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NATIONAL ENVIRONMENTAL SATELLITE, DATA AND INFORMATION SERVICE
CENTER FOR SATELLITE APPLICATIONS AND RESEARCH
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SUBJECT: **Scientific Guidance for the Design of Hyperspectral Infrared Sensors Including**:

- Recommendation on the Prioritization of the Sensors Characteristics from a Global NWP perspective

- Recommendations on the Use of ShortWave (SW) and/or LongWave (LW) Bands for Temperature and Moisture Sounding and data assimilation

Background:

The JPSS satellites are planned for operational use through the end part of the 2030 decade including hyperspectral IR sounders with longwave, midwave, and shortwave bands for temperature and moisture sounding. In parallel, the SounderSat program is planning sounding missions that will carry microwave, infrared, and radio occultation sounding instruments. In addition, the NOAA Geostationary and Extended Orbits (GEO-XO) program is exploring the potential deployment of hyperspectral infrared sensors (imagers and sounders) and microwave sounders on geostationary platforms. With improvements in technology, smallsats and, possibly to a lesser extent, cubesats may be able to provide the global sounding information needed by the NOAA community with potential significant cost savings compared to current methodologies. As part of the technology trade studies, technology experts and sensor designers often ask questions on what parameters (or sensors characteristics) are the most important for the scientific performances and quality of the data. It is also necessary to understand the risks and benefits of longwave and shortwave IR bands (from a performance perspective) so decisions can be made regarding satellite platforms.

This memo is written in order to support the following efforts:

- October/November 2020 NASA's Instrument Design Lab (IDL) and NASA's Mission Design Lab (MDL) runs. These two exercises will generate Government-driven draft designs of the next generation of hyperspectral Infrared sensors that meet the input requirements, assess the maturity of technology, and provide cost estimates.
- SounderSat Hyperspectral IR sounder instrument design and assessment studies/activities through BAA studies and other Government internal activities.
- GEO-XO Hyperspectral IR sounder instrument design and assessment studies/activities through BAA studies and other Government internal activities.

These efforts are expected to benefit from guidance on what sensors characteristics are important when exploring the trade space of the sensor design parameters. The Systems performance Assessment Team (SAT) met to discuss these items and to set priorities for the factors that have the most impact on performances of infrared sounders. An additional meeting took place to discuss specifically the aspect of whether the use of the shortwave (SW) IR band could be an alternative to using the longwave (LW) IR band, along with the midwave (MW) IR band, from the global NWP and sounding inversion perspectives. This memo documents the findings of those core-SAT discussions. Due to the constantly evolving nature of the systems that use these satellite data (e.g., physical inversion, data assimilation systems, environmental models, etc.), this guidance is likely to remain valid only for the next three to five years or sooner if some new information came to light. Note also that some of the guidance below is purposefully slightly vague (i.e. not focused on a single-design recommendation), to provide engineers the flexibility to optimize the sensor's design, cost and technology choices.

<u>Findings and Recommendation# 1:</u> Sensors characteristics Impacting Performances, in order of priority

The following sensors' characteristics have the most impact on the temperature and moisture sounding capabilities and on the usefulness of the data for global NWP applications. These are listed in decreasing order of importance. There are more sensors characteristics than listed below that could have an impact on data. The ones below were chosen because of their significant known impact(s) on global NWP.

<u>High importance (in currently operational systems):</u>

- Infrared bands choice, spectral resolution, and spectral stability (with enough information content to measure atmospheric temperature/moisture, with appropriate vertical coverage/resolution and accuracy).
- Noise levels impacting the channels (with levels low enough to offer an appropriate signal-to-noise ratio to bring value to the data assimilation (DA) and physical retrieval (PR) systems).
- Spectral response function (knowledge of the SRF is essential to be able to model properly the measured radiances and therefore allowing their use in the DA and PR systems).
- Spatial resolution (with high enough resolution to allow the spatial resolving of phenomena features such as clouds, fronts, etc.)
- Bands spatial co-registration (to allow bands to be easily used simultaneously). Note: this is important for retrievals of soundings and is expected to have increased importance in the future NWP systems. Longwave and Midwave bands are usually required to be co-registered in both NWP and in physical retrievals. Currently data from Shortwave band is not fully exploited in operational NWP systems.

<u>Moderate importance (in currently operational systems):</u>

- Viewing geometry: whether the sensor is viewing the Earth in cross track or conical fashion
- Spatial sampling approach (ex.: FOVs organized in groups and/or contiguous or with gaps) which affects the ability of the instrument to capture info in cloudy-sky regimes. Examples: IASI 2x2 non contiguous, CrIS 3x3 contiguous cross-track.

- Ability to co-register with a Microwave sensor. This could add value in active regions with opaque clouds.
- Ability to co-register with high spatial resolution IR imager: could be useful in cloud clearing techniques and in providing cloud geophysical constraint information.

<u>Findings and Recommendation# 2:</u> Tiers of sensors characteristics to trade off, in order to achieve optimal performance/cost/technology maturity compromise (temperature and moisture sounding):

The table below shows tiers or ranges of important sensor characteristics. Because the problem is multi-dimensional, each design team interested in optimizing hyperspectral IR sensors may choose varying factors within the table for their own studies. Overall, the table could be useful for engineers and designers of satellites and sensors who need to know which factors are more important. The focus in the table below is on measuring tropospheric temperature and moisture, and the main driver for prioritization of these characteristics is global NWP. Tier 1 is an ideal capability if costs allow, Tier 2 is the target where the overall current capability is to be maintained, and Tier 3 is where aspects of the sensor may be degraded but would still provide some useful information. Ideally, choosing Tier 1 yields the best technical set of capabilities whereas Tier 3 is the least capable, but may allow significant cost savings or may allow for significantly higher TRL insturments.

Priority#	Factor impacting performances	**Tier 1:** Improved capability. This could be similar to existing CrIS conf.	**Tier 2:** Target capability	**Tier 3:** Acceptable capability
1	Selection of Channels for direct Sounding temperatures and spectral resolution	All bands below: LW band around 15µm MW band around 6.3µm SW band around 4.3µm $0.25cm^{-1}$ unapodized, 10 ppm spectral uncertainty	All bands below: LW band around 15µm MW band around 6.3µm SW band around 4.3µm $0.625cm^{-1}$ unapodized, 10 ppm spectral uncertainty	Either of the bands: LW band around 15µm SW band around 4.3µm $1.25cm^{-1}$ unapodized, 10 ppm spectral uncertainty
2	Channels for direct Moisture sounding and spectral resolution	MW around 6.3µm $0.25cm^{-1}$ unapodized, 10 ppm spectral uncertainty	MW around 6.3µm $0.625cm^{-1}$ unapodized, 10 ppm spectral uncertainty	MW around 6.3µm $1.25cm^{-1}$ unapodized, 10 ppm spectral uncertainty
3	Spatial coverage (daily)	Global (for polar orbits) Full Disk (for Geostationary)	Global (for polar orbits) Full Disk (for Geostationary)	Global (for polar orbits) Full Disk (for Geostationary)
4	Swath width and impact on orbital gap	No orbital gap at equatorial crossing	POES-type gap at equatorial crossing	Allow Increase (wrt POES-type) in gap at equatorial crossing
5	Satellite Altitude	Not directly relevant for performances listed here. Satellite altitude is usually a driving factor for the swath width and it is a question that gets asked by sensor/satellite design engineers.	Not directly relevant for performances listed here. Satellite altitude is usually a driving factor for the swath width and it is a question that gets asked by sensor/satellite design engineers.	Not directly relevant for performances listed here. Satellite altitude is usually a driving factor for the swath width and it is a question that gets asked by sensor/satellite design engineers.
6	Noise Level (NEDT) for Temperature	CrIS-type NEDT levels (CrIS_NEDT)	CrIS_NEDT x 1.5	CrIS_NEDT x 2

	sounding channels			
7	Noise level (NEDT) for moisture sounding channels	CrIS-type NEDT levels (CrIS_NEDT)	CrIS_NEDT x 1.5	CrIS_NEDT x 2
8	Spatial resolution	About 2 km at nadir (changing with angle)	About 10 km at nadir (changing with angle)	About 50 km at nadir (changing with angle)
9	Viewing geometry	Cross track	Cross track	Cross track
10	Continuity of channels (do channels need to be similar to CrIS's?)	Yes for similar channels	Yes for similar channels	Not necessarily
11	Spatial sampling	Contiguous footprints	Contiguous footprints	Non-contiguous footprints

Findings and Recommendation# 3: IR Bands Comparison and Selection

The findings from the SAT meetings are the following:

- As a general overview, the table below describes the longwave, midwave, and shortwave IR ranges and their uses, as well as provide the challenges facing us in the utilization of those bands (in global NWP and physical retrievals)

	Longwave	**Midwave**	**Shortwave**
Spectral Range	$650cm^{-1}$ to $1210cm^{-1}$ 15.5µm to 8.3µm	$1210cm^{-1}$ to $2100cm^{-1}$ 8.3µm to 5.0µm	$2100cm^{-1}$ to $2760cm^{-1}$ 5.0µm to 3.6µm
Main Uses	T(p), Cloud, T_{skin}, O_3(p), H_2O(total)	H_2O(p), T(p), Cloud	T(p), Cloud, T_{skin}, H_2O(total)
Minor Species/ Spectral Interference	CFCs, NH_3, VOCs	SO_2, *CH_4, N_2O, HNO_3, HDO*	CO, *N_2O, NonLTE, Solar, HDO*, CO_2, CH_4
Spectroscopic Uncertainties (Estimated)	Line Parameters/Mixing: 0.2-0.5K	Line Parameters/Mixing: 0.2-0.5K	Line Parameters/Mixing: 0.2-0.5K NonLTE Parameterizations up to ~1K

- The longwave/midwave bands (defined below) are useful for temperature and moisture soundings. These bands also are useful for the measurement of trace gases, including ozone.
- The shortwave/midwave bands (defined below) are capable of measuring the temperature and moisture profiles, however we have more issues using them due to solar contamination, the nonlocal thermodynamic equilibrium (NLTE) process, and sensitivities to the surface layer.
- For the reasons above, the operational NWP currently uses primarily longwave IR sounding channels; Shortwave IR data is not currently being assimilated into operational NWP models.
- While the shortwave channels are still experimental in NWP, they have been shown to have potential in replacing the LWIR bands for the T sounding. Additional (and independent) analysis is recommended to increase confidence in the use of SW bands for temperature sounding..

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- Numerical experiments were conducted to assess whether a shortwave-midwave solution can achieve a positive impact in medium range global NWP models and assess its value against the longwave-midwave solution. The project used NOAA's global FV3GFS model.
- An Observing System Experiment was run for that purpose that included baseline operational, longwave IR for control, and experiments for shortwave IR only and no IR sounder data assimilated. The results of the experiment showed that shortwave IR provides a positive impact to NWP systems, suggesting that with proper bias correction, QC, RT modeling, etc., the SW/MW band pair can present a viable alternative (to LW/MW pair) for temperature and moisture information in global NWP. The impact of the SW/MW was found to be of the same magnitude as the one obtained with the LW/MW. This conclusion is being independently assessed in other NWP centers.
- *Sub-recommendation#1 (for IDL run):* Given the findings above, and since the longwave-to-midwave option meets current NWP needs and there is no defined timeline of when shortwave channels may reach an operational status within the modeling community, the recommendation for the infrared IDL run is to seek a design that has longwave-to-midwave channels. Either with or without the SW band, the IDL run is considered as an independent Government exercise to assess sensor cost and technology feasibility.
- *Sub-Recommendation#2 (for Long-term):* Measurement of the longwave, midwave, and shortwave bands should be our long term objective in NOAA, given that this provides information beyond temperature and moisture that is important for many applications as well as continuity to present IR observations. This is what NESDIS should aim for as a post-JPSS solution. Note that this recommendation is meant in the context of a constellation of sensors and not necessarily as a requirement for each and every sensor or platform.
- *Sub-Recommendation#3:* If equal cost saving is achieved by dropping either one of the bands (and to allow NOAA to be able to leverage smallsat technology), then we recommend that the priority should be given to dropping the shortwave. Indeed, if longwave and midwave bands are selected and the shortwave is dropped, then this presents a low risk solution to NOAA since this is what is operationally assimilated now and presents more capability and information content than the SW-band alone can provide.
- *Sub-Recommendation#4:* If in the context of pathfinder missions (such as early stages of SounderSat, running in parallel to JPSS) and/or if substantial cost savings can be achieved by dropping the longwave band, thus allowing NOAA to afford other capabilities/sensors, we recommend that this option (of selecting shortwave/midwave bands pair) be considered as viable. The performance in this case will likely be 'riskier' (because of the lack of maturity in using SW in operational NWP) but will still be acceptable (only for temperature and moisture sounding) if appropriate effort is done to efficiently use this band (instrument noise, RT modeling, QC, etc) as shown by Garrett's R&D efforts on NWP systems (*E. Jones, C. Barnet, K. Garrett, K. Ide, Y. Ma, S. Boukabara, Assimilation of Hyperspectral Infrared Shortwave CrIS Observations in the NOAA Global Data Assimilation System, ITSC-22 conference, October 2019*)
- Note that this solution is already a viable one for physical temperature and moisture retrieval systems.

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