIRS sounding, 1529 from method 1, 1530 from method 2, and 1528 gpdm from method 3; for the 100-30 mb thickness the values are 794, 788, 805, 819 and 805 gpdm respectively. These figures indicate that for narrow layers, method 2 can give rise to serious thickness errors because of the unlikely profiles that it produces, but for thicker layers suitably disposed with respect to the weighting functions the mean temperature or thickness is determined to a large extent by the radiances and only slightly by the assumptions implicit in the retrieval method.

Further comparisons of the 300-30 mb thickness are shown in figure 4 in which are plotted the results from the observations over the sea off the western coast of

Europe from the second orbit. The observations are in a line from 67°N, 1°E to 32°N, 16°W. Over the whole latitude range the 300-30 mb thicknesses using methods 1, 2 and 3 agree fairly well but are greater than the thickness from the sonde analysis by about 10 gpdm at the higher latitudes and 2 gpdm at the lowest latitudes. In comparison, the SIRS thicknesses are all about 10 gpdm smaller than the sonde thicknesses.

Unlike the SIRS soundings, the temperatures and thicknesses obtained here are not confined to the sea areas, so that it has been possible to compare the 300-30 mb thickness pattern over Europe with the pattern implied by sonde observations. The comparisons of the thicknesses from the three methods are shown in figure 5a, b and c. The sonde thickness pattern for 09Z is based on the CFO 300 mb height analysis and an analysis of the 30 mb height by members of the Stratospheric Analysis group of Met O 19, suitably interpolated in time between the 00Z and 12Z, and it represents the best information available at present. The features of the 300-30 mb thickness pattern over Europe at this time are the general increase of thickness from about 1450 gpdm at 35°N to about 1560 gpdm near the pole, a ridge of large thickness with an axis over Denmark and Central Europe and another ridge with its axis over Northern Russia. The thickness patterns deduced from the radiance measurements from all methods are generally in good agreement with each other over the whole extent of the chart, the thicknesses usually differing by less than 12 gpdm. At high latitudes the VTPR thicknesses are considerably greater (up to 24 gpdm) than the sonde thicknesses though the difference decreases towards lower latitudes. However apart from these differences the thickness pattern from the radiances is encouragingly similar to that from the sondes showing the presence of the two ridges of large thickness mentioned previously. With the small amount of data at our disposal it is not possible to arrive at any definite reason for the discrepancy between the radio-sonde and the radiance thickness, but if the consistent difference can be explained and removed it appears that the VTPR radiances would be useful in determining temperatures and thicknesses above cloud level, at the very least.

Finally it should be remembered that the NOAA3 spacecraft, also with two VTPRs on board, has the added feature of a "direct read-out" facility whereby the VTPR data is transmitted to the ground in real time. The coverage of the direct read-out data lies within a circle of roughly 4000 km radius, so that for data reception at Bracknell this includes the whole of Europe, (as in figures 5a, b and c), northern Africa and the Atlantic Ocean as far west as Newfoundland. Thus (with some further effort) results of the kind described here could be provided twice per day over this area, if the direct read-out data were available.

Acknowledgement:-

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References:-

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2. Fritz, S et al — "Temperature Sounding from Satellites" NOAA Tech Rept NESS 59.

3. Rodgers C D — "Remote sounding of the Atmospheric Temperature Profile in the presence of Cloud" QJR Met Soc. 96, 654 (No 410, 1970).

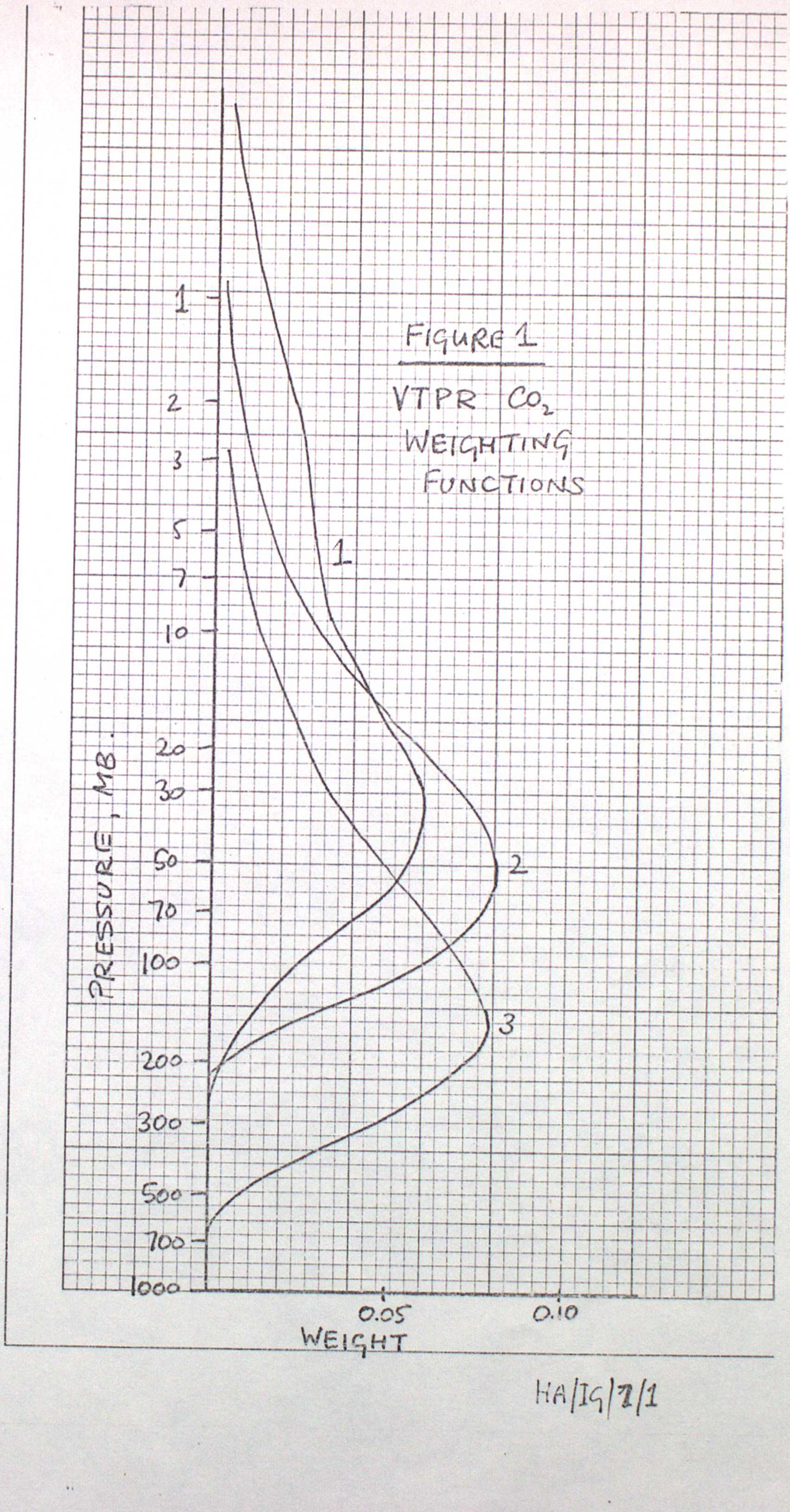


FIGURE 1
VTPR CO2
WEIGHTING
FUNCTIONS
1
2
3
PRESSURE, MB.
1
2
3
5
7
10
20
30
50
70
100
200
300
500
700
1000
0.05
0.10
WEIGHT

HA/IG/7/1

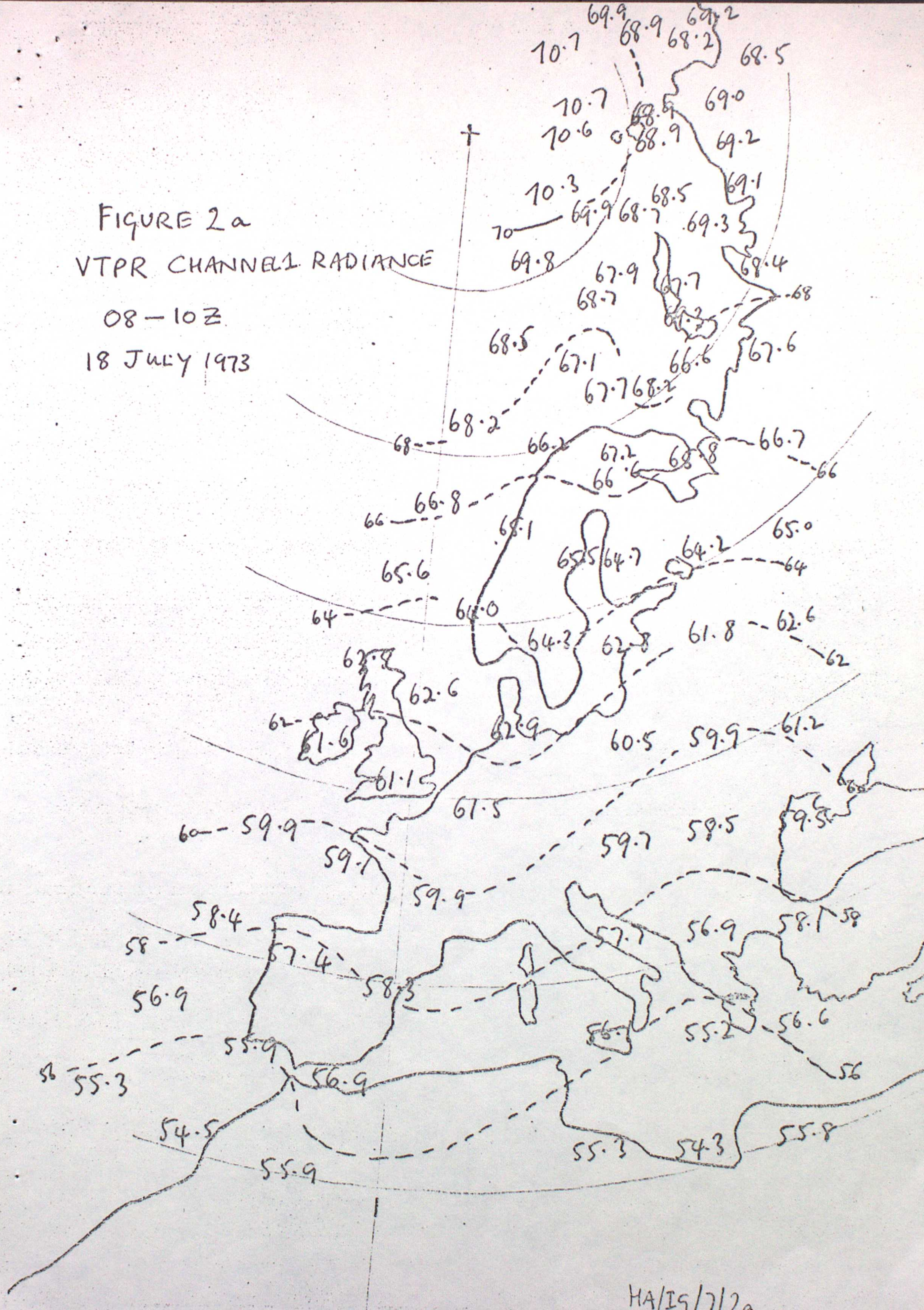


FIGURE 2a
VTPR CHANNEL 1 RADIANCE
08 – 10Z
18 JULY 1973
69.9
69.2
68.9
68.2
70.7
68.5
70.7
69.0
70.6
68.9
69.2
70.3
69.1
68.5
70
69.9
68.7
69.3
69.8
68.4
67.9
67.7
68.7
68
68.5
67.1
66.6
67.6
67.7
68.2
68.2
68
67.2
66.7
66
66
66.8
66
65.0
68.1
65.6
65.5
64.7
64.2
64
64
64.3
62.8
61.8
62.6
62
62.6
62
61.6
62.9
60.5
59.9
61.2
61.1
61.5
60
59.9
59.7
58.5
59.1
59.9
58.4
56.9
58.1
58
58
57.4
58.3
57.7
56.9
56.6
55.9
55.2
56
56
55.3
56.9
54.5
55.3
54.3
55.8
55.9

HA/IG/7/2a

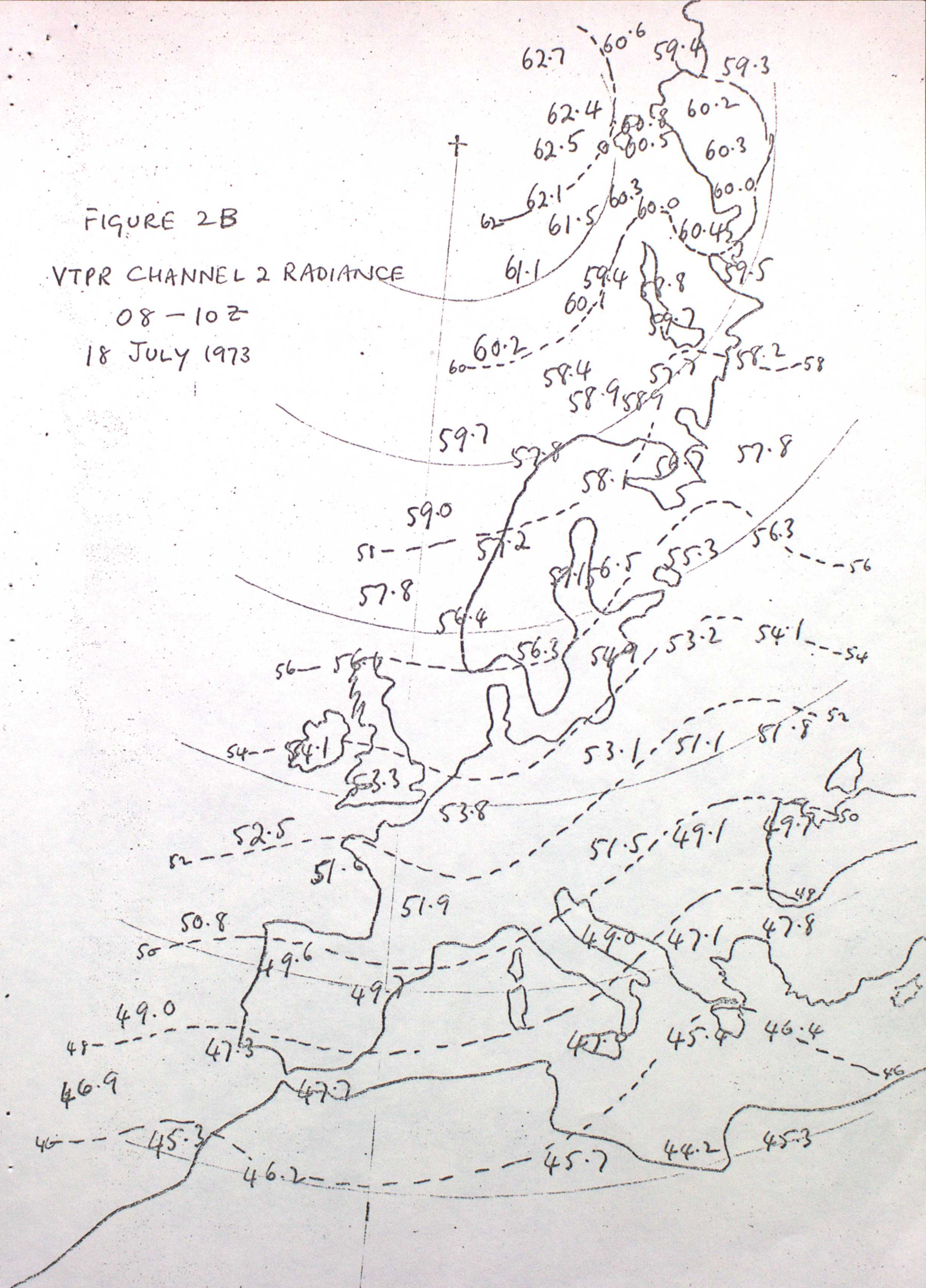



FIGURE 2B

VTPR CHANNEL 2 RADIANCE

08 – 10Z

18 JULY 1973

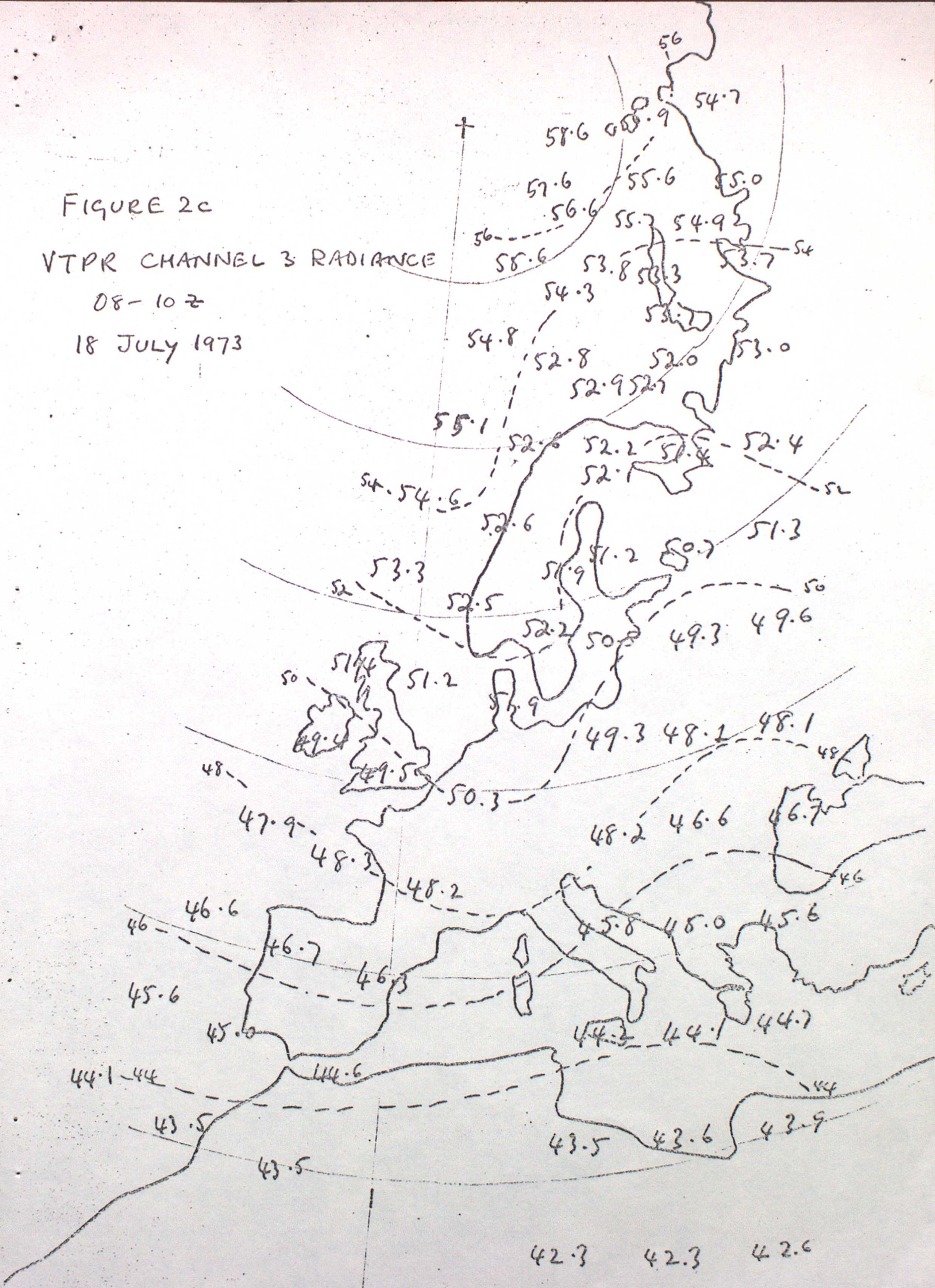
HA/IG/7/26

FIGURE 2c

VTPR CHANNEL 3 RADIANCE

08-10Z

18 JULY 1973




HA/IG/7/28c

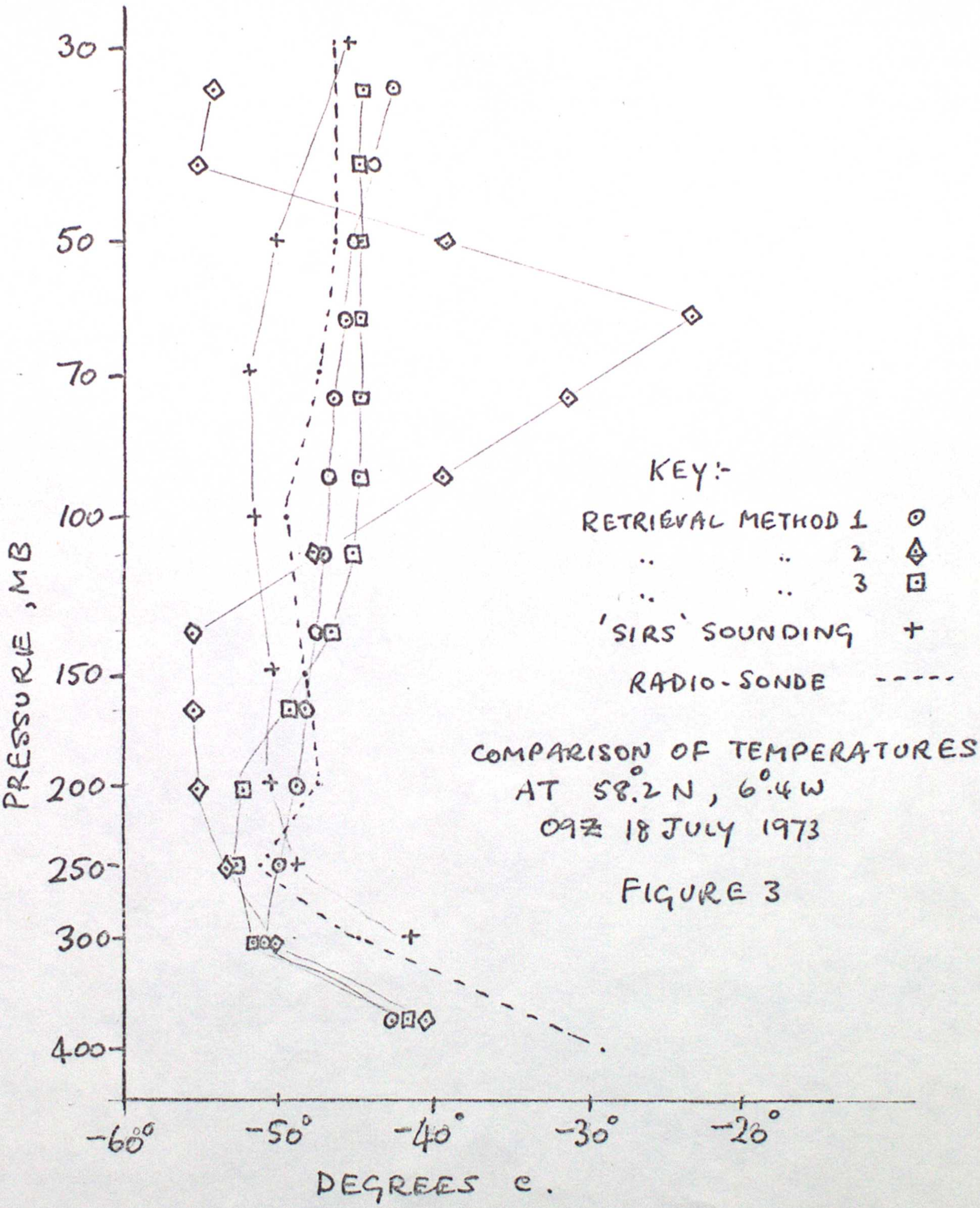



FIGURE 3 COMPARISON OF TEMPERATURES

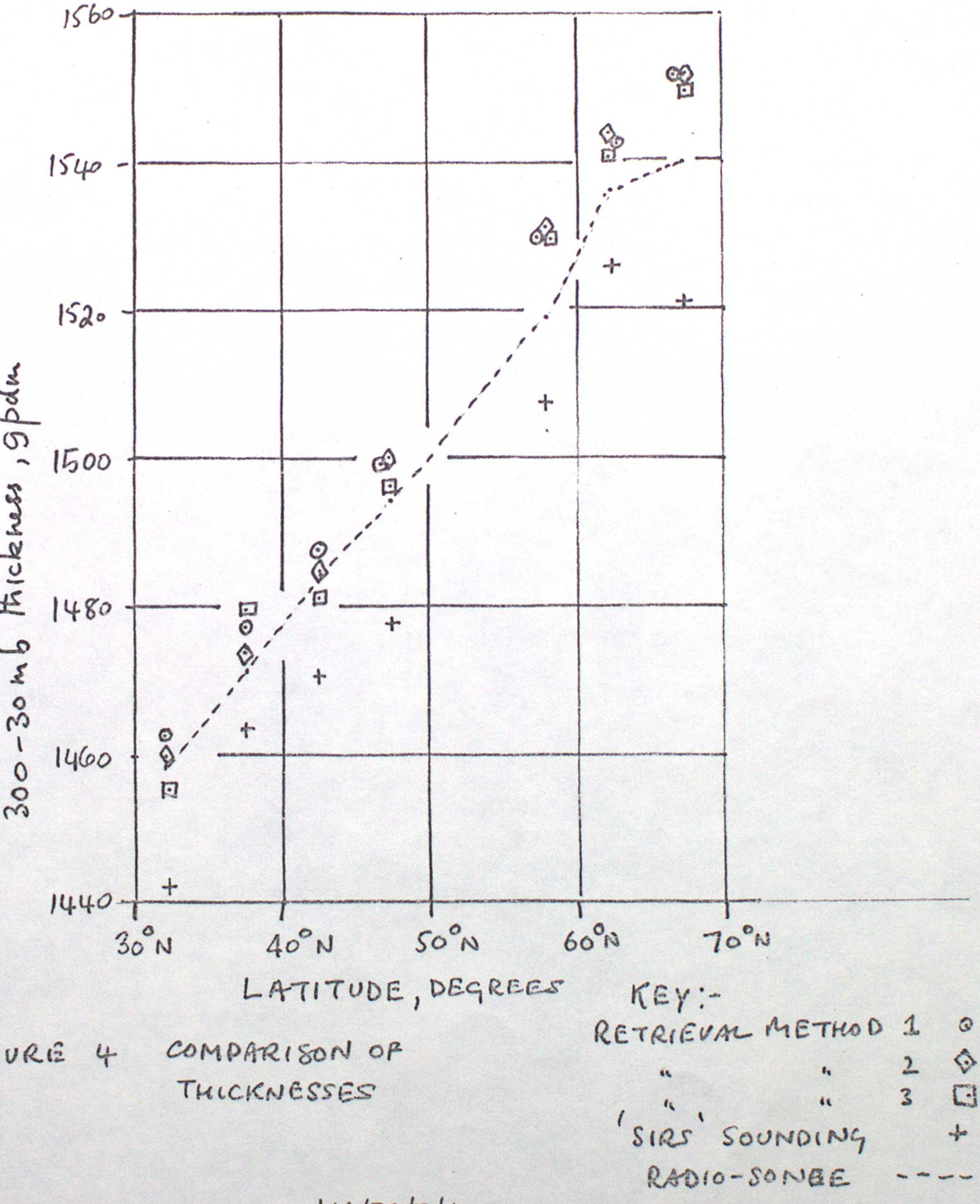



FIGURE 4 COMPARISON OF THICKNESSES

HA/IG/7/4

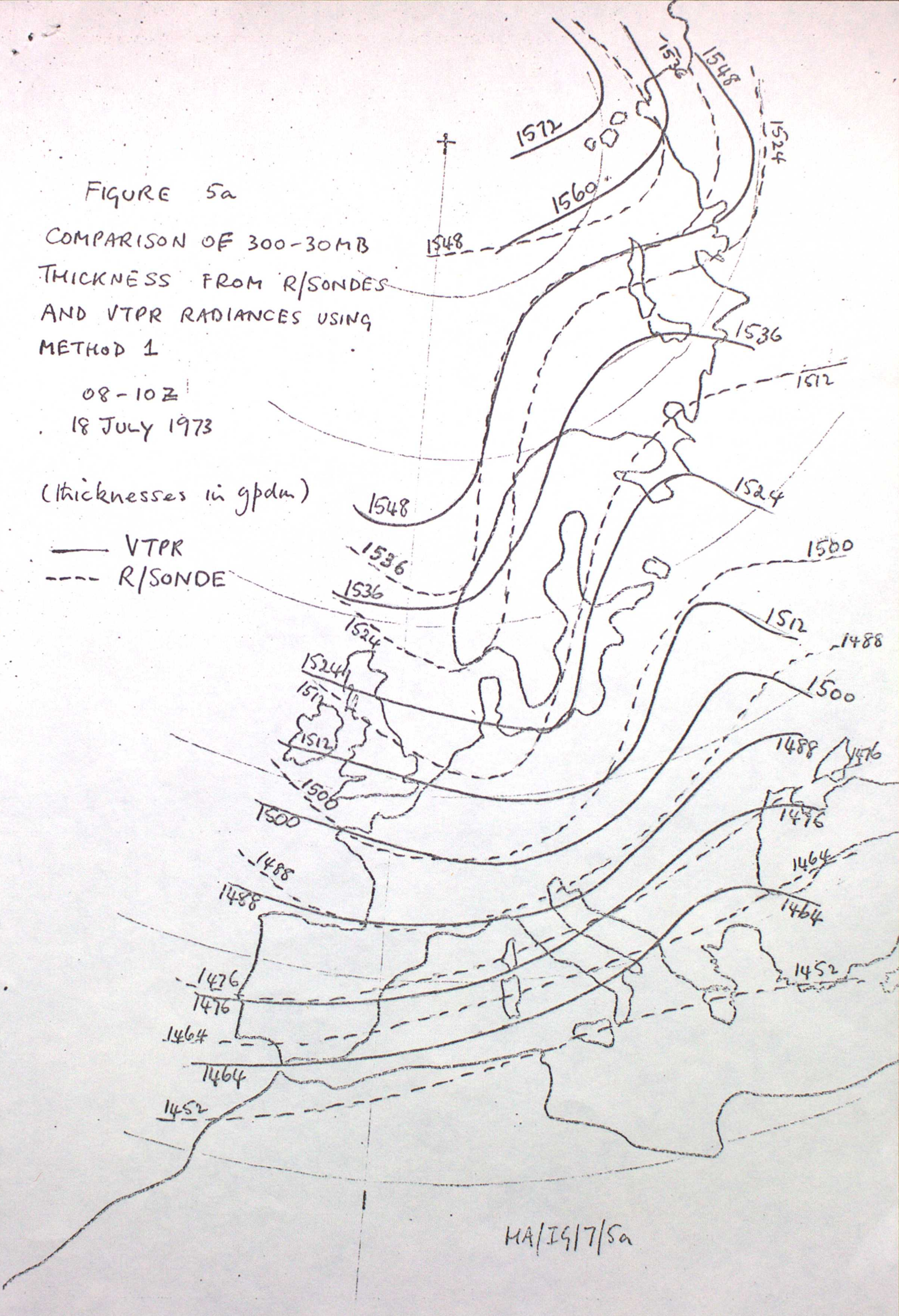
FIGURE 5a

COMPARISON OF 300-30MB THICKNESS FROM R/SONDES AND VTPR RADIANCES USING METHOD 1

08-10Z
18 JULY 1973

(thicknesses in gpdm)

—— VTPR
- - - - R/SONDE




HA/IG/7/5a

FIGURE 5b

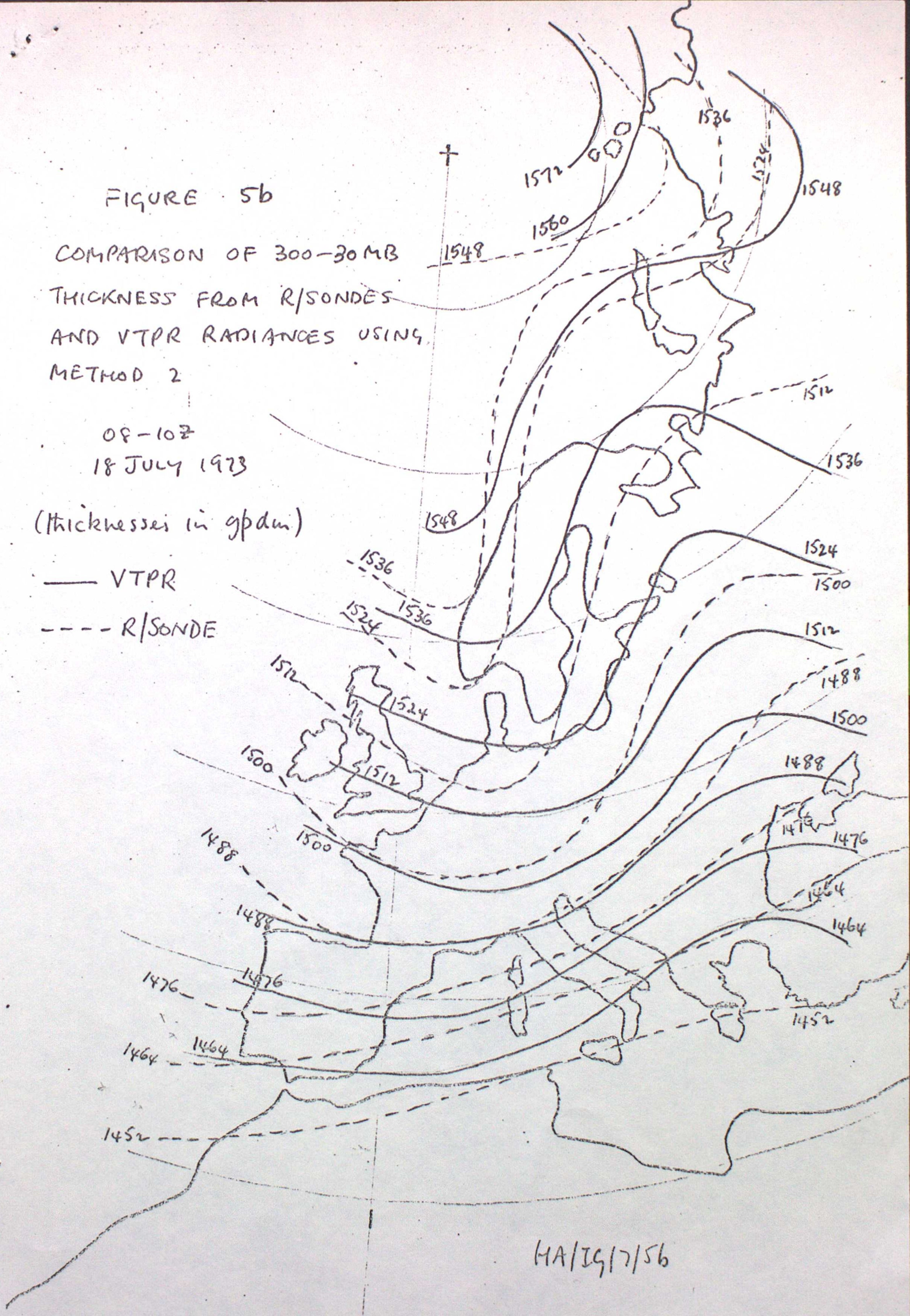
COMPARISON OF 300–30 MB THICKNESS FROM R/SONDES AND VTPR RADIANCES USING METHOD 2

08–10Z
18 JULY 1973

(thicknesses in gpdm)

—— VTPR

- - - - R/SONDE




HA/IG/7/5b

FIGURE 5c

COMPARISON OF 300-30MB THICKNESS FROM R/SONDES AND VTPR RADIANCES USING METHOD 3

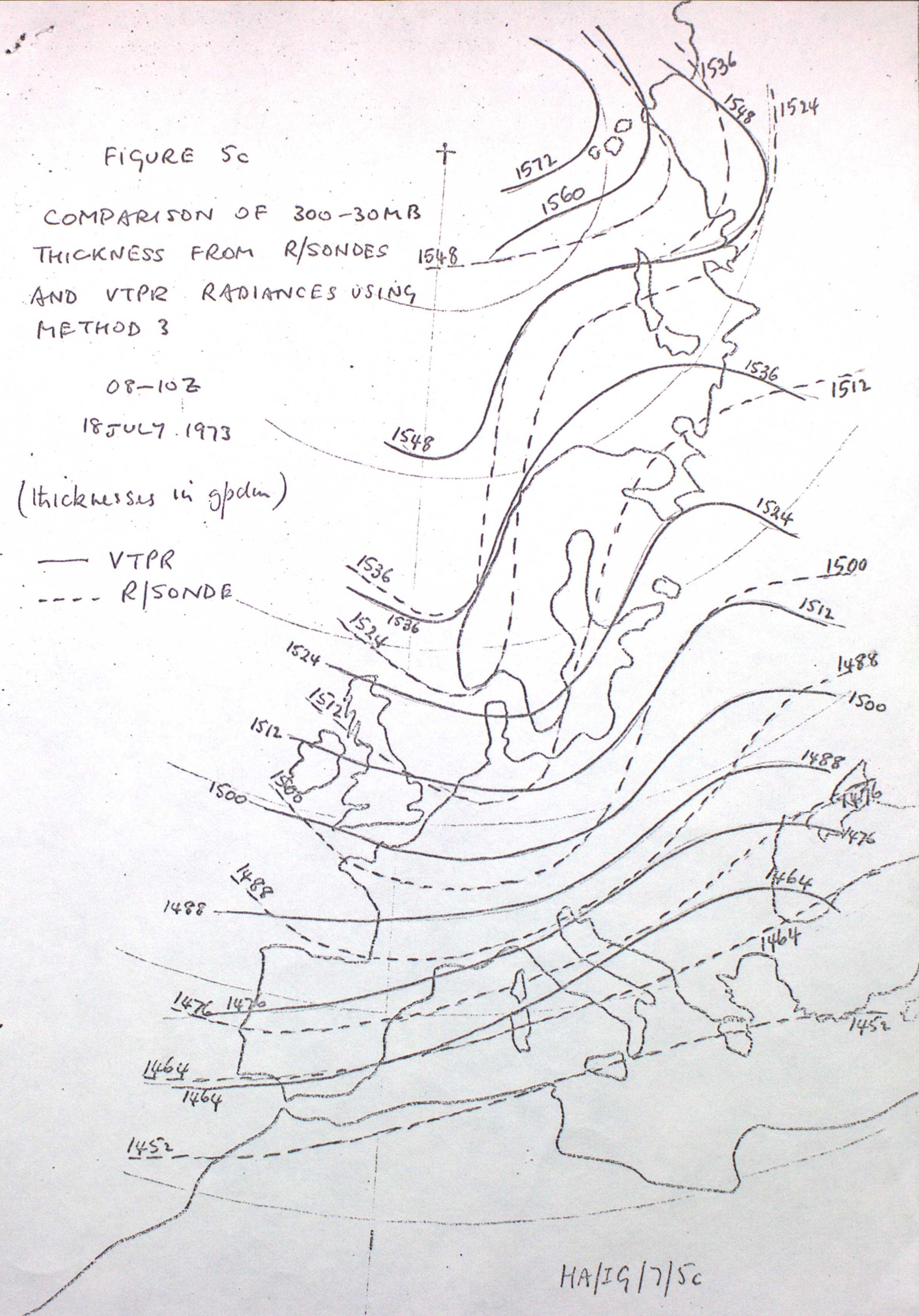
08-10Z

18 JULY 1973

(thicknesses in gpdm)

—— VTPR

- - - - R/SONDE




HA/IG/7/5c