Application of a PC-based ITPP-3 Synthetic Retrieval Package to an Investigation of Microwave Ducting in the Atmosphere

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Introduction

The phenomenon of gradients in atmospheric temperature and moisture, and hence refractivity, affecting the propagation of microwave beams in the atmosphere is well known and understood. However no facility yet exists for measuring atmospheric refractivity on the appropriate time and space scales to adequately monitor atmospheric change.

Ducting of microwave radiation is related to the wavelength of the propagating beam and consequently the spatial scales involved can be small. However the total path length over which the beam is being transmitted may be several thousand kilometers. No spaceborne sensing system currently exists which addresses both these extremes of spatial scale. Thus there is some purpose in assessing the capability of current sensors and analyzing the performance improvement expected from the next generation of sensors to be deployed in the next decade.

Project Review

This project reviews the contribution which satellite sensors with an atmospheric sounding capability are able to make to refractivity profiling and the detection of ducting situations. Some existing and future sensors are examined and their capabilities and limiting factors addressed.

The full study being undertaken has three components as noted below.

(1) The study was commenced using data sets from the NOAA TIROS-N satellite series TOVS sensor to investigate the quality of temperature and moisture sounding products. To this end a data set has been collected in time coincidence with satellite overpasses, comprising ship-launched sondes and sea surface meteorological parameters including sea surface temperature. The processing of these data sets is reported elsewhere (Lynch et al, 1989).

(2) A synthetic retrieval software package has been developed to enable simulation of the NOAA TOVS data corresponding to various atmospheric conditions and

(3) The authors have been fortunate to have access to high spectral resolution infrared data from a prototype next generation sensor. The data is presently being examined to establish the prospects for future refractivity measurements from space platforms. The data sets were made available by the Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin-Madison. The quality of the temperature and moisture products from this advanced High-resolution Interferometer Sounder (HIS) has been reported elsewhere (Staff members CIMSS et al, 1989).

**Refractivity and Ducting**

Richter and Hitney (1980) have reviewed the ducting problem and emphasized the role of atmospheric water vapor. Refractivity assumes a linear form for a standard atmosphere as shown in Figure 1. The figure also illustrates the formation of a duct directly attributable to an elevated trapping layer. It is structure of this type in the refractivity profile which leads to the ducting of a propagating microwave beam and the associated fluctuation in the strength of the received microwave signal.

**NOAA Satellite Series**

The NOAA polar orbiter series comprises a sequence of operational satellites used primarily for meteorological applications. The series commenced with TIROS-N in the late 1970's and presently the sixth and seventh satellites in the series, NOAA-10 and NOAA-11, are operational. The satellites have separate sensors for sounding the atmosphere, and for imaging the oceans and land. The High-resolution Infrared Sounder (HIRS) and the Microwave Sounding Unit (MSU) have 19 channels and 4 channels respectively for atmospheric sounding. Data from these two sensors is together known as TOVS (TIROS Operational Vertical Sounder). The imaging sensor is the Advanced Very High Resolution Radiometer (AVHRR). While data from the AVHRR has not been used in this study, it has a potentially useful role in defining the near surface region, especially over the ocean.

**Retrieval Software**

The satellite data were acquired directly from the NOAA spacecraft by the Curtin University of Technology receiving station. Subsequent data processing was done using the International TOVS Processing Package Version 3 (ITPP-3) software developed at CIMSS. The DEC-VAX version of the package was adapted to run on an IBM-PC system to permit ease and flexibility of use in terms of choice of input parameters and selection of various processing options. The synthetic retrieval package developed for the IBM-PC is described in a companion paper in this volume (Gumley et al, 1989).

When provided with a set of radiance observations the ITPP-3 retrieval algorithm generates a 'first guess' profile of atmospheric temperature and moisture using either a climatological database, or a regression scheme using previous collocated radiance and atmospheric profile observations. The retrieval algorithm then adjusts the guess profile so that the corresponding calculated radiances match the radiances observed by the sensor. When the calculated and observed radiances match each other within prescribed error limits, the updated guess profile (or retrieval) is presumed to match the real atmospheric profile.
Atmospheric refractivity and modified refractivity profiles for a standard atmosphere (dashed line) showing the linear dependence. The same quantities are plotted (solid line) for an atmosphere which is characterized by an elevated trapping layer and an associated elevated duct.
Results

Radiances have been calculated for a series of atmospheric temperature and moisture profiles and the ITPP-3 retrieval algorithm used to retrieve profiles from these radiances. An initial focus of this research concerned the investigation of the performance of the retrieval algorithm by comparing the retrieved profiles to the original input profiles. Careful evaluation of the various features of the retrieval algorithm and examination of the products has been undertaken in order to optimize the retrieval algorithm performance. Details of the results are discussed in the companion paper in this volume (Gumley et al, 1989).

Reproduced here are the synthetic input profiles of temperature and moisture for which TOVS radiances have been calculated. Also shown are the profiles retrieved from these synthetic radiances using the ITPP-3 retrieval algorithm, and the corresponding refractivity profiles for both the input and retrieved profiles. For example, Figure 2(a) shows the temperature and moisture profiles, and Figure 2(b) the associated refractivity profile for a situation where the synthetic input profile was chosen to be identical to the climatological 'first guess' profile used by the retrieval algorithm. In this case, the retrieval algorithm ideally should retrieve the input profile exactly, as the first guess matches the input profile. However, it can be appreciated that in most situations the guess profile will not exactly match the observed profile. Figures 3 through 10 illustrate similar situations, but where the profile used in the radiance calculation is different to the guess profile generated by the retrieval algorithm.

Figures 7(a) and 7(b) are worthy of note in that the input profile has been perturbed substantially from the guess profile by increasing the temperature and moisture relative to the guess as may be shown by comparison with the initial profile shown in Figure 2(a). Similarly, Figure 8(a) corresponds to a case where the temperature and moisture have been decreased relative to the guess. Figure 8(b) shows the refractivity for the input and retrieved profiles.

In Figures 9 and 10 the input profile has been adjusted so as to incorporate structure which leads to ducting situations, characterized by a layer of cool, moist air near the surface with a warmer, drier layer above. For these the retrieval was performed first without surface data, and then with surface data included. A feature to note in the dewpoint profile for the retrievals in Figures 9 and 10 is a sharp increase in the retrieved dewpoint at the 780mb level. It appears that this is an artifact of the retrieval algorithm, and the origin of this feature is currently being investigated. Figure 11 shows a retrieval in which the input profile was a sonde profile obtained over the ocean during daytime off the Northwest Shelf of Western Australia in late summer. The dewpoint increase at 780mb in the retrieved profile is again evident.

In these three cases, the climatological guess profile produced by ITPP-3 differs considerably from the input profiles and hence recovery of this detail in the output profile is a severe test of the retrieval algorithm. It should be noted that even an ideal retrieval algorithm cannot recover vertical detail accurately if that vertical detail is not resolved in the radiance observations. For the TOVS sensor, the vertical resolution is limited principally by the sensor design.

To illustrate this point, it is necessary to consider the weighting functions for the various TOVS spectral channels. Smith et al (1979) have shown that the shape of the TOVS weighting functions in the vertical is very broad. Accordingly, if vertical structure in the synthetic input profile is too sharp, it will not be resolved by the
sensor and the vertical structure information will not be present in the radiance observations. Typically, the vertical resolution of the TOVS in both temperature and moisture is limited to several kilometers.

Future Prospects

Prospects for future spaceborne sensors are encouraging with the emphasis in the late 1990's on higher spectral resolution instruments. A prototype high resolution sensor, the HIS developed by CIMSS at the University of Wisconsin, has at present been operated in both airborne and ground configurations. This instrument is an interferometer and offers several thousand spectral channels. Recent research (Staff members CIMSS et al, 1989) has shown that this sensor offers much higher quality vertical temperature and moisture profiling than current sensors. These benefits will directly translate into improved refractivity profiling. Investigations of the expected performance of the next generation sensors is in progress.

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References


Figure 2 (a)

A comparison of the synthetic input profile and the retrieval. The forward radiance calculation was performed with the gammas and deltas initialized to 1.0 and 0.0 respectively. The retrieval was performed using the default gammas and deltas.

Dashed: Input
Solid: Retrieval

Pressure (mB)

Dewpoint and Temperature (C)
Figure 2 (b)

Modified refractivity change with height for atmospheric profile shown in Figure 2(a).

Dashed: Input
Solid: Retrieval

Modified refractivity

Geopotential height (m)
The same input data as used in Figure 2 with the exception that the gammas and deltas in both the forward calculation and the retrieval were initialized to 1.0 and 0.0 respectively. The retrieval is degraded compared with that obtained in Figure 2.
Figure 3 (b)

Modified refractivity change with height for atmospheric profile shown in Figure 3(a).
Figure 4 (a)

For this example the input profile to the forward calculation is a modification of the climatological guess. The input profile has been moistened by 5 g/kg between 750 mb and the surface. The increased moisture is not recovered in the retrieval.

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Dashed: Input
Solid: Retrieval

Pressure (mb)

Dewpoint and Temperature (°C)
Figure 4 (b)

Modified refractivity change with height for atmospheric profile shown in Figure 4(a).

Dashed: Input
Solid: Retrieval

Geopotential height (m)

Modified refractivity

300 400 500 600 700
Figure 5 (a)

The same input profile as for Figure 4. In the retrieval the surface skin temperature has been assigned the value used in the synthetic input profile (28.6 °C). The moisture profile is somewhat improved in the surface to 750 mb region.
Figure 5 (b)

Modified refractivity change with height for atmospheric profile shown in Figure 5(a).

Dashed: Input
Solid: Retrieval

Geopotential height (m)

Modified refractivity

300 400 500 600 700
Again the same input profile as used for Figures 4 and 5. The retrieval surface skin temperature was assigned the value used in the synthetic input profile (28.6°C). The ERO value in TOVRET was reduced to 0.25 K for all spectral channels. The improvement in the lower level moisture retrieval over that in Figure 5 is significant.
Figure 6 (b)

Modified refractivity change with height for atmospheric profile shown in Figure 6(a).

Dashed: Input
Solid: Retrieval
Figure 7 (a)

The input profile has been derived from a perturbation to the climatological guess throughout the whole atmospheric column. Specifically, the temperature profile has been warmed and the moisture increased as may be shown in a comparison with the climatological guess shown in Figure 2. The retrieval is made with the four channel regression surface skin temperature estimator.

Dashed: Input
Solid: Retrieval

Pressure (mB)

Dewpoint and Temperature (°C)
Figure 7 (b)

Modified refractivity change with height for atmospheric profile shown in Figure 7(a).

Dashed: Input
Solid: Retrieval
Figure 8 (a)

Similar to Figure 9 except that the input profile has been cooled and dried relative to the climatological guess. The retrieval performance is less satisfactory than that in Figure 9.

\[ \text{Dashed: Input} \]
\[ \text{Solid: Retrieval} \]
Figure 8 (b)

Modified refractivity change with height for atmospheric profile shown in Figure 8(a).

Dashed: Input
Solid: Retrieval

Geopotential height (m)

Modified refractivity

300  400  500  600  700

0  500  1000  1500  2000  2500
Figure 9 (a)

Input and retrieved profiles for a synthetic atmospheric profile showing duct structure. Surface data was not used in retrieval.

Dashed: Input  
Solid: Retrieval
Figure 9 (b)

Modified refractivity change with height for atmospheric profile shown in Figure 9(b).
Note duct structure in input profile.
Figure 10 (a)

Input and retrieved profiles for a synthetic atmospheric profile showing duct structure. Surface data was used in retrieval.

Dashed: Input
Solid: Retrieval

Dewpoint and Temperature (°C)
Figure 10 (b)

Modified refractivity change with height for atmospheric profile shown in Figure 10(b). Note duct structure in input profile.

Dashed: Input
Solid: Retrieval
Figure 11 (a)

Input and retrieved profiles for a synthetic atmospheric profile. Atmospheric profile was derived from ship-launched sonde at 22.7S, 113.4E on 24 March 1985. Surface data was not used in retrieval.
Modified refractivity change with height for atmospheric profile shown in Figure 11(b).

**Figure 11 (b)**

Dashed: Input
Solid: Retrieval

**Geopotential height (m)**

**Modified refractivity**
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