GOES High-Resolution Interferometer Sounder Retrieval Performance Simulations[1]

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ABSTRACT

An evolutionary improvement to the existing GOES I-M Sounder has been proposed as the GOES High-Resolution Interferometer Sounder (GHIS). This instrument will be based upon technology developed during successful demonstrations of an airborne Michelson interferometer instrument for the temperature and moisture sounding of the atmosphere from passive infrared measurements. The spectral resolution afforded by the interferometer technology will substantially improve retrieval accuracy and vertical resolution of the sounding information. Simulations of the spectral radiance measurements have been used to study the expected retrieval performance of the GHIS. A fast transmittance code has been used in the simulations and in the calculation of the retrieval operator in an iterative, non-linear physical retrieval scheme. The effects of instrument noise and spectral operating mode have been considered in the retrieval simulation. A measure of the vertical resolution of the retrieved profiles has been developed. This measure considers the correlation in the retrieval error between atmospheric levels of the retrieved parameters. The effects of both the instrument characteristics and those of the retrieval algorithm are thus considered in this measure. The results indicate that the GHIS is expected to provide temperature retrieval accuracy on the order of 1 °C throughout the troposphere which will be a significant improvement over the existing GOES-8 sounder. The vertical resolution simulations also show improvement over GOES-8 capabilities.

Keywords: GOES, Interferometer Sounder, Retrieval Simulation, Vertical Resolution

1. INTRODUCTION

With the advent of the first two flight spacecraft of the GOES-Next series, GOES-8 and -9, full time operational geostationary sounding has become a reality. The hourly satellite soundings retrieved from the data have proven to be useful aids in qualitative interpretation as well as quantitative inputs to numerical weather prediction models. These applications of sounder data represent a major step forward in the development of geostationary sounders begun with the VISSR Atmospheric Sounder first flown on GOES-4 in 1980.

While the ultimate utility of the GOES-Next Sounders is just being explored, planning and development work has been ongoing for the next generation of geostationary infrared sounders. In 1988, the University of Wisconsin, the Hughes Santa Barbara Research Center, and ITT Aerospace/Communications Division prepared a study of a concept for replacing the filter wheel in the GOES-Next Sounder with a Michelson interferometer as a potential upgrade[1,2]. This concept, named the GOES High-Resolution Interferometer Sounder (GHIS), offered an attractive way to implement a high-resolution sounder onboard the GOES platform without having to redesign the entire instrument.

Since 1993, MIT Lincoln Laboratory has been performing risk-reduction technology development on the GHIS concept. Lincoln is currently developing a hardware prototype of the GHIS which will be integrated into the GOES Sounder pathfinder instrument and undergo a variety of instrument-level testing to demonstrate fit and functionality. This demonstration will hopefully smooth the procurement of flight models.

In parallel with the hardware risk reduction activity, Lincoln has been exploring system performance trades through the use of radiometric performance models and retrieval simulations. Through detailed detector and system models we obtain estimates of the NEΔN which is then used in the retrieval simulation to explore the impact of noise and spectral resolution on atmospheric profile retrieval performance.

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2. GHIS UPGRADE

This section briefly describes the origin of the GHIS concept, the risk-reduction effort at Lincoln Laboratory and covers the general instrument specifications as they were at the time of writing.

2.1 GHIS Concept

In the late 1980's it was recognized that advances in weather forecasting would drive requirements on satellite sounding accuracies higher than those developed for the GOES-Next Sounder. Higher vertical resolution and more accurate soundings would soon be necessary to support the next-generation numerical weather prediction models. Based on their experiences with the airborne High-resolution Interferometer Sounder (HIS)[3], University of Wisconsin (UW) scientists recognized that a Michelson interferometer with approximately 1 cm^{-1} spectral resolution could possibly meet those requirements.

Working together with engineers at Santa Barbara Research Center and ITT Aerospace/Optical Division, the UW scientists explored the feasibility of replacing the filter wheel section of the GOES-Next Sounder with a Michelson interferometer without a major redesign of the instruments optics, housing, detectors, and cooling assemblies. Their study produced a preliminary concept and recommended proceeding forward.

Unfortunately, about the same time this study was being released, the fabrication and test of the GOES-Next satellite instruments was running into several technological problems which were delaying development of the series. Being preoccupied with these problems, the proposal for the sounder upgrade languished on the shelves.

In 1993, with the GOES-Next program back on track, NOAA initiated a two phase review of the UW/SBRC/ITT GHIS proposal at MIT Lincoln Laboratory. In phase 1, Lincoln engineers reviewed the technology and risks associated with the GHIS concept. They concluded that the concept appeared feasible, but identified several risk areas. During phase 2, they developed a detailed point design that established the feasibility of the concept and recommended an approach to risk-reduction through a technology demonstration effort including a brassboard prototype.

2.2 MIT/LL Brassboard Development

Starting in mid-1995, Lincoln Laboratory begun development of a GHIS brassboard prototype to explore design issues and reduce risks associated with flight-model development by demonstrating a design, fabrication and test approach that will result in a GHIS module that will operate as specified in a modified GOES-Next sounder. This effort is well under way[4] and in 1997 will demonstrate through thermal vacuum testing the operation of GHIS integrated into an early engineering model of the Sounder. The experience and lessons learned through this activity will be shared with the instrument vendor for the flight model procurement. Together with an engineering study at ITT, this effort will provide input to NOAA for a decision on the upgrade by mid-1997. If approved for development, the GHIS module could be carried on GOES-N slated for launch in 2004.

2.3 GHIS Specifications and Radiometric Performance Predictions

In the time since the original GHIS feasibility study, the design specifications for GHIS have evolved through additional experience gained with the HIS instrument and through additional engineering design and trade studies. While the final instrument specifications have yet to be decided, the following describes the relevant instrument parameters as of this writing.

Since the GHIS concept replaces only the spectral selection subsystem of the GOES-Next Sounder, many of the characteristics will remain the same including the spatial resolution, scan strategies and calibration techniques. However, with the inclusion of the Michelson interferometer, many of the radiometric, calibration and registration requirements may have to be tightened to obtain the desired improvements in performance of the sounder.

Table 1 presents a summary of the GHIS specifications that relate to sounding performance as explored in this study. As mentioned above, these parameters are subject to change as the design and development process proceeds. Given a nominal set of optical parameters, detector performance and instrument temperatures, the predicted radiometric accuracy in terms of noise-equivalent delta temperature (NEΔT) is shown in Figure 1.

Table 1. GHIS spectral specifications used in retrieval simulation study.

Parameter	Band 1	Band 2	Band 3
Spectral band range	620 - 1150 cm^{-1}	1210 - 1740 cm^{-1}	2150 - 2720 cm^{-1}
Interferometer scan pattern by spectral operating mode			
Full Resolution (double-sided)	-0.8 to 0.8 cm	-0.4 to 0.4 cm	-0.2 to 0.2 cm
Partial Scan (single-sided)	-0.05 to 0.10 cm 0.58 to 0.73 cm	-0.05 to 0.1 cm	-0.05 to 0.1 cm
Low Resolution (double-sided)	-0.13 to 0.13 cm	-0.1 to 0.1 cm	-0.1 to 0.1 cm
Spectral resolution* by spectral operating mode			
Full Resolution	0.76 cm^{-1}	1.5 cm^{-1}	3.0 cm^{-1}
Partial Scan	0.75 cm^{-1}	6.0 cm^{-1}	6.0 cm^{-1}
Low Resolution	4.64 cm^{-1}	6.0 cm^{-1}	6.0 cm^{-1}

*Defined as the FWHM of the main lobe of the unapodized spectral response function.

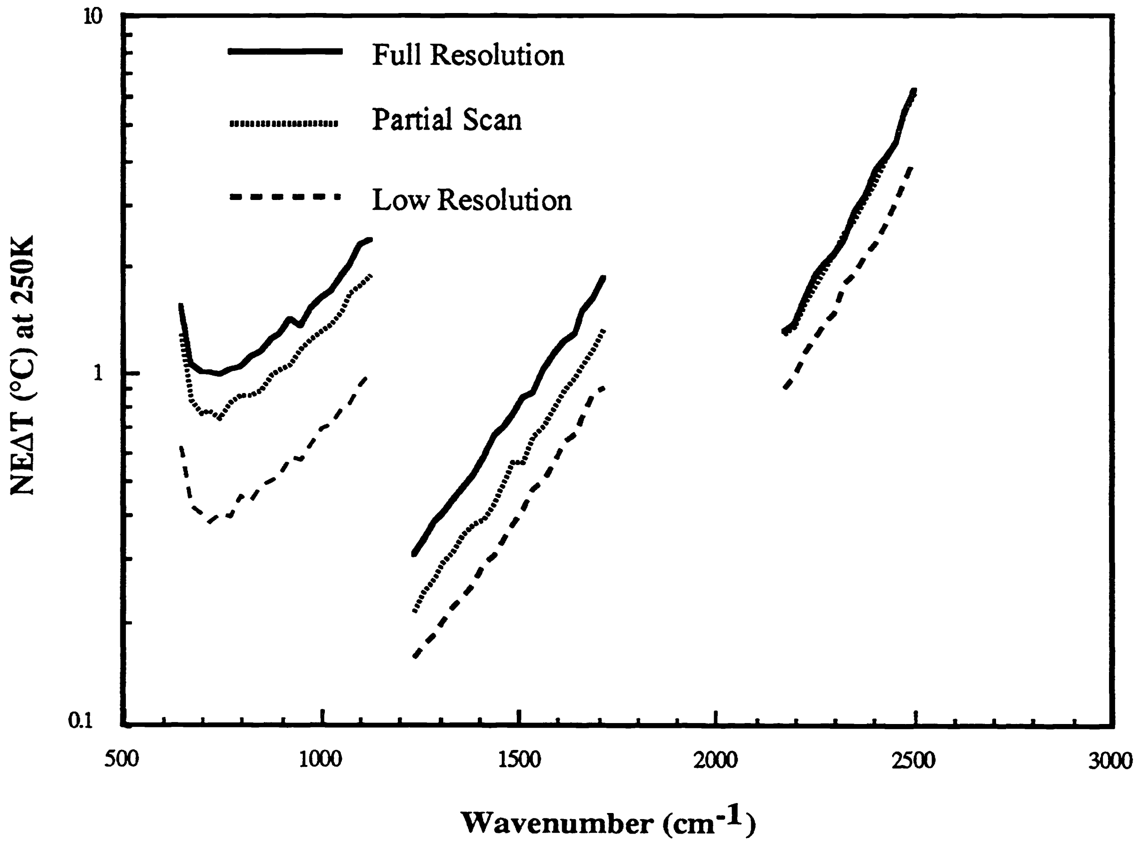

Figure 1. Nominal NEΔT prediction for GHIS given typical instrument parameters and specifications shown in Table 1.

The Partial Scan mode was added to the concept to allow high spectral resolution data to be collected at a rate required by the National Weather Service, but with lower noise. The NWS has specified a coverage rate of scanning a 3000 x 3000 km area within one hour. The Partial Scan mode works in Band 1 by scanning the interferometer mirror slowly through ZPD (Zero Path Difference), rapidly slewing to an OPD (Optical Path Difference) of 0.58 cm, and then taking data slowly out to 0.73 cm. Bands 2 and 3 are the same as in the Low Resolution mode except data is collected on only one side of the interferogram. This scan pattern was adopted from earlier work[5] and is matched to the resonance of the 15 µm CO_2 band which appears in the interferogram at ~0.65 cm OPD.

The Low Resolution mode is included to also meet the spatial coverage rate requirement as well as to provide a lower resolution double-sided interferogram which typically has fewer potential calibration problems than the single-sided Partial Scan interferogram.

3. RETRIEVAL SIMULATION METHODOLOGY

This section details the approach developed for exploring the retrieval performance of the GHIS concept.

3.1 Simulation Methodology

The basic approach is to simulate atmospheric radiances as will be measured by the instrument in space (including the effects of radiometric noise), perform retrievals, and then compute accuracies by comparing the retrieved profiles to the original ones used to generate the atmospheric radiance. Two sets of atmospheric profiles are used in the process; one for use in "training" and developing the background statistics and a first guess linear regression operator, and the second for use in "testing" by actually performing the retrievals and determining accuracy. This approach is shown in Figure 2.

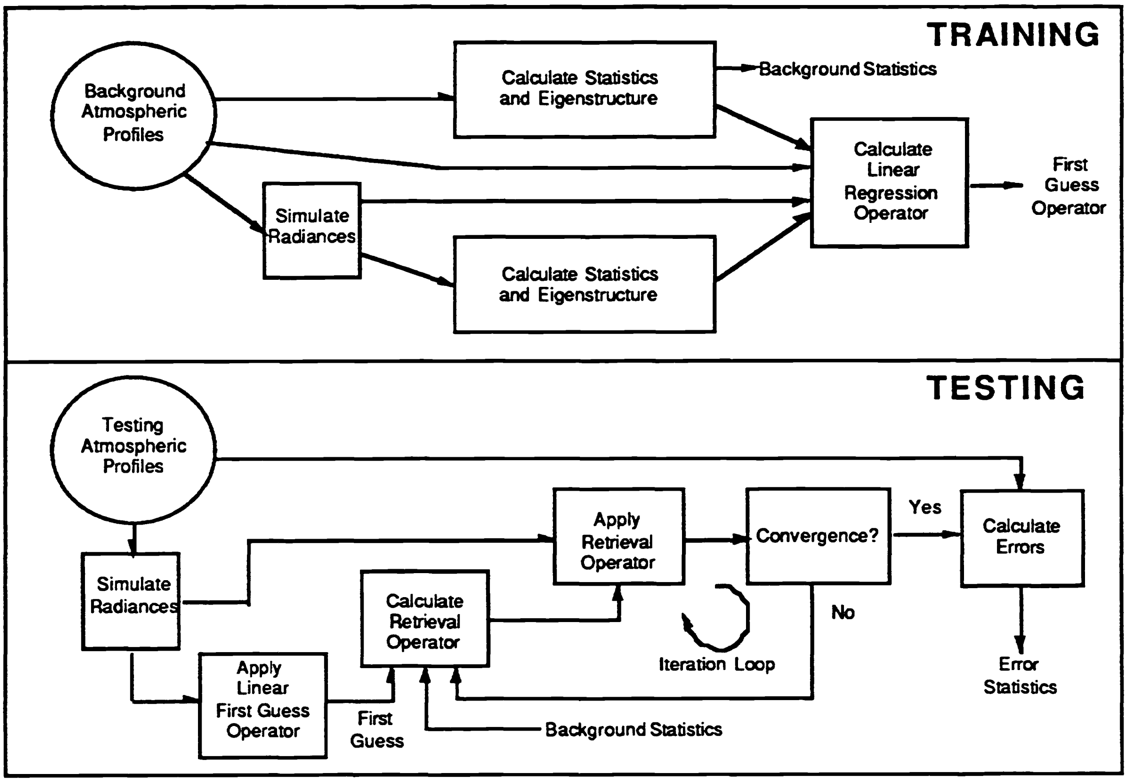

Figure 2. Block diagram of retrieval simulation approach.

The two key components of this simulation approach are the model used to simulate the atmospheric radiance and calculate the transmittance for use in the full retrieval operator, and the particular algorithm used in deriving the equations defining the operator. These two components are described in the following two sections.

3.2 Fast Transmittance Code

The fast transmittance code is used in two separate places in the retrieval simulation. It is used to generate the atmospheric radiance as seen by the satellite as well as to calculate level-to-space transmittances within the full retrieval operator. The simulation of atmospheric radiances need not be necessarily fast, but it is convenient to be consistent with the retrieval code. The retrieval operator transmittance calculations, however, need to be fast since they must be performed for slightly different conditions to calculate derivatives and they are recomputed for each iteration and for each profile in the retrieval simulation.

The fast transmittance code used in this study was developed by scientists at the University of Wisconsin under a subcontract. The code follows an approach developed by scientists at the European Center for Medium-Range Weather Forecasts[6] and uses a regression between atmospheric profiles and transmittances as calculated by the USAF line-by-line atmospheric code FASCD3P. The regression data base was interpolated to 0.1 cm^{-1} resolution to which the GHIS Full Resolution unapodized spectral response was then applied.

This code was used as provided for the Full Resolution mode, but required additional processing for use in the other two modes. For the Partial Scan and Low Resolution mode, the spectral transmittances were transformed to the interferogram domain through the use of an FFT algorithm, a mask applied to simulate the interferogram mirror scan pattern for the appropriate mode, and then transformed back to the spectral domain. This has the effect of applying the appropriate spectral response and works fine, although it is computationally burdensome. A much better approach would be to implement the fast code with the proper spectral response initially applied; however, while design studies are still under way it is nice to have the flexibility of trying arbitrary scan patterns.

This same fast transmittance code was also used to simulate the GOES-8 Sounder radiances and transmittances by applying the measured instrument spectral responses to the high-resolution output of the code. This was done to ensure consistency among the different comparisons.

3.3 Retrieval Algorithm

The retrieval algorithm is an adaptation of a published algorithm[7] designed for the TIROS Operational Vertical Sounder (TOVS) instrument suite on the NOAA polar orbiters. The algorithm is simultaneous in temperature and water vapor, uses a linear regression first guess based on eigenvectors, and iterates until convergence criteria are met.

3.4 Atmospheric Profiles

The training and testing profiles are extracted from a subset of the TOVS Initial Guess Retrieval (TIGR) profiles. A version of the TIGR dataset with 1761 profiles has been used by the NASA/EOS AIRS Science Team for algorithm development. Scientists at the University of Wisconsin[8] have ordered these profiles based on the residual error between the original profiles and ones reconstructed using a limited number of eigenvectors from the temperature covariance matrix. Profiles with sharp gradients and complicated vertical structure have a greater residual error We have used a set of 587 profiles from the middle of this ordering which implies they are of a "moderate" degree of retrieval difficulty (at least in temperature). Of these, 440 profiles were used to calculate the background statistics and the other 147 profiles were used to provide an independent set for retrieval performance prediction.

4. RETRIEVAL RESULTS

Retrieval simulations were performed for the three proposed GHIS operating modes along with GOES-8 characteristics to investigate their relative performance.

4.1 Review of Conditions

For these experiments we used a subset of the spectral channels available from the GHIS instrument. Table 2 shows the number of channels used for each operating mode. Also, the retrievals were done assuming the radiance measurements are the average of cloud-free samples within a 50 x 50 km grid (5 x 5 IFOV's) which was 50% cloudy. This results in lowering the noise shown in Figure 1 by the square root of the number of samples (we assume the measurements are independent samples of a homogenous area). The numbers here were derived assuming each mode was operated in such a way as to meet the NWS requirement of covering a 3000 x 3000 km area in under one hour.

Table 2. Number of spectral channels and noise factors assumed for retrieval simulation study.

GHIS Operating Mode	Number of Spectral Channels	Spatial/Temporal Noise Factor
Full Resolution	369	0.558
Partial Scan	333	0.288
Low Resolution	150	0.288
GOES-8	18	0.288

4.2 Results

The following tables show the 1 km layer averaged accuracies for the different modes and for different stages of the retrieval algorithm. The Linear First Guess result is that obtained using the linear regression operators derived from the background set of profiles. Temperature and water vapor are retrieved separately in this step using channels sensitive to each parameter. The Iteration Result is the final answer from our current algorithm which stops iterating when the forward brightness temperature calculation converges to a constant value.

Table 3. Tropospheric (1000-100 mbar) RMS temperature errors (°C) for 1 km layers.

GHIS Operating Mode	Linear First Guess	Iteration Result
Full Resolution	1.53	1.14
Partial Scan	1.42	1.16
Low Resolution	1.56	1.47
GOES-8	2.11	1.76

Table 4. Stratospheric (100-10 mbar) RMS temperature errors (°C) for 1 km layers.

GHIS Operating Mode	Linear First Guess	Iteration Result
Full Resolution	1.64	1.57
Partial Scan	1.60	1.55
Low Resolution	1.90	2.05
GOES-8	3.57	2.95

Table 5. Tropospheric (1000-300 mbar) RMS water vapor mixing ratio errors (g/kg) for 1 km layers.

GHIS Operating Mode	Linear First Guess	Iteration Result
Full Resolution	0.57	0.53
Partial Scan	0.68	0.63
Low Resolution	0.53	0.56
GOES-8	0.87	0.69

These results provide an example of the improvement in retrieval accuracy possible for the GHIS as compared to the current GOES-8 Sounder. In all cases an improvement is seen. The higher resolution modes improved tropospheric temperature accuracies by ~ 50% and stratospheric accuracies by nearly a factor of two. Even the Low Resolution mode (which offers slightly faster coverage rates and lower data rates) promises a significant improvement over GOES-8. The improvements are less dramatic in the water vapor, but the GHIS results are expected to improve with further algorithm development.

As a design issue, the Full Resolution and Partial Scan modes are seen to provide comparable performance, although the Partial Scan did do poorly on the water vapor in these experiments. This may be due to the lower resolution and fewer channels available in the water vapor band of the Partial Scan mode. However, since the Full Resolution mode in these experiments had higher noise corresponding to an equivalent spatial coverage rate of the Partial Scan, and it did as well (or better), it would seem preferable to the added design complexity required by the Partial Scan mode.

5. VERTICAL RESOLUTION

This section discusses the concept, algorithm, and results of calculations of the vertical resolution for the GHIS.

5.1 Vertical Resolution Algorithm

In the sounding retrieval community the term "vertical resolution" has been used to mean a variety of quantities. One definition has been the full-width half-maximum (FWHM) of the instrument's weighting function, $d\tau/d\ln p$. This quantity is a fair representation of the thickness of an atmospheric layer sensed by an individual channel, but ignores the added information present from other channels, or the retrieval algorithm. Another definition has been the thickness of the vertical layer over which points in the retrieved profile are averaged. This definition ignores the instrument characteristics and leads to an arbitrary number that does not fit with our intuitive understanding of resolution.

A more useful approach to the concept of vertical resolution is to consider an application of the retrieved profiles and define a measure that is significant in this application, as well as fits our intuitive model. A primary application of satellite soundings is their use in Numerical Weather Prediction (NWP) models. There, atmospheric layers are defined and the values of temperature and water vapor quantities are state variables in the model. One issue of importance in these models is the correlation in the values of the state variables between layers. An important feature of new data to be inserted in the model is the correlation of errors between layers. It is undesirable to adjust a model profile to a retrieved profile that has correlated errors over several layers.

Thus, a useful definition of vertical resolution is the distance, or correlation-length, between atmospheric levels over which the error in the retrievals are uncorrelated. Figure 4 shows the correlation functions of retrieval error at three different altitudes: 1 km, 10 km and 20 km. As one can see, the correlation functions approximate the shape of a sin (x)/x curve. Just as in considering the resolution of unapodized interferograms which typically have a sin(x)/x instrument line shape, a useful definition is the FWHM. Here, this definition is seen to result in resolutions of approximately 1 km in the lower troposphere, 2 km in the upper troposphere and 3 km in the stratosphere which fit well with intuition.

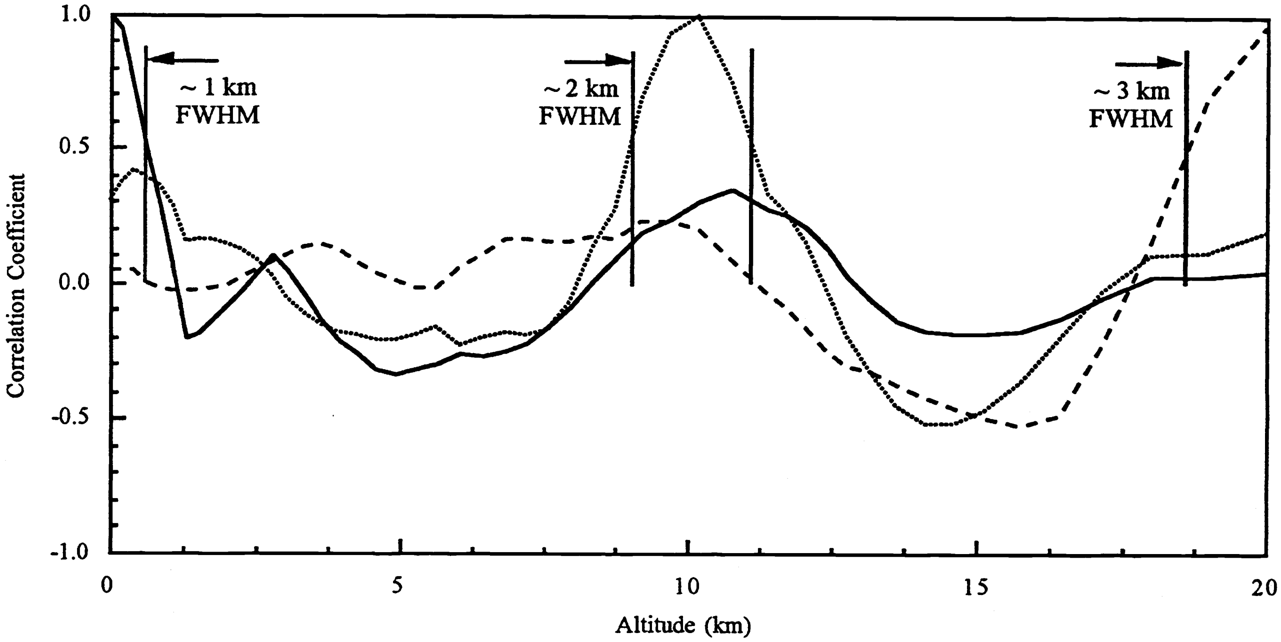

Figure 4. Typical retrieval error correlation coefficient functions for three difference altitudes.

5.2 GHIS Vertical Resolution Results

The following tables show the results of applying this vertical resolution algorithm to GHIS and GOES-8. They provide a glimpse at the expected improvement in going from the filter wheel to the interferometer. The improvement is pretty dramatic in the stratosphere, but not quite as significant as expected in the troposphere. This may be attributed more to the capabilities of the GOES-8 Sounder than the deficiencies of the GHIS.

The GHIS is shown to achieve vertical resolutions in the troposphere of just over 2 km, instead of the anticipated 1 km resolution. Further work will be done to fine tune the vertical resolution algorithm, but these results indicate that even with GHIS there may be significant correlations between errors over several kilometers in the retrieved profiles. Data assimilation methods have been developed for NWP models using current sounder data and these results suggest they will still be required in the future, although the correlations show promise of being reduced. Also, the resolution reported for the tropospheric region is an average from the surface to 100 mbar while the actual results show a profile with the resolution being 1 km near the surface and increasing to 3 km at 100 mbar.

Table 6. Tropospheric (1000-100 mbar) temperature vertical resolutions (km).

GHIS Operating Mode	Linear First Guess	Iteration Result
Full Resolution	2.6	2.4
Partial Scan	2.6	2.2
Low Resolution	2.6	2.4
GOES-8	3.2	2.7

Table 7. Stratospheric (100-10 mbar) temperature vertical resolutions (km).

GHIS Operating Mode	Linear First Guess	Iteration Result
Full Resolution	3.6	3.4
Partial Scan	3.5	3.3
Low Resolution	3.9	4.0
GOES-8	6.1	5.6

6. SUMMARY AND CONCLUSIONS

The retrieval performance of an upgrade for the GOES-Next Sounder has been studied through simulations. The GHIS design is seen to provide retrieval performance improvements relative to the GOES-Next Sounder by 50 to 100% in temperature retrieval accuracy. Water vapor improvements are less dramatic, but nonetheless significant. A measure of the vertical resolution achieved by these sounders based on the correlation of retrieval error has been developed and used to show the improvement possible from the GHIS upgrade. The retrieval performance shown for GHIS should be considered as a minimum and is expected to improve as the understanding and capability of performing retrievals with high resolution, high dimensional spectral data develops.

7. ACKNOWLEDGMENT

The authors would like to thank David Hearn of MIT/LL for performing the GHIS radiometric noise calculations.

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