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SIMULTANEOUS RETRIEVAL OF CLOUD HEIGHT AND EFFECTIVE EMISSIVITY FROM HYPERSPECTRAL RADIANCE MEASUREMENTS

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1. INTRODUCTION

New instrumentation and innovative communication technology enable great advancement of development of the next generation weather satellite infrared profile sounding instrument that simultaneously achieves semi-continuous measurements in spectral, spatial, and temporal domains. While these instruments are been made and planned to be flown on the research (IMG, AIRS and GIFTS), and operational (CrIS, IASI and ABS) space-borne satellite systems. The new and improved processing algorithm must be developed to keep up with the unique features provided by these new observations. The most important and common feature of these spectral radiance data which posses not only improved spectral resolution (~ 0.25 to 1 wavenumber) but also semi-continuous sampling through out the infrared spectrum. For example, AIRS infrared sounding measurements has 1200 resolving power and achieve spectral data of every 0.4 wavenumber between cloud and surface sensitivity longwave window region of 700 to 1000 wavenumber. In this spectral region approximately 750 spectral radiances are available for retrieving spectrally related characteristics such as temperature profile, cloud and earth surface emissivity property. These measurements provide unprecedented opportunity when it compares to the current and past geostationary and polar orbiting weather satellite making measurements of less than 10 discrete piece of data in this part of infrared longwave region. In this paper, we are demonstrating a simple novel approach which takes the advantages of semi-continuous high spectral resolution radiances that are sensitivity to both cloud optical property of emission and cloud altitude geometry, and can be used to simultaneously retrieve cloud emissivity spectrum and altitude. Using a controlled simulation study, the Minimum Local Emissivity Variance (MLEV) approach can be fully demonstrated to be physical and the achieved accuracy can be quantified under variety of assumptions and atmospheric conditions.

2. Minimum Local Emissivity Variance (MLEV) Algorithm

Neglecting scattering processes, the infrared clear sky radiance measured by high spectral resolution instrument for a specific spectral channel within an instantaneous filed of view (IFOV) is

$$R_{clr}(\nu) = \varepsilon_s(\nu)B_s(\nu)\tau_s(\nu) - \int B(\nu)d\tau(\nu) + (1-\varepsilon_s) \int B(\nu)d\tau^*(\nu), \qquad (1)$$

Where clear spectral channel radiance $R_{clr}(\nu)$ measured by high spectral resolution radiometer or interferometer; ν denotes spectral channel, ε_s is the surface emissivity; subscript s denotes surface; B is the Planck radiance; τ is the atmospheric transmittance function; $\tau^* = \tau_s^2/\tau$; and $\int$ indicates integration limit from surface to satellite altitude (~ 0 hPa). For complete cloud covered IFOV with opaque cloud (ε_c=1) at pressure P_c, the cloud radiance is

$$R_{cld}(\nu) = B_c(\nu)\tau_c(\nu) - \int^* B(\nu)d\tau(\nu), \qquad (2)$$

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Where subscript c denotes the cloud top, and $\int^{*}$ indicates integration limit from cloud pressure altitude P_c to0 hPa. The upwelling radiance R for a partially cloud-covered IFOV is

$$R(\nu) = (1 - N\varepsilon_c(\nu))R_{clr}(\nu) + N\varepsilon_c(\nu)R_{cld}(\nu),(3)$$

Where the cloud emissivity spectrum $N\varepsilon_c(\nu)$ is modulated by the cloud fractional coverage N and the quantity $N\varepsilon_c(\nu)$ used through out this paper is referred to as the effective cloud emissivity spectrum.
It can be shown that spectral region 750 to 950 wave number provides best sensitivity to both $N\varepsilon_c$ and P_c. Cold and isothermal condition provides unfavorable environmental factor towards retrieving $N\varepsilon_c(\nu)$ and P_c. The conduits between $N\varepsilon_c(\nu)$ and P_c can be explored through MLEV algorithm to optimize cloud signal (at least cloud detection) at these unfavorable condition since $N\varepsilon_c(\nu)$ and Pc can still provide complementary cloud sensitivities
Rewrite Eq. (3) one can reach

$$N\varepsilon_c(\nu) = (R(\nu) - R_{clr}(\nu)) / (R_{cld}(\nu) - R_{clr}(\nu))(4).$$

Which is the effective cloud emissivity spectrum that MLEV algorithm tries to derive simultaneously with cloud altitude. Besides the estimation of $R_{clr}(\nu)$ is the necessary input, $R_{cld}(\nu)$ need to be calculated by the guess of P_c. The fundamental principal of MLEV is to seek the optimal solution of $N\varepsilon_c(\nu)$ that exhibits the smallest local variation and its matching P_c claims to be the optimal altitude solution as well. Objective searches for the true combination of $N\varepsilon_c(\nu)$ and P_c becomes the focus of this MLEV paper. Finding the retrieved cloud emissivity spectrum that has the smallest variation will simultaneously determine the "correct" cloud altitude information. An objective procedure of MLEV is to minimize the averaged local variation of

$$\Sigma\, (N\varepsilon_c(\nu)\text{-Bar}(N\varepsilon_c(\nu)))^2 \quad (5),$$

where $\text{Bar}(N\varepsilon_c(\nu)) = (\Sigma\, (N\varepsilon_c(\nu))$ over $\nu - \Delta\nu/2$ to $\nu+\Delta\nu/2)/\Delta\nu$ and $\Delta\nu=5$ cm^{-1}. Physical speaking, if cloud altitude is incorrect (under- or over- estimated), then $N\varepsilon_c(\nu)$ will displays molecular absorption spectral features which are relatively high frequency compared to cloud optical spectral feature. Thus, one can solve for that cloud altitude which minimizes the local variation of the derived cloud effective emissivity spectrum.

3. MLEV RESULTS

MLEV cloud height and effective emissivity spectrum retrievals are demonstrated using simulated GIFTS (Huang, et.al, 2000) longwave infrared measurements. A set of 177 continental U.S. profiles covering 10 to 35 north latitude and 90 to 110 west longitude over whole year of 2000 , which represent diverse atmospheric conditions coincident with GIFTS geographical coverage were selected for this demonstration. Forty combinations were formed from each profile by assigning four cloud heights (200, 300, 500, and 850 hPa corresponding to very high, high-, medium-, and low- level clouds) and ten effective emissivity (0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0 corresponding to low cloud cover/very transparent to overcast/ opaque cloudy conditions). The GIFTS longwave cloudy radiance spectra were simulated for all forty combinations of each profile. No spectral emissivity variation is introduced and GIFTS baseline measurement noise of 0.25 mw/sr.cm^{-1}.m^{2} is randomly added to simulate real instrument measurements. Figure 1 displays MLEV cloud altitude root mean square error (RMSE) and bias as functions of cloud altitudes (four panels) and effective cloud emissivity (X- axis). MLEV algorithm shows little bias for all level of clouds and opaqueness. For very high and high clouds, retrieval RMSE of cloud altitude is around 30 hPa, except for transparent clouds ($N\varepsilon_c(\nu)$ is smaller than 0.2). For medium level cloud, the RMSE is about 10 hPa, except $N\varepsilon_c(\nu)$ is smaller than 0.2. For low cloud, RMSE is increased to ~ 50 hPa and large error for transparent clouds. Figure 2 is similar to figure 1 except for cloud emissivity MLEV retrieval RMSE of 800 and 900 cm^{-1}. Again, four-panel represents four different level of clouds simulated. Effective emissivity RMSE of both wavenumbers are shown as function of effective cloud emissivity as well. For medium and higher clouds the average RMSE of $N\varepsilon_c(\nu)$ is about 0.02 to 0.04 except for very transparent cloud (when $N\varepsilon_c(\nu)$ is smaller than 0.2). For low cloud case, significant degraded performance of MLEV $N\varepsilon_c(\nu)$ is shown. At this cloud level about 0.2 of retrieved effective emissivity RMSE is shown. For comparison, CO_2 (Smith and Platt, 1978, Menzel et al., 1983) slicing cloud altitude retrieval using GOES sounder data (Menzel and Purdom 1994) and GIFTS MLEV retrieval cloud altitude RMSE is presented in figure 3. The cloud altitude information content of GIFTS and GOES demonstrates the needs of the prompt advancement of high spectral resolution instrument development.

The results shown in these three figures all assumes atmospheric uncertainties of 1.0 K for temperature profile, 1.0 K for surface skin temperature and 15 % for water vapor profile, respectively.

Figure 4 displays example MLEV derived emissivity spectra (high spectral resolution spectra collected during April 21, 1996 SUCCESS HIS field campaign) that depicts the fundamental principal of the MLEV (minimum variance of 1%) can be found when the cloud height is optimally determined. In another words, minimum variance of 1% is associated with optimal cloud altitude of 300 hPa is verified by Cloud Lidar System (CLS) 280 hPa cloud. Figure 5 demonstrates time series of the retrieval cloud height and its associated cloud emissivity at 900 1/cm. The single layer cloud heights determined by CLS are also overlaid to validate the MLEV can achieve optimal cloud height information, regardless of cloud transparency. Around record 210 (2112 Z) when cloud emissivity is near 20 % level, MLEV over estimated cloud height (retrieved too high). All other time period the MLEV is performed consistently with CLS measured, despite cloud emissivity varies from opaque (100 %) to semi-transparent (20%).

4. CONCLUSIONS

In summary, MLEV is a novel but simple technique that takes advantage of semi continuous sampling of cloud sensitive longwave infrared radiance measurements, simultaneously finding cloud altitude and effective emissivity spectrum. The optimal cloud altitude and emissivity spectrum solution is the one that yields the smallest local spectral variation of the derived emissivity spectrum. Since cloud absorbs, reflects, scatters, and radiates smoothly within local spectral region. Any abrupt high frequency feature exists in the retrieved emissivity spectrum is an indicative of suboptimal cloud altitude determination.

5. REFERENCES

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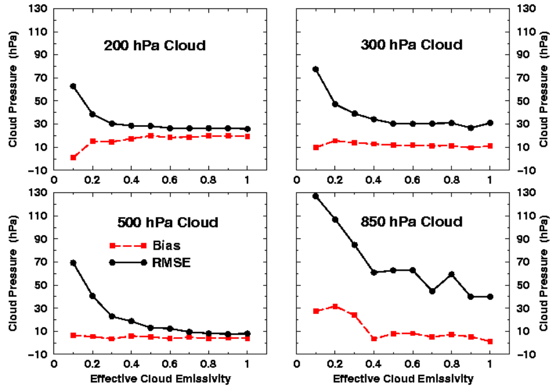

Figure 1, GIFTS MLEV cloud pressure retrieval RMSE and bias for cloud at level of 200, 300, 500, and 850 hPa.

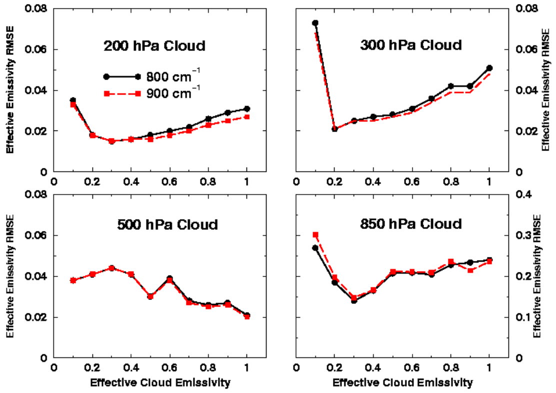

Figure 2, GIFTS MLEV retrieval of effective cloud emissivity RMSE of 800 and 900 cm^{-1} for cloud at level of 200, 300, 500, and 850 hPa..

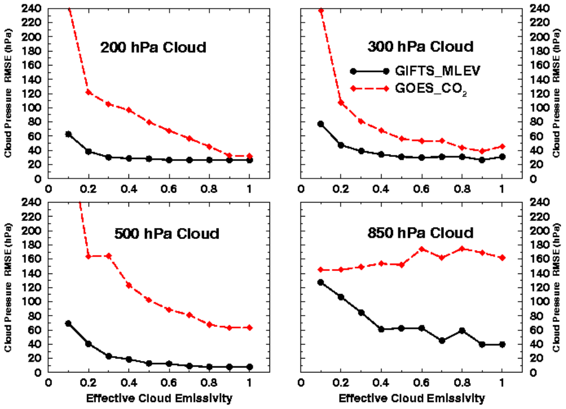

Figure 3, MLEV cloud pressure retrieval RMSE for GIFTS and GOES comparisons.

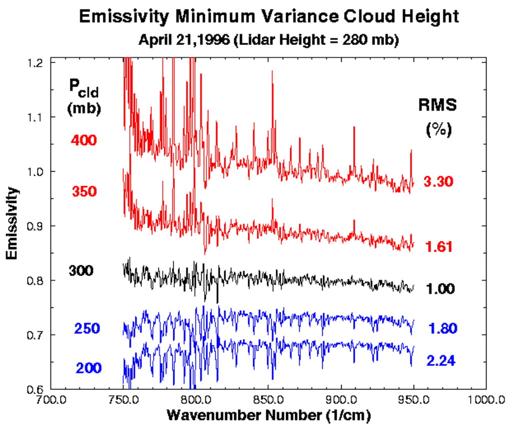

Figure 4, Retrieved local emissivity variance example for HIS data collected during April 21 of 1996 SUCCESS field campaign. Cloud Lidar System (CLS) identified single layer of cloud was located at 280 hPa.

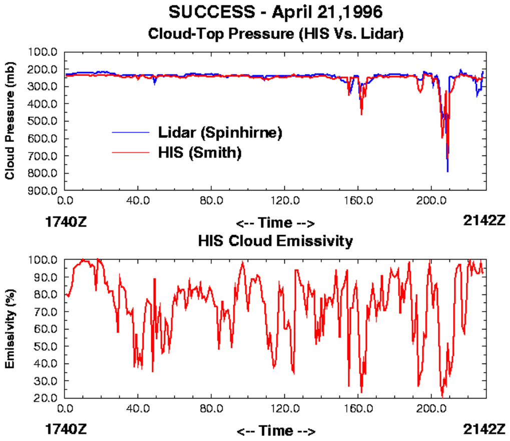

Figure 5, Time series of MLEV cloud altitude (upper panel) and effective emissivity (lower panel) for April 21, 1996 HIS measurements. Single layer cirrus cloud altitude determined by CLS is also overlaid for verification.