A REPORT ON

THE FIRST INTERNATIONAL TOVS STUDY CONFERENCE

Igls, Austria

29 August - 2 September, 1983

(Edited by W. P. Menzel and M. J. Lynch)

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FORWARD

The inference of atmospheric temperature profiles from spectral radiances measured by satellite borne radiometers has a history of about 25 years. Probably the first paper on this topic was published by Kaplan in 1959. Within this relatively short time period, this technique has been developed into a powerful observational tool for meteorology. To arrive at this level, it was necessary to install highly sophisticated instrumentation on board satellites, to perform extremely accurate transmission measurements of atmospheric gases in laboratories and in the open air, and to develop the mathematical inversion theory to a degree where it could be applied to the ill conditioned cases of cloudy atmospheres.

For many years, COSPAR, the Radiation Commission of IAMAP, and WMO have been trying to stimulate scientists to contribute to the improvement of this unique system. Thanks to the dedicated work of mainly a few individual scientists, we now see that a broad community from all over the world is using the satellite data and is working on the removal of limitations in the method. What is even more encouraging is that this community has decided to approach remaining problems jointly and to intercompare their findings in workshops.

An immense benefit can be foreseen from such cooperation for the WWW system. More recently it has also become evident that improved measurement and evaluation techniques increase the feasibility of applying the data to climate studies, which require a very high long term stability of both the instrumentation and the algorithms to infer temperature fields. This application could result in the detection of global temperature trends and thus contribute significantly to the objective of the World Climate Programme.

Substantial work still must be done to make the inferences of humidity profiles as reliable and useful as temperature profile determinations. Therefore, it is hoped that the First International TOVS Study Conference will soon be followed by others, addressing different aspects of the system.

Drs. W. L. Smith and R. Rizzi have invested many years of long effort to organize this Study Conference and to make it the success it was. We are very grateful for their initiative as we are to Drs. W. P. Menzel and M. J. Lynch for the fine work they did in editing this material.

Innsbruck, 7 December 1983

H. J. Bolle
President IAMAP

I. EXECUTIVE SUMMARY

A. Introduction

The First International TIROS Operational Vertical Sounder (TOVS) Study Conference was held in Igls, Austria, from 29 August to 2 September 1983. Thirty-three scientists from fourteen countries participated. Included were experts from Australia, Austria, Canada, People's Republic of China, France, Federal Republic of Germany, German Democratic Republic, Italy, Japan, New Zealand, Poland, Sweden, the United Kingdom, and the United States. While the level of expertise in the processing of satellite sounding data varied among the participants, many countries were already producing soundings with high horizontal resolution from the direct read-out of TOVS data for research and operational applications. It was evident that a high level of skill in performing satellite sounding retrievals has been achieved on an international scale.

The information derived from the TOVS sounding data can impact local short term weather forecasts of national interest as well as global extended range forecasts of international interest. Several centers in different countries have already begun to use the TOVS data, obtained regionally by direct readout, in their weather analysis forecast operation. As the utility of the TOVS data becomes more established, there is a growing need for standardizing the TOVS processing procedures and for making the TOVS capabilities available to a larger user community.

To date, only limited standards have been defined for processing these sounding data and for their dissemination. A common goal is to optimize and further standardize TOVS processing procedures so that accurate and uniformly consistent data sets can be available to the international community. The objectives of the TOVS Study Conference were to address this goal by reviewing the state of the art of processing TOVS data, identify existing problems, and suggest solutions. The presentations and the working group discussions led to several broad conclusions that are summarized below.

While the focus of activities at the conference was on evaluating the TOVS processing procedures, several discussions concerning the availability of the data did take place. As the microprocessor technology advances, TOVS data processing facilities could become affordable to many more users. The organized transfer of this technology to new users in developing countries and the probable impact on existing weather networks must be addressed at a future conference. This report mentions some of the related concerns only briefly.

Most of the progress at the conference was in the open comparison of processing techniques and data analyses. The conference made a good start, but more work needs to be done to arrive at definitive conclusions. The specific recommendations and actions in the next section summarize the work that this group will be addressing in the next year to improve the TOVS products and their evaluation.

Initial data analyses comparisons are reviewed in Section III. Both the shortcomings of the present comparisons and plans for future improvements are presented. The summary of working group discussions in Section IV presents some of the background information that produced the earlier recommendations. The abstracts outline the presentations from the participants of the conference. The complete text will be available in the forthcoming Technical Proceedings of the TOVS Study Conference.

B. Conclusions

As a result of five days of discussions and data comparisons, an international consensus was achieved on a number of broad issues.

1. The open access to the TOVS data on the US polar orbiter satellites by the international community has been vital in the effective use of the satellite data. Continuation of such sounding programs is strongly supported and considered an essential element of the World Weather Watch (WWW) Program.

2. Collaborative research by the international user community is essential for better definition of procedures for generating satellite sounding retrievals and for utilizing the satellite derived products in weather and climate analysis and forecast programs.

3. Substantial progress has been made in the development and application of procedures to obtain vertical soundings from TOVS radiances. Meteorological centers in several countries now provide such satellite soundings routinely for national use and/or international exchange. Through the general dissemination of software routines (often referred to as the TOVS Export Package in this report) by the Cooperative Institute for Meteorological Satellite Studies (CIMSS) in Madison, Wisconsin an important start has been made toward providing a common basis for producing retrievals. Nevertheless, several differences in processing techniques do exist which can have significant impact on the compatibility of the results. Therefore, it is possible to make only limited statements about the compatibility of the various techniques at this time. Further analyses of the data are being coordinated so that quantitative evaluations can be performed within a year.

4. Upon comparison of the various retrieval techniques and the inherent assumptions regarding the associated physical processes, several areas were identified that require further investigation:

   - the physical properties of the sensors affecting calibration,
   - the spectral response characteristics in the wings,
   - the variation in the absorption of the atmosphere due to trace gases and aerosols,
   - the attenuation due to rain,
   - the surface emissivity,
   - improved cloud filtering to reconstruct clear column radiance values using the higher horizontal resolution AVHRR data,
   - improved statistical and physical relationships for better retrieval of temperature profiles,
   - improved utilization of surface observations, upper level temperature and wind data, and ozone concentration determinations from ancillary observing systems.

5. The accuracy and utility of the TOVS sounding products in mesoscale analyses and forecasts needs careful assessment. These products include not only temperature profiles, but also moisture profiles, thermal gradient winds, integrated ozone concentration, geopotential heights, etc.

6. To carry forward the work started at this conference, the following efforts need to be coordinated through selected international agencies, satellite operators, and research groups:

   - An international systematic evaluation of data processing procedures for satellite soundings should be completed,
   - A series of forecast and/or analysis experiments need to be conducted to evaluate the utility of the TOVS data, particularly at the smaller spatial scales, so that the needs of both modelers and data suppliers can be integrated into improved operational procedures,
   - These tests and evaluations should transition from the research to the operational environments as soon as possible,
   - Appropriate action needs to be taken to standardize procedures used to process satellite sounding data and that data should be exchanged on the Global Telecommunications System (GTS).

C. Future Concerns

Several important issues arose during the Study Conference which were left to be considered more formally in a future Study Conference. They address the broader utilization of the polar orbiter data by the international community and therefore concern international meteorological agencies and national meteorological services. These issues are:

1. Development of standards for processing and presenting the satellite data;

2. Education and training programs which communicate the utility of the TOVS data;

3. The likely impact of TOVS data on conventional meteorological data gathering networks upon incorporation into the conventional meteorological data bases;

4. Assistance for future data users regarding procedures for receiving the satellite signal, processing the raw data, and generating sounding information;

5. The impact of emerging technologies, particularly microprocessor technology, on the reception, processing, and wider utilization of TOVS data;

6. The creation of a committee of experts on TOVS data utilization which could communicate major technical and policy issues to the WMO for consideration and possible international dissemination;

7. Encouragement of broader based participation by the international community in the TOVS Study Conference activities.

II. SPECIFIC RECOMMENDATIONS AND ACTIONS

The TOVS Study Conference was structured as a workshop so that retrieval and analysis methods could be discussed and the results from processing common data sets previously distributed to the participants could be compared. Data sets for the Southern Hemisphere (Tasman Sea region) and Northern Hemisphere (Alpex region) were included. The comparison of these case study results led to several recommendations which are detailed below. Particular emphases were placed on (a) instrument calibration, (b) viewing angle correction, (c) earth location, (d) atmospheric transmittance calculations, (e) numerical retrieval procedures, (f) surface effects, (g) cloud contamination, (h) the use of ancillary information, and (i) structure of future comparisons. The participants at the Study Conference will be addressing these issues in the next year.

A. Specific Recommendations

Several specific recommendations were made regarding the data preparation activities (a), (b) and (c). These centered on the need to identify a common set of calibration information necessary for retrievals and to establish a systematic procedure for assembling and distributing this information.

1. Satellite operators and/or appropriate agencies should be urged to provide measurements of instrument response functions (especially in the wings) with the maximum accuracy and precision attainable. A standard set of TOVS/AVHRR information should be maintained and distributed to users on a regular basis. For additional information, users should be able to contact a specified focal point to be identified as soon as possible.

2. A study of the precision of different angle correction techniques should be undertaken and an optimum technique be suggested for synoptic scale application. (For mesoscale applications, physical retrieval methods which do not require angle corrections to the measurements are preferred).

3. Navigation packages (in particular those for AVHRR and TOVS) should be improved and then made available to the user community.

Regarding the calculation of atmospheric transmittance (d), the conference recommended:

4. Through the International Radiation Commission (IRC) Working Group on Remote Sensing (WGRS) further work should be encouraged regarding:

   - A comparison of the existing line-by-line techniques for transmittance calculation and the selection of those standard techniques which yield the best estimates of transmittance,

   - An intercomparison of the various fast transmittance algorithms with a recommendation for a standard operational technique,

   - A sensitivity study to assess what physical parameters (e.g. line shape, temperature dependence, etc.) contribute most to the uncertainties which make empirical adjustments necessary,

- A determination of the influence of trace gases and aerosols on overall transmittance,

- A determination of the effect of variability of carbon dioxide in time and space on the calculation of outgoing radiances and on the solution of the inverse problem,

- Spectroscopic measurements of actual atmospheric conditions simultaneous with measurements of atmospheric state and composition.

Several recommendations addressed the numerical retrieval procedures (e):

5. Increased efforts should be made to further incorporate the physical characteristics of the radiative transfer processes into the operational retrieval techniques.

6. A standard procedure to determine the quality of retrievals should be developed. Indicators of quality could then be disseminated with the retrievals to assist proper utilization of the satellite derived information.

7. For mesoscale applications, the statistical and physical retrieval methods need to be studied regionally for different meteorological conditions (cloud situations, water vapor distributions, surface temperature situations, etc.).

8. Further refinements to the statistical regression methods should be developed and their use on small computers as part of low cost TOVS utilization systems be explored.

The problems of dealing with horizontal inhomogeneities in the satellite fields of view at the surface due to temperature and emissivity discontinuities (f) and in the atmosphere due to clouds (g) were largely addressed through the use of ancillary data. Specific recommendations are:

9. An investigation should be undertaken into the advantages of using AVHRR data for better cloud definition and clear column radiance retrieval and for supplementary surface temperature determinations. These studies should be coordinated with (a) the Sea Surface Temperature Intercomparison Workshop conducted at the Jet Propulsion Laboratory, (b) the International Satellite Land Surface Climatology Project coordinated through the International Association for Meteorology and Atmospheric Physics (IAMAP), and (c) the NASA sponsored International Satellite Cloud Climatology Project (ISCCP).

Other recommendations regarding the use of ancillary data (h) centered on the establishment of an independent baseline sounding capability from radiosondes, better definition of the temperature profile in the lower layers (below about 700 mb) and in the vicinity of the tropopause, additional information on vertical wind shear, and new possibilities for radiometric calibration of the TOVS. They are:

10. In addition to normal radiosonde launches at synoptic times, launches should be scheduled at times coincident with satellite overpasses to establish a data base for instrument calibration. Such soundings would reduce the temporal discontinuity in the comparisons. For these launches, special emphasis should be placed on obtaining (i) surface information (station pressure and temperature), (ii) accurate temperature and humidity data, especially below 700 mb, (iii) the height and the minimum temperature in the region of the tropopause, and (iv) winds over the entire profile. Coincident rocketsonde launches, when possible, should also be encouraged.

11. A study should be conducted into the utility of ozone derived tropopause information (such as available from the Total Ozone Mapping Spectrometer) in profile retrievals.

12. For possible improved calibration of the TOVS, the measurement of high resolution radiance spectra from calibrated spectrometers which can be retrieved from orbit should be explored.

To facilitate future intercomparisons of the data (i) and to expedite standardization of TOVS data processing procedures, it is recommended that:

13. A center for meteorological studies should be solicited by WMO to carry out the numerical evaluation of the TOVS data. In addition, a number of operational forecasts centers should be asked to participate in the evaluation of the utility of these data for forecasting.

B. Specific Actions

Several immediate action items were assigned.

1. All TOVS data processed for the intercomparison tests will be produced in a common tape format and sent to one center which will perform an analysis using fine mesh numerical analysis methods. Evaluations with co-located radiosondes also will be included. The Bureau of Meteorology, Melbourne, Australia, is being requested to perform this function (Graeme Kelly).

2. A verification package in IBM format for data evaluation will be produced and distributed. Again, the Bureau of Meteorology, Melbourne, Australia, is being asked to undertake this task (Graeme Kelly).

3. A small number of additional cases will be chosen which include meteorological situations posing problems for satellite soundings (e.g., cirrus cloud, rain effects, hot ground, variable terrain, etc.). Cases will be selected only if adequate independent data is available. Several representatives have volunteered to collaborate in this effort (John Eyre, Tadao Aoki, Graeme Kelly).

4. The Technical Proceedings of the TOVS Conference will be published within calendar year 1983. Also, the TOVS Study Conference Report will be distributed to the appropriate organizations and interested parties. The Cooperative Institute for Meteorological Satellite Studies (CIMSS) in Madison, Wisconsin, is equipped to perform this task and has volunteered to do so (Paul Menzel).

5. In the interim, until official action is taken, the focal point for TOVS/AVHRR information distribution will reside in the CIMSS (William Smith).

6. The next TOVS conference will be held in Europe (exact location to be determined) in the third week of August 1984 (William Smith).

III. THE DATA ANALYSES COMPARISONS

Prior to the conference, TOVS data from NOAA-7 had been distributed to all interested groups. The data were calibrated and earth-located and consisted of two sets: four passes over Europe and 4 and 5 March 1982 (during the ALPEX period) and four passes in the region of the Tasman Sea for 28 October 1982.

The participants processed some or all of the passes from these data sets using their selected algorithms and displayed the data in the form of geopotential thickness fields for the 1000-500, 1000-700, 700-500, 500-300 and 300-100 mb layers. When possible, fields of total precipitable water above 1000, 700, and 500 mb were calculated.

There was a broad international participation in the comparison of the results. The comparisons were made by contrasting plotted and analyzed TOVS retrievals with archived observations, analyses and satellite imagery. They are mostly qualitative. To complete the comparisons, it was decided that all retrieved data from the test orbits would be verified from standardized computer tapes against RAOB and fine mesh analysis data soon after the TOVS Study Conference. Several conference recommendations and action items address this goal.

A. ALPEX Study

The participants with results for comparison in the ALPEX assessment were:

- NOAA/NESDIS, Washington, D.C., USA
- Laboratoire de Meteorologie Dynamique, Paris, France
- Cooperative Institute for Meteorological Satellite Studies, Madison, WI, USA
- University of Bologna, Bologna, Italy
- Meteorological Office, Bracknell, UK
- University of Oxford, Oxford, UK

Other contributions were received from:

- Deutsche Forschungs-und Versuchsanstalt fur Luft-und Raumfahrt, Oberpfaffenhofen, FRG
- Institute of Atmospheric Physics, Beijing, PRC

The retrieval methods used by the participants are the statistical method and the iterative method with statistical first guess available in the software routines distributed by CIMSS, the NESDIS operational statistical method, and the minimum information method, and the Bayesian estimation method.

Retrievals made by different methods and expressed as thickness fields were compared with each other, with conventional analysis (resolution of approximately 200 km), with plotted radiosonde values, and with a hand-drawn analysis from the Meteorological Office in Bracknell, UK. An analysis based on the high-resolution ALPEX data set was not available at this stage. Most of the effort in the comparison exercise concentrated on the 1000-500 mb thickness field, although other layers were also studied. Both thermal patterns and absolute values were examined.

The conclusions of the ALPEX study were as follows:

1. In general, differences in retrieval fields produced using different methods and between retrieval fields and conventional analysis fields were small in this case study. This made it difficult to draw many firm conclusions about strengths and weaknesses of the various methods. Known retrieval problems, which have given rise to large errors with other data sets, were not evident in this limited set.

2. Determinations of trough/ridge axes were generally consistent, whether accomplished with conventional data or with retrieval methods. Some significant differences in gradients were found but no consistent conclusions could be drawn. In regions of steep gradients, the archived ECMWF (European Center for Midrange Weather Forecasts) analysis tended to have gradients less steep than those of the retrievals, which were in turn less steep than the hand-drawn conventional analyses. However, this only illustrates that the archived ECMWF analysis is probably not a suitable comparison tool for this type of exercise.

3. The density of retrievals obtained by all methods from the TOVS data (HIRS and MSU) was surprisingly good in many regions where satellite images indicated fairly heavy cloud cover.

4. A problem was identified during the study concerning the retrievals around 200 mb. 300-100 mb thickness fields showed basically the same patterns as the radiosonde analysis, but the amplitude of the patterns was generally underestimated in the satellite retrievals leading to lower retrieval gradients in the fields. Results suggested that the magnitude of the underestimation may be sensitive to the retrieval method used. The same problem was evident to a lesser extent in the 500-300 mb layer.

Two other relevant points were noted from previous studies:

5. It has been shown that problems occur when using adjacent field-of-view cloud-clearing methods with 3 x 3 boxes in areas which include the edge of high terrain.

6. Problems of interpretation sometimes occur when displaying consecutive passes (100 minutes apart) on the same chart. The time difference must be borne in mind, particularly when fast moving systems are present.

B. The Tasman Sea Study

Results used in the Tasman Sea assessment came from:

- Australian Bureau of Meteorology and the Australian Numerical Meteorology Research Centre, Melbourne, Australia
- CIMSS at the University of Wisconsin, Madison, WI, USA
- NESDIS Operations, Suitland, MD, USA
- New Zealand Meteorological Service, Wellington, NZ

Other contributions came from:

- CIRA at Colorado State University, Ft. Collins, CO, USA
- Institute of Atmospheric Physics, Beijing, PRC
- Western Australian Institute of Technology, Perth, Australia

The retrieval methods used by the contributors are the those of the CIMSS statistical retrieval package and a modified version of the package using discriminate analysis. A more recent CIMSS developed full physical retrieval scheme, the NESDIS operational statistical scheme, and two iterative schemes are also used.

The comparisons were based on the 1000-200, 1000-500, 700-500, 500-300 and 300-100 mb thickness fields and charts of total precipitable water above 1000, 700 and 500 mb. Other materials used in the comparison included the operational analysis charts from the Australian Bureau of Meteorology and the New Zealand Meteorological Service, and conventional radiosonde data. The intercomparison of satellite retrievals with radiosonde data was hampered by the absence of adequate radiosonde sounding data in the region. In spite of this limitation, it was still possible to identify several characteristics of the retrievals and to make some general comments about their accuracy.

Conclusions from the Tasman Sea comparisons are:

1. A comparison of thickness fields showed that there was a high degree of correspondence between retrievals from all schemes in cloud free areas and for the 300-100 mb layer where it was above cloud. The retrieved thicknesses were also similar to the values shown on the weather service analyses.

2. The effect of precipitation and layer cloud on observed radiances was not adequately handled by any of the methods. In this data set, it appeared that the physical scheme was a little more sensitive to this problem.

3. There was evidence of an underestimation of thickness gradients in some areas; there was indication that this was less of a problem for the physical solution.

4. It was noted that the coarseness of the one degree resolution topography file commonly used for the Southern Hemisphere retrievals and problems with navigation from erroneous orbital elements can lead to errors in microwave emissivity, rainfall checks, and surface elevation and therefore reduces the retrieval accuracy.

5. Some sub-synoptic scale features identified by the retrievals were not present in the operational analyses. The existence of some of these features was supported by inspection of the cloud imagery, while others will require further substantiation.

C. Structure of Future Comparisons

The First TOVS Study Conference has shown the need for standardization of intercomparison procedures. It was very difficult, particularly in the ALPEX case, to objectively compare different methods. There were different analysis methods and different products (e.g., layer mean temperature and level temperatures). An important parameter, gradient wind sheer, was not evaluated but should be included in future study. Evaluation by operational forecasters would also add to the study because of their local meteorological experience.

For future comparisons, it is suggested that all TOVS data be produced in a common tape format and sent to one center which could perform a common analysis using a fine mesh numerical scheme. The initial guess profile used in physical methods should be included in the exchanged data sets and its source should be identified. Impact tests should be performed using a fine mesh forecast model. Comparisons of TOVS radiances with radiosonde data should also be included.

Quantities which should be compared are:

- the mean temperature of a layer between standard levels,
- geopotential thickness between the surface and standard levels,
- precipitable water above standard levels,
- total ozone concentration,
- cloud height and type,
- surface temperature,
- geostrophic and gradient wind shear.

IV. SUMMARY OF THE WORKING GROUP DISCUSSIONS

A. Data Preparation

In the area of data preparation, three categories were discussed. They are angular correction, calibration, and earth location.

1. Calibration

Currently there are several areas of confusion surrounding the calibration of the TOVS data. (i) The spectral band corrections and the spectral response functions specified in the NOAA memorandum for NOAA-7 are not in agreement. (ii) Three differing calibration techniques are currently in use by the international community; calibration in the data gap, halfway between gaps (both of these techniques can introduce discontinuities as large as three times the instrument noise), and calibration by continuous interpolation (a technique that does not introduce any discontinuities). (iii) The misregistration of different filter detector combinations and the misalignment of the AVHRR and TOVS have not been published in the technical literature.

There would be substantial benefit in a standard set of TOVS/AVHRR information being maintained and distributed to users on a regular basis. This standard set should include:

- definition of the spectral response function (including wing contributions where possible),
- central wavelength and band correction coefficients, field of view centroid location, cross-section, misalignment parameters, antenna patterns of MSU,
- definition of a standard calibration procedure (the interpolation procedure seems most advantageous).

For additional information (e.g., technical documentation, tape information) users should be able to contact a specified focal point. This should be arranged as soon as possible.

Attempts to establish international standards for calibration should be encouraged not only for ground based data (e.g., radiosondes) but also satellite based data (polar orbiting and geostationary). While this is a difficult task, the benefits to international studies would be substantial.

2. Angular Correction

It was demonstrated that without the angular correction, the raw TOVS image data reveals very little meteorological information (this is true especially in the microwave). It is only after careful correction for the viewing angle of the TOVS instrument that the meteorological patterns emerge in the images and that the retrieved temperature profiles can demonstrate the desired accuracies.

In statistical retrieval schemes, there are presently two general approaches toward angular correction. The statistical regression techniques use either an angle independent set of coefficients on radiances corrected to nadir view, or regression coefficients that are a function of viewing angle on uncorrected radiances. In the former case, the measurements are corrected by a separate set of regression coefficients which are dependent on (i) the sample of soundings chosen to perform the statistical regression, (ii) the surface emissivity, (iii) the cloud condition, (iv) the liquid water, and (v) the water vapor. In the latter case, regression coefficients are empirically determined and do not require any synthetic data. Temperatures generated by physical retrievals are calculated with transmittances at the angle of observations, and hence the need for angular correction is alleviated. In the more recent CIMMS research software package, the algorithm iterates with the angle dependent transmittance after initializing with a regression guess based on angle corrected radiances (dependence on the angle correction of the guess is minimal). In the 3I (improved initialization inversion) method developed at the Laboratoire de Meteorologie Dynamique (LMD), the angle is incorporated directly in the pre-computed TOVS Initial Guess Retrieval (TIGR) data base and both the initial guess and transmittances entering the algorithm are angle dependent.

There is some evidence that the statistical regression technique is inadequate for large angles beyond 30° from nadir. This causes problems for synoptic scale applications. Since the statistical regression technique will continue to be used widely (especially as more small computer based satellite research centers emerge), a study of the precision of different angle correction techniques should be undertaken. For mesoscale applications the coefficients should be determined regionally for different climatological situations (clouds, water vapor distributions, ...). It is highly desirable that the cloud filtering be done before the angle correction for these sounding applications. In this area much work needs to be done and future studies for mesoscale applications should be encouraged at various satellite research centers.

3. Earth Location

Earth location of the fields of view of the TOVS data can be done to field of view accuracy when the orbit parameters of the satellite are calculated on a daily basis. It was pointed out that often the orbit parameters available on the WEFAX are not updated and hence cause considerable earth location problems. The correct orbit parameters should be part of the TOVS/AVHRR standard set of information. Other parameters, such as satellite attitude, affect the scan geometry of the TOVS and must also be specified accurately for reliable earth location of all fields of view.

B. Transmission Function Calculation

There is a growing tendency for scientists working on vertical temperature and moisture profile problems to use physical retrieval techniques. Given adequate knowledge of atmospheric transmittance, such methods have potential for estimating true atmospheric variance more accurately than statistical retrieval methods. Operational retrieval systems require the generation of these transmittance profiles in a computationally efficient manner. However, some of the necessary ingredients for fast accurate transmission function calculation still need to be researched.

1. Spectroscopic data

Pertinent information about spectroscopic parameters in the infrared and microwave region (such as line strength, line position, half-width, etc.) have been compiled for a number of atmospheric constituents by several institutions. However, for the purposes of remote sensing, further spectroscopic information is required, especially for the trace gases. A better knowledge of lineshape in the wings and of continuum effects is needed.

2. Line-by-line codes

Given the assumption that the spectroscopic parameters are correct and that the shape of the line wings is known, calculation of line-by-line (LBL) transmittances should be sufficiently precise for remote sensing purposes. However, significant differences have been found in the outputs from several LBL codes run with identical input parameters. A standard should be set and the various LBL codes should be measured against it.

3. Fast transmittance algorithms

Operational retrieval systems require the ability to rapidly generate transmittances. LBL calculations do not satisfy this requirement unless they have been precomputed for a large set of well sampled atmospheric conditions (as at the LMD). Several fast transmittance algorithms have been developed which calculate transmittance values to an acceptable degree of accuracy, and therefore are suitable for routine use. However, a proper intercomparison is required to select the optimum procedure.

4. Trace gases and aerosols

Trace gases and aerosols are not adequately treated in some of the TOVS channels, particularly those in the window regions. For some trace species, knowledge of spectroscopic line parameters is totally lacking; in other cases, information regarding geographical and seasonal variations in concentration of these species is inadequate.

While it is customarily assumed that carbon dioxide has a constant mixing ratio in time and space, it is known that this assumption is not strictly true. Thus, the effect of the variability of the CO_2 concentration in the atmosphere on the accuracy of transmittance calculations needs to be assessed.

5. Empirical adjustments

Experience has shown that it is usually necessary to make empirical adjustments in order to achieve agreement between computed and observed outgoing radiances. One of the more common adjustments is the gamma-delta procedure, which takes the form:

$$L = N + \delta, \; N = RTE\,\{\tau^{\gamma}\}$$

where

L is the observed radiance,
N is the computed radiance,
δ is the residual,
τ is the computed atmospheric transmittance profile,
γ is the empirically determined adjustment parameter, and
RTE { } is a functional representation of the radiative transfer equation.

This adjustment attempts to account for several effects, including:

- shortcomings in the spectroscopic parameters,
- influence of trace gases and aerosols,
- uncertainties in the instrument response function,
- uncertainties in the true carbon dioxide mixing ratio.

However, the adjustment also contains several sources of error, such as:

- errors in the radiosonde measurements and extension of these data to the top of the atmosphere,
- mismatching of satellite and radiosonde observations in time and space, as well as differences in the nature of the two types of observations,
- difficulty in estimating the earth's skin temperature.

Uncertainties in the instrument response function may be responsible for a reported airmass dependence of gamma and delta.

It is important to realize that it is probably impossible to make the computed and observed radiances agree exactly. The radiosonde measures temperature and humidity at a point, along a non-vertical path between the surface and stratosphere over a period of a few hours. The satellite instrument, on the other hand, obtains essentially instantaneous measurements of the outgoing energy in several layers of an atmospheric volume with a horizontal extent of several tens of kilometers.

Gamma delta adjustments should be investigated and a recommended adjustment should be put forth to the TOVS user community.

C. Retrieval Methods

Improvements in understanding the physics of retrievals has led to a convergence in the two basic techniques for retrievals: statistical and physical. The trend is to further refine the physics to make the retrievals less dependent upon statistical parameters. Efforts to further refine and adapt statistical methods for use on small computers are also currently underway.

There is a general agreement that the procedure used to invert the radiative transfer equation for a clear atmosphere is not a serious problem. However, satellite data are often contaminated by clouds and surface effects which tend to degrade the accuracy of the derived temperatures. Different cloud and surface filtering techniques lead to different approximations to the reconstructed clear-column radiance values. These in turn, lead to different retrieval techniques. Since cloud filtering techniques affect the retrieval results and, at present, there at least three major cloud filtering algorithms, more research is needed in this area before the most suitable technique(s) can be recommended.

The radiance angular correction is well understood. Physical approaches to inversion tend to avoid the need for accurate angular correction of radiances. However, when a regression initial guess is used for physical inversion, radiance angular correction is necessary. For pure regression methods, improvements are needed in performing radiance angular correction.

Retrieving the tropopause height and temperature is still an open issue. Ancillary data are required (see section E). However, no specific ancillary data can be isolated at this time. A basic inversion problem is the precise location of the minimum atmospheric temperature. Additional investigations are needed to determine which ancillary data (such as, independent ozone measurements, radiosondes, forecasts fields, improvement of the initial guess, additional limb radiance measurements) can help to resolve this difficulty.

The criteria for determining the quality of retrieved profiles should be standardized. At present, retrievals are flagged accepted or rejected using a variety of subjective schemes, while others have objective criteria. These objective criteria vary from technique to technique. A standard for quality flags needs to be developed. A 3-D based analysis should also be investigated.

The importance of the initial guess has been recognized for physical retrievals. The type of the initial guess used in these methods should always be described in conjunction with the resulting retrievals so that meaningful comparisons can be made and appropriate interpretation of the data is possible by an operational user.

D. Effect of Clouds and Surface Properties

The observed HIRS and MSU radiances are affected by radiation coming from the earth's surface and clouds in the atmosphere. One must be able to account precisely for these factors so that accurate atmospheric soundings can be achieved. The two problems are independent of each other provided the surface is essentially homogeneous in the field of view and the only inhomogeneity is due to broken cloudiness. Broken cloudiness over a variable surface, such as mountainous areas or coastlines, is a more complicated problem.

The effect of variable surface is straightforward to solve. The important quantities to consider are surface temperature, surface emissivity (as a function of spectral region), the bi-directional reflectance of solar radiation, the surface type and surface elevation. In a statistical regression solution, surface conditions may introduce a considerable error if they are not represented in the statistical data base used to generate the coefficients. The infrared brightness temperatures are much less sensitive to surface emissivity than those in the microwave region. For this reason, the surface emissivity has not as yet been determined in the infrared regions. Fortunately, if one assumes reasonably typical values for land and ocean at short (3.7μm) and long (11 μm) wavelengths, errors in surface temperature will be less than 3°C, with much smaller errors in atmospheric temperature profile. Topography and surface type can be accounted for in a straightforward manner. A 0.1° surface topography is now available and should be used in analysis of the data. It would be advantageous if a high resolution surface classification field was generated so that infrared surface emissivities could also be prescribed more precisely (e.g., vegetated, plains, ocean, etc.). The AVHRR should be more fully exploited for determining surface characteristics.

The cloud problem is more complex. For an inhomogeneous surface, it is sufficient to determine the average value of the appropriate quantity for that field of view. In the case of broken clouds, however, one must determine what the radiances would be if clouds were not present. There are three basic situations: (1) areas considered to be clear, in which case no cloud correction is made, (2) areas of broken cloudiness in which cloud corrections of sufficient accuracy can be made to the infrared observations, and (3) areas of extensive cloudiness in which cloud correction cannot be made to a number of the infrared channels which are weighted to the surface and lower regions of the atmosphere.

The fundamental questions are: (1) under which conditions is it sufficiently clear to use the uncorrected infrared radiances, (2) under which conditions should a cloud correction be made to certain infrared channels, (3) if some surface and lower tropospheric soundings infrared channels cannot be used, under which conditions should an essentially microwave-only tropospheric solution be produced, and, (4) under what conditions should profiles not be attempted.

There are a number of approaches to the cloud problem. Operationally, NOAA/NESDIS uses one of three schemes (selected statistically) for clear (type 1), cloud corrected (type 2), and microwave plus stratospheric HIRS channel retrievals (type 3). Accuracies of the type 1 and type 2 retrievals are comparable, but type 3 precision is degraded.

Three basic methods of cloud correction criteria were reviewed at the meeting: (i) A two-field of view approach which uses differences of observations in adjacent fields of view to both assess if it is clear on the one hand, too cloudy on the other, or if neither, to extrapolate the observed radiances to estimated clear column values. The method is the N* method used operationally by NOAA/NESDIS and incorporated in the statistical software routines distributed by the NESDIS/DL for this study conference. The extrapolation parameter can be determined as part of a physical rather than a statistical scheme. It has been shown that accurate retrievals can be obtained under most cloud conditions. If it is deemed to be too cloudy to correct the IR channels, no retrieval is performed. Serious problems may occur along coastlines or mountainous terrain. In some cases, problems due to these effects may be found by internal consistency checks which would cause the retrieval to be rejected. (ii) To deal with problems of background inhomogeneity, single field of view approaches have been introduced. One method determines whether it is clear, and if not, which IR channels are cloud contaminated (from the microwave observations and other prior information) then use only the uncontaminated IR radiances in the inversion. Alternately, another method attempts to reconstruct clear column radiances from the single field of view observations using microwave observations, first guess information, and statistics. (iii) Finally, a different method uses high spatial resolution AVHRR measurements, colocated with HIRS fields of view. Clear and cloudy radiances of the AVHRR within each HIRS field of view are catalogued. The AVHRR data, in turn, are used to determine cloud free areas and to specify the fractional cloudiness in the HIRS channels.

The extent to which AVHRR data can be used to account accurately for cloud effects on HIRS data over ocean and land areas must be tested further. Even if quantitative cloud corrections cannot be made using AVHRR data, the high spatial resolution is extremely useful in discriminating between clear and cloudy areas. Efforts to improve navigation of AVHRR and TOVS data and attempts to standardize colocation of fields of view should be maintained.

Significant research could be done to provide a detailed assessment of the success of different approaches. The goal of any assessment should be to determine under what conditions different techniques give acceptable results and, considering this, how to select the most appropriate method for use, given observed radiances and topographical information. This will require a number of standard data sets covering different geographical and synoptic situations. Techniques should be tested in clear, partly cloudy and overcast conditions over oceans, over plains, and in mountainous regions.

In evaluating techniques, one should not merely state that technique A is better than technique B for a given scenario, but analyze the performance in terms of geographical and synoptic conditions. It may be that one approach works well over plains, while another works better in mountainous regions and a third better over oceans.

Some synoptic sites to be considered are:

- cyclogenesis,
- convective regions (over ocean and land),
- extensive cirrus,
- mid-level and high-level cloud regimes.

Some geographical regions to be considered are:

- Arctic, Antarctic,
- Mountains (Alps, Rockies),
- Oceans, North Atlantic, Tasman Sea,
- Tropics, subtropics.

E. Ancillary Data

The parameters most needed for improved temperature profile retrievals are temperature and height of the surface and of the tropopause. The height and amount of clouds within the instrument field of view is also very important. Any data useful for defining these parameters should be investigated. Data from the AVHRR and the TOMS show promise.

The Advanced Very High Resolution Radiometer (AVHRR), on the same satellite platform as the TOVS, has the high horizontal resolution that enables better definition of surface topography and that provides more clear views of the surface through holes in clouds and around cloud edges. Early indications are that the AVHRR can assist in better determination of surface temperature, both over land and sea. Use of the data depends heavily on reliable and efficient navigation of the AVHRR. With the data properly navigated, two studies need to address (i) the accuracy of surface temperature determination over land and sea using AVHRR data and (ii) the advantages of AVHRR data for better cloud definition and clear column radiance retrieval.

Observations from the Total Ozone Mapping Spectrometer (TOMS) have been shown to be strongly correlated to tropopause height and temperature. The accurate depiction of horizontal gradients at the tropopause can greatly assist retrieval algorithms. Incorporation of ozone derived tropopause information into profile retrieval techniques should be investigated. Limb sounding is another possible source of tropopause information and it needs to be explored further.

Ancillary data is also vital as a reference for calibration of satellite derived radiances. Until the demonstration of reliable alternate references for calibration, the radiosonde remains the only independent standard for calibration. Therefore, a baseline radiosonde network is necessary. It could provide a reference point for monitoring satellite performance over its lifetime and it could pinpoint degradation in detector performance. In addition to radiosonde launches, additional launches should be attempted at times coincident with satellite overpasses as often as possible. This would eliminate any temporal discontinuities in the comparisons. Meanwhile, efforts should continue for independent calibration using a space shuttle borne high resolution spectrometer (or alternate systems) where a recalibration of the instrument back on ground would be possible.

Finally, since the boundary layer is not readily delineated from satellite observations, station data and forecast models should continue to be incorporated into retrieval schemes.

V. ABSTRACTS FROM THE FIRST INTERNATIONAL TOVS STUDY CONFERENCE

Abstracts of presentations at the meeting are appended. The full text of presented papers is available in the Technical Proceedings of the TOVS Study Conference.

CLEAR RADIANCE RETRIEVAL OF HIRS CHANNELS WITH THE USE OF AVHRR DATA

Tadao Aoki
Meteorological Satellite Center
Nakakiyoto, Kiyose, Tokyo 204, Japan

The retrieval of the clear radiance R from observed intensity $I_i = R + N_i (I_{c,i} - R)$, where i denotes the spot number, is very difficult because the cloudy radiance I_c is not constant over the area concerned. However, by incorporating the AVHRR data within each HIRS spot we can estimate the value of the term $N_i (I_{c,i} - R)$. Using this information we can estimate an accurate value of R by a probabilistic method such as the maximum likelihood method.

TIP DATA PROCESSING ACTIVITIES IN POLAND

Les Baranski
Institute of Meteorology and Water Management
Poitra Borowego Str. 14
PL 30-215 Krakow, Poland

The Institute of Meteorology and Water Management in Kracow is receiving TIP data transmitted by NOAA-7 and 8 satellites. The receiving station, designed and built in the Institute, is composed of:

- Yagi antenna with autotracking device,
- preamplifier,
- receiver,
- demodulator,
- bit and frame synchronizer.

The receiving station is connected to computer system via an interface.

Hardware for preprocessing of the TIP data is based on a MERA-60 processor with 32K words operating memory. This system contains peripherials and additional magnetic tape transports and disc drives.

This system will be used also for producing vertical temperature profiles. A limited memory capacity allows processing of data from one or two passes. The processing will be composed of the following steps:

- preprocessing of TIP data,
- extraction of proper data subset,
- cloud effect correction,
- retrieval of temperature profile from clear radiances

Additionally, the statistical retrieval method will be used after creation of the statistical data base for Poland. In the method mentioned above, the initial-guess temperature profile and atmospheric transmittances are required. The regression method will be applied for calculation of initial-guess profile. The regression coefficients suitable for generating the initial guess profile are recorded on the "TOVS WG" magnetic tape obtained from CIMSS. FORTRAN programme for transmittance calculation recorded on this tape will be applied too. The most convenient method for calculation of temperature profile will be selected taking into account the possibilities of MERA-60 computer system.

IMPROVED INITIALIZATION INVERSION PROCEDURE ("3I")

A. Chedin, N.A. Scott
Laboratoire de Meteorologie Dynamique
Ecole Polytechnique
Palaiseau, Cedex, France

The "3I" (Improved Initialization Inversion) procedure is a physical-statistical algorithm for retrieving meteorological parameters from the satellite data of the TIROS-N series at a spatial resolution of 100km x 100 km. Accounting for the physics of the phenomena involved, this procedure explicitly takes into consideration local properties of terrain, including surface elevation, surface emissivity, percentage of water, viewing angle. Considerable effort is given to the optimization of the initial guess solution which is retrieved using a large precomputed data set (the "TIGR" - TOVS Initial Guess Retrieval data set) which describes the physical properties of a large number of well sampled atmospheric situations, to which the observed situation may be compared. Retrieval of the initial guess also relies upon the operational forecast of the temperature and of the geopotential heights of the lowest atmospheric levels. The quality of the initial solution obtained is demonstrated by the fact that only one iteration with the retrieval scheme is required to obtain the final solution. Although preliminary results of the "3I" procedure have been obtained quite recently, they show a satisfactory agreement with conventional data, in particular in the 500 mb to 1000 mb pressure range. Additional experience and tuning of the method are required and are in progress. Usual by products of the temperature retrievals, such as cloud amounts, cloud heights, ozone content,...in addition to retrievals of water profiles will be soon implemented in the "3I" scheme.

MESOSCALE ANALYSIS USING SATELLITE INFORMATION

Y. Durand, R. Juranon du Vachat
EERM/CRMD, 2 Avenue Rapp 75007
Paris, France

A mesoscale analysis is developed in the French Weather Service to provide the initial conditions for a short-range numerical weather prediction model over France (mesh size = 35 km). Since we lack of classical data in the upper layers of the atmosphere, we make use of TOVS data whose resolution is approximately the mesh size of the model.

The analysis scheme uses directly clear HIRS-2 radiances, without retrieval procedures, together with classical observations in a three dimensional multivariate optimum interpolation method. It also uses the cloud information deduced with AVHRR data col-located with HIRS-radiances in the Esther data bank provided by CMS/Lamion. A first guess of meteorological fields is provided by a 3-hour forecast and is modified by linear combination of observed and forecasted values. The use of radiances implies the creation of "guess radiances" with the CIMSS provided TOVS Export Package and the forecast profiles of temperature and humidity. It is necessary to compute, before the run, statistical values (covariances and bias) between the errors of every field involved in the analysis. The preliminary results show that the direct insertion of raw satellite data into an objective analysis scheme is feasible and is economical in computing time for a regular assimilation cycle.

HIGH-RESOLUTION TEMPERATURE RETRIEVALS AT THE U.K. METEOROLOGICAL OFFICE

J.R. Eyre
Meteorological Office
Bracknell
Berkshire, UK

The UK Meteorological Office is currently implementing a scheme to acquire and process in real-time TOVS data for use in operational forecasting. Locally received data covering the European and North Atlantic areas are being processed by a statistical retrieval scheme (from the TOVS Export Package) using regression coefficients from NOAA/NESDIS, Washington,D.C., updated weekly. This scheme has been used to process the TOVS data for the ALPEX period distributed prior to the meeting. Comparison of the results expressed as thickness fields with equivalent radiosonde charts shows generally good agreement. A statistical analysis of retrieval-radiosonde differences has also been performed.

PRECIPITABLE WATER VAPOR AND THICKNESS FIELDS OVER THE TASMAN SEA ON 28 OCTOBER 1982

D.W. Hillinger and T.H. Vonder Haar
Cooperative Institute for Research in the Atmosphere (CIRA)
Colorado State University
Fort Collins, CO 80523, USA

Examples of total precipitable water vapor and 100-50 kPa thickness fields are given for the Tasman Sea case of 28 October 1982. Of the four satellite passes available, the one at approximately 1600 MT was the least cloud contaminated and showed an interesting dry tongue off the east coast of Australia. The analysis of TOVS was performed using an iterative retrieval scheme and a climatological first guess profile. No ancillary information was used, thus the satellite retrievals are independent of all conventional observations.

THE AUSTRALIAN OPERATIONAL TOVS DIRECT READOUT AND PROCESSING SYSTEM AND ITS APPLICATION TO THE TASMAN SEA INTERCOMPARISON STUDY

G.A. Kelly
Australian Numerical Meteorology Research Center (ANMRC)
Melbourne, Victoria, Australia

and

J.F. LeMarshall
National Meteorological Analysis Centre (NMAC)
Head Office, Bureau of Meteorology
Melbourne, Victoria, Australia

The Australian Bureau of Meteorology has had the capacity, since May 1980, to receive, process and utilize remotely sensed meteorological data from the TIROS-N/NOAA series of satellites. The system is used operationally by both the National Meteorological Analysis Centre and regional forecast centres. A discriminate analysis technique is used for the selection of regression coefficients for the statistical retrieval procedure and the operational numerical analysis and prognosis system is used for data editing and for supplying surface parameters. The four Tasman Sea orbits were processed for the First TOVS Study Conference.

USE OF TOVS IN CANADA

P. King
Atmospheric Environment Service
Downsview, Ontario
Canada

Canada is running a TOVS retrieval scheme based on the TOVS Export Package. Statistical retrievals have been made on a routing basis since June 1982. Charts of temperature, thickness and moisture analyses are being sent to Weather Centers in Toronto and Winnipeg on an experimental basis.

TEMPERATURE RETRIEVALS OVER MOUNTAINS USING ONE FIELD OF VIEW

F. Loechner
Oberpfaffenhofen DFVLR
Federal Republic of Germany

For mesoscale applications, an effort was undertaken to obtain a better horizontal resolution in cloud free situations. Single FOV retrievals of adjacent FOV's were compared and profiles derived from 3x3 boxes of FOV's with single FOV retrievals. No significant differences could be found in the temperature profiles over sea, flat terrain and snow covered mountains. At the border of mountains, comparisons with RAOB showed better agreement for single FOV computations. Problems arose with 3x3 retrievals because of the slowly varying mean elevation of the terrain. The programs MXTI and MYTI, both developed at CIMSS, were used in this study.

THE OPERATIONAL TOVS RETRIEVAL METHOD

L. McMillin
NOAA/NESDIS
Suitland, MD
USA

Soundings for the study cases were produced using the operational TOVS processing system at NESDIS. These soundings are part of the (~16,000) that are produced each day and are subjected to automated error detection procedures. Because of the reliance on automated procedures, problems not previously identified may not be detected. For this reason, communication with data users, who may spot features that are unknown, is important, especially when persistent problems occur.

The operational retrievals, produced on a global scale, are sbject to constraints such as speed which do not necessarily apply to experimental retrievals or to retrievals processed for a local area. In some instances, small decreases in accuracy are accepted at the cost of other benefits. Thus, it should be expected that experimental approaches can be more accurate. The system has been developed to optimize both speed and accuracy.

A STUDY OF SEVERAL DIFFERENT NUMERICAL ITERATION SOLUTIONS OF THE RADIATIVE TRANSFER EQUATION (RTE)

W.P. Menzel
NOAA/NESDIS
1225 West Dayton Street
Madison, WI 53706
USA

TOVS data from the ALPEX region and the Tasman Sea were processed to determine temperature profiles at locations where time coincident radiosonde data were also available. This work was accomplished on an IBM personal computer. Radiance data was calibrated, located, and limb corrected before it was ingested into the IBM personal computer for the retrieval calculations. Two modifications of the Chahine relaxation method and the Smith iteration method were studied.

The IBM personal computer demonstrated a considerable capability for analyzing the TOVS data. The numerical iteration solutions compared well with the radiosonde data except in the region of the tropopause, where the HIRS radiance data provides very little information. First guess dependence was especially noticeable at the tropopause and at the surface.

W.A.I.T TASMAN SEA STUDY

W.P. Menzel* and M.J. Lynch
NOAA/NESDIS
1225 West Dayton Street
Madison, WI 53706
USA

School of Physics and Geosciences
W.A. Institute of Technology
Kent Street
Bentley, W.A. 6102, Australia

Temperature retrievals from TOVS data have been made in cloud free regions for the four NOAA-7 Tasman Sea orbits of 28 October 1982 using both Smith and weighted Chahine physical retrieval schemes with statistical initial guess profiles. Thickness fields for the 1000-500 mb and 300-100 mb layers have been generated in the clear regions.

* Work undertaken while a Visiting Research Fellow, W.A. Institute of Technology, Perth, Australia

IMPROVEMENT OF MSU TEMPERATURE RETRIEVALS BY USE OF TROPOPAUSE HEIGHTS DERIVED FROM TOMS OZONE MEASUREMENTS

M.J. Munteanu
John Hopkins University and Laboratory for Atmospheric Sciences
NASA/Goddard Space Flight Center, MD 20771, USA

Satellite soundings frequently exhibit very large errors in the region of the tropopause due to poor vertical resolution. This study investigates the potential use of TOMS total ozone from the NIMBUS-7 satellite for the improvement of satellite retrievals in the region of the tropopause. For two different regions of Europe in April 1979, the correlation coefficient of 0.96 has been found between TOMS and the tropopause heights from radiosondes. Temperature profiles from simulated MSU brightness temperatures were generated over the locations of the radiosondes with and without the ozone derived tropopause height information. The accuracy and resolution of the derived profiles are considerably improved especially in the region of the tropopause when the predicted tropopause height from total ozone data is used. Another conclusion is that the total ozone contains additional information in comparison with the MSU measurements about the gradients of the lows and highs of certain geopotential fields. This could be very helpful presently in the cloudy regions and in the context of future three and four dimensional satellite retrievals.

DETERMINATION OF CLEAR HIRS-2 PIXELS AND CLEAR RADIANCES RETRIEVAL BY USING AVHRR

T. Phulpin, A. Brard and M. Derrien
Centre de Meteorologie Spatiale
Lannion, Cedex, France

AVHRR data are proposed for use in discriminating clear and cloudy HIRS 2 pixels and for retrieving the sea surface temperature. The procedure, called ESTHER, has two versions. For daily conditions a two-dimensional histogram technique is used; for nighttime low level clouds are discriminated from the background and the remaining pixels are processed with the IR histogram technique. The total cloudiness obtained in each array are compared to that given by nephelometer analysis for ALPEX selected orbits. The results are discussed.

AN APPRAISAL OF RETRIEVAL METHODS USED FOR OBTAINING TEMPERATURE PROFILES FROM TOVS RADIANCES

F. Prata
Department of Atmospheric Physics
University of Oxford
England, UK

Three different retrieval methods have been used to obtain temperature profiles from TOVS radiances and the results are compared. The methods used are the regression retrieval, the iterative retrieval and a special case of constrained linear inversion known as minimum information. Measured minus calculated brightness temperatures for a sample of 100 profiles from one orbital pass of NOAA-7 ALPEX data of 4 March 1982 were computed for all three retrieval methods. A large bias of 2K was found for HIRS-2 channel 16, indicating that this measurement may be inappropriate for the type of atmospheric conditions which existed. Temperature profiles and derived thickness fields were compared directly and differences of up to 5K at single levels and 5 dm in layer thicknesses were found for some cases. In general the iterative method retrieves lower level thickness values better than the regression method. With the regression as first guess, the minimum information method appears to give some improvement in the retrieval at stratospheric levels, provided the solution is not underconstrained. The methods were tested for sensitivity to measurement noise by perturbing the radiances by a known error and examining the propagation of the error into the retrieved profile. It was found that errors on HIRS-2 channel 2 and MSU channel 4 tend to cause large noise amplification in the stratosphere for regression retrievals. The iterative retrievals on the other hand appear to be more sensitive in the lower troposphere near the surface. Propagation of measurement error by the minimum information method tends to result in a vertically uniform profile error.

EXPERIMENTS ON TOVS DATA AT THE FREIE UNIVERSITAT BERLIN

E. Reimer and H. Billing
Meteorological Institute
Freie Universität Berlin
D1000 Berlin 33, FRG

AVHRR data are received regularly at the Freie Universität Berlin. The TOVS data can be extracted and calibrated at the satellite station. The full TOVS Export Package is now installed on the University Cyber 835 computer. The results are compared with the actual forecast. For the ALPEX period, the results will be used for the numerical fine mesh analysis.

SATELLITE SOUNDINGS OVER THE ALPEX AREA

R. Rizzi
Dipartimento di Fisica
Universita di Bologna
Bologna, Italy

Calibrated, localized radiances are computed using software based on the physical retrieval scheme in the TOVS Export Package. The first guess profile is computed using a statistical regression technique. The 1000 mb surface analysis produced operationally by ECMWF are used solely to compute hydrostatic surface pressure. Temperature is computed using three window channels and two fields of view (FOV) at a time to account for varying cloud amount within the pair of TOVS FOV's. The agreement between satellite-derived and conventional thickness fields is satisfactory in the layers 1000-700, 700-500 and 100-500 mb. Ridge and trough axes are coincident. In the layers 300-100 mb and 500-300mb, the satellite-derived gradients are weaker than ECMWF. A lack of ability to detect the tropopause inversion is evident.

A NUMERICAL STUDY OF VERTICAL RETRIEVALS OF TEMPERATURE OF THE ATMOSPHERE DERIVED FROM SATELLITES

G. Rochard
Meteorologie Nationale
Centre de Meteorologie Spatiale
Lannion, France

The RTE on clear radiances can be linearized using a library of representative profiles, associated clear radiances and weighting functions (computed line by line). A theoretical study of the linear operator obtained locally (in the library) leads (Picard's theorem and the D property of Kellog) to a numerical study of its kernel for HIRS 2. The results show the necessity of using a priori information on the tropopause and low level inversions for regularized inversions of profiles.

TOVS RETRIEVALS OVER THE ALPINE REGION

H. Rott and H. J. Bolle
Institut für Meteorologie und Geophysik
Universität Innsbruck
Schopfstrasse 41
A-6020 Innsbruck, Austria

The software of the iterative TOVS retrieval method supplied by the CIMSS in Madison, WI was installed at the University's Cyber 74 in 1981. Temperature and moisture profiles over central Europe were calculated for several test periods in 1981 and 1982, based on calibrated and localized radiances received from DFVLR. Comparisons of geopotential thickness fields with conventional analyses and comparisons of profiles with colocated radiosondes revealed major differences near the tropopause level and in some cases also below 700 mb.

THE PHYSICAL RETRIEVAL TOVS EXPORT PACKAGE

W.L. Smith[1], H.M. Woolf[1], C.M. Hayden[1], A.J. Schreiner[2], J.M. LeMarshall[3]
Cooperative Institute for Meteorological Satellite Studies (CIMSS)
University of Wisconsin
Madison, Wisconsin, USA

1 NOAA/NESDIS, Development Laboratory
2 Space Science and Engineering Center
3 Visiting Scientist, Bureau of Meteorology, Melbourne, Australia

An improved TOVS Export Package developed by CIMSS and made available to numerous direct readout users has been modified to include the physical retrieval algorithms. The new algorithm more correctly handles the effects of surface variables, reflected sunlight, and clouds. No limb correction is needed, thereby eliminating a potential source of error. Ozone concentration is also produced.

The results of application of this processing package to the ALPEX orbits shows satisfactory performance; bias differences and standard deviations with radiosondes ranging between 1 and 3°C depending upon pressure level. A major improvement, yet to be implemented, is the use of full resolution AVHRR data to better define surface skin temperature and to account for the influence of clouds upon the TOVS sounding channel radiances. An effort is now underway at CIMSS to implement the AVHRR option to the TOVS Export Package sounding processing system.

COMMENTS ON TOVS TRANSMITTANCES

D. Spänkuch, W. Döhler and J. Güldner
Meteorological Service of the GDR
Potsdam, German Democratic Republic

It has been shown that the differences in line-by-line calculations of atmospheric transmittances using different line source data and slightly different numerical procedures are one order of magnitude larger than the McMillin-Fleming approximation for matching line-by-line calculations. The calculations have so far only been made for the 15 μm channels. The results obtained clearly emphasize the need for further basic spectroscopic investigations.

SYSTEMATIC UNDERESTIMATION OF CIRRUS SHIELD TOP HEIGHTS BY INFRARED WINDOW CHANNEL MEASUREMENTS

D. Spänkuch
Meteorological Service of the GDR
Potsdam, German Democratic Republic

Based on interferometric measurements from the Meteor 28 satellite over a mid latitude low pressure system, it has been shown that the cloud top temperature of cirrus shields are underestimated by about 1.4 km if the 11 µm window channel (AVHRR channel 4) is used. The cirrus cloud top temperature was estimated from measurements in a region with strong water vapor absorption (ν_o = 488 cm^{-1}) with a spectral resolution of 5 cm^{-1}. At this wavelength the tropopause temperature was exactly derived as compared with a nearby radiosonde ascent.

THE GLAS PHYSICAL NUMERICAL ALGORITHM FOR ANALYSIS OF HIRS 2/MSU DATA

J. Susskind and M.T. Chahine

J. Susskind
NASA/GLAS
Greenbelt, MD
USA

M.T. Chahine
Jet Propulsion Laboratory
Pasadena, CA
USA

A physical inversion method of HIRS/MSU data was described which includes guess fields of atmospheric temperature, ground temperature (sea or land), surface emissivity (which is a measure of ice and snow cover), and percent cloud cover and cloud top pressure. Global retrievals (19,000 per day) have been run for 6 months of 1979. RMS temperature errors, under cloud cover of up to 40%, are comparable to those under clear conditions. Monthly mean fields of sea/land surface temperature day-night difference in surface temperature and surface emissivity are shown for January 1979.

Work is just beginning on NOAA-7 transmittance function calculations using empirical correction factors. Therefore, the cases were not analyzed in time for this meeting. However, a case over the ALPEX region was analyzed for January 22, 1979 using TIROS-N data. Shown are operational NESDIS retrievals, GLAS retrievals on a global scale (250 km spacing), GLAS retrieval in the regional scale mode (80 km), and radiosonde reports. Also shown were the thickness fields derived from the GLAS retrievals.

A NON-LINEAR APPROACH FOR DERIVATION OF TEMPERATURE-PROFILES FROM TOVS-DATA

J. Svensson
The Swedish Meteorological and Hydrological Institute
Norrkoping, Sweden

Most inversion methods for derivation of temperature profiles from TOVS data are based on statistical techniques. A physical, non-linear approach is presented and an iterative method is suggested. The calculated temperature profile depends on water content and surface emissivity, which are also to be calculated. Calculations have been done for cloud-free areas of the ALPEX data of March 1982.

THE FIRST INTERNATIONAL TOVS STUDY CONFERENCE CASE STUDY REPORT

B.F. Taylor
New Zealand Meteorological Service
Wellington
New Zealand

The TOVS processing software employed by the New Zealand Meteorological Service is basically that supplied in 1979 in the TOVS Export Package by the CIMSS in Madison, WI. Extensive adoption of the package has taken place in order to allow execution on a DEC PDP 11/70 computer with its 16-bit word length and 32 kbyte addressable memory limit. Although many modifications have also been made for reasons of speed and convenience, the processing/retrieval strategy remains essentially unchanged except for the addition of a precipitation check in the microwave processing. The Tasman Sea data has been analyzed and thickness fields generated for the region. Comparisons with the conventional analysis have been undertaken.

TEMPERATURE RETRIEVALS FROM TYPICAL SHAPE FUNCTIONS

D.Q. Wark
NOAA/NESDIS
Washington, D.C. 20233
USA

Temperature retrievals from satellite measurements of the earth's spectral radiances are frequently reliant upon some statistical relation between the measurements and known temperature profiles. Examples may be found in the statistical regression procedure employed with the TOVS operational and statistical inversion methods, which combine the statistical behavior of profiles with the optical properties of the atmosphere. Mathematical methods, which make use only of the atmospheric transmittances are handicapped by the vertical dimensions of the weighting functions.

Statistical data are normally selected in large sets with little attention to loss of knowledge regarding the physical nature of the data. Stratification of these data by latitude would produce a group of histograms, each having less variability, but the significant meteorological implication would still be obscured. To retain the physical structure of temperature profiles, the sample must be divided in such a way that the means retain the structures, the distributions about the means are Gaussion, and the variance is small.

This separation of data would not be useful unless the various subclasses could be distinguished using the satellite radiances. By means of discriminate functions, appropriate TSF's can be identified to levels of confidence dependent upon how well a particular profile fits as a member of any sub-class.

Results from a sample of 61 independent samples are presented with the RMS differences obtained for the solutions, TSF physical retrieval, TSF regression and zonal regression. The results reveal that TSFs have an advantage over zonally stratified statistics, particularly around the tropopause, and are well suited to physical retrieval methods.

SOME PRELIMINARY RESULTS FROM THE POLAR-ORBITING SATELLITE DATA RETRIEVAL

F. Zhou and G. Zhao
Institute of Atmospheric Physics
Academia Sinica
Beijing, PRC

A Taylor expansion, non-linear iterative method is used interactively for temperature and moisture retrieval from NOAA-7 TOVS data over ALPEX area. General consistency is shown when comparing with radiosonde observations. This work was performed on the IBM 4331 McIDAS system at Beijing.

APPENDICES

A. Events leading to TOVS Study Conference

Vertical temperature and moisture profiles in the troposphere are some of the most important observations for operational weather analysis and prediction. They are also essential for most meteorological research applications, including the study of climate. Therefore, a large effort has been put forth during the last decade to develop satellite techniques for measuring those parameters. Extensive tests of the vertical temperature profile as derived from radiance measurements are taking place in a number of meteorological organizations. The results are still provisional, as the latest availabe sounder, the TIROS Operational Vertical Sounder (TOVS), has not yet been fully exploited.

Recently, the International Council of Scientific Unions (ICSU) appointed a Joint Scientific Committee (JSC) for the Global Atmospheric Research Program (GARP) and the World Climate Research Program (WCRP). During the first session of JSC held in Amsterdam (26 March and 3 April, 1980) "... the Committee felt that the current level of effort being devoted to the problem of the retrieval of temperature from satellite radiances was quite inadequate and certainly not commensurate with the very great effort and cost of the satellite program. The Committee, therefore, recommended that WMO arrange for urgent and vigorous efforts to be made to improve and refine the retrieval techniques so as to urge meteorological research groups, not only in the satellite operator nations, to actively participate in these efforts..." (quoted from page 4 of the JSC-1 Report).

The International Radiation Commission (IRC) of the International Association of Meteorological and Atmospheric Physics (IAMAP) at its meeting in August 1980 formed an ad hoc working group on inversion problems which submitted a short preliminary status report to the second meeting of the JSC. The JSC made a number of recommendations on this topic, the essence of which is summarized as follows:

- Extensive impact studies should be initiated by the Working Group on Numerical Experimentation in order to establish the impact of vertical soundings on the observing system.

- Greater efforts are necessary to develop more effective ways to use satellite soundings operationally and more attention needs to be given to the basic information content of satellite soundings which contain unused information on the horizontal distribution of temperature.

- The scientific community should investigate with greater emphasis the problems involved in the retrieval of temperature and moisture profiles, especially over land.

- ALPEX represents one unique opportunity to validate satellite retrievals with its higher radiosonde density during the special 14 day observation period.

At a meeting of mostly German meteorologists held in Oberpfaffenhofen, 12-13 February, 1981, an ad hoc group was spontaneously formed to further investigate the quality and applicability of temperature profiles for operational purposes and to participate in the mountain overflow experiment, ALPEX, as a first and most urgent application. Following an initiative by the IRC of IAMAP, a group of European scientists met on June 22-23, 1981 in Innsbruck to form a European TOVS Inversion Group and to organize its work with special emphasis on ALPEX. Finally, at the IRC business meetings held in Hamburg, Germany during the IAMAP symposium (18-28 August, 1981), the TOVS working group was expanded to include non-European scientists. Two co-chairmen were selected: Dr. Rolando Rizzi (Italy) as chairman of the European working group and Dr. William Smith (U.S.A.) as chairman of the non-European scientists. The IRC further recommended that a study conference on the results of activities to improve inversion algorithms be organized and held in 1983 after the conclusion of ALPEX. The First International TOVS Study Conference at Igls, Austria the week of 28 August 1983 is the result of that recommendation.

B. Technical Information

TIROS-N is the first of a new series of operational polar-orbiting meteorological satellites. Aboard each spacecraft is a third-generation complement of vertical sounding instruments capable of providing complete global coverage of vertical temperature data between the surface and the stratopause, and the total column moisture content of the troposphere. (There are currently two spacecraft of the series in orbit - NOAA-7 and NOAA-8). The following paragraphs (excised mainly from the article in BAMS Vol. 60 No. 10 of October 1979 entitled "The TIROS-N Operational Vertical Sounder" by Smith et al. and the paper delivered at the COSPAR Conference on Remote Sounding of the Atmosphere from Space in 1979 entitled "Satellite Sounding Applications to Mesoscale Meterology" by Smith et.al.; both of these articles are excellent references for the reader unfamiliar with TOVS) describe the TIROS-N system, including a scenario to process the data.

1. Instrument

The TOVS consists of three instruments: (1) the second version of the High resolution Infrared Radiation Sounder (HIRS-2) originally tested aboard the Nimbus-6 satellite, (2) the Microwave Sounding Unit (MSU), which is similar to the Scanning Microwave Spectrometer (SCAMS) flown on Nimbus-6, and (3) the Stratospheric Sounding Unit (SSU) provided by the British Meteorological Office which is a Pressure Modulated Radiometer (PMR) similar to the one flown on Nimbus-6. Table 1 provides the characteristics and purpose of the radiance observations provided by the various spectral channels of each instrument. Demonstration of the vertical resolution of the radiation observed within each channel is given in Fig. 1. Each curve in the figure shows the sensitivity of the radiance observed in the spectral interval of the indicated channel to a local variation in atmospheric temperature. These are usually referred to as "weighting functions" because they appear in this fashion in the integral equations relating atmospheric temperature to the observed radiances. These weighting functions vary somewhat according to the water vapor and ozone content of the atmosphere, and also weakly with atmospheric temperature.

The scan pattern of the HIRS and MSU instruments for two adjacent orbits over North America is portrayed in Fig. 2. The HIRS instrument resolves a circular area that is 30 km diameter at the subsatellite point (represented by the dots in Fig.2), whereas the MSU resolves a circular area of 110 km diameter at the satellite subpoint. The HIRS samples 56 fields of view within each scan line covering a linear dimension of about 2250 km. The MSU samples 11 fields of view along its swath having the same linear extent. The fields of view enlarge and become elliptical as the instruments scan away from the satellite subpoint. Each SSU scan line (not shown) has eight fields of view with a linear extent of 1500 km. As a consequence, there is no overlap of the SSU fields of view and the HIRS and MSU fields of view at the edges of the HIRS and MSU swaths.

2. Accessing the Data

Direct reception of TIROS-N satellite sounding data is possible with a VHF antenna or an S-band antenna (the latter enables access to the AVHRR data as well). A brief description of the receiving system in Madison, WI follows to give the reader an example. A VHF antenna will receive real time measurements of earth-atmosphere emitted radiance from TIROS-N while the satellite is within line-of-sight. The antenna is controlled by a microprocessor which is also programmed to ingest, calibrate, and locate the radiance observations. The calibrated, located radiance data will be sent to the McIDAS (Man-computer Interactive Data Access System) where it will be stored with other contemporary data, including conventional surface and upper air observations and geostationary satellite imagery. Such data can be processed into meteorological parameters at resolutions between 30 and 75 km on the McIDAS at the command of the terminal operator.

Direct access to processed products is also possible. Processed TOVS thickness fields (at 250 mile resolution) are available on the Global Telecommunications System (GTS).

3. A Processing Scenario

The processing scenario described below is roughly five years old and no longer reflects current processing techniques; however, it does illustrate the typical concerns that are present when the TOVS data are processed.

In order to achieve the accuracy and reliability required for small scale applications, the meteorologist must interact with the computer in the satellite data processing. The meteorologist insures that soundings are achieved with the highest possible resolution and density in the meteorologically active regions. He may enhance and edit an objective product by adding soundings where severe horizontal gradients exist and by removing soundings on the basis of the meteorological consistency of the results. For timeliness, the data processing must be done with an interactive computer system, possessing video displays and console and cursor controls, such as the Man-computer Interactive Data Access System (McIDAS) developed by the University of Wisconsin.

Raw radiance data are calibrated and located before being ingested into the McIDAS for meteorological interpretation. The McIDAS terminal operator instructs the computer to display several channels of data (e.g., visible, infrared window, and microwave) so that he can select the geographical region for which he desires satellite sounding information. The operator then instructs the computer, through the keyboard, to provide magnified data images for a region of interest and to produce vertical temperature and moisture profiles at relatively course (~150 km) resolution over the region. Basically, two types of infrared-based soundings are attempted over each 150 km grid area: (1) a "clear sounding" from the single 30 km field of view within the grid area which is determined to be least cloud contaminated (on the basis of objective radiance comparison tests), and (2) a "partly cloudy sounding" which is achieved from data at two adjacent 30 km fields of view utilizing an algorithm which assumes, (a) only cloud coverage differs between the two fields of view, and (b) the observed radiance (brightness temperature) of the mid-tropospheric sounding microwave channel can be specified from a linear combination of hte clear-column infrared radiances. The validity of this latter assumption is apparent from the overlap of this mid-tropospheric microwave channel's weighting function by those of the numerous HIRS channels (Fig. 1). The best partly cloud result from the many different neighboring fields of view within each 150 km area is selected on the basis of being in best RMS agreement (sum of squares of vertical difference) with a lower resolution sounding produced directly from the three microwave channel observations for the 150 km area. A selection between the best "partly cloudy sounding" and the "clear sounding" for the area is made on the same basis. The RMS selection criterion is not believed to bias the infrared sounding result to the lower resolution microwave product since cloud-induced errors should always tend toward poorer agreement in a vertical RMS sense. Soundings are discarded completely if the RMS difference is excessive, which is generally the case in heavily clouded areas.

The operator may edit erroneous results on the basis of sharp horizontal discontinuities (assumed to be due to cloud induced noise) but will retain larger scale inconsistencies assuming that they are due to the improved horizontal and vertical resolution of the infrared sensor. The operator also enhances the objective product by instructing the computer, through cursor selection and keyboard command, to produce additional soundings in high gradient regions. Images of the visible, infrared, and microwave data assist in selecting both the high gradient regions and the individual infrared fields of view which possess least cloud and therefore are best suited for sounding determinations. The computer returns on the TV graphics the result for the particular parameter being displayed, and portrays the complete sounding with associated quality control figures on the associated CRT display device. The operator retains final judgement on the acceptance or rejection of each result.

In cloud overcast areas, soundings produced from microwave data alone are generated under manual control to enhance the infrared data coverage. Horizontal inconsistencies between these microwave soundings and their infrared neighbors are alleviated by adding to the microwave result any systematic differences between microwave and infrared soundings in neighboring clear or partly cloudy areas. The differences are interpolated into the overcast region where the microwave soundings are generated.

A final check of meteorological consistency is generally performed. This check involves determining geopotential heights (or thicknesses) and thermal winds (or gradient or geostrophic winds) from the analyzed temperature data.

The operator rapidly assesses the meteorological validity of the result based on the sounding-implied wind directions and speeds. Soundings which produce meteorologically inconsistent thermal winds can be recognized and deleted.

4. Profile Retrieval Techniques

There are currently two types of temperature profile retrieval techniques -- the statistical regression and the direct physical. Both types are referred to extensively in this report.

The statistical regresion technique yields a temperature profile from a linear regression relationship with HIRS and MSU brightness temperatures. The regression coefficients are derived from a dependent sample of measured radiances and quasi-coincident radiosonde observations.

The direct physical solution depends upon the physical properties of the measurements (as opposed to empirical relations) and upon the ability to describe the measurements by the radiative transfer equation. Direct inverse solutions of the radiative transfer equation by numerical iterative techniques are often used.

Table 1. Characteristics of TOV sounding channels.

HIRS Channel number	Channel central wavenumber	Central wavelength (μm)	Principal absorbing constituents	Level of peak energy contribution	Purpose of the radiance observation
1 2 3 4 5 6 7	668 679 691 704 716 732 748	15.00 14.70 14.50 14.20 14.00 13.70 13.40	CO_2 CO_2 CO_2 CO_2 CO_2 CO_2/H_2O CO_2/H_2O	30 mb 60 mb 100 mb 400 mb 600 mb 800 mb 900 mb	*Temperature sounding.* The 15-μm band channels provide better sensitivity to the temperature of relatively cold regions of the atmosphere than can be achieved with the 4.3-μm band channels. Radiances in Channels 5, 6, and 7 are also used to calculate the heights and amounts of cloud within the HIRS field of view.
8	898	11.10	Window	Surface	*Surface temperature* and cloud detection.
9	1 028	9.70	O_3	25 mb	*Total ozone* concentration.
10 11 12	1 217 1 364 1 484	8.30 7.30 6.70	H_2O H_2O H_2O	900 mb 700 mb 500 mb	*Water vapor sounding.* Provides water vapor corrections for CO_2 and window channels. The 6.7-μm channel is also used to detect thin cirrus cloud.
13 14 15 16 17	2 190 2 213 2 240 2 276 2 361	4.57 4.52 4.46 4.40 4.24	N_2O N_2O CO_2/N_2O CO_2/N_2O CO_2	1 000 mb 950 mb 700 mb 400 mb 5 mb	*Temperature sounding.* The 4.3-μm band channels provide better sensitivity to the temperature of relatively warm regions of the atmosphere than can be achieved with the 15-μm band channels. Also, the short-wavelength radiances are less sensitive to clouds than those for the 15-μm region.
18 19	2 512 2 671	4.00 3.70	Window Window	Surface Surface	*Surface temperature.* Much less sensitive to clouds and H_2O than the 11-μm window. Used with 11-μm channel to detect cloud contamination and derive surface temperature under partly cloudy sky conditions. Simultaneous 3.7- and 4.0-μm data enable reflected solar contribution to be eliminated from observations.
20	14 367	0.70	Window	Cloud	*Cloud detection.* Used during the day with 4.0- and 11-μm window channels to define clear fields of view.

MSU	Frequency (GHz)	Principal absorbing constituents	Level of peak energy contribution	Purpose of the radiance observation
1	50.31	Window	Surface	*Surface emissivity* and *cloud attenuation* determination.
2 3 4	53.73 54.96 57.95	O_2 O_2 O_2	700 mb 300 mb 90 mb	*Temperature sounding.* The microwave channels probe through clouds and can be used to alleviate the influence of clouds on the 4.3- and 15-μm sounding channels.

SSU	Wavelength (μm)	Principal absorbing constituents	Level of peak energy contribution	Purpose of the radiance observation
1 2 3	15.0 15.0 15.0	CO_2 CO_2 CO_2	15.0 mb 4.0 mb 1.5 mb	*Temperature sounding.* Using CO_2 gas cells and pressure modulation, the SSU observes thermal emissions from the stratosphere.

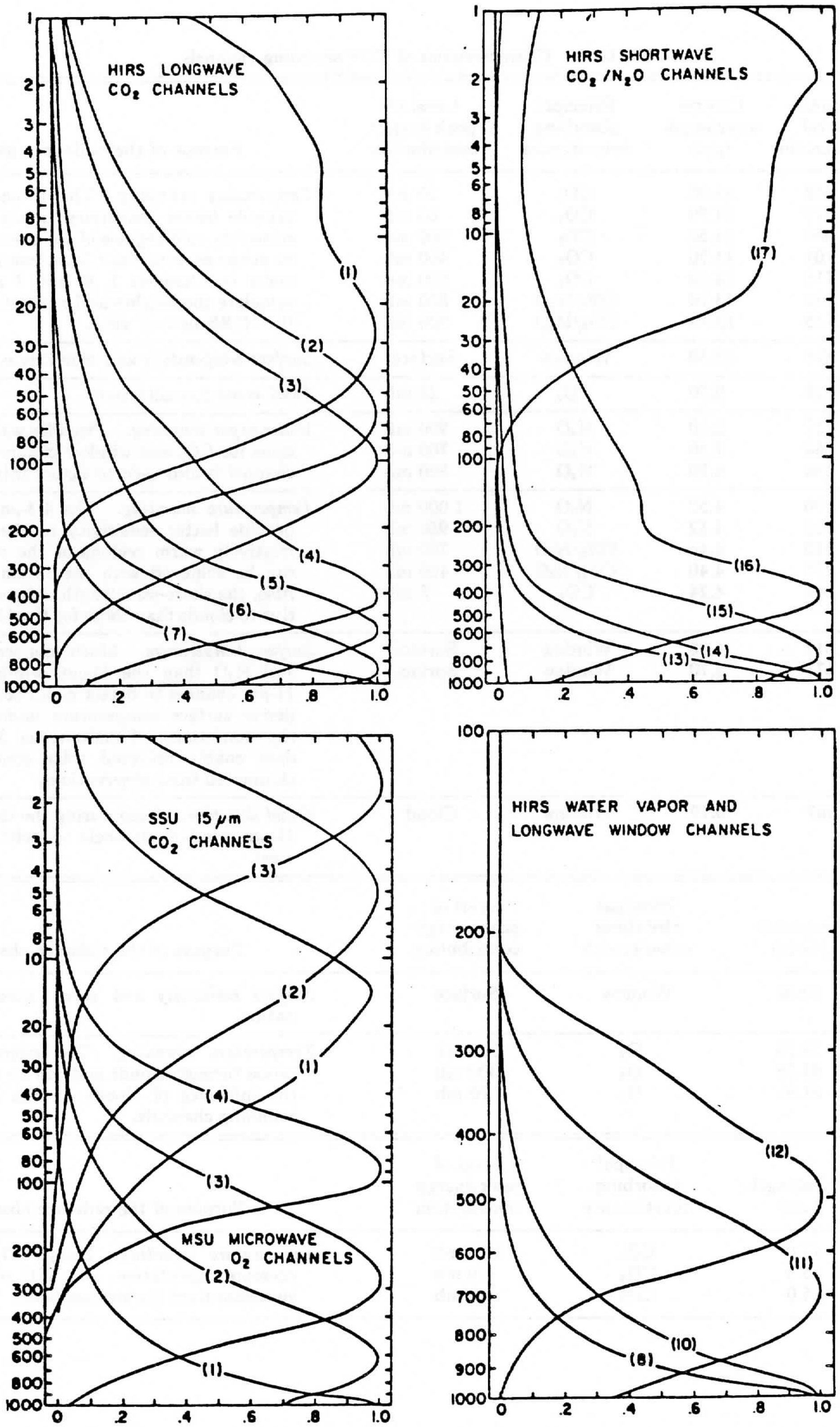

FIG. 1. TOVS weighting functions (normalized).

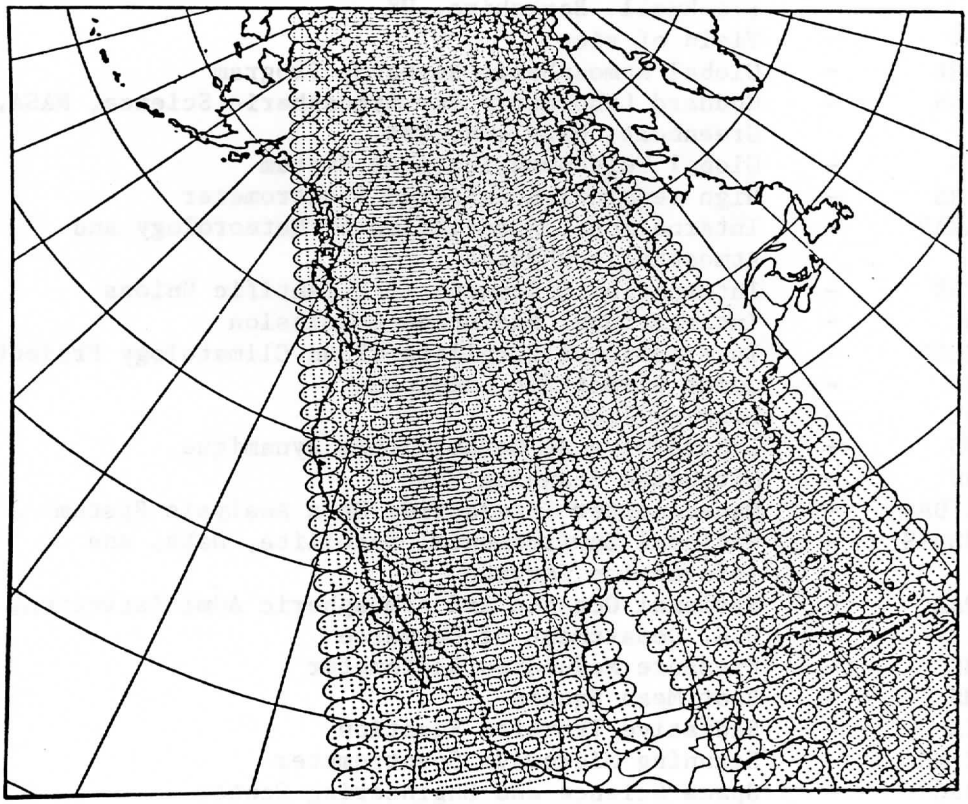

FIG. 2. HIRS and MSU scan patterns for two consecutive orbits.

C. List of Acronyms

ALPEX	-	Alpine Experiment
AVHRR	-	Advanced Very High Resolution Radiometer
CIMSS	-	Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin-Madison, Madison, Wisconsin, USA
CIRA	-	Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, Colorado, USA
CMS	-	Centre de Meteorologie Spatiale, Lannion, Cedex, France
DFVLR	-	Deutsche Forschungs -und Versuchanstalt fur Luft- und Raumfahrt, Oberpfaffenhofen, Germany
ECMWF	-	European Centre for Medium range Weather Forecasting Bracknell, Berkshire, UK
FOV	-	Field of view
GARP	-	Global Atmospheric Research Program
GLAS	-	Goddard Laboratory for Atmospheric Science, NASA, Greenbelt, Maryland, USA
GTS	-	Global Telecommunications System
HIRS	-	High resolution Infrared Spectrometer
IAMAP	-	International Association of Meteorology and Atmospheric Physics
ICSU	-	International Council of Scientific Unions
IRC	-	International Radiation Commission
ISCCP	-	International Satellite Cloud Climatology Project
JSC	-	Joint Scientific Committee
LBL	-	Line-by-line
LMD	-	Laboratoire de Meteorologie Dynamique
MSU	-	Microwave Scanning Unit
McIDAS	-	Man-computer Interactive Data Analysis System
NESDIS	-	National Environmental Satellite, Data, and Information Service
NOAA	-	National Oceanic and Atmospheric Administration, U.S. Department of Commerce
PMR	-	Pressure Modulated Radiometer
RMS	-	Root Mean Square
RTE	-	Radiative Transfer Equation
SCAMS	-	Scanning Microwave Spectrometer
SSEC	-	Space Science and Engineering Center University of Wisconsin, Madison, Wisconsin, U.S.A.
SSU	-	Stratospheric Sounding Unit
TIGR	-	TOVS Initial Guess Retrieval
TIP	-	TIROS Information Processor
TOMS	-	Total Ozone Mapping Spectrometer
TOVS	-	TIROS Operational Vertical Sounder
TSF	-	Typical Shape Functions
VHF	-	Very High Frequency
WCRP	-	World Climate Research Program
WEFAX	-	Weather Facsimile
WGRS	-	Working Group on Remote Sensing
WMO	-	World Meteorological Organization
WWW	-	World Weather Watch

D. Addresses of TOVS Study Conference Participants

Dr. Tadao Aoki
Meteorological Satellite Center
Nakakiyoto
Kiyose
Tokyo 204
JAPAN

Dr. Les A. Barånski
Satellite Data Receiving
Centre, Institute of Meteorology
and Water Management
Piotra Borowego Str. 14
PL-30-215 Krakow
POLAND

Dr. H. Billing
Freie Universität Berlin
Institut für Meteorologie
Fachbereich 24, WE07
Podbielskiallee 62
D-1000 Berlin 33
FEDERAL REPUBLIC OF GERMANY

Dr. H.J. Bolle
Institut für Meteorologie und
Geophysik
Universität Innsbruck
Schopfstrasse 41
A-6020 Innsbruck
AUSTRIA

Dr. M.T. Chahine
Jet Propulsion Laboratory
California Inst. of Technology
4800 Oak Drive
Pasadena, CA 91109
USA

Dr. A. Chedin
Laboratoire de Meteorologie
Dynamique
Ecole Polytechnique
Route Departementale 36
F-91128 Palaiseau Cedex
FRANCE

Dr. Yves Durand
Centre de Recherche en 3-235,
Météorologie Dynamique
63, rue de Sèvres
F-92100 Boulogne
FRANCE

Dr. John R. Eyre
Meteorological Office
London Road, Bracknell
Berkshire, RG12 2SZ
UNITED KINGDOM

Dr. H. Fischer
Meteorologisches Institut der
Universität München
Theresienstrasse 37
D-8000 München 2
FEDERAL REPUBLIC OF GERMANY

Mr. Jim Giraytys
World Weather Watch Department
World Meteorological Organization
41 Guiseppe-Motta
Case Postale No. 5
CH-1211 Geneve 20
SWITZERLAND

Mr. Graeme A. Kelly
Australian Numerical Met.
Research Center
P.O. Box 4089 AA
Melbourne, Victoria
AUSTRALIA 3001

Dr. Patrick King (ARMA)
Atmospheric Environment Serv.
Department of Environment
4905 Dufferin Street
Downsview, Ontario M3H 5T4
CANADA

Mr. Thomas J. Kleespies
Research Meteorologist
Naval Environmental Prediction
Research Facility
Monterey, CA 93940
USA

Dr. John F. LeMarshall
Cooperative Institute for
Met. Satellite Studies
University of Wisconsin
1225 W. Dayton Street
Madison, WI 53706
USA

Dr. Frank Loechner
Deutsche Forschungs- und
Versuchsanstalt für Luft-
und Raumfahrt
Oberpfaffenhofen
D-8031 Wessling
FEDERAL REPUBLIC OF GERMANY

Dr. Mervyn J. Lynch
Senior Lecturer
School of Physics and
Geosciences
Western Australian Inst.
of Technology
Haymon Road, South Bentley 6102
AUSTRALIA

Dr. Larry McMillin
United States Dept. of Commerce
NOAA
National Earth Satellite Service
Washington, D.C. 20233
USA

Dr. W. Paul Menzel
Space Science & Engr. Center
1225 W. Dayton Stret
Room 201
Madison, WI 53706
USA

Dr. M.-J. Munteanu
NASA Code 911
Goddard Space Flight Center
Greenbelt, MD 20771
USA

Dipl.-Met. K. Paetzold
Deutscher Wetterdienst
Zentralamt
Frankfurter Strasse 135
D-6050 Offenbach/Main
FEDERAL REPUBLIC OF GERMANY

Dr. T. Phulpin
Centre de Meteorologie Spatiale
B.P. 147
F-22302 Lannion Cedex
FRANCE

Dr. Fred Prata
University of Oxford
Department of Atmospheric Physics
Clarendon Laboratory
Parks Road
Oxford
OX1 3PU
UNITED KINGDOM

Dr. Rolando Rizzi
Dipartimento di Fisica
Universita di Bologna
Via Verti Pichat 8
I-46126 Bologna
ITALY

Dr. G. Rochard
Centre de Meteorologie Spatiale
B.P. 147
F-22302 Lannion Cedex
FRANCE

Dr. Helmut Rott
Institut für Meteorologie
und Geophysik
Schopfstrasse 41
A-6020 Innsbruck
AUSTRIA

Dr. J. Svensson
SMHI, The Swedish Meteorol. and
Hydrological Institute
Box 923
S-601 19 Norrköping
SWEDEN

Dr. N. Scott
Laboratoire de Meteorologique
Dynamique
Ecole Polytechnique
Route Departementale 36
F-91128 Palaiseau Cedex
FRANCE

Dr. Brian F. Taylor
NZ Meteorological Service
P.O. Box 722
Wellington
NEW ZEALAND

Dr. William L. Smith
National Environmental Satellite
Service/NOAA
1225 West Dayton Street
Madison, WI 53706
USA

Dr. R. Juvanon du Vachat
Centre de Recherche en
Météorologie Dynamique
73, rue de Sèvres
F-92100 Boulogne
FRANCE

Dr. D. Spänkuch
Meteorologischer Dienst der
D.D.R., Met. Hauptobservat.
Telegraphenberg
1500 Potsdam
GERMAN DEMOCRATIC REPUBLIC

Mr. H. M. Woolf
United States Dept of Commerce
NOAA, Development Laboratory
1225 West Dayton Street, Room 219
Madison, WI 53706
USA

Dr. Joel Susskind
NASA
Goddard Space Flight Center
Greenbelt, MD 20771
USA

Ms. Feng-Xian Zhou
Institute of Atmospheric Physics
Academia Sinica
Beijing
PEOPLE'S REPUBLIC OF CHINA