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SATELLITE MICROWAVE SOUNDING MEASUREMENTS IN WEATHER PREDICTION

A Report of The Virtual NOAA Workshop on Microwave Sounders

Washington D.C.
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US DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Environmental Satellite, Data, and Information Service

Edited by

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Abbreviations and acronyms

AMSU	Advanced Microwave Sounding Unit
ATMS	Advanced Technology Microwave Sounder
AWIPS	Advanced Weather Interactive Processing System
CMORPH	Climate Prediction Center's Morphing
DMSP	Defense Meteorological Satellite Program
ECMWF	European Centre for Medium-Range Weather Forecasts
EPS-SG	EUMETSAT Polar System-Second Generation
EFSOI	Ensemble Forecast Sensitivity Observation Impact
eTRaP	Ensemble Tropical Rainfall Potential
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FSOI	Forecast Sensitivity-based Observation Impact
GFS	Global Forecast System
GMAO	Global Modeling and Assimilation Office
GPS	Global Positioning System
GHz	Gigahertz
HISA	Hurricane Structure and Intensity
IPWG	International Precipitation Working Group
IR	Infrared
JMA	Japan Meteorological Agency
JPS	Joint Polar Satellite
JPSS	Joint Polar Environmental Satellite System
JTWC	Joint Typhoon Warning Center
MHS	Microwave Humidity Sounder
MIRS	Microwave Integrated Retrieval System
MIST	Moisture In-Flux Storm Tool
MW	Microwave
MWHS	MicroWave Humidity Sounder
MWS	Microwave Sounder
MWRI	MicroWave Radiation Imager
MRMS	Multi RADAR Multi Sensor
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NPP	National Polar-orbiting Partnership
NWP	Numerical Weather Prediction
PCT	Polarization Correct brightness Temperature
POES	Polar Orbiting Environmental Satellites
RF	Radio Frequency
RFI	Radio Frequency Interference
RO	Radio Occultation
SSMI/S	Special Sensor Microwave Imager/ Sounder (SSMIS)
TC	Tropical Cyclone
WIGOS	WMO Integrated Global Observation System
WMO	World Meteorological Organization

Executive Summary

Microwave (MW) sounders on polar orbiting satellites operated by NOAA and EUMETSAT have been the most impactful remote sensing observations in numerical weather prediction (NWP) models for the past two decades, and are expected to continue to be so in future. These measurements from NOAA and EUMETSAT operated satellites are the backbone of NWP. In July 2021, NOAA invited experts from several NWP centers around the world to a one-day virtual workshop to understand how the data are used, the impacts of MW soundings on weather prediction applications, and the outlook of these measurements to enable future mission planning.

The key message and recommendations from the expert panel are captured in this report:

1. MW soundings have the highest impact on NWP among various satellite data that are used in data assimilation.
2. NWP models rely on the current 3 orbit polar satellite constellation backbone with sensors providing data in the 23 GHz to 183 GHz frequencies, and this capability should be maintained and continued in future.
3. Future backbone MW sounders should have minimum capabilities that are similar to the current Advanced Technology Microwave Sounder or better.
4. New sensors should aim to achieve lower noise and striping than current sensors.
5. Frequencies in the 50-60 GHz frequencies have more information content than the 118 GHz channels for temperature sounding, and 118 GHz channels should not be considered as a replacement for lower frequency channels.
6. Measurements in frequencies at 23, 31, 50, 51, and 89 GHz are also used for surface sensing in clear conditions, QA/QC and Cloud clearing in DA, and precipitation.
7. The 183 GHz channels are important for humidity soundings.
8. MW sounders on older satellites that are operating beyond their mission life still provide impactful measurements and should be continued as long as technically possible.
9. MW sounders with fewer frequencies than the backbone that are being developed and flown on small satellites and cubesats hold promise and could complement the recommended 3 orbit polar backbone MW sensor configuration. But further studies are needed to define an ideal MW sounder constellation that includes the backbone and supplemental missions. These studies should not only include the selection of frequencies for augmentation, but different orbits as well.
10. The typical transition time to operationally incorporate new satellite measurements in to NWP models is about one to two years, and it is therefore imperative to plan for long mission life to minimize the frequent updates and associated efforts on the user side as well as to maximize the use of new missions.
11. Expanding commercial demand for Radio Frequency (RF) spectrum can degrade the ability to maintain and to improve NWP forecast capability. Both future backbone and supplemental MW sounder missions should incorporate technology to address radio frequency interference (RFI). Periodic real-world RFI surveys would provide highly valuable guidance.
12. A constellation architecture that combines diverse backbone and supplemental missions with differing launch dates and mission lifetimes needs a robust calibration strategy that recognizes inter-calibration, absolute calibration, and traceable calibration as intertwined. This will also help achieve NWP advances from future coupled models.

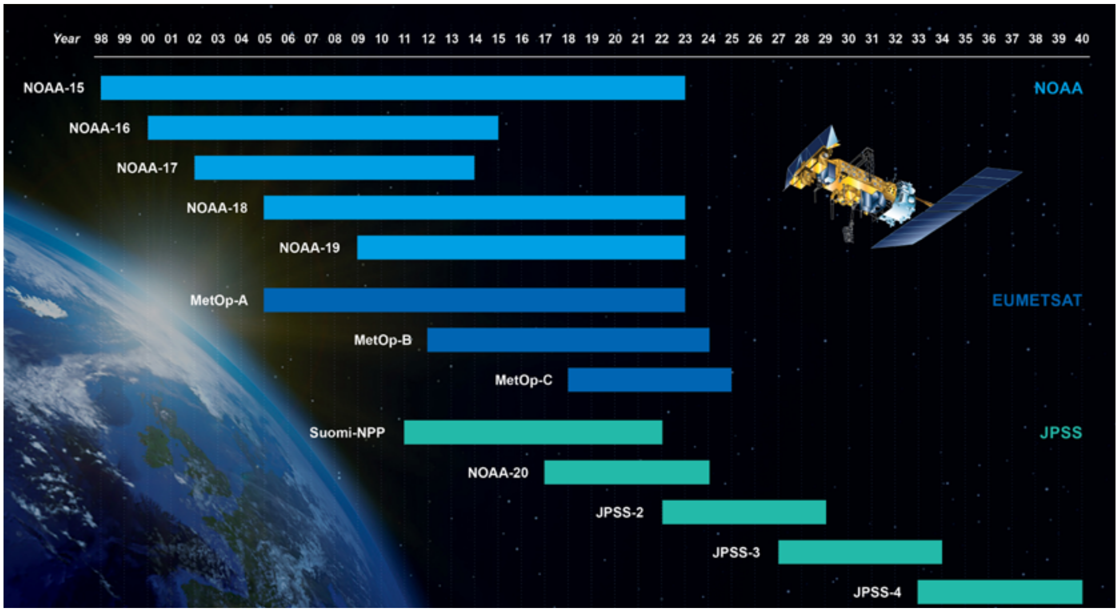
Introduction

Microwave (MW) sounders on Polar Orbiting Environmental Satellites (POES) provide critical measurements for Numerical Weather Prediction (NWP) models. Operational microwave sounder data currently ingested at NWP centers in the United States and around the world include data from NOAA's legacy POES satellites, the Joint Polar Environmental Satellite System (JPSS), and the Metop satellites operated by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT). The timeline of polar orbiting operational meteorological satellites that carry NOAA's MW sounders is shown in Figure 1. The legacy POES includes NOAA 15, 18 and 19 satellites that were originally launched in 1998, 2005 and 2009 respectively. These POES satellites have drifted from their original orbits, therefore improving significantly the temporal coverage (particularly at low and mid-latitudes), and are operating beyond their design life at the time of writing this report.

Through the next decade and beyond, both NOAA and EUMETSAT plan to launch and operate polar orbiting satellites with microwave sounders in the midafternoon and midmorning orbits respectively, to provide these critical measurements to NWP centers.

In parallel, NESDIS is exploring innovative technologies in microwave soundings for demonstration in the 2020s to augment and eventually potentially replenish the JPSS program of record. Over twenty years of data are available from a variety of microwave sounders on different orbits and missions. The experience gained in exploiting this extensive data record provides a unique opportunity for NOAA and other operational weather satellite operators to assess the impact, utility and criticality of these data when planning and designing future microwave sounders. To this end, the JPSS program office invited expert scientists from several NWP organizations around the world and held a workshop on July 28, 2021 to seek inputs and guidance in future mission planning. This report is a summary of the workshop.

Figure 1: NOAA has been flying advanced MW sounders since 1998 on polar satellites operated by NOAA and EUMETSAT



Background

Several NWP centers around the world operationally ingest data from the following sensors on NOAA and EUMETSAT missions:

- The Advanced Microwave Sounding Unit-A (AMSU-A) and the Advanced Microwave Sounding Unit-B (AMSU-B) on NOAA legacy POES satellites,
- AMSU-A and Microwave Humidity Sounder (MHS) on Metop satellites, and
- Advanced Technology Microwave Sounder (ATMS) on Suomi NPP and JPSS satellites

AMSU-A and MHS on the current Metop satellites will be replaced by a more advanced Microwave Sounder (MWS) on the second generation Metop satellites (EUMETSAT Polar System-Second Generation or EPS-SG satellites) that are scheduled to be launched by EUMETSAT in the first half of this decade to provide continuity in the mid-morning orbit under the Joint Polar Satellite (JPS) agreement between NOAA and EUMETSAT. These sensors collect measurements in the frequency range from 23-229 GHz of the electromagnetic spectrum, shown in Table 1.

The channel selection for the current NOAA and EUMETSAT sounders is based on the absorption features of oxygen in the 50- 60 GHz region used for temperature retrieval and water vapor in the 23 and 183 GHz region. Channels at 23.8, 31.4, 89, and 165.5 GHz are used for inferring cloud, hydrometeor, and surface parameters (Figure 2). In addition to the MW sounders on NOAA and EUMETSAT satellites, several NWP centers also assimilate data from MW imagers including the Special Sensor Microwave Imager/Sounder (SSMI/S) on the US Defense Meteorological Satellite Program (DMSP) and the Global Precipitation Measurement (GPM) Microwave Imager (GMI) instrument, a NASA mission.

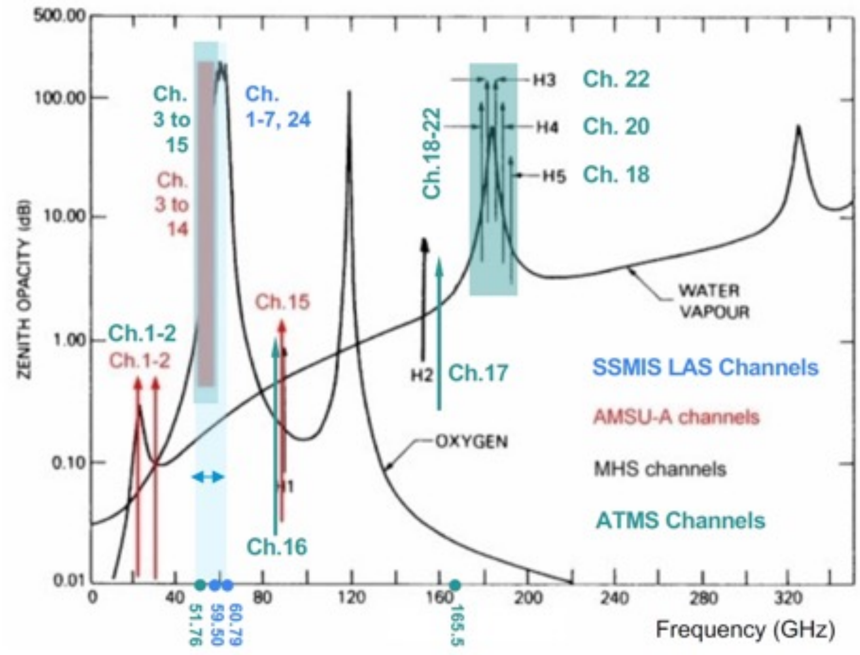


Figure 2: Channel center frequencies of Special Sensor Microwave Imager Lower Atmospheric Sounding Channels (SSMIS LAS), ATMS, AMSU-A and MHS sensors overlaid on the absorption spectra of oxygen and water vapor in the atmosphere.

Source: E. Liu

Table 1: Channel numbers and frequencies of Advanced Technology Microwave Sounder (ATMS), Advanced Microwave Sounding Unit (AMSU), Microwave Humidity Sounder (MHS) and Microwave Sounder (MWS).

Channel Number				*Frequency (GHz)*			
ATMS	**AMSU A+B**	**MHS**	**MWS**	**ATMS**	**AMSU A+B**	**MHS**	**MWS**
1	1		1	23.8	23.8		23.8
2	2		2	31.4	31.4		31.4
3	3		3	50.3	50.3		50.3
4				51.76			
5	4		4	52.8	52.8		52.8
			5				53.246 ± 0.08
6	5		6	53.596 ± 0.115	53.596 ± 0.115		53.596 ± 0.115
			7				53.948 ± 0.081
7	6		8	54.4	54.4		54.4
8	7		9	54.94	54.94		54.94
9	8		10	55.5	55.5		55.5
10	9		11	57.29	57.29		57.29
11	10		12	57.29 ± 0.217	57.29 ± 0.217		57.29 ± 0.217
12	11		13	57.29 ± 0.322 ± 0.048	57.29 ± 0.322 ± 0.048		57.29 ± 0.322 ± 0.048
13	12		14	57.29 ± 0.322 ± 0.022	57.29 ± 0.322 ± 0.022		57.29 ± 0.322 ± 0.022
14	13		15	57.29 ± 0.322 ± 0.010	57.29 ± 0.322 ± 0.010		57.29 ± 0.322 ± 0.010
15	14		16	57.29 ± 0.322 ± 0.0045	57.29 ± 0.322 ± 0.0045		57.29 ± 0.322 ± 0.0045
16	15		17	88.2	89		89
	16	1			89	89.0 ± 0.9	
17	17	2	18	165.5	150 ± 0.9	157	164-167
18	20		19	183.31 ± 7.0	183.31 ± 7.0		183.31 ± 7.0
19			20	183.31 ± 4.5			183.31 ± 4.5
20	19	4	21	183.31 ± 3.0	183.31 ± 3.0	183.31 ± 3.0	183.31 ± 3.0
21			22	183.31 ± 1.8			183.31 ± 1.8
22	18	3	23	183.31 ± 1.0	183.31 ± 1.0	183.31 ± 1.0	183.31 ± 1.0
		5				190.311	
			24				229

As seen in Figure 3, the discrete sounding channel frequencies for current and planned NOAA and EUMETSAT sensors have been selected to provide temperature and water vapor information in different layers of the atmosphere. The bell-shaped curves or weighting functions peak at different layers of the atmosphere where the contribution of the signal is most sensitive.

While the legacy NOAA 15, 18 and 19 POES satellites have drifted from their original launch orbits, the AMSU sensors on these satellites are still providing high quality measurements that are operationally ingested into NWP models. The mix of current operational polar satellites provide temporal coverage during different times of the day (Figure 4) which allows for frequent measurement of temperature and moisture profiles for operational meteorology.

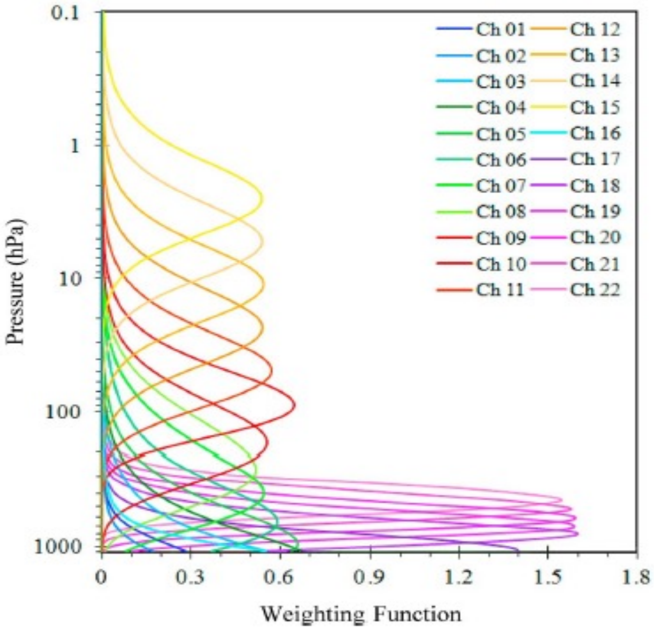


Figure 3: ATMS weighting functions.

Source: E. Liu

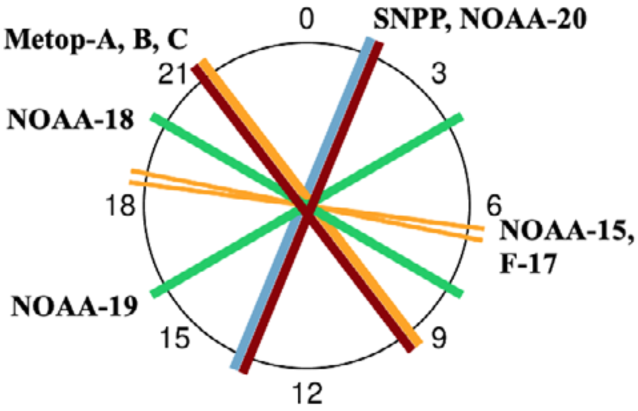


Figure 4: Equatorial crossing time of various polar orbiting satellites that are currently operational. The orbits continue to drift, and the equator times shown are valid for mid-2018.

Source: Bormann

Microwave Soundings in NWP Models

NWP systems process current weather observations from multiple sources to produce future forecasts. In recent decades, MW Sounding data has accounted for an increasing percentage of input observations, leading to measurable increases in forecast accuracy, and better long-term forecasts overall. Microwave sounding data are also used in reanalysis, produced at many centers to establish a consistent long-term record of the evolution of the atmosphere. For this workshop, multiple agencies were consulted regarding their use of MW sounding data in their NWP models, and their analysis of impacts for improved or reduced temporal and spectral coverage.

European Centre for Medium-Range Weather Forecasts (ECMWF)

ECMWF currently ingests microwave sounder data from all operational NOAA, EUMETSAT and DMSP polar satellites in their models, alongside Chinese Meteorological Administration MW sounders on the FY-3 (FengYun) series (Table 2). Most MW sounding data are used over all surface types. Window channels on sounding instruments are used to estimate surface emissivity or cloud-related uncertainty.

MW sounding data currently have the strongest impact among all satellite data (Bormann et al 2019). Forecast Sensitivity Observation Impact (FSOI) analysis of ECMWF models shows the growing impact of humidity-sensitive MW radiances, making it comparable in impact to temperature-sensitive MW radiances (Figure 5).

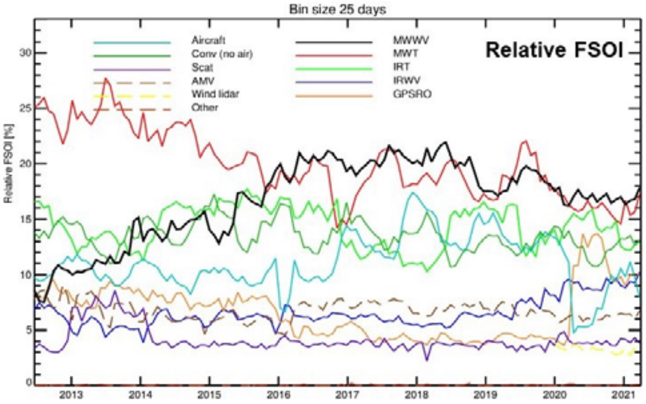


Figure 5: Growing impact of humidity-sensitive MW radiances.

Source: Bormann

Bands	**Instruments used**	**Usage**
Temperature-sounding *(52-57 GHz)*	6 AMSU-A; 2 ATMS	Clear channels only; AMSU-A to be moved to all-sky in Oct 2021
Temperature-sounding *(118 GHz)*	2 MWHS-2	All-sky
Humidity-sounding *(183 GHz)*	4 MHS; 2 ATMS; 2 MWHS-2; 2 SSMI/S; GMI	Mostly all-sky (except ATMS)
Window/imager channels *(19, 24, 37, 89/91, 150/166 GHz)*	1 SSMI/S; AMSR2; GMI; MWRI	All-sky

Table 2: Current use of passive MW instruments at ECMWF

In response to the workshop objectives, ECMWF scientists identified key characteristics of impactful MW Sounders. These features include:

- Channels in the 50-57 GHz, 183 GHz bands, combined with window channels. While 118 GHz has been discussed as a potential alternative to 50-57 GHz frequencies, it would be a good supplement, but not a replacement to the 50-57 GHz channels
- The three window channels at 23.8, 31.4, and 89 GHz on sounding instruments are used to estimate surface emissivity or cloud-related uncertainty.
- Good noise performance and calibration stability are needed to reduce biases and uncertainty in models.
- Good timeliness and contiguous spatial sampling are required to minimize temporal gaps and spatial gaps.
- Long lifetime – It typically takes 1-2 two years after a sensor is declared operational for the models to start assimilating the data, and it is therefore imperative to have a long lifetime to reap the investments.

ECMWF also pointed out the use of MW sounding data in reanalysis applications. Instrument requirements for reanalysis largely follow those for operational NWP, though with a particular emphasis on absolute calibration. Data monitoring suggests that absolute calibration has improved over time, with values of around ±1 K for newer instruments, and ECMWF advocate further improvements in this area for the backbone constellation.

The ECMWF assessment indicated that a 3-orbit backbone provides a critical reference system for global forecasting. (This is an expansion of the WMO Integrated Global Observation System (WIGOS) 2040 Vision, discussed later.) They envision utilizing supplemental orbits and instruments of varied capabilities. Along these lines, keeping functional instruments past their mission life has also proved beneficial, and they report continued benefit from adding MW sounders (Duncan et al 2021). In line with the WIGOS 2040 Vision, ECMWF scientists recommend two tiers of MW sounders. Tier 1 covers the 3-orbit baseline requirements for the backbone; Tier 2 covers the additional MW Sounder capabilities that would supplement the baseline. Tier 1 should have the following attributes:

Aspect	Requirement
Channel set	EPS-SG-MWS-like or better; RFI aware (ch4 of ATMS outside protected bands)
Noise performance	Better than ATMS performance (over comparable footprints) (ideally much better for T-sounding channels)
Stability	Within one orbit: << noise performance Over a few days: < noise performance
Absolute calibration	Better than 0.5 K
Lifetime	> 5 years
Horizontal resolution/ sampling	Comparable to ATMS/EPS-SG-MWS or better Contiguous/over-sampled

ECMWF is performing studies to flesh out an enhanced system utilizing SmallSats and CubeSats for Tier 2 missions that could augment the backbone. While enticing, there are some caveats and considerations when employing SmallSats, namely how to guarantee quality assurance of the products, and how to handle the challenge of shorter mission lifetimes. NWP users need to be engaged in the quality assessment for these missions to ensure data will be assimilated in a timely manner. International collaboration on these developments are also critical to design the right systems to advance the microwave soundings for NWP applications.

Met Office

MW sounder and imaging data from several NOAA satellites and those of other agencies (Table 3) have the highest overall impact on Met Office global NWP forecasts compared with other measurement types. The Met Office routinely monitors the effects of radiances at the sensor channel level so that observational uncertainties can be understood. Routine monitoring includes:

- Mean and standard deviation of observed-minus-forecast brightness temperatures, “O-Bs”:
  - For each channel, and
  - For each assimilation cycle

Table 3: Microwave sensors used in NWP at the Met Office

MW Sensor	Mission
AMSU-A	Metop-B,-C NOAA-15,-18,-19
MHS	Metop-B,-C NOAA-18,-19
ATMS	Suomi-NPP NOAA-20
SSMIS	DMSP-F17
AMSR-2	GCOM-W
GMI	GPM
MWHS-2	FY-3C,-3D
MWTS-2	FY-3D
MWRI	FY-3D

For tropospheric temperature sounding, a standard deviation of (O-B) is typically in the range of 0.1-0.2K, which includes both observation and forecast error (Figure 6). For tropospheric humidity sounding channels, the standard deviation of (O-B) is 0.8-1.5K (Figure 7).

Based on their analysis, Met Office scientists identified key components that would be important for future sounding missions. For temperature sounding requirements, low NEdT and calibration stability are crucial. Marking agreement with the ECMWF analysis, the 50-57 GHz channels are preferred over the 118 GHz. The 118 GHz frequency channels have lower vertical resolution, greater impacts of water vapor and cloud contamination, and hence smaller impact on forecast temperatures, compared with the 50-57 GHz channels. While a 50km horizontal spatial resolution is adequate for temperature sounding, similar to AMSU-A channel beam width, higher spatial resolution would be more useful for NWP quality control and for discriminating features with different structure and larger signals such as tropical cyclones. The 183GHz channel allows direct sounding of humidity. Retrievals of water vapor at this frequency also allow for indirect sounding of wind through tracer effect (i.e. tracking humidity and cloud/precipitation features over time).

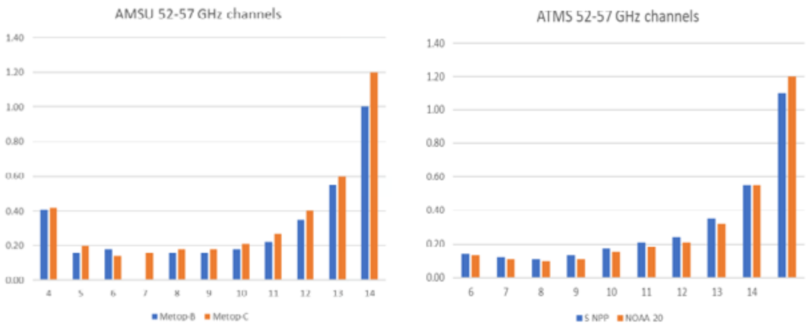


Figure 6: Met Office monitoring statistics for AMSU-A on Metop B and C satellites (left) and ATMS mapped to AMSU-A resolution (right) temperature sounding channels. Sensor channels are in the x-axis and standard deviations of observed- minus-forecast brightness temperatures (K) are on the y-axis. Data are averages for 2 weeks in June-July 2021.

Source: Eyre

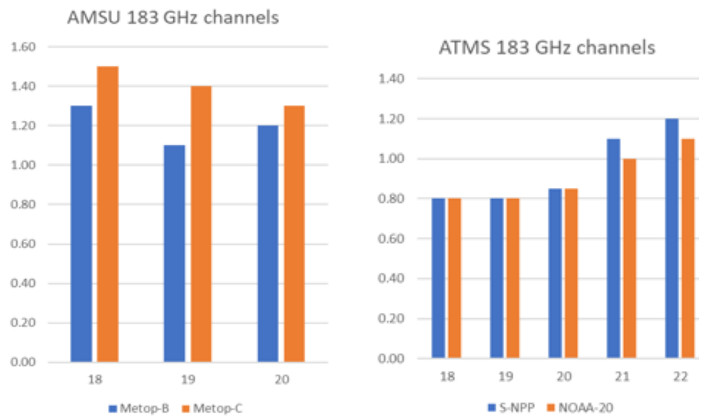


Figure 7: Met Office monitoring statistics for MHS at AMSU-A resolution on Metop-B and C (left) satellites and ATMS on SNPP and NOAA20 satellites (right) water vapor sounding channels at 183 GHz. Sensor channels are in the x-axis and standard deviations of observed- minus-forecast brightness temperatures (K) are on the y-axis. Data are averages for 2 weeks in June-July 2021.

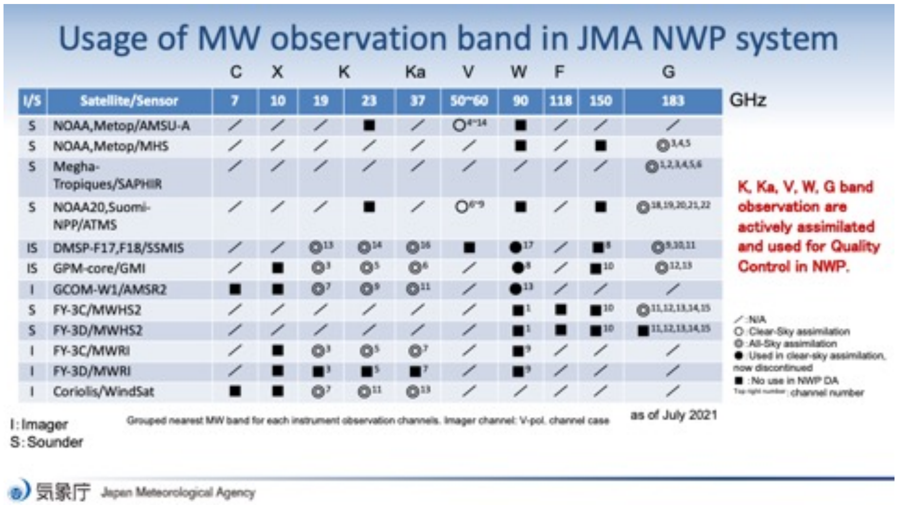
Source: Eyre

Regarding the NEdT, the low NEdT of 0.1-0.2K in the temperature channels is already marginal at 50 km spatial resolution. However, the calibration accuracy should be better than this, particularly around the orbit and over periods of 1-2 days. Also, the instrument specifications should consider 1/f striping noise. It is suggested that materials requirements may help keep the 1/f noise low, so that it may be managed rather than simply characterized.

Based on the impacts of the current constellation of polar satellites on NWP at the Met Office, it is emphasized that maintaining a backbone with ATMS-like performance is important, and keeping legacy satellites flying as long as they are contributing valuable observations.

Japan Meteorological Agency (JMA)

JMA assimilates satellite MW observations into their global, meso-scale, and local NWP models at 6- and 3-hour windows (Figure 8). In some cases, older data is not used. For example, data older than 2h20m is not used for global early analysis, while 50m is not used for meso-scale, and 30m for local. Delayed global analysis with a longer data-cutoff time are operated every 6 hours to produce more accurate first-guess field for the global early analysis. Cloud-screening channels are necessary for quality control and data assimilation of other frequencies. JMA uses AMSU-A channels 1-3 (23, 31, 50 GHz) and MHS Channels 1,2 (89, 157 GHz) to identify cloud and precipitation signals. JMA performed several data denial experiments and demonstrated that the loss of the 50-60 GHz temperature channels has the largest negative impact on the forecast scores (Figure 9).



Usage of MW observation band in JMA NWP system

		C	X	K		Ka	V	W	F		G
I/S	Satellite/Sensor	7	10	19	23	37	50~60	90	118	150	183 GHz
S	NOAA,Metop/AMSU-A	/	/	/	■	/	○$^{4\sim14}$	■	/	/	/
S	NOAA,Metop/MHS	/	/	/	/	/	/	■	/	■	◎^{3,4,5}
S	Megha-Tropiques/SAPHIR	/	/	/	/	/	/	/	/	/	◎^{1,2,3,4,5,6}
S	NOAA20,Suomi-NPP/ATMS	/	/	/	■	/	○$^{6\sim9}$	■	/	■	◎^{18,19,20,21,22}
IS	DMSP-F17,F18/SSMIS	/	/	◎^{13}	◎^{14}	◎^{16}	■	●^{17}	/	■^{8}	◎^{9,10,11}
IS	GPM-core/GMI	/	■	◎^{3}	◎^{5}	◎^{6}	/	●^{8}	/	■^{10}	◎^{12,13}
I	GCOM-W1/AMSR2	■	■	◎^{7}	◎^{9}	◎^{11}	/	●^{13}	/	/	/
S	FY-3C/MWHS2	/	/	/	/	/	/	■^{1}	■	■^{10}	◎^{11,12,13,14,15}
S	FY-3D/MWHS2	/	/	/	/	/	/	■^{1}	■	■^{10}	■^{11,12,13,14,15}
I	FY-3C/MWRI	/	■	◎^{3}	◎^{5}	◎^{7}	/	■^{9}	/	/	/
I	FY-3D/MWRI	/	■	■^{3}	■^{5}	■^{7}	/	■^{9}	/	/	/
I	Coriolis/WindSat	■	■	◎^{7}	◎^{11}	◎^{13}	/	/	/	/	/

I: Imager
S: Sounder

Grouped nearest MW band for each instrument observation channels. Imager channel: V-pol. channel case

as of July 2021

K, Ka, V, W, G band observation are actively assimilated and used for Quality Control in NWP.

/ :N/A
○ :Clear-Sky assimilation
◎ :All-Sky assimilation
● :Used in clear-sky assimilation, now discontinued
■ :No use in NWP DA
Top right number :channel number

気象庁 Japan Meteorological Agency

Figure 8: Microwave sensors and frequencies used by the Japanese Meteorological Agency in their NWP

Source: Kazumori

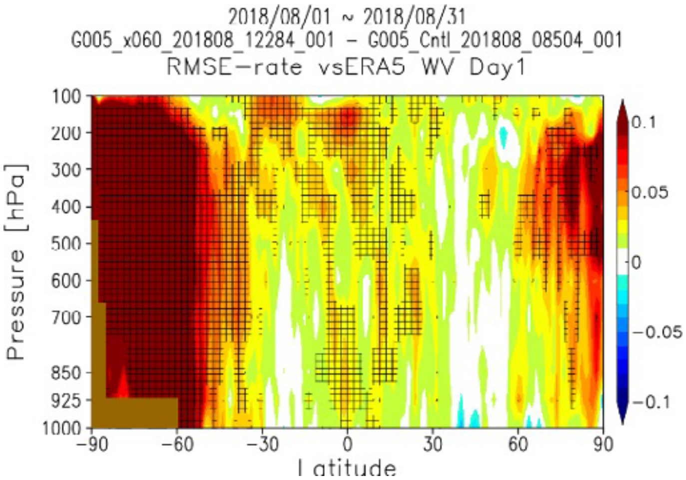


Figure 9: Results from data denial experiment of the 50-60 GHz frequencies from the JMA operational global NWP model for August 2018. Data are normalized change of RMSE of wind vector in Day 1 forecast compared to the reference ERA5 model output. Positive warmer values indicate degradation and cooler negative values indicate improvement.

Source: Kazumori

The water vapor sounding channel at 183 GHz on MW sounders and MW imager have large contributions to accuracy of water vapor prediction. These data are assimilated under all-sky conditions. Supplemental data from SmallSats are expected to contribute to rapid change in water vapor field associated with typhoon development. Multiple sensors help fill in temporal gaps at mid-latitude for meso-scale analysis, since analysis is run every 3-hours. Figure 10 shows the relative importance of Direct Broadcast data in meso-scale analyses. MW sounding data sets provide key information in NWP models at all scales, and are more impactful in global analysis where the delayed analysis allows inclusion of more data. However, higher latency of satellite sounding data results in less number of observations being assimilated into mesoscale and local models. Therefore, direct broadcast capability and/or fast data delivery function is expected for future satellite missions.

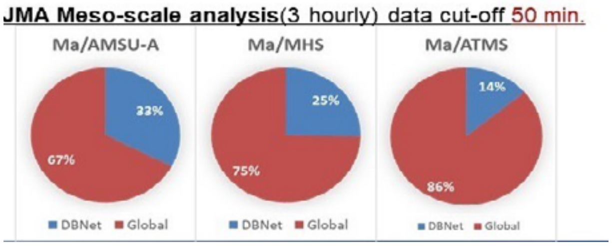


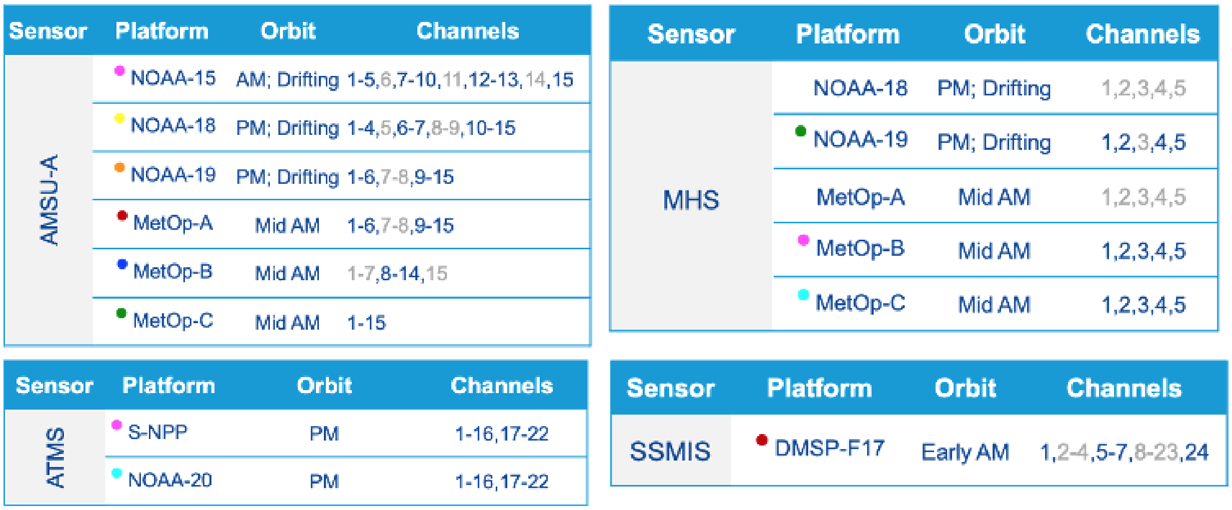
Figure 10: Relative importance of MW Sounder Global Data vs. Direct Broadcast Network for meso-scale analysis.

Source: Kazumori

NOAA NCEP

The NOAA National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) assimilates data from MW sensors across multiple platforms including AMSU, ATMS, MHS, and SSMI/S sensors (Figure 11). GFS assimilates all radiances that are below 200 GHz frequency within the 6 hour assimilation window. Measurements in frequencies above 200 GHz will improve detection of ice clouds, which is a limitation of current sounders that do not have frequencies above 200 GHz. AMSU-A and ATMS radiances are assimilated over clear and non-precipitating clouds only over oceans, and clear sky radiances only over land. MHS and SSMIS clear sky radiances only are assimilated over oceans and land. Observing System Experiments (OSE) conducted by NCEP demonstrated that adding MW sounders to baseline system that only assimilates conventional observations and Global Positioning System (GPS) Radio Occultation (RO) has a positive significant impact on forecasts. In GFS, the highest impact is from AMSU-A radiances followed by ATMS and MHS radiances. However, MHS has the largest impact per observation compared to AMSU-A and ATMS. NCEP performs Ensemble Forecast Sensitivity Observation Impact (FSOI) analysis for each channel and every sensor on 24 hr forecast error reduction; this information is used to help further tune the quality control and observational errors for each sensor. Figure 12 shows an example of FSOI assessment done by NCEP for all AMSU-A channels on Metop-B. This example (Figure 12) shows that all AMSU-A channels have positive impact on the forecast over majority of the locations. Comprehensive analysis on impacts of adding Suomi NPP and NOAA20 to the baseline, i.e. the impact with two satellites vs one satellite alone shows improvements on forecast scores even though both the satellites are in the same orbit. The impacts have been demonstrated across temperature, humidity, winds, and more. Additionally, infrared and MW sounders co-located with imagers (IASI with AVHRR, ATMS with VIIRS) can lead to better handling of cloud sub-grid heterogeneity and overlap in a field of view. The operational GFS has extended model layers from 64 to 127, raising model top from 55 km to 80 km. This upgrade provides much finer resolution in the troposphere and higher vertical resolution in background error. A hyperspectral MW sounder may provide better vertical resolution of temperature and moisture and could contribute to GFS's improved vertical range. GFS is ready to assimilate any new MW soundings that can provide better vertical resolution than current sensors.

NCEP recognizes the caveats for implementing new, short-lived data sources such as TEMPEST and TROPICS, and emphasizes the need for clear strategic planning to get this data into their models. New, passive bias correction capability may make it easier to assimilate new satellite data. While there is a lot of interest in exploiting data from potential MW Hyperspectral Sounders, comprehensive experiments have not been completed.



Sensor	Platform	Orbit	Channels
AMSU-A	● NOAA-15	AM; Drifting	1-5,6,7-10,11,12-13,14,15
	● NOAA-18	PM; Drifting	1-4,5,6-7,8-9,10-15
	● NOAA-19	PM; Drifting	1-6,7-8,9-15
	● MetOp-A	Mid AM	1-6,7-8,9-15
	● MetOp-B	Mid AM	1-7,8-14,15
	● MetOp-C	Mid AM	1-15

Sensor	Platform	Orbit	Channels
MHS	NOAA-18	PM; Drifting	1,2,3,4,5
	● NOAA-19	PM; Drifting	1,2,3,4,5
	MetOp-A	Mid AM	1,2,3,4,5
	● MetOp-B	Mid AM	1,2,3,4,5
	● MetOp-C	Mid AM	1,2,3,4,5

Sensor	Platform	Orbit	Channels
ATMS	● S-NPP	PM	1-16,17-22
	● NOAA-20	PM	1-16,17-22

Sensor	Platform	Orbit	Channels
SSMIS	● DMSP-F17	Early AM	1,2-4,5-7,8-23,24

Figure 11: Microwave radiances assimilated by NOAA/NCEP/GFS in the Global Forecasting System. The darker blue channel numbers are those that are being assimilated at the time of the workshop and the light grey channels are those that have degraded in performance and are no longer assimilated.

Source: E. Liu

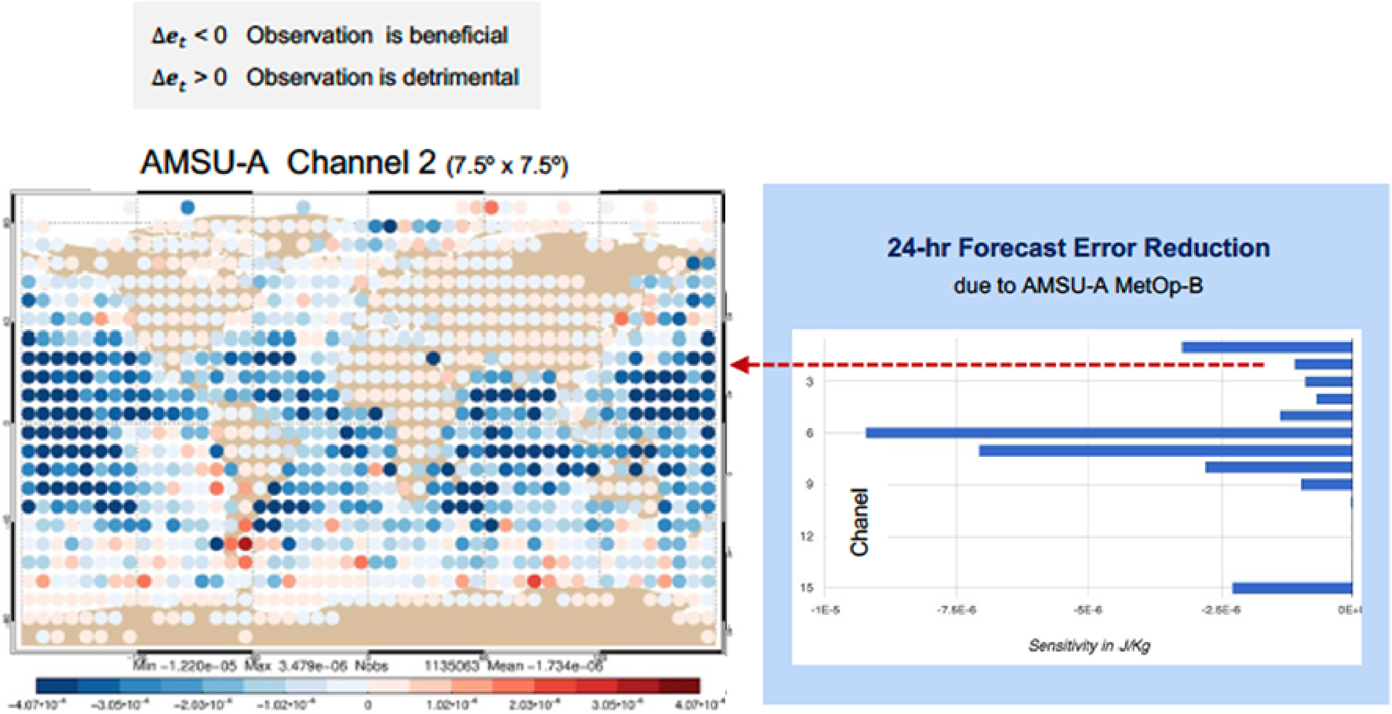


Figure 12: Impact of AMSU-A channels on NOAA/NCEP/GFS forecasts and EFSOI for each channel.

Source: E. Liu

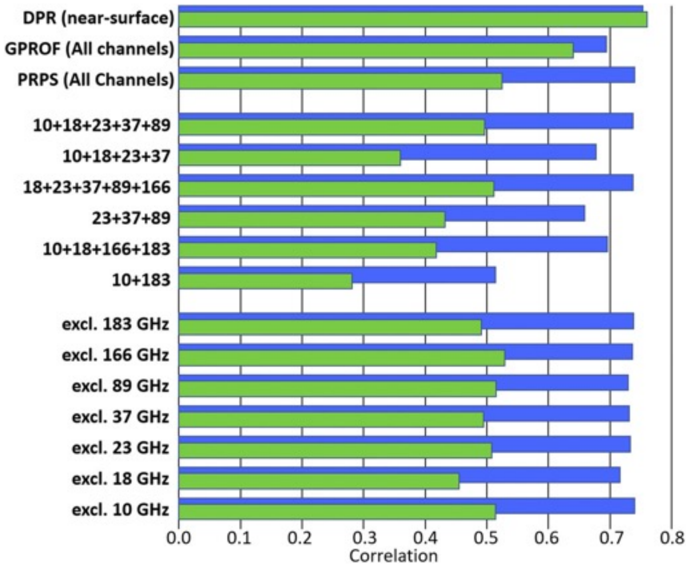
Microwave Soundings in non-NWP Applications

International Precipitation Working Group (IPWG)

Members of the IPWG performed a comprehensive analysis of the channels used for precipitation remote sensing ranging from 10 GHz to >200GHz and provided insights into how microwave frequencies are used for precipitation remote sensing. Due to high temporal and spatial variability of precipitation frequent sampling is critical. Increasing spatial resolution necessitates increased temporal sampling. Global precipitation estimates are based on algorithms that blend measurements from several microwave imagers, sounders as well as infrared imagers on geostationary satellites to produce higher level 3 global products. Measurements in the following frequencies are important in precipitation models: 10 GHz, 18 GHz, 23 GHz, 37 GHz, 89 GHz, 166 GHz and 183 GHz. The exclusion of a single channel has relatively little effect in precipitation models, except for the 18 GHz primarily over land. Generally, the more channels that are available, the better the retrieval as seen in the multi-frequency 10-89 GHz or 18-166 GHz retrievals (Figure 13). A narrow frequency range results in poorer performance, particularly at high frequency channels. The inclusion of a low frequency water vapor channel in microwave radiometers significantly improves the performance over the ocean.

In order to fill in gaps between MW overpasses, various gap mitigation strategies have been developed by the community, including making use of IR data, but ultimately precipitation retrievals perform better when they are directly derived from MW imagers and MW sounders. Measurement reliability decreases as the time between measurements increases.

In addition to having higher temporal resolution, in general, the more channels that are available, the better the retrieval as seen in the multi-frequency 10-89 GHz or 18-166 GHz retrieval. Having multiple channels at 183 GHz allows using channel differences as predictors of rain rate. Alternate channel sets are still being explored,



DPR = Dual-Frequency Precipitation Radar (DPR) on Global Precipitation Measurement (GPM) mission

GPROF = Goddard Profiling algorithm

PRPS = Precipitation Retrieval and Profiling Scheme

Figure 13: Scenarios used to study the effects of channel loss and channel combinations, based upon instantaneous Precipitation Retrieval and Profiling Scheme (PRPS) retrievals from the 13-channel, 7-frequency GMI sensor, compared with surface radar data over the United Kingdom for 2017. The blue bars are for over ocean retrievals, while the green bars are for over land.

Source: Kidd et al 2021. © American Meteorological Society. Used with permission including using standard ATMS/MWS channels that are traditionally for temperature sounding. Low frequencies (e.g. 23 GHz) have significant positive impact on rain retrievals. For snowfall, 50 GHz and > 200 Ghz may be used to improve snowfall retrievals, but this process is still being evaluated.

NOAA/STAR/MIRS

The Microwave Integrated Retrieval System (MIRS) is a physically-based microwave retrieval system designed to treat both atmospheric and surface parameters which affect passive microwave measurements. MIRS ingests data from several MW sounders and imagers including ATMS, AMSU and the Global Precipitation Mission Microwave Imager (GMI) to retrieve atmospheric profiles of temperature, water vapor, cloud water, graupel water and rain water at 100 layers as well as surface emissivity in twenty frequencies and skin temperature. These retrieved geophysical parameters are used in other downstream products such as the Ensemble Tropical Rainfall Potential (eTRaP), blended total precipitable water (TPW), blended Rain Rate, snow and ice cover analysis, and NESDIS microwave sounder-based Tropical Cyclone (TC) Products: Hurricane Structure and Intensity (HISA), and Moisture Flux (MIST). These products are widely used for several applications by NWS forecasters and some products such as TPW are also available in the NWS Advanced Weather Interactive Processing System (AWIPS).

The 23.8 GHz water vapor channel provides vital information to the total column water vapor products in MIRS. The impact of losing the channel is significant over land and water. This product provides vital information on extreme rain and flooding events. Similarly, satellite-based precipitation estimates provide pivotal information to forecasters, especially over ocean and sparsely populated land areas. The NOAA/NWS Climate Prediction Center's Morphing (CMORPH) technique uses precipitation estimates that have been derived from low orbiter satellite microwave observations and geostationary satellite IR data. CMORPH is constructed by integrating information from retrievals of instantaneous precipitation from passive microwave (PMW) and infrared (IR) measurements aboard multiple (>15) satellites (Joyce et al. 2004; Xie et al. 2015; Xie et al. 2018). Primary sources of information to the CMORPH are level 2 precipitation retrievals derived from brightness temperatures of various combinations of PMW channels (Table 4) depending on sensor channel availability and algorithm designs (Ferraro 1997; Kummerow et al. 2015; Grassotti et al. 2020).

A combination of measurements from low frequencies (emission channels, e.g. 23.8GHz) and high frequencies (scattering channels, e.g. 88/89GHz) provides the maximum information for precipitation retrievals. Over land where emission channel measurements are contaminated by noise from other geophysical factors, only the measurements from the scattering channels are usable for the level 2 precipitation retrievals.

A loss of MW data from legacy POES and DMSP satellites would cause a significant loss of skill in precipitation estimates (Figure 14). When considering core channels for a MW Sounder, the 50-70 GHz absorption band offers more information than the 118 GHz band (Figure 15). Additional window and water vapor channels are recommended.

Joint Typhoon Warning Center

The Joint Typhoon Warning Center (JTWC) is the U.S. Department of Defense agency responsible for issuing tropical cyclone warnings for the Pacific and Indian Oceans.

Both satellite and ground observations are heavily leveraged in tropical cyclone (TC) modeling and analysis with microwave sounder data contributing almost 64% of location fixes of the center of a tropical or subtropical cyclone. Microwave sounder data is used in the analysis of TC internal structure including positional fixes, cross-section cyclone phase determination, intensity, wind radii estimation and TPW from MIRS.

The 85-91 GHz frequency (hereafter, 89GHz) passive microwave imagery has been long employed by forecasters for monitoring the convective organization of TCs and for center location. Upwelled microwave signals from the ocean at 89GHz are both re-emitted by warm rain and clouds (a warm signal), and scattered by larger

Table 4: Microwave sensor data used in CMORPH precipitation retrievals at NOAA

Global Precipitation Measurement (GPM) mission Microwave Imager (GMI) on GPM

Frequency (GHz)	10.65	18.7	23.8	36.5	89	165.5	183.31	183.31
	V/H	V/H	V	V/H	V/H	V/H	+/-3 V	+/-7 V

Advanced Microwave Scanning Radiometer 2 (AMSR 2) on GCOM-W1

Frequency (GHz)	6.925 / 7.3	6.925 / 7.3	10.65	18.7	23.8	36.5	89
	V/H	V/H	V/H	V/H	V/H	V/H	V/H

Special Sensor Microwave Imager / Sunder (SSMIS) on DMSP F15,16,17, &18

Frequency (GHz)	19.35	22.235	37	91.665	150	183.311	183.311	183.311
	V/H	V	V/H	V/H	H	+/-1 H	+/-3 H	+/-7 H

Advanced Technology Microwave Sounder (ATMS) on SNPP & N20

Frequency (GHz)	23.8	31.4	50.3	51.76	52.8	53.596	54.4	54.94
						+/-0.115		
	55.5	57.290344	57.290344	57.290344	57.290344	57.290344	57.290344	88.2
			+/-0.217	+/-0.3222	+/-0.03222	+/-0.03222	+/-0.03222	
				+/-0.048	+/-0.022	+/-0.010	+/-0.0045	
	165.5	183.31	183.31	183.31	183.31	183.31		
		+/-7	+/-4.5	+/-3	+/-1.8	+/-1		

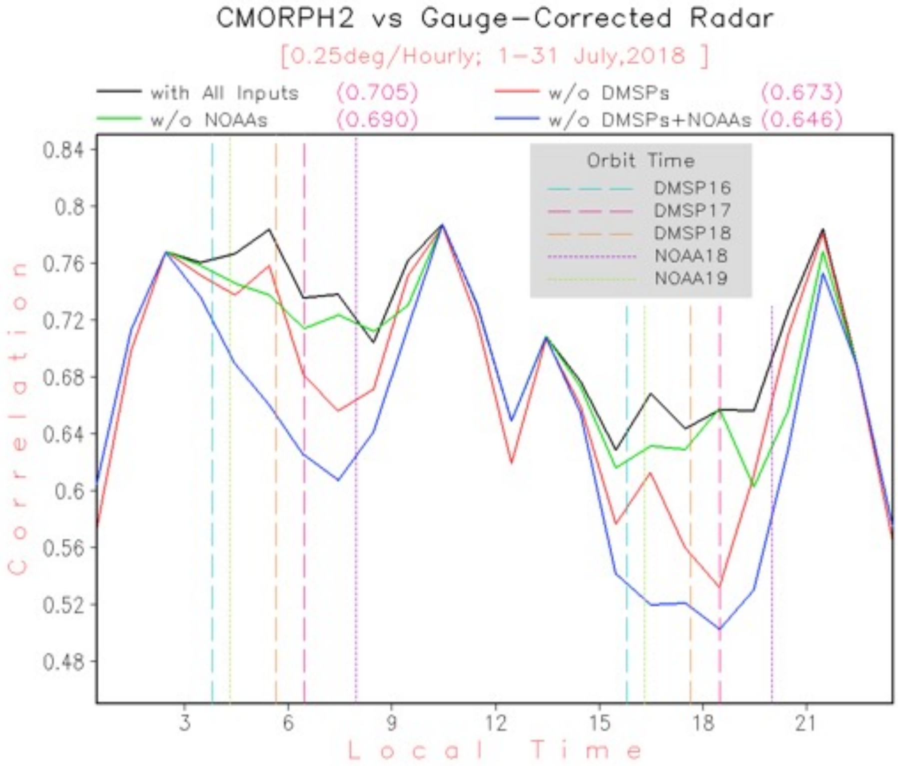


Figure 14: Correlation between Multi RADAR Multi Sensor (MRMS) gauge-corrected radar estimates and CMORPH2 constructed using PMW retrievals from all available satellites (black) and with retrievals from DMSP and/or NOAA satellites dropped. Correlation is computed using co-located data on a 0.25olat/lon grid over CONUS for 1-31 July, 2018.

Source: Xie

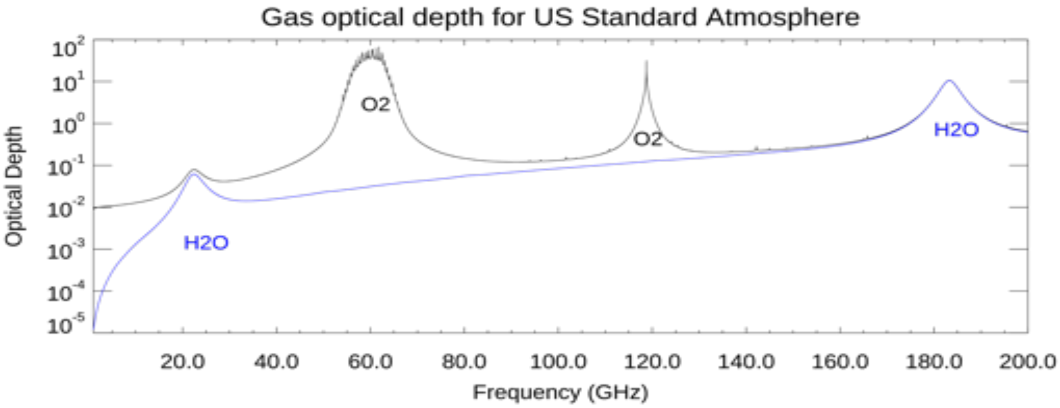


Figure 15: The 50-70 GHz O_2 absorption band is wider and has more absorption lines (33) than that of 118 (1) GHz O_2 absorption band.

Source: M. Liu

ice particles in deep convection (a cold signal). As these signals propagate upwards, they avoid attenuation by the small ice particle in cirrus clouds due to their relatively long wavelength. As a result, forecasters can use 89GHz imagery to get a glimpse of structure below the cirrus shield that so often limits the utility of geostationary infrared (IR) imagery of TCs, and shapes in both the warm and cold signature enable TC center to be more easily inferred. The cold signature acts much like a standard weather radar, where the coldest pixels in a cloudy scene are indicative of the deepest convection. The radar-like images allow for monitoring of rainband and eyewall organization, and inference of important features like degree of rainband curvature and evolution of secondary eyewalls. The degree of banding and eye features help forecasters improve their current intensity estimates and anticipate short-term intensity changes.

The 89GHz imagery also elucidates the appearance of secondary eyewalls in intense TCs, and this is often a precursor to stalled intensification or even weakening. Such imagery is thus used frequently and subjectively to improve TC situational awareness (Figure 16). In a slightly different application, 37 GHz channels are used to monitor warm structures related to the organization of low-level circulation centers, particularly in the more formative stages of development when such structures are not visible in 89 GHz imagery. During the pre-hurricane phases of the storm the appearance of “cold ring” structures in the 37 GHz Polarization Corrected brightness Temperature (PCT) (PCT37 = 2.18 × 37V – 1.18 × H37) are often precursors to rapid intensification and can be used in combination with intensity guidance to improve intensity forecast confidence.

In addition, passive microwave retrievals from MIRS are the basis for an operational intensity and structure algorithm. The algorithm estimates maximum sustained 1-minute winds, central pressure, and the maximum extent of 34-, 50-, and 64- knot winds, the latter are called wind radii. This information, along with other intensity and wind radii fixes from other sensors (Dvorak, Scatterometers, SAR, 89GHz, etc.) provide the information from which forecasters create subjectively-derived TC vitals (e.g., current location, intensity, wind radii, central pressure, pressure of the outermost closed isobar, radius of outermost closed isobar, and radius of maximum winds) that is provided to global numerical weather prediction centers for model initialization as part of the 6-hourly forecast cycle.

From the user perspective, it is important to limit “black box” technology. JTWC analysis is subjective, and knowledge of the input data sources is critical so that forecasters understand new technology and variables feeding into a resource. Data latency is another vital factor for accurate typhoon warnings. With warnings issued every six hours, the watch timeline is rigorous. Data must be in the hands of a forecaster in under six hours. Improving temporal resolution to under three hours is highly desirable.

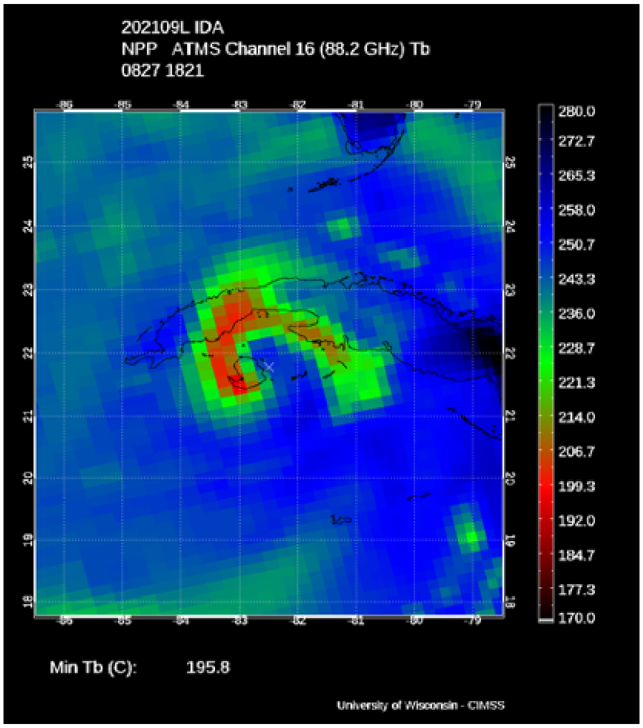


Figure 16: SNPP ATMS channel 16 (88.2 GHz) image of hurricane Ida on 27 August 2021 at 1821 hrs.

Source: CIMSS

Discussion

Constellation Configuration

NOAA asked the community to recommend an ideal configuration for a MW Sounder constellation, and repeatedly met the theme that the current backbone be maintained and improved. The notion of a backbone system was expounded in the WMO WIGOS 2040 vision. The WIGOS vision provides clear goals for NWP systems using enhanced Earth System models, including exploitation of emerging capabilities. The need for a backbone system providing continuity of measurement remains a key feature. Beyond continuity, future systems must also address the need for increased temporal coverage, as well as provide traceable calibration for the system to reference. A well-calibrated backbone constellation is also considered crucial for reanalysis applications.

The current 3-orbit constellation includes the legacy NOAA POES satellites that were launched in to Longitude of Ascending Node (LTAN) of 1930, EUMETSAT's Metop A/B/C satellites (LTAN 2130) and NOAA JPSS (LTAN 1330) which provide several day and night time observations (Figure 4). Several NWP centers are actively using MW sounders on legacy POES satellite even though they are operating beyond their planned mission life as they are still providing valuable data and having a positive impact on NWP model performance. At the constellation level, the recommendation is at a minimum to preserve spectral and temporal coverage as it exists today. A backbone instrument should focus on spectral coverage and spatial resolution, having the capability of performing at the current level or better. Improvements in performance and spatial resolution are expected with engineering advances.

In terms of quantity, the user community observed no saturation point, and recommended against decommissioning older satellites as long as they continued to provide stable, calibrated data. This is likely because temporal resolution is a major driver in NWP modeling and forecasts. For local and meso-scale forecasts especially, the need for low-latency data creates restrictions on what is assimilated. Improving temporal density of soundings could have a significant positive impact on precipitation and other highly variable products. For tropical cyclone tracking especially, bringing the refresh rate below three hours would be preferred. While NWP centers rely primarily on cross-track scanning MW sounders that have a large swath, other applications such as tropical cyclone analysis prefer conical scanning MW imagers that offer measurements in dual polarization which improves retrievals and maintains constant spatial resolution that enables better spatial analysis.

Cubesat or smallsat MW sounder missions offer the possibility to provide higher temporal sampling, and several missions have either been launched or are planned (TEMPEST-D, TROPICS, ESAS's Arctic Weather Satellite). NWP centers still need to establish whether these missions could provide data quality that is acceptable for operational real-time purposes, and efforts to facilitate this are recommended. In addition, the optimum constellation of MW sounders that should augment the backbone is to be determined. ECMWF is performing studies parallel to those at NOAA, evaluating use of sounders of varying capability in a range of orbits and planes.

Channel Selection

Leading into the workshop, users were asked to assess which channels were most critical and impactful to NWP models, or to other applications. Multiple NWP modelers from around the globe provided feedback regarding the assimilation of MW Sounder channels into their models. FSOI analyses repeatedly showed that cornerstone channels for analysis are the 50-60GHz for temperature sounding and 183 GHz for humidity sounding. These channels have been used historically on AMSU, MHS, and ATMS. MWS on EPS-SG will continue these channels.

Of particular interest to the Sounder project was the feasibility of focusing on a high-frequency MW sounder, and which of the lower frequencies might be dropped. Users repeatedly emphasized that the 118 GHz channel, while a good supplement to the temperature sounding capability of the 50-60GHz channels, is not a suitable replacement for it. While this may suggest that supplemental MW Sounders should minimally include these channels, studies are on-going regarding the utility of TROPICS data, which does not include the 50-60 GHz channels. Without supplying a full constellation architecture for user analysis it may not be clear what impact temporal gap filling with the 118 GHz channels may provide.

The other channels impacted by selection toward higher frequency is the 23/31 GHz channels. These low-frequency bands are used primarily for cloud-screening, and quality assurance in NWP data assimilation systems. While some NWP practitioners feel they can overcome the loss of these channels by utilizing window channels at higher frequencies, optimism was not universal.

Low-frequency channels provide vital water vapor information for precipitation products, and in extreme weather situations, rapid refresh of these channels could have significant positive impact. Increasing the number of channels at 183 GHz may help rain rate retrievals as well.

Instrument Lifespans and Data Access

A repeated concern and consideration that came up in the workshop was related to the lifespan of the instrument and how that might impact data access. WMO presented considerations for the future space-based microwave observations that captured requirements and policy needs. One point of emphasis was the need for an overarching data policy defining ‘free and unrestricted’ exchange of data, including re-use and sharing without charge or conditions. As the private sector become major data users and data providers, mutually beneficial rules must be established. The user community should leverage lessons learned from experiences with radio-occultation, which has demonstrated the value and considerations of commercial data buys and unrestricted global data sharing.

NOAA/STAR scientists discussed plans for assimilating passive MW SmallSat data in NOAA NWP, with focus on MicroMAS-2, TEMPEST, and TROPICS. Projected data quality from these CubeSats suggests that these instruments can provide positive impact to NWP forecasts. However, experience with actual data in an operational NWP context is currently lacking, and it is hence recommended to use these existing small satellite programs to gain experience in this area.

However, when working with CubeSats, data quality and stability will be drivers. Longevity and Transition to Operations (T2O) timelines may also impact the utility of the new data sources. The utility of these platforms would increase greatly if their lifetimes could be extended to the five-year range. These platforms fill gaps in temporal refresh and spectral coverage when combined with the current backbone.

Users repeatedly pointed to the long list of legacy platforms they leveraged to fill in temporal gaps, and showed AMSU instruments remain incredibly impactful in NWP models, even though they are decades old. The combination of stable calibration over time and low noise are key to their continued usefulness. Moving forward, these key features should be considered in addition to the placement of new platforms into the larger architecture.

Along these lines, it was noted that it can take about a year for a new data source to begin being used operationally in NWP systems. In recognition of the new paradigm of constellation opportunities, some data assimilation scientists are looking for ways to streamline the integration of new sources, however, these processes are still developing and may face practical limits, especially for the first generation instruments. Therefore, longer lifespans of missions are preferred.

Long lifespans and stable calibration are also critical features for reanalysis applications. These are produced at several centers (e.g., ECMWF, NASA, JMA) and are vital for numerous studies, including climate trend monitoring and process analyses. ■

Summary

MW Sounders provide valuable information to NWP and other weather applications. With a future eye toward maintaining and expanding our current capabilities, while also exploiting the power of CubeSats, the user community provided the following insights:

1. The 50-60 GHz, 183 GHz channels are preferred for temperature and humidity sounding.
2. The 118 GHz channel lacks sufficient information content compared to the 50-60 GHz channel to act as a full replacement.
3. Measurements in frequencies at 23, 31, 50, 51, and 89 GHz are also used for surface sensing in clear conditions, QA/QC and Cloud clearing in DA, as well as in precipitation models.
4. Window channels in the 23/31 GHz are also used to estimate surface emissivity or cloud-related uncertainty.
5. Maintaining a 3-orbit constellation backbone is necessary for providing critical reference measurements that have low noise, are well calibrated, and have long mission life, will ensure continuity and are the minimum baseline for temporal and spatial coverage.
6. Instruments flown in supplemental orbits are desired to improve the temporal density of soundings. Legacy instruments currently act as vital input sources to fill temporal gaps.
7. Owing to current limitations on R2O and T2O, longer lifespan instruments are preferred. Stable calibration over the lifetime of the instrument is key. Well calibrated long life mission data is also vital for reanalysis and climate studies.
8. Future satellite MW sensors should mitigate the impact of 5G and other communication frequency interference on observations.
9. Low latency of data distribution is important so that the data is available for assimilation in models before the cut off period.

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Presentations

All presentations are archived at: https://www.jpss.noaa.gov/science_events/20210728-noaa-microwave-sounder-workshop/

1. Bormann, N., Use and impact of MW sounders at ECMWF and perspectives for future systems
2. Chambon, P., Utilization of microwave frequencies for precipitation remote sensing
3. Darlow, J., JTWC Technical Services
4. Eyre, J., Microwave soundings in NWP at the Met Office: experience and suggestions for future systems
5. Garrett, K., Toward assimilating passive microwave smallsat data in NOAA NWP
6. Holmlund, K., Considerations for future space-based microwave observations
7. Kazumori, M., Use of satellite microwave observation in JMA NWP systems and expectation for future NOAA microwave sounding mission
8. Liu, E., The Use of Microwave Sounder Data in NCEP Global Forecast System - Current Status and Outlook
9. Liu, M. and Xie, P., Microwave Remote Sensing and Applications
10. McCarty, W., Microwave Sounder Radiance Assimilation at the Global Modeling and Assimilation Office