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The High Altitude Millimeter-wave Limb Sounder Sensor Concept

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The High Altitude Millimeter-wave Limb Sounder (HAMLS) is a proposed instrument designed to perform millimeter-wave limb sounding to measure CO, O_2, O_3, temperature, and line-of-sight winds. These measurements will advance understanding of the middle and upper atmosphere, including the effects of energetic particle precipitation on the upper atmosphere. HAMLS is designed to be mounted on a single three-axis stabilized spacecraft in a sun-synchronous orbit.

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THE HIGH ALTITUDE MILLIMETER-WAVE LIMB SOUNDER SENSOR CONCEPT

1. INTRODUCTION

The High Altitude Millimeter-wave Limb Sounder (HAMLS) is a proposed instrument that has been designed to perform millimeter-wave limb sounding to measure CO, O_2, O_3, temperature (T), and line-of-sight (LOS) winds. These measurements will advance understanding of the middle and upper atmosphere (~50-90 km), including the effects of energetic particle precipitation on the upper atmosphere. HAMLS is designed to be mounted on a single three-axis stabilized spacecraft in a 600 km, 12 AM- 12 PM, sun-synchronous orbit.

HAMLS spectrally resolves the O_2 magnetic dipole transition at 118.75 GHz (from which atmospheric T can be derived), both the J=1-0 and 2-1 CO lines at 115.27 and 230.54 GHz, and O_3 line at 235.71 GHz. These measurements are made by observing limb emission from 20 to 140 km. Doppler shifts of these lines are used to derive LOS winds. This design draws from NRL's Millimeter-wave Atmospheric Sounder (MAS) [1] and the NASA Millimeter-wave Limb Sounder (MLS) instruments, which successfully measured T profiles using 118-GHz O_2 spectral line measurements, CO profiles using the 230-GHz line, and LOS winds from observed Doppler shifts [2,3].

To provide the necessary radiometric measurements to retrieve CO, O_2, O_3, temperature (T), and line-of-sight (LOS) winds HAMLS has been designed to meet the sensor requirements listed in Table 1.

Table 1 - HAMLS functional requirements and predicted performance.

		HAMLS	
Observable	Attribute	Functional Requirement	Projected Performance
CO Emission	Center Frequency	230.538 GHz	230.53797 GHz
	Bandwidth	45 MHz	45 MHz
	Spectral Res	100 kHz	100 kHz
	Integration time	3 sec	1 sec
	NEDT (Sensitivity)	11.1 K	10.1 K
	Field of View	5 km	4.6 km
O_2 Emission	Center Frequency	118.750 GHz	118.75034 GHz
	Bandwidth	400 MHz	400 MHz
	Spectral Res	100 kHz	100 kHz
	Integration time	3 sec	1 sec
	NEDT (Sensitivity)	5.0 K	4.5 K
	Field of View	10 km	9.2 km
O_3 Emission	Center Frequency	235.710 GHz	235.70964 GHz
	Bandwidth	400 MHz	400 MHz
	Spectral Res	100 kHz	100 kHz
	Integration time	1.5 sec	1 sec
	NEDT (Sensitivity)	11.1 K	10.1 K
	Field of View	5 km	4.6 km

Manuscript approved January 29, 2020.

2. HAMLS INSTRUMENT DESIGN

HAMLS comprises four subsystems: 1) antenna and calibration; 2) RF and Intermediate Frequency (IF) receivers; 3) digital spectrometer system (DSS); and 4) command, telemetry, and data handling (CT&DH). Figure 1 shows a simplified block diagram. HAMLS uses two mm-wave front ends to receive, down-convert and amplify signals from four atmospheric emission lines. Following down-conversion to IF and amplification, the input signal is divided into four channels centered on each resonance. These are input to the digital spectrometer system (DSS), which applies an FFT to measure the spectral content around each line with a resolution as fine as 100 kHz. The HAMLS structure is shown in Figure 2.

2.1 Antenna and Calibration

HAMLS has a 1.0×0.75 m Cassegrain off-axis parabolic reflector antenna that reflects incident energy to a subreflector, which in turn focuses the beam into a diplexer. The diplexer separates the signal into orthogonal polarizations, which are then split between a low frequency (115.5-GHz) and a high frequency (231-GHz) feed horn. Each feed output connects to a mm-wave front-end receiver (MFER). The main reflector and subreflector are fabricated of carbon fiber-reinforced polymer with a vapor-deposited aluminum (VDA) coating, providing a highly reflective (low emissivity) surface at mm wavelengths, as demonstrated on DoD's Special Sensor Microwave Imager Sounder (SSMIS) and NASA's Global Precipitation Measurement Mission Microwave Imager (GMI).

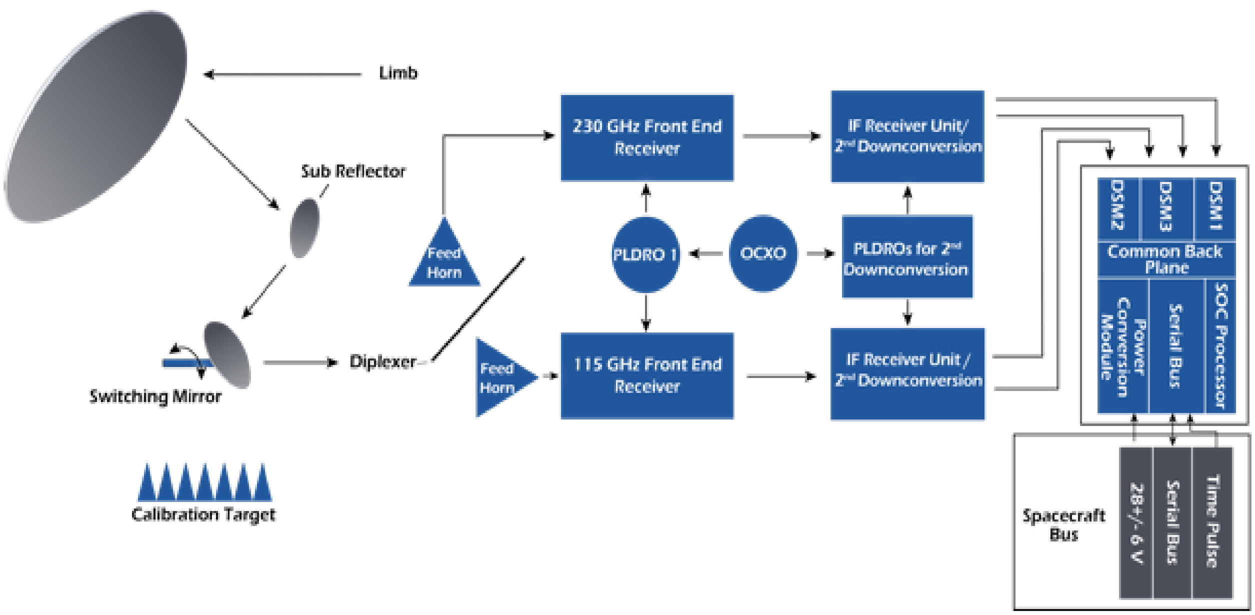

Figure 1: Conceptual design of the HAMLS instrument

HAMLS uses a 2-point calibration technique. Viewing deep space provides the low end or cold scene of approximately 3 K. A blackbody absorber target, or warm load, serves as the hot calibration point. The thermally stable target is packaged inside the HAMLS electronics housing, monitored by high-accuracy, high-precision platinum resistance thermometers (PRTs). The warm load is viewed by inserting a calibration plate between the diplexer and subreflector to redirect the feed antenna beams to the warm load. A mechanism moves the plate in and out of the feed beam once during every HAMLS scan cycle. Since the warm load is much larger than the feed beam, this mechanism does not require high-precision repeatability. This calibration concept is illustrated in Figure 1.

Limb radiance data are collected as the S/C scans the HAMLS FOV down through tangent altitudes from ~140-20 km. The S/C then slews upward ~4.0º to 200 km providing cold-sky-viewing for calibration. Warm-load calibration data are collected during the first part of the upward slew, to ~120 km. The calibration plate retracts, and the sensor collects cold-sky calibration data for the rest of the upward slew and start of the downward scan. The HAMLS scan cycle lasts 100 seconds.

2.2 Receivers

The two receiver chains share nearly identical architectures so we describe only the high-frequency chain (231 GHz). From the feed, the signal enters MFER-2, a double sideband downconversion receiver front end. A subharmonic mixer downconverts the RF signal and results in an IF signal from 0.40 to 4.5 GHz. The IF output from the mixer is then amplified with a low-noise IF amplifier and low-pass filter. This amplification establishes the noise figure of the receiver and removes higher frequency products from the mixer. MFER-1, centered at 115.5 GHz, operates the same.

The IF receiver unit applies additional gain and channelizes the signal into the bands of interest surrounding the spectral resonance lines. Two of the IF channels are below 500 MHz and two are above 3000 MHz. A second heterodyne stage downconverts the upper IF channels to below 1000 MHz to ensure that the IF signals are well within the analog-to-digital converter bandwidth.

2.3 Digital Spectrometer System

The DSS consists of three spectrometers. The O_2 and O_3 spectrometers combine narrow-band and wide-band digital sampling of the respective resonance lines. The narrow spectrometer samples the line with 100 kHz resolution over 40 MHz of bandwidth centered on the resonance line. The wide spectrometers have 1.0 MHz resolution over 400 MHz of bandwidth. The two CO lines share one spectrometer, and each line is sampled at 100 kHz resolution over 45 MHz bandwidth. Each spectrometer consists of an analog-to-digital converter (ADC) and related circuitry. Following digitization, the signals go through FFT algorithms in the FPGA fabric. The spectral resolution is maintained near the peaks of the resonance lines. Away from resonance peaks, multiple channels are averaged together to reduce the data rate. This averaging process will be carried out in the spectrometer and will use uploadable lookup tables to control data binning. Spectral averaging can be temporarily disabled for calibration and diagnostics.

2.4 Command, Telemetry, and Data Handling

The CT&DH system collects the data generated by the DSS and packages it for transmittal to the S/C via LVDS (low voltage data signaling). The CT&DH will also be responsible for turning receivers on/off, driving the calibration plate, and collecting HAMLS housekeeping telemetry. Power conversion units (PCUs) will also reside within the CT&DH assembly. The PCUs will use DC-DC converters to develop regulated power for the receivers, DSS, and the CT&DH itself from the spacecraft raw bus power.

Table 2. provides the estimated mass and power of the key subsystems and components.

Table 2 - HAMLS Subsystem and Component Estimated Mass and Power (with contingency)

HAMLS Subsystem/Component	Estimated Mass, kg	Estimated Power, W
Reflectors	11.4	
Feed	0.7	
Diplexer	6.82	
Cal Target/Cal Plate	5.72	3.1
115.5 GHz Front End Receiver	0.65	2.5
231.0 GHz Front End Receiver	0.65	2.5
IF Receiver Unit	5.58	6.3
Electronics Box	11.88	73.1
Reference Oscillator	0.65	7.5
Local Oscillators	2.15	22.5
Harness	15.50	
Thermal	9.88	
Structure	25.00	
Total Mass/Power	**96.5**	**117.5**

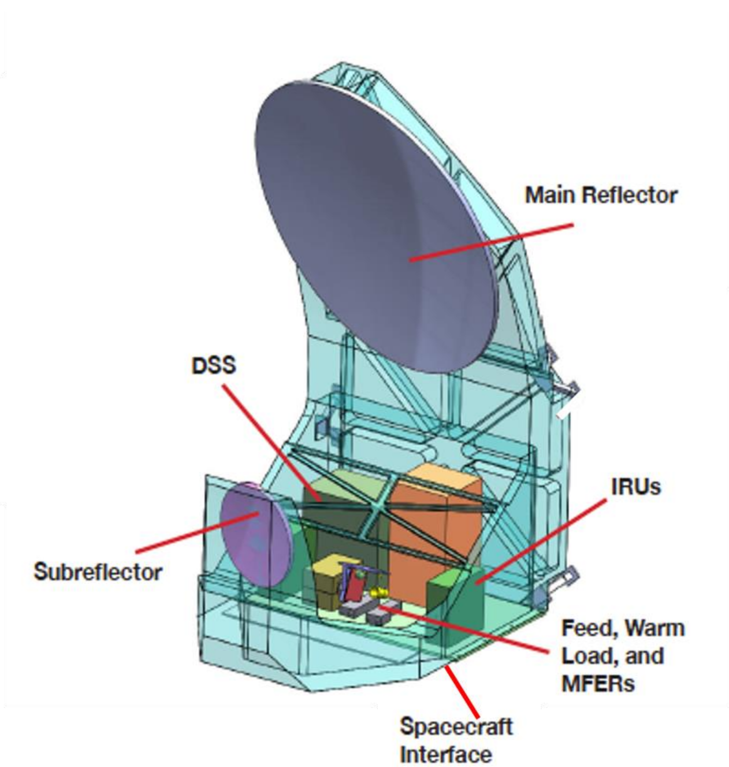

Figure 2: HAMLS model drawing

3. HAMLS PERFORMANCE CHARACTERISTICS

Table 3 summarizes HAMLS key performance parameters. Receivers rely on heritage from engineering models developed for the Microwave Imager Sounder (MIS), and millimeter wave receivers from other programs, and receivers available from multiple vendors. The maximum spectral resolution of 100 Khz and the very stable oscillator (drift of <100 ppb/year) are sufficient to resolve the Doppler core of observed spectral lines and allow measurements into the thermosphere. Section 7 discusses simulations showing that resolution and sensitivity meet requirements.

Vertical resolution is driven by reflector size and illumination, tangent altitude scan rate, and data sampling rate. The main reflector has a tangent altitude half-power beam width of 4.6 km at 231 GHz. The reflector is illuminated with a -20-dB edge taper to reduce spillover errors and improve main beam efficiency. Data sampling rate is 5 Hz, and this, coupled with the scan rate, gives a tangent altitude sampling of ~600 m which provides 5x oversampling for the final retrieval necessary to support the science mission. Vertical resolution requirements and performance are shown in Table 2.

Table 3. HAMLS Top-level Science-Driven Requirements and Performance Summary

	Units	Top-Level Requirement	Predicted Performance	Comments
115 NEDT (Sensitivity)	K	5.0	4.5	Includes Delta-G and backend noise; 1.0 sec integration time
230 NEDT (Sensitivity)	K	11.1	10.1	
Spectral Resolution	kHz	100.0	100.0	
115.5 LO Stability	kHz	12	11.50	
231.0 LO Stability	kHz	24	23.00	
Vertical Resolution – 115	km	10.0	9.2	20 km altitude
Vertical Resolution – 230	km	5.0	4.6	(worst case)

4. HAMLS ACCOMMODATION AND FUNCTIONAL CHARACTERISTICS

4.1 Mechanical

HAMLS requires a clear field of regard (FOR) defined by a 10º cone from the perimeter of the main reflector along the antenna boresight. HAMLS will mount to the S/C using a composite structure that also connects the main reflector and the subreflector. A kinematic mounting minimizes flexure between HAMLS and the S/C. HAMLS cannot view the Sun directly for an extended period.

4.2 Thermal

RF gain stability drives the receiver thermal requirements. Controlling the rate of temperature change to ~0.005˚C on timescales of the calibration period and limb scan within the operational range of 0 to 40ºC has been demonstrated on WindSat using passive control. The design uses self-heating of the electronics, intimate thermal contact of the electronics to a single baseplate, a thermal radiator plate, and MLI. Survival heaters maintain electronics within -30º to +45ºC. The warm calibration load will be passively heated by nearby electronics and protected from solar illumination. HAMLS will remain powered at all times to ensure thermal stability and therefore, RF gain stability.

Boresight pointing is maintained by a low-CTE carbon-fiber composite for the reflector structure and a near-zero thermal expansion carbon-fiber composite for the main instrument support structure. The back of the main reflector is insulated as necessary with MLI. The reflecting surface will be roughened to control worst-case focusing of solar energy.

4.3 Pointing and Stability

HAMLS requires absolute tangent altitude knowledge of better than 800 m, which equates to boresight pointing knowledge <1.0 arcmin. Each scan can be registered to 15 arcsec in elevation by using meteorological data Section 7. This allows HAMLS to register absolute tangent altitudes to ±200m each scan [4].

In the other axis HAMLS also requires absolute pointing knowledge of 1 arcmin so that LOS winds can be measured to <2 m/s. Relative (on orbit) variations of the HAMLS boresight with respect to the S/C star tracker result primarily from thermal distortions of the reflectors and supporting structure These thermal variations are on the order of the orbit time, and thus affect absolute knowledge during a science scan. The predicted total HAMLS absolute pointing error (HAMLS boresight plus S/C ACS) is 50 arcsec in the relevant time domain (worst-case). Quasi-static HAMLS boresight/star tracker offsets will be measured in orbit.

4.4 Operational Modes and Restrictions

HAMLS executes science scans continuously on both the nightside and the dayside of the orbit. HAMLS cannot view the Sun for an extended period of time, but the sun may pass through the FOR during slew maneuvers and limb scans.

4.5 Uplink and Downlink

Average downlink and uplink rates are estimated to be 86.4 kbps and <5kb/day.

The HAMLS instrument characteristics are summarized in Table 4.

Table 4 - HAMLS Instrument Characteristics

Parameter	HAMLS Characteristic
Mass MPV	96.5 kg
Power MPV	117.5 W
Peak Power CBE	96 W
Orbit Average Power CBE	96 W
Standby Power CBE	96 W
I/F Temperature	-30° C to +45° C
Detector Temperature	0° to +40° C
Data I/F	LVDS
CMD/TLM I/F Rate	51.6 kbps
Daily Data Volume	4.5 Gbits
Time Tag Accuracy	<1s abs; <10ms relative
FOV Alignment	0.15°
Pointing Knowledge	1 arcmin
Clear FOV	±10°
Volume	1m x 1.5m x 0.8m

5. HAMLS MATURITY AND HERITAGE

HAMLS subsystems and the HAMLS sensor itself are TRL-6 or higher. HAMLS leverages strong heritage from WindSat [5], CHEFSats 1 & 2, Robotic Servicing of Geosynchronous Satellites (RSGS), and technologies matured under the MIS program. The HAMLS development does not require any new technology developments.

5.1 Antenna

The HAMLS antenna architecture (folded cassegrain) has proven space heritage from the Millimeter-wave Atmospheric Sounder (MAS) mission. The main and subreflector are fabricated of graphite epoxy with heritage from WindSat and coated with vapor-deposited aluminum (VDA) using proven industry processes.

5.2 Receivers

The HAMLS receiver front-end design will leverage heritage from the MIS and GMI programs in order to take advantage of the latest technology developments in the selection of critical components such as low noise amplifiers and mixers. Vendor selection will be limited to vendors with mm-wave spaceflight heritage such as Quinstar and Millitech. Despite the heritage of the millimeter-wave front ends, engineering models will be built to further reduce implementation risk.

5.3 Digital Spectrometer System

The HAMLS Digital Spectrometer System (DSS) is a custom application based on flight-qualified System on a Chip (SoC) devices, analog/digital converters, and FFT algorithms. To maintain a low-risk profile, we will develop an engineering model DSS.

Other major elements of the HAMLS instrument use strong heritage and do not present significant development challenges. The HAMLS DSS and CT&DH systems rely on the Cubesat Space Processor (CSP) which was developed by the NSF Center for Space, High-performance, and Resilient Computing (SHREC) and licensed by Space Micro. The CSP has flown successfully on the Space Test Program Houston 5 (STP-H5), the Space Test Program Houston 6 (STP-H6), and NASA’s CeRE (Compact Radiation belt Explorer) cubesat. The HAMLS calibration mechanism is a custom application of flight-heritage mechanism (stepper motor) leveraging NRL's extensive (> 50 missions) experience with similar mechanisms.

6. DATA SUFFICIENCY

6.1 Vertical Resolution

Vertical resolution is driven by reflector size and illumination, tangent altitude scan rate, and data sampling rate. The main reflector has a tangent altitude half-power beam width of 4.6 km at 231 GHz. The reflector is illuminated with a -20-dB edge taper to reduce spillover errors and improve main beam efficiency. Data sampling rate is 5 Hz, and this, coupled with the scan rate, gives a tangent altitude sampling of ~600 m.

6.2 Resolution, Sensitivity, and LO Stability T

The maximum spectral resolution is 100 kHz, sufficient to resolve the Doppler core of observed spectral lines and allow measurements into the thermosphere. HAMLS uses an LO with a predicted stability of <100 ppb/year. LO drift is tracked as discussed in Section 7.3. Section 7.3 shows that resolution and sensitivity meet requirements.

7. SCIENCE MISSION PROFILE

The HAMLS instrument would be flown on a three-axis stabilized spacecraft in a 600-km sun-synchronous orbit. At 600 km, it has an orbit period of 96 minutes. The instruments acquire data continuously throughout each orbit. S/C attitude motion is used to obtain altitude profiles. During sampling in any mode, the S/C is inertially pointed while the instruments take data. Sampling duration depends on the mode and on angle of the boresite with respect to the orbit plane. A 7 arcsec attitude drift during inertially-fixed sampling results in a knowledge error of 100 m at the limb. Expected S/C pointing performance is 5.6 arcsec over a 45-s scan for science data collection.

Limb-scan profiles are obtained using S/C motion and inertial pointing. Once the appropriate altitude range is scanned, the S/C scans upward about 4.0º to a tangent altitude of 200 km. This altitude provides cold-sky-viewing for HAMLS. Internal calibration data is obtained by HAMLS on the upward part of each cycle. This cycle is repeated throughout the orbit except for occultation events.

For meridional LOS winds (meridional pointing), the S/C yaws on the dayside (descending) of each orbit. A yaw of 8-24º, relative to anti-ram, maintains the instrument LOS in the meridional direction from 90ºN to 46ºS latitude. Maneuvers are executed during the upward scan portion of each limb scan. Poleward of 46ºS, the yaw required for meridional pointing becomes too large. During the nightside (ascending) of the orbit, the situation is reversed, and meridional pointing can be achieved from 90ºS to 46ºN. Thus, purely meridional winds are obtained from pole to pole, and diurnal meridional winds are obtained from 46ºS to 46ºN.

On average, HAMLS profiles are obtained each 7º in latitude. Sampling requirements are met with a worst-case slew time of 100s.

The primary science data is acquired when the spacecraft is above 40 degrees latitude, in particular during the polar night. No attitude maintenance is required or performed in the primary science regions. Within the secondary science regions (lower than 40° latitude), attitude maintenance is performed as required to meet pointing requirements. The instrument pointing knowledge requirement of < 3°, required to reconstruct local pitch angle measurements, is met at all points during the orbit, including periods of eclipse.

8. HAMLS ALGORITHM & DATA PRODUCTS

The HAMLS algorithm employs a revised forward model developed for the Millimeter-wave Atmospheric Sounder (MAS) spacelab mission [114]. Line strengths, resonant frequencies, and lower state energies are obtained from the JPL catalog[115]. The algorithm uses Optimal Estimation as implemented for MAS and the NRL Polar O_3 and Aerosol Measurements (POAM II and III)[116]. The retrieval altitude grid is 2 km from 25-95 km.

8.1 HAMLS Altitude Registration

HAMLS altitude registration is accomplished by observing profiles of stratospheric O_2 radiance spectra, which vary rapidly with altitude. In conjunction with stratospheric T/P available from operational meteorological analyses, this altitude sensitivity can be used to reduce single-shift pointing uncertainty. This technique was employed successfully by MAS[114]. By simulating expected meteorological data error, a constant pointing or altitude shift can be retrieved to an accuracy of ~200 m each scan.

8.2 HAMLS Constituent Retrievals

The science analysis is fundamentally predicated on state-of-the-art modeling from the Whole Atmosphere Community Climate Model (WACCM). One full day of the WACCM fields for January 5th were simulated to estimate the precision and vertical resolution of the retrieval. Profiles for CO (collected from both 230 and 115 GHz resonance lines), O_3, and T are run through the forward model to calculate radiance, then those radiances are convolved with the antenna pattern, and simulated noise is added. Altitude knowledge error is assumed to be one arcmin (a random constant for each scan between ±800 m is added to the altitudes) and a sample-to-sample error between ±100 m in each bin. Retrievals proceed sequentially starting with T, which also calculates a pointing correction, followed by O_3 and CO using the retrieved T and pointing error.

Results are illustrated in Fig. 2a and b. Included is the error in the 230-GHz (primary) and 115-GHz CO retrievals. HAMLS precision requirements are stated as 3-day averages over specified spatial regions, which given the HAMLS sampling, encompass at minimum 12 T, 24 O_3, and 45 CO profiles per day (FO4). At most altitudes, these requirements are met even for single-profile retrievals. The only exceptions are the CO retrieval above 80 km and T in the 40-60-km region where, with a minimum of 45 CO and 12 T measurements in each space/time bin, precision requirements are easily met. HAMLS absolute accuracies are expected to be similar to those achieved with the EOS MLS sensor, which uses a similar measurement technique and the same spectral lines. These are: T: 2.5K[118], CO: 25-50%[103], and O_3: 5-10%[119]. All are within the accuracy requirements. Retrieval vertical resolution estimates meet requirements and are shown in Fig. 2c.

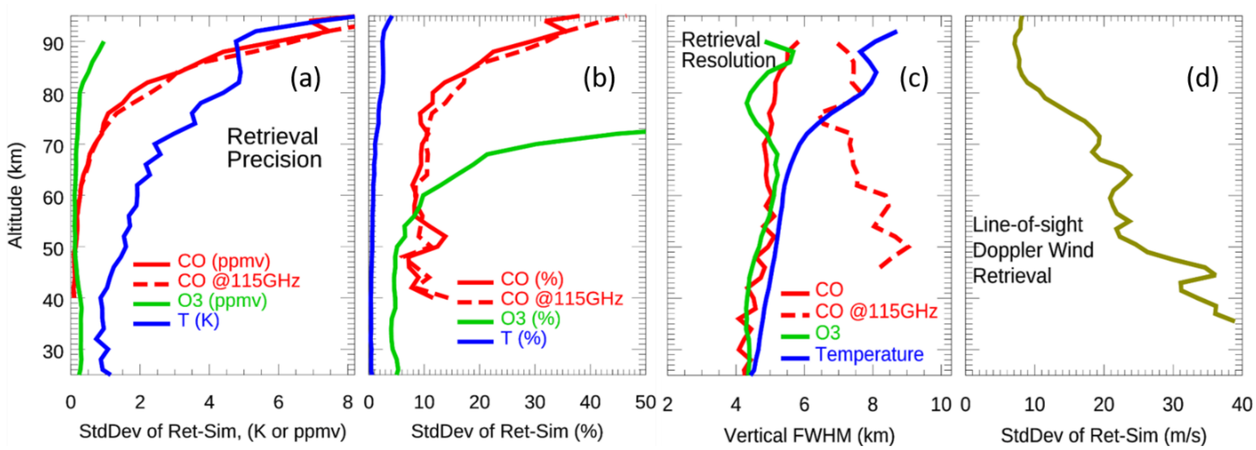

Figure 2. Standard deviation of the difference between the WACCM model profiles and simulated HAMLS retrievals in absolute (a) and % (b) units. (c). Simulated HAMLS vertical resolution. (d) Same as (a), but for LOS Doppler wind retrievals.

8.3 HAMLS LOS Wind Retrievals

We incorporate wind into the forward model by calculating atmospheric emission and transmittance using appropriate Doppler-shifted spectra. Winds are then retrieved simultaneously with the molecular species. We employ an algorithm similar to MLS[104], which estimates a single shift for each altitude bin assuming the radiance originates from that bin. The simulations use the same radiance noise, altitude uncertainty, and atmosphere as the species retrievals. Wind speed is derived from all of the spectra (O_2, O_3 and CO) simultaneously. The results are shown in Fig. 2d. In addition to random radiance errors, two other potentially important sources of error are uncertainties in the S/C velocity and HAMLS pointing. S/C velocity is known to 0.25 m/s and error from HAMLS pointing accuracy requirement of ≈1 arcmin produces a Doppler uncertainty (at the 24º max yaw angle) of ≈0.8 m/s. Both are small compared to radiance errors. Given the ~90 profiles in each temporal/spatial wind average, estimated wind precision is 2.1 m/s (60-100km), meeting the requirement.

The final important source of wind measurement error is LO frequency drift. The LO has a predicted drift of <12 kHz per year, which would result in a drift of 30m/s, but the error is mitigated because in the HAMLS LO scheme, the CO line appears on the lower sideband, and the O_2 and O_3 lines on the upper side band. The LO drift can be estimated from the systematic differences between the winds from these measurements. From weekly averages, we estimate that this error can be determined to ~0.3m/s. Combining the errors, we obtain a systematic uncertainty in the LOS winds of ~1.6m/s.

9. HAMLS HERITAGE

The HAMLS sensor development builds on NRL's 50 years of experience in developing radio frequency (RF) payloads for space. In particular, much of the HAMLS design can be derived from WindSat, which was designed, built, tested, and operated by NRL. It was launched in January 2003 and continues to operate successfully. Several of the components for HAMLS are based on work NRL did while developing the Microwave Imager Sounder (MIS) as an operational payload for the Defense Weather Satellite System (DWSS). MIS was designed to have channels covering 6.2 – 192.0 GHz. The MIS design was based on the highly successful WindSat design. Despite the cancellation of DWSS and MIS, matured technologies from that development are being leveraged for HAMLS. HAMLS components that are based on the WindSat design will also incorporate updates developed for MIS such as for parts obsolescence and reduction of power consumption. NRL also developed and flew the Millimeter-wave Atmospheric Sounder (MAS), which flew on multiple Space Shuttle missions. MAS operated at approximately 60, 183, and 205 GHz. Heritage for various elements of HAMLS is shown in Table 5.

9.1 Antenna and Calibration

Design Basis

The HAMLS antenna and calibration system has heritage in NRL's WindSat and MIS programs, as well as in numerous other space borne radiometer systems. The main reflector and subreflector are fabricated from carbon fiber-reinforced polymer (CFRP) with a vapor-deposited aluminum (VDA) coating. The reflector structural and RF design used by WindSat and MIS provides a sound basis for the HAMLS reflectors. The heritage reflectors used CFRP with a ribbed CFRP backing structure to provide the necessary strength to survive launch and maintain shape on-orbit yet remain lightweight. Quasi-optical polarization grid diplexers have heritage from ATMS, where they were used in both the Ka-/V-band and W-/G-band receive chains to separate and direct the different frequency bands to the appropriate feed horns. Corrugated horns have a long heritage, having been successfully used in many space radiometer missions such as SSM/I, SSMIS, AMSU, WindSat, MIS, GMI, and others. The calibration target uses the flight-proven pyramidal structure coated with a microwave-absorber epoxy. These targets have been successfully used in numerous space radiometer missions such as SSM/I, SSMIS, AMSU, WindSat, and MLS.

Difference from Design Basis

The HAMLS reflector is less than one quarter the size of the WindSat reflector. The smaller size makes it easier to achieve the surface tolerance and structural requirements. The feed will be newly designed based on proven antenna feed-horn designs and practices. The WindSat corrugated feeds were single frequency, but there is significant heritage for building multi-band horns. The HAMLS calibration target will be created using a scaled version of the WindSat calibration target.

Development Challenges

The two key performance requirements for the reflectors are RMS surface tolerance and the surface reflectivity. The surface tolerance affects antenna-beam efficiency, and the errors grow inversely with wavelength. HAMLS will require better than 1 mil RMS surface tolerance. WindSat required 3 mils and achieved 2 mils on a reflector more than twice as large as the HAMLS reflector. A survey of industry capability indicates that multiple vendors can achieve the surface tolerance required for HAMLS. The millimeter-wave emissivity of the reflector must be negligibly small to ensure that the HAMLS sensor is not measuring thermal energy emitted by the reflectors, which would result in calibration errors. The MIS program has developed a rigorous method to demonstrate a reflector-coating process that provides the necessary low-emissivity of up to 192 GHz and satisfies all thermal and space environment requirements. This method leveraged work done by other radiometer programs operating at millimeter wavelengths including NASA's GMI program and the DoD's SSMIS system. The reflector coating will also meet performance requirements for HAMLS. The relatively short wavelengths introduce manufacturing tolerance challenges in the building of the feeds. Exceeding the tolerances can degrade the cross polarization and other areas of feed performance. Required tolerances are achievable with available electroforming technology but require careful attention to detail.

9.2 Front-End Receiver

Design Basis

The Millimeter-wave Front End Receivers (MFERs) on HAMLS are derived from the MIS front ends but are tuned to different operating frequencies. The MIS front ends relied on heritage technologies from previous satellite and airborne programs, including NASA Global Precipitation Mission Microwave Imager (GMI). The MIS front ends were fully characterized through thermal vacuum testing at the engineering model (EM) level.

Difference from Design Basis

The MFERS will operate at 115 and 231 GHz, whereas the MIS designs from which they are derived operate at 89 and 183 GHz, respectively. The same diodes identified for MIS will work for the HAMLS application. Furthermore, the architecture of the MFER assembly will not change, but the matching circuitry, filtering, and planar waveguides will be tuned to the HAMLS frequencies.

Development Challenges

Manufacturing the receiver is the biggest challenge in developing the millimeter receiver. Robust designs exist, and existing parts that meet the performance requirements can be identified. However, the manufacturing process can result in lower performance than expected. The best way to mitigate this risk is to work closely with the MFER developer to establish achievable performance requirements, to verify processes, and to provide a sufficient schedule margin to address problems. All the MFER manufacturers under consideration have spaceflight experience and have fully developed qualification plans and procedures to assemble spaceflight hardware.

Stabilizing the frequency of the MFERs and IRUs (see below) is a second design challenge. This challenge will be overcome by the referenced ovenized crystal oscillator (OCXO). As explained in the body of the proposal, ground processing of the Doppler winds will enable us to derive the long-term frequency drift, assuming an OCXO stability on the order of 1.0e-7. This performance is standard within industry capabilities.

9.3 IF Receiver Unit

Design Basis

The HAMLS IF Receiver Units (IRUs) leverage the designs of the WindSat Receiver Electronics Units (REUs) and the MIS IRUs. For all three sensors, these units provide gain and filtering below 10 GHz. HAMLS components will be based on the WindSat/MIS designs, but will be tuned to the specific HAMLS frequencies. The packaging will be based on WindSat REU layout and packaging.

Difference from Design Basis

The HAMLS IRUs include a second downconversion stage that WindSat did not have. However, this downconversion occurs at microwave frequencies below 5 GHz and will use widely available oscillators and mixers.

Development Challenges

The HAMLS IRUs pose no significant development challenges, and no new technologies are required. Key performance issues of gain, linearity, and frequency stability are all within industry capability for the required components.

9.4 Digital Spectrometer System

Design Basis

The Digital Spectrometer System (DSS) is a custom application using flight-proven SoCs and FFT algorithms. NRL has extensive experience with SoC/FPGA technology from multiple programs.

Difference from Design Basis

The DSS itself will be newly designed and developed. The design will not require new technology development; only the application of the existing technologies is new.

Development Challenges

Based on the heritage of the elements in the DSS, its design does not present any significant challenges. Advancements in FPGA/SoC technology has minimized most, if not all, development challenges. A preliminary analysis indicates that less than 56% of any the device resources are needed to implement the HAMLS FFTs on the FPGA fabric of the SoC device on the currently baselined CSP board. As with other HAMLS subsystems, the DSS is a custom application of technologies and components with significant and relevant heritage.

9.5 HAMLS Command, Telemetry and Data Handling (CT&DH) Unit

Design Basis

The HAMLS Command, Telemetry and Data Handling (CT&DH) unit shares the flight-qualified CSP board with the DSS. The dual-core ARM Cortex-A9 processors in the SoC run the instrument flight software (FSW) while the residual SoC FPGA fabric receives commands, controls data acquisition, receives digitized radiometer and telemetry data, and packages and transfers data. Lastly, the unit contains power conversion modules, which will use flight-proven DC-DC converters.

Difference from Design Basis

The CT&DH unit compares to the numerous instrument and payload controllers that NRL has developed but contains fewer cards. The data rate requirements are not taxing. NRL has extensive heritage designing power systems and controlling mechanisms on orbit.

Development Challenges

Based on the heritage of the elements in the HAMLS CT&DH box, its design does not present any significant challenges. As with other HAMLS subsystems, the CT&DH unit is a custom application of technologies and components with significant and relevant heritage. Components of NRL's Reusable Embedded Software Packages (RESP) have already been implemented on the processing system of the CSP, and the establishment of these basic Command, Telemetry, and Data Handling (CT&DH) FSW applications will help jumpstart development on the CSP for HAMLS.

9.6 Mechanical System

Design Basis

The HAMLS mechanical system has heritage from previous NRL programs including WindSat and from Alliance Spacesystems, a leading manufacturer of composite spacecraft structures and reflectors with over 30 bus structures and more than 100 reflectors delivered. The composite reflectors are smaller versions of the WindSat reflector. The reflectors will be supported with a composite structure. NRL will also apply composite structure heritage and experience from the recently launched Upper Stage mission and other programs.

Difference from Design Basis

The HAMLS structure, including the reflectors, is smaller and simpler than the WindSat structure and those manufactured by Alliance. WindSat was a combination of composite and aluminum. Because of the lower CTE requirements levied by HAMLS, the majority of this structure will be low-CTE composite. The calibration plate mechanism is a new design for HAMLS but will not require new technology development as the new design will be a custom application of space-qualified mechanisms.

Development Challenges

NRL has extensive experience with composite structures, kinematic mounts, and mechanisms. Most of the electronics will be mounted on aluminum honeycomb panels to facilitate the thermal design. The CTE mismatch between graphite composite and aluminum will be addressed by connecting the two elements with flexures, with which NRL has extensive experience.

Table 5 - HAMLS Leverages High TRL Components from Successful Flight Programs

Major Component	Referenced Use	Modifications from Referenced Use	TRL – Justification
Reflectors	WindSat, GMI, MAS	Coating thickness customized for measurement frequencies; Reflector is smaller than WindSat, GMI	8 - Reflector designed and fabricated using standard industry processes; multiple vendors
Polarization Grid Diplexer	ATMS, MLS	Grid dimensions customized for measurement frequencies	8 - In use on operational platforms ATMS of NPP, JPSS; MLS
Corrugated Horn Feeds	WindSat, GMI, MIS	Dimensions customized for measurement frequencies and specific instrument design	8 - Used in nearly every satellite microwave and millimeter wave radiometer
Cal Target	WindSat, GMI, SSM/I, SSMIS	Size optimized for measurement frequencies	8 - Standard design and coatings; used on >10 satellite microwave and millimeter wave radiometers
115.5 GHz Front End	MIS	Frequency shift	7 - MIS engineering models fully characterized through thermal vacuum testing
230 GHz Front End	MIS	Frequency shift	7 - MIS engineering models fully characterized through thermal vacuum testing
IF Receiver Unit	WindSat, MIS	Frequency shift	8 - Standard design based on WindSat receivers. Using previously flown fliters, amplifiers and mixers.
Reference Oscillator	SPACEBUS 4000, SATCOM, HTV, HIMAWARI	None	8 - Flown on several operational satellites
Digital Spectrometer & CT&DH Box	ISEM (STP-H5), SSIVP (STP-H6), CeREs	High TRL hardware packaged for HAMLS application	8 - Flight-proven hybrid computing platform and ADCs
Primary Mechanical Structure	WindSat and others	Smaller and simpler than the WindSat and those spacecraft structures manufactured by Alliance	8 - Primary composite structure designed and fabricated using industry standard processes where strength-to-weight ratio, superior stiffness and dimensional stability are key requirements

10. SUMMARY

HAMLS is a proposed instrument that has been designed to perform millimeter-wave limb sounding to measure CO, O_2, O_3, temperature (T), and line-of-sight (LOS) winds. The design assumes deployment on a three-axis stabilized spacecraft in a noon-midnight sun-synchronous orbit at 600km altitude.

Simulations using the predicted sensor performance demonstrate that HAMLS can meet science requirements with margin. The HAMLS design leverages earlier limb sounding sensors such as MAS and MLS, plus proven technologies from multiple relevant space borne missions.

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