SpaceOps-2023, ID 620

The Joint Polar Satellite System (JPSS): Celebrating a Decade of Successful Operations and Preparing for JPSS-2 Launch

Satya Kalluri[a]*

[a] *Joint Polar Satellite System, 7700 Hubble Drive Lanham, MD 20706* satya.kalluri@noaa.gov
* Corresponding Author

Abstract

Global remote sensing measurements from Joint Polar Satellite System (JPSS) missions provide critical inputs to weather, water, and climate applications. The mission has been providing global backbone observations for operational meteorology for over a decade. With the successful launch of the third satellite in the mission series (JPSS-2, now renamed NOAA-21), there is improved redundancy and resiliency in the constellation. While the entire five satellite series constellation is expected to provide operational measurements well into the end of the next decade, planning has already begun at NOAA for follow-on missions and to supplement the JPSS measurements under the Office of Low Earth Observations (LEO). This paper provides an overview of the JPSS mission, highlights accomplishments in the past decade, and introduces the LEO formulation activities.

Keywords: Joint Polar Satellite System, Low Earth Observations, Weather, Climate

Acronyms/Abbreviations

ATMS	Advanced Technology Microwave Sounder
AVHRR	Advanced Very High Resolution Radiometer
CrIS	Cross-track Infrared Sounder
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
JPSS	Joint Polar Satellite System (JPSS)
IR	Infrared
LEO	Low Earth Observations
LP	Limb Profiler
MODIS	Moderate Resolution Imaging Spectroradiometer
MW	Microwave
NASA	National Aeronautics and Space Administration
NM	Nadir Mapper
NP	Nadir Profiler
NOAA	National Oceanic and Atmospheric Administration
NUCAPS	NOAA Unique Combined Atmospheric Processing System
NWP	Numerical Weather Prediction
POES	Polar Orbiting Environmental Satellites
UV	Ultraviolet
VIS	Visible
VIIRS	Visible Infrared Imaging Radiometer Suite
OMPS	Ozone Mapping and Profiler Suite
WMO	World Meteorological Organization
SNPP	Suomi National Polar-orbiting Partnership
TOMS	Total Ozone Mapping Spectrometer

1. Introduction

The Joint Polar Satellite System (JPSS) is NOAA's flagship mission for polar-orbiting environmental satellites. Considered the backbone of the global observing system, JPSS satellites circle Earth from pole to pole and cross the equator 14 times daily, providing full global coverage twice a day. The JPSS series constellation includes five polar-orbiting satellites with four or more instruments onboard and a versatile ground system [1]. The satellites are the Suomi National Polar-orbiting Partnership (SNPP), NOAA-20 (previously called JPSS-1), NOAA-21 (previously called JPSS-2), JPSS-3, and JPSS-4. The SNPP mission, which is considered the risk reduction mission for JPSS, successfully completed ten years of operations since its launch in 2011. NOAA-20 is in its fourth year of operations since its launch in 2017. These two satellites have revolutionized the use of remote sensing measurements in both weather prediction and other Earth observation applications that serve a variety of users. The third JPSS satellite (JPSS-2) successfully launched on November 10, 2022 and was renamed NOAA-21 after it reached its final orbit, following the NOAA convention for operational polar-orbiting environmental satellites. With these satellites, the global community continues to benefit from new applications and innovations made possible by the satellites' atmospheric, oceanographic, and environmental data.

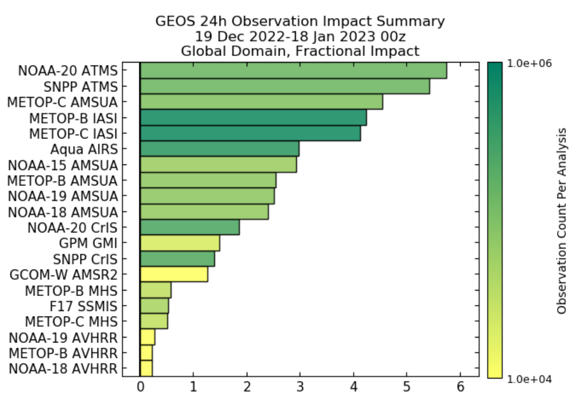
The World Meteorological Organization's (WMO) Integrated Global Observing System (WIGOS) [2] recommends a set of space-based backbone LEO observations in three sun synchronous orbits during the early morning, morning, and afternoon to ensure regular sampling for meteorological and other environmental services. The JPSS mission includes hyperspectral infrared (IR) and microwave (MW) sounders and a VIS/IR imager, that also collects ocean color in afternoon orbit and has a highly sensitive day/night band, which make significant contributions to the WIGOS vision. The contributions of the JPSS mission to the global observing system since the launch of SNPP a decade ago are described here, along with plans to continue these observations beyond the 2030s.

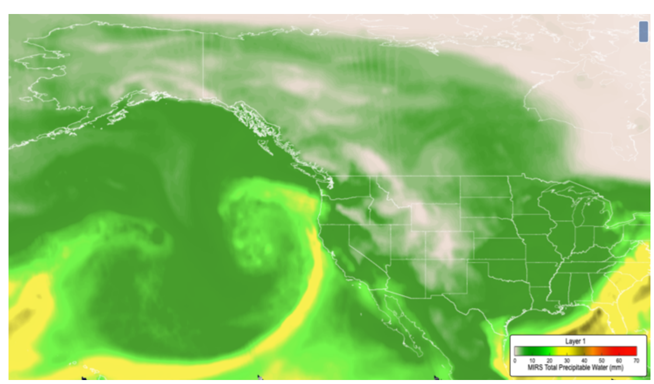
2. Contributions of JPSS to the global satellite observation system

The JPSS satellites provide comprehensive observations spanning the broad region of the electromagnetic spectrum, ranging from the ultraviolet (UV) region at lower wavelengths of the spectrum to the microwave (MW) region at the higher end, that contribute to a rich set of products critical to global remote sensing of the Earth and its atmosphere [3]. These measurements are not only critical for driving models and applications to predict and monitor life-threatening and damaging events such as severe weather, but also for monitoring the climate. Each satellite carries, at minimum, the Advanced Technology Microwave Sounder (ATMS), the hyperspectral Cross-track Infrared Sounder (CrIS), the Visible Infrared Imaging Radiometer Suite (VIIRS), and the Ozone Mapping and Profiler Suite (OMPS).

2.1 ATMS

Drawing directly from the rich and proven heritage of microwave sounders that have flown on NOAA Polar Orbiting Environmental Satellites (POES) and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Metop missions, ATMS offers improved capabilities, including reduced volume, mass, and power, and improved spatial coverage with no gaps between swaths. ATMS has 22 frequencies from 23 GHz to 183 GHz with nadir resolution varying from 15.8 to 74.8 km [4]. The channel selection for ATMS is based on the absorption features of oxygen in the 50-60 GHz region used for temperature retrieval and of water vapor in the 23 and 183 GHz region for atmospheric moisture. Channels at 23.8, 31.4, 89, and 165.5 GHz are used for inferring cloud, hydrometeor, and surface parameters. Historically, microwave sounders like ATMS have demonstrated the greatest impact on forecast accuracy among satellite observations in Numerical Weather Prediction (NWP) models [5] [6] because of their ability to penetrate non-precipitating clouds and performance in all weather conditions. In addition to being a key driver to NWP, microwave soundings are also used for estimating rain and snowfall rates [7]. Figure 1A shows the impact of observations from various satellite sensors used in the Goddard Earth Observing System (GEOS) Model, Version 5, for the period December 19, 2022 to January 18, 2023; ATMS from NOAA-20 and SNPP are the top two contributors in this system. Figure 1B shows Total Precipitable Water corresponding to atmospheric rivers on January 4, 2023, computed from ATMS. The series of atmospheric rivers and the bomb cyclone during December 2022 and January 2023 caused heavy precipitation in California resulting in massive flooding and extensive damage. ATMS data have been critical for providing accurate forecasts for these and other extreme weather events.





(1A) (1B)

Figure (1A): Observation impacts of various satellite measurements on the NASA GEOS-5 forecast system from December 19, 2022 to January 18, 2023 (Source: Goddard Modelling and Assimilation Office). (1B) Total precipitable water derived from NOAA-20 ATMS on January 4, 2023 by the Microwave Integrate Retrieval System (Source: NOAA/STAR).

2.2 CrIS

CrIS is a Fourier Transform Spectrometer providing high resolution IR spectra in 2,211 spectral channels with resolution at 0.625 cm^{-1} for all three bands [8]. Each CrIS Field of Regard (FOR) has a 3x3 array of Field of View (FOV) where each FOV is 14-km in diameter at nadir. The large number of channels that sample the atmosphere at very narrow absorption bands provide accurate and detailed atmospheric temperature and moisture observations for weather and climate applications at much finer vertical detail compared to microwave sounders such as ATMS. Assimilation of CrIS sounder data proved to be a valuable addition to the global observing system, and its low-noise characteristics compared to its legacy sensors have been beneficial against a background of ever-improving NWP forecast accuracy [9] [10] [11] [12]. In addition to assimilating IR sounding data into NWP models, CrIS data are also used with MW soundings for retrievals of vertical profiles of temperature, water vapor ozone (O_3), and trace gases (CO, CH_4, CO_2, volcanic sulphur dioxide (SO_2), HNO_3, and N_2O) using systems like the NOAA Unique Combined Atmospheric Processing System (NUCAPS) [13]. Temperature and water vapor retrievals are used by forecasters to assess atmospheric phenomenon such as instability for nowcasting, while trace gases are used for air quality and atmospheric chemistry monitoring. Figure 2 shows CO retrievals at 700mb height from CrIS over the Cedar Creek Fire in Oregon on September 10, 2022. According to the interagency all-risk incident information management system (inciWeb) [14], a lightning strike triggered the Cedar Creek Fire, which burned over 127,000 acres and spewed smoke for several weeks. Wildfires emit significant amounts of greenhouse gases and pollutants that alter the environment and affect human health, which can be measured and modelled by CrIS.

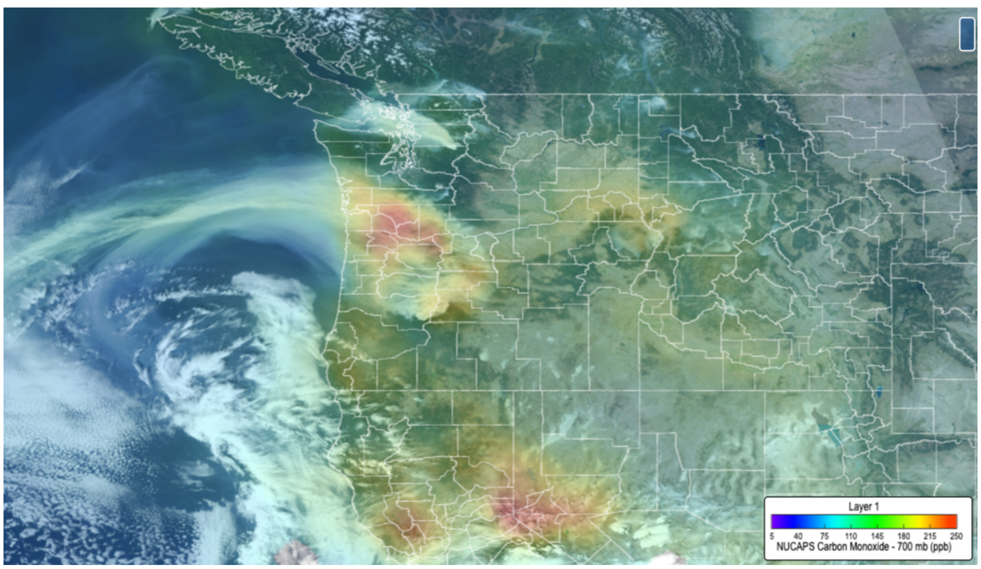


Figure 2. CrIS retrievals of CO concentration at 700mb height from NOAA-20. The CrIS retrievals are overlaid on a VIIRS image from September 10, 2022. CO emissions can be seen from several fires in Washington, Oregon (Cedar Creek), Idaho, and California (Source: NOAA/STAR).

2.3 VIIRS

VIIRS is built upon the strong and storied legacy of sensors such as the Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) that have been the bedrock of global multipurpose observations of the land, atmosphere, oceans, and cryosphere in the visible and infrared regions [15]. The VIIRS sensor has 22 spectral bands ranging from 412 nm to 12 μm with five imaging bands having a nadir spatial resolution of 375m and sixteen moderate resolution bands at 750m spatial resolution. VIIRS also has a unique day/night band (DNB) in the 05-0.9 μm region with variable gain settings to maintain constant contrast at 750m resolution. While the DNB was originally intended to observe meteorological features such as clouds, smoke, and fog at night under lunar illumination [16], the highly sensitive sensor has fostered several innovative applications such as tracking fishing vessels at night, monitoring gas flares, power outages, and other anthropogenic activity [17]. VIIRS applications are numerous and varied and also include modelling fire emissions for air quality [18], flood mapping [19], sustainable fishing [20], snow and ice mapping [21], and drought monitoring [22]. Figure 3 shows three simultaneously active Atlantic hurricanes captured by SNPP VIIRS DNB on September 8, 2017.

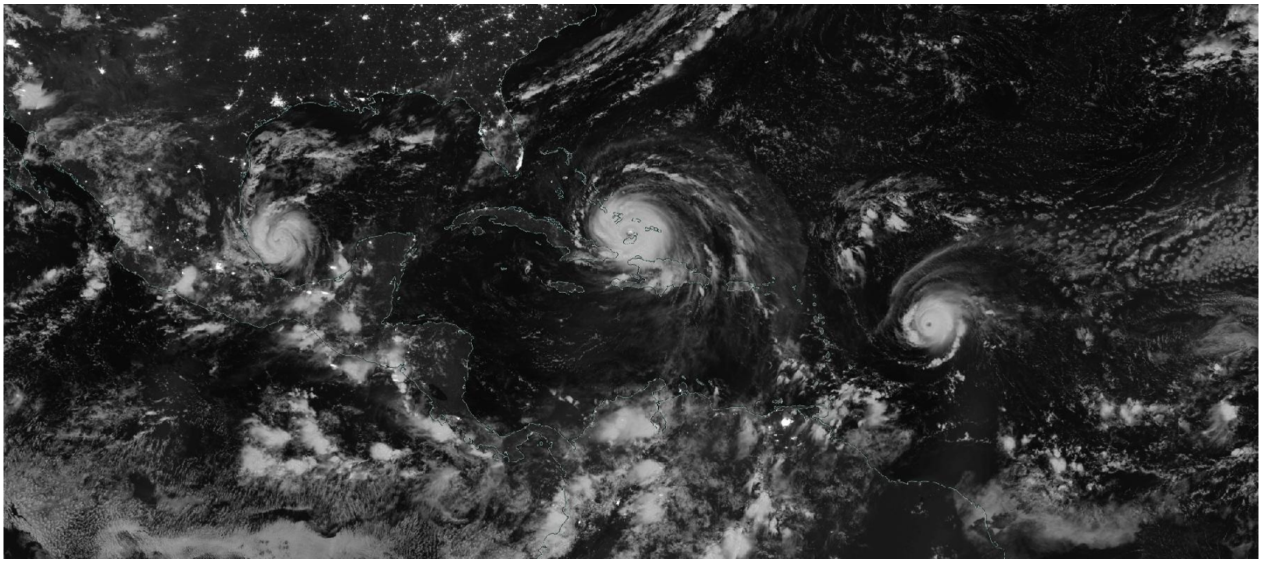


Figure 3. Hurricanes Katia (left), Irma (center), and Jose (right) are seen in the nighttime image from SNPP VIIRS on September 8, 2017 (Source: NASA Worldview).

2.4 OMPS

OMPS is comprised of three spectrometers: a downward-looking nadir mapper (NM), a nadir profiler (NP), and a cross-track viewing limb profiler (LP) [23]. All three instruments are currently aboard the SNPP and NOAA-21 satellites. NOAA-20, however, only includes the nadir mapper and profiler instruments. The NM has heritage from the NASA Total Ozone Mapping Spectrometer (TOMS) and measures Total Column (TC) ozone in the 300-420 nm range at 50x50 km spatial resolution at nadir on SNPP and 50x17 km spatial resolution for NOAA-20. On NOAA-21, the NM spatial resolution at nadir is designed to be 12x10 km. The differences in NM spatial resolution among SNPP, NOAA-20, and NOAA-21 is caused by spatial aggregation that is performed onboard the satellites due to data bandwidth constrains. The NP has heritage from the Solar Backscatter Ultraviolet Instrument (SBUV/2) flown on NOAA legacy satellites to measure stratospheric ozone profiles and TC. The NP measures the vertical distribution of ozone in the stratosphere in a single ground pixel of 250x250 km at nadir in the 250-310 nm range from SNPP and in five ground pixels of 50x50 km at nadir from NOAA-20. Both NM and NP share the same telescope. The LP measures ozone in the lower stratosphere and upper troposphere with high vertical resolution [24]. OMPS provides ozone total column and vertical ozone profile records, continuing over 40 years of ozone records from satellites that have been critical for monitoring the ozone hole. In addition to ozone, OMPS also measures several trace gases including NO_2, SO_2, and HCHO, as well as aerosols. Figure 4 shows ozone concentrations observed by OMPS over Antarctica on October 6, 2019 (left) and October 6, 2020 (right). The ozone hole over Antarctica in 2020 was one of the longest and largest observed since monitoring began 40 years ago [25].

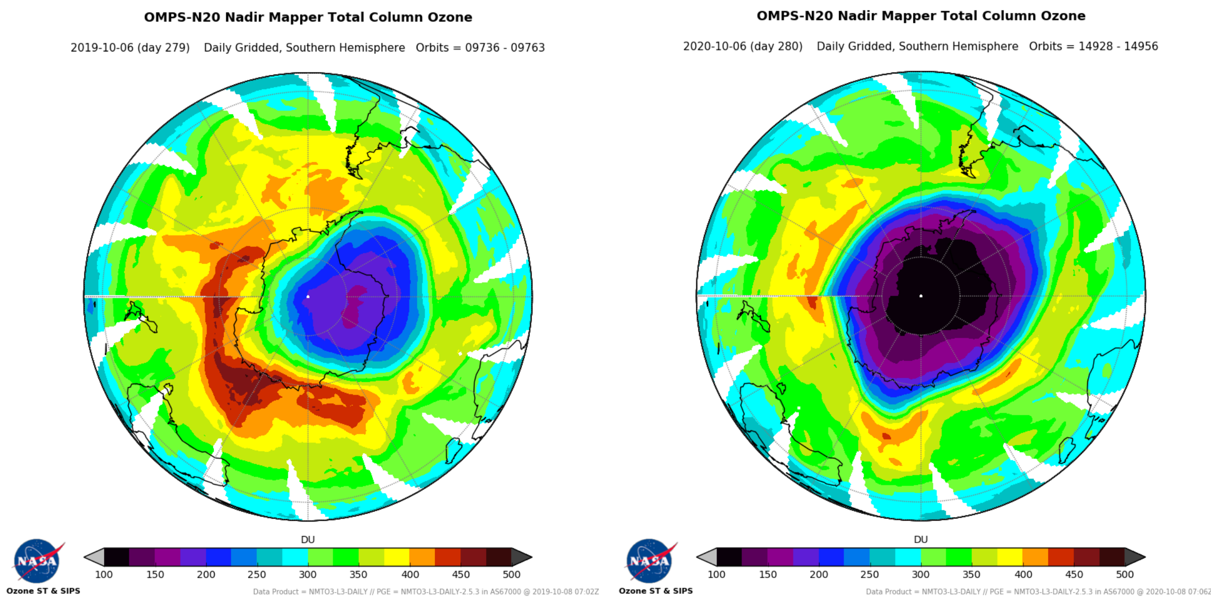


Figure 4. Ozone concentration (db) measured by OMPS over the South Pole on October 6, 2019 (left) and October 6, 2020 (right) (Source: NASA ozone and air quality: https://ozoneaq.gsfc.nasa.gov/).

3. Low Earth Observation (LEO) Program

With the success of the JPSS program, and a strong heritage and global leadership in directing, developing, and operating polar-orbiting weather satellites, NOAA has begun to look ahead and plan for the next generation of operational satellites. A Low Earth Observation (LEO) program has been established to coordinate this effort and to augment the existing fleet as NOAA users and stakeholders demand and expect improved data to keep pace with the increasing reliance on LEO observations for protection of life, property, and the Earth's climate. Earth observations in the low Earth orbit are diverse and span the entire region of the electromagnetic spectrum from UV to MW, including both passive and active techniques. NOAA not only procures and manages missions for critical observations such as JPSS, but also relies on a global partnership with other meteorological and space agencies to augment its mission needs. The LEO program will manage all observations in the low Earth orbit as a portfolio by spearheading the development of new missions to provide continuity and enhance the current observation suite, and by acquiring and exploiting new observations through partnerships with other agencies and the commercial sector.

The LEO program is a "loosely coupled" program. NASA defines loosely coupled programs as those that address specific objectives through multiple space flight projects of varied scope. While each project has an independent set of mission objectives, the projects as a whole have architectural and technological synergies and strategies that benefit the entire program [26]. The loosely coupled LEO program represents the next series of NOAA observations across all orbital domains through a comprehensive architecture and coordinated program to ensure global Earth observations are available to meet user requirements starting with the current program of record. One approach to designing future NOAA LEO satellite systems is to use a disaggregated architecture, in which smaller, specialized satellites are independently designed, developed, and launched [27, 28]. This approach is expected to offer several potential benefits such as agility and adaptability to plan new missions that cater to emerging needs compared to more traditional, monolithic satellite architectures that host several payloads on a large spacecraft and require more time to design and build. As part of future NOAA LEO mission planning, a series of new microwave sounding missions are being planned that will enable exploring concepts of "new space" that includes advances made by the commercial sector in rapid and cheap access to space, small satellites, commercial ground systems, and communications [29-31].

4. Discussion

The JPSS program continues the 40+ years legacy of polar-orbiting environmental satellites for operational weather, water, and climate applications and will remain the backbone of afternoon observations until the end of the next decade. With the successful launch of NOAA-21, the third in the JPSS series, and two more follow-on satellites being developed on schedule (JPSS-3 and -4), the JPSS constellation is not only resilient, but also robust through redundancy. The establishment of the LEO program at NOAA will bring even more global low Earth orbit satellite observations as an enterprise for high impact applications within the organization. As the examples illustrate in this paper, the JPSS measurements are vital for operational short-term forecasts and are an important contributor to creating long term climate records to monitor our fragile environment.

Acknowledgements

This work is supported by the JPSS program. The author would like to thank and acknowledge the contribution of hundreds of scientists and engineers who enable mission success through their passion and dedication to the mission objectives.

References

[1] M. D. Goldberg, H. Kilcoyne, H. Cikanek, and A. Mehta, "Joint Polar Satellite System: The United States next generation civilian polar-orbiting environmental satellite system," *Journal of Geophysical Research: Atmospheres,* vol. 118, no. 24, pp. 13,463-13,475, 2013, doi: https://doi.org/10.1002/2013JD020389.

[2] "Vision for the WMO Integrated Global Observing System in 2040," World Meterological Organization (WMO), Geneva, 2019.

[3] L. Zhou, M. Divakarla, X. Liu, A. Layns, and M. Goldberg, "An Overview of the Science Performances and Calibration/Validation of Joint Polar Satellite System Operational Products," *Remote Sens.,* vol. 11, no. 6, p. 698, 2019. [Online]. Available: https://www.mdpi.com/2072-4292/11/6/698.

[4] E. Kim, C.-H. J. Lyu, K. Anderson, R. Vincent Leslie, and W. J. Blackwell, "S-NPP ATMS instrument prelaunch and on-orbit performance evaluation," *Journal of Geophysical Research: Atmospheres,* vol. 119, no. 9, pp. 5653-5670, 2014, doi: 10.1002/2013jd020483.

[5] N. Bormann, H. Lawrence, and J. Farnan, "Global observing system experiments in the ECMWF assimilation system.," European Center for Medium-Range Weather Forecasts (ECMWF), Shinfield Park, Reading, RG2 9AX, England, January 2019.

[6] S. Kalluri, "Satellite Microwave Sounding Measurements in Weather Prediction: A Report of The Virtual NOAA Workshop on Microwave Sounders," Department of Commerce, NOAA/NESDIS, Washington, D.C., NOAA Technical Report NESDIS 155, July 28, 2021.

[7] Y. You, N.-Y. Wang, R. Ferraro, and P. Meyers, "A Prototype Precipitation Retrieval Algorithm over Land for ATMS," (in English), *Journal of Hydrometeorology,* vol. 17, no. 5, pp. 1601-1621, 01 May. 2016, doi: 10.1175/jhm-d-15-0163.1.

[8] Y. Han *et al.*, "Suomi NPP CrIS measurements, sensor data record algorithm, calibration and validation activities, and record data quality," *J. Geophys. Res.-Atmos.,* vol. 118, no. 22, pp. 12734-12748, Nov 2013, doi: 10.1002/2013jd020344.

[9] R. Eresmaa, J. Letertre-Danczak, C. Lupu, N. Bormann, and A. P. McNally, "The assimilation of Cross-track Infrared Sounder radiances at ECMWF," *Quarterly Journal of the Royal Meteorological Society,* vol. 143, no. 709, pp. 3177-3188, 2017, doi: https://doi.org/10.1002/qj.3171.

[10] S. Kalluri, "Exploring the Future of Infrared Sounding: Outcomes of a NOAA-NESDIS Virtual Workshop," (in English), *Bull. Amer. Meteorol. Soc.,* 02 Jun. 2022 2022, doi: 10.1175/bams-d-22-0054.1.

[11] A. P. McNally, "The direct assimilation of cloud-affected satellite infrared radiances in the ECMWF 4D-Var," *Quarterly Journal of the Royal Meteorological Society,* vol. 135, no. 642, pp. 1214-1229, 2009, doi: https://doi.org/10.1002/qj.426.

[12] J. R. Eyre *et al.*, "Assimilation of satellite data in numerical weather prediction. Part II: Recent years," *Quarterly Journal of the Royal Meteorological Society,* vol. 148, no. 743, pp. 521-556, 2022, doi: https://doi.org/10.1002/qj.4228.

[13] S. Kalluri *et al.*, "Validation and Utility of Satellite Retrievals of Atmospheric Profiles in Detecting and Monitoring Significant Weather Events," (in English), *Bull. Amer. Meteorol. Soc.,* vol. 103, no. 2, pp. E570-E590, 01 Feb. 2022 2022, doi: 10.1175/bams-d-20-0126.1.

[14] inciWeb. "Cedar Creek Fire." Interagency all-risk incident information management system. https://inciweb.nwcg.gov/incident/8307/ (accessed January 18, 2023).

[15] C. Cao *et al.*, "Visible Infrared Imaging Radiometer Suite (VIIRS) Sensor Data Record (SDR) User's Guide, NOAA Technical Report NESDIS 142," in "NOAA Technical Report NESDIS 142," NOAA, Washington, D.C., 2 March 2017.

[16] T. E. Lee *et al.*, "The NPOESS VIIRS Day/Night Visible Sensor," (in English), *Bull. Amer. Meteorol. Soc.,* vol. 87, no. 2, pp. 191-200, 01 Feb. 2006, doi: 10.1175/bams-87-2-191.

[17] C. D. Elvidge, F. C. Hsu, M. Zhizhin, T. Ghosh, and T. Sparks, "Statistical moments of VIIRS night-time lights," *Int. J. Remote Sens.,* pp. 1-25, 2023, doi: 10.1080/01431161.2022.2161857.

[18] R. Ahmadov *et al.*, "Using VIIRS fire radiative power data to simulate biomass burning emissions, plume rise and smoke transport in a real-time air quality modeling system," in *2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, 23-28 July 2017, pp. 2806-2808, doi: 10.1109/IGARSS.2017.8127581.

[19] S. Li *et al.*, "High Resolution 3D Mapping of Hurricane Flooding from Moderate-Resolution Operational Satellites," *Remote Sens.,* vol. 14, no. 21, p. 5445, 2022. [Online]. Available: https://www.mdpi.com/2072-4292/14/21/5445.

[20] C. Wilson and D. Robinson, "Satellite Monitoring of sea Surface Temperature and Chlorophyll for Sustainable Fishing," in *IGARSS 2022 - 2022 IEEE International Geoscience and Remote Sensing Symposium*, 17-22 July 2022, pp. 4776-4778, doi: 10.1109/IGARSS46834.2022.9884249.

[21] J. R. Key *et al.*, "Snow and ice products from Suomi NPP VIIRS," *Journal of Geophysical Research: Atmospheres,* vol. 118, no. 23, pp. 12,816-12,830, 2013, doi: https://doi.org/10.1002/2013JD020459.

[22] F. Kogan, W. Guo, and W. Yang, "Drought and food security prediction from NOAA new generation of operational satellites," *Geomatics, Natural Hazards and Risk,* vol. 10, no. 1, pp. 651-666, 2019/01/01, doi: 10.1080/19475705.2018.1541257.

[23] L. Flynn *et al.*, "Performance of the Ozone Mapping and Profiler Suite (OMPS) products," *Journal of Geophysical Research: Atmospheres,* vol. 119, no. 10, pp. 6181-6195, 2014, doi: https://doi.org/10.1002/2013JD020467.

[24] G. Jaross *et al.*, "OMPS Limb Profiler instrument performance assessment," *Journal of Geophysical Research: Atmospheres,* vol. 119, no. 7, pp. 4399-4412, 2014, doi: https://doi.org/10.1002/2013JD020482.

[25] WMO. "Record-breaking 2020 ozone hole closes." WMO. https://public.wmo.int/en/media/news/record-breaking-2020-ozone-hole-closes (accessed January 22, 2023).

[26] (2021). *NASA Procedural Requirements (NPR 7120.5F)*. [Online] Available: https://nodis3.gsfc.nasa.gov/npg_img/N_PR_7120_005F_/N_PR_7120_005F__Chapter2.pdf

[27] D. E. Hastings and P. A. La Tour, "An economic analysis of disaggregation of space assets: Application to GPS," *Acta Astronautica,* vol. 134, pp. 244-264, 2017/05/01, doi: https://doi.org/10.1016/j.actaastro.2017.02.008.

[28] D. E. Hastings, P. A. L. Tour, and D. K. Giri, "Architectural Concept of Disaggregation of Space Systems: Application to Weather Satellites," *Journal of Spacecraft and Rockets,* vol. 56, no. 5, pp. 1492-1507, 2019, doi: 10.2514/1.A34353.

[29] M. N. Sweeting, "Modern Small Satellites-Changing the Economics of Space," *Proceedings of the IEEE,* vol. 106, no. 3, pp. 343-361, 2018, doi: 10.1109/JPROC.2018.2806218.

[30] G. Martin, "NewSpace: The Emerging Commercial Space Industry," 2017, NTRS 20170001766. [Online]. Available: https://ntrs.nasa.gov/api/citations/20150023562/downloads/20150023562.pdf.

[31] R. Brukardt. (2022) *McKinsey Quarterly*. Available: https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/how-will-the-space-economy-change-the-world