CLOUD BASE HEIGHT
VISIBLE/INFRARED IMAGER/RADIOMETER SUITE ALGORITHM THEORETICAL BASIS DOCUMENT

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GLOSSARY OF ACRONYMS

AMSR	Advanced Microwave Scanning Radiometer
ATBD	Algorithm Theoretical Basis Document
CIWP	Cloud Ice Water Path
CLW	Cloud Liquid Water
CMIS	Conical Scanning Microwave Imager/Sounder
DMSP	Defense Meteorological Satellite Program
EDR	Environmental Data Record
EMD	Engineering and Management Development
EOS	Earth Observing System
FSL	Forecast Systems Laboratory
FTW	Fort Worth
HCS	Horizontal Cell Size
HRI	Horizontal Reporting Interval
HSB	Humidity Sensor - Brazil
HSR	Horizontal Spatial Resolution
IP	Intermediate Product
IPO	Integrated Program Office
IPT	Integrated Product Team
IWC	Ice Water Content
IWP	Ice Water Path
LWC	Liquid Water Content
LWP	Liquid Water Path
MODIS	Moderate Resolution Imaging Spectroradiometer
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
PACEOS™	Performance and Analyses Capabilities for Earth Observing Systems
PDR	Preliminary Design Review
RDR	Raw Data Record
RMS	Root Mean Square
RSS	Root of the Sum of the Squares

SRD	Sensor Requirements Document
SSM/T-2	Special Sensor Microwave Moisture Profiler
TBD	To be determined
TBR	To be reviewed
VIIRS	Visible/Infrared Imager/Radiometer Suite

ABSTRACT

This Algorithm Theoretical Basis Document (ATBD) describes the methodology developed to retrieve the Cloud Base Height Environmental Data Record (EDR) from VIIRS imagery. The Cloud Base Height EDR is derived by subtracting cloud thickness from cloud top height. Cloud thickness is retrieved from parameterized equations for ice and water clouds using cloud optical depth and cloud effective particle-size EDRs. Thus, the retrieval of the Cloud Base Height EDR requires the analysis of cloud top phase as a derived requirement. The accuracies of these ancillary cloud EDRs are covered in the VIIRS Error Budget *[Y3249]*.

This document presents the theoretical basis and the pre-launch agenda for the Cloud Base Height EDR. It includes an in-depth analysis of the retrieval approach for use with water clouds and ice clouds, results of sensitivity analyses, and performance summary for the EDR from extensive simulations. It also identifies primary and ancillary data requirements, and provides a risk reduction plan for developing, testing, and validating the performance of the algorithm to meet VIIRS system specification requirements in the post-launch timeframe. This document now includes initial results from case studies in which MODIS cloud data products and radiosonde observations are used to test the VIIRS cloud base height algorithms. The results are in general agreement with those predicted in the sensitivity analyses shown earlier and performance specifications provided at the VIIRS PDR.

Thus, we are encouraged by the results presented in this algorithm theoretical basis document. While the Cloud Base Height EDR is considered extremely important to civilian and military aircraft operations as well as weather and climate prediction, it is the only cloud EDR listed as a Category III requirement. Perhaps the failure to make it a Category II EDR reflects the lack of confidence that useful cloud base height information can be retrieved solely from satellite-based sensors more than the need for such information by the user community. However, results presented in this document are in good agreement with those recently reported in the refereed literature (Wilheit and Hutchison, 2000) that demonstrated the measurement uncertainty in cloud base heights that can be achieved with microwave moisture sounder data constrained by IR cloud top temperatures. The predicted performance in the retrieval of cloud base heights from two completely different (CMIS and VIIRS) sensors that exploit totally different phenomenology strongly suggests that useful cloud base heights, of about 1 km measurement uncertainty, are achievable during the NPOESS era.

1.0 INTRODUCTION

1.1 PURPOSE

This Algorithm Theoretical Basis Document (ATBD) describes the phenomenology associated with the retrieval of cloud base heights from a Visible/Infrared Imager/Radiometer Suite (VIIRS) sensor in order to satisfy the system specification requirements established by Raytheon and the Integrated Program Office (IPO) of the National Polar-orbiting Operational Environmental Satellite System (NPOESS).

1.2 SCOPE

In addition to this Introduction, the ATBD holds four sections. Section 2 describes the NPOESS program requirements and retrieval strategy along with a new specification of expected performance of the Cloud Base Height EDR. A complete definition of the theoretical basis for the retrieval of cloud base height is found in Section 3, including input parameters, processing sequence, mathematical description of the algorithms for ice and water clouds, performance summary based upon an error budget, results of sensitivity studies, and practical considerations for hosting the algorithms, along with an evaluation plan and a schedule to complete the validation algorithm performance against requirements, and initial results for the retrieval of Cloud Base Heights from MODIS imagery and cloud data products. Section 4 identifies assumptions and the resultant limitations of the cloud base height retrieval algorithm. Conclusions are also summarized in Section 4.

1.3 VIIRS DOCUMENTS

This ATBD addresses requirements specified in the VIIRS System Specification, dated June 3, 2000.

1.4 REVISIONS

This is version 5 of the Cloud Base Height Algorithm Theoretical Basis Document, and is dated March 2002. Version 1 was produced in October 1998; version 2 in June 1999; version 3 in May 2000; and version 4 in May 2001.

2.0 EXPERIMENT OVERVIEW

2.1 PROGRAM REQUIREMENTS FOR CLOUD BASE HEIGHT RETRIEVALS

System Specification requirements for the retrieval of cloud base heights from the VIIRS sensor are shown in Table 1.

Table 1. Cloud base height requirements from VIIRS System Specification

Requirement Number	Parameter	Requirement
SSV0191	EDR CLBAHT HCS:	10 km
SSV0192	EDR CLBAHT HRI:	HCS
SSV0193	EDR CLBAHT Horizontal Coverage:	Global
SSV0195	EDR CLBAHT Vertical Reporting Interval:	Base of highest cloud and lowest cloud
SSV0196	EDR CLBAHT Measurement Range:	0 to 20 km
SSV0748	EDR CLBAHT Measurement Uncertainty:	2 km
SSV0200	EDR CLBAHT Swath Width:	3000 km

Cloud base height is defined as the height above mean sea level where cloud bases occur. More precisely, for a cloud-covered Earth location, cloud base height is the set of altitudes of the bases of the clouds that intersect the local vertical at this location. The reported heights are horizontal spatial averages over a cell (i.e., a square region of the Earth's surface). If a cloud layer does not extend over an entire cell, the spatial average is limited to the portion of the cell that is covered by the layer. The bases of the highest and lowest clouds must be reported.

2.2 INSTRUMENT CHARACTERISTICS

Cloud base height is derived from other VIIRS Environmental Data Records (EDRs). It has no direct effect on the VIIRS design.

2.3 RETRIEVAL STRATEGY

The Cloud Base Height EDR is derived by subtracting cloud thickness from cloud top height. Cloud thickness is retrieved using cloud optical depth and cloud-effective particle-size EDRs, which vary greatly between ice and water clouds. Thus, the retrieval of the Cloud Base Height EDR requires the analysis of cloud top phase as a derived requirement. The accuracy of retrieved cloud top heights from VIIRS data also depends on cloud top phase, the number of cloud layers within the VIIRS Horizontal Spatial Resolution (HSR), and the surface background/terrain. Therefore, quality flags are used to identify the confidence that retrieved cloud base heights comply with VIIRS System Specification requirements for the Horizontal Cell Size (HCS) and the Horizontal Reporting Interval (HRI). The retrieval accuracy of ancillary cloud EDRs used in the Cloud Base Height algorithm are covered in separate documents.

3.0 ALGORITHM DESCRIPTION

There are two executable modules or algorithms, which may be used to retrieve the Cloud Base Height EDR: one for water clouds and one for ice clouds. These algorithms and sensitivity studies using them are described in Sections 3.1-3.4. Another module, which remains a research area, incorporates any Cloud Base Height EDRs from CMIS and conventional weather observations with those retrieved from the VIIRS and assigns a confidence flag to the merged Cloud Base Height EDR. (The "Merge Module" is still under development and is not covered in this version of the ATBD.)

The retrieval approach utilizes VIIRS cloud EDRs. Cloud thickness is estimated from input values of Cloud Optical Thickness, Effective Particle Size, and cloud phase. This thickness is subtracted from Cloud Top Height to yield Cloud Base Height. Base height is determined for each cloudy pixel. Base height values are grouped together according to the clusters/layers determined in Cloud Cover/Layers. Mean values are computed for each group. The highest and lowest Cloud Base Height means are then output as the final product.

3.1 PROCESSING OUTLINE

Cloudy pixels are initially checked for phase. Ice Cloud retrievals execute a different processing path than that for water clouds. Section 3.3 provides necessary detail.

3.2 ALGORITHM INPUT

3.2.1 VIIRS Data

Input parameters from VIIRS include cloud cover, cloud top height, cloud optical depth, and cloud effective particle size. In addition, derived VIIRS requirements are established for the retrieval of the cloud top phase, in order to accurately use cloud optical depth and cloud effective particle size EDRs in the retrieval of Cloud Base Heights, and the presence of multi-layered clouds versus single-layered clouds.

3.2.2 Non-VIIRS Data

Input parameters from the CMIS and other (non-VIIRS) ancillary databases are not used as part of the baseline VIIRS processing. They can be used and will be considered for enhanced processing by yielding more accurate information regarding cloud liquid water and ice water path.

3.3 THEORETICAL DESCRIPTION OF CLOUD BASE HEIGHT RETRIEVAL

3.3.1 Physics of the Problem

Cloud Base Height is retrieved only for pixels that are classified as cloudy by the VIIRS Cloud Mask. The Base Height algorithm requires the accurate analysis of numerous cloud EDRs of which cloud top height is considered most critical. In earlier versions of this document, it was postulated that cloud top height is more accurately analyzed when water clouds are present, as

compared to ice clouds (Hutchison *et al*., 1997). Thus, quality or confidence flags were used to differentiate between these two cloud types and cloud top phase became a derived requirement for use in the Cloud Base Height EDR. If a water cloud is present, cloud top height is accurately analyzed using brightness temperatures from a VIIRS longwave IR band, after correcting for atmospheric attenuation due primarily to water vapor. However, if ice cloud tops are present, it may be necessary to retrieve the cloud top pressure first, and then the cloud top height and temperature using atmospheric profile information (Hutchison *et al.*, 1997). Alternatively, the effective cloud height may be retrieved along with optical depth and effective particle size (Ou *et al*., 1993); however, this usually means a layered-mean cloud height is retrieved rather than the actual cloud top height, which can significantly impact the Cloud Base Height EDR.

More recently, the Raytheon VIIRS team demonstrated measurement accuracies for cloud top height as 1.0 km and 0.5 km for optically-thinner (typically ice) and optically thicker (typically water) clouds, respectively. Thus, it was concluded that many key ancillary VIIRS EDRs will meet thresholds and be available for use with the Cloud Base Height algorithms, including (1) the Cloud Cover EDR, (2) the Cloud Top Height EDR, and (3) the cloud top phase IP. It is also necessary to identify the presence of single versus multiple cloud layers. Cloud Base Height analyses are optimal when only a single cloud layer exists within the HCS.

The next step in preparation for the analysis of cloud base heights is to retrieve cloud effective particle size and cloud optical thickness. The algorithms to satisfy these threshold requirements are mature and follow the approach to exploit reflected solar energy during the daytime (King *et al*., 1997; Rao *et al*., 1995) and thermal emissions during nighttime conditions (Ou *et al*., 1995; Ou *et al*., 1993). The total error analyses necessary to complete the system definition flowdown for these critical EDRs has been completed and integrated into the performance summary for the Cloud Base Height algorithm as shown in Section 3.3.4.1.

The final step in the retrieval of Cloud Base Height relates cloud optical thickness to cloud thickness, which is done by the cloud particle scattering phase function or scattering coefficient. However, the scattering coefficient is a function of several other cloud properties, including (a) the number density distribution of water droplets or ice crystals (e.g., effective particle size), (b) the single scattering albedo, and (c) the indices of refraction at the VIIRS wavelengths. Together, these properties vary by cloud type. Thus, the possibility exists that an automated cloud typing EDR may eventually be required as ancillary data for the Cloud Base Height EDR.

Finally, an overall confidence measure or quality flag must be assigned to the retrieved Cloud Base Height EDR. The quality flag is an assessment of any contradictory information processed from VIIRS cloud EDRs or conventional meteorological reports that might be available. The quality flag is also a function of (1) the number of cloud layers determined present in the horizontal cell, (2) the cloud top phase of the highest cloud, and (3) background scene characteristics such as terrain elevation and vegetation index/surface class. A more complete discussion of retrieved accuracy and confidence flags is presented in Section 3.6.4.

3.3.2 Mathematical Description of the Algorithms

The methodology, overviewed in Figure 1, assumes the accurate specification of several VIIRS cloud EDRs in general and cloud top height (Z_{ct}) in particular.

As shown in Equation 1, Cloud Base Height (Z_{cb}) for a water cloud is determined by subtracting cloud thickness (ΔZ) from cloud top height. Cloud thickness is derived from the ratio of retrieved liquid water path (LWP), in units of g/m^2, to liquid water content (LWC), with units of g/m^3, and has the unit of length in meters. The expressions to retrieve LWP in the case of a water cloud, or ice water path (IWP) in the case of an ice cloud, are shown in Equations 2 and 5, respectively, and use cloud effective particle size and cloud optical depth EDRs. LWP is defined as the integration of liquid water content (LWC) across cloud thickness where LWC is obtained from *a priori* information on the cloud particle size distributions and cloud type (e.g., altostratus, stratocumulus, and others). Similarly, IWP is defined as the integration of ice water content (IWC) over the thickness of the cirrus cloud.

Results of sensitivity studies reported in Section 3.4.3.4 show that errors in retrieved cloud thickness are approximately 20 percent based upon inaccuracies in retrieved cloud optical properties. Additional error sources include specification of cloud top height, and choice of LWC and IWC models used in the retrieval of cloud thickness. Initial sensitivity analyses suggest these latter errors are not sufficient to levy cloud type as a derived requirement for the VIIRS sensor (e.g., sufficient accuracy in retrieved Cloud Base Height can be achieved using mean LWC values for low-level versus mid-level water clouds). However, additional research is needed to confirm this position.

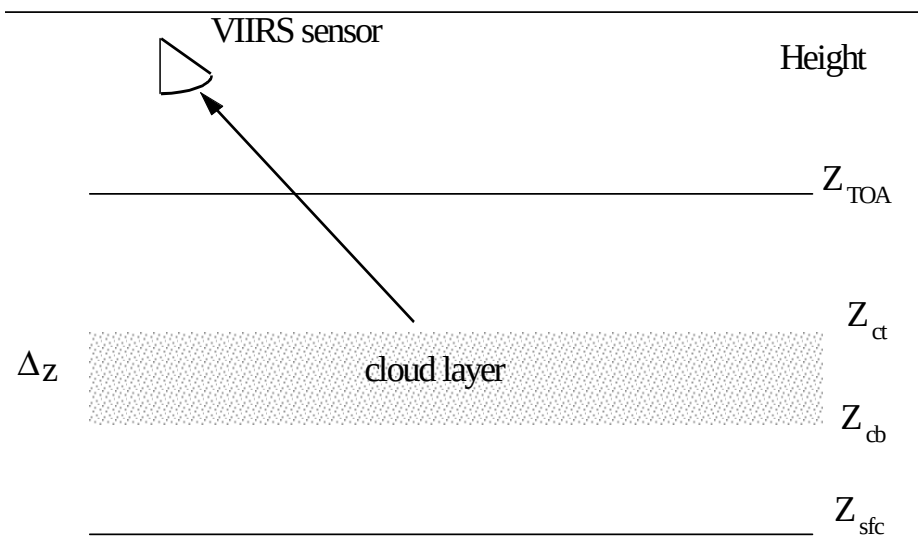

Figure 1. Overview of the methodology used to retrieve the Cloud Base Height EDR from VIIRS data.

3.3.2.1 Water Clouds

For water clouds, LWP has been related to cloud optical depth or thickness (τ) and cloud effective cloud particle size (r_{eff}) as shown in Equation 2 (Liou, 1992). Because the upper limit of the VIIRS threshold measurement range for cloud optical thickness in the VIIRS System Specification are 10 and 64, enhanced processing would use the cloud liquid water (CLW) EDR product retrieved from the CMIS sensor if this upper limit is exceeded.

$$Z_{cb} = Z_{ct} - (\Delta Z) = Z_{ct} - [LWP/LWC] \quad (1)$$

$$LWP = [2\ \tau\ r_{eff}] / 3 \quad (2)$$

where LWP is in g/m^2

3.3.2.2 Ice Clouds

When ice clouds are present, the form of the equation for the retrieval of the Cloud Base Height EDR is similar to that for water clouds with the exception that the relevant terms are now IWP and IWC rather than LWP and LWC, as shown in Equation 3. The parameterization for IWP is a function of the ice crystal size distribution and ice crystal diameter (D_e=2r_{eff}) as defined in Equation 4 (Liou, 1992). Additionally, D_e and thus IWP are functions of cloud temperature.

$$Z_{cb} = Z_{ct} - (\Delta Z) = Z_{ct} - [IWP/IWC] \quad (3)$$

$$IWP = \tau / [a+b/D_e] \quad (4)$$

with a and b being regression coefficients, defined by Liou (Table 5.4, 1992) with values

a= -6.656e-3; b=3.686. Additionally, De, IWP, and IWC are functions of cloud temperature. IWC is calculated by:

$$\ln(IWC) = -7.6 + 4\exp[-0.2443e\text{-}3(|T| - 20)^{2.455}] \quad \text{for } |T| > 20 \text{ deg C} \quad (5)$$

The dependence of D_e on cloud top temperature is given in Equations 6 and 7 by Ou *et al.*, (1993). If ice cloud optical depth exceeds 10, enhanced processing could use ice water path taken directly from the CMIS EDR.

$$D_e = c_0 + c_1T + c_2T^2 + c_3T^3 \quad (6)$$

where $c_0 = 326.3,\ c_1=12.42,\ c_2=0.197,\ c_3=0.0012$ (7)

3.3.3 Archived Algorithm Output

There are two outputs from the Single-Layered Water and Ice Cloud Base Height Algorithms: (1) a retrieved cloud base height in meters and (2) a Confidence Flag. Eventually, the confidence flag will include the use of conventional data; however, additional research is needed to determine how best to include these data in the measure of confidence. Definitions of the confidence flags are provided in Section 3.6.4, entitled Quality Assessment and Diagnostics.

3.3.4 Variance and Uncertainty Estimates

Analyses show the 1-σ measurement uncertainty for the retrieval of the VIIRS Cloud Base Height EDR in a single cloud-layered ice cloud system to be 1.4 km and 0.8 km for a similar water cloud system.

3.3.4.1 Error Budget

An error budget for the Cloud Base Height EDR has been completed using the measurement accuracies of ancillary VIIRS cloud EDRs, including cloud top height, optical depth, and effective particle size. These data are shown in Figure 2 according to cloud top phase. The budget does not include error contributions from cloud top phase since there is no NPOESS specification for this IP and the performance of the Raytheon algorithm has not yet been established.

Figure 2 contains the threshold and objective requirements for key attributes of the Cloud Base Height EDR. Also included are values from the system specification completed in 1998, and predicted performance, which is based upon most recently completed simulations. Examination of the table shows the following:

1. Initial estimates on the accuracy of the retrieved Cloud Base Height EDR were conservative. Performance should meet threshold requirements for both ice clouds (1.4 km) and water clouds (0.8 km). This error budget includes errors in cloud top height of 1.0 and 0.5 km for ice and water clouds respectively, plus 100 – 200 m errors due to inaccuracies in cloud optical depth and cloud effective particle size, and 200 m errors due to mis-specification of cloud ice/water content as will be shown in the sensitivity studies which follow. Results from initial analyses of Cloud Base Height from MODIS support the validity of this error budget.

2. While initial estimates assumed the capability to retrieve cloud bases in a single cloud-layered system, adequate margins in (1) lead to optimism that meaningful cloud bases heights can be retrieved in two cloud-layered conditions. Therefore, we believe the Cloud Base Height EDR will be better than System Specification Requirements. This capability will be case dependent. Results will be optimum if all layers are water clouds. Poorer results are obtained when cirrus clouds are present over another cloud layer.

Requirement Number	Parameter	Requirement	Predicted Performance
SSV0191	EDR CLBAHT HCS:	10 km	10 km
SSV0192	EDR CLBAHT HRI:	HCS	HCS
SSV0193	EDR CLBAHT Horizontal Coverage:	Global	Global
SSV0195	EDR CLBAHT Vertical Reporting Interval:	Base of highest cloud and lowest cloud	Base of highest cloud and lowest cloud
SSV0196	EDR CLBAHT Measurement Range:	0 to 20 km	0 to 20 km
SSV0748	EDR CLBAHT Measurement Uncertainty:	2 km	0.8 for water clouds; 1.4 for ice clouds
SSV0200	EDR CLBAHT Swath Width:	3000 km	3000 km

Figure 2. Performance summary for the Cloud Base Height EDR.

3.4 ALGORITHM SENSITIVITY STUDIES

3.4.1 Calibration Errors

Not applicable to the Cloud Base Height EDR. They are included in the error budgets for other cloud EDRs.

3.4.2 Instrument Noise

Not applicable to the Cloud Base Height EDR. They are included in the error budgets for other cloud EDRs..

3.4.3 Ancillary Data

Sensitivity analyses have been completed to quantify the expected errors in using the cloud base height algorithms as a function of ancillary data. Key cloud EDRs that are used in the retrieval of cloud base height for water and ice clouds are cloud top height, cloud optical depth, and cloud effective particle size. In turn, these cloud EDRs are a function of cloud top temperature and cloud top phase along with cloud particle size distribution, which is also a function of cloud effective particle size and cloud top temperature.

3.4.3.1 Thickness of Common Ice and Water Clouds of Maximum VIIRS Optical Depths

The upper limit of cloud thickness, which can be retrieved solely from VIIRS data using the Cloud Base Height algorithm, is derived from the requirement for measurement range of optical depth coupled with the effective particle radius associated with different cloud types (e.g., LWC). The VIIRS System Specification measurement range for optical thickness reaches a maximum value of 10 and 64 for ice and water clouds respectively. Thus, the maximum water cloud thickness that can be retrieved, as a function of cloud type, is defined as:

$$\Delta z_{max} = LWP/LWC = 2\,\tau\, r_e / (3\,LWC)$$

$$= 2\,(64)\, r_e / (3\,LWC) \qquad (8)$$

while, for ice clouds:

$$\Delta z_{max} = IWP/IWC = \tau / [(a+b/D_e)\ IWC] = 10 / [(a+b/D_e)\ IWC] \quad (9)$$

Table 2 shows the maximum cloud thickness which can be retrieved under the constraint that $\tau <= 10$, for ice clouds and $\tau <= 64$ for water clouds, based upon cloud distributions taken from Liou (Table 4.2, 1992).

Table 2. Thickness of common ice clouds with an optical thickness of 10 and water cloud clouds with an optical thickness of 64.

Cloud Type	r_e (μm)	LWC (g/m^3)	Δz_{max}(m)
Stratus I (oceans)	3.5	0.24	622
Stratus II (land)	4.5	0.44	436
Stratocumulus	4.0	0.09	1896
Altostratus	4.5	0.41	468
Cirrus	~ 100 (= D_e)	~ 0. 1 (= IWC)	3333

3.4.3.2 Optimizing Retrievals Using Cloud Liquid Water Content from the CMIS Sensor

From Table 2, it appears that a Cloud Base Height retrieval algorithm based solely upon data from the VIIRS may have more limited utility in the presence of water clouds because the optical thickness threshold requirement measurement range of 64 is more quickly exceeded by relatively thin cloud layers, when compared to the range for cirrus clouds. Thus it may become necessary to use LWP information from the CMIS sensor (i.e., cloud liquid water (CLW) EDR), as an alternative data source. The threshold measurement range for the CLW EDR is 0-5kg/m^2, and the upper limit increases Δz_{max} to 10,000 meters for typical water clouds (NPOESS CMIS SRD, 2001). Thus, using the CLW EDR from the CMIS sensor provides an alternative source of ice water path and liquid water path data and extends the range of cloud thickness that might be retrieved using the Cloud Base Height algorithms.

The assumption is made that the CMIS sensor will provide a CLW EDR that satisfies threshold requirements (i.e., meets measurement range and accuracy requirements over both land and ocean backgrounds, (e.g., 0.5 kg/m^2 and 0.25kg/m^2, respectively)). Analyses show that a 0.5 kg/m^2 error in CLW results in about 1,000 meter error in cloud base for a typical stratus cloud over water. There is concern that the CMIS CLW EDR accuracy requirements over land may not be satisfied (i.e., it is assumed that LWP over land surfaces is more accurately retrieved from a VIIRS than a CMIS sensor).

3.4.3.3 Optimizing Retrievals Using Cloud Ice Liquid Water Content from the CMIS Sensor

From Table 2, it appears that a Cloud Base Height retrieval algorithm using only VIIRS data is less limited in the presence of cirrus clouds; however, information from the CMIS cloud ice water path (CIWP) EDR continues to serve an alternative data source. The threshold measurement range for the CIWP EDR is 0-2.6 kg/m^2 (or 2600 g/m^2) with an accuracy requirement of 10 percent or 5 g/m^2, whichever is greater. The upper limit of the CIWP EDR increases Δz_{max} to over 26,000 meters for cirrus clouds with an IWC of 0.1. Thus, the measurement range for the CIWP EDR exceeds that needed to handle cirrus clouds in the troposphere. Finally, an error of 5 g/m^2 in CIWP alone translates into a Cloud Base Height error of 50 meters, while a 10 percent error could cause a maximum Cloud Base Height error of 2,600 meters.

3.4.3.4 Sensitivity to Errors in Input Parameters

A sensitivity analysis shows that the most critical cloud EDR that directly effects cloud base height accuracy is cloud top height. Errors in optical thickness, effective particle size, and size distribution models are secondary over the range of thresholds required by the cloud optical thickness EDR (i.e., 0-10). At the larger ranges (e.g., $\tau = 64$), errors in the calculation of cloud thickness become more important; however, other factors loom as potentially larger problems.

Errors in retrieved cloud optical thickness

Table 3 shows the impact of errors in cloud optical depth on retrieved Cloud Base Height for a stratus cloud over the ocean, which typically has an effective particle size of 3.5 microns, and liquid water content of 0.24 g/m^3 (Liou, 1992). The cloud top height was assumed to be 2 km and the optical depth, 10. Table 4 shows similar results for cloud optical thickness of 64.

Table 3. Impact of errors in optical depth on retrieved Cloud Base Height for stratus (water) clouds with cloud top height of 2 km, optical thickness 10, effective particle size 3.5 microns, and liquid water content of 0.24 g/m^3.

Error in τ (%)	Retrieved Cloud Base Height (m)	Error in Base Height (%)	Calculated Cloud Thickness (m)	Error in Cloud Thickness (%)
0	1902.8	0	97.2	0
10	1912.5	0.5	87.5	10
20	1922.2	1.0	77.8	20
50	1951.4	2.5	48.6	50

The results in Table 3 show that the relationship between error in optical thickness and retrieved cloud thickness is 1:1, as expected for a linear system. However, the impact of this error on Cloud Base Height is less significant because the cloud thickness is relatively small for optical

thickness values of 10 or less. Thus, the magnitude of the error in Cloud Base Height remains relatively unaffected by any error in cloud retrieved optical thickness. In fact, a 20 percent error in optical depth for an input optical thickness 100, which represents a stratus cloud of about 1 km thickness, only causes errors in cloud base heights of about 200 meters. Because stratus clouds are normally much thinner, the 1 km thick cloud might be considered a worst-case scenario (Liou, 1992).

Table 4. Impact of errors in optical depth on retrieved Cloud Base Height for stratus (water) clouds with cloud top height of 2 km, optical thickness 64, effective particle size 3.5 microns, and liquid water content of 0.24 g/m^3.

Error in τ (%)	Retrieved Cloud Base Height (m)	Error in Base Height (%)	Calculated Cloud Thickness (m)	Error in Cloud Thickness (%)
0	1378	0	622	0
10	1440	4.5	560	10
20	1502	9.0	498	19.9
50	1688	22.5	312	49.8

Results in Table 4 show that the relative errors (percent) in retrieved Cloud Base Height and Cloud Thickness increase significantly as the Cloud Optical Thickness is increased from 10 to 64. However, these errors in retrieved Cloud Base Height remains well within the System Specification requirement of 2 km even when errors in the Optical Thickness reach 50 percent, actual cloud thickness is 622 m while retrieved cloud thickness is 312 m - a difference of only 310 m.

One the other hand, optical depth values of 10 represent a much thicker ice cloud, as compared to water clouds, as shown in Table 2. In the case of the cirrus cloud shown in Table 5, the magnitude of the error in retrieved Cloud Base Height becomes larger because the cloud is relatively thick, i.e., 3310.8 m. However, 50 percent errors in the optical thickness input parameter still allows the retrieved Cloud Base Height to meet the 2 km measurement uncertainty, which is the System Specification requirement.

Currently, the cloud top height EDR specifies a measurement accuracy of 0.5 to 1.0 km for optical thickness values that exceed 1.0 and 2 km for values less than 1.0; however, the Cloud Base Height threshold requirement makes no such distinction. This apparent inconsistency should be corrected. It should be noted that for optically thin clouds, the current 2 km measurement uncertainty for cloud top height consumes the entire error margin available for the Cloud Base Height EDR, which is also 2 km. The cloud base height EDR measurement uncertainty requirement must conform to that used in specifying the requirements for cloud top height. Performance summaries of the Cloud Base Height EDR in fact confirm that retrieved bases are a function of cloud optical thickness, stratified by cloud top phase.

Table 5. Impact of errors in optical depth on retrieved Cloud Base Height for a cirrus (ice) cloud with cloud top height of 10 km, optical thickness 10, effective particle size of 100 microns, and ice water content of 0.1 g/m^3.

Error in τ (%)	Retrieved Cloud Base Height (m)	Error in Base Height (%)	Calculated Cloud Thickness (m)	Error in Cloud Thickness (%)
0	6689.2	0	3310.8	0
10	7084.5	5.6	2915.5	11.9
20	7463.2	11.5	2536.8	23.4
50	8508.9	27.2	1491.1	55

Errors in retrieved cloud effective particle size

A similar analysis on the retrieval of Cloud Base Height was completed using errors in cloud effective particle size in addition to a 10 percent error in cloud optical depth. Results are shown in Table 6. The same cloud was used in this exercise as described in Table 4. Again, the errors in Cloud Base Height were insignificant because water clouds are relatively thin, compared to the measurement uncertainty threshold requirement, even for optical thickness values of 64. A similar analysis was deemed unnecessary to draw conclusions about the impact of errors in particle size on ice clouds.

Table 6. Impact of errors in effective particle size on retrieved Cloud Base Height. The cloud is identical to that used in Table 4 except that the optical depth of 64 was assumed to have a 10% error. Actual cloud thickness is 622 m as shown in Table 4.

Error in r_e (%)	Retrieved Cloud Base Height (m)	Error in Base Height (%)	Calculated Cloud Thickness (m)	Error in Cloud Thickness (%)
0	1440	4.5	560	10
10	1496	8.6	504	19
20	1552	12.6	448	28
50	1720	24.8	280	55

Summary of Errors from Cloud Optical Properties

System Specification requirements for cloud optical thickness and effective particle size are of order 10 percent which suggests a worst-case cumulative error of about 20 percent. Thus, Table 6 shows that a 20 percent cumulative error in cloud optical properties produces a retrieved cloud thickness of 504 m and an error in cloud thickness of approxmiately 118 m. The VIIRS system specification for the cloud top height exceeds this value by about five-fold for water clouds and ten-fold for ice clouds. Thus, these analyses suggest that errors in cloud optical properties are second-order and will allow cloud thickness to be retrieved with sufficient accuracy to meet System Specification requirements for the Cloud Base Height EDR.

Errors in liquid water content and ice water content models

A potentially more significant error source surrounds the selection of the appropriate cloud droplet or ice particle distributions used in the retrieval of Cloud Base Heights. The key to the VIIRS Cloud Base Height retrieval is the relationship between LWP and liquid water content (LWC) for water clouds and IWP and IWC for ice clouds. LWC and IWC are generated *a priori* from observations of cloud particle size distributions. The use of LWC and IWC cause two concerns. First, these data are not routinely observed on a global basis thus, actual size distributions may vary by location. For example, LWC for stratus was found to vary from 0.24 g/m^3 over oceans to 0.44 g/m^3 over land while stratocumulus has a value of 0.09 g/m^3. There is often little difference in VIIRS-type imagery between stratocumulus and stratus over the ocean; thus, doubt might arise in determining which LWC should be used in the Cloud Base Height retrieval because the LWC values for these cloud types differ by a factor of nearly 3. Secondly, LWC/IWC values have been found to vary considerably between field measurement campaigns. For example, the IWC for cirrus clouds was considered 0.01 g/m^3 during the 1940s, ~ 0.02 g/m^3 during the 1970s, and most recently 0.006 - 0.30 g/m^3. A value of 0.1 g/m^3 was used in these analyses. Such variations may produce an order of magnitude difference in the retrieved Cloud Base Height. While a parameter that measures the effective droplet or particle size distribution is essential for the retrieval of Cloud Base Heights, the logic needed to support this selection process remains an open issue.

Sensitivity analyses were conducted using size distributions published in the literature (Liou, 1992). The results, shown in Table 7, reveal the same trend noted in Tables 3 and 6. Application of the wrong LWC model produces an additional error in retrieved cloud thickness on order of 100-200 m. However, using a mean LWC model limits the size of these errors in most cases, except possibly when stratocumulus is present. While these errors in the cloud thickness are quite large, the actual error in Cloud Base Height remains small because any water cloud with an optical depth of 64 is relatively thin compared to the measurement uncertainty threshold requirement with stratocumulus being the one exception since values for this cloud are many times smaller than those of the other cloud models. This may translate to a requirement for automated cloud-type classification after additional studies are completed using the complete set of cloud EDR algorithms. Errors are scaleable to thicker clouds if the value of optical thickness does not exceed the range used in the parameterizations, shown in Equations 2 and 5. However,

the literature does not define the range of optical thickness values that were used to validate this parameterization.

Table 7. The effect of errors in droplet size distribution (i.e., liquid water content), on retrieved Cloud Base Heights. The cloud is the same as the one used in Table 6 with 10 percent errors in optical depth (assumed 64, used 57.6) and r_e (assumed 3.5 used 3.15 microns). Actual cloud thickness is 622 m as shown in Table 4.

IWC (actual value = 0.24 g/m^3)	Retrieved Cloud Base Height (m)	Error in Base Height (%)	Calculated Cloud Thickness (m)	Error in Cloud Thickness (%)
0	1496	8.6	504	19.0
0.44 (st land)	1725	25.2	275	55.8
0.09 (sc)	656	52.4	1344	116.1
0.66 (cu)	1816	31.8	184	70.4

Errors associated with multiple scattering/multi-layered clouds

The most accurate Cloud Base Height retrievals are obtained for scenarios consisting of single-layered cloud systems when multiple scattering is insignificant (e.g., clouds completely fill the VIIRS field-of-view). As a corollary, the retrieved Cloud Base Heights will be degraded when multi-scattering events occur, as may be the case for with sub-pixel cloud cover or and when optically-thin clouds overlie a highly reflective surface, such as another cloud system. Thus, special emphasis must be place upon the retrieval of Cloud Base Heights for multi-layered cloud systems that occur within the horizontal spatial resolution (HSR) of the VIIRS sensor.

3.5 ALGORITHMS FOR USE WITH MULTI-LAYERED CLOUD SYSTEMS

Ancillary EDR data products from the CMIS sensor provide information for enhanced retrieval of Cloud Base Heights in multi-layered cloud systems. In particular, the LWP and CIWP CMIS data products can be used to improve the retrieval of Cloud Base Heights when multiple-layered cloud systems are analyzed within a single VIIRS HSR, especially over ocean surfaces where the risk is low that these CMIS products will fail to meet NPOESS threshold requirements. However our baseline approach does not require CMIS data

3.5.1 Processing Outline for Multiple-Layered Clouds

A Cloud Base Height is retrieved for each pixel within a single VIIRS HSR. Information from the Cloud Cover/Layers EDR is used to aggregate pixel-level values of Cloud Base Height into layers (or clusters). Mean values of Cloud Base Height are then determined for each cluster/layer. Finally, the base heights of the highest and lowest cloud layers are output.

3.6 PRACTICAL CONSIDERATIONS

3.6.1 Numerical Computation Considerations

It is assumed that all Cloud Base Height retrievals are made at the HSR of the VIIRS sensor. Results are then summarized to the desired HCS and HRI.

3.6.2 Programming and Procedural Considerations

Cloud Base Height must be retrieved last in the cloud EDR processing sequence.

3.6.3 Quality Assessment and Diagnostics

A confidence measure or quality flag will be assigned to the retrieved cloud base height. The quality flag is an assessment of the information used to process the cloud EDRs.

3.7 ALGORITHM VALIDATION

There are no heritage algorithms in the Earth Observing System (EOS) program for the retrieval of cloud base heights from an EOS sensor using passive remote sensing techniques. . While the feasibility of retrieving cloud base heights has been demonstrated using simulated DMSP SSM/T-2 microwave moisture sounder data with *a priori* cloud top information from an electro-optical imager as a constraint (Wilheit and Hutchison, 1998; 2000), the VIIRS-only approach outlined in this document represents original research.

Thus the VIIRS Cloud Base Height algorithm development process followed the conventional approach of proposing the algorithm, as was done for the Raytheon VIIRS team, conducting sensitivity studies, and performing retrievals with simulated data all of which were done during the VIIRS pre-PDR period. Initial sensitivity studies reported in Section 3.4 have been completed and some analyses were performed with simulated data as part of the Raytheon Cloud IPT. However, it was quickly realized that limitations in the simulation models precluded a thorough testing of the Cloud Base Height algorithms. Simulations were performed for a cloud of constant thickness but with variable optical properties (i.e., the cloud was always assumed to be 1 km thick but the optical depth was varied by changing the particle number density). This methodology does not conform to the real world, where clouds of a particular type have characteristic number densities and the optical properties of a cloud vary with its thickness.

Next, the proposed algorithms must be tested with real sensor data (e.g., MODIS) to ensure that the algorithm development, sensitivity studies, and simulations accurately model real-world phenomenology. In the following sections, results from the analysis of MODIS data are provided to validate that the VIIRS Cloud Base Height algorithms accurately model real-world phenomenology. The results of these case studies support the feasibility of retrieving Cloud Base Height EDR as described in this document.

3.7.1 Algorithm Testing with MODIS Data from Terra

MODIS data and data products derived from the EOS Terra mission are available over the EOSDIS for the initial evaluation of the Cloud Base Height algorithms. Since cloud top height is not a MODIS (MOD06_L2) cloud data product, this information must be obtained from another source such as radiosonde observations or lidar measurements. Therefore, extensive effort is required to identify suitable test cases and construct ground truth data sets which are needed to assess the performance of the Cloud Base Height algorithms. The process used to evaluate the accuracy of Cloud Base Heights retrieved from MODIS follows the sequence below.

3.7.1.1 Test Case Preparation

One approach for developing cases studies to test the accuracy of Cloud Base Height retrievals from MODIS data products uses match-ups between MODIS and radiosonde observations. The Terra spacecraft descends over the central US at about 1700 UTC in a sun synchronous orbit and ascends at approximately 0500 UTC. Only the 1700 UTC data are useful because cloud optical properties are not retrieved with nighttime data under the EOS program.

Since MODIS overflights of the US occur many hours after 1200 UTC radiosonde collection times, extensive manual analyses of satellite and conventional meteorological data are needed to (1) identify suitable test cases and (2) develop the ground truth data sets required to quantitatively assess the Cloud Base Height accuracy retrieved from MODIS. The task of identifying suitable test cases is most tedious and requires a variety of conventional and GOES satellite observations to define each scene. For the initial phase of algorithm validation, test scenes are restricted to single-layered, water cloud systems in order to avoid the difficulties of defining truth for both cloud bases and tops of ice clouds without lidar data. Additionally, cloud fields must be persistent while awaiting MODIS overflights many hours after the radiosonde observation time. Thus, candidate cloud fields are examined each hour in both the visible and infrared GOES imagery. Additionally, thermodynamic plots of radiosonde observations are made as soon as the observations become available to confirm the presence of well-defined cloud top height in a candidate test case. Finally, surface observations are collected hourly between radiosonde and MODIS observation times.

Figure 3 shows GOES imagery of a candidate cloud system which extended across much of Eastern Texas on April 4, 2001. MODIS overflew this area at 1705 UTC. The infrared GOES imagery shows a single layer of stratus exists across much of Eastern Texas, as confirmed in the radiosonde observation shown in Figure 4 and Table 8 for Corpus Christi, Texas. Since the characteristics of the cloud system did not appear to change significantly between radiosonde and MODIS observation times, the MOD06_L2 data product was ordered from the EOSDIS.

3.7.1.2 Determination of Cloud Top Height

Equations (1) and (3) show cloud top height is a key parameter in the retrieval of Cloud Base Height. Unfortunately, the MODIS MOD06_L2 cloud products include cloud top phase, cloud top pressure and cloud top temperature but not cloud top height. Converting from cloud top pressure to cloud top height is simple if sufficient information is available (i.e., either a priori atmospheric profiles of temperature, pressure and height or surface pressure and elevation for each MODIS pixel). Unfortunately, neither product is part of the MOD06_L2 data list.

Therefore, it becomes necessary to identify cloud top heights from radiosonde observations. The cloud top height is located at the point where the temperature inversion begins and the dew point rapidly decreases. The precise cloud top height is analyzed from the significant levels reported in the radiosonde observation, as shown in Table 8. While this is not the ideal method for determining cloud top height, it is acceptable for cases where coincident lidar observations are not available with MODIS data.

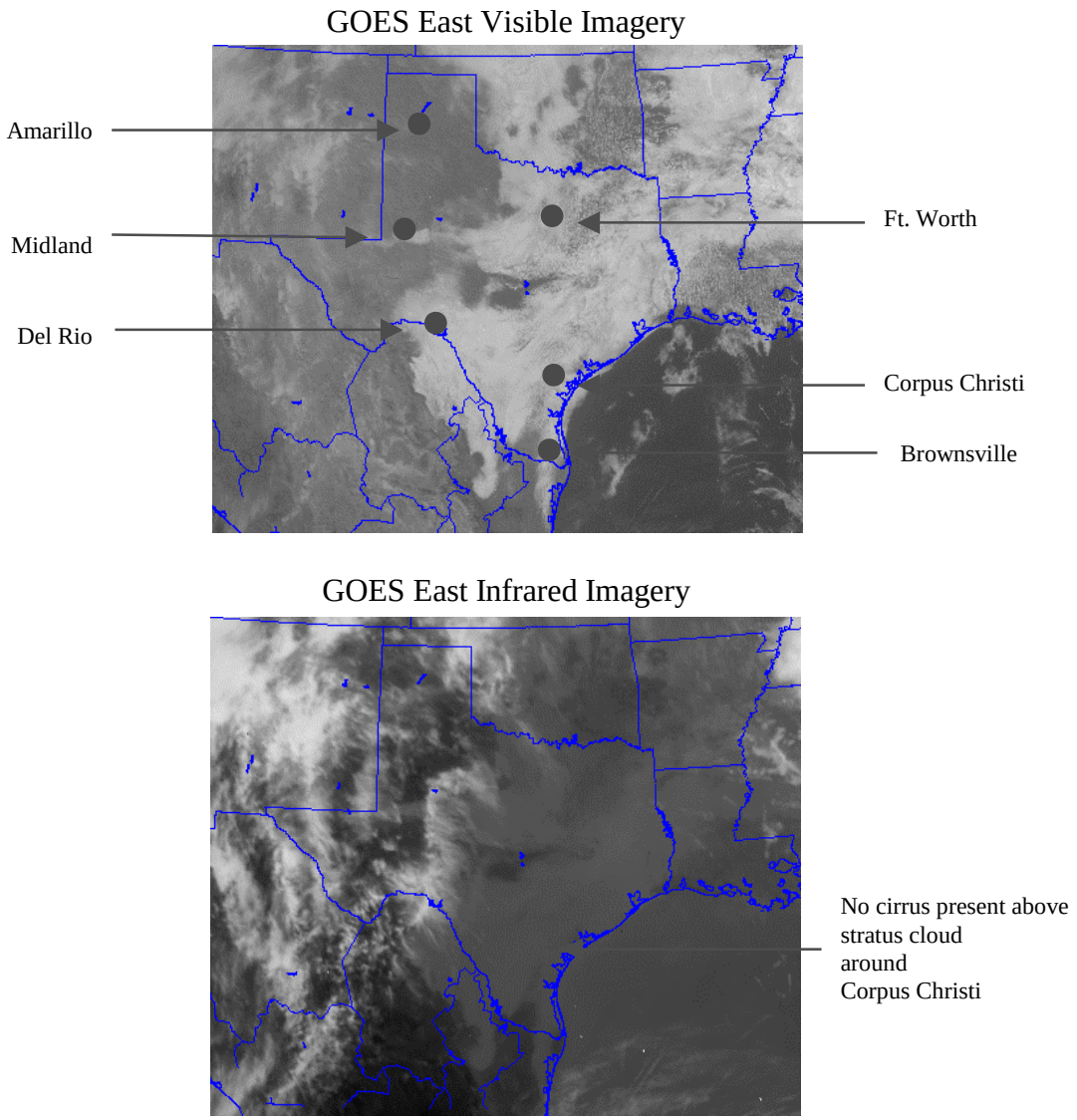

Figure 3. GOES Satellite Imagery of April 4, 2001 Cloud Base Test Case

There are six radiosonde locations in Texas that could be used with the test scene shown in Figure 3. These observations are collected at: Amarillo, Brownsville, Corpus Christi, Del Rio, Ft

Worth (FTW), and Midland. Figure 3 shows only Brownsville, Corpus Christi, and FTW were not cirrus-contaminated in the GOES imagery, although cirrus was subsequently found over FTW in the MODIS data. Initial plots of radiosonde data on Skew-T log P diagrams are available over the internet through NOAA's Forecast Systems Laboratory (FSL) and prove highly valuable. An example of this product, shown in Figure 4, is useful for evaluating the presence of a well-defined cloud top; however, a manual plot of the radiosonde mandatory and significant levels is needed to determine the exact location of the cloud top height. A partial listing of the Corpus Christi, Texas radiosonde, shown in Table 8, reveals the cloud top height of 615 m or 942 mb in the 1200 UTC sounding on April 4, 2001. It is assumed that the cloud top height does not change between 1200 and 1700 UTC; however, this assumption is incorrect since the top of the cloud is illuminated by the sun throughout this period. Thus, the cloud top height probably increased by some unknown amount.

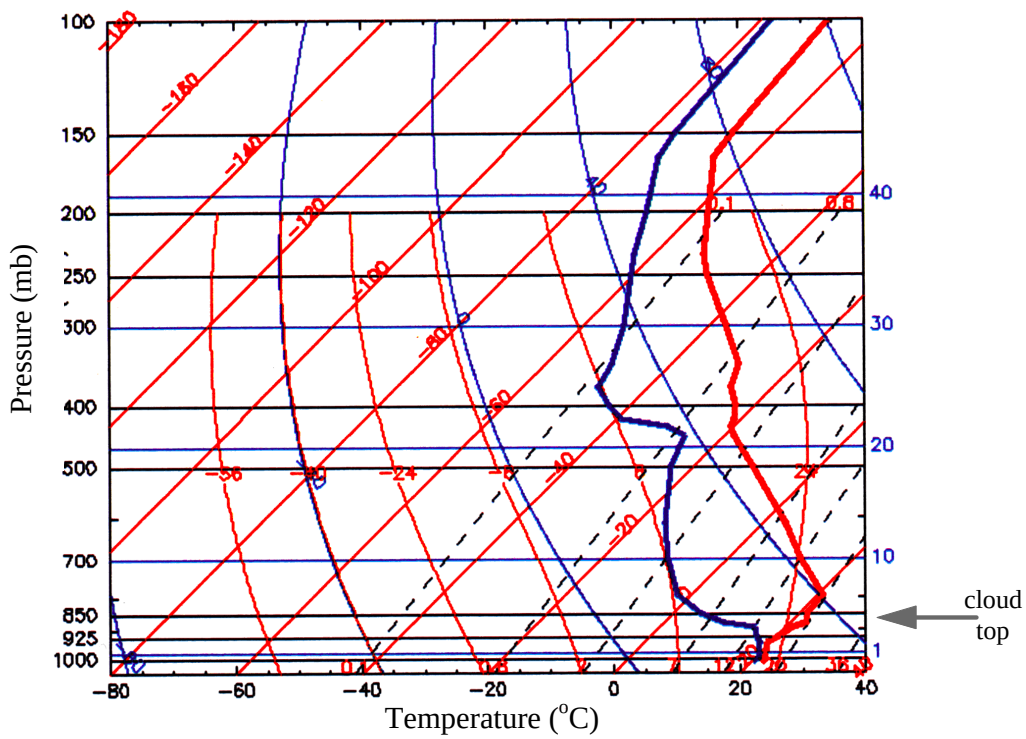

Figure 4. Skew-T plot of Corpus Christi, TX radiosonde at 1200 UTC on April 4, 2001 shows approximate location of cloud top height.

Table 8. Mandatory and significant levels reported in Corpus Christi, TX radiosonde at 1200 UTC on April 4, 2001 accurately reveal location of cloud top height.

Data Type (4 = mandatory 5 = significant)	Pressure (mb)	Height (meters)	Temperature (degree C)	Dew Point (degree C)	Wind Direction (0-360)	Wind Speed (knots)	Remarks
Surface	1010	14	21.6	20.4	130	7	
4	1000	102	21.8	20.7	140	10	
5	942	615	19.6	18.3	99999	99999	Cloud Top
4	925	778	20.4	17.1	185	27	
5	894	1071	21.2	15.2	99999	99999	
5	878	1227	22.6	9.6	99999	99999	
4	850	1512	21.4	4.4	200	24	

3.7.1.3 Cloud Base Height Ground Truth

As is the case for cloud top heights, ground truth for the cloud base height is best defined using surface-based instruments, especially lidar systems. Since these data are not routinely available, the cloud truth data are selected from surface observations made at major US airports. Reports from more fully instrumented runways are most useful, especially if both surface and radiosonde observations are available.

The Corpus Christi surface observation at 1700 UTC on April 4, 2001 reported sky conditions overcast at 1200 feet. It is noted that the potential error of these observations should be ± 50 feet since reports are to the nearest 100 feet. In this case, the Cloud Base Height ground truth is defined to be 369 m. Unfortunately, surface reports from Brownsville, Texas showed the overcast conditions of 900 feet at 1500 UTC but clouds began to dissipate quickly thereafter. By 1600 UTC, the ceiling had increased to 1500 feet but only scattered clouds were reported at 2400 feet in the 1700 UTC observation. In the 1600 UTC Austin, Texas observation, the sky was overcast with bases at 1000 feet but by 1700 UTC, three cloud layers were reported at 1000, ceiling at 1500, and overcast at 3100 feet. Austin does not make radiosonde observations.

3.7.1.4 Results

The MOD06_L2 cloud top phase product showed that the cirrus did move over the water clouds near FTW but not over regions south toward the Gulf of Mexico. Thus, the MODIS Level 2 data products of cloud optical depth and cloud effective particle size were used to analyze the scene shown in Figure 3 assuming an LWC of 0.44 g/m^3 for stratus cloud over land (Table 4.2 Liou, 1992). Ground truth for this scene consisted of cloud top height taken from the radiosonde observation at Corpus Christi and cloud base heights from surface observations at Corpus Christi, Brownsville, and Austin, Texas.

A summary of all Cloud Base Height retrievals, within a 0.25 degree latitude and longitude grid of the surface stations used in this test case, is shown in Table 9. The Cloud Base Height mean and standard deviation at each location are based upon approximately 225 individual analyses of MODIS data. Table 9 shows the truth cloud thickness analyzed from the Corpus Christi conventional weather observations to be 246 m. The mean cloud thickness retrieved from

MODIS data is 335 m with a standard deviation of 15.6 m, for the stratus cloud with a mean cloud optical thickness of 22.9 and mean cloud effective particle size of 9.5 microns. Thus, the retrieved cloud thickness is 89 m larger than the truth.

Table 9. Retrieved cloud thickness from MODIS compared to conventional weather reports for stratus cloud over Texas on April 4, 2001.

Radiosonde Location	Cloud Top Height – Truth (m)	Cloud Base - Truth (m)	Cloud Thickness Truth (m)	MODIS Cloud Optical Thickness Mean / Standard deviation (non-dimensional)	MODIS Cloud Effective Particle Size Mean / Standard deviation (microns)	Retrieved Cloud Thickness - Mean / Standard deviation (m)
Corpus Christi	615	369	246	22.9/9.9	9.5/0.75	335/15.6
Brownsville	Not applicable (na) at time of MODIS overflight	na at time of MODIS overflight	na at time of MODIS overflight	2.9/1.7	9.4/2.5	42/na
Austin	na	461	Na	29.7/8.6	9.35/0.94	429/15.0

Only complete analyses were possible for the Corpus Christi radiosonde site since cirrus moved into the Ft. Worth region and clouds dissipated over Brownsville just prior to MODIS overflight. Table 9 shows the cloud thickness retrieved for Corpus Christi was 89 m or 36 percent larger than determined in the ground truth data. Assuming MODIS retrieval accuracy for cloud optical thickness and cloud effective particle size satisfies NPOESS requirements, Cloud Base Height errors of 20 percent are expected based upon sensitivity studies shown in Section 3.4. A 20 percent error in this case translates to an expected error in cloud thickness of 49 m in this case. Thus, retrieved cloud thickness was approximately double the expected values but still relatively small compared to the System Specification uncertainty requirement of 2-km for cloud base height.

While quantitative analyses are not possible for either Brownsville or Austin, qualitative results or trends in these analyses are worth noting. Conventional observations for Brownsville showed the clouds rapidly dissipating between 1500 UTC and 1700 UTC – with only scattered clouds present at MODIS overflight. The retrieved mean cloud thickness for several hundred MODIS pixels near Brownsville was 42 m, indicating a relatively thin cloud consistent with the rapid dissipation of cloud fields at this site. On the other hand, the Austin observations showed the cloud cover continued long after MODIS overflight, with low overcast sky conditions remaining the entire day. Thus, the thickest clouds are expected over Austin and analysis of MODIS data showed a mean cloud thickness of 429 m with a standard deviation of 15.0 m. Thus, the most thin clouds analyzed in the case study occurred over Brownsville while the most thick clouds were over Austin - consistent with surface observations. The cloud thickness over Corpus Christi was larger than found in the ground truth but in general agreement with the expected error predicted by sensitivity analyses.

4.0 ASSUMPTIONS AND LIMITATIONS

4.1 ASSUMPTIONS

Assumptions made in the retrieval of Cloud Base Heights are as follows:

Accurate cloud ancillary data will be provided as input fields to the Cloud Base Height algorithms. Most critical are cloud top height, cloud effective particle size, and cloud optical depth. Cloud top phase is also needed to select the water or ice algorithm. Cloud top heights are referenced against mean sea level.

Sufficient research observations have been made to characterize cloud optical properties (e.g., LWC and IWC), and these values are relatively constant over global conditions.

Multiple cloud-layers will be differentiated from single cloud-layers in the VIIRS HSR by the Cloud Cover Layers IP.

4.2 LIMITATIONS

Limitations to the retrieval of Cloud Base Heights are as follows:

The accuracy of the Cloud Base Height is directly proportional to the accuracy of cloud top height. For example, if the cloud top height is in error by 1 km, the retrieved Cloud Base Height will be in error by at least 1 km. The current predicted performance cloud top height is 0.65 km for ice clouds and 0.35 km for water clouds.

An effective or mean cloud top height is retrieved for ice clouds while more of a physical cloud top is retrieved for water clouds. Depending upon the complexity of the scene, single versus multiple cloud layers within each HSR, and the optical thickness of the cirrus clouds, the actual error in cloud top heights will vary. Thus, the error in Cloud Base Heights will be worse for ice clouds than for water clouds.

Based upon the predicted performance of the cloud top height EDR, the Cloud Base Height requirement should vary as a function of cloud top phase and optical depth. . However, the System Specification does not allocate a larger error for optically thin clouds as compared to optically thick clouds as is done for other cloud EDRs including cloud top temperature, cloud top height, and cloud top pressure.

The accuracy of retrieved Cloud Base Heights will be degraded under the following conditions, which directly affect the retrieval of cloud optical thickness and cloud effective particle size: (a) the presence of multiple-layered cloud systems, (b) the absence of solar illumination, and (c) highly reflective surfaces (e.g., snow or sparsely vegetated conditions, especially in cirrus cloudy atmospheres).

The retrieval of Cloud Base Heights will suffer in highly variable surfaces (e.g., mountainous terrain), where an average value retrieved for a VIIRS pixel may not be representative of the worst condition.

The accuracy of Cloud Base Heights may be limited by the lack of global *in situ* observations of cloud liquid water content and ice water content. Values from research reported in the literature vary by factors of 2 or 3, and there is no process for taking routine observations from surface meteorological locations, aircraft, or active remote sensing facilities.

4.3 CONCLUSIONS

The results from these investigations suggest that useful Cloud Base Heights can be retrieved exclusively from remotely sensed, meteorological satellite data. This conclusion is based upon the preceding discussions in this ATBD and recently reported information in the refereed literature on the retrieval of cloud base heights (Wiheit and Hutchison, 2000).

- Accurate cloud top height is the "driver" for accurate retrieval of Cloud Base Height. Errors in cloud top height consume most of the error budget with predicted performance of 1.0 and 0.5 for optically-thin and optically-thick clouds. Errors in cloud optical properties and liquid/ice water content contributing an additional 100m and 200m meters respectively. Analyses of MODIS data suggest errors in cloud optical properties may approach twice those predicted by sensitivity studies. However, even these errors should permit cloud base height retrievals to remain within predicted performance of 1.4 and 0.8 km.

- Accurate cloud top phase analyses are essential for performance of the Cloud Base Height EDR. However, errors associated with cloud phase are not included in the error budget. Cloud phase is essential for selection size distribution parameters (i.e., LWC versus IWC and effective particle size, r_e versus De). The difference in water concentrations and particle sizes between water clouds and ice clouds is large. Thus, it is critical that information on cloud top phase be provided.

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APPENDIX A: GLOSSARY OF TERMS

Ancillary Data	Any data that are not produced by the NPOESS System, but which NPOESS EDR algorithms require to meet the EDR attributes (e.g., terrain height data base or conventional surface and upper air observations).
Cloud	An aggregate of minute, nonprecipitating water and/or ice particles in the atmosphere above the Earth's surface. “Cloud” is always to be interpreted to mean “detectable cloud” as defined in this glossary.
Cloud Cover	The fraction of a given area that is overlaid in the local normal direction by clouds. It is the fraction of the Earth's horizontal surface that is masked by the vertical projection of clouds.
Cloud Type	The classification of clouds into the 18 types given in Tables 3-19 and 3-20 of the Federal Meteorological Handbook FMH-1B.
Detectable Cloud	An aqueous aerosol having a vertical extinction optical depth exceeding 0.03 (*TBR*) in the visible or a contrast with the background exceeding 0.02 (*TBR*) in the visible. Contrast with the background is defined as the difference between the cloud and adjacent background radiance divided by the sum of these two radiances. “Cloud” is always to be interpreted to mean “detectable cloud.”
Drop Size Distribution	The number of aerosol, cloud, or rain droplets per specified size interval per unit volume over a specified range of sizes.
Environmental Data	Environmental data (also termed “mission data”) refers to all data, atmospheric, oceanographic, terrestrial, space environmental, and climatic, being sensed and collected by the satellite or derived, at least in part, from these measurements.
Environmental Data Records (EDRs)	Data records that contain the environmental parameters or imagery required to be generated as user products as well as any ancillary data required to identify or interpret these parameters or images. EDRs are generally produced by applying an appropriate set of algorithms to Raw Data Records (RDRs).

Horizontal Cell Size	For a parameter that is an estimate of the uniform spatial average of an environmental parameter over a square region of the Earth's surface or within a square layer of the atmosphere, the side length of this square region or layer. (For a parameter that is an estimate of an environmental parameter at a point, the horizontal cell size is defined to be zero.) For a reported parameter not of this type but defined for a square region of the Earth's surface or a square layer of the atmosphere (e.g., cloud cover, ice concentration), the side length of this square region.
Horizontal Reporting Interval	The spacing between nearest neighbor points in the horizontal direction at which an environmental parameter is estimated and reported. For atmospheric profiles the horizontal reporting interval applies to the lowest altitude samples.
Imagery	Two-dimensional array of numbers in digital format that represent the brightness of a small elemental area.
Key Attribute	An EDR attribute that is a key parameter of the system. See Key Parameter.
Key EDR	An EDR that has a key attribute. See Key Attribute.
Key Sensor	A sensor that is required to meet key parameter requirements.
Key Parameter	A parameter so significant that failure to meet the threshold requirement(s) pertaining to its measurement is cause for the System to be reevaluated or the program to be reassessed or terminated. Key parameters include key attributes of key EDRs and the data access requirement. Key parameter requirements are to be included in the Acquisition Program Baseline.
Measurement Accuracy	The magnitude of the difference between the mean estimated value of a parameter and its true value (see definition). This estimate may be the result of a direct measurement, an indirect measurement, or an algorithmic derivation. The mean is based on a set of estimates satisfying the following two conditions. The set is large enough so that the sample size error (see definition) in the measurement accuracy is much smaller than the specified measurement accuracy value. The true value of the parameter is the same for all estimates in the set.

Measurement Accuracy (continued)

The second condition is imposed because a measurement accuracy requirement must be met for any true value of the parameter within the measurement range (see definition), not in an average sense over the measurement range. In practice, such as in the analysis of simulation results or measured calibration/validation data, it is understood that measurements will be binned into sets for which the true value of the parameters falls into a narrow range, preferably a range much smaller than the required measurement range.

For an ensemble of N estimates of the parameter x, the measurement accuracy b_N is given by the following formula:

$$b_N = |m_N - x_T|$$

where m_N is the sample mean, x_T is the true value of the parameter, and |…| denotes absolute value. The sample mean m_N is given by the following formula:

$$m_N = (S_{i=1,N}\ x_i)/N$$

where x_i is the value obtained in the i'th estimate of the parameter x and $S_{i=1,N}$ denotes summation from i = 1 to i = N.

Measurement Error

The difference between the estimated value of a parameter and its true value. This estimate may be the result of a direct measurement, an indirect measurement, or an algorithmic derivation.

The measurement error ε is given by:

$$\varepsilon = x_E - x_T$$

where x_E is the estimate of the parameter x and x_T is its true value (see definition).

Measurement Precision

The standard deviation (one sigma) of an estimated parameter. This estimate may be the result of a direct measurement, an indirect measurement, or an algorithmic derivation. The standard deviation is based on a set of estimates satisfying the following two conditions:

The set is large enough so that the sample size error (see definition) in the measurement precision is much smaller than the specified measurement precision value.

Measurement Precision (continued)

The true value of the parameter is the same for all estimates in the set.

The second condition is imposed because a measurement precision requirement must be met for any true value of the parameter within the measurement range (see definition), not in an average sense over the measurement range. In practice, such as in the analysis of simulation results or measured calibration/validation data, it is understood that measurements will be binned into sets for which the true value of the parameters falls into a narrow range, preferably a range much smaller than the required measurement range.

For an ensemble of N estimates of the parameter x, the measurement precision s_N is given by the following formula:

$$s_N = [S_{i=1,N} (x_i - m_N)^2/(N - 1)]^{1/2}$$

where m_N is the sample mean (defined in the definition of measurement accuracy), x_i is the value obtained in the i'th estimate of the parameter x, and $S_{i=1,N}$ denotes summation from i = 1 to i = N.

Measurement Range

Range of values over which a parameter is to be estimated while meeting all other measurement requirements. This estimate may be the result of a direct measurement, an indirect measurement, or an algorithmic derivation.

Measurement Sample Size Error

The standard deviation of the finite sample mean (square root of the variance) over the infinite universal ensemble of possible measurements. The sample size error must be much smaller than the required value of accuracy for any simulation that purports to verify that the accuracy requirement is met.

Measurement Uncertainty

The root mean square (RMS) of the measurement errors (see definition) for an estimated parameter. This estimate may be the result of a direct measurement, an indirect measurement, or an algorithmic derivation. The measurement uncertainty is based on a set of estimates satisfying the following two conditions:

The set is large enough so that the sample size error (see definition) in the measurement uncertainty is much smaller than the specified measurement uncertainty value.

The true value of the parameter is the same for all estimates in the set.

Measurement Uncertainty (continued)

The second condition is imposed because a measurement uncertainty requirement must be met for any true value of the parameter within the measurement range (see definition), not in an average sense over the measurement range. In practice, such as in the analysis of simulation results or measured calibration/validation data, it is understood that measurements will be binned into sets for which the true value of the parameters falls into a narrow range, preferably a range much smaller than the required measurement range.

As defined herein, measurement uncertainty is due to the combined effects of all systematic and random errors. Also, as a consequence of its definition, measurement uncertainty converges to the square root of the sum of the squares (RSS) of the measurement accuracy and precision in the limit of infinitely large sets of measurements.

For an ensemble of N estimates of a parameter x, the measurement uncertainty ξ_N is given by the following formula:

$$\xi_N = [S_{i=1,N} (x_i - x_T)^2/N]^{1/2}$$

where x_i is the value obtained in the i'th estimate of the parameter, x_T is the true value of the parameter, and $S_{i=1,N}$ denotes summation from i = 1 to i = N.

Objective

A requirement that is significantly more difficult to meet than the threshold requirement but which, if met, would greatly enhance the utility of the data to the users.

Particle Size Parameter

The Angstrom wavelength exponent, alpha, defined as—

a = -Δln (tau)/ Δln (lambda)

Where tau is optical thickness and lambda is wavelength, ln denotes natural logarithm, and Δ denotes the difference between optical thickness measurements at two different wavelengths.

Precipitable Water Content

The total amount of water and ice contained in a vertical column of the atmosphere.

Sample Size Error	The standard deviation of a function of a finite set of estimates of a parameter. These estimates may be the result of direct measurement, indirect measurement, or algorithmic derivation. The standard deviation is based on the ensemble of all possible finite sets of estimates. Sample size error is a measure of the width of the probability distribution of a function of a finite set of estimates. If $\theta_N(x_1, x_2, \ldots, x_N)$ is a parameter depending on N estimates of a parameter x, i.e., $x_1, x_2, \ldots, x_N$, the sample size error is given by the following formula: $S_N = \langle (\theta_N(x_1, x_2, \ldots, x_N) - \langle\theta_N(x_1, x_2, \ldots, x_N)\rangle)^2\rangle^{1/2}$ where $\langle\ldots\rangle$ denotes the expectation value over the ensemble of all possible sets of N estimates of x. The measurement accuracy, precision, uncertainty, and short-term mean (see definition of long term stability) are all examples of functions of a finite set of estimates of a parameter.
Sensor	The mission-peculiar equipment or instrument to be manifested on a given space mission.
Sensor Data Records (SDR)	Full resolution sensor data that are time referenced, Earth-located (or orbit-located for in situ measurements), and calibrated by applying the ancillary information including radiometric and geometric calibration coefficients and georeferencing parameters such as platform ephemeris. These data are processed to sensor units (e.g., radar backscatter cross section, brightness temperature, radiance). Calibration, ephemeris, and any other ancillary data necessary to convert the sensor units back to sensor raw data (counts) are included.
Sensor Suite	One or more sensors needed to satisfy the EDR requirements allocated to a given Sensor Requirements Document (SRD). It does not include sensors from other SRD suites that provide secondary data contributions to those EDRs.
Threshold	The less stringent of the two requirements imposed on each measured or derived parameter. The more stringent requirement is the “objective.” (See definition above.) Failure to meet a threshold requirement for a non-key parameter renders the utility of the System questionable, at least to some segment of the user community. Failure to meet a threshold requirement for a key parameter is much more serious and places the entire program at risk. (See definition of “key parameter” above.)

Total Water Content	Total water content has two components: Total columnar cloud liquid water content (CLWC). Total columnar integrated water vapor (TIWV).
True Value	True value is defined in terms of ground truth generally accepted in the user community. When the output of the sensor is folded into atmospheric, radiative transfer and other models to produce EDRs, the measurement uncertainty of the EDR need not be traceable to an absolute reference standard e.g., those maintained by the National Institute of Standards and Technology. The proof of meeting the measurement accuracy, precision, uncertainty, and long-term stability requirements has to be accomplished by analysis, laboratory measurements, simulations, and comparisons to ground-based observations. The proof should include both sensor characteristics and the processing algorithms.
Visible/Infrared	Visible: 0.4 - 0.7 µm NIR: Near Infrared 0.7 - 1.5 µm SWIR: Short Wave Infrared 1.5 - 3 µm MWIR: Medium Wave Infrared 3 - 5 µm LWIR: Long Wave Infrared 5 - 50 µm