Operational Temperature Sounding of the Stratosphere

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Operational temperature sounding of the stratosphere

By D. E. Miller, J. L. Brownscombe, G. P. Carruthers,
D. R. Pick and K. H. Stewart
Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, U.K.

Observations made by the temperature sounders on the Tiros N series of operational meteorological satellites are being used for generating routine analyses for the stratosphere. One component of the sounder, the stratospheric sounding unit, is described. The methods being used for retrieving stratospheric temperatures and the available products are presented.

1. Introduction

In the early 1970s, the relevant U.S. authorities began planning a third generation of polar-orbiting meteorological satellites. It was envisaged that their payloads should include a vertical sounder to provide measurements of atmospheric temperature for use in numerical models for weather forecasting. Instruments to measure atmospheric radiance in the infrared, with a spatial scale of about 20 km, and in the 60 GHz microwave band of oxygen were expected to provide a substantial improvement in the accuracy of retrieved atmospheric temperatures compared with the existing vertical temperature profile radiometer. Few operational numerical models require data for levels above the 100 mbar surface. However, because of the spread of the individual weighting functions, the radiances observed in the spectral channels used to probe the region between the surface and 100 mbar are influenced, at least in part, by the temperature structure above 100 mbar. Thus it is essential that any sounder should include channels designed to make measurements in this region.

With the development, by Houghton & Smith (1970), of the 'selective chopping' technique – whereby a cell containing carbon dioxide acts as the primary spectral selective element – it became possible to achieve sharp weighting functions within the stratosphere. This technique was successfully demonstrated with the selective chopping radiometer on the Nimbus 4 satellite. The United Kingdom's lead in this field was an important reason for the Meteorological Office to be invited to provide the stratospheric component of the Tiros operational vertical sounders (T.o.v.s.) for the Tiros N satellites. Following a brief description of the instrument and its in-orbit performance, the use of the observations in providing stratospheric analyses is reviewed.

2. The stratospheric sounding unit

The stratospheric sounding unit (s.s.u.) is a 3-channel infrared radiometer designed to measure the radiance emitted by stratospheric carbon dioxide. The instrument exploits the 'selective chopping' principle, by which a signal is derived by viewing the atmosphere in turn through absorption cells containing differing amounts of carbon dioxide. In practice this is accomplished by the pressure modulation technique, first used in the Oxford University's pressure modulator radiometer on Nimbus 6 (Curtis *et al.* 1974). In this case the detector views the atmosphere through a single absorption cell (see figure 1) within which the pressure of the carbon dioxide can be modulated. The cell is connected to a sealed cylinder. Modulation of the pressure is induced by oscillation of a closely fitting piston, suspended within the cylinder on two diaphragm springs. The piston is maintained in oscillation at its resonant frequency (*ca.* 40 Hz) by pulses of current passed through a coil mounted on the piston's shaft and lying in the gap of a magnet. An electronic servo-system, which senses the back-e.m.f. in the coil and controls the length of the current pulse, keeps the amplitude constant. No provision is made for changing the mean pressure within the cell; its long-term stability depends on careful design and choice of materials. However, the frequency of the oscillation provides a measure of the mean pressure.

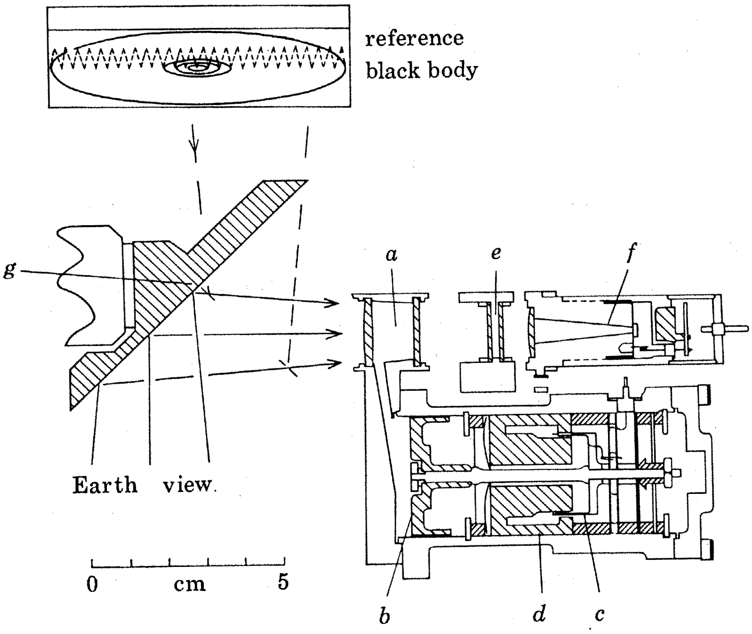

FIGURE 1. The optical system and pressure modulator of a stratospheric sounding unit. *a*, Absorption cell; *b*, piston; *c*, drive coil; *d*, magnet; *e*, interference filter; *f*, detector; *g*, scan mirror. Another two optical channels share the scan mirror.

An interference filter, with characteristics described by Evans *et al.* (1976), confines the spectral response to the 15 μm band. The pyroelectric detector which is a flake of triglycine sulphate attached to a gold-plated light-pipe, was manufactured by Plessey Limited at their Allen Clark Research Laboratory. The signal, at the modulator frequency, is amplified, rectified and integrated for about 3.5 s. The three channels of the s.s.u. differ in the mean pressure of the carbon dioxide within their modulators. Since this pressure, together with the depth of modulation, controls the effective bandwidth of the gas cell filter, the signal to noise ratio is higher for the high pressure cell than for the low pressure cell. The weighting functions are shown by the full lines, in figure 2.

The three optical channels, each of which has a field of view of 10° diameter, view the atmosphere by way of a shared mirror. This mirror can be rotated, in 10° steps, to direct the fields of view through eight positions across the satellite's orbital track, spanning ± 35° from the nadir. The ground resolution is about 200 km. Further details of the scan pattern and its relation to the other components of the T.o.v.s. have been given by Schwalb (1978). The scan mirror also allows the radiometer to view space and a 'black-body' target within the instrument. The temperature of this target is monitored. This two-point calibration is used to interpret the digitized output in terms of radiance.

Laboratory testing of s.s.us includes an exhaustive investigation of their radiometric performance. This calibration would reveal any departure from linearity in the relation between voltage and scene radiance arising from various sources of stray radiation and provides corrections, in the form of small radiance offsets, which can be applied to the in-flight calibration. The weighting functions for the s.s.u. are computed from instrument parameters and spectral line data, using a line-by-line technique and a Voigt line profile.

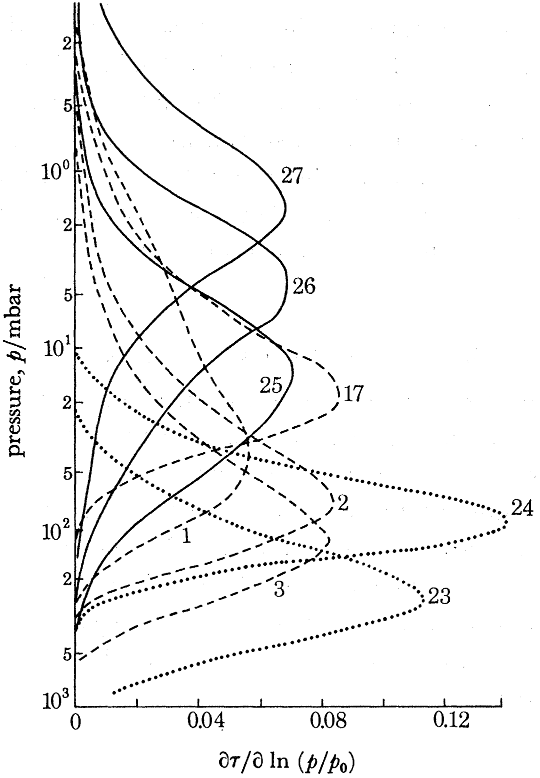

FIGURE 2. Weighting functions for those channels used for stratospheric analysis. The labels indicate the channel designations within the Tiros operational vertical sounder. The associated instruments are: ——, stratospheric sounding unit; . . . ., microwave sounding unit; – –, high-resolution infrared sounder.

To confirm these calculations, the instrument is used to measure the transmission of a 10 m path of carbon dioxide in a White cell over a range of pressures and temperatures. These transmission measurements are used to check the shape of the weighting function and to deduce an effective mean pressure for the absorption cell (which is close to the actual or filling pressure), which brings calculations and measurements into agreement at a transmission value of 0.5.

The detailed design, development and manufacture of the stratospheric sounding units has been done by Marconi Space and Defence Systems Limited, Frimley. The first flight instrument was delivered to the United States in March 1977 and launched on the Tiros N satellite on 13 October 1978.

3. The data flow

Data from the stratospheric sounding unit are recorded on board the spacecraft, replayed to one of two ground stations in the United States and relayed to Suitland, near Washington, D.C. There the data streams from the various instruments are separated and a substantial fraction of the raw telemetry data from the s.s.u. is transmitted to Bracknell via a 2400 baud dedicated telecommunications link. It is intended that these data, which mainly relate to housekeeping parameters but include the radiometer outputs, should be used to monitor the in-flight performance of the instrument. At Suitland the raw data from the various sounding instruments will be processed to derive radiances which will be used to retrieve meteorological parameters, in the form of thicknesses (i.e. mean temperatures) for various layers in the troposphere and stratosphere. These thickness values will be distributed as coded messages to meteorological services, by means of the meteorological Global Telecommunications System, principally for use in numerical forecasting models. The radiances from the s.s.u. channels and for several other T.o.v.s. channels which have significant response at or above the 100 mbar level (i.e. those shown in figure 2) are also to be transmitted to Bracknell on the dedicated link. Data received at Bracknell are up to 6 h old. They are recorded on tape for overnight batch processing on the Meteorological Office's main computer system.

4. The retrieval scheme

A multi-channel linear regression scheme is being used to retrieve atmospheric thicknesses from the radiances. The regression coefficients were derived before launch on the basis of a catalogue of about 1200 rocketsonde temperature profiles (kindly made available by Mr F. Finger of the National Meteorological Centre, Washington). The radiances which one would expect to observe (known as the 'simulated radiances') were computed for each of these temperature profiles from the best knowledge of the weighting functions of the stratospheric sounding unit and the other sounders. In this manner it is possible to process the flight data immediately, without awaiting the accummulation of an adequate collection of co-located rocketsonde and satellite observations.

5. Performance of the stratospheric sounding unit

The weighting functions of the three channels of the s.s.u. are centred at 15, 5 and 1.5 mbar respectively. The r.m.s. noise on the radiances in these channels, as observed in orbit for the instrument on Tiros N, are about 0.3, 0.5 and 40 mW/(m^2 sr cm^{-1}) (a change of 1 mW/(m^2 sr cm^{-1}) at 15 μm is approximately equivalent to 1 K over the range of scene temperatures). The noise levels for the 15 and 5 mbar channels are well within requirements. The pre-launch noise level for the 1.5 mbar channel was about 1 mW/(m^2 sr cm^{-1}); this channel developed a fault during launch (or more precisely before the instrument was switched on in orbit). The cause of the fault, which manifests itself as greatly increased noise and a negative offset, while retaining a substantial fraction of the original sensitivity to radiation, has not yet been isolated. The modulator is apparently functioning perfectly normally. The impact of the fault is to render the 1.5 mbar channel useless and limit the maximum height to which temperatures can be deduced to about 40 km for this first spacecraft. The stability of the in-flight calibration, based on views of space and the internal target at 256 s intervals, has proved better than 0.2 %, both in the short term and as long term drift over the first 2 months in orbit.

Preliminary results of comparisons between simulated radiances, computed from co-located rocketsonde profiles, and observed radiances are presented in figure 3. The differences have been plotted with, as abscissa, the change in simulated radiance corresponding to an increase of 10 % in effective mean pressure within the modulator. Thus the slope of the best-fit line provides a measure of the difference between the actual and the nominal effective mean pressure. In these cases this difference is less than 2 %. The intercepts on the vertical axis give the radiometric offsets; these are less than 0.3 mW/(m^2 sr cm^{-1}). The error bars on each point are dominated by an assumed uncertainty of 1 K in the rocketsonde temperatures.

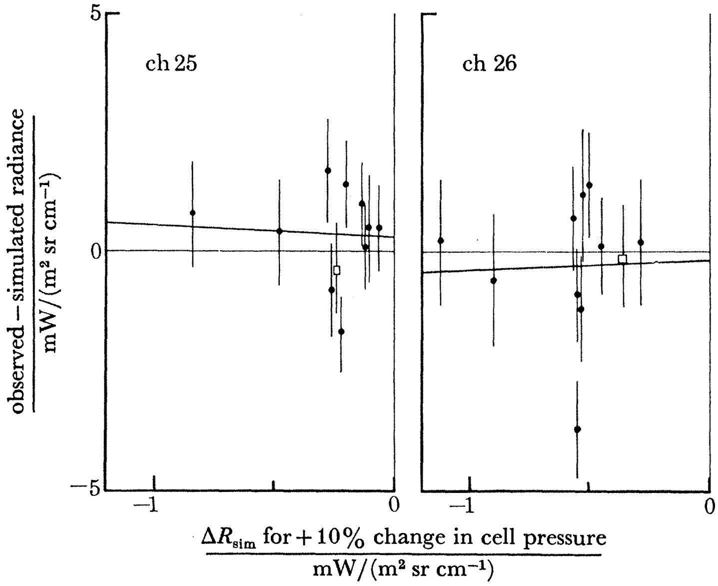

FIGURE 3. Preliminary comparison between radiances observed by stratospheric sounding unit channel numbers 25 (15 mbar) and 26 (5 mbar) and simulated radiances based on rocketsonde temperature profiles. ΔR_{sim}, change in simulated radiance; □, based on West Geirinish rocketsonde; ——, best fit trend line.

Quality control has been exercised to eliminate cases associated with large spatial or temporal changes in radiance. One point corresponds to a flight of the Meteorological Office's Skua rocketsonde from West Geirinish, made within a few minutes of an overpass of Tiros N. These comparisons will be maintained on a regular basis, to accumulate a statistically significant sample.

6. STRATOSPHERIC ANALYSIS

The aim is to produce global analyses in terms of geopotential height for the 20, 10, 5, 2 and 1 mbar surfaces. These will be based on a combination of analyses of thicknesses retrieved from T.o.v.s. radiances and a 100 mbar global height analysis. The analyses are produced by interpolating within the available observations to obtain grid-point values and subsequently smoothing these, by using an orthogonal polynomial technique, on polar stereographic projections for each of the hemispheres nearer the poles of latitude 30°. Coverage of the tropics is provided on a simple cylindrical projection.

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Since the supply of processed radiances from Suitland is not yet fully working, retrievals are at present based on the raw data from the s.s.u. (i.e. on only two out of the ten anticipated radiances). Analyses for the Northern Hemisphere at 10 mbar are being compared with hand-drawn analyses, based on radiosonde data. The mean difference in 10 mbar geopotential height between these analyses is typically 140 m, with a standard deviation of 110 m. There is a considerable latitudinal gradient in these differences; the s.s.u. analysis values are up to 300 m too high south of 45° N and up to 200 m too low around 65° N. Tests made with retrievals from simulated radiances suggest that these differences will be markedly reduced when radiances from the other channels are available.

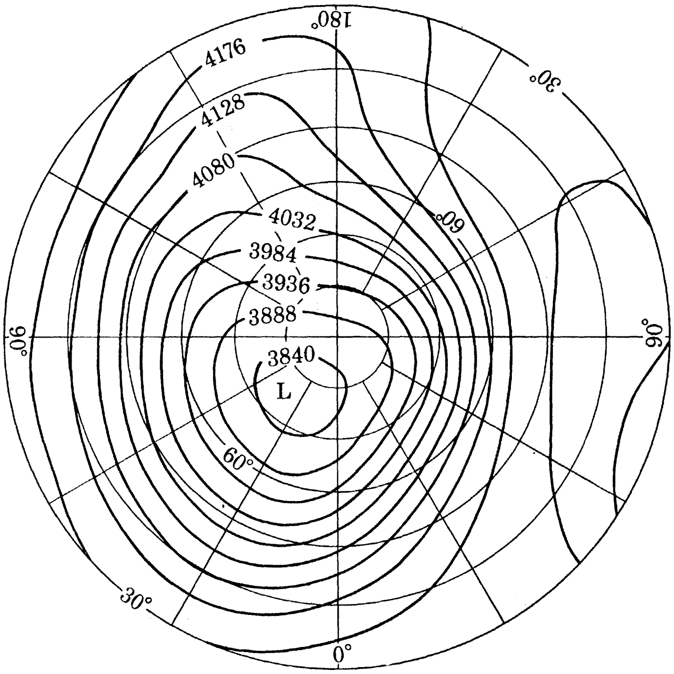

Figure 4. A typical analysis, of geopotential height of the 2 mbar surface for 0 U.T. on 4 January 1979, based on observations from the stratospheric sounding unit. Contours are labelled in decameters.

An example of a 2 mbar height analysis is shown in figure 4. The height fields are being used to produce wind fields (by the gradient wind approximation), and to determine the amplitude and phase of the planetary waves and their contributions to total and eddy kinetic energy. These investigations are being expanded to include estimates of transport and eddy fluxes of heat and momentum, by techniques described by O'Neill & Taylor (1979). The analyses and other products are being archived and will be made available on request. Radiance and height analyses are already being transmitted daily to the Free University of Berlin, to assist them in the production of Stratalerts.

7. Conclusion

A scheme of routine analysis for the stratosphere up to the 1 mbar level, based on data from the stratospheric sounding unit and other components of the Tiros operational vertical sounder, has been developed. A further seven spacecraft are planned within the Tiros N series, so continuity of observations and analyses should be possible into the mid 1980s. It is hoped that these analyses will form a valuable contribution to the Middle Atmosphere Programme by forming a basis for studying the dynamical behaviour of the stratosphere and the transport of minor constituents.

We wish to express our gratitude to the National Oceanic and Atmospheric Administration and the National Aeronautics and Space Administration for giving us the opportunity to participate in the Tiros N project and to thank various members of those organizations for their help and co-operation. The development of any satellite instrument involves effort from a large team. We would like to thank those members of the staffs of Marconi Space and Defence Systems Limited and their sub-contractors and colleagues in the Meteorological Office who have contributed to the project. We also wish to thank Professor J. T. Houghton and Professor S. D. Smith for their sound advice in the early stages of the project.

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