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Utilising an Autonomous Video Kit for Launcher to Video Deployment of the James Webb Space Telescope

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Abstract:

This paper describes the elements of a video kit comprised of terrestrial COTS equipment, modified and re-qualified for the space environment and supplied as a complete self-contained system with minimal interfaces to the host launcher. The video system was used to capture, compress and downlink the HD video images of the James Webb Telescope being deployed after launch on 25th of December 2021, and provided mankind's last direct view of the telescope as it headed on its mission. The video system provided the world's first HD video images broadcast from orbit. The paper describes the components of the video kit and the process of development, integration and qualification that led to the capture of those iconic images..

Key words: Video, Space, Telemetry, JWST, COTS.

Introduction

The use of real-time video imagery on launchers is still relatively rare. While SpaceX has led the way (using COTS equipment as early as 2011 [1]), other launcher manufacturers have been slow to follow. This is because providing a reliable video kit for a launcher is not a trivial task, and there are many challenges to overcome. Apart from the normal technical constraints of limited on-board processing power for compression and restricted bandwidth for telemetry of the images, there are the additional constraints of weight, size, shock and vibration which are critical in a launcher environment. In addition, thermal management becomes difficult once the spacecraft leaves the earth's atmosphere. Finally, since a functional video system is not mission critical for most launches, the system must in no way affect the reliable operation of the launcher or any of its on-board systems which greatly constrains the type of electrical interfaces which can be supported. From a commercial point of view, the system needs to be cost-effective in the highly competitive launcher market.

The autonomous Video Kit (VIKI) was conceived and developed by Réaltra Space Systems Engineering Ltd. (www.realtra.space) as a solution to meet these onerous requirements. The system is a complete telemetry kit consisting of cameras, data concentration unit, power distribution unit, battery, RF transmitters and antenna. While initially developed for use on a different launch mission the VIKI system was reconfigured for installation on the Ariane5 and had its maiden voyage on launch VA-256 on December 25th 2021 for the historic launch of the James Webb Space Telescope (JWST)..

Using COTS in a Space Environment

VIKI progressed from concept to qualified flight model in approximately two years. This relatively rapid development was made possible by using Commercial Off The Shelf (COTS) equipment designed for terrestrial applications and modified it for space use, coupled with a nimble development process that involved close co-engineering between all the stakeholders over the entire program life.

COTS in this context refers to complete sub-systems (as opposed to using COTS components in "New Space" design applications). Réaltra has developed a four stage process for qualifying COTS for the space environment. First, terrestrial electronics are characterised to assess their suitability for use in orbit, then the mission requirements are mapped in detail. Next, the technology is adapted so that it can function reliably in the harsh environment of space before being put through its paces in specialist test facilities ahead of launch. This is the process that was followed to develop VIKI.

Requirements Synthesis

Functional

The primary function of VIKI is to capture and telemeter HD video in real-time from the launcher during the launch mission. From an operational point of view, the key constraint is the limited link budget. In addition, the available budget changes through the course of the mission as the spacecraft travels further from the ground stations. The system therefore has to adapt to the various stages of the mission. This adaptation must occur autonomously as there is no uplink available for control.

In order to meet this operational requirement several key requirements were identified:

- A need for efficient on-board video compression. H.265 compression was selected as it offers the highest efficiency currently available in a hardware implementation
- Dynamic control of the compression algorithm to permit the system to adjust to available bandwidth, using a constant bit rate (CBR).
- Some on-board intelligence is required, both to monitor system performance and to implement configuration changes during the course of the mission
- Compliance with open video standards is required to enable the transmitted video to be processed and broadcast using common tools

Environmental

The VIKI system is designed to be installed in the equipment bay of the Upper Stage of a launcher. In this location the equipment may experience severe vibration during take-off, coupled with extreme shock when the fairings are explosively jettisoned. The envelope for the vibration and shock qualification exceeded that of the COTS elements used in the system, so these requirements had to be considered and modifications to the COTS units were implemented to mitigate the effects.

The thermal environment experienced by the unit was also challenging. On the ground, the equipment experiences high humidity and temperatures up to 40C, but during launch the temperatures quickly drop as the launcher escapes the atmosphere. Once in a vacuum, there is no longer any heat convection and localised hot-spots can quickly develop around devices such as MOSFETS, FPGAs and processors. A detailed thermal model of the unit had to be developed and validated during a campaign of ground testing in a thermal vacuum chamber. Once identified, the COTS units had to be modified to mitigate the effects of hot spats and ensure the component thermal junction temperature limits were not exceeded.

The EMC/EMI environment of a launcher can also present problems since the usual EMC profile contains “notches” in which there is very little tolerance of emitted radiation. Further modification of the power and wiring interfaces were implemented.

Radiation

The short duration of a launch mission means that long-term radiation effects (Total Ionisation Dose) are not normally a concern. However, single event upsets (SEUs) are and an SEU could lead to a part of the system failing. A detailed analysis of radiation susceptibility was performed. The distributed nature of the processing and system operation reduces the chances of an SEU causing a total failure. In addition, fault detection and mitigation was built-in to the power distribution unit and the control processor to provide a macro level of recovery.

Interfaces

The Ariane5 is an extremely reliable launcher, with a 95.5% success rate out of 111 launches. There has been only one partial failure in the 98 launches since April 2003 [2]. Given its track history and reliability, it was a necessary requirement that adding VIKI could not in any way compromise the safety, capacity or reliability of the host spacecraft. This is accomplished by minimising the interfaces between the existing spacecraft systems and VIKI. In effect the unit had to be stand-alone.

In the end, the spacecraft electrical interfaces were reduced to just five:

- 1 dry-loop (relay) for on/off control
- 1 dry-loop (relay) for on/off control
- 1 dry-loop (relay) for system reset
- 2 RF interfaces from the transmitter to antennae that were already installed on the spacecraft

In addition to the electrical interfaces the mechanical mounting required some adaptation of the spacecraft to provide mounting points for the VIKI equipment. The same mechanical interfaces provided the thermal conduction path for the equipment once in orbit. Mass is a critical parameter for launcher performance, so there was a requirement to provide the system functionality at the lowest mass possible. This presented a significant challenge since the mass constraint had to be traded off against the shock, vibration and thermal constraints.

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System Overview

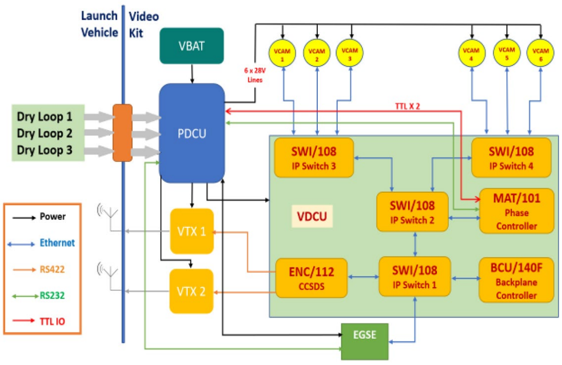
Complete System

The VIKI system is an Ethernet system built around the KAM-500 Data acquisition Unit from Curtiss-Wright Corp [3] which acts as the VIKI Data Controller Unit (VDCU). A full system block diagram is shown in Figure 1 while the network topology is shown in Figure 2.

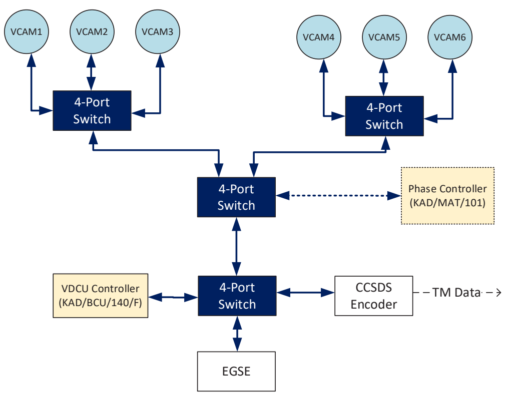
Each element of the system is a COTS part, designed and manufactured for a terrestrial aerospace environment, with the exception of the Power Distribution and Control Unit (PDCU) which was an existing space qualified design that was modified for the VIKI requirements.

While the VIKI system can support up to six cameras, just two were installed for the JWST launch.

The principal of operation is that the cameras are IP cameras, streaming video into the network architecture hosted in the VDCU. The video streams eventually end up in IP Switch 1 where they are combined with system health information and made available to the Electrical Ground Support Equipment (EGSE) while on the launch pad, and the CCSDS encoder for telemetry when in flight.



VIKI Block Diagram



VIKI Network Topology

The CCSDS encoder can filter and process the IP data for encapsulation in CCSDS transmission frames. These frames are then sent via two independent and redundant RS-422 outputs to two independent transmitters. The transmitters send the RF data to the antennae for transmission to ground.

Camera operations are dynamically controlled by the phase controller based on sequenced inputs from the dry-loops. The dry loops are also used to power the entire system on or off and to reset it to a known initial state

Data Concentrator Unit

The VDCU is based around the KAM-500 Data Acquisition system from Curtiss-Wright. The COTS KAM-500 was selected as the base unit because of its space heritage and relatively small size, mass and power footprint [4], [5].

Réaltra developed a 9-user slot space grade version of the KAM-500 chassis which acts as a host for COTS modules from the KAM-500 family.

The VDCU runs from 28V and is powered by the PDCU. It acts as the main controller and data management centre for the VIKI system. It implements several discrete functions as follows:

1. Implementation of the VIKI network via a number of 4-port network switches. The switches (manufacturer part number KAD/SWI/108) are cross-bar switches designed to be live at power up. They provide data filtering capability and support IEEE1588 time protocols. Their fixed, preconfigurable capability makes them ideally suited for this launcher application where all aspects of the network need to be deterministic and pre-configurable. Being fully FPGA based increased their tolerance to radiation upsets.

2. Operational Phase control of the entire VIKI system via an integrated micro-processor (manufacturer's part number KAD/MAT/101). The module is fed conditioned versions of the dry-loop inputs from the spacecraft over TTL. Based on the input the module selects a pre-configured state from a mission table that determines the configuration and power status of each element of the system. The module can communicate with both the PDCU and the cameras to implement the desired configuration. This allows the mission controller to control both the power utilisation and the bandwidth utilisation of the VIKI system and tailor it for different phases of the mission. The software to manage the phases was developed by Réaltra and is designed for robust operation as an

autonomous system, with built-in protections against loss of state in the event of an unexpected event. Configuration information (such as the mission state table) is stored in triplicate in non-volatile memory and uses voting techniques to detect and mitigate against radiation induced bit errors.

3. Encapsulating the IP data streams from the cameras in a CCSDS frame for transmission to the RF encoders. This is performed by a dedicated encoder (manufacturer part number KAD/ENC/112) which outputs two identical data streams for redundancy. The KAD/ENC/112 was developed by Curtiss-Wright specifically for launcher applications and was part funded by the ESA FLPP office. The encoder captures the camera data packets, along with system housekeeping packets created by the VDCU itself, and creates a CCSDS bit stream. The source cameras and the transmission bit-rate can be changed as the mission progresses to optimise data trasnfer to the available link budget.

VIKI System showing (left to right): PDCU, VDCU and two VCAM cameras

Cameras

The VCAM is based on the HDC-430 IP Camera from Curtiss-Wright. This camera was selected based on its use in aerospace applications, integrated H.265 compression, support for standard C-mount lenses and ease of control and configuration over standard IP protocols. The camera has integrated H.265 compression and can provide HD video at bit rates from 128kbps to 5Mbps. Video is output as H.265 frames embedded in an MPEG2 transport stream.

The camera required significant re-engineering to meet the shock and thermal environment encountered by the camera. A custom housing was developed to provide both protection and support for the lenses, as well as enhanced thermal conduction. The housing also integrated IR filtering and anti-fog measures. For interior mounting, an LED unit was mounted on the housing to provide illumination of the payload while the fairings were closed.

Power Distribution and Control Unit

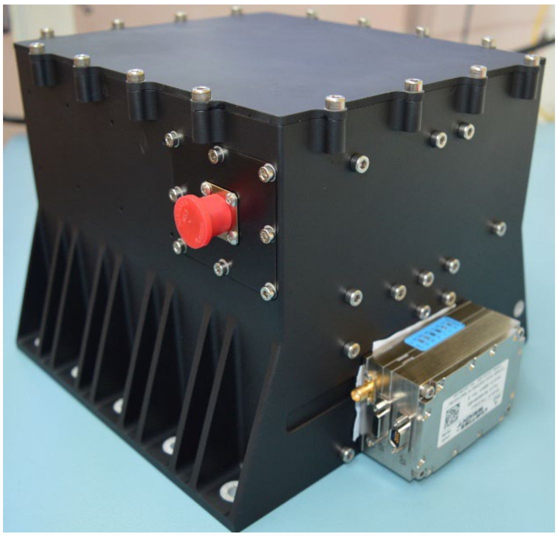
The PDCU was provided by Evoleo Technologies (Portugal), designed specifically for VIKI but as an evolution of an existing design.

The PDCU provides all the power management of the system. It accepts 28V from the battery, and distributes it to up to ten devices. Each output channel can be turned on or off under RS-232 control. The unit provides over-current monitoring and can autonomously power down an output in the event of an over-current condition.

Battery

The battery was developed for VIKI by Réaltra utilising military grade Li-MnO2 battery cells from SAFT. Two variants were developed (42Ah and 63Ah) to provide for different mission durations. The harsh shock and vibration environment presented a particular challenge for the battery design, but the unit that was eventually qualified meets all safety and environmental requirements. The battery is intended for use as a non-rechargeable primary battery.

The battery has mounting locations for the RF transmitters, one on each side. While simplifying installation, they also allows the battery, which has a large thermal mass, to act as an effective heatsink for those high power devices.



VBAT Battery for VIKI with RF Transmitter

Transmitters

The RF transmitters are COTS devices from Curtiss-Wright, model number TTS-5749. This is an S-Band transmitter ruggedised for Aerospace environments, with a power capability up to 10W. The transmitter interfaces to existing Antennae on the spacecraft.

Electrical Ground Support Equipment

An EGSE was developed to meet the needs of VIKI during testing, qualification, integration and

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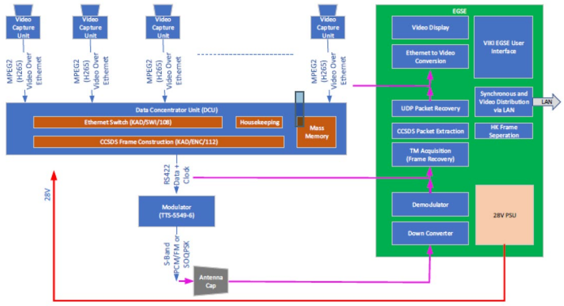
pre-flight configuration and was supplied by Celestia-STS (Netherlands).



EGSE Block Diagram

EGSE Unit

Réaltra developed additional ground support harnesses and dry-loop emulators for the test phase.

The EGSE consists of a standard 19” rack unit with an integrated laptop and a combination of standard equipment including a down convertor, and demodulator. Software developed by Réaltra builds on the Celestia STS provided interfaces to create a user-friendly interface that permits detailed control of the EGSE, and examination of the data streams from the VIKI unit both at a raw binary level and as a fully decompressed video output.

The EGSE is used for system test and configuration, and for pre-checks before launch.

Integration and Qualification

During the design and integration phase extensive analysis of the COTS units was performed. A lack of detailed information from the manufacturers meant that some critical performance parameters had to be determined empirically through development testing. A series of analyses were produced to determine worst case performances, failure modes, thermal and mechanical performance. In addition radiation effects on the COTS parts were analysed and a detailed Reliability, Availability, Maintainability and Safety (RAMS) analysis was performed.

Integration of the VIKI system took place in Réaltra’s premises in Dublin. A three model philosophy was adopted:

- Electrical Mock-up (EM): A functionally representative system both mechanically and electrically.
- Qualification Model (QM): A system that is fully representative of the flight model, used for the qualification campaign
- Flight Model (FM): The model intended for installation and flight

These models were then subjected to a sequence of tests to build up a dataset that proved the systems capabilities for operation in the mission environment (Table 1). Where possible, testing was carried out in-house by Réaltra personnel, but where specialist test equipment or facilities were required the testing was out-sourced.

Test	EM	QM	FM
Screening	X	X	X
Physical Properties	X	X	X
Full Functional Performance	X	X	X
Resonance Search		X	X
Sine Vibration		X	
Random Vibration		X	X
Mechanical Shock		X	
Thermal Cycling		X	X
Thermal Vacuum		X	
Thermal Shock		X	
EMC/EMI		X	
ESD		X	
Full Functional Performance	X	X	X

Table 1: Test Sequence

The test campaign was planned to take place at the test facilities in DLR Bremen under supervision of Réaltra personnel in early 2020. The emergence of the world-wide Covid-19 pandemic meant that travel to test facilities was prohibited, so a few hectic weeks were spent re-configuring the test plans and writing a series of software tools that would permit DLR personnel to perform the tests under remote supervision. The first series of tests were successfully performed in this way.

For the subsequent series of tests, all testing was performed on the island of Ireland once in country travel was permitted. Several test facilities undertook to upgrade their capabilities to meet the demanding requirements, and a thermal vacuum test facility was commissioned in Dublin. With the assistance of these partners,

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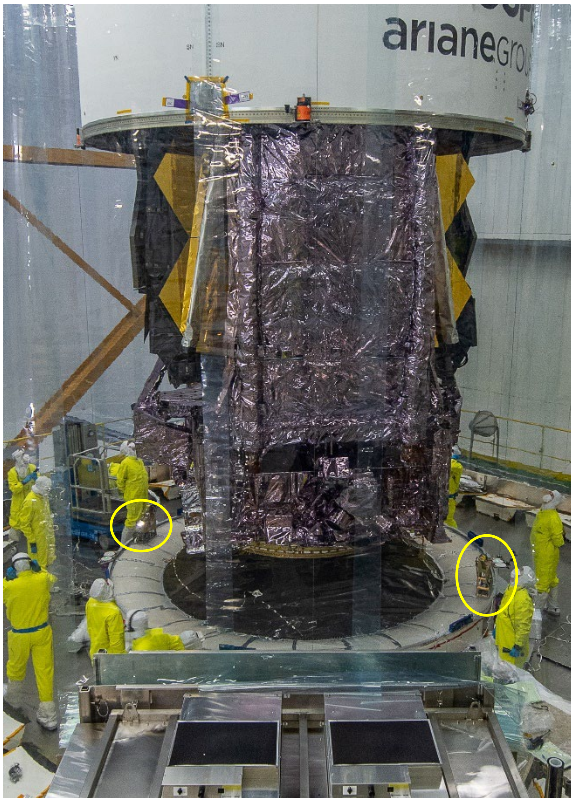
and under the guidance of Réaltra personnel, the test campaign was completed within schedule and a successful Qualification Review was held early in 2021 which enabled the system to be approved for installation on the Ariane5 for the JWST launch. This marked the first time a space system was qualified wholly on the island of Ireland.

In parallel with the system qualification, the installation plan for the equipment on the launcher was created. Once installation locations were finalised, a final thermal analysis was performed to ensure that the conduction paths were sufficient to keep the unit within functional thermal limits. This was especially critical for the cameras which were mounted on a raised framework.



Fairing being lowered over JWST. VIKI cameras visible on left and right - left camera LED is on.

Installation and Commissioning

The VIKI unit shipped from Dublin, Ireland in Q2 of 2021 to ArianeSpace in Bremen where it was installed in the equipment bay of the Ariane5 upper stage in preparation for transportation to the launch site in Kourou, French Guiana.

Once at the launch site, ArianeSpace personnel performed pre-flight checks and evaluations during launcher preparation. This included a complete test with RF being transmitted from VIKI to the ground station and video images recorded successfully. All testing and checks were completed before the payload (JWST) was lowered onto the upper stage and attached. The VIKI cameras were used to observe the process of lowering the fairings over the JWST. The margins were very tight due to the telescope's large size [6].

Performance

VA-256 launched at 12:20 UTC on December 25th 2021. The camera was configured to capture HD video (1920px x 1080px), compress and transfer it to the VDCU for encapsulation and transmission. The transmission rate was adjusted during the course of the mission.

The VIKI system was operating from before take-off and successfully recorded and transmitted conditions in the upper stage during the entire launch; before, during and after payload deployment. While most of this recording is proprietary, several key segments were shown during the live broadcast – a brief view of the JWST in-situ on the upper stage shortly after the fairings had been jettisoned (using both cameras to provide a view from each side) and the, now famous, view of the JWST being deployed from the upper stage and moving majestically away. This segment is publicly available at https://www.esa.int/ESA_Multimedia/Videos/2021/12/Webb_separation_from_Ariane_5 and demonstrates the excellent performance of the VIKI system, the first time HD video has been broadcast from space.

Conclusion

The hostile environment of a launcher, coupled with the relatively low volumes required, makes the development of a bespoke video system for launchers prohibitively expensive. However, adapting COTS equipment for the same environment is a challenging exercise which involves a series of engineering trade-offs and some degree of modification and adaption of the COTS equipment. Nevertheless, the VIKI system demonstrates that achieving a cost-effective balance of cost and performance is possible.

To create VIKI, Réaltra took a variety of COTS equipment from different suppliers and modified them to meet the mission requirements of their customer. The modified systems were then integrated and put through a rigorous qualification campaign to ensure that the overall system would perform as expected during the mission.

The entire project was completed in less than two years, and culminated in an astonishing and iconic video that gave mankind our last view of the JWST departing on its historic mission to reveal the deepest secrets of the beginnings of our universe.

Acknowledgements

The development, integration and qualification of VIKI was a complex task completed in a relatively short time. This would not have been possible without the enthusiastic and dedicated support of partners and suppliers. Réaltra would like to acknowledge the following individuals and corporations without whom VIKI would not have been possible.

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COTS and supporting equipment was supplied by Curtiss-Wright Corp. (www.curtisswrightds.com), Evoleo (www.evoleotech.com), SAFT (www.saftbatteries.com), Schneider (www.schneiderkreuznach.com) and Celestia STS (www.celestia-sts.com).

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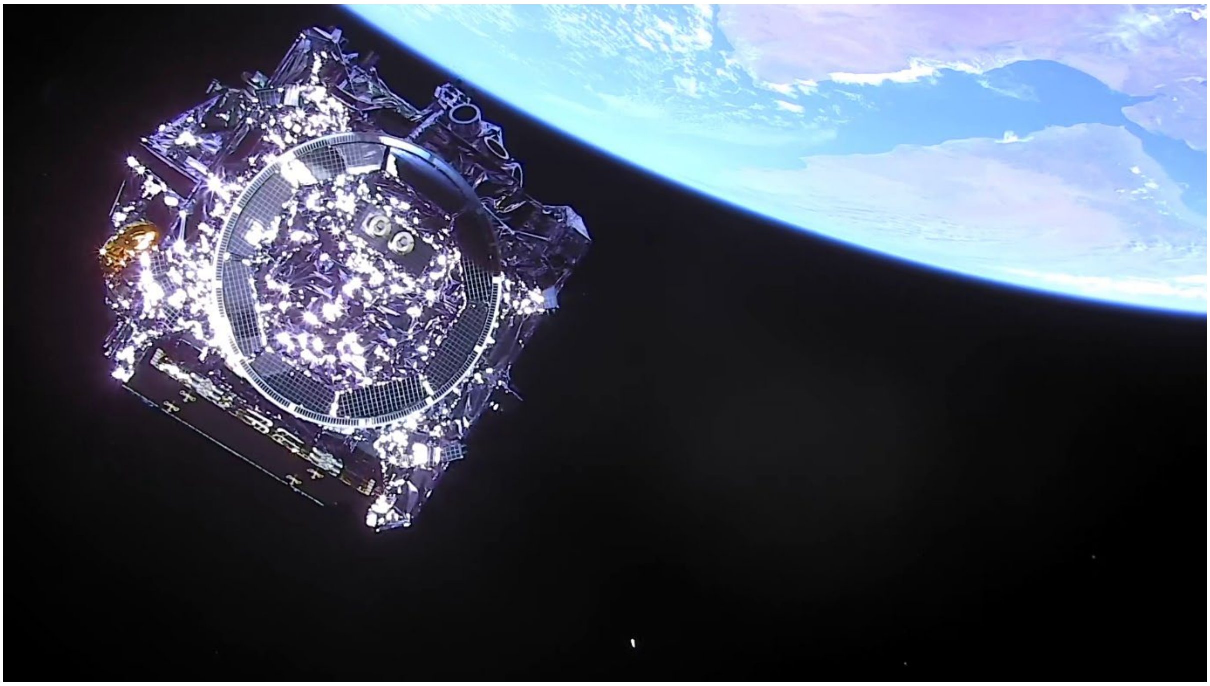

.Goodbye JWST...an image from VIKI © ArianeSpace, ESA, NASA

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