# NOAA's CubeSat-Related Activities for Gap Mitigation and Future Planning

John Pereira, Dan Mamula, Margaret Caulfield, Daniel St Jean, Frank Gallagher, Sid Boukabara, and Kevin Tewey
NOAA / NATIONAL ENVIRONMENTAL SATELLITE, DATA, AND INFORMATION SERVICE
Suite 5300, 1335 East West Highway, Silver Spring, MD, 20910
John.Pereira@noaa.gov

Robert Atlas
NOAA / Atlantic Oceanographic & Meteorological Laboratory
4301 Rickenbacker Causeway, Miami, FL 33149-1026
Robert.Atlas@noaa.gov

Joanne Ostroy
The Aerospace Corporation
Suite 6200, 1335 East West Highway, Silver Spring, MD, 20910
Joanne.Ostroy@noaa.gov

William J. Blackwell
MIT Lincoln Laboratory
wjb@ll.mit.edu

Thomas S. Pagano
Jet Propulsion Laboratory / California Institute of Technology
Thomas.S.Pagano@jpl.nasa.gov

Jacob Inskeep and Mark Seymour
Riverside Technology, inc.
Suite 6200, 1335 East-West Highway, Silver Spring, MD, 20910
Jacob.Inskeep@noaa.gov

**ABSTRACT**

The National Oceanic and Atmospheric Administration (NOAA) is undertaking a strategy to lessen the potential impact of the loss of low-Earth orbit satellite observations, which are central to NOAA's weather forecast capability. This strategy leverages mature CubeSat technology funded by the National Aeronautics and Space Administration (NASA) and purchases commercially available CubeSat-based radio occultation data. In 2017 NOAA may begin development of the Earth Observing Nanosatellite – Microwave (EON-MW). EON-MW is a miniature microwave sounder that approximates the atmospheric profiling capabilities of the Advanced Technology Microwave Sounder (ATMS) instrument on the NOAA Joint Polar Satellite System (JPSS). NOAA is collaborating with the Massachusetts Institute of Technology's Lincoln Laboratory (MIT/LL) on EON-MW. NOAA is also looking to reduce the impact of a loss of data from the infrared sounder on JPSS with a CubeSat-based infrared sounder. NOAA is collaborating with the Jet Propulsion Laboratory (JPL) to design the Earth Observing Nanosatellite-Infrared (EON-IR). NOAA is seeking to quantify the value of these CubeSat-based observations by performing observing system simulation experiments (OSSEs). Both the technology development and OSSEs will help NOAA build a more cost-effective future satellite observing system that incorporates a faster infusion of new technology.

## BACKGROUND

The mission of NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) is to *"provide 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."*

To support its mission, NESDIS acquires launch services, satellites, instruments, and data, along with required data processing, storage, and distribution hardware and software. NESDIS builds, buys, or partners with other federal organizations, such as NASA and the U.S. Department of Defense (DoD), to obtain these resources. An example of NOAA's long and successful partnership with NASA and DoD is the Suomi-National Polar-orbiting Partnership (S-NPP) satellite. Launched in October 2011, S-NPP ushered in a new generation of satellite capabilities to help improve weather prediction. S-NPP includes the Advanced Technology Microwave Sounder (ATMS) and the Cross-track Infrared Sounder (CrIS), which are primary sources of data used to improve the accuracy of 3-7 day weather forecasts. Following S-NPP, four JPSS satellites are planned in succession, with similar instrumentation. This capability will provide continuity of observations for the next two decades. Figure 1 shows that all of the NOAA polar-orbiting satellites currently on orbit have exceeded their planned design lives. Should S-NPP or a JPSS satellite fail before a replacement satellite can be launched, then a gap in critical sounder data in the early afternoon polar orbit may result.

borne from MIT/LL's efforts. Their first mission, called the Micro-sized Microwave Atmospheric Satellite (MicroMAS), was designed to demonstrate, for the first time in space, the ability of a CubeSat to measure temperature profiles.[1] The first MicroMAS satellite (MM-1), was launched to the International Space Station in August 2014 and deployed on March 4, 2015 for an approximate 100-day demonstration. MM-1 transmitted telemetry data for about 2 weeks before its radio transmitter failed. While no science data were collected, MIT/LL was able to thoroughly test MM-1's attitude determination and control system – a critical mission component for ensuring the spacecraft can be tracked and controlled with fine precision. MIT/LL followed up on its MM-1 experience by building a second MicroMAS (MM-2), which is planned for flight on a commercial launch vehicle by late 2017.[2] While similar in design to MM-1 (e.g., 3-Unit (U) CubeSat), it contains more channels,

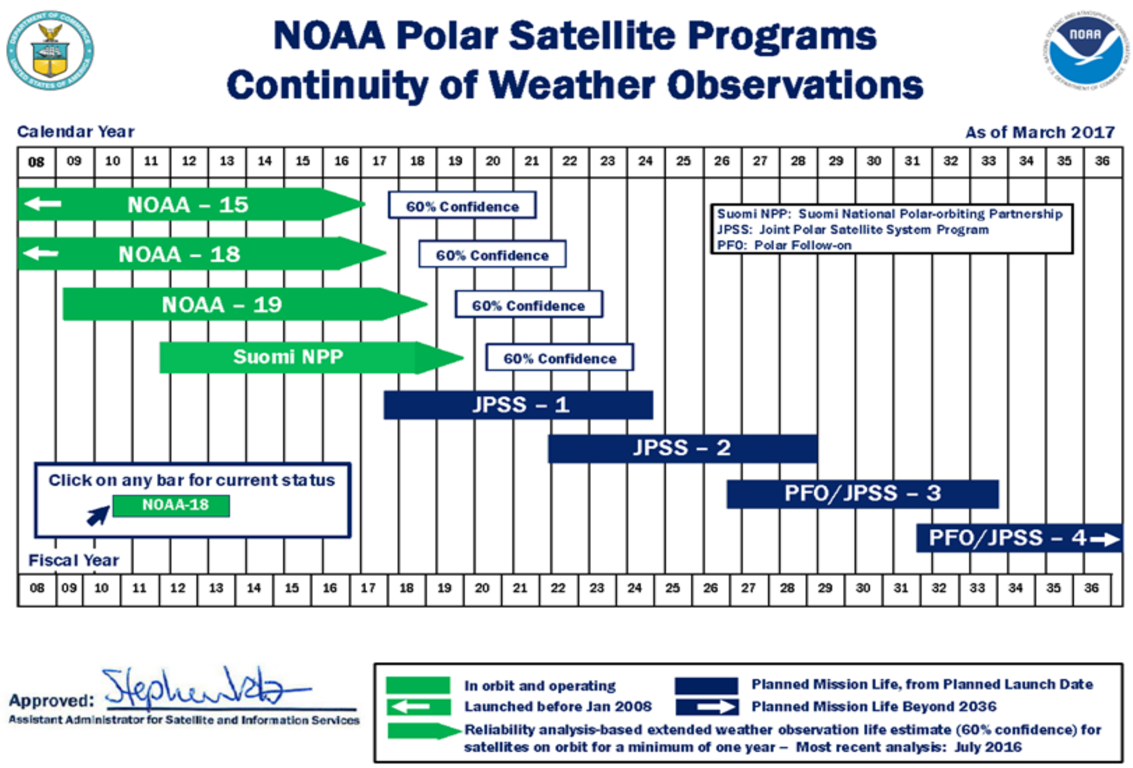


**Figure 1: Continuity of NOAA Polar-Orbiting Satellite Measurements**

NESDIS is exploring several options to mitigate a potential sounding data gap, including low-cost CubeSat technology funded by NASA. A promising development is an effort by the Massachusetts Institute of Technology's Lincoln Laboratory (MIT/LL) to validate CubeSat-based microwave sounder technology in multiple space-based missions to address NASA Earth Science objectives. The idea of the Earth Observing Nanosatellite – Microwave (EON-MW) was

by way of an additional miniaturized receiver, to provide more accurate temperature and moisture information. MM-2 also contains a slightly larger solar array in order to generate approximately 3 Watts of power for the payload, or about 60 percent more power than MM-1. A second MM-2 mission (MM-2B) is also being built by MIT/ LL for possible flight in late 2017 or early 2018.

While MM-1 was under development, MIT/LL received an award through NASA's In-Space Validation of Earth Science Technology (InVEST) program to build and fly the Microwave Radiometer Technology Acceleration (MiRaTA) 3U CubeSat. MiRaTA builds on the MicroMAS design by adding microwave channels and a GPS Radio Occultation Receiver to provide more accurate profiles of temperature and water vapor.[3,4,5,6] In 2016, NASA selected a proposal submitted by MIT/LL for award under the highly competitive NASA Earth Ventures Instrument program, called the Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS).[7,8] This mission is a constellation of MM-2 satellites to study the development of tropical cyclones through rapid-revisit sampling.[9] The combined technology advancements of MicroMAS, MiRaTA, and TROPICS all help to provide NOAA with greater confidence that the EON-MW mission will succeed.

## EON-MW REDUCTION OF RISKS

Beginning in 2014, NOAA and MIT/LL began studying the EON-MW concept. EON-MW payload heritage is based on the technology of MicroMAS, MiRaTA, and TROPICS.[10] EON-MW's objective is to provide the performance of the ATMS on the S-NPP and JPSS satellites. ATMS contains 22 channels, which is an increase from the 8-12 channels being flown in the missions described above. The greater number of channels introduces both technical and programmatic risk to EON-MW. NOAA conducted a technology readiness level (TRL) study on EON-MW in 2014, with support from the Aerospace Corporation, to assess the risks of expanding the earlier NASA-funded technology demonstrations to the meet the objectives of EON-MW. Additional studies were conducted in 2015 and 2016 to identify ways to address the technical and programmatic risks described in the 2014 TRL assessment.

One identified major risk was the complex integration of all four microwave collection bands. MiRaTA and MicroMAS provide different bands, but neither will demonstrate all 22 channels required to emulate ATMS performance. The miniaturization of the payload is another risk. A minimum 2-year design life is required for the EON-MW mission, which is at least double the mission duration for typical CubeSat technology demonstrations. Another key technology risk area is the solar array and deployment mechanism required to meet EON-MW's 100% duty cycle power needs. Proposed risk mitigation is to build a complete Radio Frequency (RF) front end (RFE) to test the integration of all microwave bands and to conduct a trade study on solar cell panels and deployment mechanisms. An analysis is also being conducted on the implications of extending the mission life to 2 years.

## EON-MW TRADE STUDY FINDINGS

EON-MW studies have found that developing an engineering development unit (EDU) would reduce most of the technical risk in the payload to provide the full ATMS capability. The benefits of this early characterization of the RFE far outweighed the additional costs. Therefore, development of an EDU has become part of the baseline concept for EON-MW. Analysis of five solar array concept designs was also completed. Three met EON-MW requirements and of those three, two were considered to be mature designs (TRL 6) (See Figure 2). More recently, at least five vendors have responded to a bus RFI from MIT/LL stating that they can meet the power requirements.

The 2015-2016 X-Band downlink study found two vendors with space qualified transmitters (TRL 7) that

| Parameter | Requirement | Tri-Fold Articulating, Dual-Wing, Articulated | Fixed with Composite Root Panel | Fixed with Titanium Root Panel |
|---|---|---|---|---|
| BOL Power (W) | 66 | | | |
| EOL Power (W) | 60 | | | |
| Mass (kg) | NA | | | |
| Mission Life (Years) | >3 | | | |
| Deployed First Natural Frequency (Hz) | >2 | | | |
| Stowed Array Volume | NA | | | |
| Drive Motor Volume | NA | | | |
| ISIS Quadpack Deployer | Conform | | | |

Most desirable
Middle ground
Least desirable

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

**Figure 2: EON-MW Solar Array Trade Study**

meet EON-MW requirements for X-band. One vendor was found with a space-qualified S-band transponder that meets EON-MW requirements (TRL 7). Currently, there are several space-qualified X- and S-band radios that could be flown on the EON-MW mission. Flying the X-band transmitter provides compatibility with S-NPP and JPSS systems. The S-band transmitter provides near omnidirectional coverage; thus, it will support satellite recovery operations in the event of a tumbling satellite. The link margin calculation using these transponders establishes more than adequate margin at a polar ground station (e.g., Fairbanks Alaska). Therefore, both the S-Band and X-Band transmitters have become part of the baseline concept for EON-MW.

Development of a detailed acquisition plan was completed by MIT/LL in early 2017. The plan shows that an EON-MW flight-ready unit can be delivered within 30 months from Authority to Proceed (ATP), and is within the cost allocation established for the program. With approval granted by Congress through the FY 2017 Omnibus Appropriations Act, NESDIS is now exploring how EON-MW can begin development before the end of September 2017, provided it does not negatively impact the schedule for long-term continuity of observations from the JPSS program.

**EON-INFRARED (IR)**

As described above, recent technology advances have allowed NESDIS to begin developing a low-cost CubeSat-based microwave sounder. However, this only solves half the problem of mitigating a potential gap in sounder data from S-NPP or JPSS. The benefit to Numerical Weather Prediction) NWP models is maximized from the combination of ATMS and CrIS sounder data. Fortunately, NASA has begun exploring the miniaturization of infrared sounders for deployment on a CubeSat at the Jet Propulsion Laboratory (JPL). NESDIS has a long-established partnering relationship with JPL to explore technology that could potentially be applied to future satellite systems. JPL's expertise in satellite infrared sounder technologies led NESDIS to partner with it in 2015 to study the potential for a low-cost infrared sounder to mitigate a potential gap in CrIS data on S-NPP and JPSS. The decision to begin this study was fortuitous. Within days of final signature of the initial study agreement, the NASA Earth Science Technology Office approved JPL's InVEST proposal to build and demonstrate the CubeSat Infrared Atmospheric Sounder (CIRAS). JPL began working on CIRAS after it completed the EON-IR study, which helped it maximize the benefit of the NOAA funding. CIRAS is a hyper-spectral sounder hosted on a 6U CubeSat, designed to operate between 4.08-5.13µm, a part of the electro-magnetic spectrum that is most sensitive to the lower part of the atmosphere (see Figure 3).[11,12,13]

Given the maturity of the technology being leveraged for CIRAS by NASA, EON-IR is the next logical step after EON-MW, for mitigating a gap in critical sounder data from S-NPP and JPSS. However, the midwave IR (MWIR) is a part of the spectrum not used for CrIS temperature and water vapor measurements. Therefore, the performance characteristics of CIRAS and CrIS are not expected to be equivalent. EON-IR risk reduction studies have two objectives: 1) to maximize the gap

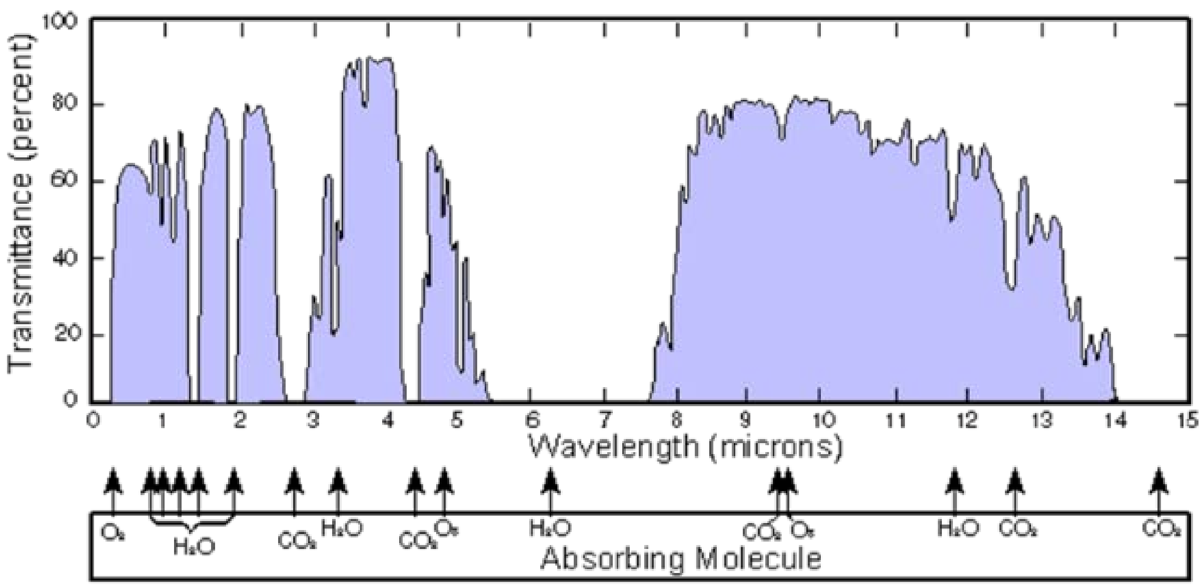


**Figure 3: Transmittance of Absorption Gases across the Electromagnetic Spectrum**

mitigation benefit of an IR sounder operating in the midwave part of the spectrum (like CIRAS), and 2) explore technologies and configurations to meet the longwave infrared (LWIR) requirements of CrIS.

## EON-IR REDUCTION OF RISKS

There are significant challenges to putting an IR sounder on a CubeSat. Temperature control is one of the highest challenges, along with a larger aperture size required for longer wavelengths. IR sensors are extremely sensitive to noise due to thermal emission of the optics and Johnson noise in the detectors, especially in the LWIR, and require a significant amount of cooling. CIRAS, for example, requires the optics to be cooled to 185K and the detectors to 115K; whereas the LWIR optics require cooling to 140K, and LWIR detectors need to be cooled to 60K. Other technology risk areas include Focal Plane Array (FPA) technologies, miniature reliable cryo-coolers, compact optics, and IR immersion grating spectrometers.

In 2015, NESDIS and JPL began studying the optimal performance of a CubeSat-based infrared sounder in comparison to CrIS performance. A TRL assessment of all mission components and subsystems was started. Recognizing the difficulty with the thermal and power requirements of LWIR sounding, the study focused on design of the MWIR only in a 6U CubeSat. The study addressed the optical, mechanical, thermal, detector, and electronic requirements from such a system. The EON-IR (MWIR-Only) instrument that resulted employed passive cooling for the spectrometer and a micro pulse tube cryo-cooler for cooling the detector. After completion of this first study, the NASA-funded CIRAS project began the design phase. Immediately it was found that the fully functional design arrived at during the NOAA study was not affordable for CIRAS. A few changes were made, including the addition of a second cryo-cooler for the spectrometer since passive cooling was more complex; and replacing the pulse tube cryo-cooler with a commercial, less expensive and less reliable cooler.

## EON-IR TRADE STUDY FINDINGS

In 2016-2017, an extension of the EON-IR study was funded to address some of the shortfalls previously identified, as well as addressing additional issues related to the design. The study will benefit from the InVEST CIRAS program by identifying additional risks associated with the requirements of an EON-IR system. The 90-day mission design for CIRAS was expanded to 2 years for EON-IR. Also, because CIRAS does not cover the LWIR bands of CrIS, an evaluation of the utility of a MWIR-only IR sounder needed to be assessed. Critical components were all evaluated for their applicability and maturity. A preliminary TRL assessment was performed, which revealed that most of the key components would be at or near TRL 6 and 7 when CIRAS is completed, due to the similarity in design to EON-IR.

Preliminary study results show that major portions of the EON-IR concept have low risk due to commonality with CIRAS; however, further definition of EON-IR revealed several life-limiting components which need further reliability study and could possibly change the TRL of EON-IR. The 2-year mission life has implications on the motor drive, commercial electronic parts selection, and cryo-coolers. Detailed thermal modeling concluded that two cryo-coolers can maintain thermal control. Passive cooling is not required as long as power can be provided continuously by the spacecraft. The reliability of the CIRAS mini cryo-coolers remains uncertain, but micro-pulse tube cryo-coolers with a 2-year design life were identified, which would lower risk significantly. A team of JPL engineers engaged in rapid design, analysis, and evaluation of mission concepts (AKA Team X) looked at fitting all CrIS channels into a CubeSat form factor, and determined the instrument would not fit in either a 12U or 16U configuration.

JPL also looked at increasing spatial resolution for EON-IR, which could improve data collection in high-cloud regions. Figure 4 provides a summary of this trade study. The two curves on the diagram show the relationship between spatial resolution and swath. A wider swath implies a faster scan rate. The legend on the figure shows the radiometric sensitivity (Noise Equivalent Temperature Difference or NEdT), related to signal to noise, expressed in Kelvin, and the spectral resolution expressed as wave number. NEdT directly correlates to sounder accuracy in retrieving vertical profiles of temperature and water vapor. Spectral resolution is related to vertical resolution in this example. The top point on the green curve therefore represents the accuracy and vertical resolution requirements for current IR sounders. EON-IR performance is being measured against this metric. The curve also shows that, as scan rate is increased, a wider swath is achieved at the expense of spatial resolution. The blue curve shows what happens when either the NEdT is requirement is relaxed or the spectral resolution is reduced. While this condition does not meet current performance requirements, the reduced performance is offset by greatly increased spatial resolution. Note also that, by allowing higher noise or coarser spectral resolution, the better spatial resolution drops off much more slowly with increasing scan rate. Particularly in areas partially covered by high clouds, this mode could increase the amount of temperature and

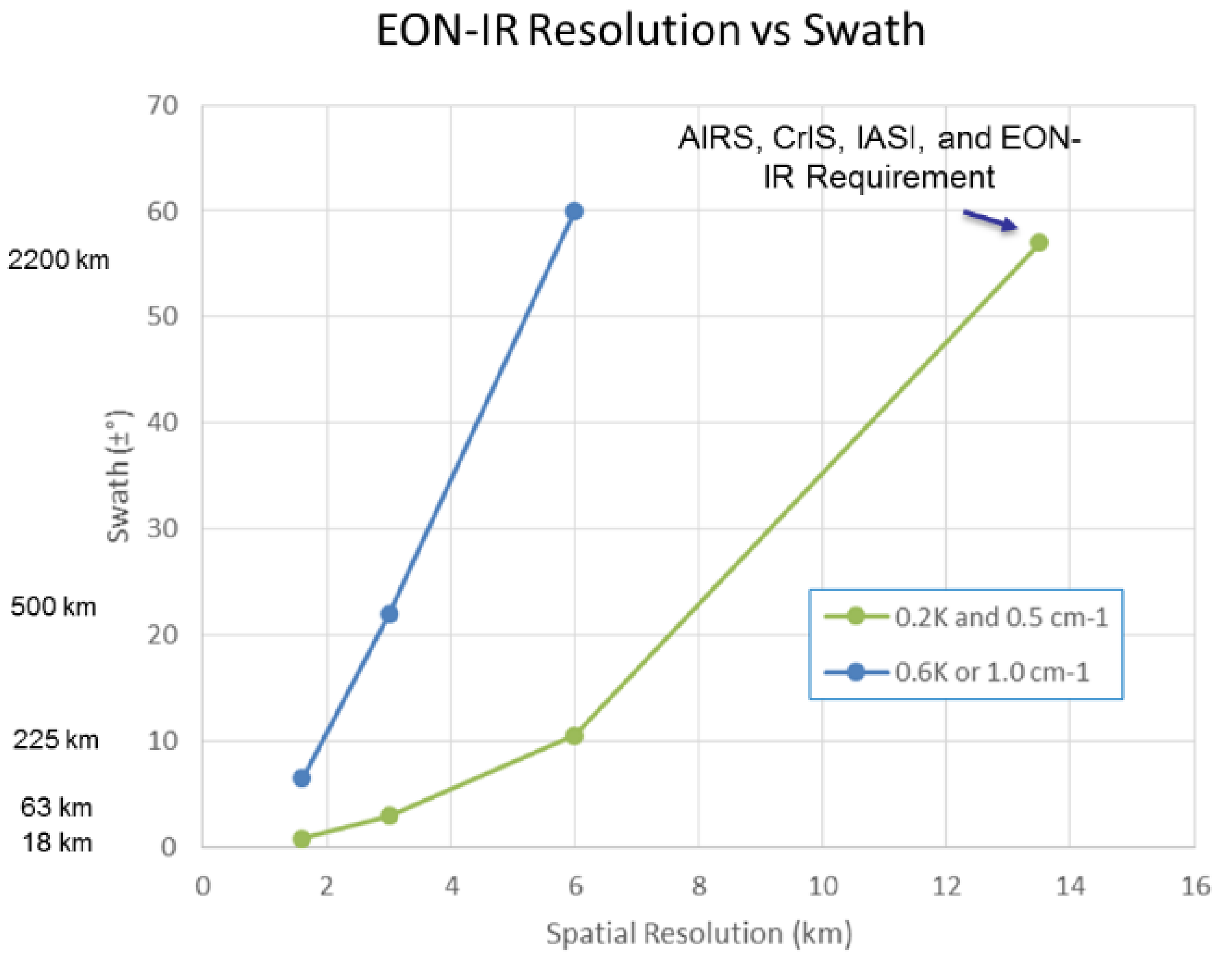


**Figure 4: Comparison of EON-IR spatial resolution versus swath based on scan rate**

water vapor profiles collected. Further study on trading coverage with accuracy needs to be performed. To further reduce the risk for EON-IR, the current approach is to assess the results of all CIRAS pre-flight testing before beginning development of EON-IR. Lessons learned can be directly applied to EON-IR development. The synergistic relationship with NASA's CIRAS and EON-IR formation has been beneficial to both programs and continues to be worked.

## OBSERVING SYSTEM SIMULATION EXPERIMENTS (OSSES)

The NESDIS Office of Projects, Planning, and Analysis is investigating the gap mitigation value of CubeSat-based microwave and IR sounder data on NWP models. The ultimate goal is to determine if the limited capabilities of MicroMAS-2 and CIRAS will produce a quantifiable reduction in forecast error if all polar-orbiting sounder data were removed from NWP models in a simulated environment. A secondary goal is to quantify potential threshold levels of performance for EON-MW and EON-IR in their gap mitigation roles, though not as replacements for ATMS or CrIS.

The investigation of the impact of CubeSat-based sounders on NWP models leverages extensive research. A very simplified summary of the steps involved in the OSSE experiment follows: (1) A "control" experiment, where all available observations are assimilated, is compared with other experiments in which specific observations are withheld from or added to the control experiment; (2) A state-of-the art weather forecast model, which includes simulated, but realistic, weather phenomena occurring in nature is used to generate a large geophysical data set commonly called a *Nature Run*; (3) A forward simulator, which translates geophysical properties into observations required for data assimilation, is used to simulate baseline as well as new sensors' observations to determine their relative impact on the weather forecast model. A more comprehensive description can be found in *Hoffman and Atlas, 2016.*[14] Collaborators from NOAA Cooperative Institutes at the University of Miami, University of Maryland, and University of Wisconsin are all involved in these experiments, with government expert oversight from NOAA centers and laboratories. The NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML) will guide the development and extension of OSSE capabilities, oversee and participate in the performance of OSSEs, and coordinate the collaborative OSSE activities between NOAA centers, laboratories, and cooperative institutes.

## OSSE ROLES AND RESPONSIBILITIES

### *Cooperative Institute for Climate and Satellites-Maryland (CICS-M)*

The University of Maryland (UMD) team with management support by the NESDIS Center for Satellite Applications and Research (STAR) is responsible for assessing the impact of simulated CIRAS and MicroMAS-2 data on global NWP.

### *Cooperative Institute for Meteorological Satellite Studies (CIMSS)*

The main objectives for the University of Wisconsin team, with management support by STAR, are to simulate CubeSat data realistically; provide simulated CubeSat data to the AOML and STAR/UMD teams as needed; and study the impact of CubeSat IR and MW sensor data on local severe storm forecasting.

### *Cooperative Institute for Marine and Atmospheric Studies (CIMAS)*

The main objectives of the University of Miami team, with management support by AOML, are to generate new ocean-basin scale nature runs and conduct regional hurricane OSSEs to evaluate alternative CubeSat observing systems.

## OSSE RESULTS

Figure 5 shows recent results from the OSSEs performed on the NOAA global data assimilation system (GDAS) The figure shows the normalized overall skill scores as defined in *Boukabara et al. 2016*, using the baseline set of sensors (control scenario, in blue); the baseline sensors without an afternoon polar orbit (observation gap scenario, in magenta); and the impact of adding simulated MicroMAS-2 or CIRAS data during the gap scenario.[15] The results show a statistically significant positive impact from assimilating MicroMAS-2 and CIRAS data simulated under realistic operational conditions. Note that results are based on perfect data simulations. On-going effort is extending this assessment to error-impacted measurements and forecast assessment. Preliminary results suggest that these conclusions hold.

Future Work:

- Impact of CubeSat sounders on regional models and hurricane forecasts
- Evaluating MicroMAS-2 and CIRAS together

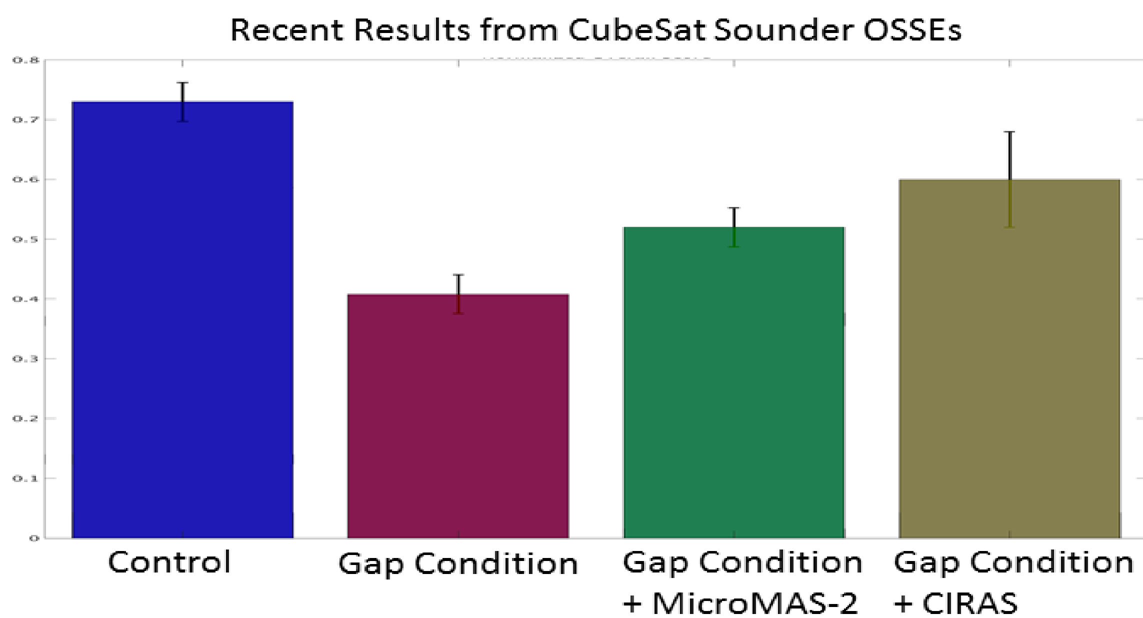


**Figure 5: Recent OSSE results showing the impact of MicroMAS-2 and CIRAS on global forecast models in realistic conditions. Scale is Overall Analysis Score (OAS) detailed in Boukabara et al. 2016**

(redundancy vs. synergy)

- Evaluating different orbit parameters and constellations
- Evaluating different sensor characteristics to determine threshold of EON projects

## COMMERCIAL ALTERNATIVES TO GOVERNMENT-DEVELOPED TECHNOLOGY

EON-MW and EON-IR are examples of cases where government investment is needed to develop and test the benefits of new technology (including tests of simulated data), because commercial entities cannot necessarily afford to risk millions of dollars on developing technology before a commercial market has been identified – i.e., the cost is not worth the benefit. Once the technology is proven and a user base has been established, commercial industry can compete to provide affordable products to meet the ongoing needs of many types of users, including government agencies. Two proven examples are satellite communications and high-resolution land imagery. An emerging commercial capability is the use of Global Navigation Satellite System signals for Radio Occultation (GNSSRO) measurements of atmospheric refractivity. GNSSRO measurements enable temperature and water vapor to be derived. NOAA purchased commercial GNSSRO data in 2017, and plans another data purchase in 2018.

## COMMERCIAL WEATHER DATA PILOT (CWDP)

In compliance with Federal Acquisition Regulations, NOAA must complete market research on commercial alternatives before developing a government solution. In 2016, three different companies offered potential solutions for provision of GNSSRO data in response to a Request for Information (RFI) and subsequent Request for Proposal (RFP). In September 2016, as a result of industry-announced plans to launch commercial RO satellites, a contract worth $370K was awarded to Spire; and a contract worth $695K was awarded to GeoOptics, for the provision of up to 3 months of Level 1 GNSSRO measurements and associated metadata.[16] NOAA has partnered with the University Corporation for Atmospheric Research (UCAR) under a National Science Foundation grant to analyze the raw satellite data for quality and then derive atmospheric data products. These products will be examined by the Joint Center for Satellite Data Assimilation (JCSDA), which will perform an initial evaluation of the suitability of the data for incorporation into NWP models. To date, eight Spire 3U CubeSat RO satellites are in orbit. Spire provided NOAA with flight data for evaluation, from March and April 2017, during the contract performance period. Figure 6 shows the CWDP Round 1 timeline, illustrating NOAA's rapid implementation and closeout of the project.

A Round 2 commercial GNSSRO data purchase project has been announced, targeting Contract Award later in 2017 to purchase a further 6 months of continuous GNSSRO data from commercial vendor(s), requiring much greater quantities and coverage of GNSSRO and additionally ionospheric data delivered in an operational-like manner. The emulation of an operational data coverage and delivery scenario would enable JCSDA to make a more definitive assessment of the contribution of commercial GNSSRO data to weather prediction, and indicate to NOAA the maturity and capability of the commercial satellite GNSSRO data provision systems.

Through these two rounds of the CWDP project, NOAA is establishing the processes by which the commercial weather satellite industry can be engaged, and is learning valuable lessons about adding commercial data sources to the mix of operational weather data. In the meantime, NOAA is monitoring how other government agencies (e.g., NASA and U.S. Air Force) are considering their own commercial weather-related data purchases.

## NOAA FUTURE ARCHITECTURE STUDIES

The NESDIS Office of Systems Architecture and Advanced Planning (OSAAP) is conducting the NOAA Satellite Observing System Architecture (NSOSA) study to plan for the future operational environmental satellite system, which will follow GOES-R and JPSS beginning about 2030. This is an opportunity to design a modern architecture driven by user needs, with no pre-conceived notions regarding instruments, platforms, orbits, etc. The NSOSA study was conducted in three discrete design cycles to develop space architecture products (see Figure 7). In each cycle, the NSOSA Architecture Development Team (ADT) explored user needs, instrument capabilities, a range of orbits, satellite/instrument combinations, concept(s) of operations (CONOPS), mission effectiveness, robustness, technology, policy, launch and ground


**Figure 6: NOAA Timeline for First Round of Commercial Weather Data Pilot**

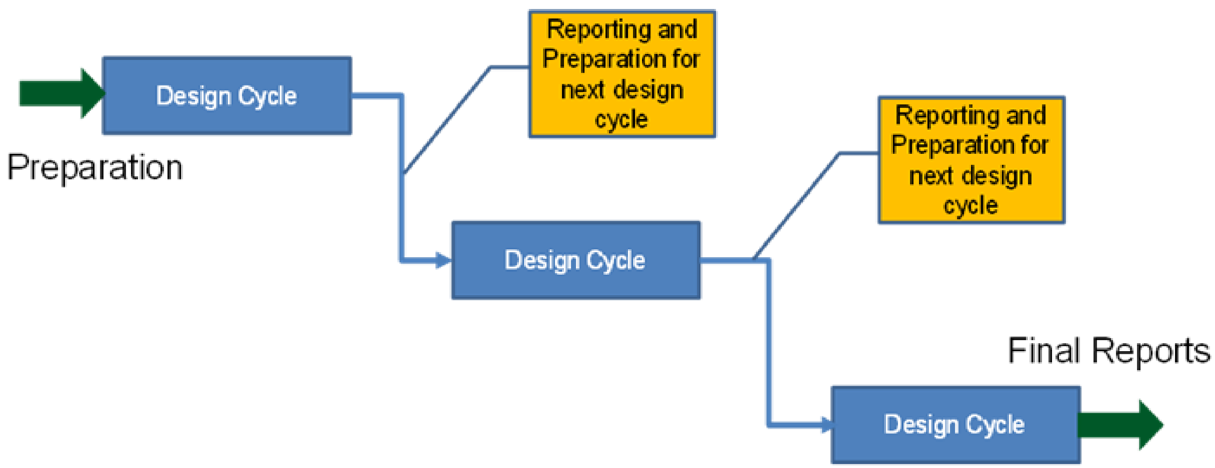


**Figure 7: The NSOSA Study Design Cycles**

system interfaces, commercial capabilities, and cost. The NSOSA study team has developed and is currently evaluating over 50 architecture alternatives to include partner and commercial contributions that are likely to become available. The measurement objectives include both functional needs and strategic characteristics (e.g., resiliency, flexibility, responsiveness, sustainability).

The results are serving as input to the process for new foundational (Level 0 and Level 1) requirements for the next generation of NOAA satellites that follow the current and planned series of operational satellite missions (e.g., GOES-R, JPSS).[17] Many candidate constellations have one or more of the following attributes:

- Use different small satellite approaches;
- Disaggregate "traditional" low Earth orbit (LEO) observation functions to small satellites with a limited number of instruments;
- Augment JPSS-type measurements with a family of small satellites that have limited instruments; or
- Replace sun synchronous LEO measurements with identical small/medium sized LEO satellites.

The NSOSA study was conducted by the ADT, supported by four sub-teams:

- Instrument Catalog Sub-team, made up of scientists and engineers at JPL and Goddard Space Flight Center (GSFC);
- Environmental Data Record (EDR – aka product) Value Model (EVM) Sub-team, made up of scientists and engineers at the Aerospace Corporation, MIT/LL, and the Johns Hopkins University Applied Physics Laboratory (APL);
- Mission Value Model (MVM) Sub-team, made up of scientists and engineers in the NOAA/NESDIS Technology, Planning, and Integration for Observations Office (TPIO); and
- Integration Sub-team, made up of scientists and engineers from across all NSOSA participants and led by APL.

The work of the four sub-teams was supported and connected to the stakeholder community through a number of outreach efforts. Key among these was the effort conducted by the Satellite Platform Requirements Working Group (SPRWG). The SPRWG, while not formally part of the NSOSA ADT, is a user advisory body consisting of members from NOAA Line Offices, cooperative institutes, academia, other research organizations, and private industry. It was specifically commissioned to advise the ADT on users' space observation needs. Reporting to OSAAP, the SPRWG looks at projections for mission CONOPS in 2030 and assesses where changes to mission CONOPS will be reflected in data quality attributes. It also advises the ADT on other aspects of value modeling and relative prioritization of user needs. The SPRWG provided the ADT with three recommended EDR performance levels for each attribute of an objective. These levels are:

- Study Threshold level (ST) - The level below which there is no point in gathering or paying for the data. Any capability below the ST level of performance would result in NOAA being unable to perform its mission.
- Expected performance level (EXP) - The performance level the SPRWG believes the community expects to be using in 2030.
- Maximum Effective performance level (ME) - The highest level of performance for which the

SPRWG believes there is scientific justification to pay for. There is no assessed increase in value for exceeding the ME performance level.

The SPRWG did not weight each objective based on intrinsic value; i.e., what the user might find most valuable. Rather, it weighted each objective based on the relative importance of improving a capability from the ST level to the ME level. Some objectives have a relatively high ST level while others have an ST level of none. All candidate architectures in the study will meet at least the ST performance level of all objectives. EON-MW was identified through this process as an instrument that would likely perform at the EXP level.

The major outcomes of the NSOSA study will provide NOAA with guidance to move forward with strategic decisions that need to be made in the near term. For example, if the highest mission value alternative turned out to be significantly different from the current architecture, then certain decisions would need to be made quickly to begin shifting toward the new architecture. Technology and integrated roadmaps are being developed during the study to provide a logical pathway to implement the new architecture by showing the timeline of when a new program or programs need to start, and when new technology improvements need to be ready. Also, the roadmaps will provide a launch schedule for each constellation component and indicate appropriate replenishment schedules in order to meet specified measurement availability.

## CONCLUSION

This paper has shown how NOAA/NESDIS is investigating ways in which CubeSat technology can help mitigate a possible gap in key sounder data required by NWP models, and potentially augment NOAA's future environmental satellite architecture. NASA's investments in CubeSat technology have helped NESDIS by maturing key technologies needed to miniaturize microwave and IR sounders to fit on CubeSat platforms. The commercial sector has also made substantial investments, particularly in obtaining GNSSRO data. Initial OSSE results show value in CubeSat-based sounder and GNSSRO technology to mitigate a potential gap in sounder coverage, even with limited capacity sensors. This technology may help NOAA become more resilient to a loss of key satellite data over the next 3-5 years, due to launch failures or sensor degradation on orbit. Ultimately, it may be incorporated into future satellite architectures in the 2030 timeframe and beyond. However, CubeSat technology is not currently a suitable replacement for government-developed systems that were built to meet the needs of the user community. The larger, proven systems can provide sufficient power, aperture size, cooling, and robustness that CubeSat technologies cannot currently meet. However, relatively small investments towards the advancement of these technologies will undoubtedly lead to lower cost systems in the future, either developed by the government or by the commercial sector for data purchase. NESDIS will continue to build, buy, or partner with other agencies in the most cost-effective manner, to acquire the satellite products and services needed to meet NOAA's mission.

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