Trade-off studies of a hyperspectral infrared sounder on a geostationary satellite

Fang Wang, Jun Li, Timothy J. Schmit, and Steven A. Ackerman

Trade-off studies on spectral coverage, signal-to-noise ratio (SNR), and spectral resolution for a hyperspectral infrared (IR) sounder on a geostationary satellite are summarized. The data density method is applied for the vertical resolution analysis, and the rms error between true and retrieved profiles is used to represent the retrieval accuracy. The effects of spectral coverage, SNR, and spectral resolution on vertical resolution and retrieval accuracy are investigated. The advantages of IR and microwave sounder synergy are also demonstrated. When focusing on instrument performance and data processing, the results from this study show that the preferred spectral coverage combines long-wave infrared (LWIR) with the shorter middle-wave IR (SMidW). Using the appropriate spectral coverage, a hyperspectral IR sounder with appropriate SNR can achieve the required science performance (1 km vertical resolution, 1 K temperature, and 10% relative humidity retrieval accuracy). The synergy of microwave and IR sounders can improve the vertical resolution and retrieval accuracy compared to either instrument alone.

OCIS codes: 010.0010, 010.1280, 120.0280, 120.6200.

1. Introduction

Historically, data obtained from the Geostationary Operational Environmental Satellite (GOES) sounder have been considered less valuable by meteorologists than radiosonde data because of the insufficient retrieval accuracy and insufficient vertical resolution.[1,2] The Hyperspectral Environmental Suite[3] [HES, previously named the Advanced Baseline Sounder (ABS)] aboard the GOES-R to be launched in approximately 2013, will have over a thousand channels with widths of the order of single wavenumbers and will replace the current GOES sounder[4] that has only 18 filter wheel IR channels with spectral widths of the order of tens of wavenumbers. HES-IR goals include (1) providing an accurate, hourly 3D picture of atmospheric temperature and water vapor in clear skies with high accuracy and high vertical resolution that is not possible with the current GOES sounder and improving surface and cloud-top pressure and temperature estimates; (2) tracking atmospheric motion at more levels with accurate height assignments; (3) distinguishing ice from water clouds and identifying cloud microphysical properties; (4) providing better viewing between clouds and near cloud edges; (5) permitting accurate land and sea surface temperature determinations in addition to IR surface emissivity estimates; (6) distinguishing atmospheric constituents with improved certainty, including dust, volcanic ash, and ozone; and (7) detecting clear-sky low-level atmospheric inversions, thus marking severe weather potential and possible fog formation. As with the Advanced Baseline Imager (ABI), more and better products including ozone profiles, surface and cloud types, and accurate microphysics properties will be provided.[6] Improvements will be realized in nowcasting, short-range weather forecasting, and longer-range numerical weather prediction. The instrument is currently in the formulation phase, and the performance parameters are not fully defined. The HES performance requirements derive primarily from the National Weather Service (NWS) summarized in Table 1.

Using HES as an example geostationary hyperspectral IR sounder to conduct general instrument design trade-off studies, this paper discusses the spectral coverage, spectral resolution, and signal-to-noise ratio

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Received 24 March 2006; revised 28 August 2006; accepted 8 September 2006; posted 11 September 2006 (Doc. ID 69240); published 21 December 2006.

0003-6935/07/020200-10$15.00/0

Table 1. NWS Sounding Requirements for Accuracy and Resolution[a]

Altitude Range	Observational Accuracy (rms Error) Temperature	Humidity	Vertical Resolution
Surface–300 mbars[b]	±1.0 K	±10%	1–2 km layers
300–100 mbars	±1.0 K	±20%	2–3 km layers
100 mbars and above	±1.0 K	—	3–6 km layers

[a]Table 2-1 in Ref. 1.
[b]1 mbar = 1 hPa.

(SNR) of HES by examining both the vertical resolution and the retrieval accuracy for temperature and water vapor sounding products with the goal of achieving the requirements in Table 1. We will investigate issues such as what part of the electromagnetic spectrum at each spatial element should be measured, what spectral resolution should be used to analyze an atmospheric or surface parameter, and what SNR is required and how accurate observations need to be. By answering these questions, this study can help in defining the performance parameters for HES as well as for other geostationary advanced IR sounders so that the best possible instrument with the minimum risk can be provided.

Section 1 gives a brief introduction of the planned HES. Section 2 applies the data density method to the vertical resolution analysis and investigates the effect of spectral coverage, SNR, spectral resolution, and instrument synergy on vertical resolution. Section 3 explores the effect of spectral coverage, SNR, spectral resolution, and instrument synergy on geostationary hyperspectral IR sounder retrieval accuracy. Our conclusions are given in Section 4.

2. Hyperspectral Environmental Suite Vertical Resolution Simulation Study

In the case of profile retrievals, vertical resolution is a measure of how well we can see the type of vertical structures that might be present in the atmosphere. Resolution here should be distinguished from the grid spacing used to represent a profile, and the choice of practical grid spacing depends on various features of the problem including the resolution of the measurement.[7] Vertical resolution is one of the most important factors in the design of satellite sounding instruments, and sufficient vertical resolution is important to improve the retrieval accuracy. The filter wheel approach with a limited number of channels prohibits high vertical resolution, and low vertical resolution is a significant concern in the study of atmospheric profile inversion techniques with current IR sounder radiances. The need for high spectral resolution is clear in order to improve the vertical resolution of retrieved profiles.[1]

When designing geostationary hyperspectral IR sounders, it is important to answer the following questions, which are explored in this paper:

(1) What vertical resolution can we achieve for temperature and water vapor with a HES-type instrument given the noise requirement? Can we reach 1 km vertical resolution, 1 K temperature retrieval accuracy, and 10% water vapor retrieval accuracy in the lower atmosphere below 300 hPa?

(2) The vertical resolution is closely associated with spectral coverage, SNR, and spectral resolution. What is the effect of spectral coverage, spectral resolution, and SNR on vertical resolution?

(3) An accurate retrieval profile extended from the troposphere to the stratosphere is important for many aspects including stratosphere research and atmospheric numerical modeling. How can the vertical resolution be improved in both the upper troposphere and the lower stratosphere? In this paper the whole atmosphere refers to the atmosphere from the surface to 40 km, and a 15 km (100 hPa) layer separates the lower and upper atmospheres.

A. Vertical Resolution Algorithm

The averaging kernel function is defined as[7]

$$A = \frac{\partial \hat{x}}{\partial x} = \frac{\partial \hat{x}}{\partial y} \times \frac{\partial y}{\partial x} = GK_J = \left(K_J{}^T S_\varepsilon{}^{-1} K_J + S_{ap}{}^{-1}\right)^{-1} K_J{}^T S_\varepsilon{}^{-1} K_J, \quad (1)$$

where A is the averaging kernel, $\hat{x}$ is the retrieval vector, x is the state vector that will be retrieved, y is the measurement (radiation/brightness temperature) vector from the instrument, G is the gain function, S_ε is the error covariance matrix of the noise equivalent delta temperature (NeDT) calculated from the interpolated noise equivalent delta radiance (NeDR) data, S_{ap} is the error covariance matrix of the given *a priori* data, and K_J is the Jacobian matrix describing the sensitivity of the radiance to the change in the profiles.

Then the data density is expressed as

$$\rho_i = A_{ii}/\Delta z_i, \quad (2)$$

where A_{ii} is the diagonal value of the averaging kernel A at level i and Δz_i is the height interval at level i.

The averaging kernel is a sparse matrix with its maximum value ideally at the diagonal in each row because the true atmospheric profile should contribute most to the retrieval at the same level. Thus A_{ii} corresponds to the peak value of each averaging kernel profile, and $A_{ii}/\Delta z_i$ describes the ratio of the height over the width, i.e., the sharpness of the Gaussian-like function. In theory, the sharper the averaging kernel profile, the smaller the vertical resolution.

In studying vertical resolution, by describing the sharpness of the averaging kernels, more than one definition has been applied in previous research, including the most popular ones[7,8]: the FWHM method, the second moment method, the Backus and Gilbert method,[9,10] and the data density method.[11] The FWHM method is satisfactory for some purposes, but it is not very helpful if algebraic manipulation of the width is needed and can be difficult to define for functions with significant lobes, positive or negative.[7] The second moment method may be a reasonable definition for positive averaging kernels, but it can cause problems with negative lobes.[7] The quantity of spread defined by Backus and Gilbert for optimization in geophysical data inversion was first introduced into satellite retrieval theory in 1971 by Conrath who used the alternative term averaging kernel for the model resolution function. However, in practice the presence and relative prominence of the negative sidelobes of a model resolution function typical of satellite data caused the spread function obtained using the Backus–Gilbert definitions to give misleading measures of the effective resolution.[12] Furthermore, there are theoretical difficulties using an idealized model whose weighting functions were Legendre polynomials.[13] In contrast, the data density method based on the diagonal of the averaging kernel matrix produces nearly ideal features for defining resolution.[7] Therefore the data density method is selected where the vertical resolution is defined as

$$r_i = 1/\rho_i. \tag{3}$$

To meet the vertical resolution requirements using an inversion-based technique, plans call for spectral resolution requirements as 0.625 cm^{-1} for long wave (650–1150 cm^{-1}), 1.25 cm^{-1} for mid-wave (1210–1740 cm^{-1}), and 2.5 cm^{-1} for shortwave (2150–2720 cm^{-1}). These numbers are subject to change based on the revision of the NWS–National Environmental Satellite Data and Information Service (NESDIS) requirements and instrument trade-off studies. In this paper with the focus on general hyperspectral sounders, the long-wave region (LWIR) is defined as 650–1200 cm^{-1} for temperature, ozone, and surface property retrievals; the longer middle-wave (LMidW) is defined as 1200–1650 cm^{-1} and/or the shorter middle-wave (SMidW) is defined as 1650–2250 cm^{-1} for water vapor retrieval.

In the simulations, the vertical resolution of the temperature and water vapor mixing ratio profiles are investigated by using U.S. Standard Atmosphere profiles to calculate the Jacobian matrix using a generic fast radiative transfer model.[14] The forecast profile prior errors are assumed to be 1.5 K for temperature and 25% for water vapor, representing current forecast error over the continental United States. In this case, we set off diagonal elements 0 for the S_{ap} matrix, which means that we do not consider the error covariance between different layers. In a future study, a more realistic S_{ap}, such as prior errors derived from the actual radiosonde observations (RAOB) and forecasts should be applied.

The measurement error is interpolated by wavenumber from the instrument noise specification in the HES performance operational requirements document (PORD).[15] Figure 1 shows the possible brightness temperature spectrum sections for a geostationary hyperspectral IR sounder and the corresponding NeDR and NeDT. The NeDR is calculated by interpolating of the radiance noise specifications from HES PORD, and the NeDT is calculated from NeDR using the brightness temperature in the upper panel according to

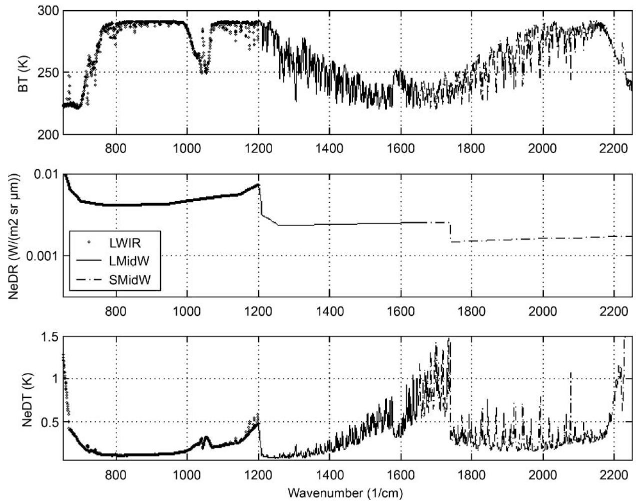

Fig. 1. Brightness temperature spectrum (upper panel), NeDR spectrum (middle panel), and NeDT spectrum (lower panel).

$$\mathrm{NeDT} = \frac{\mathrm{NeDR}}{\partial R/\partial T_B}, \tag{4}$$

where $\partial R/\partial T_B$ is calculated analytically from Planck's Law with radiance R and brightness temperature T_B. The NeDT is used to calculate its nominal error covariance matrix S_ε. The channels whose NeDT are higher than 1.0 K are discarded in the vertical resolution calculation because of their large noise. The noise factor is defined as the factor of S_ε that is selected to generate a real error covariance matrix used in the calculation.

To show the concept more intuitively, the averaging kernel function and the corresponding vertical resolution using the data density method are plotted in Fig. 2 using the current GOES sounder. It is obvious that a sharper averaging kernel causes smaller vertical resolution and vice versa.

The following sections will investigate the effect of spectral coverage, SNR, spectral resolution, and IR–MW synergy on vertical resolution separately applying the data density method.

B. Spectral Coverage Study

The LWIR is usually selected for temperature, ozone, and surface property retrievals. Using a spectral resolution of 0.625 cm^{-1} and noise factor of 1 as reference for future comparisons, three simulation experiments are performed for temperature and water vapor including LWIR + LMidW, LWIR + SMidW, and LWIR + LMidW + SMidW to compare the performance of LMidW and SMidW. The vertical resolution profiles are calculated by using Eqs. (1)–(3) and applying the parameters described above. Figure 3

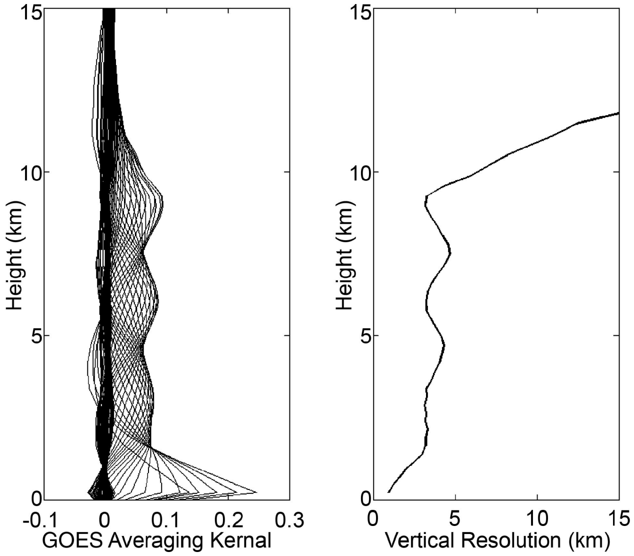

Fig. 2. GOES averaging kernel function (left panel) and the corresponding vertical resolution (right panel) using the data density method.

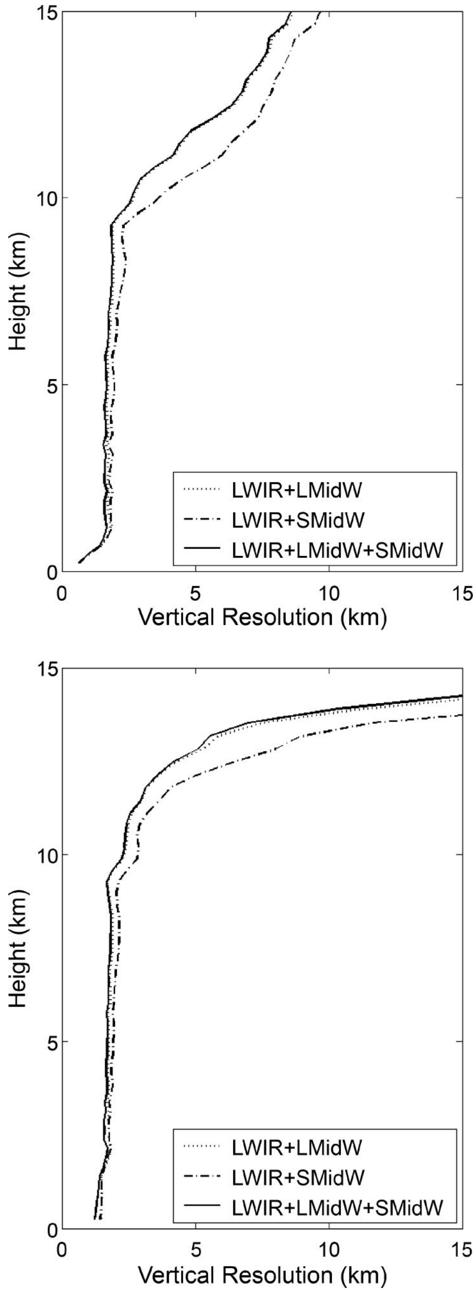

Fig. 3. Influence of spectral coverage on the vertical resolution of temperature (upper panel) and water vapor (lower panel).

shows that all three spectral coverage schemes seem to meet the vertical resolution requirements listed in Table 1, with LWIR + LMidW + SMidW and LWIR + LMidW achieving approximately 1 km better vertical resolution in the upper troposphere and lower stratosphere. Selecting both LMidW and SMidW may be a better option in terms of information, but the data volume will increase. Moreover, considering more trace gas (such as SO_2 and N_2O) contamination in the LMidW region and industry practice factors such as lower spectral resolution than SMidW, the LWIR + SMidW option is chosen for the following studies in this paper.

C. Signal-to-Noise Ratio Study

In the SNR test, a spectral resolution of 0.625 cm^{-1} and spectral coverage of LWIR + SMidW are used, and three representative noise factors of 0.33, 1, and 2 are selected to investigate the influence of measurement errors on the vertical resolution. The nominal case considers only instrument noise, which is used here for reference. The noise factor of 2 represents the cases when other errors such as radiative transfer model uncertainty and other sources of error, are considered. The noise factor of 0.33 represents cases when we use 3×3 fields-of-view to reduce the noise into approximately 1/3 of its nominal value.

The temperature results (left panel) in Fig. 4 show that the noise level exerts a very significant influence on the temperature vertical resolution in the lower atmosphere: 1–2 km difference below 10 km, and 5–10 km difference from 10–15 km between different noise factors. There is a sharp increase in vertical resolution near the tropopause, which is caused by the quick decrease of water vapor and the isothermal layer at approximately 10 km. The water vapor result (right panel) indicates the same result. Therefore decreasing the noise from all sources can dramatically increase the vertical resolution in the upper atmosphere for both temperature and water vapor.

D. Spectral Resolution Study

The spectral resolution of the sounding instrument influences the width of the weighting functions used in the retrieval algorithms, and the vertical resolution of the profiles that these algorithms produce. The availability of a far higher number of spectral channels compared to the filter-wheel approach permits the vertical resolution of the soundings to be substantially improved.[1]

To investigate the influence of different spectral resolutions on the vertical resolution, we conducted a

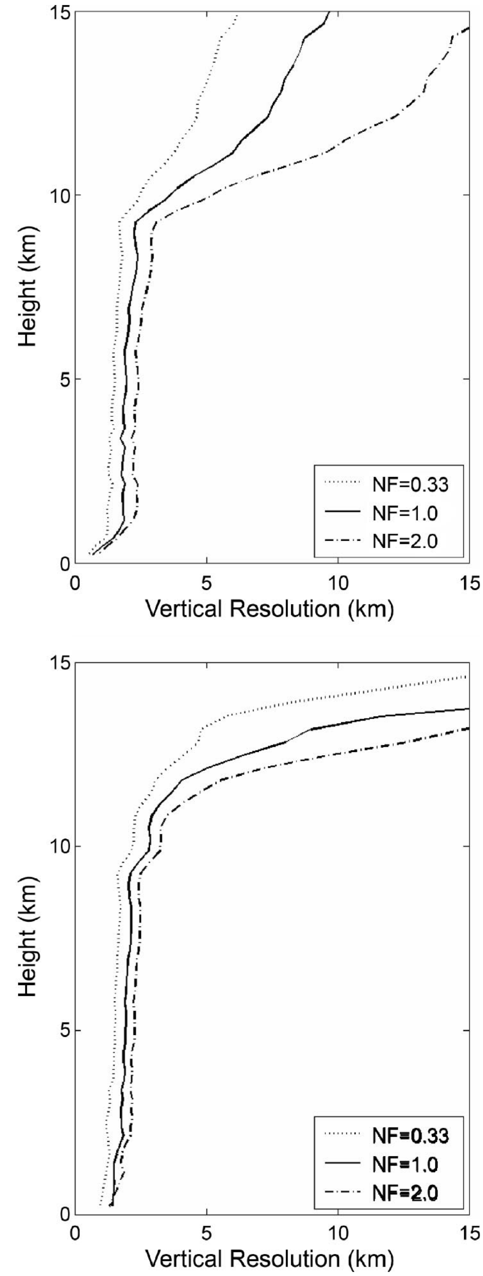

Fig. 4. Influence of the noise factor (NF) on the vertical resolution of temperature (upper panel) and water vapor (lower panel).

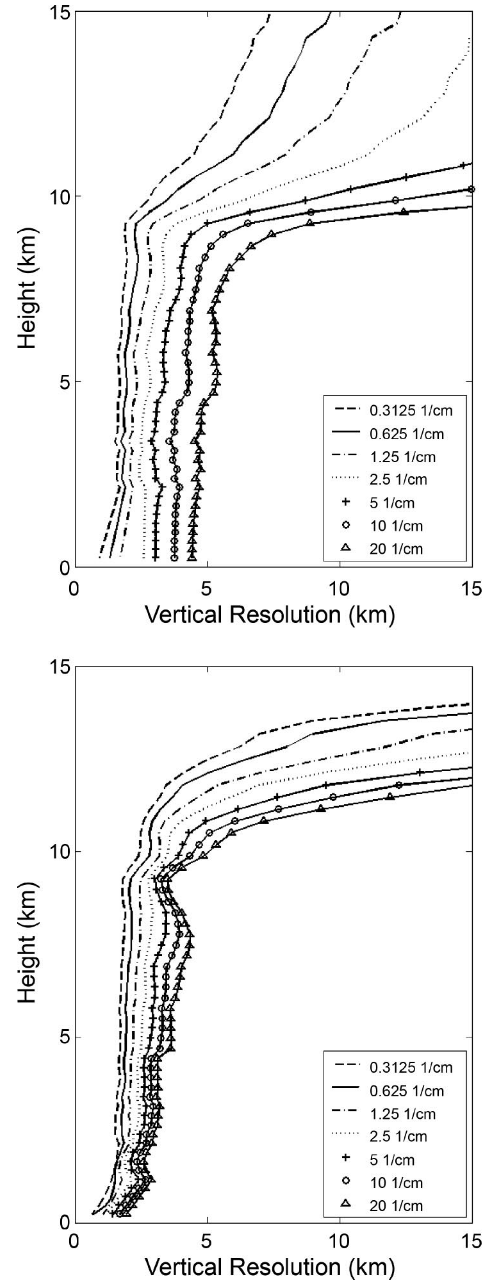

Fig. 5. Influence of spectral resolution on the vertical resolution of temperature (upper panel) and water vapor (lower panel).

spectral resolution study. A set of spectral resolutions (0.3125, 0.625, 1.25, 2.5, 5, 10, and 20 cm^{-1}) are applied in this study using nominal noise with a spectral coverage of LWIR + SMidW. From the temperature and water vapor vertical resolution comparisons (Fig. 5), we can see the strong influence of the spectral resolution on the vertical resolution. The vertical resolution decreases with decreasing spectral resolution, and for atmospheric temperature, there is a range of 0.5–1 km differences below 10 km and a 3–5 km difference from 10–15 km between different spectral resolutions. It is worthy to note here that a 20 cm^{-1} resolution is approximately equivalent to the current GOES sounder spectral resolution. It is obvious that the vertical resolution, and therefore the retrieval accuracy, of the current sounder will be greatly improved after the spectral resolution is increased in the future GOES-R HES sounder. Similarly, this result is true for water vapor.

At the same time, when the spectral resolution is increased, the instrument noise will increase with a fixed spatial resolution and dwell time. Furthermore, manufacturing of the instrument may cost more when the spectral resolution is increased, for example, from 0.625 cm^{-1} to 0.3125 cm^{-1}. While the smaller spectral resolution leads to better vertical resolution, it might also increase the noise. After looking at the trade-offs of both options, the 0.625 cm^{-1} is chosen instead of the 0.3125 cm^{-1}. Another study (not shown) also reveals that there is only a slight improvement of temperature and moisture sounding retrievals from 0.625 to 0.3125 cm^{-1}, while the improvement from 1.25 to 0.625 cm^{-1} is significant. This experiment is designed to test the influence of the spectral resolution on the vertical resolution using a nominal noise factor. Physically this might be ideal because when the spectral resolution decreases, the noise will also change. Therefore there should be a corresponding adjustment to the noise factor when the spectral resolution is changed. Thus in the future, a simultaneous simulation accounting for both spectral resolution and instrument noise should be done to provide more practical results.

To test our result under more restrictive conditions, we choose a RAOB profile from the atmospheric radiation measurement (ARM) cart site in Oklahoma with a low-level temperature inversion (Fig. 6) for study. This profile has a temperature inversion greater than 15 K; this inversion structure is more difficult to retrieve than normal profiles.

Figure 7 shows the influence of the spectral resolution on the vertical resolution of temperature and water vapor for the inversion case. The results for the inversion case lead to conclusions similar to those from the U.S. Standard Atmosphere case, specifically that the finer the spectral resolution, the better the vertical resolution for both temperature and water vapor, and that there is a significant difference in vertical resolution between the future sounder (0.625 cm^{-1}) and the current one (20 cm^{-1}). At the same time, by comparing Figs. 5 and 7, we can see that it is more difficult to achieve better vertical resolution, and thus retrieval accuracy, for inversion cases than for normal cases: The swift increase in vertical resolution happens at approximately 5 km (compared with 10 km in the normal case) and 7 km for water vapor (compared with 12 km). Also, it should be noted here that for the inversion case, because the Jacobians near the

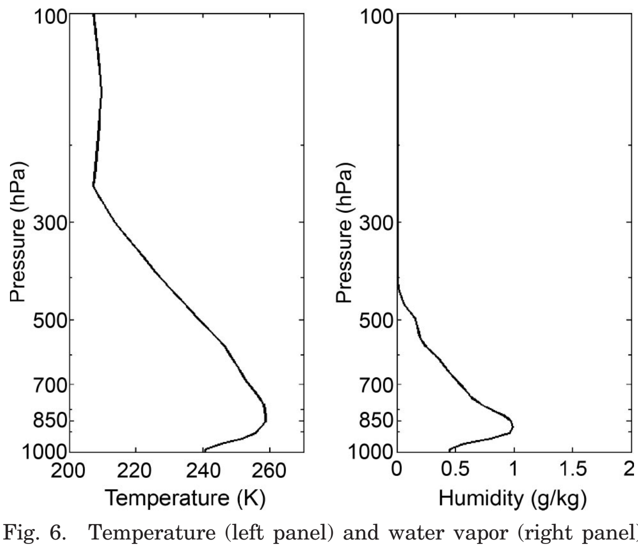

Fig. 6. Temperature (left panel) and water vapor (right panel) profiles for a medium moist inversion case.

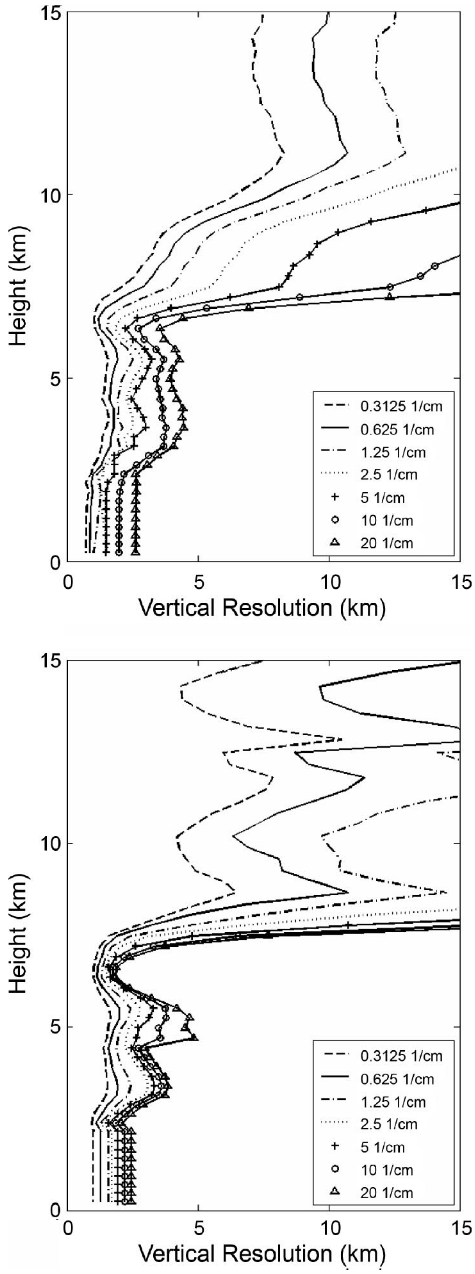

Fig. 7. Influence of spectral resolution on the vertical resolution for temperature (upper panel) and water vapor (lower panel) for an inversion case.

boundary (below 3 km) are very small, there are very large artificial values for the vertical resolution near the surface. In Fig. 7, the vertical resolutions below 3 km have been modified and are not realistic. This again demonstrates the fact that it is very hard to retrieve the lower atmosphere inversion.

E. Instrument Synergy

IR sounders achieve better vertical resolution in the lower atmosphere while microwave sounding units are more sensitive in the upper atmosphere. The synergism of geostationary Earth orbit (GEO) IR and low Earth orbit (LEO) microwave data for better atmospheric soundings from the troposphere to the lower stratosphere is investigated. The following experiments demonstrate the advantage of instrument synergy with the current GOES sounder, a future hyperspectral IR sounder such as HES, and a current microwave sounder such as the Advanced Microwave Sounding Unit (AMSU).[16]

The current GOES sounder is a broadband discrete-filtered radiometer with 18 IR channels and one visible channel (0.7 μm, used for daytime cloud detection) with a spectral resolution ranging from visible wavelengths to 15 μm. It is used to produce atmospheric vertical profiles including temperature profiles (up to 0.1 hPa) and water vapor profiles (up to 300 hPa). AMSU (−A, −B)[13] is a multichannel microwave radiometer onboard NOAA K, L, M, N spacecraft. This instrument is designed to be cross track line scanned and to measure scene radiances in 20 discrete channels. AMSU is able to measure global atmospheric temperature profiles and provide information on atmospheric water in almost all forms except small ice particles that are transparent to microwave sensors. Unlike in the IR cases, where the emissivity ε over all types of surfaces is close to unity, in the microwave cases the emissivity of an object changes depending on the permittivity, surface roughness, frequency, polarization, incident angle, and azimuth angles. In our study, for convenience, we assume an emissivity of 0.96 over land and 0.65 over the ocean in the AMSU radiative transfer model calculation. As there is little information about water vapor above the troposphere, the investigation of temperature vertical resolution is emphasized.

The comparisons of vertical resolution using the current GOES sounder alone, the current microwave sounder AMSU alone, a future IR sounder (assuming LWIR + SMidW with 0.625 cm^{-1} spectral resolution) alone, and the combination of the current IR sounder and microwave sounder are shown in Fig. 8. The overwhelming advantage of the future HES over the current GOES sounder is demonstrated with 1–3 km lower vertical resolution in the troposphere and even 5–20 km lower in the stratosphere. As expected, the IR sounders GOES and HES can achieve better vertical resolution in the lower atmosphere (approximately 3 km vertical resolution for GOES and 1–2 km for HES) than AMSU (approximately 4 km). AMSU has approximately 7–8 km vertical resolution in the upper atmosphere, much smaller than any of the IR sounders (10–40 km). Combining the current GOES sounder and AMSU can achieve better vertical resolution (3–4 km better) than using either the current GOES sounder or the AMSU alone in the upper atmosphere, while the combination is still not as good as HES in the lower atmosphere.

This experiment demonstrates the advantage of instrument synergy. Next, we examined combining AMSU with the future HES, comparing the vertical resolution with that of the current GOES sounder. Figure 9 shows the vertical resolution for the combination of AMSU and HES. The combination achieves the best vertical resolution (1–2 km vertical resolution in the lower atmosphere and 4–10 km in the upper

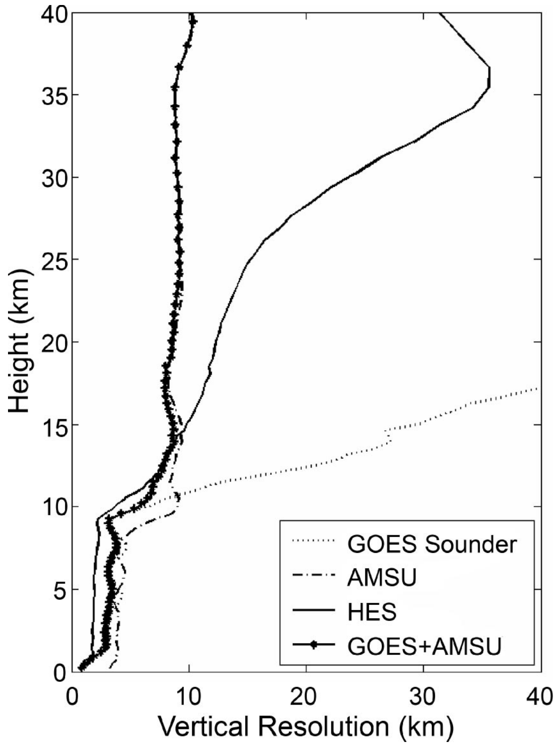

Fig. 8. Vertical resolution of the current GOES sounder alone, AMSU alone, a HES-like instrument alone, and the current GOES sounder plus AMSU.

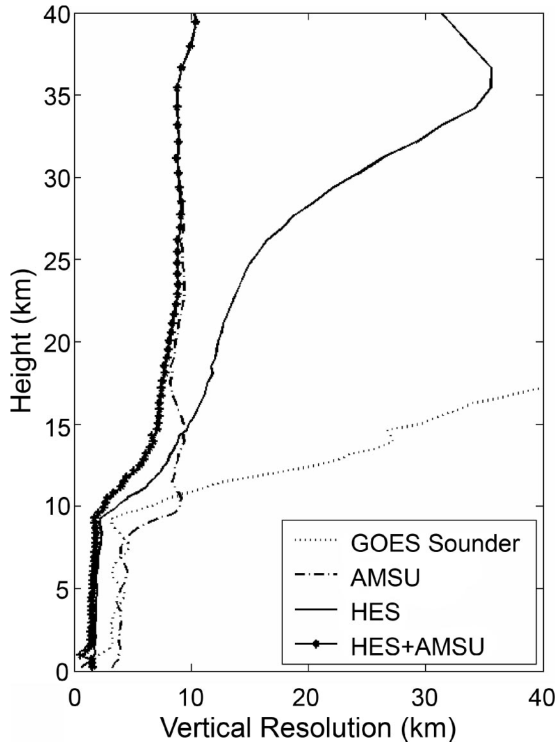

Fig. 9. Vertical resolution of the current GOES sounder alone, AMSU alone, a HES-like instrument alone, and HES plus AMSU.

atmosphere) among any of the other schemes. Therefore combining IR and microwave sounders can achieve better results through the lower stratosphere.

3. Retrieval Simulations

The effect of factors including spectral coverage, SNR, and spectral resolution on the vertical resolution of a proposed hyperspectral infrared sounder such as HES was investigated in Section 2. As the vertical resolution is a measure of how the retrieval responds to the vertical structure in the profile,[6,7] the influence of these factors on the retrieval simulation should be consistent with the influence on the vertical resolution, which we examined in the following retrieval simulations. Similarly, the effect of spectral coverage, SNR, spectral resolution, and instrument synergy on the retrieval accuracy are investigated.

The temperature and water vapor retrievals from the simulated HES radiances are carried out in two steps: a principle component regression[17] followed by a nonlinear physical retrieval method.[18,19] We have 7547 global RAOB profiles, from which 90% are randomly chosen as a training data set to determine the regression coefficient calculations, while the remaining 10% are used for testing. The regression coefficients of the 90% and their simulated brightness temperatures from the forward model are applied to the simulated brightness temperatures of the remaining 10% of the profiles to carry out the retrieval. The rms bias of the retrieved profiles from the true profiles represents the retrieval accuracy, and the smaller rms values represent better retrieval accuracy.

A. Spectral Coverage Study

Figure 10 shows the influence of spectral coverage on the retrieval accuracy by using the nominal noise and a spectral resolution of 0.625 cm^{-1}. All three schemes seem to meet the NWS requirements for sounding accuracy listed in Table 1, and similarly as in the vertical resolution part, the LWIR + LMidW + SMidW and the LWIR + LMidW schemes have comparable performances with better accuracies than the LWIR + SMidW scheme: 0.05–0.2 K better for temperature retrieval and 0.5%–2% better for water vapor relative humidity retrieval. Given the same issues with the LWIR + LMidW + SMidW scheme (data volume) and the LWIR + LMidW scheme (gas absorption contamination) noted in the earlier experiments, the LWIR + SMidW is applied in the following experiments.

B. Signal-to-Noise Ratio Study

Using LWIR + SMidW for the spectral coverage and 0.625 cm^{-1} for the spectral resolution, three noise factors (0.33, 0.5, and 1) are compared to examine the effect of SNR on the retrieval accuracy. As shown in Fig. 11, the noise factor does exert a large influence on the retrieval accuracy. The accuracy differences are 0.1–0.4 K for the retrieved temperature profiles and 1%–3% for the moisture profiles between three noise factors, and, clearly, a smaller SNR results in a better retrieval accuracy.

C. Spectral Resolution Study

Seven spectral resolutions are compared, including 0.3125, 0.625, 1.25, 2.5, 5, 10, and 20 cm^{-1}, with fixed nominal SNR and spectral coverage of LWIR + SMidW; the results are shown in Fig. 12: The smaller the spectral resolution, the better the retrieval accuracy. As we can see from this figure, the future sounder can achieve 0.5–1.0 K better accuracy in the temperature retrieval and 3%–10% better in the moisture retrieval. This result shows the great advantage of the future sounder in retrieving more accurate atmospheric profiles. As it may cost more to double the spectral resolution owing to technical reasons such as controlling the heating and noise especially from 0.625 to 0.3125 cm^{-1}, 0.625 cm^{-1} with a good NeDT may be a better choice.

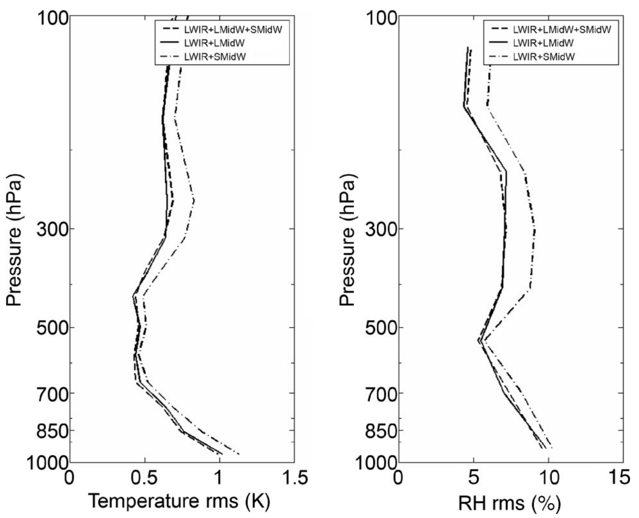

Fig. 10. Influence of spectral coverage on the retrieval accuracy of temperature (left panel) and relative humidity (RH) (right panel).

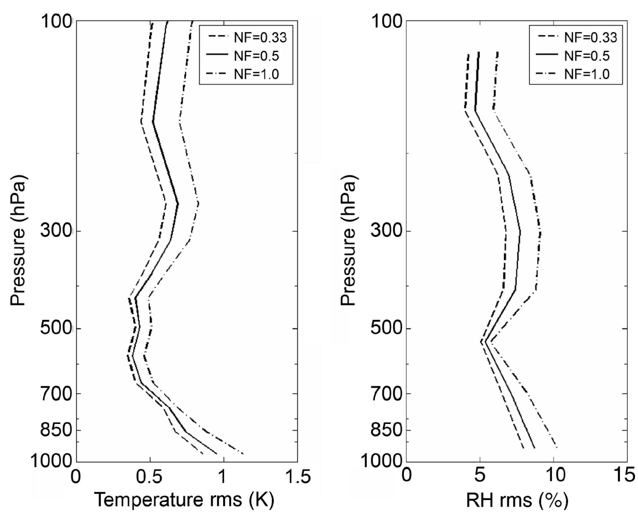

Fig. 11. Influence of noise factor on the retrieval accuracy of temperature (left panel) and RH (right panel).

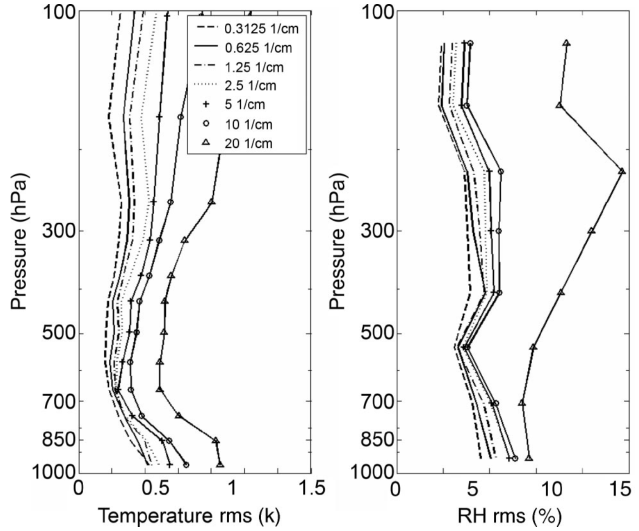

Fig. 12. Influence of spectral resolution on the retrieval accuracy of temperature (left panel) and RH (right panel).

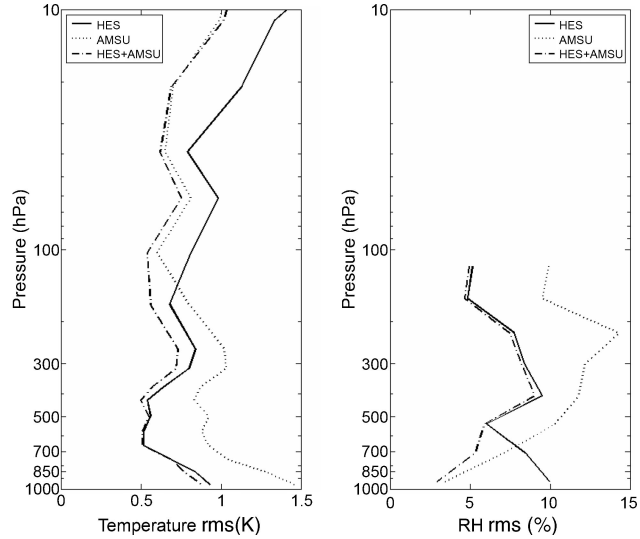

Fig. 14. Retrieval accuracy comparisons between HES alone, AMSU alone, and HES plus AMSU for temperature (left panel) and RH (right panel) over the ocean.

D. Instrument Synergy

Instrument synergy can greatly improve the vertical resolution in both the troposphere and stratosphere and therefore in theory, instrument synergy should also improve retrieval accuracy. This was demonstrated by Li *et al.*[20] through GOES sounder and AMSU synergy as shown in Fig. 13: The retrieval accuracy for the current GOES sounder below 600 hPa is 0.2–0.3 K better than AMSU, while 0.5–2 K worse from 600 to 10 hPa. The combination of the AMSU and current GOES sounder provides the best retrieval accuracy up through 10 hPa. Next, we investigated combining a hyperspectral geostationary sounder and AMSU. Fig. 14 compares the retrieval accuracy of applying HES alone, AMSU alone, and HES plus AMSU in temperature retrievals and water vapor retrievals over oceans. The results show that the instrument synergy substantially improves the retrieval accuracy, and HES has better temperature sensitivity below 150 hPa and better moisture sensitivity above 700 hPa, while AMSU has better temperature sensitivity above 150 hPa and better moisture sensitivity below 700 hPa in the boundary layer over oceans. The difference in water vapor retrieval accuracy is more obvious than with temperature because of the nonlinearity of water vapor to the radiances. By comparing Figs. 13 and 14, we can also see that the retrieval accuracy for temperature is improved by 0.5–1 K from GOES to HES.

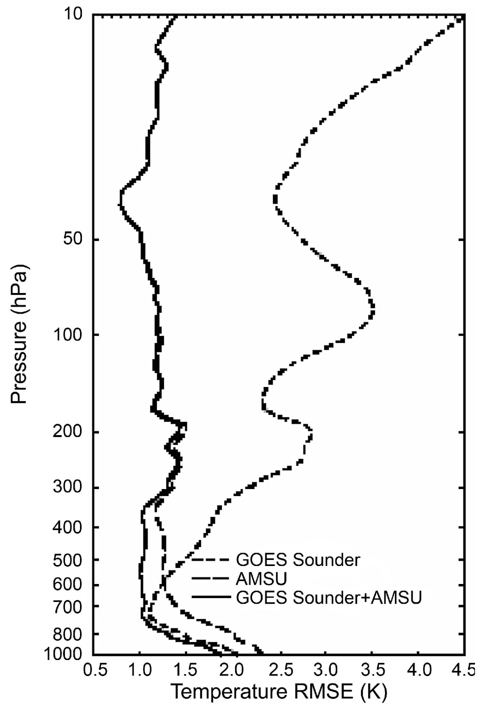

Fig. 13. Retrieval accuracy of the current GOES sounder alone, AMSU alone, and GOES plus AMSU.

Both the vertical resolution and the retrieval accuracy analyses demonstrate that, together with microwave sounding unit data from a LEO satellite [for example, the Advanced Technology Microwave Sounder (ATMS) from the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) satellites], HES is able to provide detailed atmospheric temperature and moisture structures from the surface to the stratosphere and thus provides more accurate data sets for the numerical weather predictions, thus improving the weather forecast. This result is very meaningful for the future because GEO satellites will provide IR sounder data hourly, and LEO satellites will provide microwave data over the same pixel once every 3 h. The synergy between IR and microwave sounders will be very practical and beneficial in the future for improving retrieval accuracy.

4. Conclusions

Using HES as an example of geostationary hyperspectral IR sounders, trade-off studies of spectral coverage, SNR, and spectral resolution on vertical resolution and temperature and water vapor retrieval accuracy have been performed and discussed in this paper. According to the particular results from both analyses in this paper, the spectral coverage of LWIR + SMidW may be preferred in terms of instrument performance and data storage and processing. Using LWIR + SMidW, a high spectral resolution with a good SNR is crucial to achieve good vertical resolution and retrieval accuracy. Combining GEO IR and LEO microwave data can provide better temperature information from the surface to the stratosphere than that from either instrument alone, demonstrating that the synergism of the GEO IR and LEO microwave is preferred.

This work shows some very meaningful trade-off results. It provides preferable schemes for instrument design and offers methods to perform information content studies. The method can also be used to assess future instrument design study effects on retrieval accuracy and requirements.[21]

Ideally, the correlation among factors (SNR, spectral coverage, spectral resolution, spatial resolution, and temporal resolution) should be taken into account in trade-off experiments although it is difficult to perform. Quantifying how the noise changes with spectral resolution will be included in our future trade-off studies. The simulation focused on temperature and moisture study, and it does not account for clouds, some trace gases other than water vapor and ozone, and solar reflection (in the shortwave region), and therefore, aircraft measurements from the NPOESS Airborne Sounder Testbed–Interferometer (NASTI) will also be used in these studies. The HES has been demanifested on the GOES-R series.

This program was supported by the National Oceanic and Atmospheric Administration ABI/HES program NA07EC0676 at the Cooperative Institute for Meteorological Satellite Studies. The views, opinions, and findings contained in this report are those of the authors and should not be construed as an official National Oceanic and Atmospheric Administration or U.S. government position, policy, or decision. The authors thank the anonymous reviewer's excellent and careful review and Hal Woolf for providing the radiative transfer model.

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