TECHNICAL MEMORANDUM

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A fast radiative transfer model for satellite sounding systems

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Abstract

Processing systems for exploiting satellite sounding data require fast and accurate radiative transfer schemes. A new scheme has been developed, initially for use with TOVS data but with flexibility for easy extension to other satellite sounding systems. In addition to the radiative transfer model itself, associated tangent linear, adjoint and gradient-matrix models have been developed. This work has been stimulated by the requirements of recent developments in variational data assimilation for numerical weather prediction, and specifically by projects at ECMWF on one-dimensional and three-dimensional schemes for variational analysis of TOVS radiances. The radiative transfer calculation follows the general method used at NESDIS and elsewhere (see Weinreb et al., 1981), but the architecture of the new scheme has been re-designed completely to assist efficient implementation on vector hardware. The main scientific change is a new fast transmittance model for water vapour.

The memorandum discusses the intended applications, design requirements and scientific features of the new model. It then describes the algorithms used in the radiative transfer scheme and also discusses potential developments to the scheme which have been planned in the design but not yet implemented. The roles of the tangent linear, adjoint and gradient-matrix models are described. Finally aspects of the corresponding software are presented: the software interface for the radiative transfer and associated models, the use of COMMON blocks and PARAMETER statement within the code, and examples of execution times.

1 INTRODUCTION: BACKGROUND TO DEVELOPMENT OF THE MODEL

1.1 Intended applications

An essential component of a system for exploiting data from satellite sounding instruments is an accurate and fast radiative transfer (RT) scheme which computes the radiance emitted at the top of the atmosphere, along the viewing direction of the instrument and averaged over the spectral response of each instrument channel, for a given profile of atmospheric and surface conditions. The new RT model described here has been developed initially for use with data from the High-resolution Infra-red Radiation Sounder (HIRS) and Microwave Sounding Unit (MSU) - part of the TIROS Operational Vertical Sounder (TOVS) on the TIROS-N/NOAA series of polar-orbiting satellites (see Schwalb, 1978 or Smith et al., 1979). However, its design has taken into account its future extension for other satellite sounding systems.

The development of the new model has been stimulated by recent research activities on data assimilation for numerical weather prediction (NWP), and specifically by the requirement at ECMWF to assimilate TOVS radiances directly within experimental schemes for 3- and 4-dimensional variational analysis (3DVAR and 4DVAR - see Pailleux, 1989, 1990). This application requires not only an RT model capable of performing calculations on global radiance data in a reasonable time, but also its associated adjoint model.

The model can also be used in more conventional approaches to the extraction of information from satellite radiances. Most "physical" retrieval schemes require rapid calculation of radiances as part of the inversion process. The new model has been developed for use in a retrieval scheme under development at ECMWF (see Eyre, 1990). This is a physical-statistical nonlinear scheme using a forecast profile and its expected error covariance as constraints with the method described by Eyre (1989). In the context of NWP data assimilation, this method is better described as one-dimensional variational analysis (1DVAR), and this work is closely related to the work on 3DVAR and 4DVAR. The 1DVAR requires both the RT model itself and its associated model for calculating the full gradient matrix, ie the partial derivatives of each radiance with respect to each atmospheric/surface variable. The new gradient model replaces the approximate model described by Eyre (1989).

In common with similar RT schemes, the new model will require careful tuning through comparison of measured TOVS radiances with those computed from collocated radiosondes and NWP model profiles. This aspect will be very important for successful use of the new model and is discussed further in section 2.5.

The new model is also intended to have a number of other applications. It could be used for off-line RT calculations needed to generate various coefficients required by other retrieval schemes. With minor modifications (see section 2.4), it could also be used to calculate radiances for other sounding instruments, present and planned, and to simulate the performance of proposed future satellite systems.

1.2 Design requirements

The range of intended applications places a number of requirements on the scheme which have influenced its design:

- It must be fast enough to be of practical use with global data in near real-time. This entails both simple algorithms and an architecture leading to efficient vectorization.

- It must however be accurate. In practice the error introduced by approximations in the RT calculation should not add significantly to those from other sources (such as those inherent in the underlying spectroscopic data).

- It must be flexible in several respects, including:
    - allowing calculations with or without the presence of cloud,
    - allowing further development for TOVS, through inclusion of refinements to the RT physics,
    - allowing modifications to serve other instruments.

- In addition to the RT model itself, the program suite must include corresponding tangent linear, adjoint and gradient-matrix models. These should also be fast and preferably exact.

1.3 Features of the new model and relationships to earlier models

The approach to the RT calculation follows the general method used at NESDIS (and many other centres) and described by Weinreb et al. (1981). Corresponding code is used for TOVS RT calculations in the International TOVS Processing Package (ITPP) developed by CIMSS/NESDIS at the University of Wisconsin-Madison. A modified version of the ITPP RT code was implemented at the UK Meteorological Office as the "TOVSRAD" model (Eyre, 1984).

The new RT model described here took TOVSRAD as the starting point for most of the algorithms. However, the software has been completely re-coded with a different architecture; calculations for many profiles and/or channels (channels x profiles ~ 1000) can now be computed in parallel, in order to take advantage of vector hardware.

The main scientific change in the new model concerns the transmittance calculation, and particularly the treatment of water vapour. The method used by Weinreb et al. (1981) was found difficult to vectorize and hence slow. A new fast transmittance model has been developed to overcome this problem and to provide a common model for microwave and infra-red channels (which allows all channels to be treated alike throughout the RT calculation and thus assists vectorization). Like the ITPP algorithm for transmittance of uniformly-mixed gases, the new model is of the McMillin/Fleming type (see McMillin and Fleming, 1976). It is an adaptation of the model of Eyre and Woolf (1988) which was developed for microwave channels. When this model was tested on HIRS channels, it was found to give poor accuracy for channels with strong water vapour absorption. The features which are different in the new model have been introduced mainly to overcome this problem. Whereas uniformly-mixed gases and water vapour were treated together in the Eyre/Woolf model, they have again been separated here. However, the angular dependence is now treated by one algorithm, rather than two. Ozone transmittance is still treated separately using a modified version of the algorithm given by Weinreb et al (1981).

Other scientific features of the scheme include the treatment of cloud in the infra-red (a single layer in the present implementation). The architecture allows a general treatment of surface emissivity; the present implementation includes a fixed emissivity for each HIRS channel and a single variable emissivity for MSU. Provision has been made (although not yet implemented) for the treatment of cloud liquid water in the microwave and a more complex treatment of microwave surface emissivity.

Although the model described here has been developed initially for HIRS and MSU, it is anticipated that it will be used, with minor modifications, for several other instruments. [A version for SSM/I has already been implemented at ECMWF by L. Phalippou. ECMWF also has plans to develop versions for ATOVS (ie AMSU + HIRS) and for an infra-red sounder of high spectral resolution.] Some planned and possible extensions to the RT model are discussed in section 2.4.

Although coded with vector machines in mind, the model is written in standard FORTRAN 77 and so should be readily portable to other machines. It has been successfully tested on a (scalar) CDC mainframe and on (vector) CRAY-XMP and -YMP machines. [Caution: these are all machines with 8-byte words; there should be no problems in implementing the code on 4-byte word machines, but this has not been checked.]

2 ALGORITHMS

2.1 The radiative transfer scheme

The radiance in channel i is given by:

$$R_i = (1-N_i)\, R_i^{cl} + N_i\, R_i^{o} \tag{2.1.1}$$

where R_i^{cl} is the clear-column radiance,

R_i^{o} is the overcast radiance, and

N_i is the effective fractional cloud cover (assumed to be in a single layer).

For infra-red channels, $N_i = N_c$, the same for all channels, and N_c is an input variable. For all microwave channels, $N_i = 0$, since it is planned to include the effects of cloud liquid water through a contribution to the transmittance profile.

The clear-column radiance is given by:

$$R_i^{cl} = R_i^{s} + R_i^{a} \tag{2.1.2}$$

where R_i^{s} is the contribution from the surface, and

R_i^{a} is the contribution from the atmosphere.

[An additional contribution for solar radiation reflected by the surface could also be added here.]

The surface contribution is given by:

$$R_i^{s} = \varepsilon_i^{s}\, B_i\,(T^{s})\tau_i^{s} \tag{2.1.3}$$

where ε_i^{s} is the surface emissivity,

$B_i\,(T^{s})$ is the modified Planck function for channel i for the surface skin temperature T^{s}, and

τ_i^{s} is the transmittance from the surface to space.

For infra-red channels, the surface emissivity is currently set to one for all channels. For microwave channels, the surface emissivity is an input variable. See section 2.4 for a discussion of possible future extensions for surface emissivity.

The modified Planck function takes account of the averaging of the true Planck function over the spectral response of channel i for scene temperature T and is given by:

$$B_i\,(T) = c_{1i}\,/\,\{\,\exp\,\left(c_{2i}\,/\,\left(a_i + b_i T\,\right)\right) - 1\,\} \qquad 2.1.4$$

Where c_{1i} , c_{2i} , a_i and b_i are pre-computed coefficients for each channel (see Weinreb et al., 1981; Lauritson et al., 1979). $c_{1i} = c_1\,\nu_i^3$ and $c_{2i} = c_2\,\nu_i$, where c_1 and c_2 are the normal Planck function coefficients and ν_i is the central frequency of the channel. a_i and b_i are the so-called "band correction coefficients".

The calculation of the surface transmittance, τ_i^s, is described in section 2.2.

Returning to eq. 2.1.2, the atmospheric contribution includes both direct upward emission, R_i^u, and downward emission reflected back from the surface, R_i^d :

$$R_i^a = R_i^u + R_i^d \qquad 2.1.5$$

R_i^u is obtained as a sum of the contributions from all emitting layers:

$$R_i^u = \sum_{j=1}^{N} R_{ij}^u \qquad 2.1.6$$

where $R_{ij}^u = ½\{\,B_i\,(T_j) + B_i\,(T_{j-1})\}\ \ \{\tau_{i,j-1} - \tau_{i\,j}\}$ 2.1.7

and T_j is the temperature at atmospheric level j, and $\tau_{i\,j}$ is the transmittance in channel i from level j to space along the viewing direction of the instrument (see section 2.2).

The atmospheric levels are numbered from the top down as follows:

- for $j = 0$, pressure $p_j = 0$, $T_j = T_1$ and $\tau_{ij} = 1$,
- for $j = 1$ to $N-1$, pressures p_j are for fixed levels described in section 2.3, and
- for $j = N$, p_j = surface pressure, T_j = surface air temperature and $\tau_{i\,j} = \tau_i^s$.

Note that eq. 2.1.7 is an approximation. It assumes that the form of the radiative transfer equation (RTE) for monochromatic radiation can be applied to the spectrally-averaged radiance and the spectrally-averaged transmittance. It also represents an integral by a finite summation and assumes that the mean emission from a layer is given by the average of its boundary values.

R_i^d is obtained with a similar summation:

$$R_i^d = \sum_{j=1}^{N} R_{ij}^d \qquad 2.1.8$$

where $R_{ij}^d = R_{ij}^u\left(1-\varepsilon_i^s\right)\left(\tau_i^s\right)^2 / \left(\tau_{ij}\,\tau_{i,j-1}\right)$ 2.1.9

This is equivalent to assuming that:

- the reflection at the surface is specular, and
- the total transmittance of an atmospheric path is the product of the transmittances of its constituent sub-paths (which is strictly true only for monochromatic radiation, but is usually a good approximation when the absorption is weak).

[The assumption of specular reflection could be changed to that of reflection from a mean incoming angle with a simple modification to eq. 2.1.9].

Returning to eq. 2.1.1, the overcast radiance R_i^o is obtained as follows. The overcast radiance which would result from an opaque cloud top at pressure level J is given by:

$$R_{iJ}^o = B_i\left(T_J\right)\tau_{iJ} + \sum_{j=1}^{J} R_{ij}^u \qquad 2.1.10$$

This assumes that the opaque cloud is black and non-reflective. [It would be quite simple to modify eq. 2.1.10 to accommodate a non-black, reflective cloud. Reflection of both down-welling atmospheric emission and solar radiation could be included.]

If the cloud-top pressure, p_l, lies between pressure levels J and J-1, then the overcast radiance at p_c is obtained by linear interpolation:

$$R_i^o = \left(1-f_c\right) R_{iJ}^o + f_c\, R_{i,J-1}^o \qquad 2.1.11$$

where $f_c = \left(p_J - p_c\right) / \left(p_J - p_{J-1}\right)$ 2.1.12

Note that p_c is an effective cloud-top pressure, ie the pressure at the effective radiating temperature of the cloud. It should represent a good approximation for clouds which are either optically thick in the upper layers or geometrically thin.

The radiance is converted to an equivalent black-body temperature (brightness temperature) using the inverse of eq. 2.1.4:

$$TB_i = \{c_{2i}/(\ln(1 + c_{1i}/R_i)) - a_i\}/b_i \qquad 2.1.13$$

Note that the same form of the equations is used for microwave and infra-red channels; the Planck function is computed exactly for MSU channels even though a linearized approximation would be adequate at these frequencies.

2.2 The transmittance model

The absorption by uniformly-mixed gases is treated separately from that by water vapour. However, each is obtained with an algorithm of the same form. The optical depth for the layer from pressure level j to space along a path at an angle θ to the vertical is obtained as follows: the ratio of the optical depths for adjacent pressure levels involves a polynomial with terms which are functions of temperature and specific humidity at and above these levels. If d_{ij} is the optical depth from level j to space in channel i, then:

$$d_{ij} = d_{i,j-1} \, Y_j \sum_{k=1}^{K} a_{ijk} \, X_{kj} \qquad 2.2.1$$

In the present implementation, $K = 10$ and the values of X_{kj} and Y_j for uniformly-mixed gases and water vapour models are as follows:

	uniformly-mixed gases	water vapour
X_{1j}	$\delta T_j \sec\theta$	δT_j
X_{2j}	$\delta T_j^2 \sec\theta$	$\overline{p \, \delta T_j}$
X_{3j}	$\overline{\delta T_j} \sec\theta$	δq_j
X_{4j}	$\overline{p \, \delta T_j} \sec\theta$	$\overline{p \, \delta q_j}$
X_{5j}	$(\sec\theta - 1)$	$\delta T_j \left(\sec\theta \, u_j\right)^{½}$
X_{6j}	$(\sec\theta - 1)^2$	$\delta T_j^2 \left(\sec\theta \, u_j\right)^{½}$
X_{7j}	$\overline{\delta T_j} (\sec\theta - 1)$	$\delta q_j \left(\sec\theta \, u_j\right)^{½}$
X_{8j}	$\overline{p \, \delta T_j} (\sec\theta - 1)$	$\delta q_j^2 \left(\sec\theta \, u_j\right)^{½}$
X_{9j}	$\delta T_j (\sec\theta - 1)$	$\delta T_j \, \delta q_j \left(\sec\theta \, u_j\right)^{½}$
X_{10j}	1	1
Y_j	1	$\left(\sec\theta \, u_j\right)^{½}$

where $$\overline{\delta T_j} = \frac{1}{p_j} \sum_{\ell=1}^{j} \delta T_\ell (p_\ell - p_{\ell-1}) \qquad 2.2.2$$

$$\overline{p\ \delta T_j} = \frac{2}{p_j^2} \sum_{\ell=1}^{j} (p_\ell \delta T_\ell - p_{\ell-1}) \qquad 2.2.3$$

$$u_j = ½(q_j + q_{j-1})(p_j - p_{j-1}) \qquad 2.2.4$$

$$\delta T_j = ½\left(T_j - T_j^{ref} + T_{j-1} - T_{j-1}^{ref}\right) \qquad 2.2.5$$

$$\delta q_j = ½\left(q_j - q_j^{ref} + q_{j-1} - q_{j-1}^{ref}\right) \qquad 2.2.6$$

T_j and q_j are the temperature and specific humidity (water vapour mass mixing ratio) profiles. T_j^{ref} and q_j^{ref} are corresponding reference profiles (- the mean of a set of 1200 global profiles obtained from NESDIS has been used). Further information on the reasons for choosing this formulation, its accuracy and the method used to compute the coefficients a_{ijk} are given in Appendix A.

The absorption by ozone is treated separately using a modified version of that described by Weinreb et al. (1981) and used in ITPP and TOVSRAD. The new model for ozone optical depth is:

$$d_{ij}^{O} = \sum_{k=1}^{2} \lambda_k \{1 + (\sec\theta - 1)\ \alpha_{ijk}\} \ln \beta_{ijk} \qquad 2.2.7$$

where $\lambda_2 = (\Omega - 257)/253$,

$\lambda_1 = 1 - \lambda_2$, and

$\Omega =$ total column ozone in Dobson units.

The correspondence between the original model and the new model is discussed in Appendix A.

If the optical depths for uniformly-mixed gases, water vapour and ozone are respectively d_{ij}^{M}, d_{ij}^{W} and d_{ij}^{O}, then their combined optical depth is:

$$d_{ij} = d_{ij}^{M} + d_{ij}^{W} + d_{ij}^{O} \qquad 2.2.8$$

[This is only exact for monochromatic calculations. An improved approximation is discussed in Appendix A.]

The common practice of allowing for the inclusion of an empirical correction to the transmittance model has been followed. This is usually done by raising the computed transmittance to the power γ_i, where γ_i is determined empirically. This is equivalent to multiplying the computed optical depth by a factor γ_i. Then the corrected optical depth d^c_{ij} is given by:

$$d^c_{ij} = \gamma_i \, d_{ij} \qquad 2.2.9$$

It is anticipated (see section 2.4) that versions of the scheme may be required in which the pressure levels used for the transmittance calculation are not the same as those used in the integration of the radiative transfer equation (RTE), and that some interpolation of the transmittance profile will be needed. The architecture of the code allows this to be added later. At present the RTE is integrated on the same fixed levels on which the transmittances are calculated, and the only interpolation/ extrapolation required is to obtain the surface transmittance. If the surface pressure p_s lies between standard levels L and $L\text{-}1$, then the optical depth at the surface, d^c_{iN}, is obtained by linear interpolation:

$$d^c_{iN} = d^c_{iL} + f_s \left(d^c_{i,L-1} - d^c_{iL}\right) \qquad 2.2.10$$

where $$f_s = \left(p_L - p_s\right) / \left(p_L - p_{L-1}\right) \qquad 2.2.11$$

If p_s exceeds the pressure of all the fixed levels, then L is set to the last fixed level (highest in pressure) and d^c_{iN} is extrapolated using the same equations.

Finally, optical depths are converted to transmittances:

$$\tau_{ij} = \exp\left(- d^c_{ij}\right) \qquad 2.2.12$$

Note that, in this way, only one exponent calculation is required for each transmittance.

2.3 Treatment of the atmospheric profile

The transmittance and RT calculations are performed using atmospheric layers bounded by a number of fixed pressure levels (plus surface pressure and cloud-top pressure). The 40 fixed levels currently used are defined in Table 1. [Other sets of levels could easily be used. However transmittance coefficients corresponding to them would then be required.] The atmospheric profile of temperature and water vapour and all the related parameters required in the transmittance calculations must therefore be set up for these levels and the corresponding layers.

Table 1 Fixed pressure levels (in mb)

0.1	0.2	0.5	1	1.5	2	3	4	5	7
10	15	20	25	30	50	60	70	85	100
115	135	150	200	250	300	350	400	430	475
500	570	620	670	700	780	850	920	950	1000

Table 2 Profile vector

Element No	Description
1 - 40	temperature in K at 40 fixed pressure levels
41 - 55	ln (specific humidity in g/Kg) at 15 lowest fixed levels
56	surface air temperature in K
57	surface air ln (specific humidity in g/Kg)
58	surface skin temperature in K
59	surface pressure in mb
60	total column ozone in Dobson units
61	cloud-top pressure in mb
62	effective fractional cloud coverage
63	microwave surface emissivity (50.3 GHz)
64 - 66	microwave surface emissivity parameters - not used at present
67	total column cloud liquid water in mm - not used at present

The RT model takes as input a "profile vector" of 67 elements as defined in Table 2. Humidity is currently specified as ln (specific humidity in g/Kg) for ease of use with the present formulation of the 1DVAR retrieval scheme. [It would be simple to modify the code to accept other variables such as specific humidity itself or relative humidity.] To simulate clear-column radiances, N_c is set to zero, but p_c should be set to a realistic value, as it is required in the tangent linear, adjoint and gradient calculations. Only the first parameter for microwave surface emissivity is currently used and represents the emissivity at MSU frequencies. Planned extensions to use the other parameters are discussed in section 2.4. Similarly, total column cloud liquid water is not currently used. The integration of the RTE only uses levels at and above the surface. However, the interpolation of the surface transmittance also makes use of a pressure level below the surface. It is therefore important that the temperature and humidity at this level are extrapolated in a realistic way or else set equal to the surface air values.

The humidity profile is specified by the input only for the lowest 15 levels (i.e. up to 300 mb). It is extrapolated internally to give a reasonable stratospheric profile as follows: if p_j is pressure in mb, then

for $300 > p_j \geq 70$, $q_j = \max\ \{q_{300}\ (p_j\ /\ 300)^3, q_{min}\}$

and for $p_j < 70$, $q_j = q_{min}$,

where $q_{min} = 0.003\ g/Kg$.

Using the temperature and humidity at fixed levels, the total column ozone, the surface pressure and the angle of the viewing path, all the other profile variables required in the calculation of optical depth are calculated as described in section 2.2

2.4 Potential developments

Some potential developments to the scheme have already been mentioned in sections 2.1 - 2.3 and, regarding the transmittance model, in Appendix A. This section elaborates on some of these plans and possibilities.

Cloud liquid water

Provision has been made for inclusion of the effects of cloud liquid water on microwave channels through an additional optical depth profile. This would also require methods for distributing the input of total column cloud liquid water between different layers in a reasonable way, and then for converting the amount in each layer to an optical depth. Alternatively, a more substantial change could be made in order that the profile of cloud liquid water (rather than the total) could be given as input.

Surface emissivity - microwave

At present the microwave surface emissivity is provided as a single input variable for each profile. This is adequate for MSU because the channels which "see" the surface are close in frequency. However, for other instruments (e.g. SSM/I, AMSU) this is not the case, and a different method must be used. Provision has been made for up to four variables. This should allow the implementation of parametric models such as that proposed by Grody (1988) in which a number of parameters define the emissivity as some function of frequency, where the function is appropriate for many natural surface types. Alternatively, if the surface type is known, then the surface type indicator - already an input to the model - could be used to drive a physical model of surface emissivity.

Surface emissivity - infra-red

The code allows for a number of surface types of which three are currently active (surface = black, sea or land), but infra-red surface emissivities are set to one for all channels for all surfaces. However this could easily be changed to more surface types and to a different value for each channel and surface type.

Ozone transmittance

The model used here for ozone transmittance is rather crude. It is probably adequate for the weak effects of ozone of HIRS channels 1 - 7 . However, it is not adequate for HIRS channel 9 - the ozone channel at 9.7 µm. A better model, suitable for all channels, would be desirable. Given appropriate line-by-line calculations, a fast model of the same form as the water vapour transmittance model could be implemented.

Surface humidity

Although this is an input variable, it is not currently used because it does not affect the transmittance profile; the optical depth at the surface is obtained by interpolation/extrapolation from adjacent fixed levels. A modification to this procedure would be desirable so that the input surface humidity did have some effect on the radiance through the surface transmittance.

Integration of the radiative transfer equation

This is currently performed on the same fixed pressure levels as used in the transmittance calculation. Although this is usually quite accurate, there is evidence that it can lead to undesirably large errors in certain cases. The small numbers of levels around the tropopause and in the boundary layer are particular concerns. This could be remedied in the following ways:

- changing the fixed pressure levels to more suitable values and perhaps increasing their number,

- using the fixed levels only for the optical depth calculation and performing the RTE integration on another set of levels. If a NWP model profile is used as input, then the NWP model's levels/layers could be used for this purpose. In this case the profile would have to be interpolated to the fixed levels for the optical depth calculation, and then the results interpolated back for the RTE integration.

Solar reflection

This is currently omitted, but provision has been made for its inclusion. It should be introduced consistently with the inclusion of non-black (reflective) surfaces and/or clouds. The solar zenith angle is already present as input for this purpose.

2.5 Tuning

Like similar RT models, the new model is not expected to give results sufficiently accurate for use with real data unless it has undergone empirical tuning through comparison of measured radiances with those calculated from collocated radiosonde and/or NWP model profiles. The method used in the ITPP and TOVSRAD models has been retained.

- A correction to the calculated transmittance by raising it to the power γ (implemented here by multiplying the optical depth by γ - see section 2.2). γ is a different constant for each channel and is expected to be adjusted infrequently (e.g. once per satellite).

- A bias correction, δ, to the calculated brightness temperatures. For flexibility, this has not been implemented within the RT scheme but should be applied to its output. It is expected that these values will have to be functions of latitude or air mass type and to require frequent tuning (e.g. once per month) as the biases in some channels may exhibit a seasonal cycle.

3 TANGENT LINEAR, ADJOINT AND GRADIENT MATRIX MODELS

If we represent the RT scheme as an operator for transforming an atmospheric profile vector, **x**, into a radiance (or brightness temperature) vector, **y**:

$$\mathbf{y} = \mathbf{F}\{\mathbf{x}\}, \tag{3.1}$$

then the tangent linear operation can be written in terms of the gradient of this equation:

$$\delta\mathbf{y} = \mathbf{K}\{\mathbf{x}\} \, . \, \delta\mathbf{x}, \tag{3.2}$$

where **K{x}** is the matrix of partial derivatives of **F{x}** with respect to **x**. The adjoint of this operation can be written in terms of the transpose of **K{x}**:

$$\mathrm{grad}_x = \mathrm{grad}_x y \, . \, \mathrm{grad}_y = \mathbf{K}\{\mathbf{x}\}^T \, . \, \mathrm{grad}_y \tag{3.3}$$

Therefore, in principle, both the tangent linear and adjoint operations can be performed by computing the gradient matrix, **K{x}**, and then performing the appropriate dot product. However, for very large systems it may not be feasible to calculate the full matrix, and we need to perform the tangent linear and adjoint operations without explicitly calculating the matrix **K{x}**. In this case, we may represent the operations in a general way:

tangent linear: $\delta\mathbf{y} = \mathrm{TL}\{\mathbf{x} \, , \, \delta\mathbf{x}\}$ 3.4

adjoint: $\mathrm{grad}_x = \mathrm{AD}\{\mathbf{x} \, , \, \mathrm{grad}_y\}$ 3.5

For the direct RT model described above the three associated models - K, TL and AD - have all been coded (see section 4.2). All three models are exact (cf. the **K**-matrix model developed by Eyre (1989), which is only approximate). The method for TL and AD is the same as that followed by Thépaut and Moll (1990). It is possible to develop the K-matrix code either from that of the TL or AD models. In practice it was found much easier in this case to modify the AD model.

4 SOFTWARE

4.1 The direct model

The subroutine structure of the code is given in Figure 1 and the interface to each top-level subroutine is documented in Appendix B. The code is used as follows:

- An initial call to routine RTTVI is required to set up the constant data and to read in the satellite-dependent coefficients (for all possible satellites). Coefficients are read in by the subroutine TOVCF as follows:

I/O Unit	Data set.
15	Mixed-gas transmittance coefficient file.
16	Water vapour transmittance coefficient file.
13	ITPP HIRS transmittance coefficient file (from which ozone transmittance coefficients, Planck function coefficients and HIRS γ values are extracted).
14	ITPP MSU transmittance coefficient file (from which MSU channel frequencies and γ values are extracted).

- Initially, and then whenever a change is made to the satellite for which data are being processed, a call to routine NEWSAT must be made. The argument giving the satellite identifier is defined as follows: 5 = TIROS-N, 6 = NOAA-6, 7 = NOAA-7, etc. This routine sets up the satellite-dependent data for the appropriate satellite.

- The RT model itself is called RTTOV. Its input and output are defined in Appendix B. The following should be taken into account:

  - The representation of the profile vectors, PROF, is described in Table 2 and discussed in section 2.3.

  - PRAD is the output radiance vector in $mW.m^{-2}.sr^{-1}.(cm^{-1})^{-1}$ and PTB is the output brightness temperature vector in K.

  - KPROF and KCHAN are the indices of the profiles and channels used for each radiance in the output vectors, PRAD and PTB. For example, if we wish to calculate radiances for channels 1, 3, 4 and 7 from profiles 1, 2 and 3 (12 radiances in all), then we must set:

KCHAN = [1, 3, 4, 7, 1, 3, 4, 7, 1, 3, 4, 7] and
KPROF = [1, 1, 1, 1, 2, 2, 2, 2, 3, 3, 3, 3].

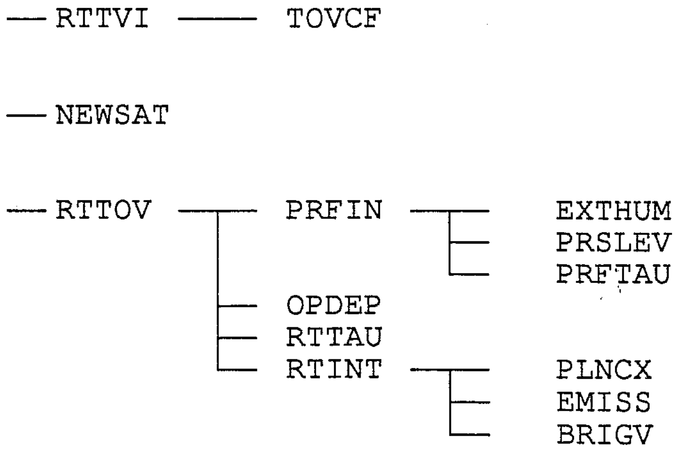
  - PANGL contains the scan angles of the satellite instrument view corresponding to each profile. Note that they are scan angles with respect to satellite nadir; they are converted internally to zenith angles with respect to the Earth's surface.

  - PANGS contains the solar zenith angles with respect to the Earth's surface for each profile. They are not currently used in the RT calculation.

  - KSURF contains the surface type index for each profile. Currently, three surface types are allowed: 1 = black, 2 = sea, 3 = land. Also at present, they have no effect, since the infra-red emissivities are set (in RTTVI) to one for all three surface types and the microwave emissivity is defined by an input variable. [KSURF could be used for these and other purposes in later versions.]

- Apart from the two set-up routines and their associated input files, the routine RTTOV is self-contained with its arguments providing all the essential input and output. However, useful intermediate variables are stored in COMMON blocks and are available to the user. These include the optical depth profiles, the transmittance profiles and the clear-column radiances and brightness temperatures and the overcast radiances at all standard pressure levels.

<u>Figure 1</u> <u>Subroutine structure</u>



4.2 The tangent linear (TL), adjoint (AD) and gradient matrix (K) models

RTTOV and all its subroutines have equivalent subroutines to perform each of the TL, AD and K operations. Each routine has the same name as the corresponding direct routine with the suffix ...TL, ...AD or ...K as appropriate. Before running the AD, TL or K models, it is necessary to run the corresponding direct calculations, as many of the intermediate variables calculated by the direct model (and stored in COMMON blocks) are needed by the TL, AD and K models.

4.3 COMMON blocks

Most of the intermediate variables are stored in and passed between routines through COMMON blocks. This is necessary for communication of the direct model with the TL, AD and K models, as it would not be convenient to pass them all through argument lists. There is a strict separation between COMMONs containing constants and those containing variables of the RT calculation. For each COMMON containing direct model variables, there is an equivalent COMMON containing either tangent linear or adjoint variables (same name as direct model COMMON with suffix ...TL) and also an equivalent COMMON containing K-model variables (same name as direct model COMMON with suffix ...K). The direct model COMMONs and their documentation are given in Appendix B.

4.4 PARAMETER statements

The dimensions of all the major storage arrays are controlled through PARAMETER statements. These appear in the module CPARAM which forms part of every subroutine (see Appendix B). The user may expect to have to change at least two of these:

- JPSAT. This controls the minimum number of satellites which the suite will process. With JPSAT = 7, it will handle the satellites TIROS-N through to NOAA-11, and so it will need to be increased to handle NOAA-12 and further satellites.

- JPPF. This controls the maximum number of profile vectors which can be processed together and can also control the total storage required by RTTOV as follows:

    - The direct model COMMON blocks occupy:
      ~7 Kwords per profile (assuming 40 pressure levels and 23 channels)
      plus ~28 Kwords x (JPSAT + 1).

- The tangent linear and adjoint model require in addition:
  ~7 Kwords per profile.

- The K-matrix model requires in addition:
  ~37 Kwords per profile.

Current plans are to set JPPF to ~50 when running either the direct model alone or (as in the 3DVAR) the direct model with the adjoint model. The 1DVAR requires the direct model and the K-matrix model, but as presently formulated, there is no advantage in setting JPPF greater than one (i.e. in processing more than one profile at a time).

4.5 Execution times

Trials on the CRAY-YMP achieved the following CPU speeds for a single processor with 19 TOVS channels processed in blocks of 50 profiles:

direct model	1.15 ms per profile (all 19 channels)
TL	1.17 ms per profile
AD	2.21 ms per profile.

Processing one profile at a time, speeds were:

direct model	1.97 ms per profile
K	2.23 ms per profile
AD	3.14 ms per profile.

Note that K is faster than AD, even though the former involves more computation. This occurs because greater gains from vectorization are possible in the K-model. This means that it is faster to compute the adjoint through the K-matrix followed by a dot product (see section 3). However, there is a trade-off: the storage requirements for the K-model may become prohibitive if ~50 profiles are processed together.

References

Eyre, J.R., 1990: Progress on direct use of satellite sounding radiances in numerical weather prediction. Preprints WMO Int. Symp. on "Assimilation of Observations in Meteorology and Oceanography"; Clermont-Ferrand, France; 9-13 July 1990; WMO Report, 117-121.

Eyre, J.R., 1989: Inversion of cloudy satellite sounding radiances by nonlinear optimal estimation. Q.J.R. Meteorol. Soc., 115, 1001-1037.

Eyre, J.R., 1984: User guide to TOVSRAD: a program for calculating synthetic HIRS-2 and MSU equivalent black-body temperatures. U.K. Met. Office Report, Met.0.19 Branch Memo 75.

Eyre, J.R. and Woolf, H.M., 1988: Transmittances of atmospheric gases in the microwave region: a fast model. Appl. Optics, 27, 3244-3249.

Grody, N., 1988: Surface identification using satellite microwave radiometers. IEEE Transactions on Geoscience and Remote Sensing, 26, 850-859.

Lauritson, L., Nelson, G.J. and Porto, F.W., 1979: Data extraction and calibration of TIROS-N/NOAA radiometers. NOAA Tech. Mem. NESS 107.

McMillin, L.M. and Fleming, H.E., 1976: Atmospheric transmittance of an absorbing gas: a computationally fast and accurate model for absorbing gases with constant mixing ratios in inhomogeneous atmospheres. Appl. Optics, 15, 358-363.

Pailleux J., 1989: Design of a variational analysis: organisation and main scientific points. ECMWF Tech. Mem. 150.

Pailleux J., 1990: A global variational assimilation scheme and its application for using TOVS radiances. Preprints WMO Int. Symp. on "Assimilation of Observations in Meteorology and Oceanography"; Clermont-Ferrand, France; 9-13 July 1990; WMO Report, 325-328.

Thépaut, J-N. and Moll, P., 1990: Variational inversion of simulated TOVS radiances using the adjoint technique. Q.J.R. Meteorol. Soc., 116, 1425-1448.

Schwalb A., 1978: The TIROS-N/NOAA A-G satellite series. NOAA Tech. Mem. NESS 95.

Smith W.L., Woolf H.M., Hayden C.M., Wark D.Q. and McMillin L.M., 1979: The TIROS-N Operational Vertical Sounder. Bull. Am. Meteorol. Soc., 60, 1177-1187.

Weinreb, M.P., Fleming, H.E., McMillin, L.M. and Neuendorffer, A.C., 1981: Transmittances for the TIROS Operational Vertical Sounder. NOAA Tech. Rep. NESS 85.

APPENDIX A. TRANSMITTANCE MODEL - FURTHER DETAILS

A.1 Calculation of coefficients

For a small number of diverse atmospheric profiles (32 were used here), transmittances were calculated. Ideally this should be done using a line-by-line model but so far the ITPP/TOVSRAD fast RT model has been used for this purpose. Results were calculated and stored separately for uniformly-mixed gases and for water vapour and, for this purpose, ozone was excluded. Transmittances were calculated for all 40 pressure levels (see table 1) and for five scan angles (at secθ = 1, 1.25, 1.5, 1.75 and 2). Coefficients a_{ijk} in equation 2.2.1 were then calculated by linear regression of $\{(d_{jk} / d_{j-1,k}) / Y_j\}$ against X_{ij}.

A.2 Rationale for the new model

The uniformly-mixed gases are treated in the same way as in the Eyre/Woolf model, except that the water vapour terms have been removed (since this component of the transmittance does not depend on them) and they have been replaced by terms representing the off-nadir effects.

The water vapour model is similar to the Eyre/Woolf model but has the following differences. Firstly, the angular dependence has been addressed in a single algorithm. Secondly, the relatively poor performance of the Eyre/Woolf model for water vapour channels was traced to the difficulty in calculating coefficients using a linear regression method when the absolute water vapour amounts vary by orders of magnitude between cold, dry profiles and warm, moist profiles. The performance is improved by replacing (d_j / d_{j-1}) by $(d_j / d_{j-1})(\sec\theta \; u_j)^{-\frac{1}{2}}$ as the predictand in the regression; the latter can be considered as an "effective absorption coefficient" in the strong absorption limit and so varies only moderately from profile to profile. This is the origin of terms 1 to 4 in the expansion. Terms 5 to 9, which correspond to fitting $(d_j / d_{j-1})(\sec\theta \; u_j)^{-1}$, are included to allow for the behaviour when the water vapour absorption is dominated by either weak lines or continuum effects. It should be stressed however that the precise form of the terms included was arrived at empirically.

A.3 Accuracy

The accuracy of the model was checked by comparing the transmittances computed directly by the ITPP model with those from the new model. For the 32 profiles used as the dependent set (i.e. for the calculation of regression coefficients), the standard deviations of the error were calculated for uniformly-mixed gases only, for water vapour only and for their combination. The transmittance errors for uniformly-mixed gases were negligible, reaching a maximum of 0.2% in HIRS channel 5. Errors were larger by up to an order of magnitude for water vapour, the maximum standard deviation of error being about 1.6% in HIRS channel 12 at 620 mb. Comparable errors were also present at lower altitudes in most other channels, but they are only significant in the combined transmittance for HIRS channel 7-8, 10-11 and 19 and for MSU channel 1.

The accuracy was also checked for three independent samples of 32 profiles each: a mid-latitude, a high latitude and a low latitude set. Results were comparable with those for the dependent sample.

A.4 Water vapour transmittance in stratosphere

Water vapour transmittances are calculated for levels $p_j \geq 100$ mb using an accurate integration of the water vapour amount from p_j to 0.1 mb. At present in the new model, no calculation is performed for $p_j < 100$ mb, i.e. $\tau_j = 1$. This is because no coefficients have been generated for $p_j < 100$ mb due to an instability in the ITPP water vapour routine in this region. This does not lead to serious problems and could be corrected if regression coefficients were calculated using line-by-line transmittances.

u_j is as defined in section 2.2 (i.e. the layer water vapour content), except (for consistency) at $p_j = 100$ mb, where u_j is the sum of the water vapour in all layers above 100 mb.

A.5 A possible extension

At present the new model follows the ITPP model in assuming that the three contributions to the transmittance are separable - see equation 2.2.8. This is equivalent to a monochromatic transmittance approximation and for real, non-monochromatic channels may not always be accurate. It could be improved if line-by-line optical depth calculations were available for:

- uniformly-mixed gases only, and
- uniformly-mixed gases plus water vapour.

The total optical depth could be calculated as:

$$d_j = d_j^M + d_j^{MW-M} + d_j^O$$

where d_j^{MW-M} is the optical depth for (mixed gases plus water vapour) minus the optical depth for mixed gases alone, represented by one polynomial expansion of the same form as currently used for water vapour alone.

A.6 The new ozone model

Using the same symbols as in section 2.2, the original model of Weinreb et al.(1981) can be written:

$$d_{ij}^{o} = -\ln \{ \sum_{k=1}^{2} \lambda_k (\beta_{ijk})^{1 + (\sec\theta - 1)\alpha_{ijk}} \}$$

and so this allows us to use the same coefficients, α_{ijk} and β_{ijk}, as in the ITPP model. The two models will agree exactly at the two values of Ω used in calculating the coefficients (257 and 480 Dobson units). Elsewhere they will differ, but the maximum difference in transmittance is found to be ~0.001, which is probably much less than the error in either model.

These models are rather crude but probably adequate for all HIRS channels except channel 9 (9.7 μm).

Appendix B. SOFTWARE DOCUMENTATION

B.1 User interfaces

```
RTTVI
          CALL RTTVI(KERR)
               KERR   -  ERROR FLAG, RETURNS KERR.NE.0 IF ERROR.

NEWSAT
          CALL NEWSAT(KSAT,KERR)
               KSAT   -  SATELLITE I/D: TIROS-N=5, NOAA-6=6,
                         NOAA-7=7, ETC
               KERR   -  ERROR FLAG, RETURNS KERR.NE.0 IF ERROR.

RTTOV
          CALL RTTOV(PROF,KNPF,KLENPF,PANGL,PANGS,KSURF,
                     KCHAN,KPROF,KNCHPF,PRAD,PTB)
               PROF   -  INPUT PROFILE VECTORS (KLENPF,KNPF)
                    EACH VECTOR:
                    1-40: TEMPERATURE IN K AT 40 STANDARD
                          PRESSURE LEVELS (DEFINED IN RTTVI)
                    41-55: LN(SPECIFIC HUMIDITY IN G/KG) AT THE
                           15 LOWEST STANDARD PRESSURE LEVELS
                    56: SURFACE AIR TEMPERATURE IN K
                    57: LN(SURFACE SPECIFIC HUMIDITY IN G/KG)
                    58: SURFACE SKIN TEMPERATURE IN K
                    59: SURFACE PRESSURE IN MB
                    60: TOTAL COLUMN OZONE AMOUNT IN DOBSON UNITS
                    61: CLOUD-TOP PRESSURE IN MB
                    62: FRACTIONAL (INFRA-RED) CLOUD COVER
                    63: MICROWAVE SURFACE EMISSIVITY
                        (AT 50.3 GHZ)
                    64-66: NOT USED, RESERVED FOR MORE MICROWAVE
                           SURFACE EMISSIVITY PARAMETERS
                    67: TOTAL COLUMN CLOUD LIQUID WATER IN MM
                        (NOT CURRENTLY USED)
               KNPF   -  INPUT NUMBER OF PROFILE VECTORS
               KLENPF -  INPUT LENGTH OF EACH PROFILE VECTOR
               PANGL  -  INPUT SATELLITE NADIR ANGLES (KNPF)
               PANGS  -  INPUT SOLAR ZENITH ANGLES (KNPF)
               KSURF  -  INPUT SURFACE TYPE INDICES (KNPF)
                         (1=BLACK, 2=SEA, 3=LAND)
               KCHAN  -  INPUT ARRAY OF CHANNEL INDICES (KNCHPF)
                    INDEX 1-19 = HIRS 1-19, INDEX 20-23 = MSU 1-4
               KPROF  -  INPUT ARRAY OF PROFILE INDICES (KNCHPF)
               KNCHPF -  INPUT NUMBER OF RADIANCES
                         (=CHANS*PROFS USED)
               PRAD   -  OUTPUT ARRAY OF RADIANCES (KNCHPF)
                         IN MW.M-2.SR-1.(CM-1)-1
               PTB    -  OUTPUT ARRAY OF BRIGHTNESS TEMPS
                         (KNCHPF) IN K
```

B.2 Subroutines

RTTVI	INITIALISATION FOR TOVS RT ROUTINE, RTTOV. TO BE CALLED BEFORE FIRST CALL TO RTTOV.
TOVCF	TO INITIALISE SATELLITE-DEPENDENT DATA AND COEFFICIENTS FOR TOVS RT ROUTINES FOR ALL SATELLITES.
NEWSAT	TO INITIALISE SATELLITE-DEPENDENT DATA AND COEFFICIENTS FOR TOVS RT ROUTINES.
ACOPY	TO COPY ALL ELEMENTS OF ONE ARRAY TO ANOTHER.
RTTOV	TO COMPUTE MULTI-CHANNEL TOVS RADIANCES AND BRIGHTNESS TEMPERATURES FOR MANY PROFILES.
PRFIN	TO SET UP PROFILE-DEPENDENT VARIABLES FOR SUBSEQUENT RT CALCULATIONS BY OTHER SUBROUTINES OF RTTOV.
EXTHUM	TO EXTEND MIXING RATIO PROFILE INTO STRATOSPHERE IN A REASONABLE WAY.
PRSLEV	FINDS THE INDICES AND FRACTIONAL LEVELS LOCATING GIVEN PRESSURES ON AN ARRAY OF FIXED PRESSURE LEVELS.
PRFTAU	TO CALCULATE AND STORE THE PROFILE VARIABLES REQUIRED IN SUBSEQUENT TRANSMITTANCE CALCULATIONS.
OPDEP	TO CALCULATE OPTICAL DEPTHS FOR A NUMBER OF CHANNELS AND PROFILES FROM EVERY PRESSURE LEVEL TO SPACE.
RTTAU	TO INTERPOLATE OPTICAL DEPTHS ON TO LEVELS OF RT MODEL (WHICH, AT PRESENT, ENTAILS ONLY SURFACE TRANSMITTANCE, AS OTHER OPTICAL DEPTHS ARE ON RT LEVELS) AND TO CONVERT OPTICAL DEPTHS TO TRANSMITTANCES.
RTINT	TO PERFORM INTEGRATION OF RADIATIVE TRANSFER EQUATION IN RTTOV SUITE, CALCULATING RADIANCES AND BRIGHTNESS TEMPERATURES.
PLNCX	TO CONVERT AN ARRAY OF ATMOSPHERIC TEMPERATURES, 1 FROM EACH PROFILE, TO PLANCK FUNCTIONS IN MANY CHANNELS FOR EACH PROFILE.
EMISS	TO SET UP SURFACE EMISSIVITIES FOR ALL CHANNELS AND ALL PROFILES.
BRIGV	TO CONVERT AN ARRAY OF RADIANCES IN MANY CHANNELS TO BRIGHTNESS TEMPERATURES.

B.3 COMMON blocks

```
C       /ALLSAT/ SATELLITE-DEPENDENT  DATA FOR ALL SATELLITES
C       7/12/90.
      COMMON/ALLSAT/CFMA,CFWA,CFOA,
     *WVNUMA,BCON1A,BCON2A,TC1A,TC2A,GAMMAA,FRQMSA,AHTSAT
      REAL CFMA(JPCOFM,JPLEV,JPCH,JPSAT),CFWA(JPCOFW,JPLEV,JPCH,JPSAT),
     *CFOA(JPCOFO,JPLEV,JPCH,JPSAT),
     *WVNUMA(JPCH,JPSAT),BCON1A(JPCH,JPSAT),
     *BCON2A(JPCH,JPSAT),TC1A(JPCH,JPSAT),TC2A(JPCH,JPSAT),
     *GAMMAA(JPCH,JPSAT),FRQMSA(JPMSU,JPSAT),AHTSAT(JPSAT)
C       CFMA: MIXED GAS COEFFS      ) NO. OF COEFFS
C       CFWA: WATER VAPOUR COEFFS ) * NO. OF PRESS LEVELS
C       CFOA: OZONE COEFFS          ) * NO. OF CHANNELS * NO. OF SATS
C       WVNUMA: WAVENUMBER IN CM**-1
C       BCON1A: 1ST PLANCK FUNCTION CONSTANT IN MW/M**2/SR/CM**-4
C       BCON2A: 2ND PLANCK FUNCTION CONSTANT IN K/CM**-1
C       TC1A: BAND CORRECTION COEFFICIENT: OFFSET IN K
C       TC2A: BAND CORRECTION COEFFICIENT: SLOPE IN K/K
C       GAMMAA: "GAMMA FACTOR" TRANSMITTANCE CORRECTIONS
C       FRQMSU: MSU CHANNEL FREQUENCIES IN GHZ
C       AHTSAT: SATELLITE HEIGHT IN KM


C       /EMISIR/ IR SURFACE EMISSIVITIES
C       4/12/90.
      COMMON/EMISIR/EMSIR
      REAL EMSIR(JPCH,JPST)
C       EMSIR: IR SURFACE EMISSIVITIES (ALL CHANS * ALL SURF TYPES)


C       /EMIZ/    SURFACE EMISSIVITIES (ALL CHANS) FOR RT CALCS
C       6/12/90.
      COMMON/EMIZ/EMS
      REAL EMS(JPCHPF)
C       EMS: SURFACE EMISSIVITY (CHANS USED * PROFILES USED)


C       /GEOCON/ SATELLITE GEOMETRY CONSTANTS
C       4/12/90.
      COMMON/GEOCON/HTSAT,RATOE
C       HTSAT: SATELLITE ALTITUDE IN KM
C       RATOE: RATIO SATELLITE-ORBIT:EARTH RADII


C       /GEOPTH/ SATELLITE AND SOLAR GEOMETRY VARIABLES
C       4/12/90.
      COMMON/GEOPTH/XPATH,XPATH1,SQTPTH,XPATHS
      REAL XPATH(JPPF),XPATH1(JPPF),SQTPTH(JPPF),XPATHS(JPPF)
C       XPATH: SECANT OF VIEWING PATH ANGLE AT SURFACE
C       XPATH1: XPATH - 1
C       SQTPTH: SQRT OF XPATH
C       XPATHS: SECANT OF SOLAR ZENITH ANGLE AT SURFACE
```

```
C       /IRCLD/  IR CLOUD VARIABLES
C       4/12/90.
      COMMON/IRCLD/NLEVCD,FRACPC
      REAL FRACPC(JPPF)
      INTEGER NLEVCD(JPPF)
C       NLEVCD: INDEX OF NEAREST STD PRESS LEVEL AT/BELOW CLOUD TOP
C       FRACPC: FRACTION OF STD PRESS LEVEL INTERVAL BY WHICH CLOUD
C            IS ABOVE LEVEL NLEVCD


C       /MSUFRQ/  MSU CHANNEL FREQUENCIES
C       4/12/90.
      COMMON/MSUFRQ/FRQMSU
      REAL FRQMSU(4)
C       FRQMSU: MSU CHANNEL FREQUENCIES  IN GHZ


C       /OPTDEP/  OPTICAL DEPTHS
C       4/12/90.
      COMMON/OPTDEP/OPDP,OPDPA
      REAL OPDP(JPCHPF,JPLEV),OPDPA(JPCHPF)
C       OPDP: OPTICAL DEPTH FROM PRESS LEVEL TO SPACE
C           (CHANS * PROFILES USED, STD PRESS LEVELS)
C       OPDPA: WORKSPACE USED IN CALCULATING OPDP


C       /PRFCON/  ATMOSPHERIC PROFILE CONSTANTS
C       4/12/90.
      COMMON/PRFCON/XPRES,XPRES2,DPRES,WPRES3,WMIN,NLEVW1,NLEVW2,NLEVW
      REAL XPRES(JPLEV),XPRES2(JPLEV),DPRES(JPLEV),WPRES3(JPLEV)
C       XPRES: STD PRESS LEVELS FOR TRANSMITTANCE (AND, CURRENTLY,
C           RT) CALCULATION; FROM TOP DOWN; IN MB=HPA
C       XPRES2: XPRES**2; IN MB**2
C       DPRES: INTERVALS BETWEEN STD PRESS LEVELS; IN MB
C       WPRES3: (XPRES/REF.PRESS)**3,
C            WHERE REF.PRESS=XPRES(NLEVW2+1)
C       WMIN: MIN WATER VAPOUR SPECIFIC HUMIDITY; IN G/KG
C       NLEVW1: UPPER LEVEL FOR WATER VAPOUR EXTRAPOLATION
C       NLEVW2: LOWER LEVEL FOR WATER VAPOUR EXTRAPOLATION
C       NLEVW: UPPER LEVEL FOR WATER VAPOUR TRANSMITTANCE CALC
C           (ASSUMED TRANSMITTANCE=0.  ABOVE THIS)


C       /PRFREF/  REFERENCE PROFILE IN TRANSMITTANCE CALC
C       4/12/90.
      COMMON/PRFREF/TREF,WREF
      REAL TREF(JPLEV),WREF(JPLEV)
C       TREF: REFERENCE TEMPERATURE PROFILE IN K
C       WREF: REFERENCE SPECIFIC HUMIDITY PROFILE IN G/KG
```

```
C       /PRFVAR/  PROFILE  VARIABLES
C       4/12/90.
      COMMON/PRFVAR/TEMP,WMIX,TA,WMIXS,TS,SURFP,
     *TOTO,CLDP,CLDF,EMSMW,CLW
      REAL  TEMP(JPLEV,JPPF),WMIX(JPLEV,JPPF),TA(JPPF),WMIXS(JPPF),
     *TS(JPPF),SURFP(JPPF),TOTO(JPPF),CLDP(JPPF),CLDF(JPPF),
     *EMSMW(4,JPPF),CLW(JPPF)
C       TEMP: TEMPERATURE  PROFILE  IN K
C       WMIX: SPECIFIC  HUMIDITY  PROFILE  IN G/KG
C       TA: SURFACE  AIR TEMPERATURE   IN K
C       WMIXS: SURFACE  SPECIFIC  HUMIDITY  IN G/KG
C       TS: SURFACE  SKIN TEMPERATURE   IN K
C       SURFP: SURFACE  PRESSURE  IN MB=HPA
C       TOTO: TOTAL  COLUMN  OZONE  AMOUNT  IN DOBSON  UNITS
C       CLDP: CLOUD-TOP  PRESSURE  IN MB=HPA
C       CLDF: FRACTIONAL  (IR) CLOUD  COVER
C       EMSMW: 4 MICROWAVE  SURFACE  EMISSIVITY  PARAMETERS;
C            CURRENTLY  ONLY IST USED, = EMISS AT MSU FREQS
C       CLW: TOTAL  COLUMN  CLOUD  LIQUID  WATER  IN MM


C       /RTSTOR/  STORAGE  FOR  RT  CALCULATION  VARIABLES
C       4/12/90.
      COMMON/RTSTOR/B,BA,BS,RADOV,RADO,BDT,BDTR,FCLD,RADCL,TBCL
      REAL  B(JPCHPF,JPLEV),BA(JPCHPF),BS(JPCHPF),
     *RADOV(JPCHPF,JPLEV),RADO(JPCHPF),
     *BDT(JPCHPF,JPLEV),BDTR(JPCHPF,JPLEV),FCLD(JPCHPF),
     *RADCL(JPCHPF),TBCL(JPCHPF)
C       B: PLANCK  FUNCTIONS  FOR  TEMPERATURES   PROFILES
C         (CHANNELS  * PROFILES  USED,  STD PRESS LEVELS)
C       BA: PLANCK  FUNTIONS  FOR  SURFACE  AIR  TEMPERATURES
C       BS: PLANCK  FUNTIONS  FOR  SURFACE  SKIN TEMPERATURES
C       RADOV:  OVERCAST  RADIANCES  FOR  CLOUD  AT EACH  STD P LEVEL
C       RADO:  OVERCAST  RADIANCES  FOR  GIVEN  CLOUD-TOP  PRESSURES
C       BDT: STORES  UPWELLING  RADIATION  FROM  ATMOSPHERE  ABOVE  EACH
C           LEVEL.
C       BDTR: STORES  DOWNWELLING  RADIATION  AT EACH  LEVEL  FROM
C            ATMOSPHERE  ABOVE
C       FCLD: EFFECTIVE  FRACTIONAL  CLOUD  COVER  FOR  EACH  CHAN * PROF
C       RADCL:  CLEAR  COLUMN  RADIANCES
C       TBCL: CLEAR  COLUMN  BRIGHTNESS  TEMPERATURES   IN K
C       *** ALL RADIANCES  IN MW/M**2/SR/CM**-1


C       /RTTEMP/  TEMPERATURE  PROFILES  ARRANGED  FOR  RT  CALCULATION
C       4/12/90.
      COMMON/RTTEMP/T
      REAL  T(JPPF,JPLEV)
C       T: TEMPERATURE   PROFILES  (PROFILES,  LEVELS)  IN K


C       /SURF/    SURFACE  VARIABLES
C       4/12/90.
      COMMON/SURF/NLEVSF,FRACPS,NSTYPE
      REAL  FRACPS(JPPF)
      INTEGER  NLEVSF(JPPF),NSTYPE(JPPF)
C       NLEVCD:  INDEX  OF NEAREST  STD PRESS LEVEL  AT/BELOW   SURFACE
C       FRACPS: FRACTION  OF STD PRESS LEVEL  INTERVAL  BY WHICH  SURF
C            IS ABOVE  LEVEL  NLEVSF
C       NSTYPE:  SURFACE  TYPE  INDEX;  1=BLACK,  2=SEA,  3=LAND
```

```
C     /TAUCFN/  TRANSMITTANCE  COEFFICIENTS
C     4/12/90.
      COMMON/TAUCFN/CFM,CFW,CFO
      REAL  CFM(JPCOFM,JPLEV,JPCH),CFW(JPCOFW,JPLEV,JPCH),
     *CFO(JPCOFO,JPLEV,JPCH)
C     CFM: MIXED  GAS COEFFS      ) NO. OF COEFFS
C     CFW: WATER  VAPOUR  COEFFS  ) * NO. OF PRESS LEVELS
C     CFO: OZONE  COEFFS          ) * NO. OF CHANNELS


C     /TOVCHN/  CONSTANTS  FOR  TOVS  CHANNELS
C     4/12/90.
      COMMON/TOVCHN/WVNUM,BCON1,BCON2,TC1,TC2,GAMMA
      REAL  WVNUM(JPCH),BCON1(JPCH),BCON2(JPCH),TC1(JPCH),TC2(JPCH),
     *GAMMA(JPCH)
C     WVNUM: WAVENUMBER  IN CM**-1
C     BCON1: 1ST PLANCK FUNCTION  CONSTANT  IN MW/M**2/SR/CM**-4
C     BCON2: 2ND PLANCK FUNCTION  CONSTANT  IN K/CM**-1
C     TC1: BAND CORRECTION  COEFFICIENT:  OFFSET  IN K
C     TC2: BAND CORRECTION  COEFFICIENT:  SLOPE  IN K/K
C     GAMMA: "GAMMA FACTOR" TRANSMITTANCE  CORRECTIONS


C     /TRANS/   TRANSMITTANCES
C     4/12/90.
      COMMON/TRANS/TAU,TAUSFC
      REAL  TAU(JPCHPF,JPLEV),TAUSFC(JPCHPF)
C     TAU: TRANSMITTANCES  FROM  EACH  LEVEL  TO  SPACE
C        (CHANNELS*PROFILES,   STD PRESS  LEVELS)
C     TAUSFC: TRANSMITTANCES  FROM  SURFACE  TO  SPACE


C     /XXTAU/   VARIABLES  USED  IN OPTICAL  DEPTH  CALCULATIONS
C     4/12/90.
      COMMON/XXTAU/SQWVAP,SQQ,XXM,XXW,XXO
      REAL  SQWVAP(JPLEV,JPPF),SQQ(JPLEV,JPPF),XXM(JPCOFM,JPLEV,JPPF),
     *XXW(JPCOFW,JPLEV,JPPF),XXO(2,JPPF)
C     SQWVAP: SQRT OF TOTAL COLUMN  WATER  VAPOUR  ABOVE  EACH  LEVEL
C     SQQ: SQWVAP  * SQRT  OF SECANT(VIEW  PATH  AT SURFACE)
C     XXM: FUNCTIONS  OF PROFILE  FOR MIXED  GAS CALCULATION
C     XXW: FUNCTIONS  OF PROFILE  FOR  WATER  VAPOUR  CALCULATION
C     XXO: FUNCTIONS  OF  PROFILE  FOR  OZONE  CALCULATION
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B.4 PARAMETER statements

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C         CPARAM.       PARAMETER STATEMENTS FOR RTTOV SUITE.
C         J.R.EYRE      *ECMWF*        10/01/91.
C
      PARAMETER (JPSAT=7)          !   ! MAX NO. OF SATELLITES
      PARAMETER (JPLEV=40)             ! NO. OF PRESSURE LEVELS
      PARAMETER (JPPF=50)          !   ! MAX NO. PROFILES
      PARAMETER (JPCH=23)              ! MAX. NO. OF CHANNELS
      PARAMETER (JPHIR=19)             ! MAX. NO. OF HIRS CHANNELS
      PARAMETER (JPMSU=4)              ! MAX. NO. OF MSU CHANNELS
      PARAMETER (JPCHPF=JPPF*JPCH)     ! MAX NO. OF PROFS*CHANS
      PARAMETER (JPCOFM=14)            ! MIXED GAS COEFFS (MAX)
      PARAMETER (JPCOFW=14)            ! WATER VAPOUR COEFFS (MAX)
      PARAMETER (JPCOFO=4)             ! OZONE COEFFS
      PARAMETER (JPST=10)              ! MAX NO. OF SURFACE TYPES
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