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Description of the "SIRS" upper-air soundings

B R May

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DESCRIPTION OF THE "SIRS" UPPER-AIR SOUNDINGS

(Based on notes for a colloquium given by B. R. May and C. R. Flood on the use of VTPR data in forecasting. A more complete description of SIRS soundings is contained in a NOAA Technical Report NESS 65 "Satellite infra-red soundings from NOAA spacecraft".).

1) INTRODUCTION:-

For about 30 years now, meteorologists have relied upon the radio-sonde as their main source of upper-air temperature and humidity data. However with the advent of artificial Earth satellites remote sensing of the temperature and humidity of the atmosphere by means of satellite-borne radiometers has become possible. The feasibility of remote sounding of the atmosphere has been demonstrated by the SIRS-A and -B and the Oxford Selective Chopper radiometers but the value of sounding especially in the troposphere is not generally accepted. It is the purpose of the studies recently started in Met O 2b and Met O 11 to investigate the SIRS soundings which are generated from the measurements made by the Vertical Temperature Profile Radiometer (VTPR).

2) THE VTPR INSTRUMENT

The VTPR is a multi-channel radiometer measuring the intensity of thermal radiation emitted by the Earth's atmosphere and surface in eight narrow spectral bands in the infra-red spectrum. Six of the channels are in the spectral region dominated by the CO_2 molecular spectrum, near 15μ, one in the H_2O band near 20μ and a window channel near 11μ. The instrument was designed by NESS (National Environmental Satellite Service) who are also responsible for the processing of the measured radiances to produce the SIRS soundings. Currently there are four VTPRs in orbit - two in the NOAA 2 spacecraft (launched November 1972) and two in the NOAA 3 spacecraft (launched October 1973), which is the current operational one. At low and mid-latitudes the SIRS soundings are made near 20 and 08 hrs local time.

The VTPR instrument as seen from below is shown in figure 1. The wheel containing the filters which select the eight frequencies can be seen, along with the scanning mirror which enables observations to be made between the tracks of the spacecraft to increase the geographical coverage of the radiometer and to overcome the problem associated with sounding in partly cloudy conditions. The scan pattern of observations on the ground is shown in figure 2. The instantaneous field of view of the radiometer is about 60 km square at the sub-satellite point and the cross-track scan consists of 23 "looks" at the atmosphere, each taking 0.5 seconds in which time the eight radiance measurements are made. The total scan takes 12.5 seconds during which time the spacecraft moves forward sufficiently for the successive scans to be adjacent. NESS group together the observations into three larger boxes (two outside boxes of 8 x 8 observations and an inner one of 8 x 7 observations, as shown in figure 2) for the purpose of processing the data, where the nominal centres of the boxes are about 500 km apart.

3) RADIATIVE TRANSFER IN THE ATMOSPHERE AND THE VTPR WEIGHTING FUNCTIONS.

Before introducing the spectral intervals in which the radiance measurements are made and why they have been chosen, it is useful to introduce the Radiative Transfer Equation (RTE) which describes the process of emission of thermal radiation by the atmosphere. The RTE is:-

$$R_{clear} = \underbrace{B(T_s,\bar{\nu}).\epsilon_s.\tau_s}_{\text{Surface}} + \underbrace{\int_{\tau_s}^{\tau=1.0} B(T_{atm},\bar{\nu})\frac{d\tau}{dz}.dz}_{\text{Atmosphere}}$$

from which we see that in clear conditions, in general, the radiance observed outside the atmosphere is made up of two components, one from the surface of the Earth and the other from the atmosphere. The surface term is simply the Planck radiation from a surface of emissivity ϵ_s for a temperature T_s and wavenumber $\bar{\nu}$ reduced by a factor τ_s, the transmission coefficient from the surface to the top of the atmosphere. The Planck function $B(T,\bar{\nu})$ is given by:-

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

(C_1 and C_2 are constants) where the units of both R and B are in W $(m^2.sr.cm^{-1})^{-1}$

(called R-units for short). The radiances measured in the channels 1 to 6 of the VTPR are at frequencies within the CO_2 molecular absorption and emission spectrum so that the way that τ varies with height depends upon the density variation of CO_2 which in turn depends on the scale height of the atmosphere, since CO_2 has a constant mixing ratio (the scale height is the height interval in which the pressure falls by a factor e^{-1}). The dependence is such that τ varies slowly with pressure so that $\frac{d\tau}{dZ}$, where Z is some function of pressure has a broad band centred on the peak of the weighting function. Near 15 μ there is also emission and absorption of radiation by H_2O so that the transmission coefficients of the CO_2 channels are modified by the presence of water vapour in the troposphere, but the general height of a CO_2 weighting function is governed by the mean absorption coefficient which depends upon the frequency. Thus by a suitable choice of frequencies a series of overlapping CO_2 weighting functions are obtained. Near 11μ there is an atmospheric "window" in which the effect of CO_2 is negligible but not negligible for H_2O which governs the transmission near this wavelength. Given a temperature and humidity profile the τ's of the CO_2 channels and the window channels can be calculated from spectral data.

Figure 3 gives details of the frequencies of the VTPR channels showing the levels of the peaks of the weighting functions and the purpose to which the radiances are put. Figure 4 shows the transmittances of the CO_2 channels where the dashed portions in the troposphere demonstrate the change in transmittance due to the presence of water vapour amounting to about 4 gm. cm^{-2} of precipitable H_2O in the total atmospheric column. Figure 5 shows the corresponding weighting functions and demonstrates their considerable breadth ranging from a half-width of about one scale-height in the troposphere to 2½ scale heights in the stratosphere.

4) "CLEAR-COLUMN" RADIANCES.

Before the radiances can be used to determine the atmospheric temperature profile, the effects of cloud must be eliminated in order to produce the "clear column" radiances. Clouds have the effect of reducing the radiances as in figure 6 which shows the variation of radiance in the six channels along a portion of the track of the spacecraft. The effect of the cloud becomes more pronounced the lower the peak of the weighting function is in the atmosphere. In terms of the R.T.E. the radiance in the presence of complete cloud cover is given by:-

$$R_{cloudy} = B(T_c, \bar{\nu})\epsilon_c . \tau_c + \int_{\tau_c}^{\tau=1.0} B(T_{atm}, \bar{\nu}) \frac{d\tau}{dz} . dz$$

where c denotes the level of the cloud top. In general the radiameter will observe a partly cloudy area so that the observed radiance is given by:-

$$R_{obs} = n R_{cloudy} + (1-n) R_{clear}$$

where n is the fractional cloud cover. R_{obs} is linearly related to n for any VTPR channel so that over an area of the atmosphere within which the temperature profile and cloud-top height are constant, the radiance in any one channel is linearly to the radiance in any other channel. More specifically the radiance in any channel 1 to 6 is linearly related to R_8, the window channel radiance. Thus for two adjacent areas the observations define a line upon which must lie the clear radiances in the two channels so that if the clear window radiance is known then the other clear radiances can be found, as in figure 7. Now the clear window radiance can be estimated accurately for areas over the sea, from a knowledge of the sea-surface temperature and assuming an emissivity of the sea-surface = 1.0, correction being made for the absorption and emission of radiation by atmospheric water vapour. This process is carried out for all adjacent pairs of observations within the boxes, leading to as many as 200 estimates of each of the clear radiances for the channels 1 to 6 within each box. The weight of each estimate depends upon the position on the regression line of two defining points - measurements made in uniformly cloudy conditions are given a low weight. It should be stressed that neither observations need be of a completely clear area - it is the variability of n that establishes the lines, as in figure 7.

Figure 8 shows typical histograms of clear-column radiances in channel 6 in the presence of a single layer of broken cloud and multiple layers of cloud. In the first case the mean clear radiance is easily identifiable and is close to the forecast value from a first guess temperature profile. In the second case it is not clear which, if either, of the modal values is correct - in this case NESS take a weighted mean of the peak modal values.

Having arrived at the clear-column radiances over the sea areas, the surface contribution to the radiances are subtracted leaving the atmospheric radiances from which are deduced the atmospheric temperature profiles. These temperature profiles are averages over the extent of each box though they are ascribed to a single location near to the nominal centre of the box.

5) RETRIEVAL OF TEMPERATURE PROFILES FROM RADIANCES.

From a set of VTPR clear-column radiances no unique temperature v pressure profile can be deduced. This is clear from a consideration of a single weighting function with which an infinite number of Planck profiles can result in the same radiance. Conversely a single radiance can generate an infinity of Planck profiles. Consequently some constraint must be applied in order to obtain a stable solution to the RTE. The method of retrieving the temperature profile from the radiances used by NESS is the "minimum information" method which can be written in this form.

$$B(T) = B(T^*) + C(R-R^*)$$

where T is the required temperature profile for the set of "clear-column" radiances R and T* is a "first guess" profile with corresponding radiances R*. The matrix C is a function of the τ's (calculated from the first guess temperature and humidity profiles), the instrumental noise, the errors in the radiances (such as those produced in the cloud-clearing process) and the r.m.s deviation of atmospheric Planck function profiles (climatological r.m.s. deviations are used). The solution found by this retrival method is such that it differs by a minimum amount (in the squared sense) from the first guess profile; if the radiances are noisy or the r.m.s deviation of Planck profiles is small then the solution tends to the first guess (i.e. more weight is given to the first guess and less to the radiances) and vice versa.

The first guess profiles used by NESS in their operational scheme to produce the SIRS soundings are :-

1) North of 18°N - computer forecast temperature and humidity profiles up to 100 mbs, previous days temperature analyses from 100-10 mb, regression

estimates relating temperature from 10-1 mb with temperatures at lower heights.

2) 18°N to 18°S - climatological radio-and rocket-sonde temperature data averaged over appropriate two-monthly periods, regression estimates for the humidity.

3) South of 18°S - previous days temperature analyses using all available data (VTPR included), regression estimates for the humidity.

It should be mentioned that the radiances can only be used to determine the temperature as a function of pressure and hence the thickness of atmospheric layers. Previous to mid-March 1974, for areas north of 18°N, the SIRS "heights" were calculated thicknesses from the 850 mb level added to a forecast 850 mb height, while for areas south of 18°N the heights were simply thicknesses from the 1000 mb level. After that date, for all areas, the SIRS heights are thicknesses from the 1000 mb level.

Finally, figure 9 is a diagram of the NESS operational system from the playback of the spacecraft tape recorders by the Command and Data Acquisition stations to the teletype output which is received by the Met Office via the G.T.S. The time delay from the radiance observations being made to the transmission of the SIRS sounding can be as little as two hours but is usually nearer four hours.

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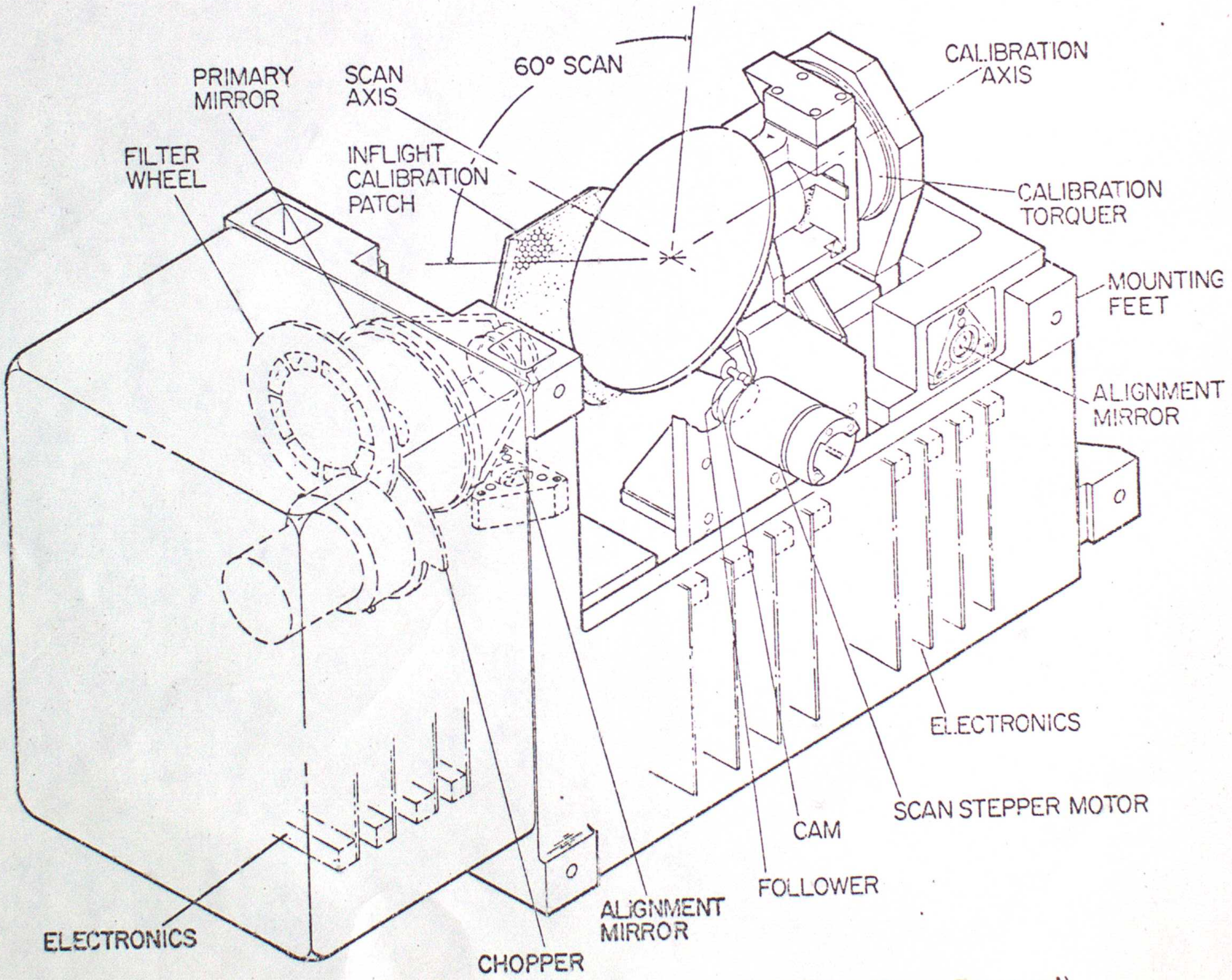
Postscript to the "Description of SIRS upper-air soundings" by B R May (HA/IG/6)

On page 3 it was mentioned that the weighting functions of the VTPR have a considerable vertical breadth, but the consequences of this were not stressed adequately.

Because of the considerable breadth of the weighting functions the vertical resolving power of the radiometer (the ability of the radiometer to "see" what is happening at a specific level of the atmosphere) is poor. However the radiometer is much more sensitive to changes in the mean temperature, or thickness, of layers of the atmosphere which are comparable with or greater than the half-width of the weighting functions. It is better to regard the radiometer as an instrument making observations from which can be deduced a smooth vertical temperature profile containing no small-scale features. In effect obtaining a detailed temperature profile from radiance measurements is an exercise in adding the small-scale temperature structure to a highly-smoothed profile. In theory this can be done using a forecast or climatological profile but both of these types of profile (especially the machine produced forecast) are usually very smooth themselves and so are incapable of introducing small-scale structure into the retrieval profile. As a result the SIRS temperature at the standard levels are unreliable (except in cases where the true profile is smooth) but the thicknesses are much more strongly dependent upon the information contained in the radiances and rely less on assumptions made about the presence of small-scale structure.



ISOMETRIC VIEW OF VTPR (Cover Removed)

Figure 1 --View of a VTPR instrument (courtesy of RCA)

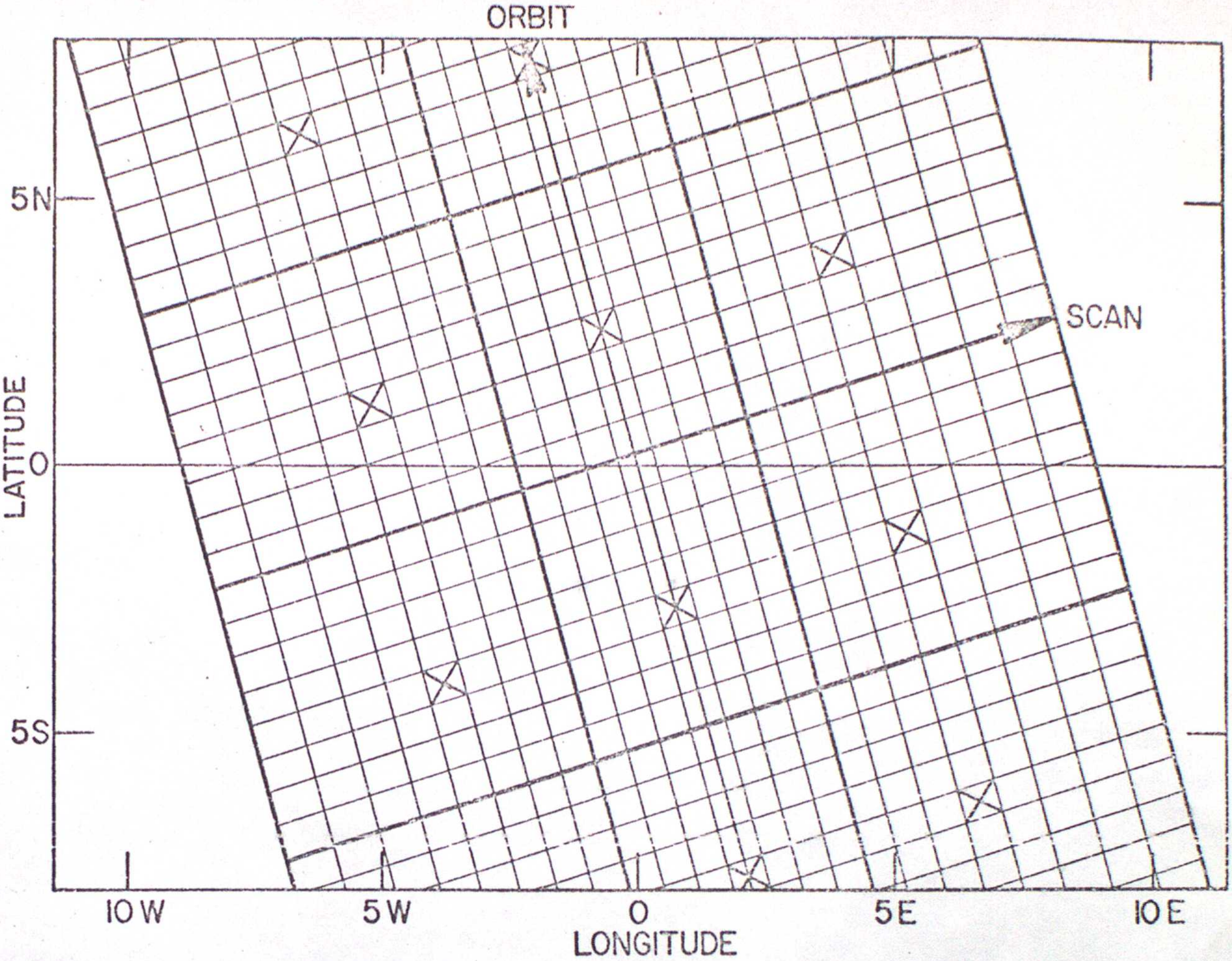


Figure 2.--VTPR scan pattern and data analysis array

VTPR CHANNELS

CHAN. NO.	$\bar{\nu}$ cm^{-1}	TYPE	PURPOSE	APPROX. LEVEL OF WEIGHTING FUNCTION PEAK
1	669	CO_2	TEMPERATURE SOUNDING	40 MB
2	678	"		60
3	695	"		170
4	708	"		400
5	725	"		700
6	747	"		SURFACE
7	535	H_2O	WATER VAPOUR CONC. IN TROPOSPH.	~0.8 gm OF H_2O
8	833	H_2O	WINDOW CHANNEL FOR REMOVING CLOUD EFFECTS	SURFACE

FIGURE 3

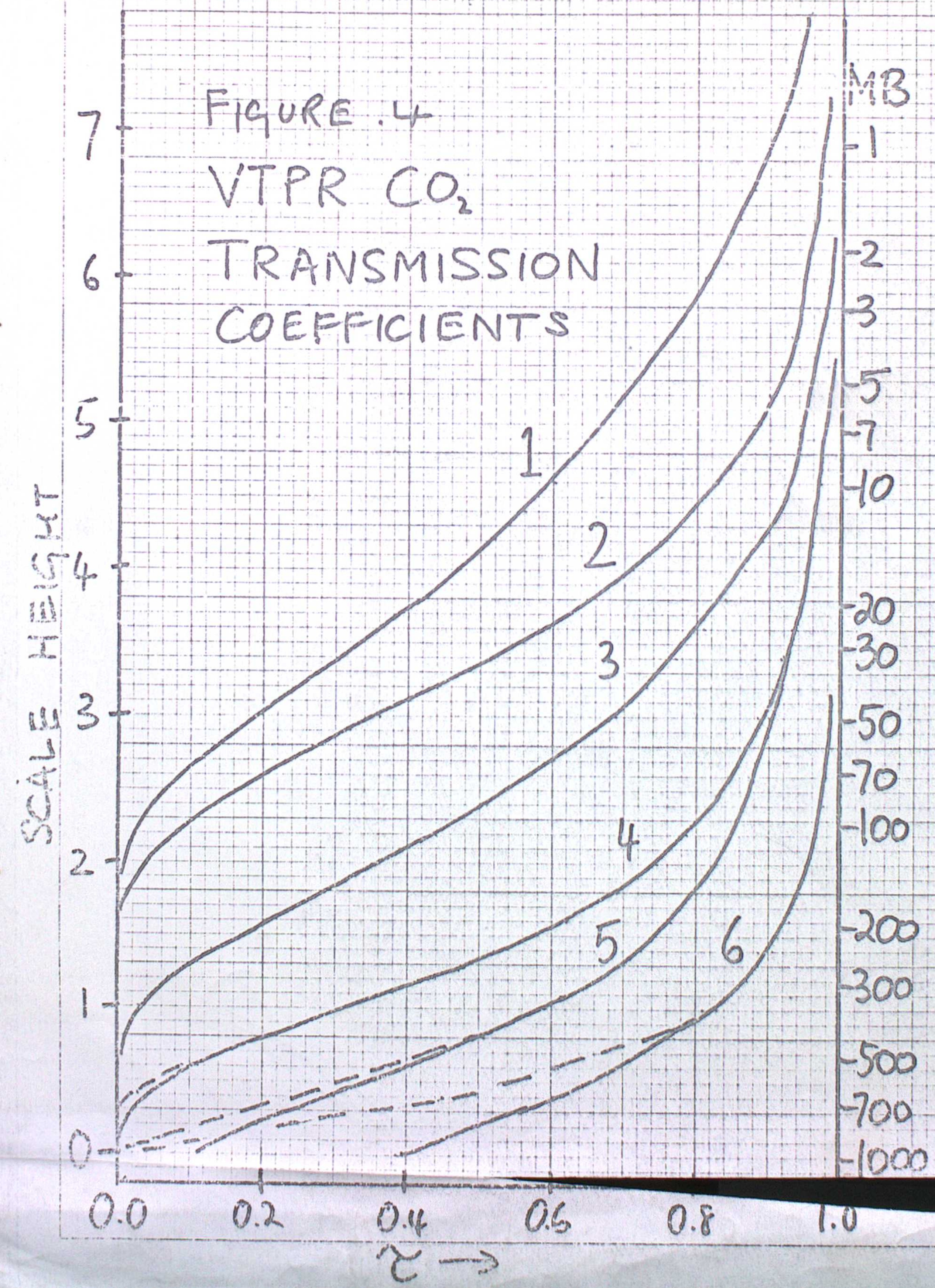


FIGURE .4
VTPR CO_2
TRANSMISSION
COEFFICIENTS
SCALE HEIGHT
0
1
2
3
4
5
6
7
MB
1
2
3
5
7
10
20
30
50
70
100
200
300
500
700
1000
1
2
3
4
5
6
0.0
0.2
0.4
0.6
0.8
1.0
τ →

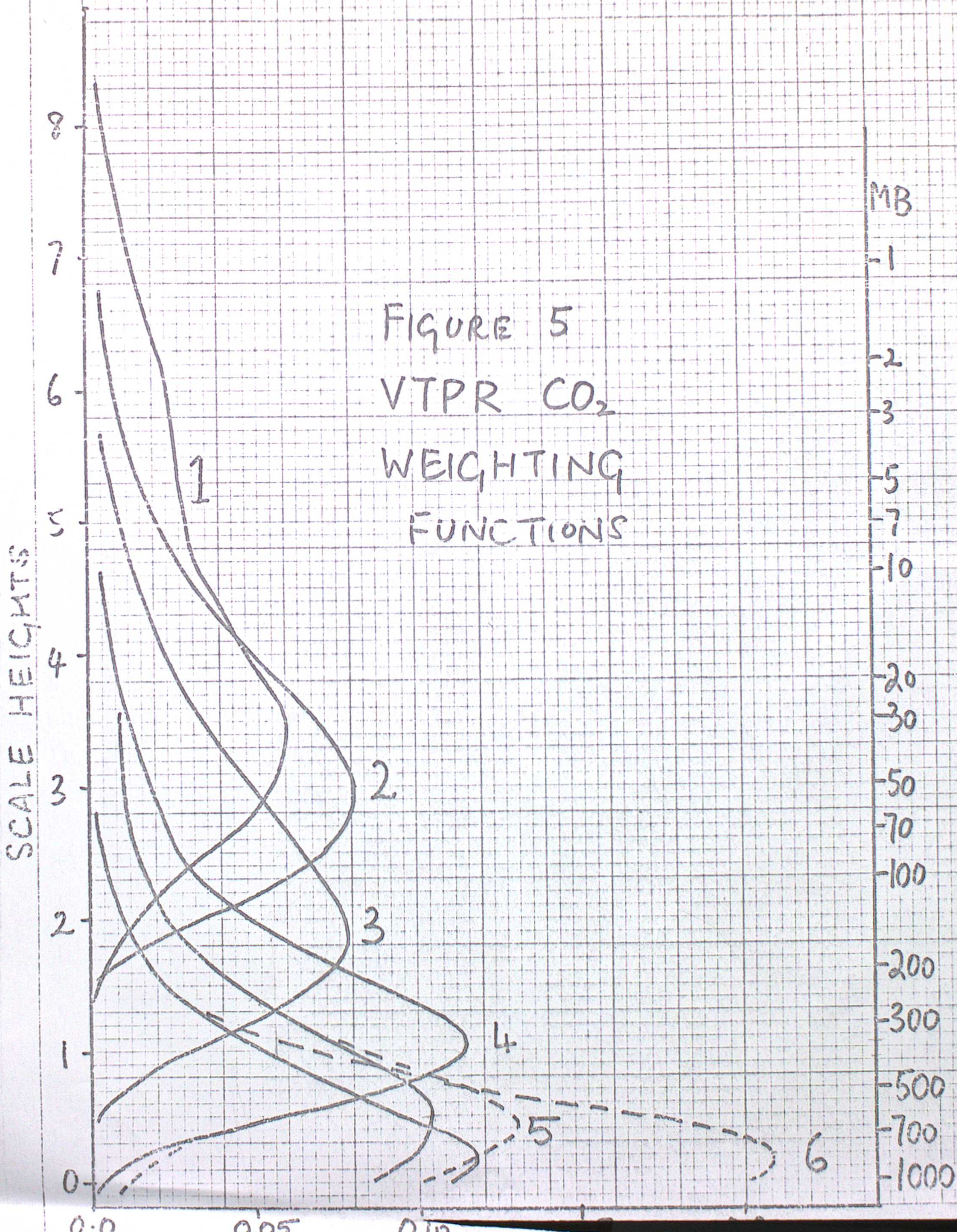


FIGURE 5
VTPR CO_2
WEIGHTING
FUNCTIONS

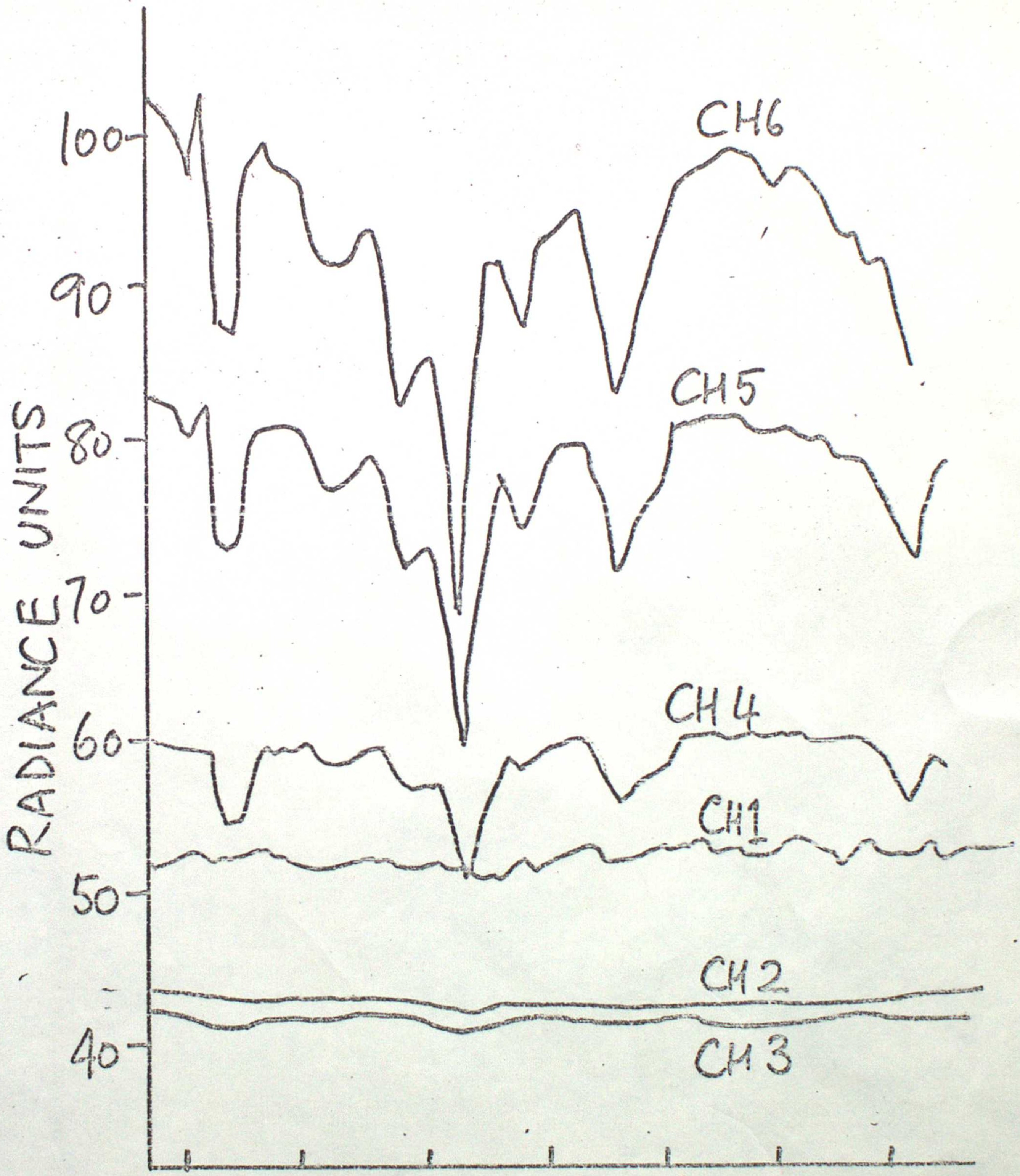
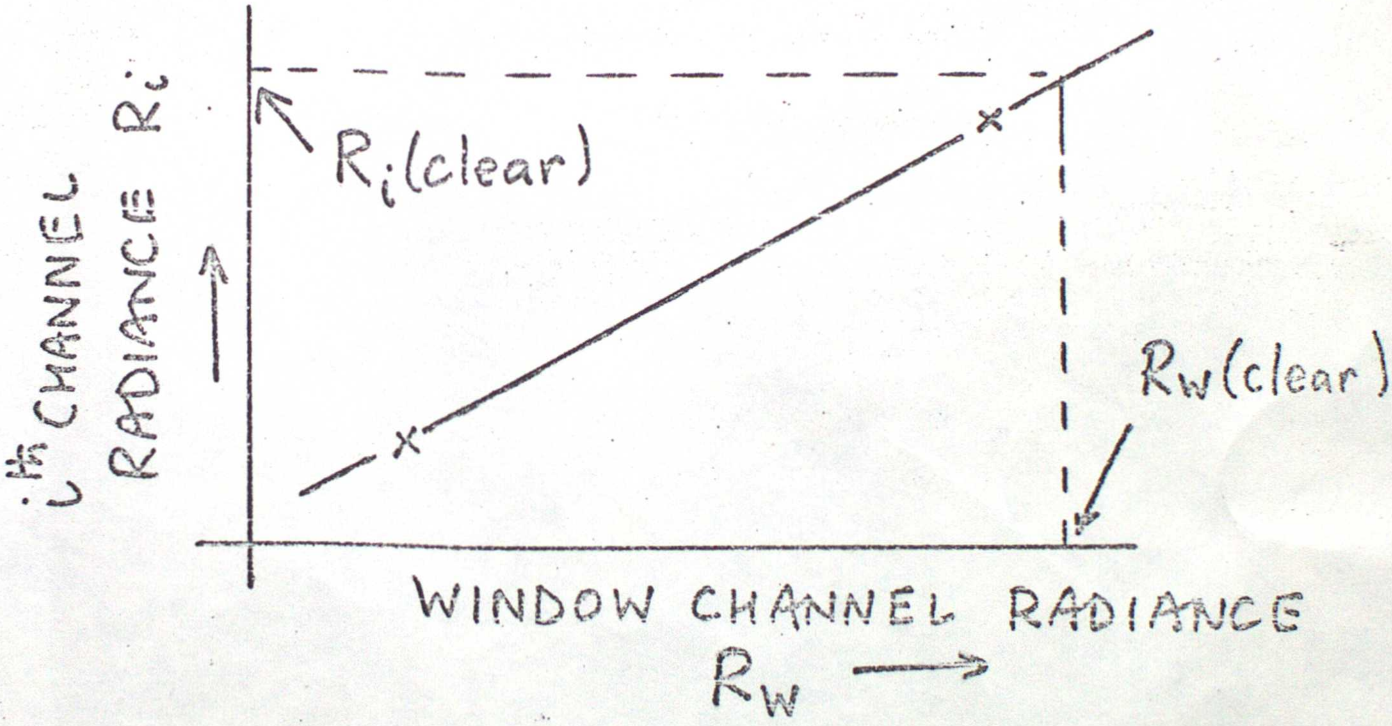


FIGURE 6 VTPR RADIANCES IN CLOUDY CONDITIONS

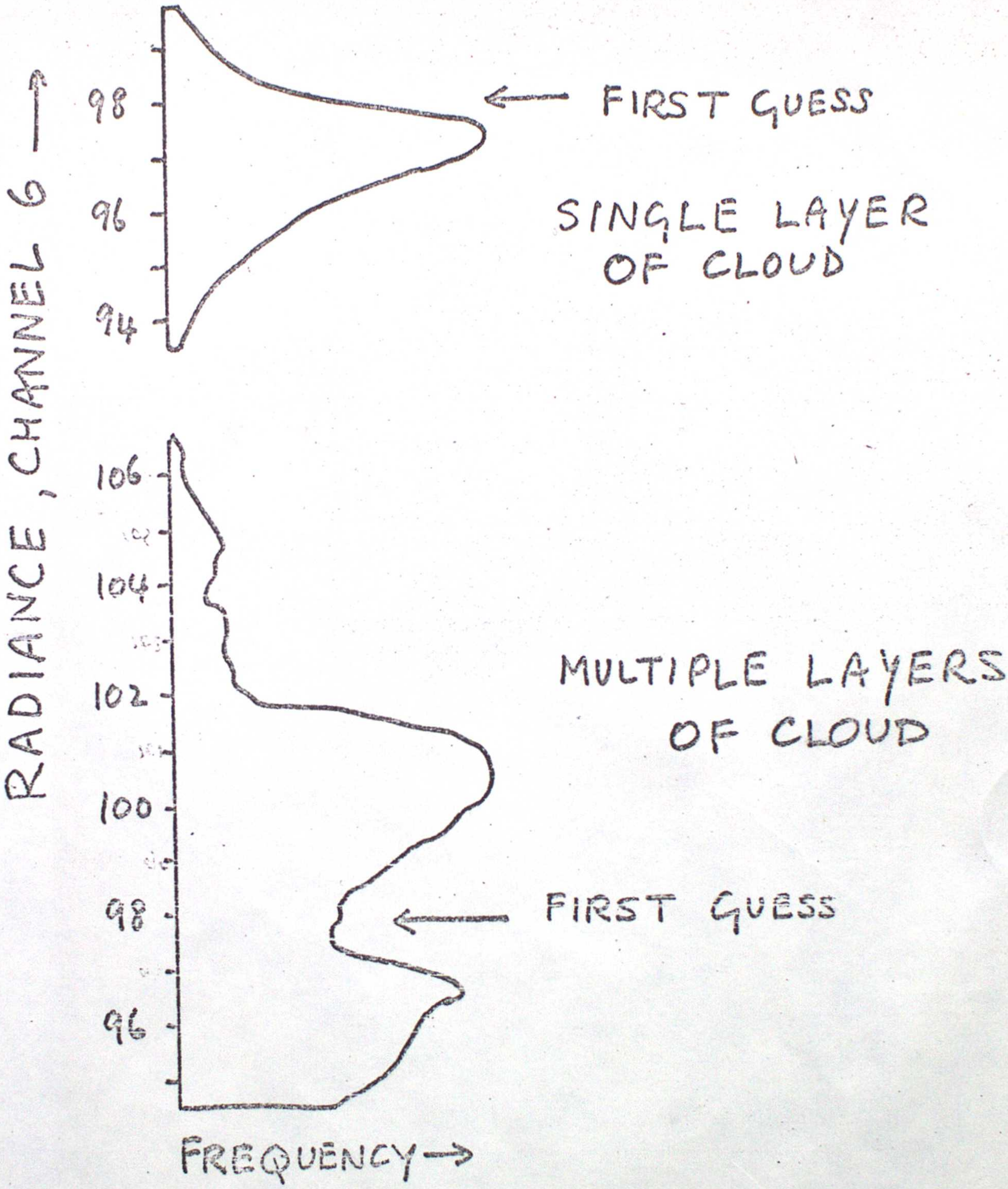
CLEAR COLUMN RADIANCE
— THE RADIANCE THAT WOULD BE OBSERVED IN THE ABSENCE OF CLOUD

FOR OBSERVATIONS MADE IN ADJACENT FIELDS-OF-VIEW:—



R_W IS CALCULATED FROM THE SEA-SURFACE TEMPERATURE

FIGURE 7



HISTOGRAMS OF CLEAR-COLUMN RADIANCES

FIGURE 8

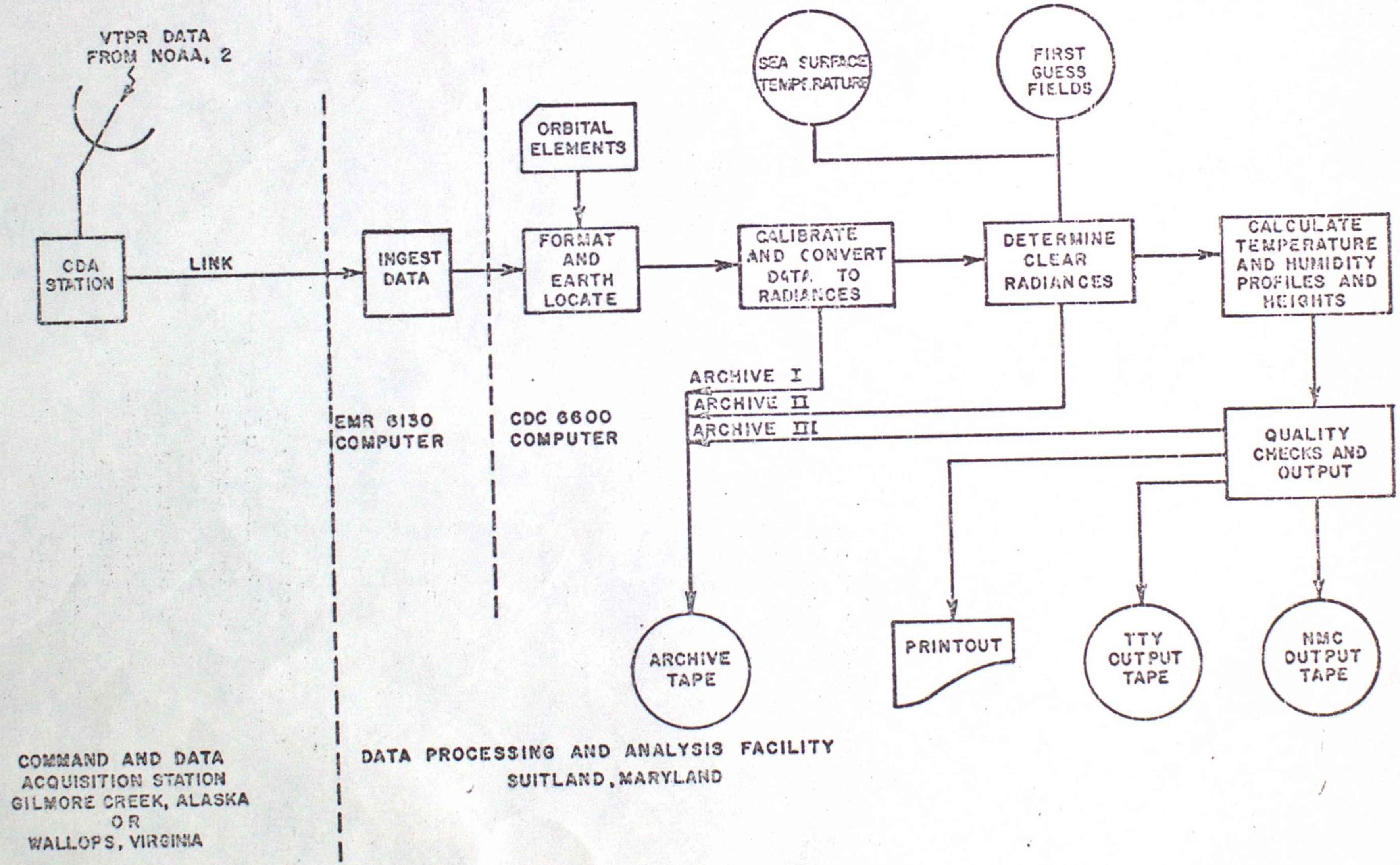


Figure 9.--VTPR software system