The Technology Maturation Program (TMP)

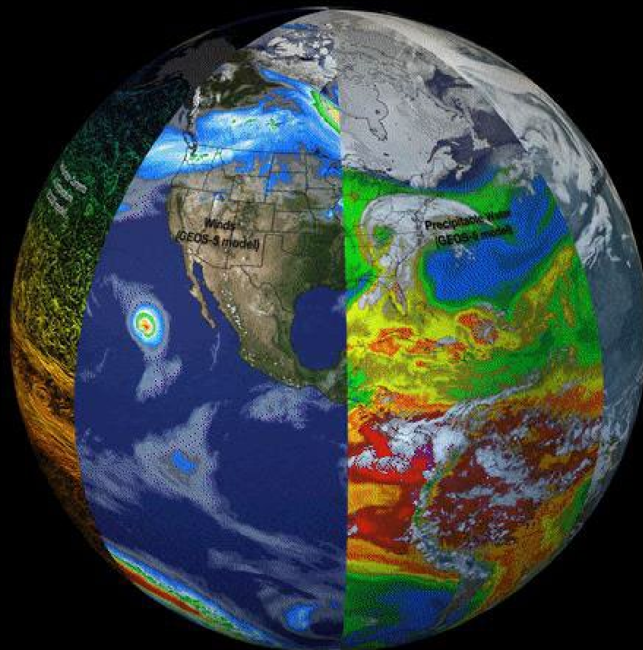
FY 2019 Annual Review

15 November 2020

Preface

"The dream of yesterday is the hope of today and the reality of tomorrow."

— Dr. Robert Goddard



NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) provides secure and timely access to global environmental data and information from satellites and other sources to promote and protect the Nation's security, environment, economy, and quality of life. The Earth's weather and climate vary on timescales ranging from minutes and hours to months and decades. Society's requirements for weather and environmental data and information constantly evolve. This evolution drives updates to requirements that are reflected in every new generation of NOAA's operational Earth observing systems. Technological advances, from miniaturization to machine learning, are emerging that, if leveraged, offer enormous potential for new capabilities at reduced cost.

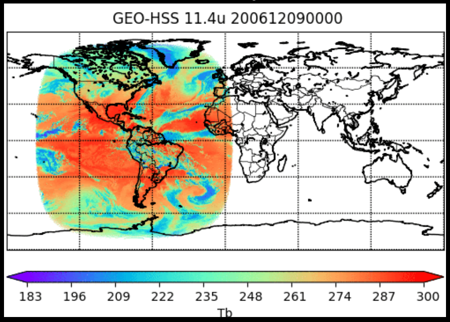
The goals of NOAA/NESDIS' Technology Maturation Portfolio (TMP) are to bridge gaps with rapid, targeted, peer-reviewed investments, to leverage new agency investments, to enable a radically lower cost, higher performing future, to demonstrate new enabling technologies that reduce risk and time to operations, and to exploit opportunities to collaborate with experts. NOAA follows a repeatable and agile process, the TMP, to guide technology maturation and advancement towards its most-pressing operational needs. This helps to ensure the most beneficial and affordable suite of future satellite and decision support systems are developed and available in time for operational deployment and exploitation. Five strategic priorities guide TMP towards bridging gaps with rapid, targeted, peer-reviewed investments: (1) ***Newly Enabling***, by providing new or alternative capabilities; (2) ***Closing Gaps*** – via existing or potential; (3) ***Enhancing Agility*** – deliver faster replacements, fresher technologies; (4) ***Reducing Cost*** – through reductions in size, weight, and power or other drivers; and (5) ***Leveraging*** other-agency investments. In this second year, the TMP delivered a wealth of technological demonstrations and advancements. These accomplishments have direct downstream operational payoffs. This FY 2019 End-of-Year conference summary highlights the accomplishments of the 15 TMP projects performed by NOAA's Center for Satellite Applications and Research (STAR) and Atlantic Oceanographic and Meteorological Laboratory (AOML).

Elsayed Talaat
OPPA Director

Patricia Weir
TMP Portfolio Manager

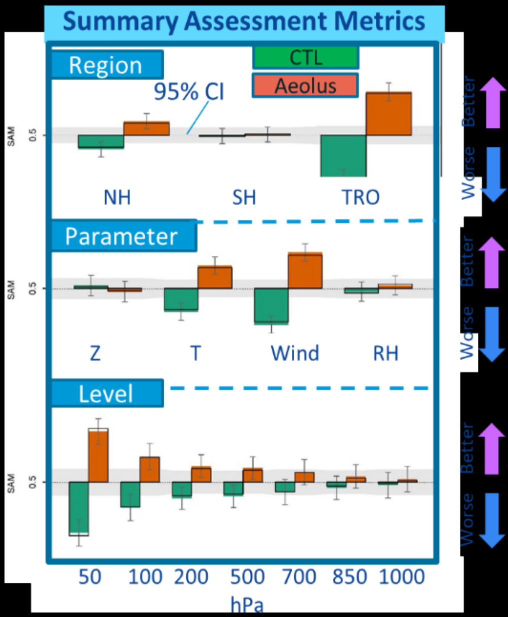
Selected TMP 2019-2020 Accomplishments

Newly Enabling *– add new or alternative capabilities:* ✓



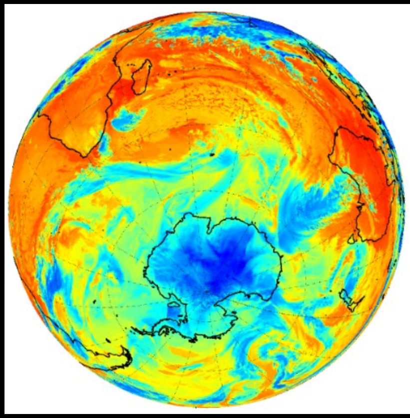
TMP results show we can improve the forecast skill of NOAA's numerical weather prediction models by flying a hyperspectral sounder in geostationary Earth orbit. Hyperspectral sounders probe the atmosphere by dividing the observed infrared spectrum into many hundreds of pieces to resolve the vertical profiles of temperature, moisture, and winds.

Leveraging *other-Agency investments:* ✓



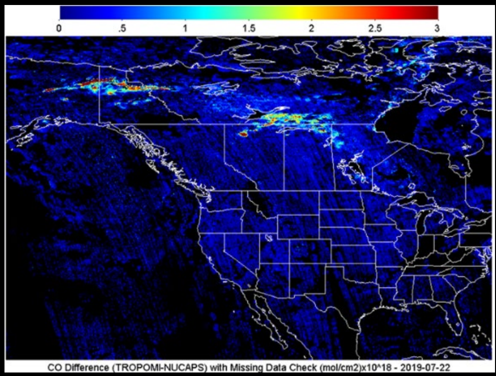
Global Observing System Experiments (OSEs) that include the European Space Agency's Aeolus lidar retrievals of horizontal winds demonstrate improvements in tropical wind forecasts over control runs at many vertical levels.

Improve Agility *– faster replacement, fresher technology, confirmed by return-on-investment (ROI) analyses and simulations:* ✓



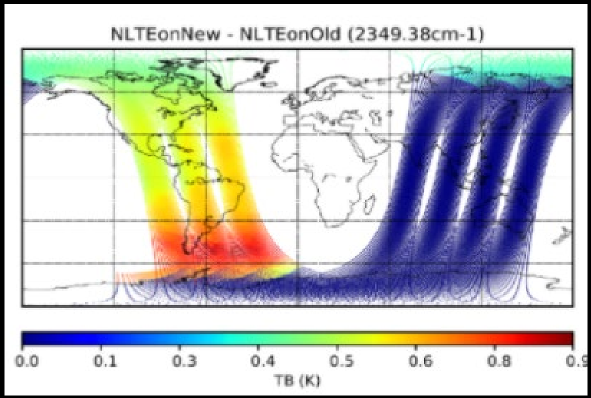
Simulation of "Tundra-orbit" imaging satellite capabilities to fill a coverage gap at high latitudes. If flown, these high inclination/high altitude orbits would allow significant time dwelling over the north polar region.

Close Gaps *– existing or potential:* ✓



Demonstrating retrieval of a new capability for boundary layer CO concentration retrievals that map where and when wildfire smoke is near the surface.

Cost Reduction *– reduction in size, weight, and power or other cost drivers:* ✓



Validation of miniaturized shortwave/midwave infrared sensors capabilities to provide temperature and water vapor profile information for assimilation into numerical weather prediction models. These would exploit a region of the spectrum not currently utilized.

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1. TMP Background and Motivation

NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) Aspiration is to "*Provide a truly integrated digital understanding of our Earth environment that can evolve quickly to meet changing user expectations by leveraging our own capabilities and partnerships.*" Dr. Stephen Volz, NOAA Assistant Administrator for Satellite and Information Services, sets the strategic vision and implementation objectives for the Nation's civilian operational Earth observing satellite fleet.

Dr. Volz views the period 2020-2030 as "*The Coming Decade of Development*" for creating next-generation systems for 2025, 2030, and beyond. While delivering needed weather and environmental satellite data and information services, NESDIS seeks to enable a comprehensive understanding of the Earth as an integrated system. This necessitates capabilities sustainment and evolution in Low Earth Orbit (LEO), Geosynchronous Earth Orbit (GEO) and Extended Orbits (GeoXO), the Space Weather Follow-On (SWFO), and commensurate ground system architectures and systems. Realizing these strategic objectives requires NESDIS, in the decade to come, to sustain and enhance leadership in innovative systems, products, and services delivery, including leveraging partner satellite technologies (Figure 1).

At the September 2020 Community Meeting on NOAA Satellites, Dr. Volz presented a look ahead that highlighted the weather and environmental satellite system changes expected over the upcoming decade and the six NESDIS strategic objectives required to achieve them. The presentation, entitled "The Coming Decade of Development: Creating the Next Gen Systems for 2025, 2030 and Beyond," noted that achieving these strategic objectives will require an enterprise-wide evolution of technical capabilities—many of these can be greatly facilitated through a managed program of technology development.

Within NOAA, the NESDIS Office of Projects, Planning, and Analysis (OPPA) manages a portfolio of technology maturation projects under the Technology Maturation Program (TMP). OPPA focuses on important and innovative projects, executed with domestic, international, and commercial partnerships, to meet NOAA observation requirements. Sustaining this role spans small-scale flight projects, domestic and international partnerships, and data exploitation initiatives, including project management, systems engineering, scientific analysis, and other acquisition duties. A key element is ensuring cost-effective maturation and implementation of missions, instruments, technologies, and measurement concepts to address specific high-priority science and applications requirements—both existing and anticipated. As such, funded TMP projects span flight and ground systems, from sensing through decision support. OPPA designed and proactively managed TMP to function in service of NESDIS' Aspiration and NOAA's threefold mission of Science, Service, and Stewardship:

- To understand and predict changes in climate, weather, oceans, and coasts
- To share that knowledge and information with others
- To conserve and manage coastal and marine ecosystems and resources

The TMP was stood up by OPPA in 2018 to bridge gaps with rapid, targeted, peer-reviewed investments, to leverage new agency investments, to enable a radically lower cost for a higher performing future, to demonstrate new enabling tech to reduce risk and time to operations, and to exploit opportunities to collaborate with experts. Examples of benefits deriving from TMP projects that met objectives and impacted future NOAA systems and operations show that they have enabled superior performance, agility, and adaptability with faster Research to Operations (R2O) of new data, and the exploitation of new techniques. OPPA is continuing technical project management for FY19 and FY20 efforts and planning to transition TMP into a Joint Venture Program for FY21.

NOAA's mission statement highlights the unique technologies enabling the Agency's continued success, calling out the existential importance of the application of "emerging science and technology to user needs." NOAA deploys a unique infrastructure that underpins the suite of core mission functions: satellite systems, ships, buoys, aircraft, research facilities, high-performance computing, and information management and distribution systems. Due to the continual advance of technologies, combined with our nation's evolving and emerging needs, a transparent, repeatable, and sustainable portfolio approach that oversees relevant technology maturation and advances NOAA's mission is a key executive imperative.

This level of technology prioritization was highlighted in the Statement of Task to the Earth Science and Applications from Space (ESAS 2017) Decadal Survey, "*Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*," included NOAA-specific task elements focused on how to make existing and planned programs more effective with respect to their utility to users and their cost-effectiveness, including through technology innovation. In building a Strategic Framework for Decadal Progress, the Survey recognized that "*The coming decade is one in which we must not only accelerate the advance of our science and applications but do so within constrained resources…Rising to this challenge requires innovation, not just doing things the way we have in the past but aggressively implementing new means to be efficient and effective in how we work.*" Noting that "*Successful organizations formally review, and track key enabling trends and proactively incorporate them in their activities*," the Survey recommended that, as a part of a strategic framework, NOAA "*Exploit external trends in technology and user needs*."

OPPA stood up the TMP in 2018 to address NOAA Satellite Observing Systems Architecture (NSOSA) questions that needed to be answered to help inform future architecture decisions. NSOSA stressed that traditionally long timelines required for satellite acquisition, are giving way to more rapid models that require continuous innovation and careful investment in technology-driven disruption. As such, NOAA formulated the TMP project to bridge gaps with rapid, targeted, peer-reviewed investments that are:

- Newly Enabling –demonstrate paths towards new or alternative capabilities
- Close Gaps – identify approaches that eliminate existing or potential observation gaps
- Increase Agility – enable faster replacement paths and fresher technologies, confirmed by Return On Investment studies
- Cost Reduction – achieve reductions in size, weight, and power or other drivers

- Synergies - leverage other agency investments

2. TMP Annual Review Overview

The Annual TMP Review was kicked off by OPPA Director Dr. Elsayed Talaat, who noted that TMP is aligned with and supporting NESDIS' Strategic Objectives. The primary meeting goal was to report on End-Of-Year (EOY) progress made on NESDIS/Center for Satellite Applications and Research (STAR) and NOAA's AOML TMP projects, while linking the projects to higher-level NESDIS priorities including LEO, GEO, and future architecture studies. Participants described their latest accomplishments and how they advance NOAA's technological readiness for future weather and Earth science observations. A secondary benefit of the review was the enhancement of collaboration among participating technologists, scientists, and managers. Ongoing TMP projects with external entities were outside the scope of this review.

NASA's nine Technology Readiness Level (TRL) definitions formalize the maturation levels from TRL 1 (Basic principles observed and reported) through TRL 9 (Actual system flight proven through successful mission operations). OPPA's TMP projects are selected to range from TRL 2 (Technology concept and/or application formulated.) through TRL 6 (System/sub-system model or prototype demonstration in an operational environment), as TRLs 7-9 mark the transition from research and development into operations. TMP projects follow the TRL ladder definitions, and are designed to:

- Enable a radically lower cost, higher performing future
- Demonstrate new enabling technology to reduce risk and time to operations
- Exploit opportunities to collaborate with experts in NOAA, Federally Funded Research and Development Centers (FFRDCs), Cooperative Institutes (CIs), etc. to future goals
- Monitor work done by NASA Earth Science Technology Office (ESTO), FFRDCs, etc.
- Monitor technology status at Small Satellite Conference, ESTO Forum, and others
- Collaborate to solve gaps in maturity and specific NOAA needs
- Deliver benefits value assessments

Trish Weir, while working as a Senior Systems Engineer in OPPA, managed all programmatic and technical aspects of the TMP Portfolio to be both forward-looking and collaborative. Participants in the review, held virtually using Google-Meet, spanned NESDIS, other NOAA Line Offices, other government agencies, industry, and academia.[1] Three sessions were held:

- Session 1 (Eight Projects): Maturing LEO Architecture (technology, platforms, data)

[1] Including Brad Pierce, Changyong Cao, Chi Ao, Chris Barnet, David Helms, David Santek, David Spencer, Diana Guerrero, Dimitrios Vassiliadis, Ed Grigsby, Elsayed Talaat, Emily Liu, Eric Leuliette, Eric Maddy, Flavio Iturbide-Sanchez, Haidao Lin, Haixia Liu, Hui Liu, Jacqueline Le Moigne, James Yoe, Janice Sessing, Jason Dunion, Jeff Key, Jeffrey Best, Jennifer Clapp, Joanne Ostroy, Jordan Gerth, Jun Li, Karina Apodaca, Katherine Lukens, Kayo Ide, Kevin Garrett, Kevin Schrab, Kuo-Nung Wang, Lidia Cucurull, Ling Liu, Lisa Bucci, Mark Middlebusher, Martin Yapur, Menghua Wang, Michael Maddox, Mike Hardesty, Mitch Goldberg, Nai-Yu Wang, Parminder Ghuman, Patricia Weir, Paul Chang, Peter Marinescu, Philip Ardanuy, Quanhua Liu, R Bauer, Ralph Ferraro, Robert Knuteson, Sachidananda Babu, Sarah Ditchek, Satya Kalluri, Sean Casey, Sharon Yaary, Shu-peng Ho, Sid Boukabara, Steven Miller, Tim Schmit, Tommy Jasmin,

- Session 2 (Three Projects): Maturing GEO Architecture (technology, Session 2 (Three Projects): Maturing GEO Architecture (technology, platforms, data)
- Session 3 (Four Projects): Maturing Ground Processing and Exploitation of Technology Maturing LEO Architecture (technology, platforms, data)

3. Session 1: Maturing LEO Architecture (technology, platforms, data)

Of the set of six NESDIS Strategic Initiatives illustrated earlier, the eight TMP projects in this session are responsive to the third initiative, to:

"Evolve LEO architecture to enterprise system of systems that exploits and deploys new Observational capabilities."

TMP 18-05: Enable SW/MW IR Data Use

Kevin Garrett is the NESDIS STAR Data Assimilation Science Team lead.

TMP 18-05 explores the use of shortwave Infrared (SWIR) observations in NCEP's global data assimilation system.

The Principal Investigator (PI) and presenter is Kevin Garrett (STAR). The twin objectives of this project are to: (1) Expand SWIR (2155-2550 cm^{-1} spectral range) used in global data assimilation and enable MWIR for the Cross-track Infrared Sounder (CrIS), and (2) modify global data assimilation (DA) to assimilate both longwave infrared (LWIR) and shortwave infrared (SWIR) and assess the impact. Traditional infrared (IR) sounders in polar orbit have dimensions measured in meters and are expensive to both build and launch. SmallSats can accommodate miniaturized IR sounders that exploit the SWIR region, thus avoiding cryogenic cooling systems needed in the LWIR range. Cubesat technology supports an alternative/cost effective/agile constellation of shortwave/midwave IR (SW/MWIR) sensors to provide temperature and water vapor profile information to NWP. A SWIR constellation could complement LWIR sounders and add robustness to the global observation system. SWIR data (4 µm CO2 band), however, is not operationally assimilated in NWP models (LWIR only). This project addresses this question: To help shape future satellite global observing system architecture, can a SWIR-only solution achieve or exceed positive impact provided by LWIR radiances in medium-range, global NWP? Associated risk-reduction steps include:

- Extend NOAA global NWP to assimilation SWIR data (CrIS/IASI/AIRS)
- Improved radiance forward operator for SWIR (CRTM)
- Compare impact of SWIR vs LWIR assimilation on FV3GFS forecasts
- Transition SWIR/LWIR assimilation to NCEP operations (pending impact results)

The primary FY19 accomplishments included developing an improved non-Local Thermodynamic Equilibrium (LTE) correction for the Community Radiative Transfer Model (CRTM), implementing an enhanced CrIS quality control system, setting up the Observing System Experiment (OSE), and assessing the combined CrIS LWIR and SWIR assimilation performance in the Global Data Assimilation System (GDAS). The project has shifted focus from the CrIS 431 channel dataset to 2211 Full Spectral Resolution (FSR) dataset; this shifted focus to assimilation of SWIR+LWIR simultaneously and a transition to an operationally ready system, including expansion to CrIS SWIR from 2211 dataset (Figure 2).

What does this mean? Quantitatively, in terms of forecast impacts, when assimilated SWIR data alone,

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Vanessa Griffin, Wayne Feltz, Wei Han, Wei Xia-Serafino, William McCarty, Xi Shao, XingMing Liang, YJ Noh, Yong Chen, Zhenglong Li.

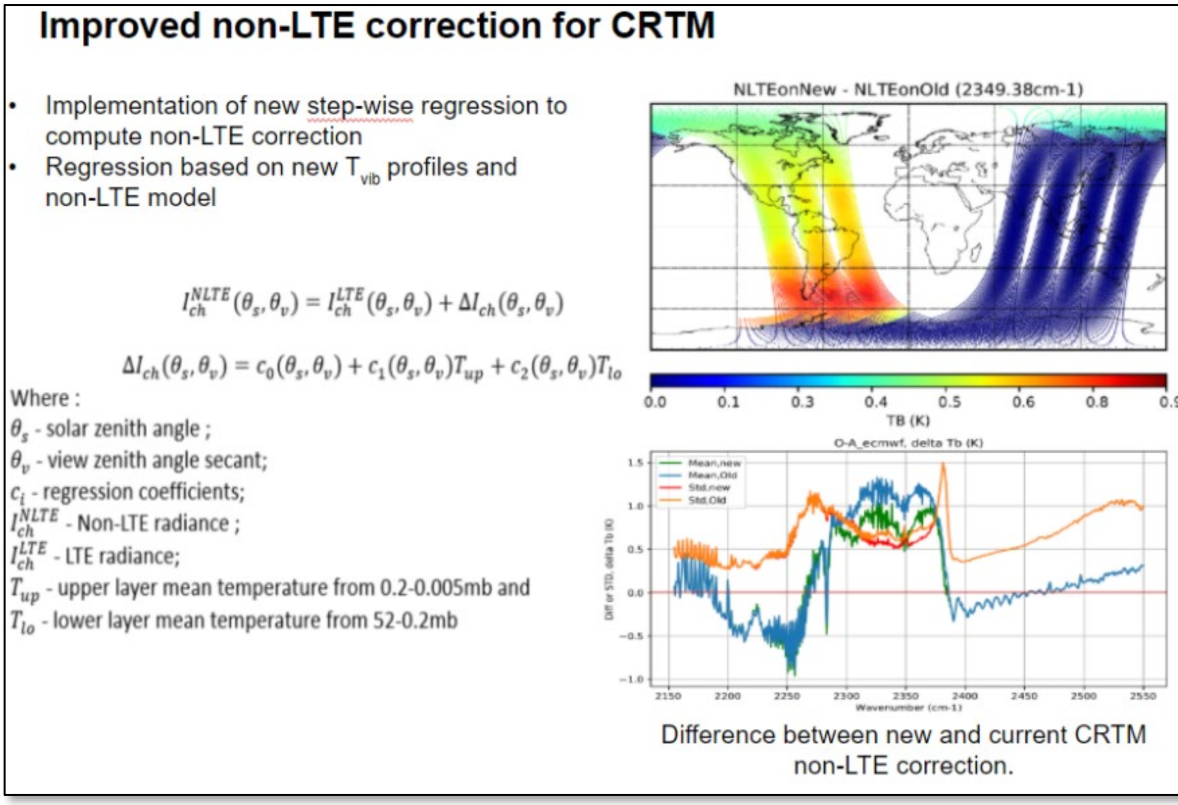


Figure 2. TMP 18-05 made noteworthy progress in handling non-local thermodynamic equilibrium (NLTE) emission, improving NWP model assimilation of hyperspectral SWIR radiance observations.

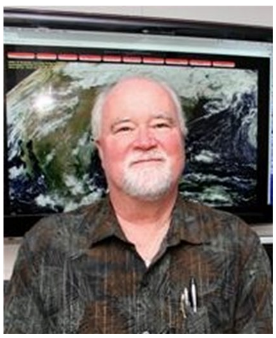
results from this TMP project showed that the SWIR DA outperformed the LWIR DA (in terms of improved predictive skill of medium-range weather forecasts as verified against European Centre for Medium-Range Weather (ECMWF) analyses. Qualitatively, from an NWP perspective, Jim Yoe of the National Weather Service (NWS) and Chief Administrative Officer for the Joint Center for Satellite Data Assimilation (JCSDA, informal communication) felt that a lot of solid work is going on here results from this TMP project showed that the SWIR data assimilation (DA) outperformed the LWIR DA (in terms of improved predictive skill of medium-range weather forecasts as verified against European Centre for Medium-Range Weather, ECMWF, analyses). Qualitatively, from an NWP perspective, Jim Yoe of NWS and Chief Administrative Officer for the Joint Center for Satellite Data Assimilation (JCSDA, informal communication) felt that a lot of solid work is going on here addressing questions on how we use data we currently have (exploiting SW as fallback is appealing). If we can use both SW and LW IR the combination would provide a greater total benefit and leverage investments we have already made in CrIS. The biggest concern is at the total system level: as we make clear and significant scientific progress, when there is an architectural change in how satellites are providing data (including commercial data), science advancements alone are not enough. We will need to plan carefully on how we implement these changes into the system and actual assimilation and model forecasting process. We need to look towards this goal with a long-term plan to ensure our performance and resource implementations are complementary and aligned. STAR is developing a DA group, creating a process where STAR would do perform experiments and make sure they are in the same environment that operations uses.

Work remaining on the project is the optimization of SWIR+LWIR data assimilation, running a final OSE to assess the optimized SWIR+LWIR impact, finalizing the assessment of CrIS SWIR from the

2211 FSR dataset, including updated CRTM non-LTE correction and nitrogen dioxide (NO_2) background, incorporating refined quality control and observation errors, and running an OSE for CrIS 2211 SWIR, compared with previous OSEs. In terms of TRL, the project team internally assessed the TRL of SWIR and LWIR+SWIR DA using the CrIS 431 subset has advanced to TRL 8. The TRL of SWIR-only using the CrIS 2211 dataset is assessed at TRL 4 (but can accelerate rapidly).

Expected completion of this TMP project was the end of Q1 FY21, at which time this project transitioned to CrIS/Infrared Atmospheric Sounding Interferometer (IASI) LW/MW IR optimization project supported by the Joint Polar Satellite System (JPSS) through the STAR-Environmental Modeling Center (EMC) Joint Development Agreement. The early results of SWIR assimilation are encouraging. There is a similar study underway at ECMWF. If this independent effort verifies our SWIR results, then overall confidence in the results would be increased.

TMP 18-09: Exploit TropOMI Sensor



Brad Pierce, Director of the Space Science and Engineering Center (SSEC) at the University of Wisconsin-Madison, has more than 25 years of experience in the design, development and execution of global atmospheric models.

TMP 18-09 exploits composition retrievals from the European Commission's TROPOspheric Monitoring Instrument (TROPOMI) to improve air quality forecasts through better constraints on long-range pollution transport and timely updates of global NOx emission inventories.

Air quality forecast improvements are being achieved through chemical DA using the TROPOMI carbon monoxide (CO) and NO_2 retrievals within the Next Generation Global Prediction System (NGGPS) Unified Forecast System (UFS) with Real-time Air Quality Modeling System (RAQMS) chemistry. As such, this TMP project supports situational awareness for NWS Incident Meteorologists through better estimates of the vertical distribution of pollution from wildfires (Figures 3 and 4). This is accomplished by combining the NOAA Unique Combined Atmospheric Processing System (NUCAPS) and TROPOMI CO retrievals to constrain boundary layer CO concentrations. The PI and presenter is R. Bradley Pierce (UW-Madison/SSEC). The primary TMP objectives are to demonstrate the potential for operational product and services improvements through the utilization of TROPOMI data by:

- Combining NUCAPS and TROPOMI CO retrievals to improve boundary layer CO concentrations within UFS
- Utilizing TROPOMI tropospheric NO2 retrievals to improve UFS global nitrogen oxide (NOx) emission inventories
- Developing a multi-sensor level 3 (L3) boundary layer CO product by combining NUCAPS and TROPOMI CO retrievals

The project's approach was to collect TROPOMI CO and NO_2 retrievals used for chemical DA within UFS-RAQMS and evaluate them using measurements from the FIREX-AQ field campaign. The project supports situational awareness for NWS Incident Meteorologists through better estimates of the vertical distribution of pollution from wildfires. Several of the main FY19 accomplishments included:

- Developing and testing L3 multi-sensor boundary layer CO retrieval
- UFS-RAQMS TROPOMI NO2 offline NOx emission adjustment experiments

- UFS-RAQMS TROPOMI CO assimilation experiments

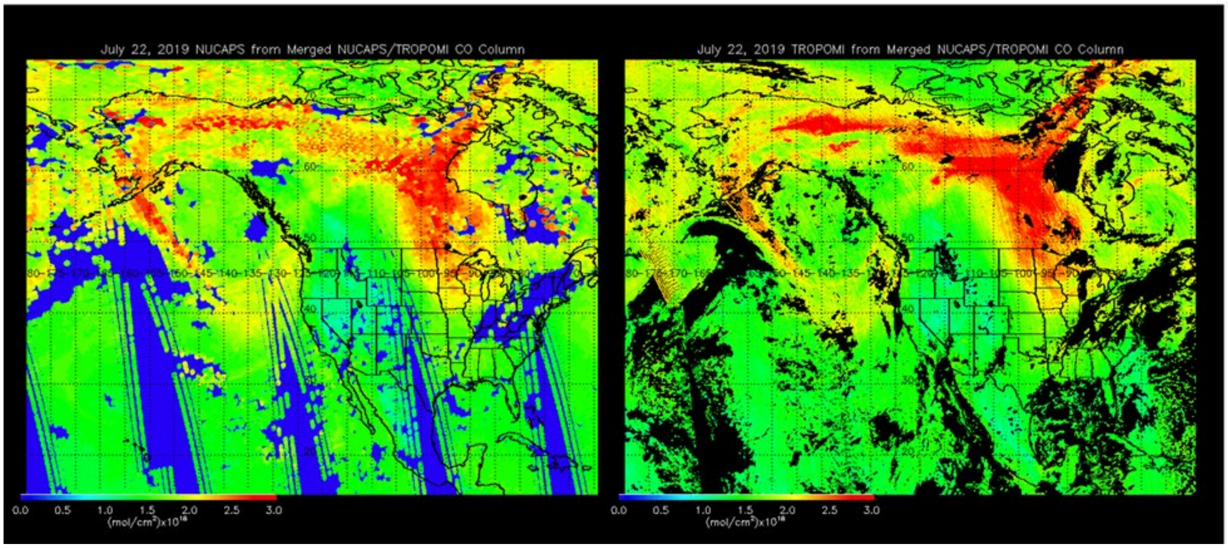


Figure 3. A major TMP 18-05 FY 19 accomplishment was the development and test of a multi-sensor boundary layer CO retrievals combining information from TROPOMI SWIR retrievals which use reflected solar radiances and is sensitive to the total CO column with NUCAPS TIR retrievals which use thermal emission and is most sensitive to mid tropospheric CO concentrations.

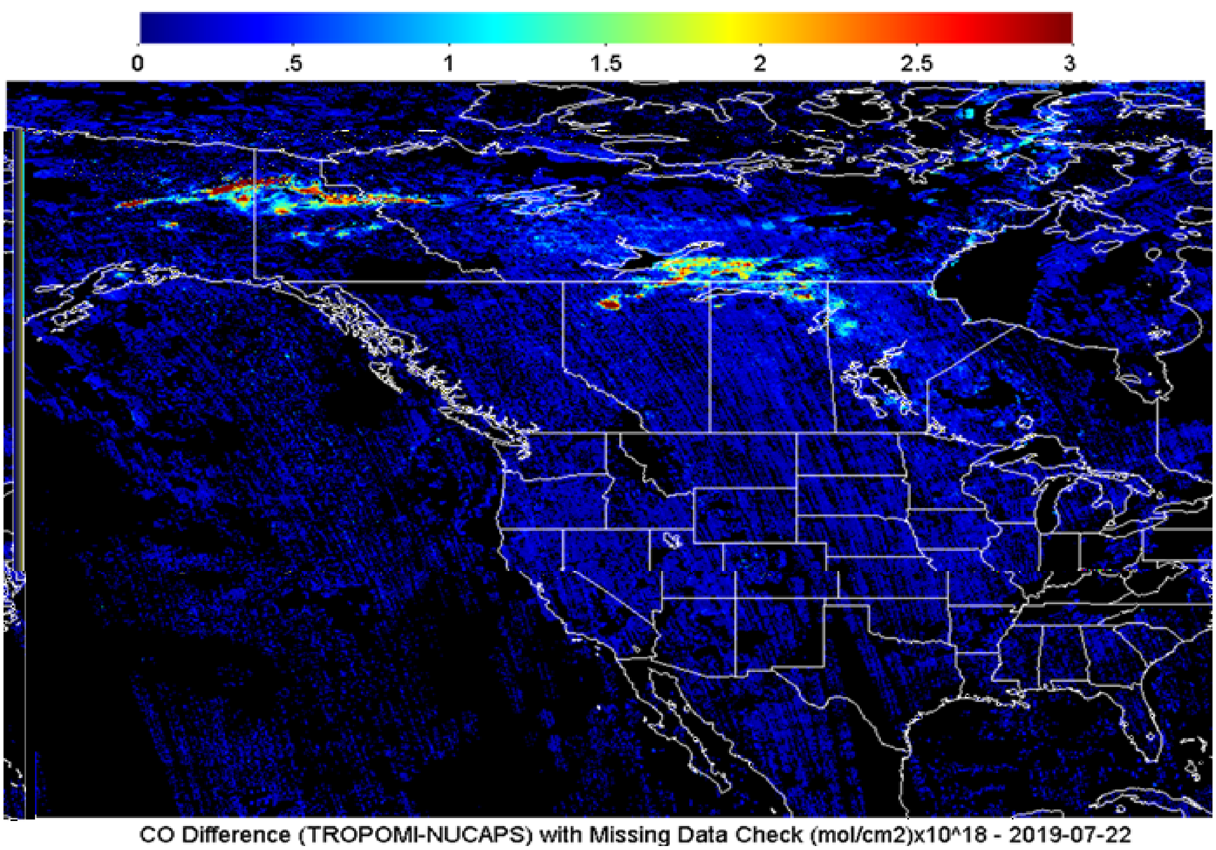


Figure 4. TROPOMI-NUCAPS highlights boundary layer CO concentrations showing near-surface wildfire smoke.

"Nose-level" air quality is difficult to retrieve from downward-looking satellite observations that must sense through the entire atmosphere. This project shows how such observations may be achieved through a combination of measurements from different instrument systems. As such, the project aligns with strategic goals of both NESDIS and NWS, as well as the WMO's Integrated Global Observing System (WIGOS) vision. The NSOSA study prioritized atmospheric composition measurements as one of the future product needs for National terrestrial and ocean observation objectives. Exploitation of TROPOMI atmospheric composition measurements aligns with NESDIS's Mission to provide global environmental data from satellites to protect the Nation's environment and quality of life through improved air quality forecasts. With respect to the NWS, Annex 10 "Aerosols and Atmospheric Composition" of the Strategic Implementation Plan for Evolution of NGGPS to a National Unified Modeling System outlines the need for including aerosol and chemistry within the UFS. Project 10.2 of Annex 10 "Data Assimilation for Atmospheric Composition" identifies essential chemical data assimilation (CDA) and emission data assimilation (EDA) capabilities needed to accomplish these goals. One focus of the strategic plan is on DA for atmospheric composition. It identifies the need for both essential chemical DA (CDA) and emission DA (EDA) capabilities needed to accomplish goals. By combining NUCAPS CO with TROPOMI CO, the difference (TROPOMI-NUCAPS) highlights enhanced sensitivity in the boundary layer (shows where smoke is near the surface).

TMP 18-08: Evaluation of Next-Generation Satellite Architecture Solutions to Nocturnal Low-Light Visible Observations in the Arctic and Beyond

Steve Miller is a Senior Research Scientist at CSU and serves as Deputy Director of CIRA. His research includes developing satellite algorithms geared toward operational end-users, focusing on nocturnal low-light visible sensing.

TMP 18-08 continued efforts led by the Cooperative Institute for Research in the Atmosphere (CIRA) to evaluate science requirements for a CubeSat/SmallSat Pathfinder that meets and potentially exceeds low-light visible Key Performance Parameter (KPP) requirements defined by the Joint Polar Satellite System (JPSS).

The PI and Presenter was Steven Miller (Colorado State University / the Cooperative Institute for Research in the Atmosphere (CSU/CIRA). The Visible/Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band (DNB) on Suomi National Polar-orbiting Partnership (S-NPP) and the JPSS brings a paradigm shift to the way we observe the nocturnal environment—via low-light visible imagery (Miller et al., 2009, 2012, 2013). Until recently, civilian visible-light imagery of clouds and the Earth's surface was restricted to daytime only. Now, we can view the Earth at night in both emitted and reflected light. The DNB was elevated to key performance parameters (KPP) status at high latitudes (poleward of 60° N) shortly after operational commission, satisfying specific requests from Alaska Region users who benefit from its gap-filling information during the dark polar winter months.

Looking toward with NOAA's future satellite architecture, there is interest in providing continuity to this novel measurement, and potentially augmenting its utility to the lower-latitude users—requiring multiple satellites and thus a more economical solution. The approach of this project was to:

- Finalize inventory of low-light visible research/operational uses by understanding the key user applications and informing NOAA on priorities for low-light observations
- Design orbital architectures for CubeSat constellations meeting sampling needs
- Consult with Aerospace on science, coordinate conjunction analyses with ISARA/CUMULOS and the Near Infrared Airglow Camera (NIRAC) on the International Space Station

As illustrated by CLAVR-x cloud retrieval products with S-NPP VIIRS (DNB), sustaining a night-time (low light) reflective imaging capability on satellite imagers will greatly improve future night-time cloud optical properties observation (Figure 5). It is likely that with a robust calibration strategy and accurate geolocation, uncalibrated SmallSat sensors can potentially replicate much of the VIIRS DNB performance for cloud products. Under moonless conditions, clouds observed by NOAA-20 DNB and NIRAC sensors are due to reflected airglow. NIRAC is in a stronger airglow band near 1.6 μm provides improved cloud detection on moonless nights (rivals the full moon). At lower light levels, there is more radiometric noise with CUMULOS over the VIIRS DNB. NIRAC takes more advantage of non-lunar nights. Increasing the number of SmallSats with low-light capability in the overall observing architecture would be moving toward observing more effectively during lunar nights.

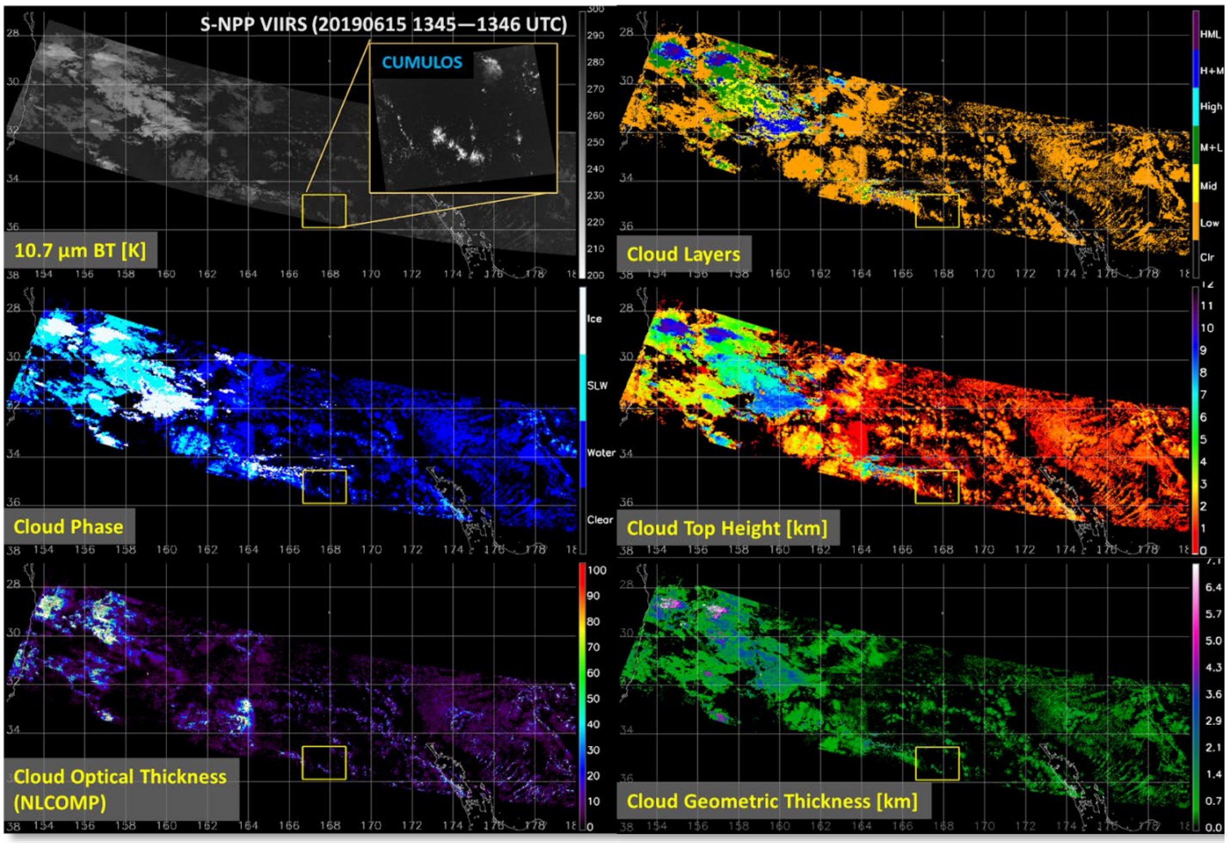


Figure 5. Example of simultaneous nadir overpass imagery between the NOAA/NASA S-NPP and the Aerospace Corporation CubeSat Multispectral Observing System (CUMULOS) for a Suomi National Polar-Orbiting Partnership (moonlight case study near New Zealand on June 15th, 2019. The case provided an opportunity to examine techniques for calibration transfer from the Visible/Infrared Imaging Radiometer Suite (VIIRS) Day/Night Band (DNB) to CUMULOS, and subsequent application of the calibrated CUMULOS data to operational NOAA cloud detection and characterization algorithms. The exercise yielded promising results which suggest that smaller, cost-effective low-light sensors hosted on a CubeSat or SmallSat constellation have the potential to yield useful imagery and cloud products.

The Project completed a low-light visible inventory and analysis in the context of various user applications. It delivered orbital simulations and swath analysis (presented last year) to Aerospace Corporation for GALAGO design studies, conducted additional orbital simulations to understand constellations and nighttime availability. It conducted a quantitative study of DNB/CUMULOS conjunctions, calibration transfer, and cloud properties analysis. Additionally, the project began working on DNB vs NIRAC, following a similar protocol to CUMULOS, as a way of examining the benefits and caveats to a near-infrared version of the DNB measurement. References were compiled on the use of the DNB, and showed that, in recent years, DNB is beginning to dominate low-light literature.

TMP 18-01: 3D Winds with Track and ADM-Aeolus

Lidia Cucurull is Deputy Director and Chief Scientist of NOAA's Quantitative Observing System Assessment Program (QOSAP).

NOAA designed the TMP-18-01 project to explore the value of active and passive 3D wind retrievals on NOAA's mission by:

- Evaluating European Space Agency's Aeolus horizontal line-of-sight wind quality through comparison against numerous references including field campaigns/reconnaissance
- Assessing the impact of Aeolus on global and hurricane NWP
- Investigate synergies between Aeolus and atmospheric motion vectors (AMVs)
- Assessing impacts of active and sounder-based 3D winds on global NWP through an Observing System Simulation Experiment (OSSE)
- Coordinating US/International Aeolus cal/val activities

The PIs and Presenters were Kevin Garrett (previously pictured) and Lidia Cucurull from NOAA's AOML. ESA's 2017 designated atmospheric 3D winds in the troposphere and Planetary Boundary Layer as a "targeted observable and observing system priority" for describing the transport of pollutants/carbon/aerosol and water vapor, wind energy, cloud dynamics and convection, and large-scale circulation. 3D winds were also determined to be the highest priority observable by NSOSA.

The European Space Agency's (ESA's) Aeolus satellite mission carries a Doppler wind lidar to acquire

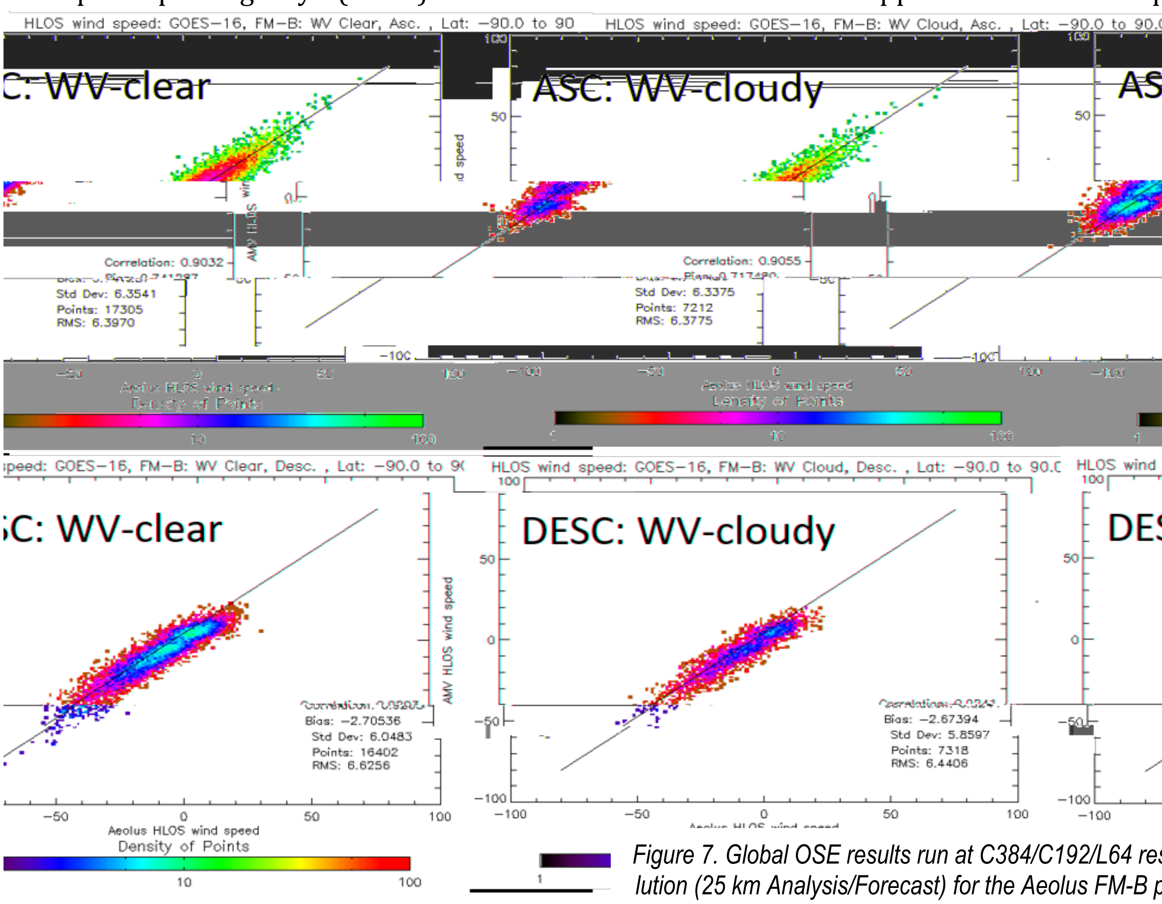


Figure 6. GOES-16 water vapor-clear AMVs exhibit a

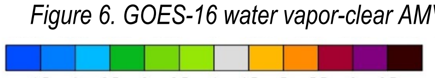


Figure 7. Global OSE results run at C384/C192/L64 resolution (25 km Analysis/Forecast) for the Aeolus FM-B period (2 Aug – 16 Sep 2019) showed a large reduction in analysis error in the Tropical Easterly Jet (show here, the 100 hPa U-wind Aeolus-ECMWF vs CTL-ECMWF).

profiles of Earth's wind on a global scale (Figure 6) with the goal of improving weather forecasts and climate models. The approach the TMP 18 team used in evaluating the Aeolus data was to leverage the FV3GFS global workflow and the Hurricane Weather Research and Forecasting (HWRF) model (a specialized model used to forecast tropical cyclone track and intensity) for impact assessments, develop variational bias correction (VarBC) schemes based on Aeolus to improve AMV data assimilation, exploit schemes to improve Aeolus assimilation near tropical cyclone environments, and leverage Community Global Observing System Simulation Experiment (OSSE) Package/COSS OSSE packages to explore active/passive 3D winds. They determined that Aeolus has demonstrated positive impact on NOAA's global NWP (Figure 7), NOAA's global and regional data assimilation systems are prepared for future Doppler Wind Lidar (DWL) observations, and that Aeolus can be used to characterize AMV height assignment errors. The team is running observing system impact experiments (OSEs) for different Aeolus time periods; preliminary results show large improvement in wind RMSE forecast fields in northern hemisphere (NH) and tropics (Figure 8). Further, they continued coordination with calibration/validation (Cal/Val) teams and the Aeolus Science Advisory Group.

Mike Hardesty of UC-Boulder/CIRES presented an overview of the project's international coordination efforts over the past year. The NOAA effort is recognized by the Aeolus group as significant effort of Cal/Val activities. The current Aeolus mission has been extended through 2022, and ESA is supporting several research tasks to investigate a possible follow-on mission that would be similar to current configuration, but with a few adjustments to increase return signal and improve resolution. The decision timeframe is 2022 or 2023, and international collaboration is welcome.

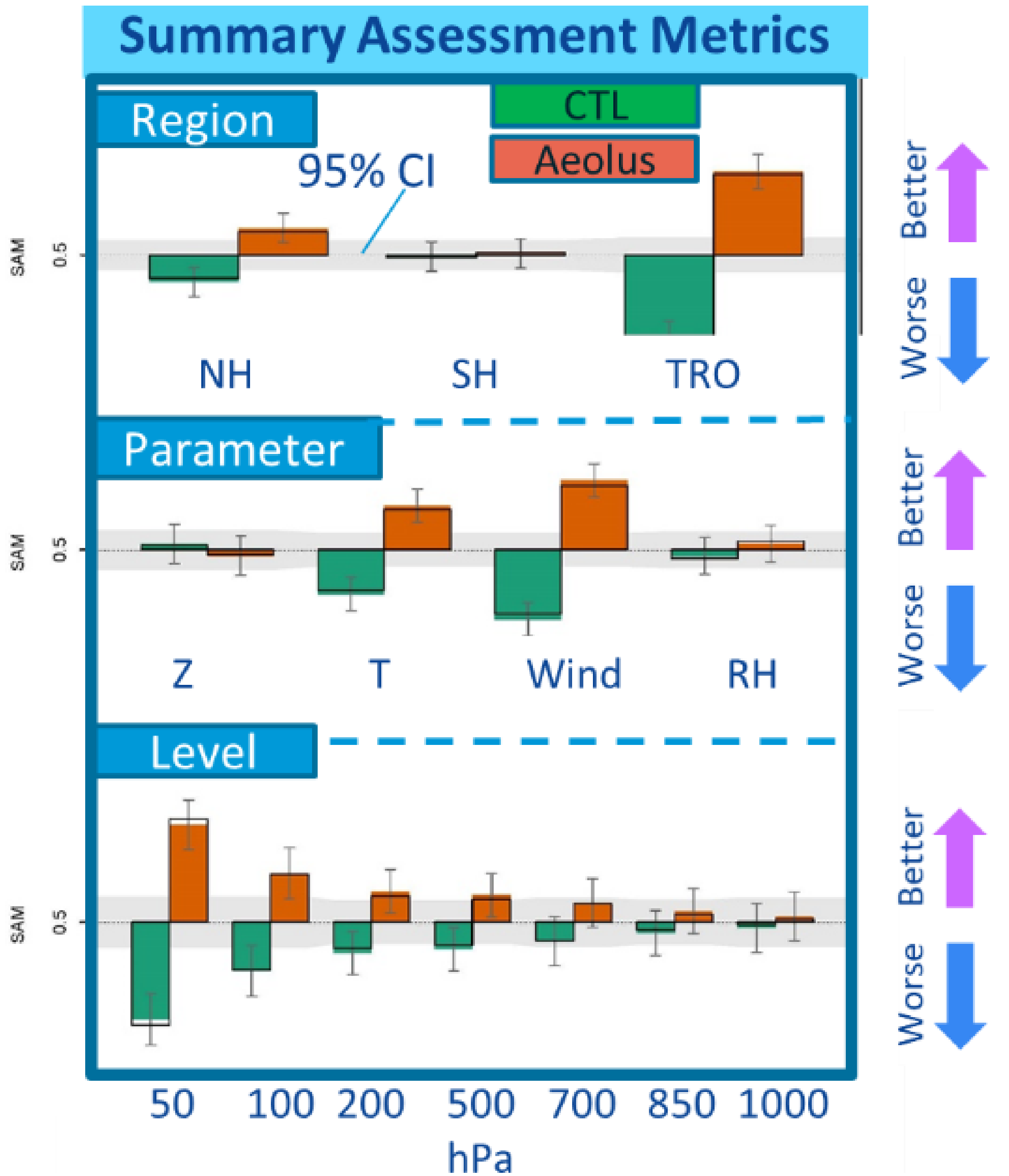


Figure 8. Global OSE results including the Aeolus winds demonstrated improvements in tropical wind forecasts over the control (CTL) runs at many vertical levels.

TMP 18-16: Spire GNSS Phase-Delay Altimetry

Eric Leuliette is the branch chief of the STAR Laboratory for Satellite Altimetry. As the NOAA Jason Program Scientist and Project Scientist, he co-chairs the Ocean Surface Topography Science Team.

TMP 18-16 is a continuation of the earlier TMP Phase I study on grazing angle GNSS-R (GAG-R) sea surface and sea ice height altimetry using Spire's commercial GNSS-RO satellite constellation.

The PI and Presenter was Eric Leuliette. Spire has implemented the GAG-R technique on its operational GNSS-RO satellites and has been collecting global ocean observations since February 2019. Altimetric inversion is possible when the sea or sea-ice surface is relatively smooth compared to the L-band wavelength and the reflected signal remains coherent. Spire operationalized a coherence detection and a phase-delay altimetric inversion processing system for these new data types. Spire found that: only 3% of open ocean reflections are coherent (e.g., Gulf of Mexico and Indonesian Throughflow), but a high percentage of sea-ice reflections are coherent; only about 1% of ocean reflections result in an altimetric estimate, but yield high precision: <10 cm RMSE (< 5 cm RMSE in some tracks); and 25% of sea ice reflections result in an altimetric estimate with high precision < 10 cm RMSE (<3 cm RMSE in some tracks), and phase coherence can distinguish between water, ice and first year versus multi-year ice. Such sea-ice observations have good potential for precision, along-track altimetry, sea ice extent mapping and sea ice type classification. The most promising results tended to be in the Arctic (Figure 9), prompting a shift in focus this year towards Arctic sea-level and sea-ice-height measurements. Tasks performed included continued ongoing global collection of observations using Spire's growing constellation of GNSS-RO CubeSats, refinement of reflector height retrieval algorithms, including implementation of more state-of-the-art geophysical corrections typical of precision altimeters, and calibration and validation of the altimeter estimates using ancillary sea surface height and sea-ice thickness data.

From a NOAA strategic perspective, leveraging existing GNSS-RO constellations to provide GAG-R observations of sea surface heights would supplement the coverage provided by nadir radar altimeters (Jason-3, Sentinel-3, and Sentinel-6 named in honor of Michael Freilich who headed NASA's Earth science program for many years). The operational altimeters have exact repeat coverage of 10 & 27 days—increased coverage would improve resolution of fronts and coastal sea level. This aligns with the NESDIS Mission Statement, the NWS Strategic Plan to Harness cutting-edge science, technology, and engineering to provide the best observations, forecasts, and warnings, and NSOSA which identifies global sea surface height as a priority for improvement.

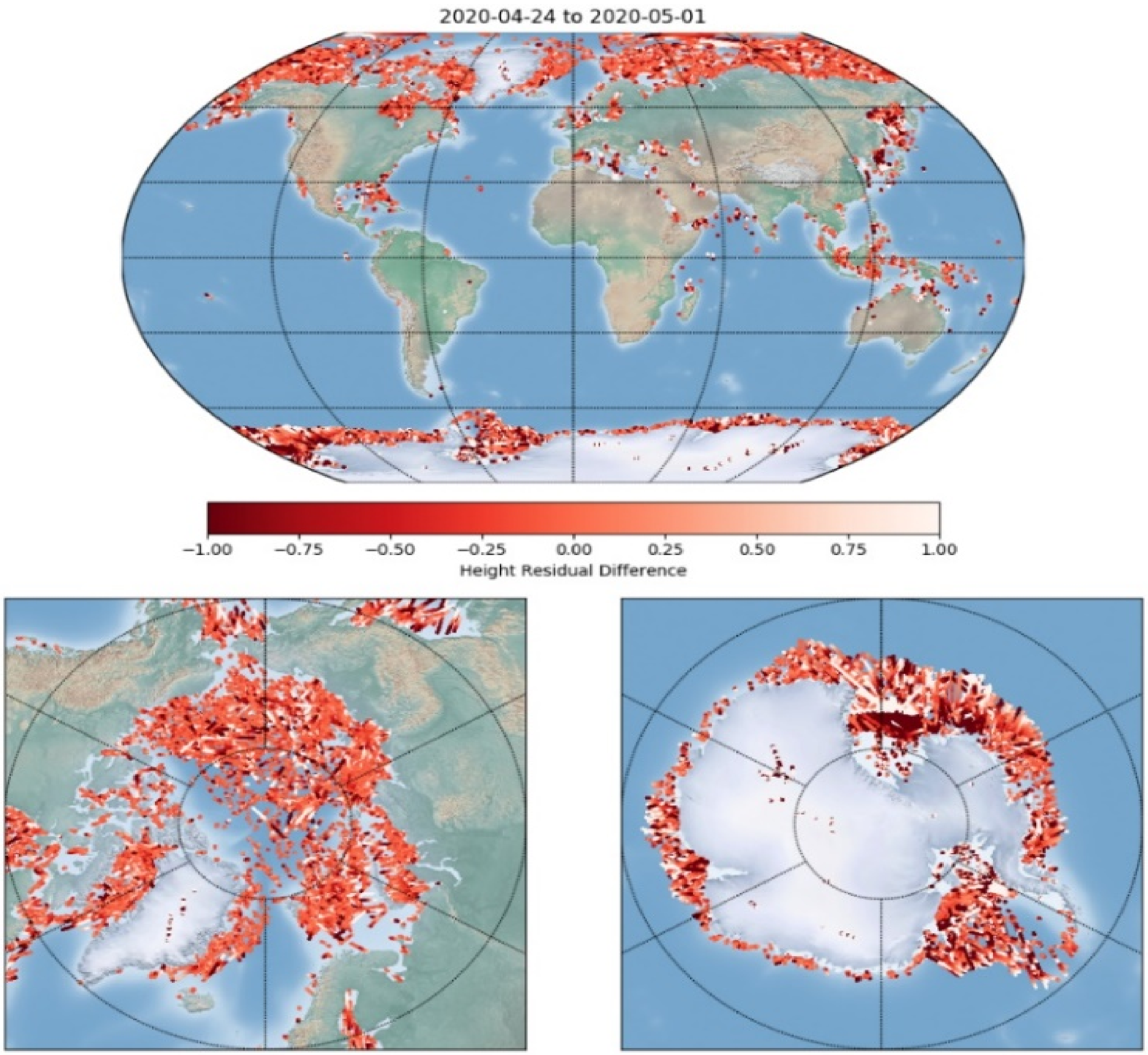


Figure 9. Coherence detection and a phase-delay altimetric retrieval RMS errors over one week (4/24-5/01).

TMP 18-17: Dual-Band Radar Satellite Altimeter Instrument Studies for Sea Ice and Sea State

> TMP 18-17 aimed at maturing the technology of a dual Ku-band/Ka-band nadir radar altimeter for ocean and cryosphere applications. To date, these radars have flown on separate satellites, and a mission combining these sensors would allow for synergistic observations of ocean sea states and determination of sea ice thickness.

The PI and Presenter was Eric Leuliette (pictured earlier). Earlier in 2020 ESA approved Sentinel-9, whose mission concept is a dual-band Ku/Ka radar mission CRISTAL (Copernicus polaR Ice and Snow Topography Altimeter; Figure 10). Radar penetration differences at different bands allows for measurement of both the air/snow and snow/ice layers. Exploitation of the different backscatter characteristics and penetration depths from each band can be used to retrieve snow depths to determine the true freeboard (sea ice thickness) needed for sea ice model assimilation and the needs of the National Ice Center. Dual-band observations would also allow for better determination of sea ice characterization (first-year versus multi-year ice) for navigation needs. This work aligns with the NESDIS Mission Statement and Vision, the goals of the NWS Vision: A Weather-Ready Nation, and a ESAS 2017 science and applications priority to improve regional-scale seasonal to decadal predictability of Arctic and Antarctic sea ice cover, including sea ice fraction (within 5%), ice thickness (within 20cm), location of the ice edge (within 1km), timing of ice retreat and ice advance (within 5 days).

The project had a primary goal of improving AltiKa mission sea ice / radar freeboard products utilizing the crossovers from AltiKa and CryoSat-2 separated by short times (< 3 days) and assumed that the retracked difference between the two is a proxy for snow depth (aka ”Altimetry Snow Depth”, or ASD). Crossover analyses were performed with a goal of developing an AltiKa retracker to understand stand-alone AltiKa radar freeboard estimates. For sea state studies, the team used crossover differences of existing Ka and Ku missions to study the relative biases on sea surface heights and roughness (as a proxy for wind speed) at each band. For sea ice thickness studies, the team developed a Ka-band retracker, compatible with existing Ku-band retrackers, to study the ability of dual-band missions to determine snow-depth and therefore the true thickness of sea ice.

The team spent most of the project developing Ka-band sea ice retracker for estimating freeboard. Using the Ka-band sea ice freeboard retracker, crossovers between AltiKa and CryoSat-2 were estimated over the period 2016-2019. The team loosened some of the filtering steps (pulse peakiness, AltiKa MP, etc.) to ensure that the literature thresholds are correct, and to determine the ability to use AltiKa alone for sea-ice / freeboard retrieval. The project confirmed that adapting Ku tracker to Ka-band has the best performance of methods tested. They found that the “sea-ice” retracker does the best job at retrieving heights comparable to CS-2, which is presumably at the snow/ice interface.

The project’s development of Ka-band sea ice retracker software had an entry TRL of 3/Proof of Concept (analytical and experimental critical function and/or characteristic proof-of- concept) and achieved a final TRL: 4/Component Validation (experiments with full-scale problems or data sets). The results of the study indicate that future progress could be accomplished using a radar waveform classification algorithm (e.g. machine learning). With Sentinel-9 in development, the Ka retracker could be adapted for delay-Doppler radar altimetry studies.

TMP 18-18: Exploiting CubeSat Ocean Color Data

Menghua Wang is a Supervisory Oceanographer and Chief of the STAR Marine Ecosystems & Climate Branch. He is the STAR Ocean Color Team leader and leads the JPSS VIIRS Ocean Color Environmental Data Record (EDR)/application team and calibration and validation (Cal/Val) team.

The intent of TMP 18-18 this project was to utilize/explore measurements from the emerging technology SeaHawk cubesat for potential production of quality ocean color products for scientific research and applications.

Menghua Wang is the PI and Presenter for TMP 18-18. The focus was on SeaHawk-measured Level-1B data and ocean color products compared with those from VIIRS, evaluation of CubeSat-like global ocean color data, make suggestions and recommendations as how to improve the system or how to use CubeSat data, and report on CubeSat-like systems for future ocean color measurements.

SeaHawk was developed as a part of Sustained Ocean Color Observations with Nanosatellites managed by the University of North Carolina Wilmington, The CubeSat system consisted of a pair of low-cost, multispectral, ocean-color sensors designed for better spatial resolution than SeaWiFS for coastal-margin to near-shore data:

- 8 SeaWiFS spectral bands
- 120m (vs. SeaWiFS 1km) spatial resolution
- 230km swath from 575 km orbit
- 125x smaller (10×10×10cm) & 45x lighter (<1kg) than SeaWiFS
- SeaWiFS-comparable Signal-to-Noise Ratio (SNR)

The original intent was to use SeaHawk data in the study; however, SeaHawk data (Figure 11) have not yet been released publicly. The SeaHawk team made a status update on December 24, 2019, indicating that "the most challenging one has been maintaining the highly accurate pointing stability that we require for the high-resolution imaging and high rate (100 mbps) x-band data downlinks that are two of the key test objectives of our mission."

The team obtained the SeaHawk sensor spectral response functions and compared them to VIIRS. They also worked on the satellite ocean color data processing system, completing all required updates for implementation of the SeaHawk ocean color data processing capability from Multi-Sensor Level-1 to Level-2 (MSL12). They worked on *in situ* data analysis for satellite ocean color product validation, including the successful completion of the 5th dedicated cruise over US east coastal region during September 8-17, 2019. While waiting for the SeaHawk data release, they have begun to explore uses of other CubeSat data, including the PlanetScope daily imaging constellation.

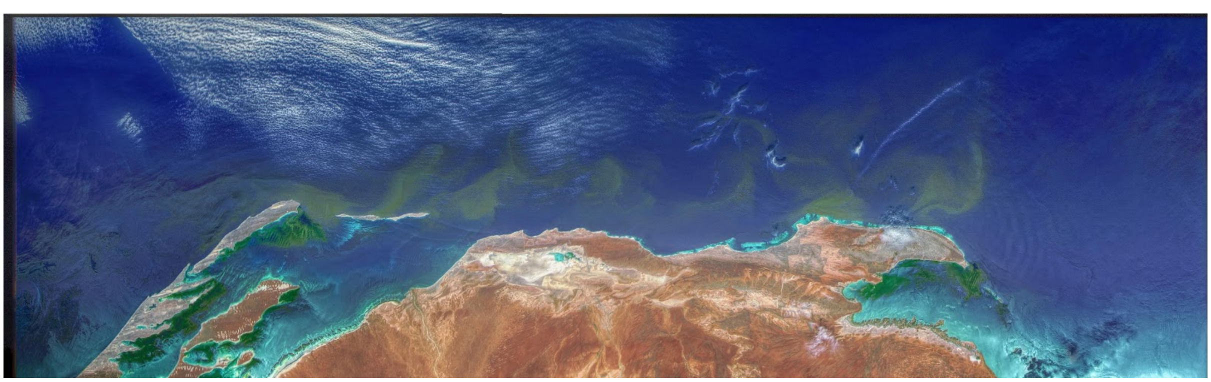


Figure 11. SeaHawk acquired its first fully stable image over northwestern Australia, showing the impressive capability of the SeaHawk instrument when it is operating on a stable platform.

TMP 19-08: Exploiting CYGNSS for land application

Ralph Ferraro is Branch Chief for the Satellite Climate Studies Branch, co-located with the Cooperative Institute for Satellite Earth System Studies (CISESS).

The objective of TMP 19-08 is to explore the exploitation of new GNSS-R data and new methodology from NASA's Cyclone Global Navigation Satellite System (CYGNSS) mission to maximize the benefit of the global observing system for land applications.

The project PI is Ralph Ferraro. The objective of this project is to explore the exploitation of new GNSS-R data and new methodology from NASA's Cyclone Global Navigation Satellite System (CYGNSS) mission to maximize the benefit of the global observing system for land applications. NASA's CYGNSS was developed to measure tropical sea surface parameters. Eight microsatellites were launched in 2016, each receiving existing GPS signals forming a bistatic radar. CYGNSS has demonstrated sensitivity to land surface properties including soil moisture and mapping of flooded areas. The availability of CYGNSS data is producing increasing interest in remote sensing land applications, but the exploitation of such signals is still in its early stages.

This TMP project is in line with NSOSA's strategic objective to explore new observation capability in GNSS-Reflectometry for land applications, including flood inundation mapping and soil moisture. Challenges still lie ahead for this new remote sensing data before they can be accepted as well-understood and reliable measurements. These include: (1) vegetation (biomass) and land cover effect; (2) terrain effect; (3) incidence angle dependence on GNSS-R sensitivity to flood inundation and soil moisture. The project objectives are to: (1) increase our understanding of the sensitivity of CYGNSS data to identify inundated area for different land types/surface covers and (2) increase our understanding of the sensitivity of CYGNSS data to monitor soil moisture changes in different vegetated land covers and terrains. CYGNSS reflectivities over SE Texas show a region impacted by Hurricane Harvey (Figure 12). We are trying to associate changes in surface wetness with the CYGNSS signals.

The primary FY19 accomplishments include the selection of cases for study, collection, collocation, classification of CYGNSS L1b data, collection of other ancillary data (e.g., land cover/land type, vegetation state index, and soil moisture from SMAP), and initiation of analysis of CYGNSS L1b signal sensitivity to inundation for different land cover types and vegetation types, and incidence angle. One challenge is data quality and quantity—data that were reported are not necessarily validated. The question that remains is: Despite a complex scanning geometry and narrow sampling pattern, can we amplify enough signal out of this product to sense water on the land surface?

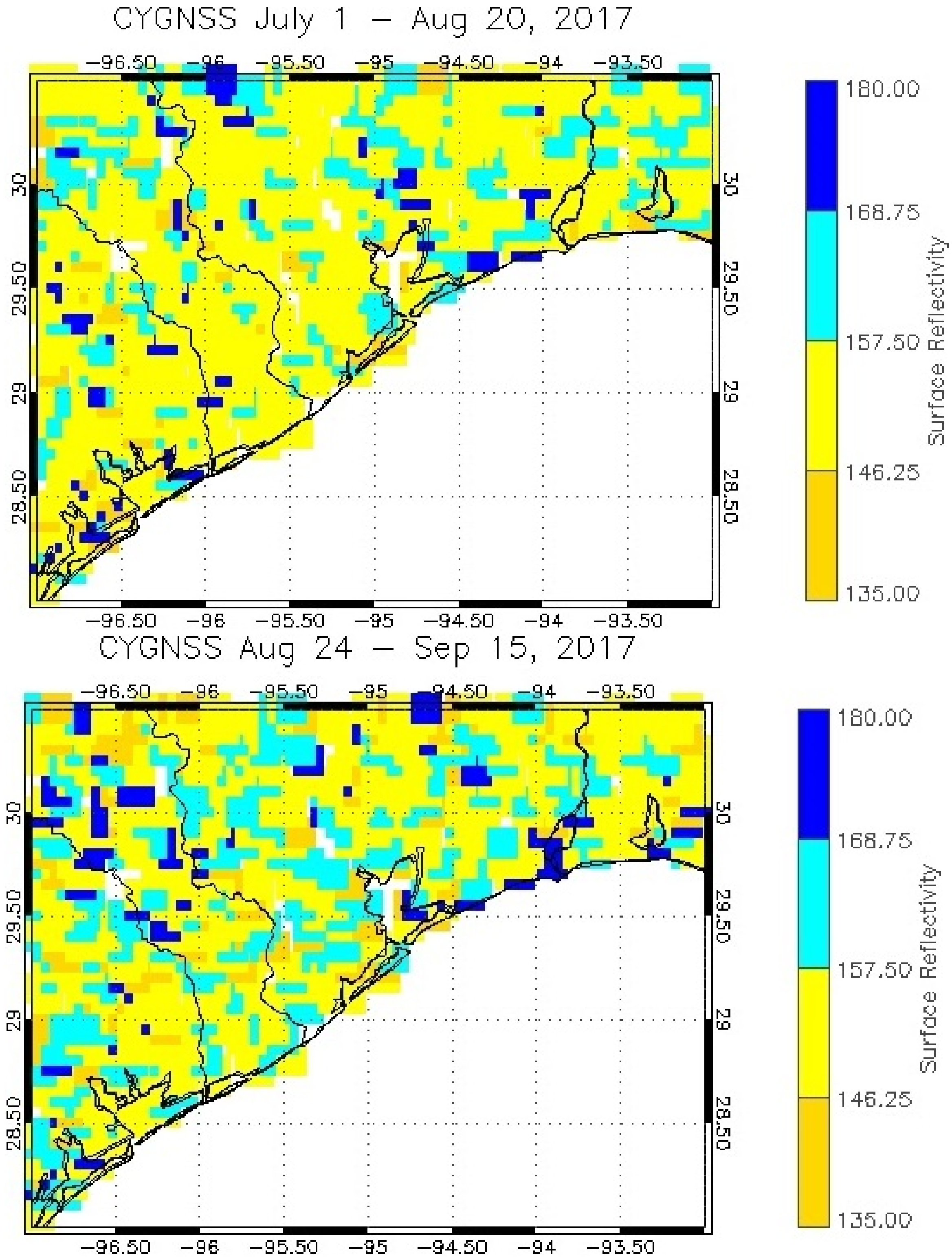


Figure 12. CYGNSS Surface Reflectivity before and after Hurricane Harvey.

4. Session 2: Maturing GEO Architecture (technology, platforms, data)

The three TMP projects in this session are responsive to the first NESDIS Strategic Initiative, to:

"Advance terrestrial observational leadership in geostationary and extended orbits,"

TMP 18-10: Exploring Use of Near-Space Observations for Satellite Data Validation and Global NWP

Katherine Lukens is a Post-Doctoral Associate with the Cooperative Institute for Satellite Earth System Studies (CISESS) and NOAA/NESDIS/STAR.

TMP 18-10 explores the value of using high altitude balloon observations in NOAA (1) for the comparison/validation of remote sensing retrievals produced by NESDIS and (2) in NOAA global numerical weather prediction (NWP) applications.

TMP 18-10 was presented by Kevin Garrett (PI, pictured earlier) and Katherine Lukens. There is a gap in *in situ* stratospheric observational data which challenges product validation and numerical weather prediction DA. Loon stratospheric balloon observations have the potential to help fill this gap (Figure 13) and improve analyses and forecasts through DA.

This project explores near-space observations specifically from stratosphere balloons, which have a primary function of providing communications infrastructure to remote areas of the world based on their demographic needs. The project's goal is to investigate the value of these observations for NOAA missions and applications by exploiting these observations within our weather prediction systems. Loon

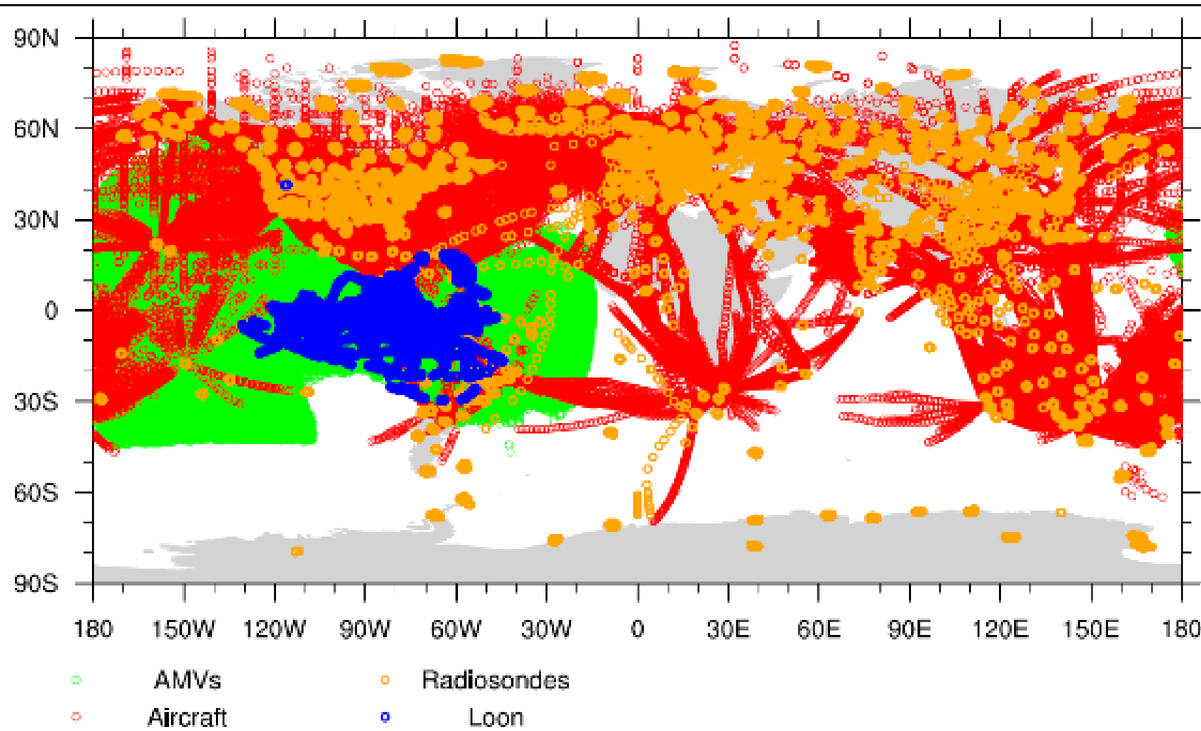


Figure 13. Wind observation locations with p < 200 hPa during Loon Monitor Experiment: 2018120100-2018123018 to see impact of assimilated Loon winds over eastern Equatorial Pacific (where balloons tend to reside during period).

balloons by nature are not uniformly distributed, and the team encountered a few challenges because of this. The focus this year is the integration of *in situ* observations into NWP. The principal FY19 accomplishments included:

- Extension of the gridpoint statistical interpolation (GSI) to ingest and assimilate Loon balloon observations, focusing on winds which are treated as individual aircraft observations in the GSI. The experimenters wish to treat the individual Loon balloon flights as separate sets of observations due to the varying biases and spatial and temporal coverage among the balloons (this is how aircraft flights are treated in the GSI).
- Running new FV3GFS Baseline (Control) Experiment on the Hera supercomputer, which was necessary due to retirement of the supercomputer where the original baseline was completed. All subsequent experiments are run on Hera.
- Completed the Loon monitor experiment, which is a precursor to the actual assimilation of Loon winds. In this experiment, Loon winds are ingested and monitored, but not yet assimilated.
- Established Loon preprocessing algorithms in preparation for assimilation. This includes removing erroneous data and duplicates, as well as identifying and removing maneuver periods, which are defined as intentional adjustments in altitude made by Loon to avoid passing storms or to move the balloon into different air streams to move the balloon to its desired location.

At present, the team is wrapping up the last few preprocessing determinations needed before the assimilation experiment can begin. The plan is to run two experiments. The first will include all wind observations. The second one, if time allows, will repeat the first experiment but with more refined specifications. Loon is exploring the commercial environmental data market based on TMP 18-11 study on radio occultation (RO). Loon has deployed five balloons with GNSS-RO receivers. Once data are available, Loon will seek NOAA feedback on data quality and potential. This project has the potential for exemplary future outcomes with continued collaborations with Loon.

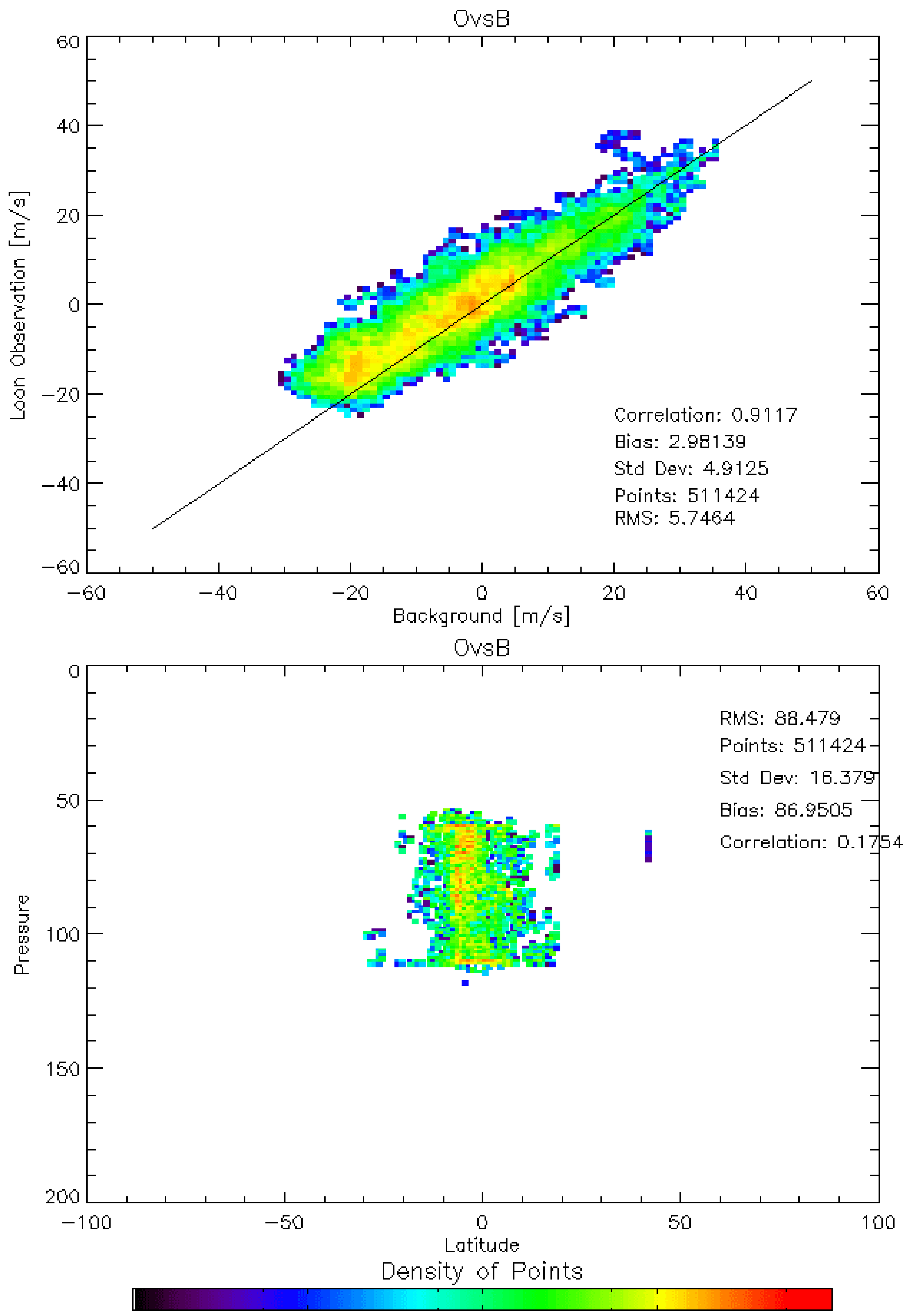


Figure 14. Loon U-wind vs Background [m/s]—bias is thought to be due to the model background, as few wind observations exist at the Loon level (left) and Number Density of Loon Observations (Pressure [hPa] vs Latitude; right).

TMP 18-19: Demonstrating the Potential Benefits of a Tundra Orbit

Research Scientist Timothy Schmit is internationally recognized as an expert in meteorological remote sensing from geosynchronous orbit.at the STAR Advanced Satellite Products Branch co-located at the University of Wisconsin.

TMP 18-19 focuses on studying the potential advantages and disadvantages of Tundra orbits and potential impacts on nowcasting, weather forecasting, and other hazard monitoring, such as high latitude volcanoes and fires.

TMP 18-19 was presented by PI Timothy (Tim) Schmit. Accurately forecasting the high impact weather events in high latitudes, such as Alaska, is highly desired. Current satellite observing systems, either GEO or LEO, do not meet the requirements of high temporal/spatial resolution and spatial coverage. This project studies whether tundra orbits can fill the data gap, providing needed information to the NWS to help with weather forecasts. Currently, NWS relies, in part, on the Advanced Baseline Imager (ABI) on board GOES-17 for weather forecasting in high latitudes and polar regions, such as the Alaskan region. However, due to large local zenith angles, the ABI observations in the Alaskan region have coarse resolution, making it difficult to monitor fine scale weather and environmental events. High-inclination elliptical ("Tundra") orbit satellites, coupled with existing imaging capability from ABI, may fill the gap, providing needed environmental data and helping NWS to build a Weather-Ready Nation, especially in high latitudes and the polar region. This project is in line with NSOSA's strategic objective to study whether tundra orbit can provide "availability of core capabilities" for high latitudes. Note geostationary or polar orbiting satellites may only provide "availability of all capabilities," which do not meet the requirements for high-impact weather forecasts.

The team applied a simulated ABI in mode 6 to Tundra satellites (Figure 15): imaging a full disk every

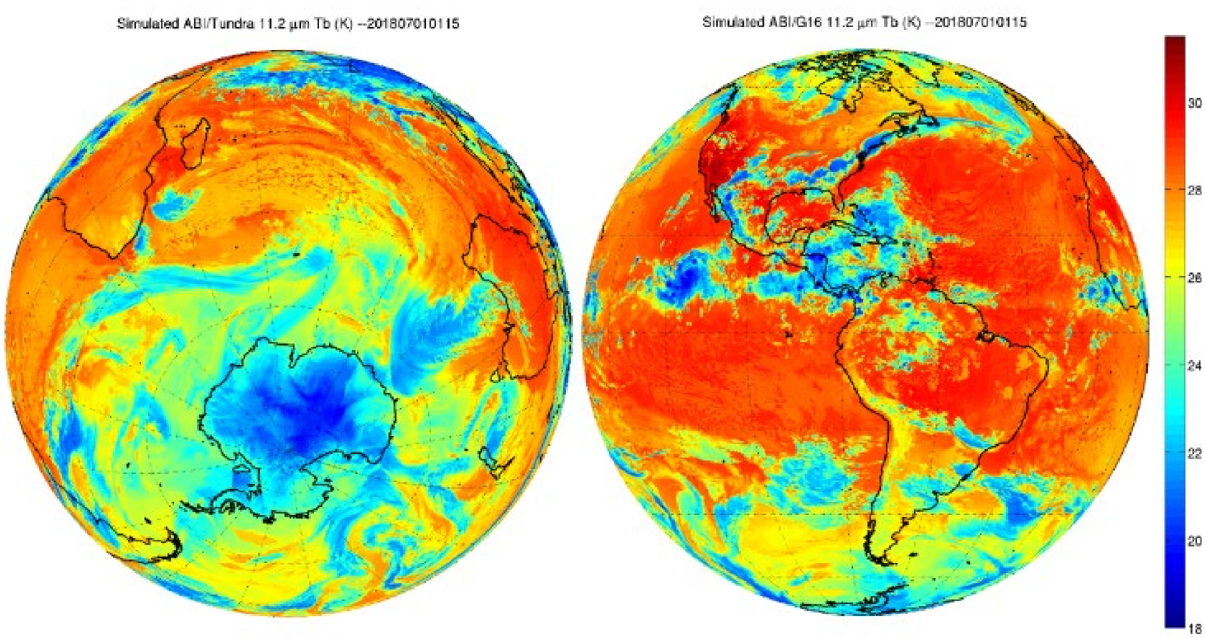


Figure 15. Simulated ABI 11.2 micron brightness temperature (Tb) from (left) Tundra orbit and (right) GOES-16 using G5NR as input at 0115 UTC on July 1, 2018.

10 minutes with max viewing angle of 8.7 degrees in both front/rear and left/right directions. They developed and applied three criteria to quantitatively evaluate the imaging capability from single or multiple satellites. They determined a set of orbital parameters for optimized coverage of the Alaskan region based on imaging capability evaluation. They found:

- Constellation of two Tundra satellites can be used to continuously monitor the Alaskan region
- Constellation of three Tundra satellites are more suitable for global applications than 3 GEOs over high latitudes and polar regions, but not for Tropics and mid-latitudes
- Both GEO and Tundra are better than three LEO imagers
- Tundra satellites or combination of Tundra with GEO can provide continuous imaging capabilities for regional applications with large domain coverage, fulfilling NWS requirements

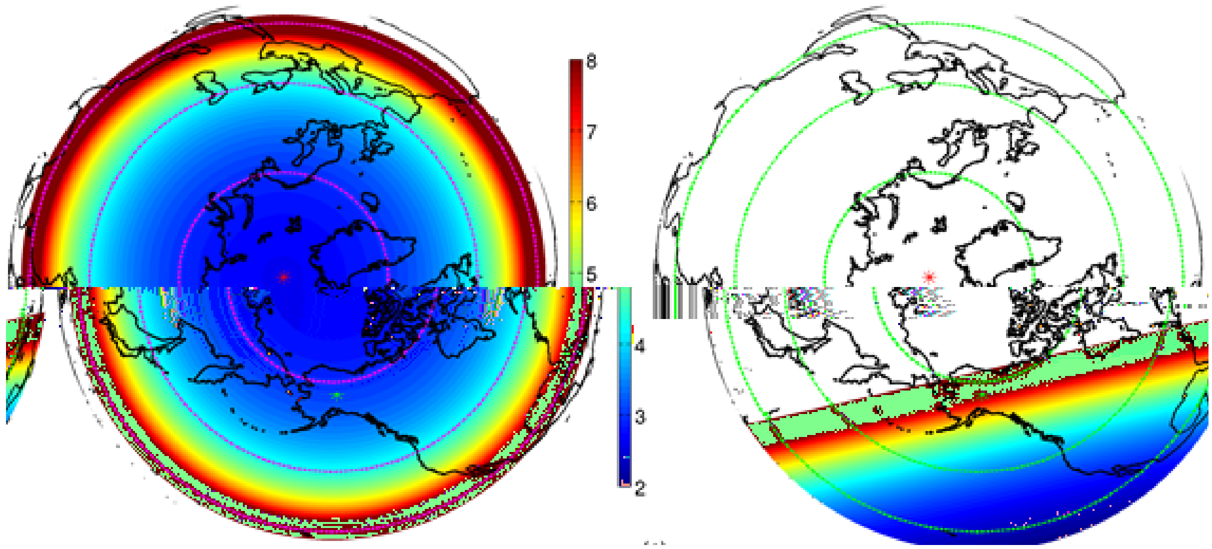


Figure 16. Simulated ABI footprint size (km) for the Tundra orbit (left) and GOES-17 (right); a local zenith angle threshold of 80° is applied.

In terms of comparisons, LEO is best for field of view size (Figure 16). Each Tundra platform would give good coverage of the Arctic. GEO gives much less coverage and much worse spatial resolution at high latitudes. To provide an equivalent temporal refresh would require ~10 LEOs to cover Alaskan region all continuously. However, the three-satellite GEO is more useful for the tropics.

TMP 19-09: Assessment of Value and Impact: OSSE for GEO Hyperspectral IR

TMP 19-09 was funded to assess the value of a GEO hyperspectral IR sounder over GOES domains for NOAA by creating simulated GEO data over GOES-East and -West domains, developing retrieval algorithms to assess products and information content, developing data assimilation systems to assimilate GEO sounder radiances, and assessing the value and impact on NOAA short/medium-range weather forecasting, hurricane prediction, Warn-on-Forecast (WoF), and nowcasting.

TMP 18-19 was presented by PIs Kevin Garrett (STAR) and Lidia Cucurull (AOML; both pictured earlier). It seeks to answer the question: “How will a GEO IR sounder over the U.S. further NOAA’s mission?” This work is integral to NOAA’s compliance with H.R.353, The Weather Research and Forecasting Innovation Act of 2017 (WRFIA), which requires that OSSEs to assess the value and benefits of observing capabilities and systems be conducted before acquisition of major government-owned or government-leased operational observing systems with a lifecycle cost of more than $500 million. From a strategic perspective, the timing is critical. The next-generation GEO architecture studies are currently in progress, with considerations for IR and microwave sounders, visible/IR imagers, ocean color, DNB, atmospheric composition, and lightning mapper sensors. The

results have been contributed to the GeoXO IR Sounder Value Assessment Team report as a part of the NOAA/NASA Pre-Phase-A study.
The approach followed the MTG IRS instrument design, including channels, resolution, and scan characteristics. The team used the Community Global Observing System Simulation Experiment (OSSE) Package (CGOP) to simulate GEO sounder data with 5-minute refresh for Continental U.S. (CONUS) scans for retrievals for Warn on Forecast (WoF) application and 30 minute full-disk refresh for global NWP application at 4-10 km spatial resolution. The team completed simulation of the GEO hyperspectral sounder (HSS) orbit and radiances following the IASI spectral coverage for the GOES-East spacecraft, completed integration of the GEO-HSS into CGOP and performed impact experiments/assessments.

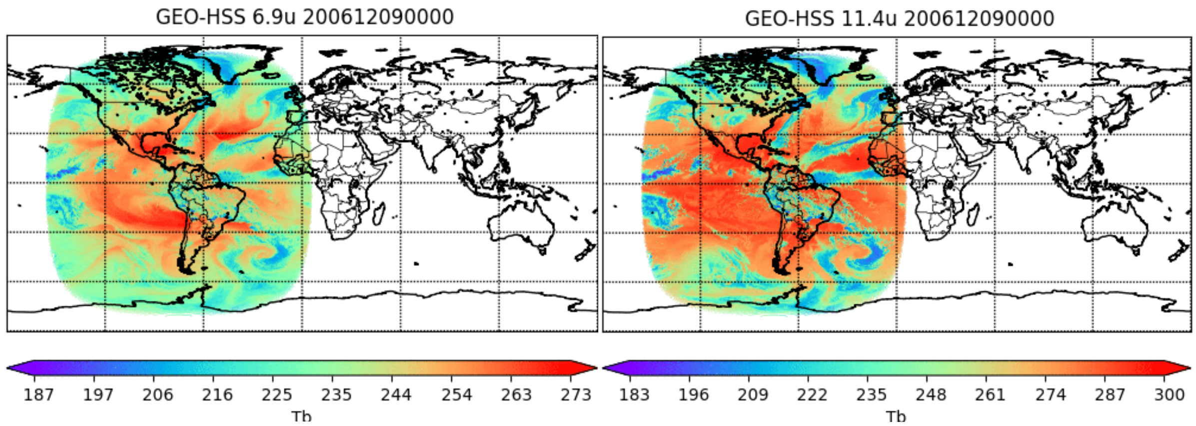


Figure 17. Full disk, ½ hourly simulation at 6.9 and 11 µm from the simulated U.S. GEO hyperspectral sounder

The results show positive impact to global NWP forecast skill from a single GEO IR HSS, even with the 4 km observations thinned to a 140 km thinning grid. Overall positive impact resulting from assimilating GEO-HSS in FV3GFS was particularly evident for stratospheric temperature, Pacific-North American temperature, and tropical winds. The planned WoF OSSE should be completed in Q3 FY21.

A second activity of TMP 19-09 completed a hurricane OSSE to quantify the impact of GEO HSS assimilation in HWRF. GEO HSS observations were thinned to every 5th point (~20 km horizontal resolution at nadir), with a temporal resolution of 6 hrs. centered at the analysis time (1 hr. temporal resolution for HWRF runs). The global runs used 20 ensemble members (40 ensemble members for the HWRF runs) during the August – September 2014 observing system. Impacts were evaluated by conducting two OSSEs using the latest implementation of HWRF valid as of July 2020. Both OSSEs used the same model, domain, resolution, and physics as the operational version of HWRF. Differences arose, however, in the initialization options used for each OSSE. The across-track errors were mainly a function of initialization location of the cyclone. The synoptic steering flow imparted by the trough present over the CONUS would, therefore, be different. The team is now moving towards a higher-resolution Nature Run, the result of a high-performance computing collaboration between the U.S. Department of Energy and the ECMWF Forecasts. The TMP project team will use the Nature Run developed during this collaboration for upcoming OSSEs to better represent the high-resolution information.

5. Session 3: Maturing Ground Processing and Exploitation of Technology

The four TMP projects in this session are responsive to the fourth NESDIS Strategic Initiative, to:

"Develop agile, scalable ground capability to improve efficiency of service deliverables and ingest of data from all sources,"

TMP 18-03: Accelerate Satellite Data Exploitation (Calibration, Assimilation, Product Generation) in the Era of Small Satellites

TMP 19-09 was funded to assess methodologies for optimally exploiting constellations of SmallSats which have very limited lifespans, and to assess the potential utility of small satellite constellations for NOAA's NSOSA study. The predecessor project TMP 18-03 focused on the steps in the end-to-end processing chain toward operational exploitation that present the most opportunity for cost (time) savings.

The PI and Presenter was Kevin Garrett (pictured earlier). This project continued work done using FY18 funds. This presentation reports on activities that were achieved after the 2018 EOY Annual Review.

SmallSat platforms offer the potential for hosting payloads for IR, microwave, and RO sensors, and may be able to meet NOAA's observational requirements from a cost-effective, agile satellite architecture (complementary to programs of record). Typical SmallSat payloads may have short design life (< 2 years), therefore it is critical to accelerate the steps toward operational use of SmallSat data. Additionally, with potential for large constellations of SmallSats, data volumes and variety will also present challenges for operational exploitation.

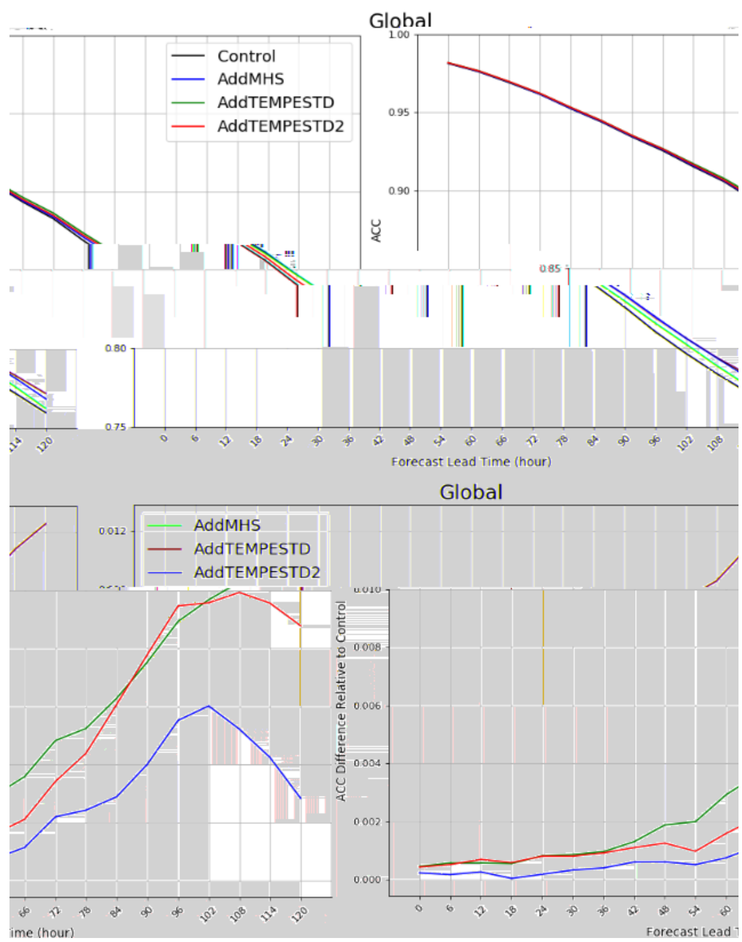


Figure 18. TPW Anomaly Correlation Coefficient (ACC) averaged over all December 2018 cycles. The experiments have slightly higher forecast scores in terms of TPW, likely due to the slightly reduced dry bias in the Tropical region.

The main FY19 accomplishments included: (1) finalizing the implementation of TEMPEST-D in FV3GFS; (2) performed OSEs to assess the impact of TEMPEST-D; (3) assessing the relative impacts of TEMPEST-D and MHS (e.g., for the global 500 mb Geopotential Height and total precipitable water anomaly correlation coefficients); and (4) continuing study of Aeolus assimilations and comparisons of forecast fields with Aeolus assimilated to field campaign observations. Three cycled FV3GFS experiments for two time periods (December 8-12, 2018 and May 12-

22, 2019) were run:

- Control: assimilate all observations as operational configuration, but only include MHS from NOAA 19 and Meteorological Operational Satellite (MetOp)-B, and leave GMI out for verification purpose
- "AddMHS": same as control, and assimilate MHS from MetOp-A
- "AddTEMPESTD": same as control, and assimilate TEMPEST-D
- The cycled FV3GFS experiment configuration included both deterministic: C384 (nlon, nlat, nlev) = (1536, 768, 64) and ensemble (80 members): C192 (nlon, nlat, nlev) = (768, 384, 64) configurations

The project found that the level of effort needed to exploit SmallSat data in NWP follows the sensor and mission maturity level. Demonstration missions require more intensive Cal/Val, quality control, and error characterization. As sensors and systems mature, processes become more routine. For operational SmallSat missions, processes must be efficient and R2O infrastructure must be agile. This project will restart in FY20 to focus on the development of tools to rapidly assess SmallSat data quality and NWP impact to facilitate seamless R2O transitions.

TMP 18-04: RO Data Exploitation

Shu-peng Ben Ho is Lead Scientist, Global Navigation Satellite System Radio Occultation Program at STAR. Before joining NOAA, Ho was a COSMIC project scientist at UCAR.

The objective of TMP 18-04 is to evaluate COSMIC-2 impact in global NWP at NOAA; optimize current RO data assimilation methodology to improve COSMIC-2 impact; develop, test, and implement new radio occultation (RO) data assimilation strategies to optimize COSMIC-2 (RO) impact in NOAA's models (global and hurricane prediction); and improve the assimilation of RO observations in the lower troposphere. Furthermore, efforts will focus to continue to characterize, and potentially correct, the COSMIC-2 signal-to-noise ratio (SNR) related observation biases and define the optimal observation errors for NWP applications.

The PIs were Lidia Cucurull (AOML, pictured earlier) and Shu-peng Ben Ho (STAR). The Constellation Observing System for Meteorology, Ionosphere and Climate-2 (COSMIC-2), was successfully launched into equatorial orbit on June 24, 2019. With an increased SNR due to improved receivers and digital beam steering antennas, COSMIC-2 is expected to produce about 5,000 high-quality RO profiles (Figure 19) daily over the tropics and subtropics. Further exploitation of the new RO data from COSMIC-2 and optimization of the utilization of COSMIC-2 observations will improve NOAA's weather analyses and forecasts (Ho et al., 2020a).

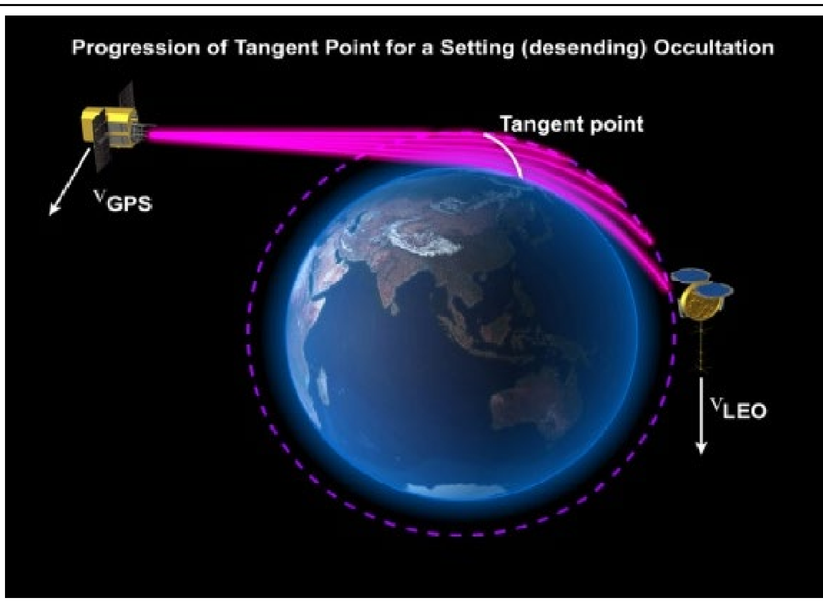


Figure 19. Bistatic radio occultation remote sensing geometry.

Main FY19 accomplishments included the completion of extensive quantitative evaluations of impact

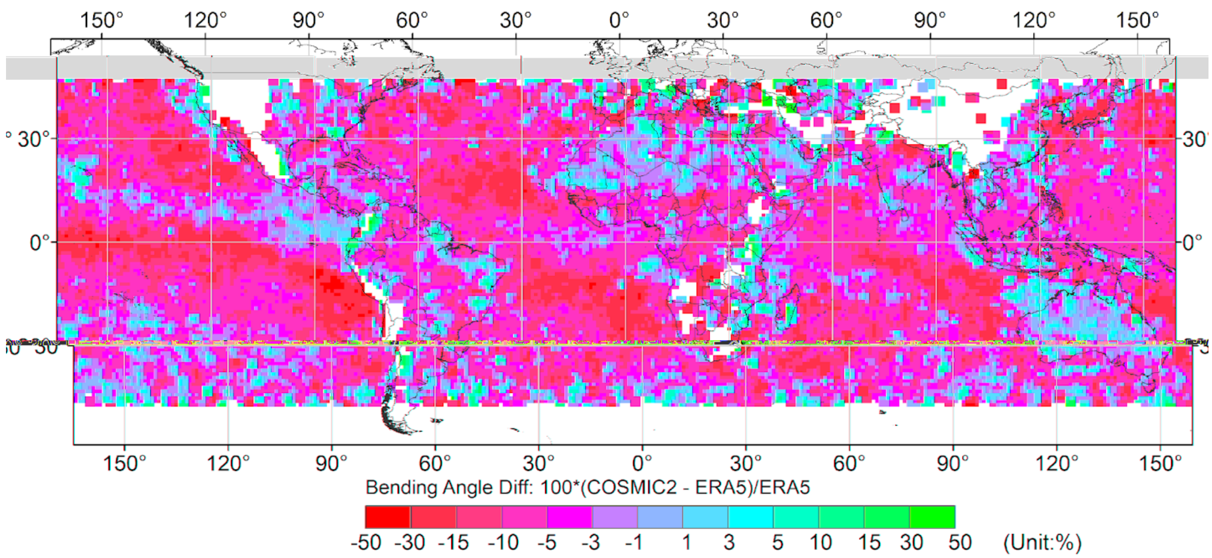


Figure 20. The percentage bending angle difference of COSMIC-2 relative to ERA5 on geopotential height.

from COSMIC-2 and other RO missions in NOAA's current NWP configuration, implementation of changes to COSMIC-2 quality control procedures in assimilation algorithms to improve performance and enable the operational implementation (R2O transition), and developed and published a baseline configuration for an enhanced RO DA methodology to improve impacts in the lower troposphere (Cucurull and Purser, JGR, 2020).

COSMIC-2 improved winds in NH and to some extent the tropics. An issue was identified where NWP model performance degradation in the southern hemisphere was caused by assimilation of COSMIC-2 only. The same level of degradation existed in pre-operational runs at NCEP (v15.3) and EMC had informed that COSMIC-2 was not going to be operationally assimilated because of the current impact. A stricter quality control configuration for COSMIC-2 profiles fixed the southern hemisphere degradation. As a direct result, COSMIC-2 became operationally assimilated at NCEP on May 27, 2020. This was a coordinated effort between NESDIS, OAR, NWS/EMC, and JCSDA.

A second aspect of TMP 18-04 is to assess the quality of COSMIC-2 data—is it consistent or better than those of COSMIC-1 (see Ho et al., 2020b) in terms of precision, long-term stability, accuracy in the lower stratosphere, troposphere, and particularly in the lower troposphere? To do this, the team is optimizing the use of RO bending angles in altitudes where the observations provide the most pertinent information developing methods to characterize the bending angle observation errors (Figure 20), using a full-wave (multiple phase screen) forward operator to characterize the spread of the bending angle spectrum due to small-scale atmospheric irregularities, verifying the effectiveness of improving error estimates in data assimilation, and quantifying the uncertainty in the bending angles under low SNR conditions and initial setup for the DA sensitivity studies.

TMP 18-12: Artificial Intelligence and Machine Learning for Next-Gen Algorithms – Operational Implementation

Eric Maddy is employed as a senior research scientist (on-site contractor) at STAR's Satellite Meteorology and Climatology Division; his specialty is leveraging modern artificial intelligence for remote sensing and NWP applications.

TMP-18-01 applies artificial intelligence techniques to optimize the exploitation of satellite data, including the calibration of near-real-time weather Imagery, data fusion, and assimilation and exploitation.

The PI is Kevin Garrett (pictured earlier) and the presenter was Eric Maddy. As background to this project, NESDIS is addressing a Big Data challenge and the trend suggests it may increase in terms of variety and potentially volume with SmallSat constellations in the future. Artificial Intelligence (AI) and machine learning are natural technologies to leverage when moving to cloud-based infrastructure, and especially to process large volumes of data. AI has been proven to provide similar scientific performances as heritage approaches but with significant CPU time savings in some cases. This has ramifications for IT infrastructure (and cost), as AI is a good fit technology to develop next-generation algorithms.

The team developed an AI-based technique to match or slightly improve temperature and water vapor soundings relative to NUCAPS and produce retrievals at 3x the resolution of NUCAPS. A comparison of the number of days that can be processed per day using the same computing resources and using either the next generation (MIIDAPS-AI) algorithm or traditional variational approaches (Multi-Instrument Inversion and Data Assimilation Preprocessing System-Artificial. Intelligence (MIIDAPS-AI), Microwave Integrated Retrieval System (MIRS), or NUCAPS) shows exceptional potential for gains in computational efficiency (~100x for CrIS; Figure 21).

	ATMS/MIIDAPS-AI	ATMS/MiRS	CrIS/MIIDAPS-AI	CrIS/NU-CAPS	CrIS/ATMS/MIIDAPS-AI	CrIS/ATMS/NU-CAPS
Algorithm (days/day)	720	3.6	400	3.9	250	3.9

Figure 21. AI-based remote sensing techniques show exceptional computational efficiency potential.

In addition to implementing and assessing AI-based remote sensing techniques, the team successfully applied AI to high-priority observing systems, which require processing high-volume, big data, (Boukabara, et al., 2019a and Boukabara et al., 2019b; see Section 6, References) and assessed the efficiency of those methods. Those projects included:

- AI-based atmospheric winds (3D winds) from polar satellites
- Real-time weather imagery –infrared- (Performing AI-based calibration of operational sensors, including high-visibility geostationary GOES-17 imager data to assess whether we can mitigate the effects of the heat pipe anomaly)
- Global near-real-time microwave imagery: AI-based use of microwave sensors
- Data fusion/assimilation to generate coherent geophysical analyses

The team successfully demonstrated AI-based approaches for all projects and significant improvements in the computational efficiency (and hence cost) and quality (Figure 22) was achieved in all projects. As an example, statistical assessment of AI-based data fusion/assimilation approaches based on Berkeley-AI's Pix2Pix image-to-image translation software shows improvement over GFS forecasts in regions with and without simulated satellite data coverage, and overall. These global analyses of up to 15 geophysical variables (T(p), RH(p), U,V-winds(p), surface pressure and temperature) at 25km resolution run on a single CPU and are produced in <1sec.

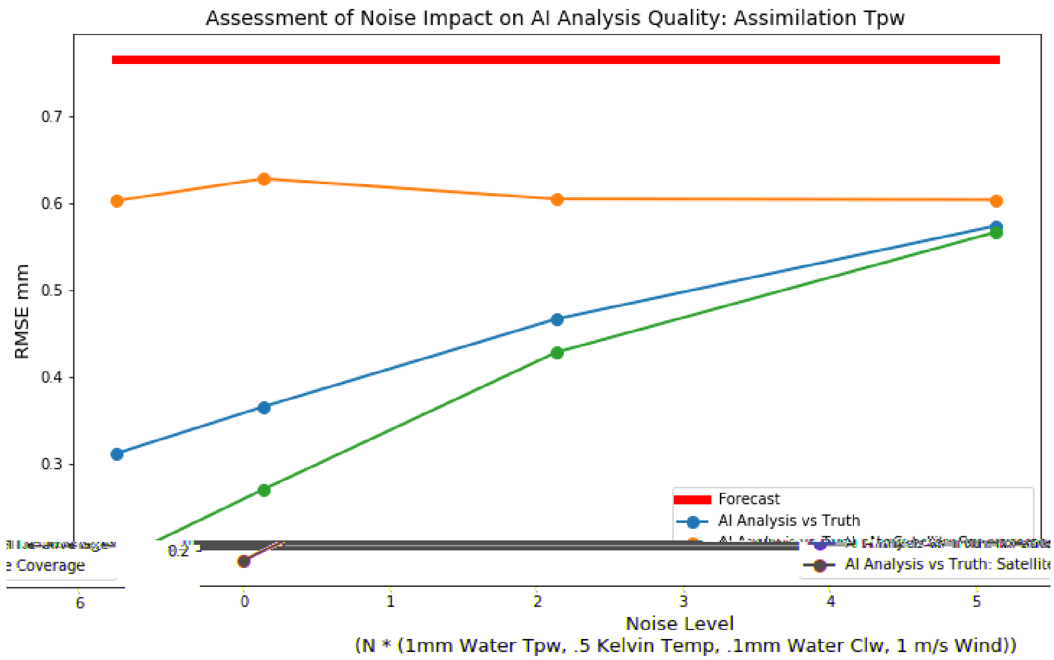


Figure 22. Global average GFS forecast (red) and AI-based analysis total precipitable water (TPW) root-mean-squared error relative to GDAS analysis as a function of simulated polar-orbiting microwave observation noise for January 2019. AI-based analysis errors are computed for locations with satellite coverage (green), without coverage (orange), and overall (blue). In general, the AI-based analysis decreases GFS forecast background uncertainties at all simulated observation noise levels.

TMP 19-07 Geostationary Infrared Hyperspectral Sounder Ground Processing System Study

Satya Kalluri is the Chief of the Cooperative Research Programs (CoRP) at STAR. He was the lead NOAA scientist for GOES-R ground segment algorithms and product generation system development,

TMP-19-07 was funded to perform a comprehensive study and develop a preliminary cost estimate for developing a ground processing system of a future hyperspectral infrared sounder in the geostationary orbit.

The PI was Satya Kalluri (STAR). Hyperspectral IR sounders on sun synchronous polar orbiting satellites are routinely assimilated into NWP models and have demonstrated improvements in forecast skills (e.g. AIRS, IASI, CrIS). They are considered vital for retrieval of atmospheric profiles of water vapor, temperature and trace gases (e.g., CO, CO_2, CH_4, O_3) for forecasters and NWP model initialization. NOAA is conducting pre-formulation studies for initial technical and cost assessments for including a hyperspectral IR sounder in a future GEO architecture. Existing hyperspectral infrared sensors were reviewed to model what a NOAA GOES hyperspectral IR sounder would look like to determine data characteristics.

A geostationary sounder will provide improved observations of temperature, moisture, and wind profiles at a higher refresh rate than those that are observed in LEO that will allow advancements in NWP to predict, detect, and monitor severe weather events that will improve weather forecasts to support the NWS Mission to: "*Provide weather, water, and climate data, forecasts and warnings for the protection of life and property and enhancement of the national economy*" and Vision for: "*A Weather-Ready Nation: Society is prepared for and responds to weather, water, and climate-dependent events*." The NWS 2019-2022 Strategic Plan, "*Building a Weather-Ready Nation*" seeks to: "*Harness cutting-edge science, technology, and engineering to provide the best observations, forecasts, and warnings...The NWS will accomplish this, in part, through transformative impact-based decision support services (IDSS), better information for better decisions, integrated observations, and research to operations and operations to research (R2O/O2R)."*

The National Research Council's 2018 Earth Science and Applications from Space (ESAS) Decadal Survey identified that, "The high temporal sampling of geostationary hyperspectral sounders allows for rapidly evolving weather to be observed from space to improve the forecasting of severe weather events, and will also support air quality monitoring and atmospheric chemistry observations." Further, the WIGOS 2025 and 2040 Visions noted that: "*...the evaluation of the potential of hyperspectral sounders on GEO was performed with the GIFTS mission…Several operators of geostationary satellites have firm plans to include hyperspectral IR sounders for the next series of satellites…These planned sounders put the emphasis on high horizontal resolution (better than 10km), and on high vertical resolution (about 1km). Their main objective is to provide frequent information on the 3D structure of atmospheric temperature and humidity, for the whole Earth disk."*

The WMO Implementation Plan for the Evolution of Global Observing Systems (EGOS-IP) originally set as an action: "*All meteorological geostationary satellites should be equipped with hyperspectral IR sensors for frequent temperature and humidity soundings, as well as tracer wind profiling with adequately high resolution (horizontal, vertical, time) [by] 2015-2025 for making the instruments operational."* With MTG IRS, GIIRS, and a second Chinese hyperspectral sensor (and a possible Japanese planned flight on Himawari), 3 of the 5 satellites originally envisioned by the WMO 2025 WIGOS vision are being realized within the next few years…setting the stage for the new U.S. capability that could bring the updated "Vision for WIGOS in 2040" GEO ring vision to full reality (Grigsby et al., 2020). The WIGOS Vision 2040 states hyperspectral sounding from 5 geostationary orbits. The realization of that capability has started, but only 2–3 orbital slots are currently considered to be filled in the coming decade (not "next few years" in the draft report). NOAA is moving towards flying a GEO IR Hyperspectral Sounder over the Western Hemisphere in the 2030s.

A data simulator was built to create a synthetic GEO HSS dataset (Figure 23). The simulated data were processed from raw data format to Level-2 products such as temperature and water vapor retrievals. Processing of data was benchmarked on existing STAR computers to determine CPU needs. The Software Lines of Code (SLOC) from the processing modules were input to SEER-SEM model to determine labor resources needed for development. An Automated Cost Estimating Integrated Tool was used to develop cost estimates for the labor.

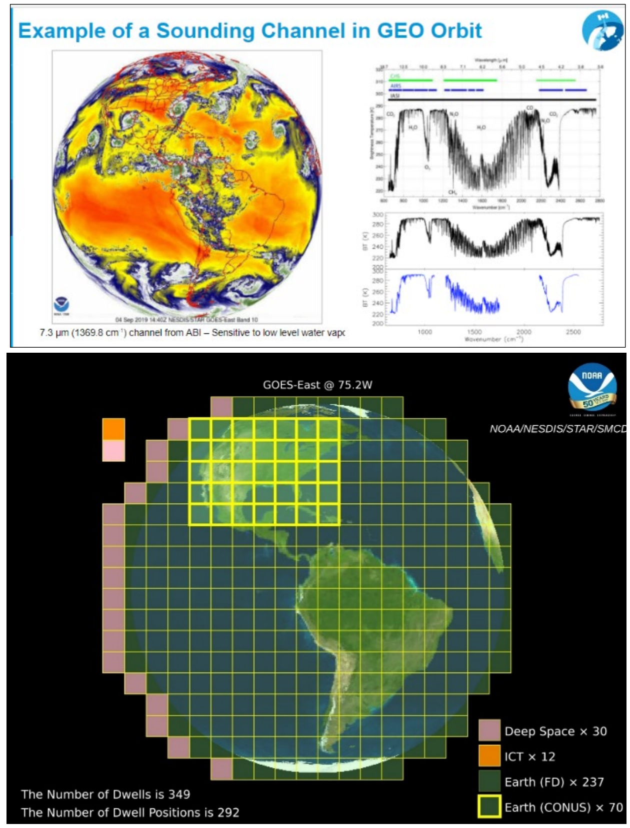


Figure 23. Top: an example of a simulated sounding channel in GEO from the ABI 7.3 µm (1369.8 cm-1) channel – sensitive to low-level water vapor. Bottom: a proposed GEO hyperspectral IR sounder 60-min scanning scheme designed to cover the CONUS every 30 minutes and the full disk every 60 minutes.

The project began with the development of geostationary hyperspectral proxy data from CrIS observations. CrIS has 2211 spectral channels at FSR mode, with resolution at 0.625 cm^{-1} for all three bands: SWIR: 3.92-4.64µm; MWIR: 5.71-8.26µm; LWIR: 9.14-15.38µm. Nadir resolution of CrIS is 14km diameter, with 1km vertical layer resolution capabilities. The potential future U.S. GEO HSS characteristics (similar to future EUMETSAT IRS): Nadir resolution of FOV 4km diameter, with 1km vertical layer resolution capabilities. CONUS temporal coverage was assumed to be every 30 minutes, and full disk every 60 minutes. The team estimates raw data ground processing needs based on a prototype processing system that would meet expected latency and refresh rates. They further provided estimates of SLOC for processing raw to L1b to Level 2 products and hardware needed to process the data in real time, based upon NUCAPS heritage, which was the basis of the cost estimate.

The project team developed an independent government cost estimate for developing a Product Generation system for an IR HSS in a geostationary orbit. In this estimation, the development efforts begin in FY 2025 and continue through Post-Launch tests (2031), gradually ramping down and ending in FY 2033. Operations, sustainment, and maintenance begins in FY 2031 and continues through FY 2051. Development costs are estimated to equal $173M, and O&M costs are estimated to be $240M.

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