

LONDON, METEOROLOGICAL OFFICE.

Met.O.19 Branch Memorandum No. 24.

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from satellite infra-red radiances. By
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London, Met. Off., Met.O.19 branch Mem.No.24,
1975, 31cm.Pp.34, pls.9.23 Refs.

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7120874

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November 1975

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RETRIEVAL OF METEOROLOGICAL INFORMATION FROM

SATELLITE INFRA-RED RADIANCES.

B. R. Barwell and F. Rawlins.

1. INTRODUCTION

For a number of years vertical temperature profiles of the atmosphere have been deduced operationally from satellite data in the U.S. by the National Environmental Satellite Service (NESS), a department of the National Oceanic and Atmospheric Administration (NOAA). These profiles have been distributed worldwide but in the experience of the Meteorological Office the retrieved soundings ('SIRS' soundings) have been found to be somewhat variable in quality both in space and time. This variability is doubtless connected with the details of the considerable amount of processing required to convert satellite measured radiances into atmospheric temperatures. From time to time alterations are made to the retrieval scheme some of which may be small and have little effect on the results while others may be more significant such as the introduction of a new temperature profile retrieval method. The details of such changes are not generally available until some time after the change has been made and the effects on the deduced temperature soundings are not known in advance.

In view of this a computer program to process 'raw' satellite radiances has been written for use within Met O 19 using NESS work as a basis. With this program some experience has been gained in understanding the advantages and disadvantages of the various methods used in extracting useful meteorological information from satellite infra-red data. This report discusses the computations involved and the methods available to perform them, and identifies some of the good and bad points that have arisen from experience during the development stages of the Met O 19 program. It is hoped that this report will be followed some time in the future by a second report in which the quality of the retrieved information will be compared with more conventional data

with a view to making the best possible use of the former in forecasting. An outline of plans for future use of the computer program is given in the conclusion of this report. It is expected that much of the experience gained with the program will be useful in the analysis of data from the Tiros Operational Vertical Sounder (TOVS) instruments to be flown on the TIROS-N series of satellites. During 1978, data from the TOVS instruments will replace the current Vertical Temperature Profile Radiometer (VTPR) data as the source of radiance information for operational satellite temperature soundings.

VTPR instruments have been flown on the NOAA series of satellites since NOAA-2 was launched in October 1972 and have been the source of operational data since then. Section 2 of this report briefly describes the VTPR instrument and the data from it currently available in the Meteorological Office together with the sources of other data such as first guess fields used in the retrieval process. A knowledge of the atmospheric transmittances for each channel of the instrument is vital for many retrieval methods; section 3 describes how they can be calculated. After a discussion of how the measured radiances may be treated to remove the effects of cloud, sections 5 and 6 describe methods of retrieving temperature and water vapour profiles respectively. Although NESS retrieve water vapour soundings, they do not consider the results to be reliable enough to include in the transmitted SIRS soundings. Section 7 goes beyond NESS work and looks at the possibilities of extracting information on cloud heights and amounts from the VTPR channels which are most affected by clouds. Finally, looking back over the entire retrieval process there is a brief discussion of how errors in one part can affect those in a later part and the main needs for improvement are outlined. Further information about much of the work described here can be found in McMillin et al.(1973) which describes the VTPR instrument and the NESS retrieval scheme as it stood at the time. Occasionally we shall refer to other work which, though not applicable to VTPR data will be useful in connection with TIROS-N.

2. VTPR DATA

2.1 VTPR instrument

The VTPR is an 8-channel scanning radiometer designed to provide information about atmospheric temperature profiles and water vapour content operationally on a global scale. The first one was flown on the NOAA-2 satellite and similar instruments have been flown on subsequent NOAA satellites. Since 1972 they have provided the data on which the operational satellite temperature profiles prepared by the U.S. have been based replacing the earlier Satellite Infra-Red Spectrometer (SIRS) instruments flown on NIMBUS-3 and NIMBUS-4. A description of the VTPR instrument is given by Schwalb (1972).

The eight channels of the VTPR consist of six channels in the 15 micron (15μ) carbon dioxide absorption band for temperature profile sounding, one channel at about 19μ for water vapour sounding and a 'window' channel centred near 12μ for sensing surface and/or cloud top temperature. Details of the central wavenumbers of each of these filters for the VTPR instrument on NOAA-2, and the reference numbers of the channels which will be used throughout this report are given in table 1. The half-widths of the filter profiles range from 4 cm^{-1} to 16 cm^{-1} with most channels around 10 cm^{-1} . Further details are given in McMillin et al. (1973). Typical weighting functions for channels 1 to 6 are shown in figure 2 which is described in more detail in section 2.3.

Figure 1 shows part of the VTPR scan pattern. The instrument scan consists of 23 equal steps in viewing angle out to 30.3° either side of the sub-satellite track which, at the orbital altitude of 1464 km. corresponds to a width of 1876 km. The width of the individual fields of view varies from 57 km. directly below the satellite to 91 km. at the extremes of the scan as shown in the figure. Radiances are measured for all eight channels for each of the 23 locations of the scan and a complete scan cycle takes 12.5 seconds during which the sub-satellite point advances a distance of 73 km. The satellite is in a sun-synchronous orbit giving complete coverage of the earth's surface at latitudes greater than 49° . Nearer the equator

successive orbits do not overlap, and at the equator itself the gap has its maximum value of about 11° of longitude or 1200 km. (measured parallel to the equator).

For the purpose of retrieving temperature profiles the individual fields of view or 'spots' are grouped in larger 'boxes' as indicated in figure 1. Eight consecutive scans make up three such boxes containing either 56 spots (7×8) for boxes centred on the sub-satellite track or 64 spots (8×8) for those on either side. They measure approximately 500×600 km. and 700×600 km. respectively. Two sets of three boxes are shown in the figure. From the radiances for the spots in any particular box a single set of cloud-free radiances is determined from which mean temperature and water vapour profiles are deduced for the box. Temperature profiles are thereby produced in rows of three with a separation of about 600 km. The mean viewing angle is taken as zero for the centre box and $23^{\circ} 47'$ for the outer boxes for the purpose of calculating the atmospheric transmission profiles for the channels.

2.2 Available VTPR data

VTPR data consisting of raw radiances are archived in the U.S. and are available from the National Climatic Center, Asheville, North Carolina. The Meteorological Office has copies of the archive tapes for the periods 16 - 20 July 1973 and 20 February to 3 March 1974, and data for the first of these two periods has been used in the present study. The archive tapes also contain a considerable amount of processed information including sea surface temperatures but the only data of interest for the present work are the raw radiances and the latitudes and longitudes of the boxes. Archived data covers the whole surface of the earth but we have followed U.S. practice in attempting to retrieve temperature profiles over sea areas only. Over land the uncertain surface albedo combined with topography and the rather more variable surface temperature pose extra problems for retrievals. Land areas generally have a much better radiosonde coverage anyway.

Further VTPR data will be obtained from the direct readout facility at Lasham and will be available for processing shortly after being received. From this data, retrieved soundings and thickness charts for the N. Atlantic will be produced in near real time. At present it is hoped to receive data for one day from Lasham about once per week to allow time for the results to be assessed and improvements in processing methods to be tested.

2.3 Other data

As well as satellite radiances a number of other pieces of information are required for the retrieval program. The set of height or pressure levels at which the temperature and water vapour profiles will be expressed is one of these. Ultimately the standard radiosonde levels are probably the most useful ones to express the results but they are too widely spaced to get the best out of the temperature retrieval process. A commonly used scale for the levels is one which is linear in log (pressure) which has the advantage of spacing the levels at roughly equal height intervals, but for present purposes a scale with a smaller spacing in the troposphere (where most of the weighting functions lie) and greater spacing in the stratosphere is more suitable. Following U.S. work we have used a set of 100 levels ranging from 1000 mb. (assumed surface pressure) to 0.01 mb. in equal steps of $p^{2/7}$. The pressure at every fifth level is given in table 2 to give some idea of the distribution in the vertical; note that about half the levels are below 100 mb. Using this set of levels, the weighting functions for channels 1 to 6 normalized to unit area are shown in figure 2. They were calculated using the methods described in section 3 for a tropical temperature profile with a mean water vapour profile but they are not strongly dependent on the profiles used.

Sea surface temperatures are required for the elimination of the surface contribution to the measured radiances as explained in section 5.1. These can be obtained from a high resolution infra-red window channel such as that on the Scanning Radiometer (SR) or Very High Resolution Radiometer (VHRR)

instruments also flown on NOAA satellites since NOAA-2 (Salter 1975), but for the 4-day period in July 1973 for which we have VTPR data, sea surface temperatures were collected from ship reports in the North Atlantic. From an analysed chart of these temperatures, mean sea surface temperatures can be determined for latitude-longitude boxes arranged to be approximately the same size and shape as the VTPR boxes. The temperature used is then a value interpolated from the four sea boxes nearest to the centre of the VTPR box (May 1975). Areas other than the North Atlantic have not been studied very much and the sea surface temperatures on the archive tapes have been used as they are the most convenient.

We will briefly refer to another method of sounding sea surface temperatures which, although unsuitable for use with VTPR data, will be usable on the next generation of operational temperature sounders to be launched on the TIROS-N satellites. This method requires simultaneous radiances in two window channels at different wavelengths (e.g. 3.7μ and 11μ) and relies on the very different variation of Planck function with temperature in these channels. When viewing a uniform cloud-free scene both channels record the same equivalent black body temperature but if there is partial cloud cover the temperatures do not agree. Thus clear areas may be identified and surface temperatures deduced. For details see Smith, Hilleary et al. (1974) or Smith, Woolf et al. (1974).

In the infra-red the sea radiates almost like a black body and an emissivity of 99% has been assumed as a mean value for the entire globe. Over land the emissivity varies with the type of surface which is the main reason why retrievals are confined to sea areas.

2.4 First guess profiles

In order to generate weighting functions for the VTPR channels, initial estimates of temperature and water vapour profiles are required before final values of these quantities are retrieved from the data. These profiles may also be used as first guesses or mean profiles in the retrieval processes

themselves and there may be a requirement that they are representative of the local climatological mean. The United States Standard Atmosphere Supplements, 1966 are a convenient source of mean temperature profiles for this purpose. These consist of a mean profile for latitude 15° and separate summer and winter mean profiles for higher latitudes at 15° intervals. They have been used as far as 60°N with linear interpolation to provide a first guess for the latitude of the satellite sounding. Interpolation reduces the problems associated with a discontinuous change of first guess at latitude boundaries. Previous experience without interpolation when using NIMBUS-5 data resulted in contour and thickness charts which showed evidence of a 'step' in values at these boundaries.

The first guess water vapour profile used depends on the water vapour retrieval method used (see section 6). Initially, while working with a simple retrieval method a 10-year mean, mid-latitude, ocean mixing ratio profile for July was used as the first guess. Later, the more complicated retrieval method used by NESS was used and as this requires some statistics on the correlation between temperature profiles and water vapour profiles a convenient first guess may be deduced from these statistics and the first guess temperature profile. For further details, refer to section 6.2.

3. ATMOSPHERIC TRANSMITTANCES AND WEIGHTING FUNCTIONS

3.1 Background

The intensity of radiation measured by the i^{th} channel of the VTPR is given by the radiative transfer equation,

$$R_i = \epsilon \tau_{oi} B_i(T_o) + \int_{\tau_{oi}}^1 B_i(T) d\tau_i \quad (3.1)$$

where R is measured radiance, B is Planck function, τ is the transmittance between a level in the atmosphere and the satellite, T is the temperature and ϵ is surface emissivity. The suffixes 'i' and 'o' refer to channel number and surface conditions respectively. The integration through the atmosphere is easier to handle if written in terms of a vertical scale related to pressure

rather than transmittance. For example, if this scale is $p^{2/7}$ which we shall denote 'y',

$$R_i = \epsilon \tau_{oi} B_i(\tau_o) + \int_0^{y_o} B_i(\tau) \left(- \frac{d\tau_i}{dy} \right) dy. \quad (3.2)$$

The Planck function profile appears convoluted with $(- \frac{d\tau_i}{dy})$ which is consequently known as the weighting function. (The minus sign has been included since the function would otherwise be negative). These are the functions shown in figure 2; one for each channel.

Perhaps the most accurate way to calculate the transmittances is to integrate the absorption line by line over the wavenumber range covered by the channel filter using, for example, McClatchey et al. (1973) as a source of line parameters. A program for this type of computation is available in Met O 19 but because of the number of spectral lines and the difficulty of the numerical integration, the computing time involved makes line-by-line calculations out of the question for operational work. Smith (1969) overcame this problem by performing line-by-line calculations for carbon dioxide and water vapour over 5 cm^{-1} ranges for various conditions of pressure, temperature and quantity of absorbing gas present. Regressing the results against the parameters varied, a set of regression coefficients was obtained for each 5 cm^{-1} over the range investigated from which transmittances can be found quickly and easily though less accurately. Although this still leaves the problem of applying the results to a non-uniform atmosphere the idea of using the detailed spectral calculations as a basis for a semi-empirical but much quicker computation of τ_i has been generally used for satellite temperature sounding work.

The subroutines for computing atmospheric transmittances are the same as those used by NESS and were provided by them together with the necessary data to use them. The effects of carbon dioxide, water vapour and ozone are taken into account separately and combined by multiplication:

$$\tau_{\text{total}} = \tau_{\text{CO}_2} \times \tau_{\text{H}_2\text{O}} \times \tau_{\text{O}_3}, \quad (3.3)$$

which is possible since the spectral lines of any two components do not generally coincide with each other. We will therefore deal with each component separately.

3.2 Carbon dioxide

Carbon dioxide transmittances are based on the detailed computation of transmittances for the U.S. Standard Atmosphere, 1962 and for atmospheres warmer or colder by 10, 20 or 30°C. From these hypothetical atmospheres a set of coefficients is deduced which can be used to adjust the standard atmosphere transmittances to values applicable to any given temperature profile. As the method has apparently not been published exact details are uncertain. Because of the different viewing angle for the outer VTPR boxes a different set of coefficients must be computed for an angle of 23° 47'. No allowance is made for the small carbon dioxide absorption in channels 7 and 8.

3.3 Water vapour

Transmittances for water vapour are computed using a method similar to that used by Smith mentioned in section 3.1 but using more terms in the regression equation. Rather than integrate over 5 cm.⁻¹ ranges the original transmission spectrum has been convoluted with the filter profile to give a single set of regression coefficients for each channel. The transmittances from the regression equation are applied to an inhomogeneous atmosphere by treating each slab (i.e. region between adjacent levels) as homogeneous. The transmittance for the (n+1)th level is found by replacing the slabs above the nth level by a uniform path whose transmittance is unchanged from the already calculated nth level value but whose pressure and temperature are that of the (n+1)th slab. The atmosphere is then uniform down to the (n+1)th level and the regression equation gives the transmittance for this level directly. In this way transmittances are computed by working down through the atmosphere from one level to the next. Details are given by Weinreb and Neuendorffer (1973).

As a result of experiments on water vapour, Burch (1970) reported that the absorption coefficient around 8-14 μ appeared to show some dependence on the partial pressure of the vapour rather than the total gas pressure as would be the case for the normal line spectrum. Bignell (1970) also found the

same effect and suggested water vapour dimer molecules $(H_2O)_2$ were responsible. Using 'p' and 'e' for total and partial pressure respectively, Bignell treated the absorption coefficient as the sum of the two components,

$$k = k_1 p + k_2 e \quad (3.4)$$

where the first term is the usual line spectrum contribution and the second is the 'dimer' absorption. Though measurements are difficult to make, Burch gave curves for k_2 at three temperatures between room temperature and $120^\circ C$, but the behaviour at typical atmospheric temperatures is a little uncertain though important as k_1 has a negative temperature dependence. The NESS subroutine uses a simple fifth power law dependence integrated through the atmosphere. The absorption due to the second term in equation (3.4) may then be written

$$\log \tau_e = K_i \int_{p_1}^{p_i} p q^2 T^{-5} dp \quad (3.5)$$

where τ_e is the transmittance between pressure level p_1 and the top of the atmosphere due to the partial pressure dependent component only; q is the water vapour mixing ratio, p and T are pressure and temperature and K_i is a constant for each channel. τ_e calculated from this equation is multiplied by the transmittance for spectral lines to obtain the total water vapour transmittance.

The effect of water vapour is allowed for in all eight channels though it plays a minor role in channels 1 to 4. In 5 and 6 water vapour is responsible for the pronounced falling-off of the weighting function near the ground (see figure 2). The 'dimer' component is important in the window channel but has a small effect in the other channels where carbon dioxide or water vapour line spectra dominate. In channels 7 and 8 water vapour is taken to be the only significant absorber.

3.4 Ozone

The effect of ozone absorption is taken into account for channels 1 to 6. As the effect is small transmittances for an average ozone profile have been

computed and applied for all latitudes and seasons. The computation was carried out using a line-by-line method for upper levels and a band model nearer the ground.

3.5 Weighting functions

Equation (3.2) can be approximated to the N-level finite difference equation,

$$R_i = \epsilon \tau_{oi} B_i(T_o) + \sum_{j=1}^N W_{ij} B_{ij} \quad (3.6)$$

where suffix 'j' refers to level. The W_{ij} are the values of $(-\frac{d\tau_i}{dy})$ for slabs of the atmosphere centred on each level and the set of W_{ij} for a given channel makes up the weighting function for that channel. Values of W_{ij} are computed from the transmittances by means of a polynomial interpolation to find the transmittances for the top and bottom of each slab. The weighting function is then the set of differences between these pairs of transmittances. Since the bottom of one slab is the top of the next, they are automatically normalized,

$$\sum_{j=1}^N W_{ij} + \tau_{oi} = 1. \quad (i = 1, 2, \dots, 8) \quad (3.7)$$

For the 100 levels used, the bottom slab is only half as thick and is not centred on the 100th level (i.e. the ground). To allow for this, when using the weighting functions to compute radiances the Planck function for level 100 is adjusted to a value more representative of the mean for the smaller slab.

4. DETERMINATION OF CLEAR RADIANCES

4.1 The cloud problem

Satellite measured radiances are generally contaminated by clouds whose effect must be removed to give 'clear' radiances required for the retrieval of temperature profiles. The simplest cloud model is one in which there is a single cloud layer covering a fraction 'n' of the sky radiating like a black body at the cloud top temperature. The measured radiances are made up of the contributions from the clear and cloudy regions of the field of view:

$$R = nR_1 + (1-n)R_0 \quad (4.1)$$

where R is the measured radiance in any channel and R_0 and R_1 , are the radiances which would be measured for the same channel in a cloud-free area and a completely cloudy area respectively. (If the clouds are assumed to radiate like a grey body with emissivity ϵ equation (4.1) applies with ' n ' replaced by ' $n\epsilon$ '. We have assumed $\epsilon = 1$.) This simple model is used both for clearing the radiances and for the extraction of cloud cover information (see section 7).

In the absence of a value deduced from the satellite (see section 4.3) an estimate of the clear radiance in one channel is required for removing cloud effects. The atmospheric window channel is the most suitable one to choose both because the calculated radiance in this channel is less dependent on the first guess temperature and water vapour profiles used and because it is affected significantly by clouds at any level in the atmosphere. Thus we calculate a clear radiance for channel 8 using the first guess profiles with the appropriate sea surface temperature and weighting functions computed as in section 3.

4.2 Simple regression method

Writing equation (4.1) for channel 8, (indicated by dashed quantities),

$$R' = nR_1' + (1-n)R_0' \quad (4.2)$$

where the ' n ' will be the same as that for any other channel radiance for the same spot. Eliminating the cloud amount from equations (4.1) and (4.2),

$$R - R_0 = \left(\frac{R_1 - R_0}{R_1' - R_0'} \right) (R' - R_0') \quad (4.3)$$

R_1, R_1' , and R_0 are unknown but we now assume that they are all constant over any given VTPR box so that the equation becomes

$$R - R_0 = K(R' - R_0') \quad (4.4)$$

where K is a constant. This indicates that a plot of R against R_1' should

be a straight line passing through the point (R_0, R_0^1) . With an estimate of the clear channel 8 radiance (R_0^1) the clear radiance in the other channel (R_0) may be read off this line.

Figures 3 to 5 show examples of the regression lines for channels 5 and 7 for two boxes in the North Atlantic on the same orbit. For the more northerly box (54.3N, 337.3E - figure 4 and top of figure 3), the regression line is quite well defined. This is the type of plot generated by boxes with medium or high level cloud and a wide range of cloud amounts in individual spots giving a wide variation in the measured radiances. Not all cases are as straightforward as these, however. The box at 41.8N, 346.0E (figure 5 and bottom of figure 3) is an example of a case where the plotted points tend to form a cluster. Whether due to an almost complete absence of cloud over the box or the presence of low clouds which do not affect the radiances significantly, it is clear that the regression line is less well defined, especially in figure 5 where the scatter of the points indicates some non-linear variation. Such variation may come from several sources among which are variations in water vapour and temperature profiles and in sea surface temperature over the box, variations in cloud top temperature (or the presence of more than one level of cloud) and the failure to allow for the different viewing angle over the box.

In order to estimate the reliability of the values of R read off the regression lines, estimates of the standard deviation of the error in the intercept with the clear radiance on channel 8 were computed. Assuming the deviation of the points from a straight line relationship is due only to a random error in R, the standard deviation ' σ ' is given by

$$\sigma^2 = \left(\frac{1-r^2}{N-2} \right) \left(s^2 - [R_0' - \bar{R}']^2 \left[\frac{s}{s'} \right]^2 \right) \quad (4.5)$$

where r is the correlation coefficient between R and R^1 , N is the total number of spots, s and s^1 are the r.m.s. deviations of R and R^1 , R_0^1 is the estimated clear radiance for channel 8 and \bar{R}' is the mean channel 8 radiance. Typical values of σ are in the range zero to one radiance unit with larger values

for bad cases (e.g. 1.83 for figure 5). Channels 1 to 3 generally show smaller values of σ than the other channels because the radiances are smaller and less variable being less affected by cloud. In fact the radiance plots for these channels are similar to those illustrated but the regression line usually has a much smaller slope.

It should not be thought from what has been said that clear radiances accurate to one or two radiance units can necessarily be deduced. Equation (4.5) completely ignores any errors in channel 8 measurements whereas the instrumental noise in this channel is as great as in most of the others. In particular, the estimated clear radiance in channel 8 is assumed to be exact whereas in practice values are commonly obtained which appear to be higher than that suggested by the range of measured radiances. For example, for the case shown in figures 3 (bottom) and 5 the estimate was 112.5 radiance units; several units higher than any of the measured radiances. Similarly for the other two graphs shown the estimate was 103.1 radiance units. It may have been the case that no individual observations were completely cloud-free in these two boxes but the frequency of occurrence of this effect suggests that the initial estimate of R_0^1 may be at fault. It is considered that this estimate is one of the main weaknesses of the current retrieval scheme especially as it affects both retrieved temperatures and water vapour profiles. Discussion of the effects on these quantities will be left until the conclusion of this report after retrieval methods have been dealt with. At this stage we will simply point out that errors in the first guess profiles and sea temperature and in the calculation of the weighting functions can all affect R_0^1 . The first guess temperature profile may be a little warm near the ground as the standard atmospheres are intended to be representative over land and sea instead of sea alone, but this should not affect the window channel by more than about one or two radiance units. Similarly the first guess water vapour profile may be too dry because of the autumn sample used (see section 6.2) but again the effect should be small. Sea temperatures from analysed charts should be fairly accurate but errors in the weighting functions are

uncertain as indeed is the total error in R_0^1 itself.

4.3 Other methods

The method used by NESS to clear the radiances involves comparing the radiances in any channel with those in channel 8 for two adjacent spots. (McMillin et al. 1973) Four equations of the form of equation (4.1) can be written down, one for each channel in each spot. Assuming that the cloud top level is the same for both spots, the unknown cloud amount for each spot and the 100% cloudy radiance for each channel can be eliminated leading to an equation connecting the clear radiances in the two channels. This equation states that on the radiance plot the two points corresponding to the measured radiances for the spots and the point corresponding to clear conditions all lie on a straight line. Having an estimate for R_0^1 it is then possible to deduce a value of R_0 for each pair of adjacent spots. These need checking to remove unreliable values and the distribution of the remainder which may contain up to 196 values requires smoothing to pick out the best value. Although this method can allow for differences in cloud level, air and sea temperatures and viewing angle over each box, the initial estimate of the clear window channel radiance is still required. As this defect, regarded as the weakest point of the regression method described above is still present we have preferred to use the straightforward regression which uses less computer time.

The method of obtaining sea surface temperatures from high resolution window channel data outlined in section 2.3 can also provide clear window channel radiances. These do not depend on first guesses or weighting function calculations but come direct from the radiance data itself. Perhaps this is the best way to deduce an intercept for the regression line but as mentioned before, two window channels are required. The method is therefore not capable of being used with VTPR data but may be useful for the TIROS-N temperature sounders to be launched in a few years time.

5. TEMPERATURE PROFILE RETRIEVALS

5.1 Preliminary calculations

From the clear radiances deduced by the methods of section 4, the surface

contribution term is subtracted from each of the temperature sounding channels to determine the atmospheric contribution R_{ai} ;

$$R_{ai} = R_i - \epsilon \tau_{oi} B(\nu_i, T_o) \quad (i=1,2,\dots,6) \quad (5.1)$$

where ϵ is the surface emissivity, τ_{oi} is the transmittance of the entire atmosphere for channel 'i' and T_o is the surface temperature. Thus sea surface temperature information is removed from the radiances at this stage rather than being retrieved with the temperature profile as a kind of 101st level. The justification for this step is that the sea surface temperature is likely to be known more accurately from ship reports and available mean sea temperature charts than it could be determined by the retrieval process. The calculation of τ_{oi} can be performed with sufficient accuracy using the first guess temperature and water vapour profiles. For the worst case (a dry atmosphere) the surface contribution to the radiance is typically 20%, 10% and 1% for channels 6, 5 and 4 and is invariably zero for channels 1 to 3.

At any given location where satellite observations are made there is a single temperature profile, but the Planck function profile which appears in the radiative transfer equation differs from channel to channel because of its dependence on wavenumber. It has been found convenient in most retrieval methods to work with radiances 'normalized' to a common 'reference' wavenumber. By this means it is possible to use a single Planck function profile at the reference wavenumber which may be retrieved and converted to an unambiguous temperature profile. The normalization process requires care if the channel wavenumbers cover a wide range (Smith, Woolf et al. (1974)) but for VTPR channels 1 to 6 the range is small. Normalization can then be carried out by using the Planck function in reverse to find the brightness (black body) temperature for each radiance, which can then be converted to the radiance at the reference wavenumber which has the same brightness temperature.

Mathematically this is expressed

$$T_{Bi} = c_2 \nu_i / \log \left(\frac{c_1 \nu_i^3}{R_{ai}} + 1 \right), \quad R'_{ai} = c_1 \nu^3 / \left[\exp \left(\frac{c_2 \nu}{T_{Bi}} \right) - 1 \right] \quad (5.2)$$

where R_{ai}^1 is the normalized value of R_{ai} and ν is the reference wavenumber which for VTPR channels is conveniently taken as 700 cm^{-1} . To simplify the notation in the rest of this section, B_j will be used for the Planck function at reference frequency for level 'j' and R_i will now represent the normalized radiance in channel 'i' with the surface contribution removed. Equation (3.6) for channels 1 to 6 then becomes

$$R_i = \sum_{j=1}^N w_{ij} B_j \quad (i = 1, 2, \dots, 6) \quad (5.3)$$

which can be expressed in matrix form as

$$R = W^T B \quad (5.4)$$

where R and B are column matrices of the R_i and B_j , W is the matrix of weighting functions stored columnwise and the superscript 'T' indicates a transposed matrix. An inversion method is now required to determine B from a set of radiances R.

5.2 Inversion methods

Early inversion methods were summarised by Rodgers (1966) and a more up to date review has been published by Fritz et. al. (1972). The basic problem is that equation (5.4) requires a large number of temperatures to be determined from a small number of radiances. There is therefore no unique solution and some constraint must be applied to decide which one to choose. A further difficulty arose when attempts were made to build up the temperature profile from a small number of patterns (e.g. polynomials or, better, eigenvectors of a temperature profile covariance matrix), namely that solving (5.4) using the same number of patterns as channels gave profiles with wild oscillations (Wark and Fleming 1966). The reason is that the similarity in shape and in some cases considerable overlap of the weighting functions is responsible for ill-conditioning in the solution. Attempts to 'tie down' the solution to something more realistic have involved using less patterns than radiances together with least squares fitting to the radiances, and finding a solution which minimises a combination of the squares of radiance errors and the

deviations from a guessed solution (Rodgers 1966, Twomey 1963).

It is convenient to express radiances as deviations from a set of mean radiances \bar{R} obtained from some mean profile \bar{B} (a standard atmosphere or first guess etc.). If the deviations from these mean values are denoted by ΔR and ΔB then we can use instead of equation (5.4),

$$\Delta R = W^T \Delta B \quad (5.5)$$

formed by subtracting the equation $\bar{R} = W^T \bar{B}$. The majority of retrieval methods involve the determination of a matrix P to convert radiances to Planck function profiles according to

$$\Delta B = P \Delta R, \quad (5.6)$$

and differ only in the criteria on which the derivation of P is based.

Perhaps the most fundamental method of applying a regression technique to the inversion problem is to obtain a sample of known temperature profiles and corresponding satellite radiances and determine the P -matrix which minimises the sum of the squares of the errors in the retrieved Planck function profiles (Rodgers 1966, Fritz et al. 1972). If DB is the matrix of known ΔB profiles stored columnwise and DR is the matrix of sets of radiance deviations also stored columnwise, the resulting optimum value of P is given by

$$P = DB DR^T (DR DR^T)^{-1}. \quad (5.7)$$

This method does not require any knowledge of weighting functions but involves the collection of a sample of radiosonde (or possibly rocketsonde) profiles and coincident satellite observations. Such coincidences in both space and time are not as common as one might imagine so that quite a lot of work may be involved in building up a representative sample. However, once the sample has been obtained P may be calculated once and for all and the retrieval process (5.6) is very fast.

The 'maximum probability' method of Rodgers (1970) applies probability theory to the solution of equation (5.5) while making the best use of atmospheric statistics. Regarding ΔB - profiles at N levels as points in N -dimensional

space and assuming these points are normally distributed with a mean and covariance determined from a sample of radiosonde or rocketsonde profiles, the most probable profile for ΔB given a set of radiance deviations ΔR is

$$\Delta B = C_B W (W^T C_B W + C_E)^{-1} \Delta R \quad (5.8)$$

where C_B and C_E are the covariance matrices for Planck function profiles and instrumental noise (assumed known from pre-launch measurements) respectively. As this method does not require radiosonde profiles to be coincident with satellite measurements, collection of representative samples is easier. Also different C_B matrices may be calculated representing different areas of the globe such as different latitude bands. Equation (5.8) can also be derived from (5.7) assuming a knowledge of the weighting functions but it is important to remember that whichever derivation is preferred, it is required that \bar{B} be the mean B-profile for the sample used to calculate C_B and \bar{R} must be the corresponding set of mean radiances computed from \bar{B} and W . Once again equation (5.8) is easy to use as the matrix inversion can be performed in advance leading eventually to a fixed P-matrix (see equation (5.6)) for each geographical region over which a particular C_B applies. Among the limitations of the maximum probability method is the assumption of a normal probability distribution in B-space which may not be applicable during atmospheric disturbances such as sudden warmings. Another limitation occurs in the calculation of C_B from sonde data. As well as recording true atmospheric covariances, spurious high values may also appear in C_B due to systematic differences between different types of sonde and other non-random differences. There is therefore a basis for making a simple assumption about the form of C_B rather than collecting atmospheric statistics. This is done in the minimum information method described below which has been used in the past by the U.S. to produce operational soundings.

5.3 Smith's iterative method

Before discussing the minimum information method we will deal with an older iterative method due to Smith (1970) which we have also used. This method involves the following steps using the first guess profiles for the first iteration. (A superscript refers to iteration number).

- (1) From the Planck function profile for the n^{th} iteration (B^n) compute the cloud-free radiances (R^n).
- (2) For each channel compute a new Planck profile (B_i^{n+1} , $i = 1, 2, \dots, 6$) by adding a constant to each level sufficient to fit the measured radiance (R_i) exactly; i.e.

$$B_i^{n+1} = B^n + (R_i - R_i^n). \quad (5.9)$$

- (3) Combine the profiles into a single profile using the weighting functions to weight corresponding levels in different profiles; i.e. for each level 'j',

$$B_j^{n+1} = \left(\sum_{i=1}^6 W_{ij} B_i^{n+1} \right) / \left(\sum_{i=1}^6 W_{ij} \right). \quad (5.10)$$

- (4) Check B^{n+1} against B^n . If satisfactory convergence is not achieved repeat the steps from (1). If it is, convert B^{n+1} to the final temperature profile.

(The method described here differs slightly from that described in Smith's original paper).

Smith's method is simple to program and to use and produces a sensible-looking profile even from a ridiculous first guess (e.g. an isothermal profile at 0°K!). It requires no atmospheric statistics (though this may detract from its performance) and can serve as a useful basis on which to compare other methods. Perhaps the most noticeable disadvantage of Smith's method is the slowness of convergence of the iterative procedure - the profile tends to 'drift' to final solution. Probably because of this drift Smith proposes what would otherwise seem a severe convergence criterion;

$$|R_i^{n+1} - R_i^n| \leq 0.0001 R_i. \quad (i = 1, 2, \dots, 6) \quad (5.11)$$

Using this criterion retrievals have been found to require 40 or 50 iterations.

5.4 Minimum information method

The minimum information method can be considered a special case of the maximum probability method. It avoids any reliance on sondes and instrumental noise measurements by assuming that the two covariance matrices in equation (5.8) are multiples of unit matrices.

$$C_B = \sigma_B^2 I, \quad C_E = \sigma_E^2 I. \quad (5.12)$$

These assumptions lead to the result

$$\Delta B = W(W^T W + \gamma I)^{-1} \Delta R \quad (5.13)$$

where $\gamma = \sigma_E^2 / \sigma_B^2$. A full derivation of this equation is given in Smith, Woolf and Fleming (1972). The value of γ is not very critical as long as it is small (but not zero) and the value 0.001 has been used both in the present study and by other authors (Smith, Woolf and Fleming 1972, Goddard and Hunt 1974).

There has been some disagreement as to whether the minimum information method should be used iteratively. (Iteration involves converting ΔB in equation (5.13) to a B-profile and hence a set of radiances. These differ from the measured radiances by a small amount which is used as the new ΔR in (5.13) to derive a new ΔB .) In the U.S. where this method was used operationally until earlier this year iterations were performed on the grounds that unacceptable radiance deviations may otherwise occur due to an unrepresentative value of γ . It was also stated that as the atmospheric covariance matrix C no longer appears explicitly in equation (5.13), it was no longer essential that the mean profile should be used when calculating ΔB or ΔR , and some other profile (forecast, previous iteration etc.) could be used instead. However, thinking of the minimum information method as a special case of the maximum probability method where, as pointed out in section 5.2 the mean profile must be the mean of the statistics, there seems no reason to deviate from that procedure here. The difficulty is that while the first of equations (5.12) clearly defines the form of C_B , the covariance matrix of Planck function profiles, it says nothing about the mean profile \bar{B} that these

deviations are measured from. In the absence of a mean profile, freedom to choose one's own \bar{B} was assumed and the way was clear for the application of the iteration technique.

We have used the minimum information method without iteration using an estimate of the appropriate climatological mean profile for \bar{B} . The latitude-interpolated standard atmospheres have been used to provide these estimates. The method is easy to use and program and has a rather more firm theoretical basis than Smith's method. For these reasons and because the method has been used operationally by NESS the minimum information method is regarded as the primary retrieval method for use with VTPR data with Smith's method being used only occasionally for comparison purposes etc. The minimum information method is fast: even when used iteratively, convergence to within instrumental noise levels (typically 0.2 radiance units or about 0.2°K brightness temperature) required only three or four iterations at most.

5.5 Discussion

Throughout all the sections on retrieval methods it has been assumed that the weighting functions are known before the temperature profile is calculated whereas they are to some extent dependent on temperature and other quantities unknown at this stage such as the water vapour distribution. This assumption which is common in retrieval methods is not without foundation as the weighting functions are fairly insensitive to small changes in the temperature profile and water vapour affects only those weighting functions which peak low in the troposphere and is only noticeable at the bottom few levels. However to keep these effects to a minimum the weighting functions are calculated from the mean or first guess temperature and water vapour profiles prior to each retrieval.

It is well known that temperature profiles retrieved from satellite radiances cannot resolve small-scale details in the profile because of the broadness of the weighting functions. This means that a retrieval method

will not introduce small fluctuations into a profile but it also means that such small detail will not be removed if it is present in the first guess profile \bar{B} . In cases where real or artificial profiles were used for \bar{B} containing regions of small-scale temperature fluctuations these details were preserved in the retrievals whichever method was used. In view of this it seems preferable to use a smooth profile as the first guess \bar{B} unless there is a good reason for wanting any detail in \bar{B} to be physically present in the retrieval. Averaged profiles such as the U.S. Standard Atmosphere Supplements, 1966 are a convenient source of smooth profiles for this purpose when using retrieval methods where the user is free to choose his own profile for \bar{B} .

When using the minimum information method for retrievals over the North Atlantic it was found that the retrieved temperature profile depended strongly on the first guess profile at the few lowest and highest levels where the weighting functions indicate that the radiances contain little information (see figure 2). Smith's method produced comparatively greater deviations from the first guess in accordance with having many iterations.

Several comparisons of co-located radiosonde and VTPR soundings have so far been obtained. Figure 6 shows the VTPR retrieval for 11Z on 17 July 1973 at 59.3N, 340.0E compared with the radiosonde at 12Z from Ship 'I' (58.5N, 340.8E). The retrieval was performed using the minimum information method with a sea temperature of 283.8°K and is typical of results so far obtained. Temperatures retrieved at low levels have been consistently too high indicating that the first guess profile may be too warm near the ground. This has also produced retrieved water vapour profiles which appear too wet.

5.6 Future work

The two methods used so far have relied upon the subroutines written by NESS to calculate the weighting functions accurately for any given temperature and water vapour profiles. However, NESS themselves have become more concerned

about the accuracy of these calculations and earlier this year they changed from using the minimum information method to a regression method which does not require the computation of weighting functions. The method is similar to that mentioned in section 5.2 (see equation (5.7)) but makes use of eigenvectors of temperature and radiance covariance matrices instead of relating these quantities directly. This method, which is currently being used by NESS to produce the SIRS soundings, is being studied in the branch together with other regression methods such as the direct regression between radiances and thicknesses thereby by-passing the temperature profile. Thicknesses derived from retrieved temperature profiles have generally been found to be in better agreement with radiosonde values than the temperatures are, due to the broadness of the weighting functions.

6. WATER VAPOUR RETRIEVALS

6.1 Background

In temperature profile retrieval work we have tacitly assumed (in the calculation of the weighting functions) that the carbon dioxide mixing ratio has a known constant value at all levels. Knowing the distribution of the absorbing component of the atmosphere we can then determine the temperature profile. In water vapour sounding this situation is reversed: we now assume that the temperature profile is known from channels 1 to 6 and we want to find the vertical distribution of water vapour in the atmosphere. Channel 7 is the only channel designed specifically for this purpose which means that after removing the effect of clouds as in section 4, there is a single radiance available for the derivation of a complete water vapour profile. It is therefore unreasonable to expect to be able to retrieve much detail in the shape of the profile though it may be possible to determine the total water vapour content more accurately. In the following discussion we will use water vapour mixing ratio as the parameter to be determined rather than dew point or relative humidity.

The first method used to derive mixing ratio profiles involved choosing a first guess profile and multiplying the mixing ratio at every level by a constant factor. Using an iterative procedure different factors were tried until a profile was found consistent with the measured clear radiance in channel 7. This simple method which preserves the shape of the first guess profile will not be discussed further except for the following two points which have been retained in the method currently used. Firstly, in temperature retrieval methods it is assumed that the weighting functions, being relatively weak functions of temperature can be computed sufficiently accurately in advance using a guessed temperature profile. For the water vapour channel the situation is different as the weighting function is more sensitive to mixing ratio changes than temperature changes, and the mixing ratio varies over a much wider range. In view of this it is necessary to compute the weighting function anew for each iteration in order to determine an accurate radiance. Secondly, to avoid supersaturation in the retrievals, the mixing ratio at each level is compared with the saturated value and reduced to that value if it has been exceeded.

6.2 Current retrieval method

The method currently used is due to Weinreb and Crosby (1973) and has been used in the past in the U.S. It is assumed that the water vapour mixing ratio profile is correlated with the saturated mixing ratio profile which can be determined from the temperature profile alone. The mixing ratio profile denoted by the column matrix q is assumed to be randomly distributed with mean \bar{q} and covariance matrix C_q . Similarly we define s , \bar{s} and C_s for the saturated mixing ratio profile. The most probable q -profile given the saturated profile s is then given by

$$\hat{q} = \bar{q} + C_{qs} C_s^{-1} (s - \bar{s}) \quad (6.1)$$

where C_{qs} is the cross-covariance matrix of q and s . In general this profile will not agree with the measured radiance. We therefore add a multiple of a given column matrix ϕ to \hat{q} to obtain a final profile,

$$q = \hat{q} + k\phi. \quad (6.2)$$

The constant k is chosen to fit the clear radiance for channel 7 which may be done using an iterative scheme. The best choice for ϕ is the largest eigenvector of C_{res} , the covariance matrix of residual errors of \hat{q} from the true profile. C_{res} is given by

$$C_{res} = C_q - C_{qs} C_s^{-1} C_{qs}^T. \quad (6.3)$$

Values of \bar{q} , \bar{s} , ϕ and the quantity $C_{qs} C_s^{-1}$ appearing in equation (6.1) have all been calculated in advance from a sample of radiosonde data. The sample used consisted of about 300 oceanic and coastal soundings for autumn 1973, and no water vapour was assumed to be present above 300 mb.

The matrix C_s was found to be ill-conditioned causing instability of its inverse when all levels below 300 mb. were used. Stability has been improved by using only nine levels of the temperature profile to compute C_s while retaining all the levels for C_q . Even with this arrangement \hat{q} has occasionally been found to contain negative mixing ratios though this has not happened in the final retrieved profile.

6.3 Results

Since the radiance in channel 7 depends not only on the temperature at each level but also on the concentration of water vapour in higher levels, the variation in radiance with water vapour content is very non-linear. However in general, wet profiles produce lower radiances since the weighting function peaks higher in the atmosphere where temperatures are lower.

In the majority of water vapour retrievals the final profile was wetter than the first guess. This also occurred in the several radiosonde co-locations obtained where the retrieved water amounts were usually too high. This could possibly be because an autumn sample was used for the original statistics which may therefore be too dry. Also, if the first guess temperature profile is too warm, the guessed water vapour profile would be too wet and the clear radiance on channel 7 would be too low.

In most cases two or three iterations are sufficient to fit the observed

radiance. However, in one particularly unfavourable case the computed radiance was always too high even when all of the levels below 300 mb. were saturated, possibly for the reason given above. Also errors in the clear channel 7 radiance would be expected to be relatively high due to the large variability in water vapour amount and the non-linearity of radiance with water vapour.

7. CLOUD RETRIEVALS

7.1 Theory

The effect of clouds on radiances has so far been regarded as a form of contamination but as several channels are significantly affected by clouds it should be possible to extract some information on cloud height and amount from them. Assuming constant cloud-top height, temperature and water vapour profiles and sea surface temperature over a VTPR box, we have as in section 4.1 (equation (4.1)),

$$R = nR_1 + (1-n)R_0 \quad (7.1)$$

for the observed radiance in any channel. With the above assumptions this relation is true for every spot and hence a fractional cloud cover can be determined for each spot from

$$n = \frac{(R - R_0)}{(R_1 - R_0)} \quad (7.2)$$

once the cloud top height and hence R_1 is known. Two cloud retrieval methods have been used both of which assume that all cloud top heights are below 100 mb. and that the cloud emissivity is always 1.0.

7.2 Retrievals using channels 6 and 8

Eliminating n for the two channels most affected by cloud (6 and 8) and using dashed quantities for channel 8, we have for each spot as in equation (4.3),

$$\frac{\Delta R}{\Delta R'} = \frac{R_1 - R_0}{R'_1 - R_0} = \frac{R - R_0}{R' - R_0} \quad (7.3)$$

Taking the average over a VTPR box, the right hand side becomes K , the slope of the regression line for channel 6 plotted against channel 8 (see equation (4.4)).

Using the weighting functions already determined, the cloudy radiances R_1 and R'_1 for each level are calculated and $\Delta R/\Delta R'$ may be plotted against cloud

top level. Then, with the regression determined value of K for that VTPR box the appropriate cloud top level can be read off.

The variation of $\Delta R / \Delta R'$ with cloud top height for two different boxes is shown in figures 7a and 7b. In figure 7a there is no ambiguity. However, if the sea temperature is lower than the temperature of the lower atmosphere or if the temperature profile contains an inversion near the ground, a variation such as in figure 7b can result. The correlation coefficients between the window channels and other channels are used to limit the solution for cloud height. If high correlations for channels 4, 5 and 6 are obtained high cloud is assumed to be present and the higher intercept is taken as the true cloud height (e.g. P rather than Q in figure 7b). The cloud amount can then be determined from equation (7.2) using either channel 6 or 8 but the latter should give the better estimate since this channel is affected by cloud at any level. The value of n for channel 6 can then be used as a check. Ideally, the values from the two channels should be identical.

7.3 Retrievals using all cloud-affected channels

The method described above uses information only from channels 6 and 8. In order to extract the maximum cloud information the remaining cloud affected channels must also be considered. This can be done by comparing the characteristic pattern of the observed radiances with the pattern of cloudy radiances at each level. Writing equation (4.1) in matrix form and including errors (instrument noise, cloud top height etc.) in the matrix E we have

$$\Delta R = \Delta C n^T + E \quad (7.4)$$

where element ΔR_{ij} of ΔR is the difference between the measured radiance for the i^{th} channel and the j^{th} spot and the clear radiance for that channel, and n and ΔC are column matrices of the cloud cover for each spot and the (cloudy-clear) radiance difference ($R_1 - R_0$) for each channel. Minimising the sum of the squares of the elements of E with respect to n and ΔC results in

$$\Delta R n = \lambda^2 \Delta C, \quad (7.5)$$

$$\Delta R^T \Delta C = \mu^2 n, \quad (7.6)$$

where λ^2 and μ^2 are scalars defined by

$$n^T n = \lambda^2, \quad \Delta C^T \Delta C = \mu^2. \quad (7.7)$$

Eliminating n from equations (7.5) and (7.6),

$$\Delta R \Delta R^T \Delta C = \mu^2 \lambda^2 \Delta C \quad (7.8)$$

which shows that ΔC is proportional to an eigenvector of $\Delta R \Delta R^T$. The principal eigenvector is calculated and correlated with computed ΔC matrices for each level, the highest correlation giving the cloud top height. Then from equation (7.6) the matrix of cloud cover can be found. In this method channels 1 and 2 were excluded because they were too high to be affected by cloud. Channel 7 was excluded because of a less linear response to cloud amount. Since the eigenvector method utilizes more data than the previous method and also has no ambiguity in cloud height retrieval, it is to be preferred.

7.4 Results

The basic assumptions of the two methods mentioned do not always hold well resulting in a poorly defined regression line for radiances. In cases where there are two or more layers of cloud for instance some weighted mean values will be produced which have only mathematical significance.

Results when low clouds are retrieved (below about 800 mb.) are very unreliable with cloud amounts often negative or greater than unity. This is related to the difficulty in obtaining accurate clear radiances. Low cloud produces only small radiance differences $R_1 - R_0$ and values of the clear radiances hence become very critical.

Cloud amounts in adjacent boxes show a lack of continuity at the box boundaries in many cases due to the assumption of a constant cloud height over such a large area as a VTPR box. The assumption of taking the cloud emissivity as 1.0 leads to an overestimate in the retrieved cloud amount. An alternative view of the parameter n is cloud amount multiplied by emissivity (see section 4.1).

8. CONCLUSION

8.1 General comments

We have already referred in many of the earlier sections to the likely

sources of error associated with each part of the retrieval process separately but it should be remembered that these errors are not independent of one another. An error at an early stage in the processing can be passed on to later stages and cause other errors. Some of the results obtained so far show evidence of this effect so we will briefly indicate the paths which such errors can follow.

It is thought that errors in the transmittances computed by the NESS subroutines could be the major source of errors in retrievals. This especially applies to the estimate of the clear radiance in channel 8 on which so much of the rest of the retrieval depends. If this estimate is too high as suggested in section 4.2 the clear radiances in nearly all the other channels will be too high since most channels are positively correlated with channel 8. High radiances will lead to temperature profiles which are too warm especially in the troposphere. It will then be necessary to put too much water vapour into the atmosphere to fit the water vapour radiance. Also, if the clear radiances are too high the cloud height will be overestimated and the cloud amount underestimated. Some evidence of this chain of events seems to be present in the results so far obtained. Although the magnitude of the effect is uncertain, Braun (1975) suggests that uncertainties in spectral line parameters may be 'too great to permit retrieval of temperature profiles from measured radiances and first guess radiances computed from calculated transmittances alone'. It is difficult to see how clear radiances can be obtained easily without calculating transmittances unless a second window channel is available. Regression methods for temperature and water vapour retrievals as developed by NESS help to prevent clear radiance errors from being passed on to the retrieved profiles but the required sample of radiances and co-located radiosonde soundings may take considerable time to accumulate. Cloud heights and amounts are difficult to treat by regression methods because of the difficulty of obtaining a sample of 'true' values.

Retrieved temperature profiles may be affected by the first guess profiles though this probably occurs to a greater extent through the calculation of the clear radiance in channel 8 than through the retrieval process directly. Channels in the wings of the 4.3μ absorption band of carbon dioxide may improve temperature retrievals as the Planck function varies more strongly with temperature at these wavenumbers.

Water vapour and cloud retrievals are at the end of the chain of computations and are therefore not responsible for passing on errors to other areas. It is difficult to see how a quantity as variable as atmospheric water vapour can be treated adequately by a one-parameter model. We may therefore have to wait until the three water vapour channels on TIROS-N make a three-parameter model available before reliable moisture profiles can be determined. It may also be questioned whether it is fair to assume that the water vapour profile is uniform over an area as large as a VTPR box.

The assumption of uniformity over a box is even more questionable when applied to cloud height. It is thought that the radiances contain more details of cloud height information since a retrieval in which a cloud height was deduced for each spot showed some evidence of detail in the cloud pattern within VTPR boxes, and also less discontinuity across box boundaries. However, improvements in the accuracy of individual cloud heights and amounts will primarily come only with more accurate clear radiances on which the cloud retrievals are so dependent.

The stability of the entire retrieval program was clearly confirmed by a run in which all the retrieved parameters were fed back in as first guesses for a further iteration. Three or four such iterations were sufficient to generate a high degree of convergence.

8.2 Future work

Preparations are already under way for receiving VTPR data in real time for the direct readout area centred on the receiving station at Lasham. In the near future this data which includes a considerable portion of the North Atlantic will be obtained regularly and will be processed using methods

described in this report to produce temperature and water vapour soundings for comparison with co-located radiosondes, and thickness charts which can be compared with those drawn from conventional data. This study will take place over the next few months and the results will be presented in a future report. The minimum information method will be used for temperature retrievals but regression methods are also being studied. Eventually it is hoped that data from the SR and VHRP instruments will also be available from Lasham. These could provide sea surface temperature data and may throw light on the quality of cloud information deduced from VTPR radiances.

References

- Bignell, K. J. "The Water-vapour Infra-red Continuum". Quart. J.R. Met. Soc., Vol. 96, pp.390-403, 1970.
- Braun, C. 'Dependence of VTPR Transmittance Profiles and Observed Radiances on Spectral Line Shape Parameters'. NOAA Tech. Memo. NESS 70, 1975.
- Burch, D. E. 'Semi-annual Technical Report. Investigation of the Absorption of Infrared Radiation by Atmospheric Gases'. AFCRL Publication U-4784 under Contract No. F19628-69-C-0263, 1970.
- Fritz, S., Wark, D. Q., Fleming, H. E., Smith, W. L., Jacobowitz, H., Hilleary, D.T. and Alishouse, J. C. 'Temperature Sounding from Satellites'. NOAA Tech. Report NESS 59, 1972.
- Goddard, J.W.F., and Hunt, R.D. 'Some Results on the Comparison of Retrieval Methods - Maximum Probability, Minimum Information and Tychonov Regularization'. Met O 19 Branch Memo. No. 11. 1974.
- McClatchey, R. A., Benedict, W. S., Clough, S. A., Burch, D. E., Calfee, R. F., Fox, K., Rothman, L. S. and Garing, J. S. 'AFCRL Atmospheric Absorption Line Parameters Compilation'. AFCRL Env. Res. Paper No. 434, 1973.

- McMillin, L. M., Wark, D. Q., Siomkajlo, J. M., Abel, P. G., Werbowetzki, A.,
Lauritson, L. A., Pritchard, J. A., Crosby, D. S., Woolf, H. M.,
Luebbe, R. C., Weinreb, M. P., Fleming, H. E., Bittner, F. E.,
and Hayden, C. M. 'Satellite Infrared Soundings from
NOAA Spacecraft.' NOAA Tech. Report NESS 65, 1973.
- May, B. R. 'The processing of Sea-surface Temperature Measurements
for Use in the Met O 19 VTPR Retrieval Programme'.
Met O 19 Branch Memo. No. 21, 1975.
- Rodgers, C. D. 'Satellite Infrared Radiometer. A Discussion of Inversion
Methods'. Oxford Univ., Clarendon Lab., Memo. No. 66.9, 1966.
- Rodgers, C. D. 'Remote Sounding of the Atmospheric Temperature Profile
in the Presence of Cloud'. Quart. J. R. Met. Soc.,
Vol. 96, pp. 654-666, 1970.
- Salter, P. R. S. 'Interim Report on the Processing of Satellite Imagery
Data in Met O 19'. Met O 19 Branch Memo. No. 18, 1975.
- Schwalb, A. 'Modified Version of the Improved TIROS Operational
Satellite (ITOS D-G)'. NOAA Tech. Memo. NESS 35, 1972.
- Smith, W. L. 'A Polynomial Representation of Carbon Dioxide and Water
Vapour Transmission'. ESSA Tech. Report NESC 47, 1969.
- Smith, W. L. 'Iterative Solution of the Radiative Transfer Equation
for the Temperature and Absorbing Gas Profile of an
Atmosphere'. Appl. Opt., Vol. 9, No. 9, pp 1993-1999, 1970.
- Smith, W. L., Hilleary, D. T., Fischer, J. C., Howell, H. B. and Woolf, H. M.
'Nimbus -5 ITPR Experiment'. Appl. Opt., Vol. 13, No. 3,
pp. 499-506, 1974.
- Smith, W. L., Woolf, H. M., Abel, P. G., Hayden, C. M., Chalfant, M. and Grody, N.
'NIMBUS -5 Sounder Data Processing System. Part I:
Measurement Characteristics and Data Reduction Procedures'.
NOAA Tech. Memo. NESS 57, 1974.

- Smith, W. L., Woolf, H. M. and Fleming, H. E. 'Retrieval of Atmospheric Temperature Profiles from Satellite Measurements for Dynamical Forecasting'. J.Appl. Met., Vol. 11, pp. 113-122, 1972.
- Twomey, S. 'On the Numerical Solution of Fredholm Integral Equations of the First Kind by the Inversion of the Linear System Produced by Quadrature'. J. Assoc. Comp. Mach., Vol.10, No. 1, 1963.
- U.S. Standard Atmosphere, 1962. NASA, USAF and U.S. Weather Bureau, 1962.
- U.S. Standard Atmosphere Supplements, 1966. NASA, ESSA and USAF, 1966.
- Wark, D. Q. and Fleming, H.E. 'Indirect Measurements of Atmospheric Temperature Profiles from Satellites: 1. Introduction.' Mon. Wea. Rev., Vol. 94, No. 6, pp 351-362, 1966.
- Weinreb, M. P. and Crosby, D.S. 'Estimation of Atmospheric Moisture Profiles from Satellite Measurements by a Combination of Linear and Non-linear Methods'. 3rd Conf. on Prob. and Stat. in Atmos. Sci., Boulder, Colorado, June 1973.
- Weinreb, M. P. and Neuendorffer, A.C. 'Method to Apply Homogeneous - Path Transmittance Models to Inhomogeneous Atmospheres'. J.Atmos.Sci. Vol.30, No.4, pp 662-666, 1973.

Channel number.	Central wavenumber. (cm. ⁻¹)	Purpose.
1	667.2	Temperature sounding
2	677.6	Temperature sounding
3	695.2	Temperature sounding
4	708.0	Temperature sounding
5	725.0	Temperature sounding
6	747.7	Temperature sounding
7	533.1	Water vapour sounding
8	835.5	Atmospheric window

Table 1. Central wavenumbers of VTPR channels on NOAA-2.

Level Pressure		Level Pressure		Level Pressure	
1	0.010	35	30.21	70	299.0
5	0.122	40	46.64	75	377.2
10	0.687	45	68.64	80	469.1
15	2.172	50	97.21	85	575.9
20	5.158	55	133.40	90	699.0
25	10.316	60	178.32	95	839.9
30	18.392	65	233.12	100	1000.0

Table 2. Pressures in millibars at every fifth level used for VTPR retrievals.

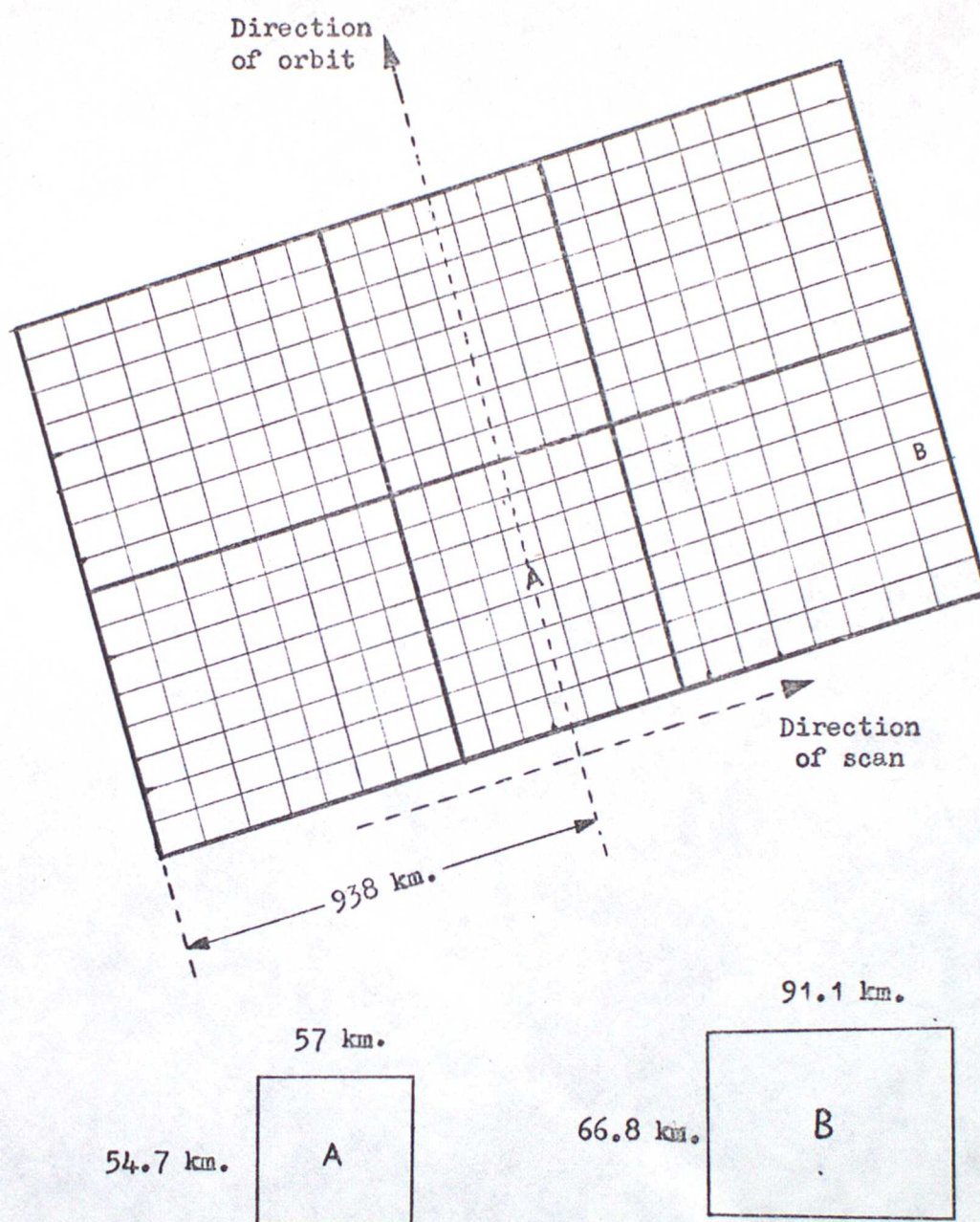


Figure 1. VTPR scan pattern and dimensions of two individual fields of view. (Adapted from McMillin et al. 1973).

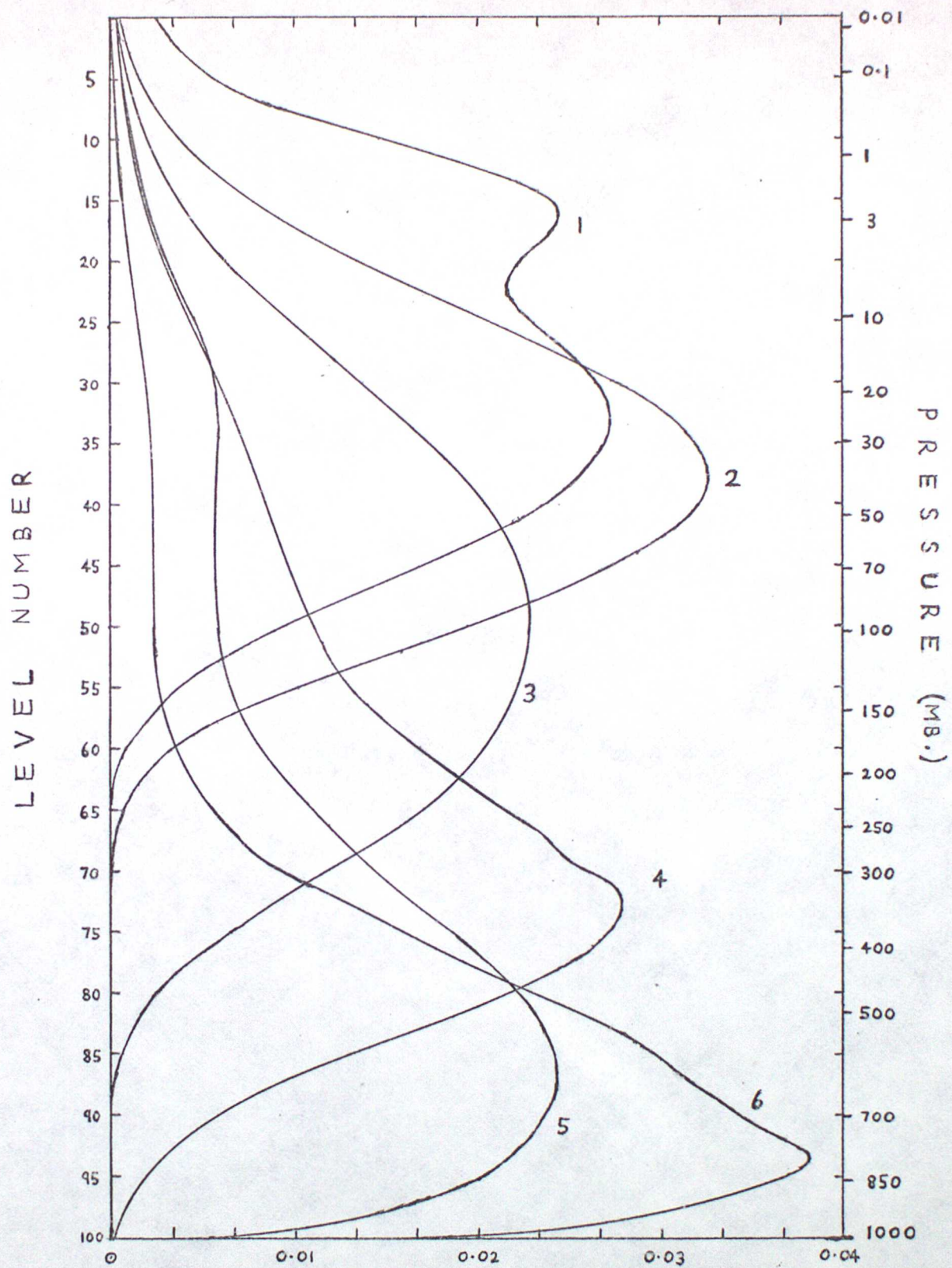


Figure 2. Weighting functions for channels 1 to 6.

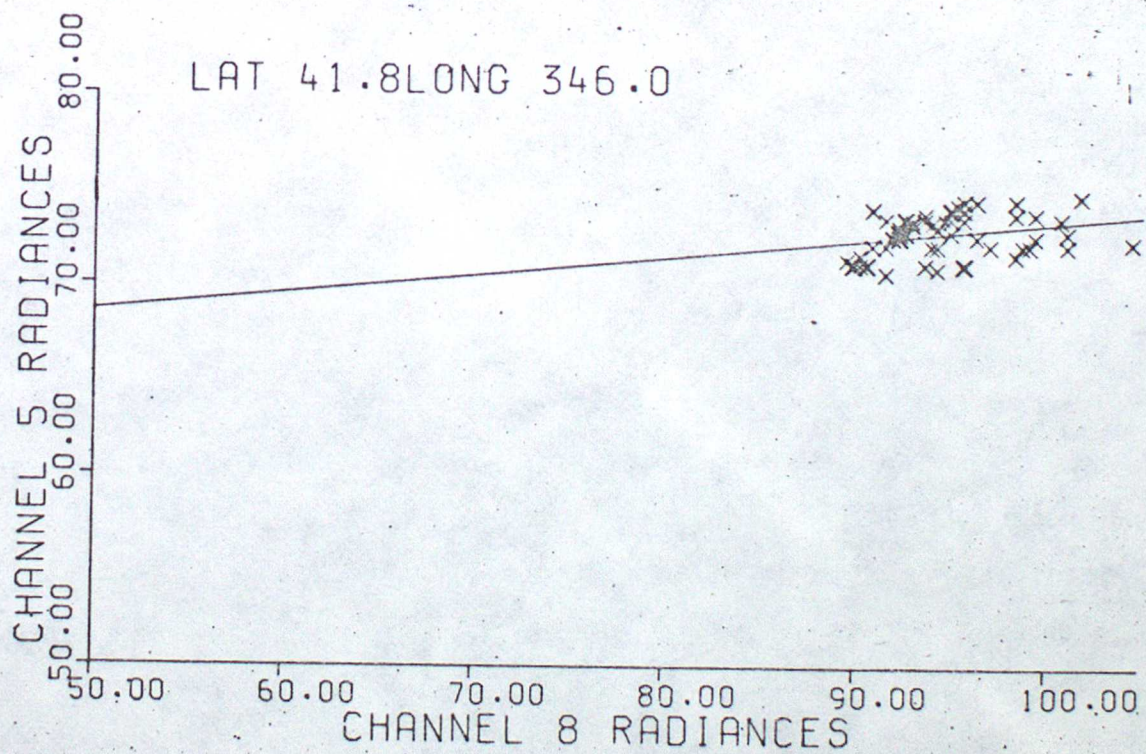
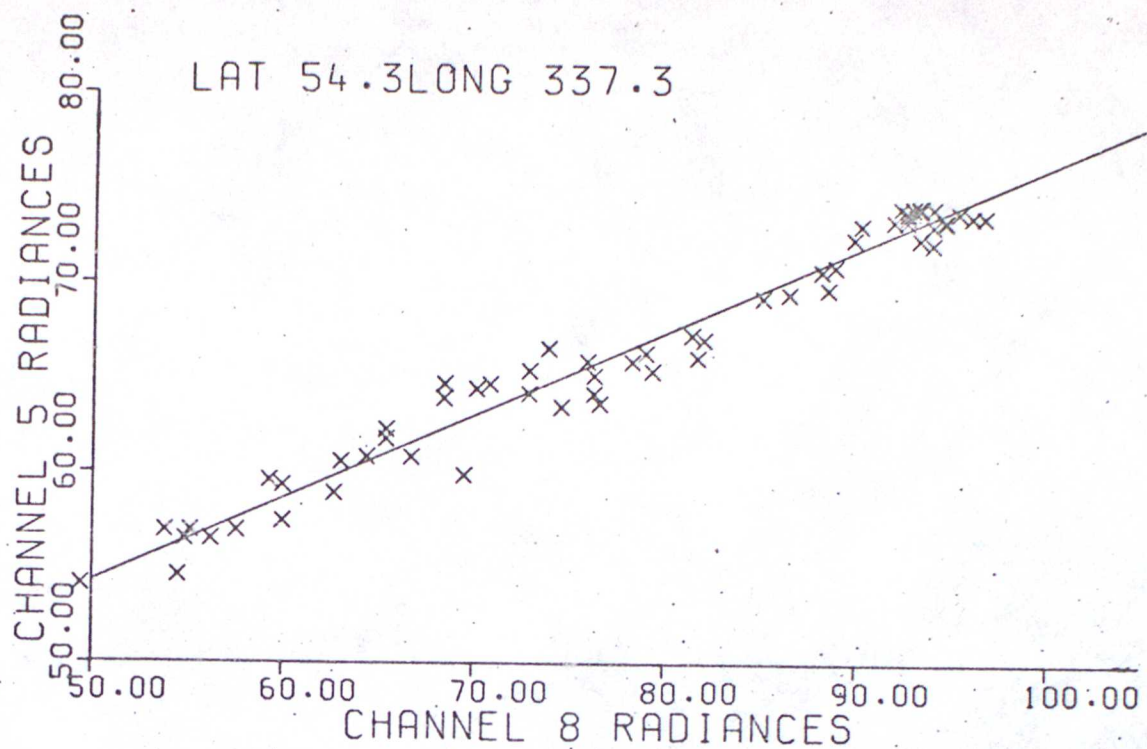


Figure 3. VTPR channel 5 regressed against channel 8.
(17 July 1973, 54.3N, 337.3E and 41.8N, 346.0E)

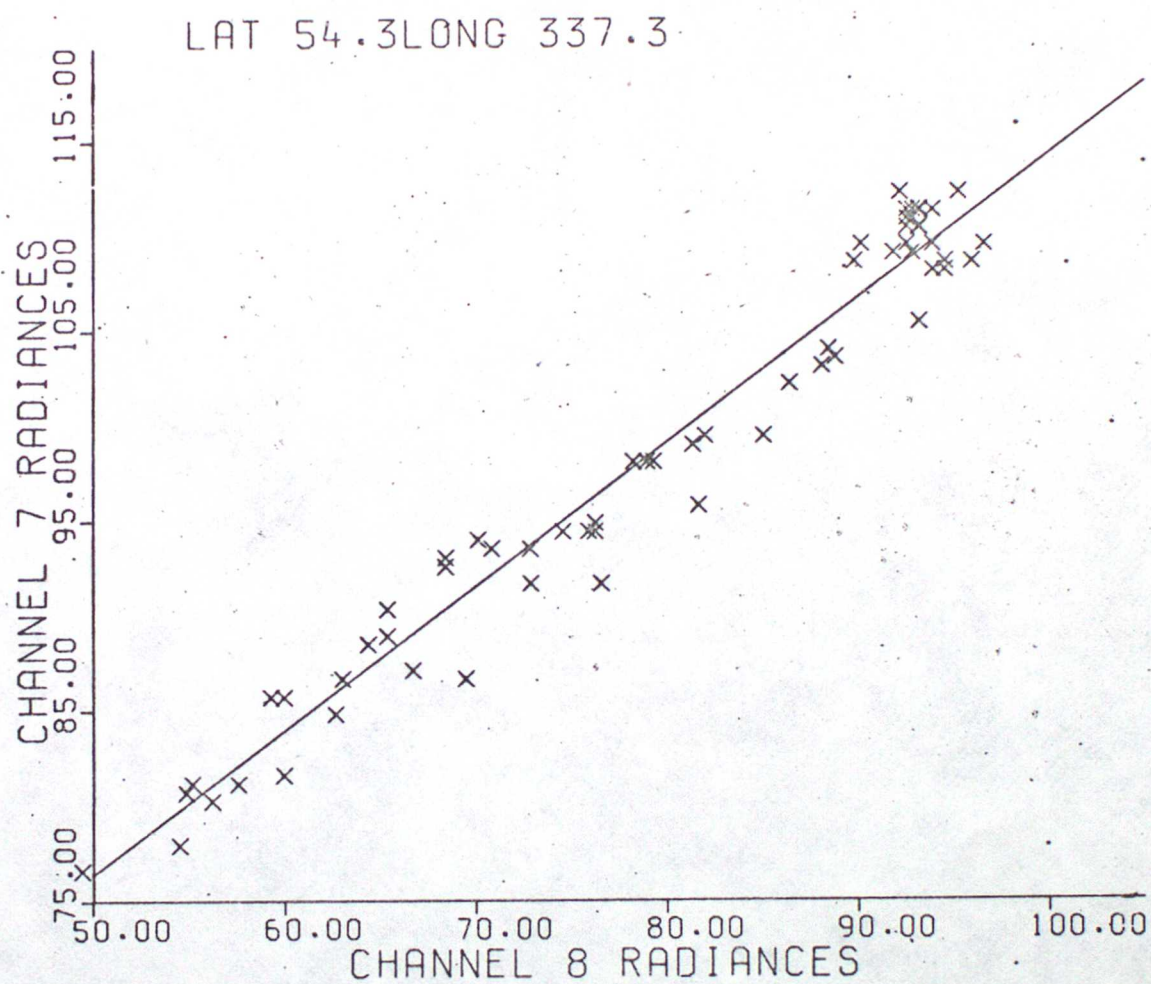


Figure 4. VTPR channel 7 regressed against channel 8.
(17 July 1973, 54.3N, 337.3E)

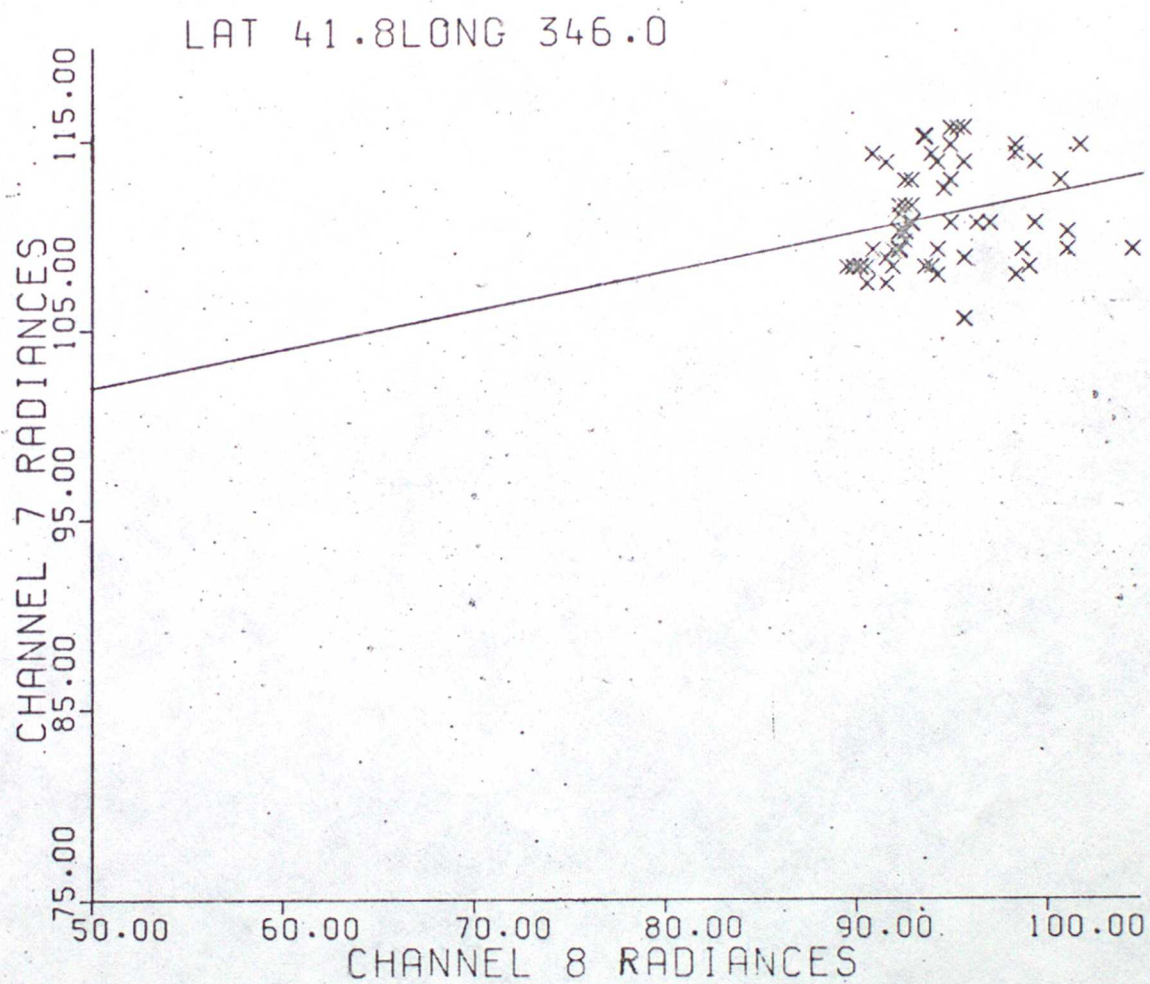
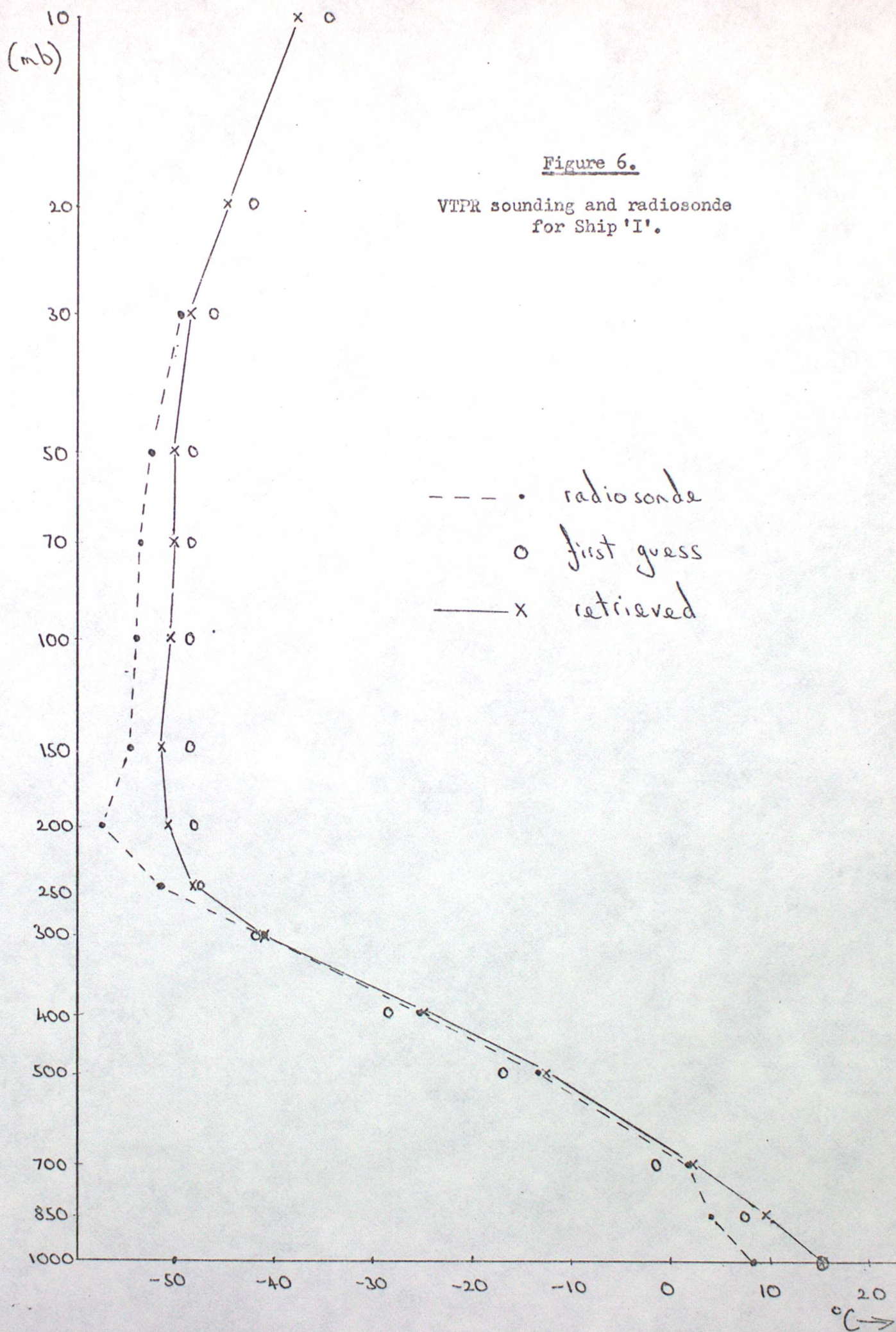
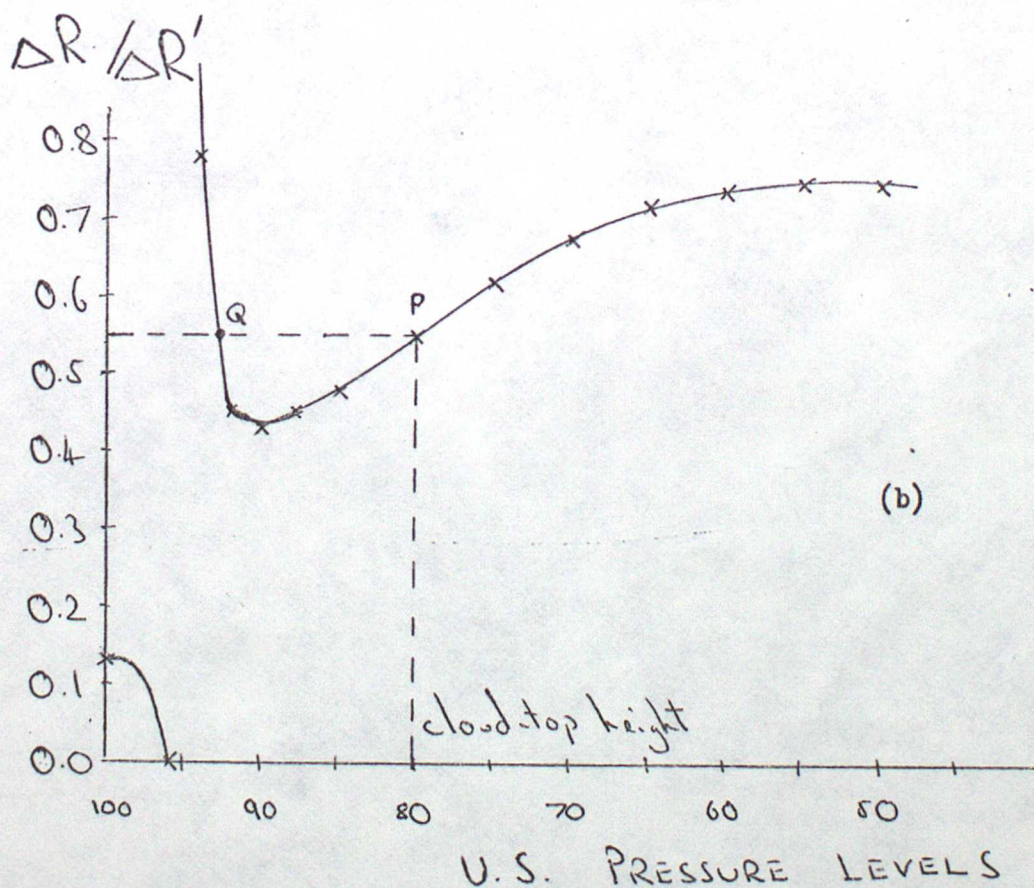
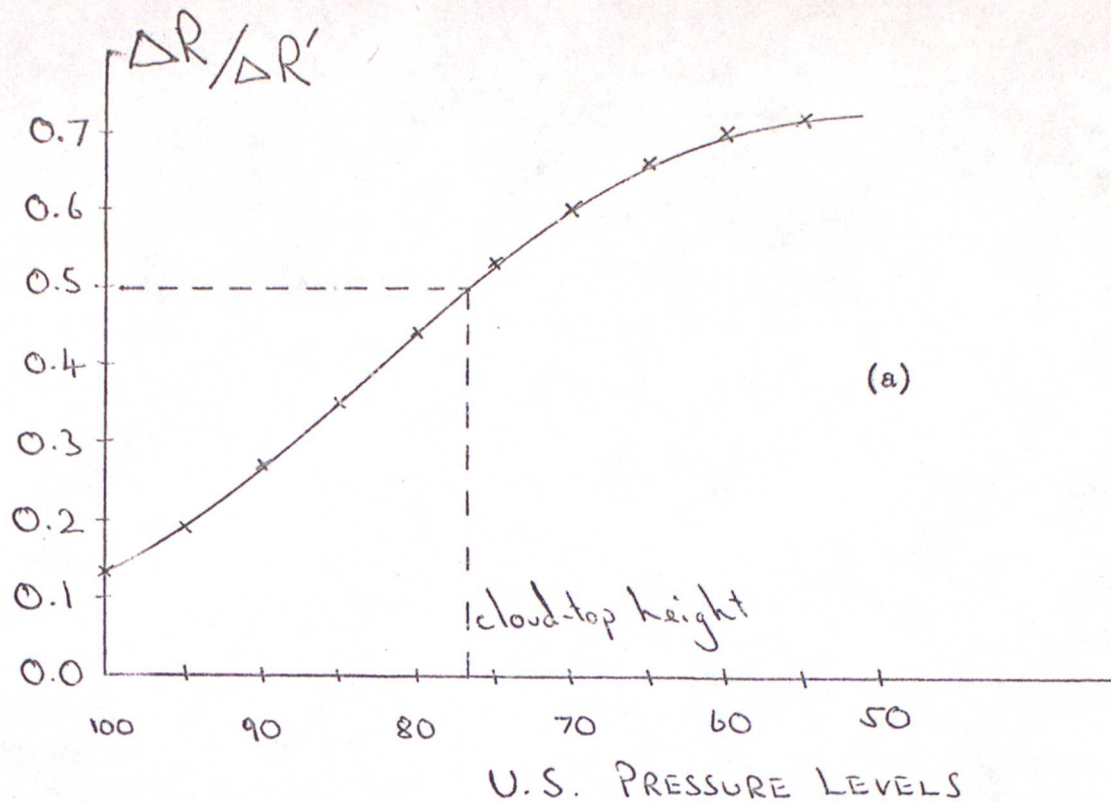


Figure 5. VTPR channel 7 regressed against channel 8.
(17 July 1973, 41.8N, 346.0E)





Figures 7a and 7b. $\Delta R / \Delta R'$ for two VTPR boxes.