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A Building Block Approach to Satellites and its Impact on Changes in Late AI&T Athena – A Case Study

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ABSTRACT

The Space Force, NASA, and NOAA partnered to fly the pathfinder Athena climate-change mission using NovaWurks' building block approach to demonstrate a new way to build and fly sensorcraft. This mission to measure Earth Radiation Budget was originally planned for launch in 2023 on a LauncherOne rideshare. Due to cessation of Virgin Orbit launch operations, Athena was shifted to a Falcon 9 with a different LTAN. The change from 1300 to 1800 in a sun-synchronous LEO orbit dramatically impacts the solar illumination of the satellite and frequency/duration of eclipse, resulting in severely impacted CONOPS. NASA asked NovaWurks whether the vehicle could be reconfigured to accommodate the new LTAN in just a few months. The eight identical blocks were re-arranged to allow the sensor to operate effectively in the new orbit. Launch is now planned for later this year. The paper will show how the physical arrangement changed dramatically after it had already been delivered for integration, along with the minimal steps required to make a major change in a short time.

From the outset, the building block approach allowed the NASA sensor to be significantly simplified, which was a major consideration for NASA. In addition, the building block approach simplified the payload by using capabilities integral to the blocks. The NASA sensor is taking advantage of the building blocks' ability to gimbal the payload to scan the earth. The blocks also process and store data before transmission to the ground.

While redesigning an already-built satellite would be costly and time consuming, the building block approach allows resolution of unexpected changes which may occur late in I&T. In a Sun Synchronous Orbit (SSO), Athena's original configuration enabled the sensor to point NADIR 100% of the time, gathering data continuously. Without reconfiguration, the LTAN change from 1300 to 1800 would severely impact the duty cycle due to solar illumination angles on the arrays. A simple reconfiguration permits mission requirements to be met in the changed orbit.

The entirety of the reconfiguration consists of updating drawings and fabrication of a few mechanical items. This whole process can happen in a matter of weeks and at any point in the I&T timeline.

This is not the first time NovaWurks blocks enabled a configuration change late in the I&T cycle. On the 2018 SSOA rideshare, the NovaWurks eXCITe spacecraft was reconfigured to satisfy the rideshare Coupled Load Analysis. Note, eXCITe met all LV requirements as it was. The change was made to accommodate the launch provider and rideshare neighbors. Once on orbit, the spacecraft self-deploys to final configuration, so the launch configuration can be completely different.

This paper will describe the reconfiguration of NovaWurks' spacecraft on the ground, which successfully resolved external impacts on eXCITe and Athena. It will also describe In Space Assembly and Manufacturing (ISAM), allowing vehicles to be reconfigured, or built, in space.

MISSION OF ATHENA

Athena's pathfinder mission includes the use of an Earth science sensor; however, its broader mission is to gain wisdom which will inform future missions by using a new type of satellite host. Athena will demonstrate critical science measurement, but also an architecture that is adaptable and cost effective.[1] NASA provided the sensor to NovaWurks, which provides everything else required to complete the mission.[2] Aside from a government provided launch, NovaWurks operates the mission and provides the resulting data to the other mission partners.

The construct of a spacecraft assembled from building blocks to support a simplified payload sensor is being called a sensorcraft. This fundamental construct choice enables a variety of benefits, one of which is the ability to reconfigure the entire spacecraft in the late stage of integration. This benefit was not foreseen until the launch vehicle changed, resulting in an unfavorable orbit. The fact that the sensorcraft could be reconfigured for the new orbit is a significant lesson.[3] And one which took place even before launch.

Flight heritage of NovaWurks HISat (Hyper Integrated Satlet)[4] vehicles include – SIMPL[5], eXCITe[6], and PODSat-1[7,] which were all assembled from multiple identical building blocks, which at the initial stages were called satlets.

Learning new, non-traditional ways of conducting space operations is a primary mission objective. The partners sought to learn from 'New Space' in a continuous learning opportunity aimed towards advancing the art of conducting space operations.[8] Having the payload function well on orbit is not the main criteria. Learning is the primary objective.

THE EARTH SCIENCE MISSION

The science mission of the sensorcraft is to measure Earth's radiation budget at top-of-atmosphere (TOA). The instrument is a simplified version of the CERES (Clouds and Earth Radiant Energy System) sensor which has flown on five previous missions.[9] The sensor is approximately 15 cm on each side and has a mass of less than 5kg. Figure 1 depicts CERES in an early configuration of Athena. Critical CONOPS constraints include maintaining 100% duty-cycle and the ability to scan deep space every ~6-seconds providing a zero-radiance reference.

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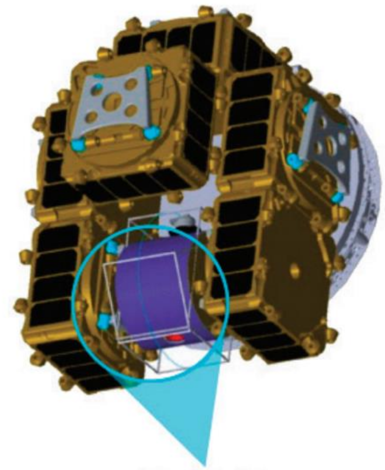

Figure 1: The CERES sensor

THE CHOICE TO USE A BUILDING BLOCK SENSORCRAFT

Athena is not a technology demonstration; it is a pathfinder. The technology itself has been demonstrated.[10] What is new is that the sensorcraft does not conform to the standard bus/payload architecture.[9] Instead, it incorporates a simplified sensor which is integrated into NovaWurks SLEGO™ blocks.

An optical sensor alternates between Earth observation and calibration. At the outset, there was discussion of providing a complete payload to NovaWurks, however, certain required functionality of the payload was already inherent in the SLEGO™ blocks. The original CERES payload included gimbals to scan, and data handling to manage the data prior to download to earth. The SLEGO™s include sufficient data processing capacity, integrated actuators to eliminate these items from the payload, simplifying the payload suite significantly.[11]

MISSION PARTNERS

NASA Science Mission Directorate's Earth Science Division, NOAA/NESDIS and the Space Force have partnered to fly Athena.[1]

Figure 2: Athena Mission Patch

NASA provided the sensor and Space Force provided the launch. All partners are closely following the lessons being learned from this pathfinder with an eye towards future missions.

NovaWurks role could be described as a Satellite as a Service (SaaS) as it provides system integration and operates the spacecraft, providing the mission data to the partners.[12]

SELECTION OF BUILDING BLOCK SENSORCRAFT

LaRC was aware of the three demonstration missions which NovaWurks had completed, however it had never been involved in a mission using a building block sensorcraft itself. It believes that a lot could be learned from attempting to build and operate a flexible approach.

HISats are engineered to aggregate, share resources and conform to different shapes and sizes of satellites, to allow every SLEGO™ satellite to be right sized.

"A satellite should be the right size". Dave Barnhart, DARPA Phoenix PM

For Athena, NovaWurks used eight units of its standard product -- HISat building blocks, now referred to as SLEGO™s. Two solar arrays and a COTS TT&C radio are also included.[13] NovaWurks integrated the sensor and is conducting functional and environmental testing. NovaWurks is contracting with commercial ground network providers to operate Athena and deliver data to all stakeholders.

Each SLEGO™ contains the essential elements of a satellite -- C&DH, power management, power storage, sensors/actuators for GN&C and related systems.

ISAM INTERFACE BETWEEN BLOCKS

NovaWurks ISAM interface allows the blocks to be attached to each other in a multitude of orientations. Intended to dock and undock on orbit, they also facilitate integration on the ground. Power and data cross the interface which means that resources are available in each block regardless of the configuration.[14]

Each SLEGO™, has 5 ISAM interfaces which allow it to directly connect to others in any orientation. Four of the ISAM interfaces are on the four sides of the SLEGO™. The fifth ISAM interface is on the rotating carousel. The carousel may be used as either reaction wheels or as an actuator. A Universal Device Adapter (UDA) is used to connect any payload or peripheral to the SLEGO™ ISAM interfaces.

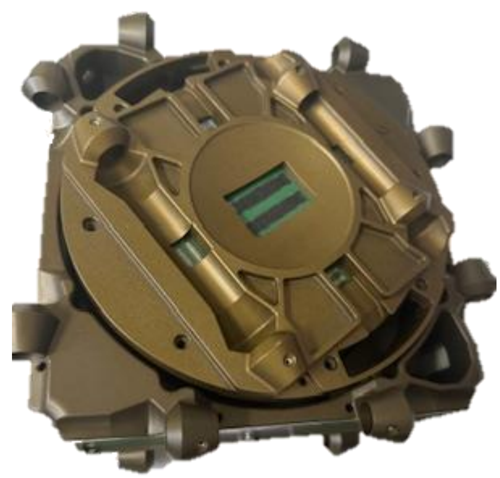

Figure 3: SLEGO™ block showing ISAM interfaces on each side and also on the carousel

CONFIGURING ATHENA FROM 8 IDENTICAL BUILDING BLOCKS

Figure 3 depicts the eight SLEGOs™, identified as A through H. The CERES sensor is integrated between the carousels of two blocks (G and H), which allow it to scan the Earth and also swivel away for calibration. The sensor is attached via two UDAs which transfer power and data, as well as being a mechanical interface.

The solar arrays, (SA-1, SA-2) shown in their stowed state in this rendering, are attached to the carousels of two other blocks (B and C), each via a UDA. Once deployed from the clamshell, the arrays track the sun using the carousel.

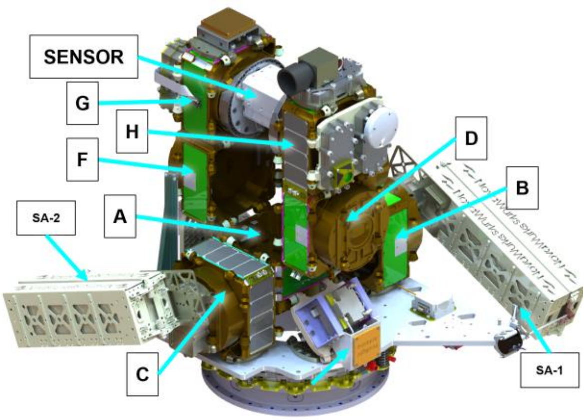

Figure 4: Original Configuration

Additional hardware (shown but not labelled) is attached to the blocks using UDAs. Additional hardware includes a Vulcan Wireless SDR, antennae, calibration star camera, torque rods, and GPS antenna. Since UDAs may be attached to five of the six sides of a SLEGO, there are multiple options for placement of each.

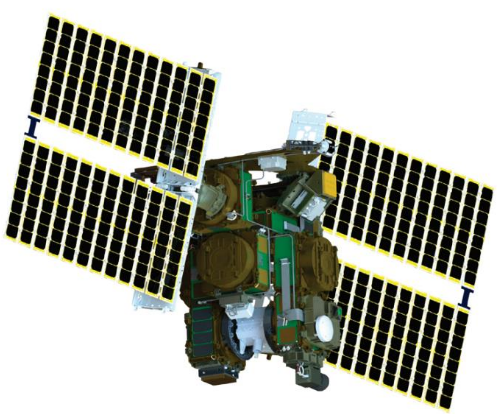

Figure 5: Showing solar arrays deployed

FLIGHT SOFTWARE

NovaWurks' Flight Software (FSW) is highly configurable, making physical reconfiguration simple and straightforward. In order to support the various vehicle arrangements, the FSW only required a revised system configuration file, called a "mission board", that defines how the SLEGOs are connected to one another and how payloads are connected. This tells the system what software must be instantiated per SLEGO building block to drive the available hardware.

PLANNED LAUNCH

Athena was manifest on STP-28C, which was a Virgin Orbit LauncherOne. The sun-synch orbit had an LTAN of 1300. Athena was configured to allow optimal solar power generation, thermal balance and sensor visibility and protection at this LTAN.

CHANGE OF THE LAUNCH

In 2023, Athena was at an advanced stage in AI&T when the government changed launch vehicles from Virgin Orbit's LauncherOne (1330 SSO) to a SpaceX Falcon-9 rideshare (1800 SSO).[15]

The change in LTAN caused a problem since the original configuration had the solar arrays and the sensor rotating across nearly orthogonal axes. Each according to the optimal axis for its required purpose. With the change in orbit, the original configuration could either optimize pointing of the arrays at the sun, or scan orthogonal to the ground plane, but not both simultaneously. The transition from a 1300 to 1800 orbit means a nearly 90-deg shift in the solar illumination of the spacecraft.

OPTIONS FOR PROCEEDING

One option was to accept the new LTAN and operate at a dramatically reduced duty cycle. A second option was to wait for a launch with the desired orbit. That would have meant further delay.

The configurable architecture meant that a third option was available. Athena could be disaggregated, and reconfigured with the sensor pointing in a different direction and slewing across an axis which permitted a complete scan and therefore full duty cycle. Table 1 outlines these options. These changes would not have been so straightforward on a typical bus/payload architecture. In this case, it would be more likely that a new satellite would be built from scratch.[16]

Table 1: Launches and Orbits

	LauncherOne	Falcon-9	Reconfigured on Falcon-9
SSO Orbit:	550 km	500km	500km
LTAN	1300	1800	1800
Duty Cycle	100%	~50%	100%
Verdict	Cancelled	Unacceptable	Good choice

RECONFIGURATION

Snap-together colored plastic models illustrate the configuration of the sensorcraft.

Figure 6: Original Configuration

Figure 7: Reconfigured for 1600 LTAN

In the revised configuration, the solar arrays deploy in the same orientation as the sensor sweeps. This prevents the arrays from obscuring any portion of the imaging areas, which includes both the earth, and space (calibration). The rendering in Figure 8 shows that the sensor is still positioned between the carousels of HISat blocks G and H. The clamshell devices from which the arrays deploy are attached in the same plane as SLEGOs™ G and H. Other changes were also required to allow antennas, sensors and other items to be optimally positioned. However, since these are attached via UDA the changes were not a challenge. Their new location is simply noted in the FSW "mission board."

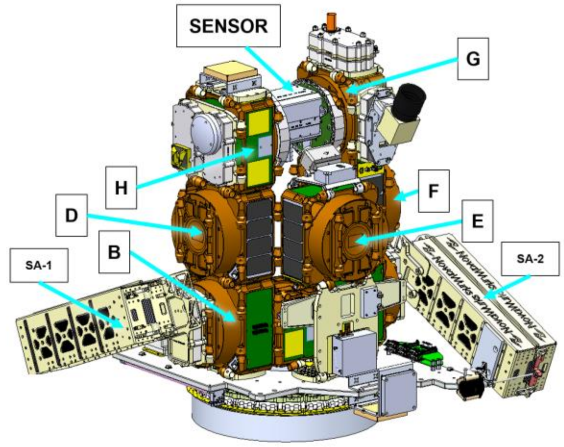

Figure 8: After reconfiguration

TIMELINE REQUIRED FOR CONFIGURATION

Reconfiguring the spacecraft could be completed in a handful of months. This is primarily an exercise in documentation. Assembly itself is not time consuming due to the ISAM interfaces. Although the integrated spacecraft requires specialized ground handling equipment to move, individual blocks may be lifted by hand without special equipment.

The timeline is such that integration and test need not be done until just a few months before launch

BENEFITS IN LATE STAGE AI&T

In the case of Athena, some unexpected benefits stemmed from the ability to accommodate an exogenous change to mission parameters. From the outset, the mission partners knew that adaptability was an inherent benefit to the design. What was not known was the particular adaptation which might be required. Previous missions with this architecture were configured once and launched as originally planned. Now that this capability has been demonstrated, it is easier to envision planning multiple configurations, with the final choice only to be decided closer to the launch date.

Since the spacecraft is assembled from identical blocks which may be taken from inventory, unit level testing which identifies an issue may be resolved by simply replacing that one block. While the ISAM interface was designed to allow in-space assembly, it facilitates near *last-minute* assembly. This was demonstrated on-orbit when the SIMPL was assembled and tested onboard the ISS by NASA astronauts, who then deployed her into space.[17]

Furthermore, the blocks themselves are of a size that they may be assembled by hand, reducing the need for mechanical ground handling equipment until the spacecraft is complete.

CURRENT STATUS OF ATHENA

At the time of writing (June) Athena is being integrated into its updated configuration. The blocks, sensor and peripherals such as radios, antennas, etc. have been kept unassembled in flight-stores. These are tested at the unit level before being assembled. Once fully assembled, the spacecraft will undergo environmental test in September. Launch is planned for Q1 2025.

In an ironic twist, assembly is taking place in a Long Beach, CA clean room formerly used by Virgin Orbit for LauncherOne.

ADDITIONAL BENEFITS OF BUILDING BLOCK SPACECRAFT

Manufacturing identical blocks in quantity, and in advance, offers a multitude of benefits including just in time spacecraft production. Depending on the sensor, mission, payload or orbit, a satellite of the appropriate capability can be built, in weeks or even days.

Quantity production reduces cost and increases quality. SLEGO™ are tested at the unit level in a batch process. Figure 9 is a photograph of 11 HISats, of which 8 are used in Athena.

The intended benefit of this architecture was to configure only once upon orbit. DARPA's Phoenix concept was to take undifferentiated 'cells' to space, which would then self-assemble as required.[18]

Figure 9: 8 of these 11 HISats are integrated on Athena

FURTHER ADVANCEMENTS OF THE ARCHITECTURE

Additional capabilities have been added to the current version of SLEGO™s. SLEGO-3 incorporates enhanced C&DH, additional and higher data rate I/O, and increased power handling. Performance specifications are at current state of the art and are protected by NovaWurks proprietary shielding.

SLEGO-3 is physically larger and may also interface with each other on the carousel surface with the option to rotate or not rotate.

Heritage HISat flight software carries over into the upgraded SLEGO™-3. Additional FSW modules have been added to enhance the GN&C capabilities.

Beyond the current design, efforts are underway for a Super-SLEGO™ with blocks over one meter on a side. The same benefits of aggregation will be available for satellites with masses into the tons. A nine-block configuration, for example, could support an RF payload with a phased array up to a possible nine square meters. Even larger configurations are possible.

OTHER MISSIONS WHERE LATE-STAGE RECONFIGURATION WAS ADVANTAGEOUS

On the 2018 SSOA rideshare, the NovaWurks eXCITe spacecraft was reconfigured to satisfy the rideshare Coupled Load Analysis. It is important to note that eXCITe itself met all rideshare requirements. The combined rideshare, however, was not within the LV requirements. This change was made to accommodate the launch provider and rideshare neighbors.

FUTURE MISSIONS

NASA Langley Research Center (LaRC) is considering a similar architecture for its DEMETER mission.[19] Historically, LaRC focused primarily on the development of sensors and payloads. Based on initial learnings from Athena, LaRC believes that the relative ease of building a sensorcraft will allow it to manage complete missions to measure the Earth's radiation budget.

Other customers have expressed an interest in NovaWurks SLEGO™ concept and multiple units of an upgraded version are currently under contract.

Athena does not take advantage of one of the key features of this architecture, that is, the ISAM capability. Future missions are expected to make use of the ability to change from launch configuration to another very different shape depending on the mission requirements.

All HISat and SLEGO™ building block missions to date have been unclassified. The authors believe that the ability to wrap unclassified building blocks around classified sensors or payloads offers significant benefits in terms of cost, schedule, reliability and security.

LIMITATIONS

Not all missions are suited to the use of the building block approach. Satellites which must be deployed from a canister, such as a P-POD or similar dispenser, require fixed external dimensions. Spacecraft under 50 kg may not benefit since a HISat has a mass of 10 kg and at least three units are required for 3-axis control.

At the other end of the spectrum, there is no reason why spacecraft of many tons cannot benefit from the building block approach. NovaWurks is in discussions for vehicles whose launch would require a Falcon Heavy. In these cases, questions related to its capabilities pertain more to the SLEGO™ advanced GN&C features and modes between the various blocks which are autonomously handled. This development is currently advancing.

SUITABLE MISSIONS

The architecture used for Athena is well suited for SmallSat missions where resiliency and high performance are required. Resiliency is provided through *n of m* redundancy inherent in having multiple identical resources. This allows any SLEGO™ to be taken offline without impacting the mission, akin to the operation of a server farm. This capability offers elastic data processing capability for payloads and can create a self-healing satellite.

CONCLUSIONS

The authors anticipated finding multiple advantages to using NovaWurks building block approach. The advantages were expected to include cost, schedule, and ease of integration. Reconfiguring the satellite prior to launch was not something that was ever anticipated. One might have thought that this would not be feasible, however, it was by far the most elegant solution.

Athena is still '*next on the pad'* so it is too early to declare a success. However, to the extent that a primary mission objective was to learn a new approach, this objective has been achieved even prior to launch.

ACKNOWLEDGMENTS

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REFERENCES

1. K. Priestley, "Athena Overview," NASA Langley Research Center, 30 October 2019. [Online]. Available: https://ceres.larc.nasa.gov/documents/STM/2019-10/5-WED_1205pm_Priestley.pdf. [Accessed 6 June 2024].

2. NASA, "Athena," NASA Langley Research Center, 2022. [Online]. Available: https://science.larc.nasa.gov/wp-content/uploads/sites/147/2023/03/Athena_FactSheet_March23.pdf. [Accessed 6 June 2024].

3. D. Werner, "NovaWurks Reveals Contracts, Expansion Plans and Slego," SpaceNews, 9 August 2022. [Online]. Available: https://spacenews.com/novawurks-reveals-contracts-expansion-plans-and-space-legos/. [Accessed 6 June 2024].

4. Jaeger, T. and W. Mirczak, "Phoenix and the New Satellite Paradigm Created by HISat," in *Small Satellite Conference*, Logan, UT, 2014

5. G. D. Krebs, "SIMPL (HISat)," Gunter's Space Page, 14 January 2023. [Online]. Available: https://space.skyrocket.de/doc_sdat/simpl.htm. [Accessed 6 June 2024].

6. P. Host, "DARPA Plans Phoenix Satlet Flight Experiments In Fiscal Year 2017," Defense Daily, 21 October 2016. [Online]. Available: https://www.defensedaily.com/darpa-plans-phoenix-satlet-flight-experiments-in-fiscal-year-2017/space/. [Accessed 6 June 2024]

7. G. D. Krebs, "PODSAT 1," Gunter's Space Page, 14 January 2023. [Online]. Available: https://space.skyrocket.de/doc_sdat/podsat.htm. [Accessed 6 June 2024]

8. SpaceRef, "NovaWurks Founder Talbot Jaeger to Attend Global Space Congress," SpaceRef, 26 January 2017. [Online]. Available: https://spaceref.com/press-release/novawurks-founder-talbot-jaeger-to-attend-global-space-congress/. [Accessed 6 June 2024]

9. K. J. Priestley, "Future Earth Radiation Budget Observations Utilizing Agile sensorcraft," SPIE, 28 October 2022. [Online]. Available: https://remotesensing.spiedigitallibrary.org/conference-proceedings-of-spie/PC12264/PC1226405/Future-Earth-radiation-budget-observations-utilizing-Agile-sensorcraft/10.1117/12.2636286.short#_=_. [Accessed 6 June 2024].

10. NASA, "2022 Annual Report," Science Directorate at NASA's Langley Research Center, 2022. [Online]. Available: https://storymaps.arcgis.com/stories/6e71aa01f4af4c6ba0aa56ebdc975e0f. [Accessed 6 June 2024]

11. Vivian Slater, "NovaWurks' eXCITe Spacecraft Successfully Deployed from Spaceflight's Historic SSO-A: SmallSat Express," GlobeNewswire, 10 December 2018. [Online]. Available: https://www.globenewswire.com/news-release/2018/12/10/1664436/0/en/NovaWurks-eXCITe-Spacecraft-Successfully-Deployed-from-Spaceflight-s-Historic-SSO-A-SmallSat-Express.html. [Accessed 6 June 2024]

12. GovTribe, "EPIC Athena sensorcraft," GovTribe, 16 November 2021. [Online]. Available: https://govtribe.com/opportunity/federal-contract-opportunity/epic-athena-sensorcraft-fa881422c0006. [Accessed 6 June 2024].

13. D. Messier, "Reverse Engineering: Satellites Designed Around Scientific Instruments," Space.com, 27 March 2017. [Online]. Available: https://www.space.com/35885-novawurks-building-satellites-around-instruments.html. [Accessed 6 June 2024]

14. D. Arney, J. Mulvaney and C. Williams, "In-space Servicing, Assembly, and Manufacturing (ISAM) State of Play," NASA Langley Research Center, 2023. [Online]. Available: https://www.nasa.gov/wp-content/uploads/2023/10/isam-state-of-play-2023.pdf. [Accessed 6 June 2024]

15. C. Simpson, "Virgin Orbit Ceases Operations," Spaceflight Now, 8 June 2023. [Online]. Available: https://spaceflightnow.com/2023/06/08/virgin-orbit-ceases-operations/. [Accessed 6 June 2024]

16. S. Volz, "Case Studies from CEOS Agencies: NOAA," Committee on Earth Observation Satellites, March 2022. [Online]. Available: https://ceos.org/document_management/Meetings/SIT/SIT-37/Presentations/4.2_Volz_Case%20Study%20NOAA_v2.pptx. [Accessed 6 June 2024]

17. NovaWurks, "NovaWurks ISS Accomplishments," NovaWurks, 30 May 2019. [Online]. Available: https://www.youtube.com/watch?v=-MNfjnfjzUg. [Accessed 9 June 2024].

18. P. Melroy, "On the Cusp: What's Next DARPA Perspective on Space," in *53rd Robert H. Goddard Memorial Symposium*, Greenbelt, MD, 2015.

19. K. Priestley and Anum Sharaf, "DEMETER: DEMonstrating the Emerging Technology for Measuring Earth's Radiation" ESTF 2023 June 20, 2023 [Online].Available: S2P1_Ashraf_ESTF2023.pdf (nasa.gov) [Accessed 7 June 2024]