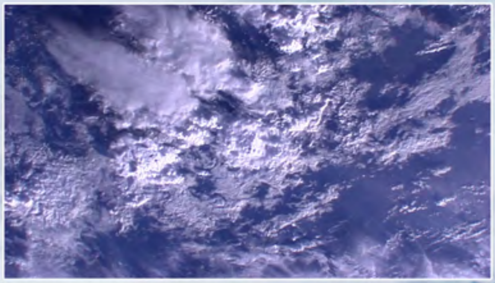
HIGH DEFINITION EARTH VIEWING



Final Report, June 2020

High Definition Earth Viewing (HDEV)
Final Report
June 2020

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The authors wish to acknowledge all of the people involved in the concept, design, development, manufacture, and operation of HDEV's numerous components, including the software and hardware that made it all possible. Many of the people on the HDEV team are seen here in 2012, with the completed HDEV assembly shortly after it was closed up and sealed in preparation for final testing and hardware delivery.

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INTRODUCTION

The International Space Station (ISS) High Definition Earth Viewing (HDEV) payload [1] began as a drawing on a napkin by Carlos Fontanot, Space Station Imagery Manager, in response to a question from the Space Station Technology Demonstration Office's Dave Hornyak and George Nelson. An opportunity to use an external space station payload facility became available that was ideal for a camera system pointing at the Earth. The idea was to investigate how commercial-off-the-shelf (COTS) cameras perform in space for the purpose of aiding in the selection of cameras for future space flights. HDEV exceeded expectations for longevity and produced questions about why good imagery quality remained over its 5.2-year lifespan.

Figure 1
HDEV mounted on the nadir side of the CEPF. Visible are the windows for the two aft-viewing video cameras (rectangle and circle) and the nadir-viewing camera (semicircle in center of dark gray panel).

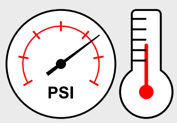
HDEV was designed, built, certified and delivered in only 9 months using the innovative COTS hardware and streamlined verification and certification processes, which became the prototype of the current Class 1-E Experiment Flight Hardware development process. Delivered by SpaceX Cargo Resupply Services (CRS) 3, HDEV was the first payload to be robotically removed from the SpaceX Dragon trunk and installed on the space station on the European Space Agency's (ESA) Columbus External Payload Facility (CEPF) depicted in Figure 1. It was activated April 30, 2014 and after 5 years and 79 days on July 18, 2019 it reached its end of life. HDEV's live streaming video was viewed by more than 318 million viewers across the globe on Ustream alone, and had an average of 1333 viewers at any given moment from up to 237 countries and dependencies plus 54 US states and territories.

The decision to make HDEV's streaming video of Earth available to the global public while monitoring the primary objective had a large impact to HDEV's additional success as a payload. The live streaming video expanded HDEV's contributions to NASA and the Space Station Program in the areas of education and public awareness across diverse audiences. HDEV's video served as a catalyst for students to learn about the Earth and remote sensing such as with the Columbus Eye program by the University of Bonn, Germany. It expanded the public's awareness of the station orbiting the Earth including the invention of a commercially marketed device, ISS-Above, which indicates when the station passes overhead and shows the HDEV video, in addition to other space station downlinked video. HDEV created awe in those watching the Earth from space, and provided imagery for numerous creative uses including art installations, music videos, quilt squares, and developing educational material for Science, Technology, Engineering, Arts, and Math (STEAM) engagement with learners of all ages.

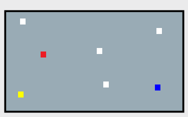
HDEV HARDWARE AND RESEARCH OPERATIONS

HDEV Research Overview

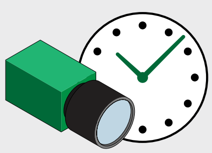
HDEV's primary objective was to validate the space-based performance of its four different commercial, high definition video cameras and the outer housing while mounted externally on the space station CEPF [2]. HDEV would operate in a variety of modes to exercise and demonstrate the features and longevity of the commercial-of-the-shelf (COTS) equipment for future Space Station Program usage. Specific measurements and observations to accomplish the primary objective included:



Routine monitoring of the internal pressure and temperature within HDEV's housing



The number of damaged pixels, to assess the video quality from each camera while taking imagery of Earth



The length of time the cameras remained operational, to assess the hardware's ability to survive and function in the radioactive environment of low Earth Orbit (LEO)

Education and outreach became a secondary objective and a large part of HDEV and the benefits it contributed to the Space Station Program and NASA early in the payload's life cycle. Initially, during hardware construction, the only planned educational activity involved students in the High Schools United with NASA to Create Hardware (HUNCH) program who fabricated some of the HDEV flight components. The decision to distribute HDEV's live streaming video on Ustream provided the opportunity for several unplanned high impact educational [3] and outreach activities to be initiated. Those activities and products engaged large numbers of the public with HDEV and the space station.

Hardware Description

HDEV was an external Earth viewing, multiple camera payload using a set of four (4) COTS high definition video cameras. The HDEV integrated assembly is composed of the cameras, COTS Command and Data Handling (C&DH) avionics (1533 Bus and/or Ethernet, Visionary Solutions Inc. AVN443 encoder), and a power & data distribution box for integration of the payload's components interface to the space station Columbus Module and CEPF. The cameras, encoder and other electronics were enclosed in a thermally controlled and pressurized box to provide a level of protection to the electronics from the space environment. The enclosure contained dry nitrogen at one (1) atmosphere pressure.

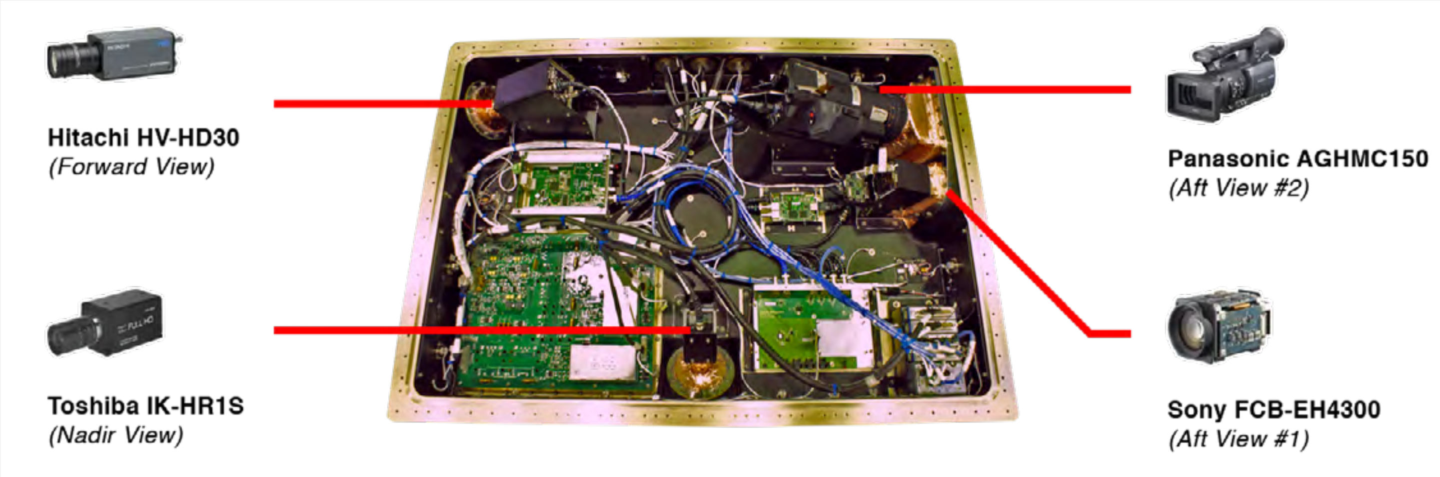


Figure 2
The completed internal assembly of the HDEV hardware. The four cameras are identified in their respective locations inside the container.

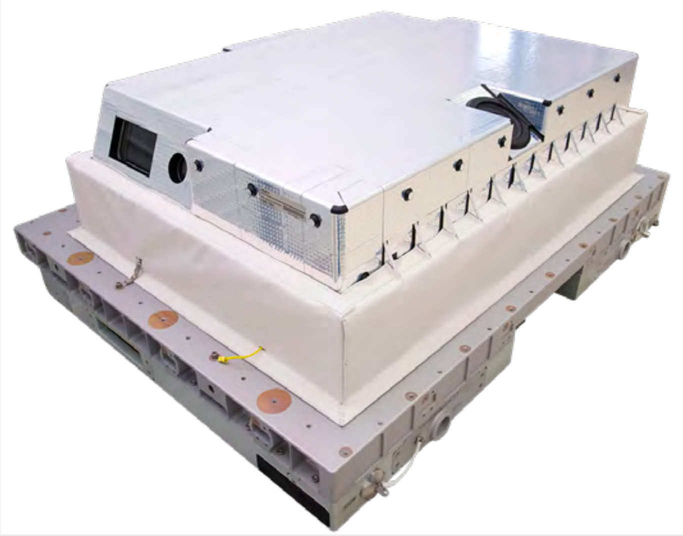


Figure 3
The completed HDEV assembly. Visible are the two aft cameras (dark rectangle and circle on the left) and the nadir camera (dark circle inset on the right).

The four cameras chosen were from Panasonic, Sony, Hitachi and Toshiba. The cameras' sensors were either a charge coupled device (CCD) (Panasonic) or complementary metal-oxide semiconductor (CMOS) (Hitachi, Sony & Toshiba). See Figure 2 for camera configuration in the HDEV housing.

The camera lenses consisted of two 4 mm Fujinon on the Hitachi and Toshiba, a Leica Dicomar set at 3.9mm on the Panasonic, and an integrated camera lens with the shortest focal length being 4.7 mm where it was set on the Sony. They looked through fused quartz cover glass used for the camera windows, which provided a transmissivity of greater than 90% over the visible spectrum (390 – 750nm).

The HDEV system was designed to have the cameras fixed in location, viewing angle, and in camera and lens settings. This design required no pan or tilt mechanisms, no zoom and no iris adjustments. The four fixed cameras were positioned to capture imagery of the Earth's surface and its limb as seen from the space station (i.e., one camera pointed forward along the station's velocity vector (ram facing), two cameras aft (wake), and one camera pointing down (nadir). The two wake-viewing camera ports are visible in Figures 1 and 3. The most significant modification to the COTS cameras was to change the power source from a battery to space station power and install control input covers and interface modules where needed.

The camera exposure and lens settings where fixed and tested on the ground before launch to capture the best visible, high definition video during the daylight portion (~45 minutes) of each space station orbit. The cameras have varying degrees of low-light imagery capability, but none of them were able to capture visible imagery of Earth during orbital night. Only one camera had an auto iris (Panasonic) which was configured so it would not operate automatically. An auto iris on cameras sometimes has trouble handling extreme lighting changes such as what occurs below the space station along the orbit track, creating an unstable or fluctuating video image. See Appendix A for camera specifications.

The video imagery was encoded into an Ethernet compatible format (in packets) for transmission to the ground through the payload operations communications system. Once the data was received on the ground, computer workstations were used to depacketize the data, extract the video, and decode the video for further distribution. Once distributed on Ustream, the video could be viewed from any computer connected to the Internet.

See Appendix A for additional HDEV Hardware Technical Specifications.

Hardware Testing

In addition to the required HDEV flight hardware system operation and communications testing, a camera distortion characterization of each HDEV camera with flight lens was conducted using the Matlab Bouguet Camera Calibration Toolbox (CCT) [4]. This characterization produces a full distortion map and the important parameters: principal point, focal length, radial and tangential coefficients, which are needed for photogrammetric analysis. In summary, all of the distortion plots looked reasonable, the characterization for each camera was successful and the HDEV cameras could have been used for analysis if needed. An example of the lens distortion map for the Toshiba camera is provided in Figure 4. The X,Y axis contain the pixel numbers. The numbers on the curved lines in the plot are the degree of distortion. The higher the number the more distortion. The circle in the center of the distortion map is the location of the principal point representing the perspective center on the sensor. If everything were lined up perfectly, the circle would line up with the 'x.' But there is lens distortion, and there could be a very slight misalignment of the lens that caused the principal point to shift. This amount of misalignment is within tolerances and would not keep the Toshiba imagery from being useful for analysis.

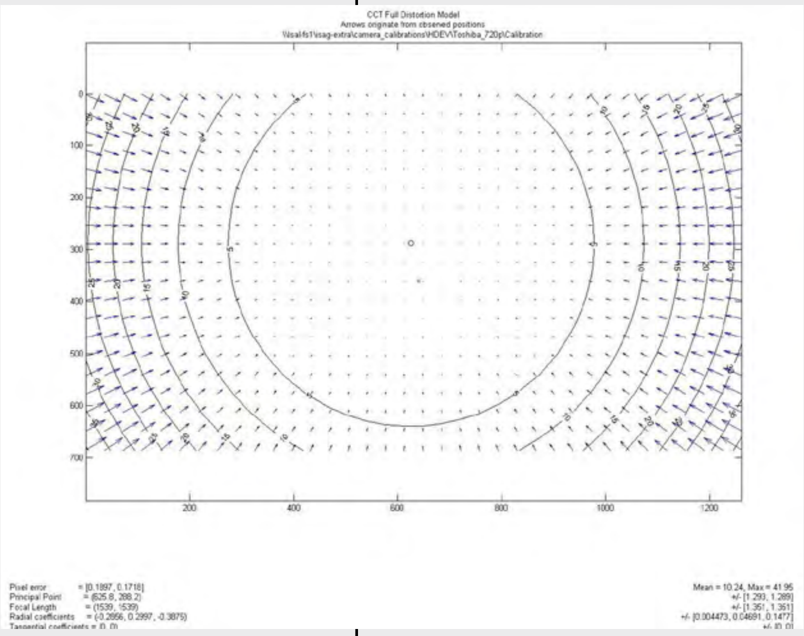


Figure 4
This distortion model or map shows the results of the camera/lens characterization of the Toshiba camera.

Over the life of HDEV, the video was never needed to perform a photogrammetric analysis of one of the vehicles which passed through the view of the HDEV cameras.

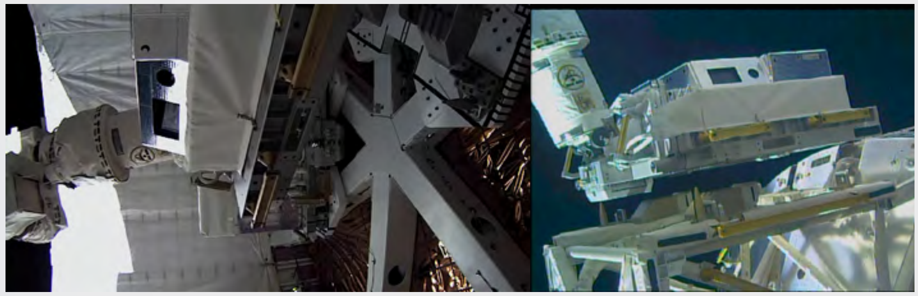


Figure 5
Left: The SpaceX CRS-3 launch. Above: Two views of the robotic operations during the HDEV installation activity.

HDEV Operations

HDEV was launched on SpaceX CRS-3 on April 18, 2014. Once delivered to the space station, HDEV was the first payload to be removed from the SpaceX trunk and installed on the space station CEPF by robotic ground controllers (as seen in Figure 5) and was activated just 12 days later on April 30, 2014. On July 18, 2019, all data stopped being downlinked from HDEV. After conducting contingency operations for resolving issues and system analysis, HDEV's End of Life was declared on August 22, 2019. The plan upon design was to dispose of HDEV on a capable vehicle with a Flight Releasable Attachment Mechanism (FRAM) interface configuration (HTV, Dragon, Cygnus). HDEV was disposed of using Northrop Grumman's (NG) Cygnus resupply spacecraft (NG13) in May 2020, marking the second time a Cygnus vehicle disposed of an external payload (Figure 6).

Figure 6
HDEV (gray rectangle) is seen attached to the exterior of the Northrop Grumman Cygnus-13 vehicle shortly after unberthing from the space station.

Camera Operations

HDEV operated one camera at a time. It was designed with a default camera mode so that when the system is initially powered on, after a 1 to 2 minute warm up period, the cameras were turned on one at a time in a repeating sequence. The forward looking (ram viewing) camera was powered first, followed by the downward looking (nadir) and each aft looking (wake viewing) camera, such that the HDEV video “follows” a location on the Earth as the space station passed overhead as described in Figure 7. HDEV was designed to operate any time that the space station power and data resources were available, without requiring a ground controller present to operate the payload. The only command required, was the initial “power on” command, which was performed by ESA’s Columbus Control Center (Col-CC) as scheduled by Space Station Payload Operations.

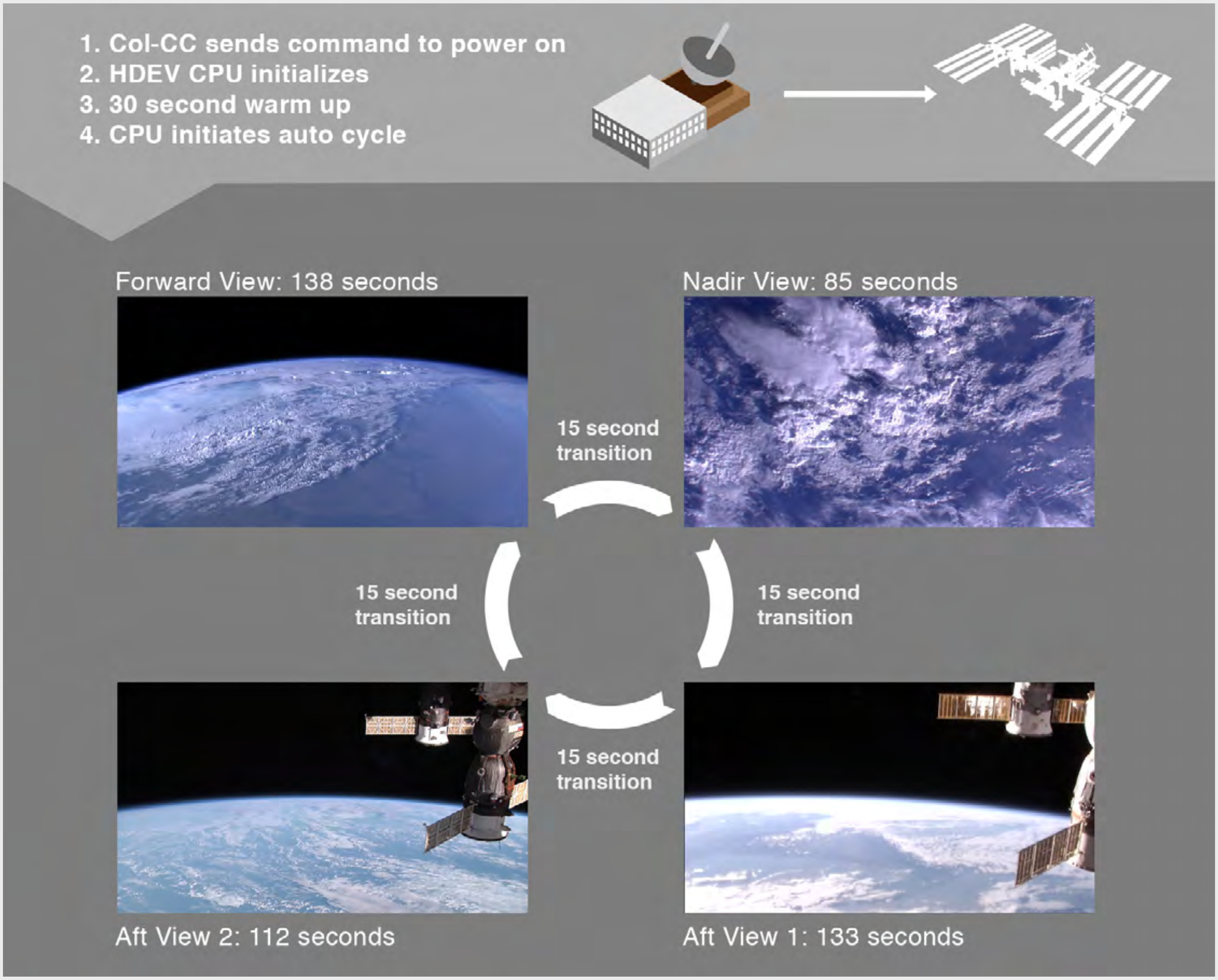


Figure 7
HDEV system design for default auto-cycle operations. The camera views were pre-planned and the cameras in the HDEV housing were mounted accordingly. The objective of the default camera rotation was to view and follow a feature in the forward-looking camera through the other cameras as it passed underneath the space station. The transition times for the cameras to switch broke the flow of viewing for most viewers, so the normal mode of operations changed to having each camera operate for one orbit then switch to the next camera.

After installation on orbit, the cameras were turned on and video was downlinked and processed on the ground using a standard Space Station Telescience Resource Kit (TReK) workstation and HDEV-specific software. The initial video downlink was recorded to establish baseline camera image quality to start meeting the major goal of HDEV: to monitor camera/system longevity and performance. Periodically during HDEV operations, video from each camera was recorded and compared to previous video. The video image analysis over time was a method to document how well each of the camera systems performed in the space environment. At first, video was captured during the night time portion of the space station orbit every two weeks and analyzed using image correcting software which provided the number of pixels it would have corrected. After a few months of no apparent damaged pixels the time frame for sampling the video increased to monthly then after 2 years it was extended to occasionally, if any potential damaged pixels were visible.

Alternatively, as desired by ground operators, the HDEV cameras could be commanded. Ground operators could change the cycle of the cameras noted in the default auto-cycle mode (Figure 7) (either changing which cameras were in the operational rotation or changing the length of time they are powered on), or, if desired, could command a single camera to remain powered on and no auto-cycle take place. As will be discussed in the Lesson Learned section (page 11), the alternate auto cycling of having three cameras in the rotation and having each camera operate for one full station orbit before cycling to the next became the preferred operational mode as compared to the default auto-cycling.

Data Handling Operations

All HDEV video was transmitted to the ground in real time. HDEV did not record video on the payload, or on board the space station. Though not required, the payloads on board system, the Medium-rate Communications Outage Recorder (MCOR), would occasionally record the packetized video when the data could not be downlinked for a variety of reasons, for any later data retrieval. All HDEV payload operations beyond initialization occurred via 1553 and Ethernet communications with the US Operating Segment (USOS) C&DH System. See Figure 8 for the HDEV Command and Data Handling flow. There were no requirements to archive HDEV video so any desired recording of the video occurred as ground operations such as for comparing the number of damaged pixels or capturing unique views like interesting geographic features, major weather events, and visiting vehicles to the station which crossed through the HDEV field of view. The streaming video was distributed through Ustream [5] to any public computer which could connect to it, including a special HDEV page on the Gateway to Astronaut Photography of Earth website [6].

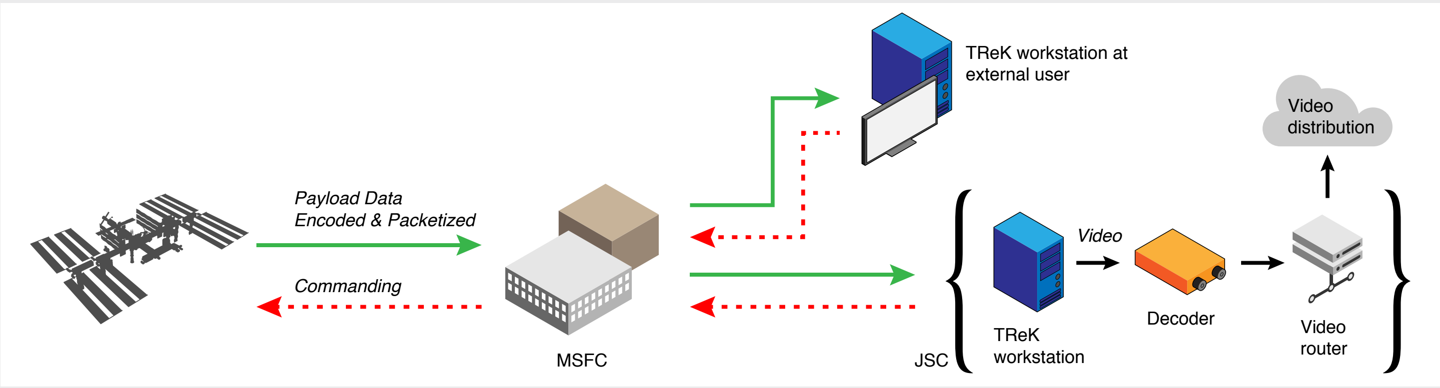


Figure 8
HDEV Command and Data Handling flow diagram.

Operational and Hardware Anomalies

A total of nine Payload Anomaly Reports (PARs) were generated during the lifetime of HDEV with several recurrences of a few of the PARs. HDEV was designed to be mostly autonomous with limited commanding to each of the four cameras and internal processor. Having the default software execute automatically after each “REBOOT” command or when Col-CC conducted a power cycle simplified the process to correct anomalies. The Col-CC’s main functions are to command and control the systems of the European space laboratory Columbus. It is located at the German Aerospace Center (DLR) in Oberpfaffenhofen, near Munich, Germany.

The capability to upload or change existing software was not included in the design and some of the components did not have sensors to monitor activity. This resulted in not being able to determine the exact cause of anomalies. However, looking at the reaction of other components and the flow of usual or unusual activity, the most likely component which had the issue(s) could be determined.

The course of actions to correct any anomaly was limited to first finding out what the Data Management Coordinator (DMC) at the Marshall Space Flight Center witnessed to focus actions on either the HDEV hardware on the station or on the HDEV ground system, or occasionally on the space station systems hardware or software. Correcting any issues with HDEV on board hardware was limited to using the HDEV commands: “STANDBY”, “REBOOT”, and “MAC address” to point at the correct Payload Ethernet Hub Gateway (PEHG) and/or, if needed, asking Col-CC to conduct a power cycle for HDEV. Conducting hardware analysis to determine the cause of each anomaly generating the PAR was not normally conducted because the resulting course of actions would be the same regardless of the anomaly.

Overall, there seemed to be no pattern or correlation between the symptoms and the specific steps in the course of action(s) which would “fix” the issues. Some anomalies were fixed by leaving HDEV in STANDBY mode for 5 or 10 minutes, sometimes using the “REBOOT” command worked, and several times a power cycle by Col-CC was needed. Appendix B contains a list of the PARS.

The impact of anomalies over HDEV’s operational life was minimal pertaining to the loss of HDEV video imagery during each anomaly event. There was no requirement to record or distribute all video. As long as the video returned, and the number of damaged pixels could be monitored HDEV was collecting the data needed to meet the primary objective of monitoring the performance of HDEV in the harsh environment of space. The HDEV DLR partners at the University of Bonn recorded all the downlinked HDEV data. Fortunately, none of the anomalies occurred while the University of Bonn was specifically recording views from the nadir viewing camera. They had the HDEV video data which they needed to conduct their STEAM concepts and test their curriculum in the classroom.

HDEV LESSONS LEARNED, FIRSTS, AND RESULTS

HDEV Lessons Learned

Overall HDEV hardware and software and the associated operations ran very well. There are a few lessons learned to note from HDEV system development, camera operation and video distribution, as listed below:

1. **HDEV served as a prototype for the Class 1-E Experiment Flight Hardware development process and demonstrated the concept was possible**

   HDEV was designed, built, certified and delivered in only 9 months, using the innovative COTS hardware and streamlined verification and certification processes. This classification is now an expeditious process to provide flight hardware which is more lean and agile while not compromising safety.

2. **A radiation monitor in the HDEV housing may have provided useful data to provide more insight or serve as a flag to monitoring damaged pixels which appeared and disappeared**

   Depending on the data from the radiation monitor, it may have verified or eliminated the speculation of why there were only three apparent damaged pixels in HDEV's video at the end of operations. The three damaged pixels will be discussed more in the HDEV Results section.

3. **The default auto cycling did not produce the desired result of following a feature passing under the space station due to the interruption of the time delay needed between camera views during the transition**

   The default auto-cycling did not produce the desired result of following a geographic feature passing under the space station. The time delay for switching between cameras created too much of an interruption in the flow of viewing the feature. During the default auto cycling, the transition time to switch to the next camera became too much of an interruption and distraction to the viewer. Questions received from viewers indicated that many did not realize that the default rotation was intended to follow a feature in the view as the station was passing overhead. Only three cameras were used in the alternate auto-cycling because during launch something happened to one of the aft (wake)-viewing cameras to make the focus slightly soft and the exposure for the typical daytime scene too bright.

4. **Cameras with day and night time imaging capability and settings needed to maintain larger public interaction**

   The largest number of individual viewers existed during the first year of HDEV's operation in 2014. The large number decreased through 2014 and 2015. One reason for this may be that every 45 minutes, there was a 45 minute period of darkness being displayed as the space station went through the night portion of the orbit. This is discussed further in HDEV's Impact on Connecting the Space Station to the Public using Ustream Metrics (page 22).

5 Though built to be nearly autonomous HDEV required operational personnel specializing in HDEV to be monitoring and available on a routine basis

HDEV was built to be as autonomous as possible and the Marshall Payloads Operations and Integration Center (POIC) was monitoring for any loss or out of range Health and Safety Status and video packet downlink. HDEV still required a significant amount of time to maintain account credentials for TReK and various payload web portals, conduct Certification of Flight Readiness reviews, re-initiate the Ground Support Equipment (GSE) packets after various maintenance, visiting vehicle, new payload installation on the same power distribution unit, and address issues occurring outside of the normal operations expected of the payload and ground support system. For instance, on the primary ground support computer for HDEV video data reception and distribution there would be unplanned IT upgrades which required the system to be rebooted and the HDEV unique software reinitialized.

6 A primary HDEV hardware and software engineer was needed periodically through the life of the payload

The HDEV system engineers were needed to help analyze or assess major payload issues or to reprogram the payload specific ground support software to remain compatible with any space station payload software upgrades, for example with TReK upgrades.

7 Reloadable on board software

HDEV was not designed with the capability to upload or upgrade its onboard software. Though not needed for HDEV, during a few anomalies with unknown causes the thinking was that if the basic software was corrupted by a radiation event, there would be no way to recover the payload even if the hardware was still functional.

8 When HDEV video became popular on Ustream, a more accessible distribution architecture was needed for external users

Although generally effective in reaching the public, Ustream presented challenges to some end users. To help expand the use of the HDEV imagery, broader distribution of video to the public via multiple channels is recommended.

9 Returned HDEV cameras and other hardware for inspection would have been beneficial

HDEV was designed to be disposed of using a cargo resupply vehicle that does not return to Earth. Due to the fact that few damaged pixels were observed, it would have been beneficial to return the hardware to Earth for thorough analysis of the camera sensors and other hardware. The actual number of damaged pixels on the CMOS/CCD image collectors could have been determined. The processor in the cRIO may have held the clues as to what ultimately caused HDEV to fail.

HDEV Firsts

1. **Class 1-E concept pioneer**

   HDEV was the first experimental flight hardware to test the concept for Class 1-E engineering development as listed in the HDEV Lessons Learned section.

2. **Large Payload delivered by SpaceX**

   HDEV was the first large unpressurized payload to be delivered and robotically maneuvered from the SpaceX Dragon trunk and installed on the space station. It was placed on the nadir attach site of the CEPF.

3. **Commanding capability from Johnson Space Center (JSC) Video/Imagery Facilities**

   The JSC imagery group has always received, distributed and managed imagery downlinked from space, but has never had the capability to command and control an imaging payload aboard a space vehicle. HDEV marks the first time this has occurred.

HDEV Results for Payload Technology Demonstration and Research Objectives

HDEV's primary objective was to validate the space-based performance of its four different commercial, high definition cameras and the outer housing while mounted externally on the CEPF. The results for the specific measurements and observations to accomplish the primary objective are as follows:

1. **Housing Integrity: Routine monitoring of the internal pressure and temperature within HDEV's housing**

   The container holding the cameras performed as designed for the duration of HDEV.
   a. Pressure maintained at one atmosphere with the nitrogen gas throughout the operational life of HDEV.
   b. HDEV remained thermally controlled. The temperature stayed within reasonable tolerances even with an occasional warming when a component stopped working properly.

2. **Assessment of Camera Quality Performance: Counting and tracking the number of damaged pixels from each camera while taking imagery of the Earth**

   HDEV tested commercially available high definition cameras as a concept for future space missions. Using off-the-shelf products are often more cost-effective than designing new ones for space applications. Ground tests showed that the HDEV COTS cameras could survive the simulated space environment, but actual exposure to low-Earth orbit for 5.2 years provided insight into how durable and well they work in the extremely harsh conditions of space.

Unexpectedly, only three damaged pixels were visible at the end of HDEV operations in the nadir-viewing camera. Figure 9 shows the damaged pixel in 2014, where the first damaged pixel became apparent on August 21, 2014, about 4 months after being installed. The two additional damaged pixels, appearing in September of 2017, are apparent in the 2018 view. In comparison, Figure 10 shows damaged pixels that are routinely found in video or still imagery from the space station after a few months.

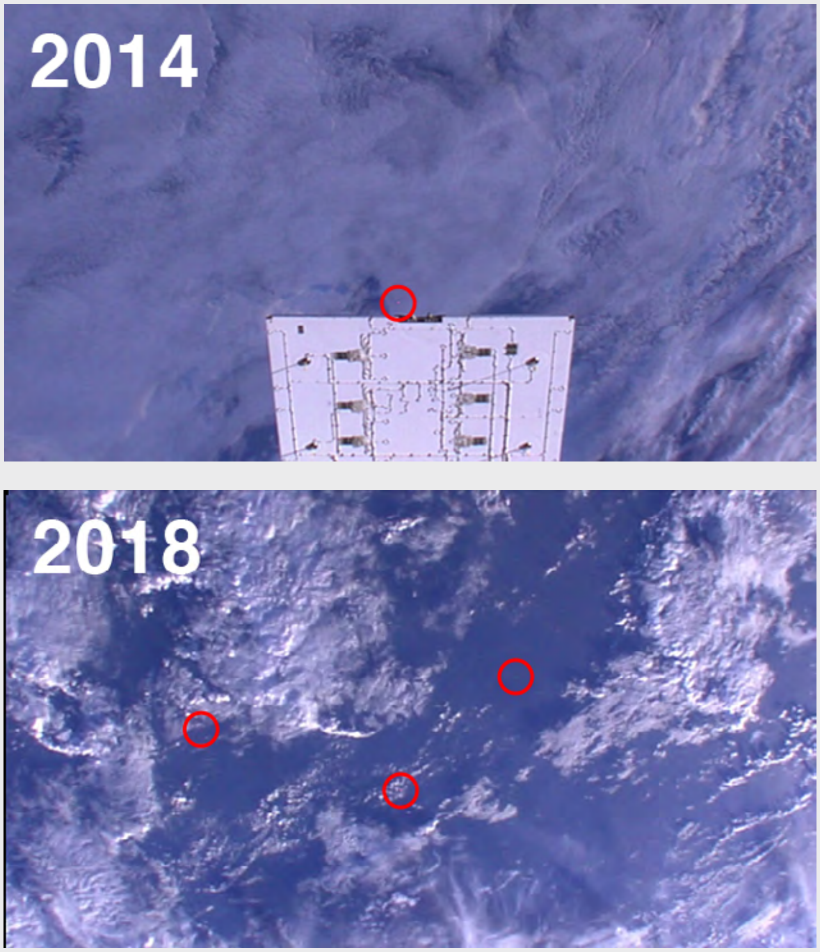


Figure 9
The only apparent damaged pixels occurred in the HDEV camera which looked nearly straight down on the Earth from the space station. The first damaged pixel appeared in August 2014 and remained for HDEV's operational life. The other two became apparent in September 2017 and are also shown in the 2018 view.

In 2017, on GMT 254, Sept 11 and 255, Sept 12, an Energetic Solar Particle Event (ESPE) impacted the space station from about 05:51 to 12:59 and 04:59 through 12:55 GMT respectively. Approximately ten (10) to fifteen (15) damaged pixels were visible in only the nadir camera view. These damaged pixels were still visible on Oct 3, 2017. After monitoring the nadir view for approximately another week, most of the newly damaged pixels faded away and were no longer noticeable. However, two (2) damaged pixels of the ten (10) did remain and are depicted in Figure 9. The three (3) damaged pixels were the only visible ones remaining at the end of HDEV's operational life. The question remains; where did all the expected "bad" pixels go? The inconclusive reasons for these results may be due to one or a combination of several possible factors: the video is compressed to 6 mbps using the H.264 codec before downlink; HDEV housing and interior components; angles of the cameras; the location on station and the CEPF; sensor technology for auto correction; unequal camera operational time. A brief description of possible factors follows:

Video Compression: From HDEV to the ground, there are two places where video data compression occurs before being displayed as streaming video. Within HDEV, the integrated Command and Data Handling (C&DH) avionics includes a Visionary Solutions, Inc AVN443 video encoder which enables H.264 encoding and an MPEG-2 Transport Stream to be moved, via Real-time Transport Protocol (RTP), then formatted by the Compact Reconfigurable Input/Output (CRIO) computer, and delivered through the space station Columbus module payloads communications system. The AVN443 encoder is the same model that is used for space station internal video where several damaged pixels are apparent after a few months in space as seen in Figure 10. Given that HDEV video is encoded as an H.264 stream, 720p/60 frames per second output per NASA standard at 6Mbps, the compression, and data rate of the encoder also affects the resolution, which can mask bad pixels [2]. Once on the ground the video data undergoes another compression cycle as it passes through a decoder to be displayed as streaming video.

Housing, internal components, and/or angles of cameras in housing: HDEV's box was machined from aluminum with o-ring sealing at cover and viewing ports. The box is filled with Nitrogen gas (N2) at one (1) atm. There were also heater plates mounted in 6 places around the side walls of the box. Each camera had a heater plate on both sides of them. The structure has been successful in keeping the pressure and temperature within limits for the last 5.2 years. Aluminum reduces the amount of radiation which enters the interior of the housing [7] while the heater plates may have further reduced the radiation from reaching the camera sensors.

Placement on space station structure: HDEV was mounted on the nadir attach point of the CEPF; the structure of the CEPF could have shielded HDEV from radiation. Future comparisons of the radiation environment and video quality between the Columbus module and the US. Lab module or other sites where crew video is often taken over a given period of time, may provide insight into any differences in radiation influences at the different sites on the station.

Sensor Technology: Sensor technology has improved. When damage occurs below a certain level the sensor can recover. Hot or bad pixels are not corrected by an image sensor's internal image correction functions as demonstrated in a test, after irradiation to 5 krad (Si) with 50-MeV protons [8]. Were the HDEV cameras sensors' internal image correction able to compensate for most radiation which occurred?

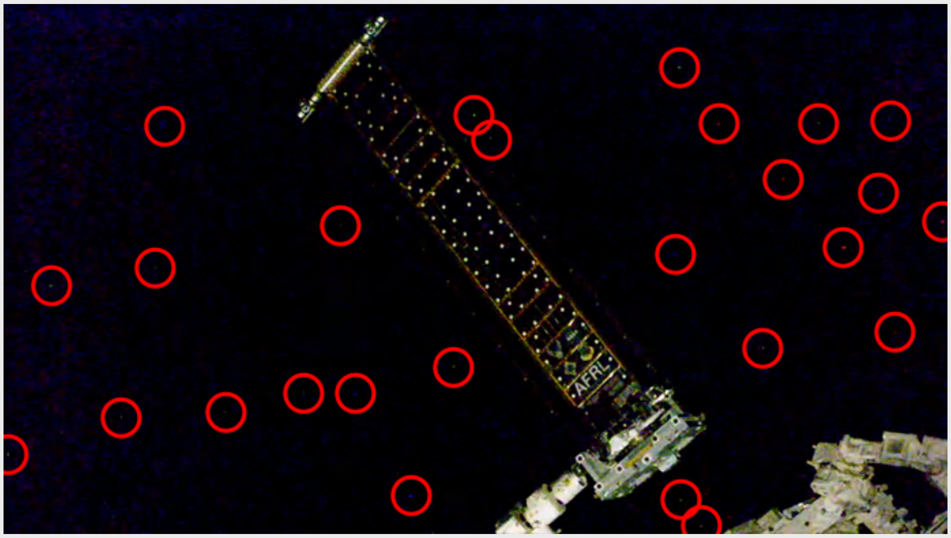


Figure 10
After only a few months on the space station, damaged pixels are very noticeable in images taken by on-board cameras. The same type of encoder (Visionary Solutions Inc. AVN443) used in the downlink process for this image was also used in HDEV. This image shows a selection of damaged pixels seen after approximately 1 year. Why did HDEV have only 3 apparent damaged pixels?

3 **Assessment of HDEV performance in space by monitoring longevity**

Monitoring the length of time HDEV and cameras remained operational provided an understanding into the hardware's ability to survive and function in the radioactive environment of Low Earth Orbit (LEO). HDEV was designed to occupy an available location on the CEPF, with the expectation that the location would only be available for approximately 3 years. However, HDEV remained on board and operational for a 5.2-year period. All of the 4 cameras remained operational until the end of HDEV's operational life. The reason for HDEV's failure is unknown but it appears from the final downlinked data that the processor failed in the CRIO system

HDEV Results for Education, Outreach, Innovations, and Remote Sensing Technology Verification

Outreach and education became an unplanned secondary objective and a large part of HDEV's impact, benefits, and success for NASA and the space station program. Its streaming video generated numerous unique applications developed through the ingenuity of the audience. Some of the highlight applications and Ustream metrics are discussed in this section.

1 **High Schools United with NASA to Create Hardware (HUNCH)**

Students were involved with HDEV from the beginning through the HUNCH program. The students manufactured HDEV camera brackets and hardware that isolated the HDEV electronics mechanically and thermally from the space station mount to the CEPF. The camera brackets and isolator must have performed as designed because no apparent issues ever surfaced involving those pieces.

2 **Columbus Eye: Using HDEV to raise awareness of the sustainable treatment of the Earth to students across Germany**

Prior to launch, a partnership was built through a Memorandum of Understanding with the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt (DLR)), the University of Bonn, and Ruhr University Bochum to use the HDEV video for a program called Columbus Eye: Live Images from the Station in the Classroom [9]. It started as an activity during the space station flight of an ESA astronaut from Germany, Alexander Gerst, and continued after his time on orbit was complete.

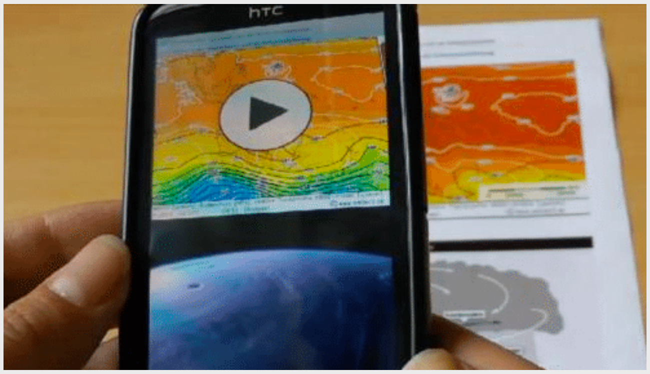


Figure 11
Demonstration of the Android App “The Eye of the Cyclone.” (Image courtesy of Ortwein, A. et al. [12])

The Columbus Eye investigation allows students to observe Earth from the astronaut's perspective while applying remote sensing analysis tools utilizing the High Definition Earth Viewing (HDEV) camera [10]. Its main purpose is the development of curricula oriented teaching resources using space station Earth observation, focusing on HDEV. However, as of this report, almost 10,000 students and 3000 teachers have been directly involved through face-to-face interaction in this investigation. Lessons have also aired on television and radio, and visits to the website have reached about 130,000 students and teachers. The program raised student awareness across Germany of sustainable treatment of the Earth, supplemented by curriculum made available online.

HDEV video provided a tool which aided the Columbus Eye program through a progression of improvements in interactive educational tools. Initially the program used HDEV's Earth views from the station in a learning portal [11] for students where interactive teaching materials, such as in Figure 11, were provided to get students interested in STEAM fields [12]: then to building interactive augmented and virtual reality tools for students [13]: and then identifying what is needed beyond HDEV imagery to produce 3D models to incorporate into the augmented and virtual reality tools and plan to fly the necessary imager on the space station [14].

On-line Learning Portal: The learning portal included online curriculum and activities such as the exercises in Figure 12 (Columbus Eye Observatory) and Figure 13 (Averaging Calculation from the space station). Figure 14 outlines the topics and types of learning tools used in the classrooms for the views from the individual cameras. Exhibiting a spatial resolution of ~280 m, the HDEV data was well suited for observing sudden and rapid changes and processes of the land surface and the atmosphere like volcano eruptions along the space station's orbital track [12]. HDEV recordings continued being used in the material after the live video stopped.

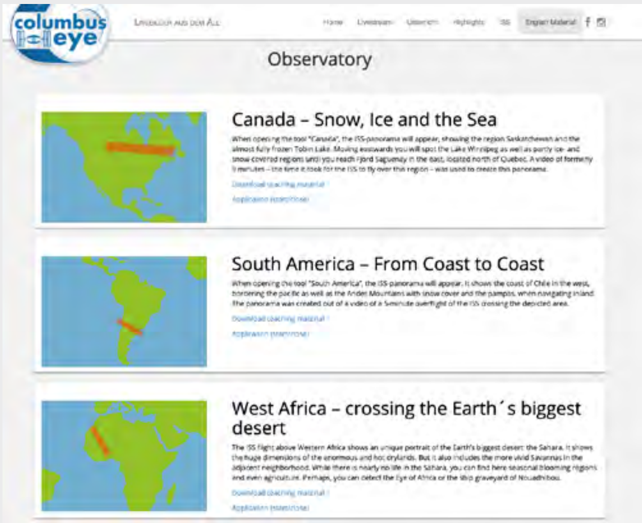


Figure 12
Columbus Eye Observatory. This screen shot from the Columbus Eye website [11] shows the location of the HDEV video and links to the associated teaching material and application to start the activity.

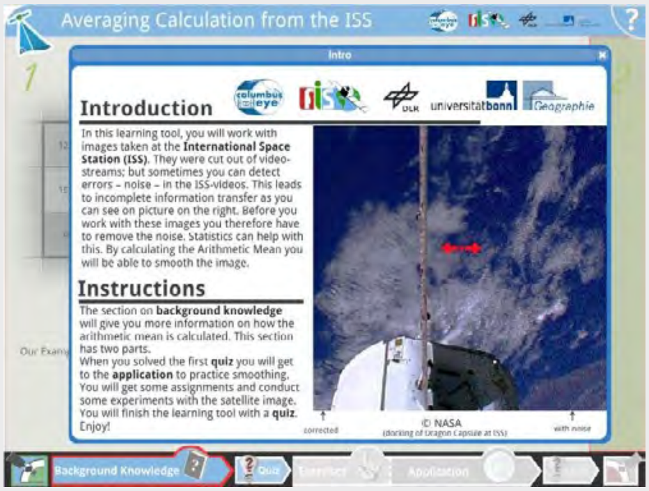
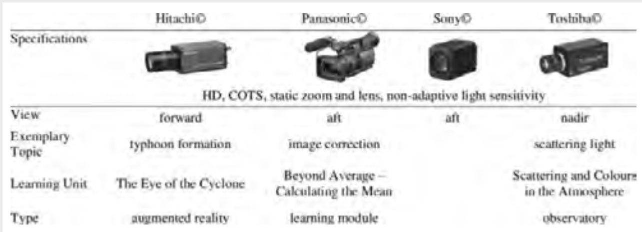


Figure 13
Pupils calculate the mean to correct image noise. (Image courtesy of Ortwein, A. et al. [12])



Specifications	Hitachi©	Panasonic©	Sony©	Toshiba©
	HD, COTS, static zoom and lens, non-adaptive light sensitivity			
View	forward	aft	aft	nadir
Exemplary Topic	typhoon formation	image correction		scattering light
Learning Unit	The Eye of the Cyclone	Beyond Average – Calculating the Mean		Scattering and Colours in the Atmosphere
Type	augmented reality	learning module		observatory

Figure 14
Specifications of the HDEV cameras and application in school lessons. (Image courtesy of Ortwein, A. et al. [12])

Building Augmented Reality/Virtual Reality Tools: The Columbus Eye program used HDEV, other space station remotely sensed imagery, and satellite data to produce the material for immersive media such as augmented and virtual reality applications [15]. A sample topic of this app development was one to teach Kepler's laws. The features of the app include using the distance between two celestial bodies for discussing Kepler's laws and perceived versus real distance, and size of the moon as seen in the sky, supported by an HDEV video from the station showing moonrise and –set. To understand the principle of a barycenter — the gravitational center that celestial bodies revolve around — a 3D animation was displayed in the app as depicted in Figure 15. [16].

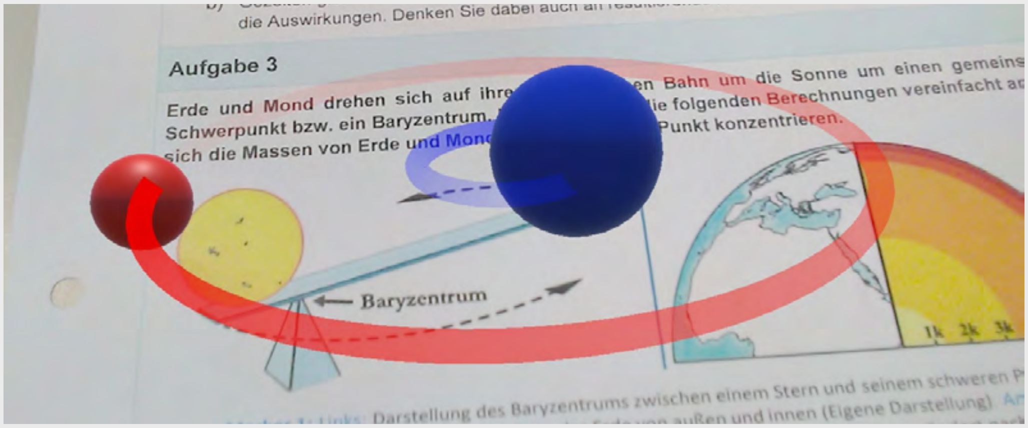


Figure 15
The Columbus Eye Augmented Reality app "The Earth Moon System" in a closed Alpha test in a school class. A celestial body and its companion revolve around their common barycenter in a 3D animation, fixated by the figure underneath. HDEV video was used to demonstrate using Moon rises and sets. [16]

Better Imagery for Enhanced Augmented Reality for Students: Using HDEV helped define the next level of imagery capture needed from the space station to implement 3D modeling for improved augmented reality tools for classrooms [16]. Being the only freely available source for continuous video Earth observation data, HDEV was the basis for evaluation of the usability of video data, as a pre-study for videos with better spatial as well as radiometric resolution. The delivered products served not only scientific purposes but are integrated in school lessons to evoke the students' fascination for earth sciences and space. The images from HDEV represent varying camera angles, light conditions and overlaps, making it difficult to derive a sufficiently accurate 3D model. The challenges and limitations of HDEV's video data for low-resolution 3D model generation (Ground Sample Distance (GSD) of 500 m) generated ideas for taking the next steps to obtain the data needed [17]. An HDEV video comparison to other camera's video was conducted to determine what was better for 3D model generation, and resulted in a plan for a follow-on imager to the space station.

3 ISS-Above: A product that displays HDEV video, indicates a fly-over of the space station, and includes education curriculum

An entrepreneur developed a product called ISS-Above which includes a device that calculates space station fly-over times and shows live HDEV video, other space station video and information, as well as peer-reviewed curriculum on Earth and space observation, engineering, and robotics designed for elementary to high school grade levels.

> *"ISS-ABOVE has been one of the best pieces of science equipment I have. It allows teaching and learning every day. It never gets old. There is always something new and exciting. Every science classroom would be better by simply having an ISS-ABOVE unit on in class. I think all Geography / Social Studies classes would benefit from it as well. It is fantastic!*
>
> Gary Pinkall, Science Teacher

The curriculum contains ten (10) lesson plans and is also available on line and in Spanish [18]. As of this report, ISS-Above is installed in 3,600 locations, in 382 schools and has reached over 263,300 students in several countries. This number includes ISS-Above units set up and running full time in classrooms across the US which routinely engage 84,000 students. An example of a student's reaction to the space station passing overhead is seen in Figure 17. These numbers do not include the impact or reach at in-person student/school presentations such as in Figure 18.

Figure 17
Left: ISS-Above curriculum, available to educators around the world. Right: Students at Barrett Elementary School react to the information displayed by ISS-Above. (Photo and image courtesy of ISS-Above)

ISS-Above is active in exhibitions, events and location such as the Makers Fairs, ISS R&D and teachers conferences, over 20 Science Centers and libraries worldwide, coffee-shops and wine bars, in addition to participating in Amateur Radio on the International Space Station (ARISS) (Ham Radio contacts with the space station) events. Most of the Space Operation Centers around the world have ISS-Above as one of the displays. It is even installed at one of the entry gates at Johnson Space Center, which activates a blue light that illuminates the entry gate area when the space station passes overhead.

Figure 16
An ISS-Above unit, with lights indicating when the space station passes overhead. (Photo courtesy of ISS-Above)

Figure 18
ISS-Above's Founder and Inventor, Liam Kennedy, talks with a school about the space station and how they can see it pass overhead. (Photo courtesy of ISS-Above)

4 Artificial Intelligence (AI) technology and additional applications for HDEV video

The Aurora CubeSat team at St. Louis University experimented with HDEV video to provide in-space video for the AI software testing by students for the CubeSat instrument Intelligence Mapping and Monitoring (IMMP): a flying laboratory for testing space sensing, mapping, and monitoring. (Launched 2019)

While trying to solve the issue in Earth-observing CubeSat-class satellites of having a lack of high-performing attitude determination and control systems, students from the Kyushu Institute of Technology, Japan used HDEV video imagery. They used HDEV's nadir-viewing video in their simulations, as depicted in Figure 19, to validate a proposed approach with their proto-type for visual-inertial attitude propagation for Earth-observation small satellites [19].

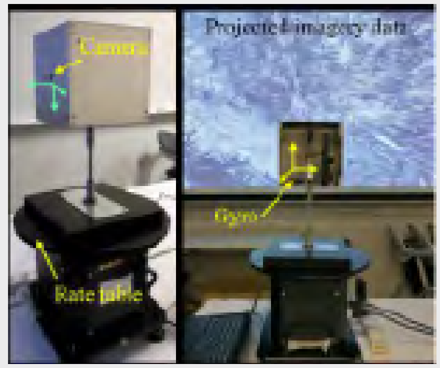


Figure 19
Prototype hardware design for the visual-inertial approach [19].

5 Space Station awareness and awe of seeing Earth from space


Figure 20
HDEV views inspired this "sunburst" quilt square which was used in a global community space quilt project initiated by Expedition 37 astronaut Karen Nyberg.

HDEV video was and is used for various types of media and artistic outlets ranging from TV, social media, to art projects/installation and galleries around the world in places such as Sweden, Germany, Korea, Cambodia, and Israel. Examples where HDEV video has been used include: many space agency lobbies, operations or visitor centers, the Weather Channel and other news outlets, documentaries, NASA TV for 4 hours a week, YouTube movies, Blogs such as Adventures and Musings of Dr. Owl [20], Twitter, Facebook, etc. posts, and inspiration for a sunburst quilt square for a global community space quilt project initiated by space station Expedition 37 astronaut, Karen Nyberg.

HDEV impact on Connecting the Space Station to the Public: Ustream Metrics

The large impact from publicly distributing HDEV live streaming video over Ustream was unanticipated. It increased contributions to the HDEV investigation, and to NASA and the International Space Station program, in a variety of ways, beyond what was expected of the technology demonstration objectives. Over its 5.2-year lifetime HDEV had over 318 million views to watch Earth pass by from the space station, resulting in an average of over 81,000 unique viewers per day, and up to 9,736 web domains embedding the HDEV Ustream display on their websites.

During the last 3.5 months of HDEV operations:

- There were over 13 million views counted from 226 countries (where Ustream could identify the country by the Uniform Resource Locator (URL)).
- Most countries of the world looked at the HDEV view on Ustream, as illustrated in figure 21.
- Sixteen (16) of the two hundred and twenty six (226) countries and states each viewed HDEV on Ustream over 200,000 times (see Appendix C).
- Appendix C contains graphs by total views of countries during the last 3.5 months.
- Appendix D is a list of the total views by country during the last 3.5 months.

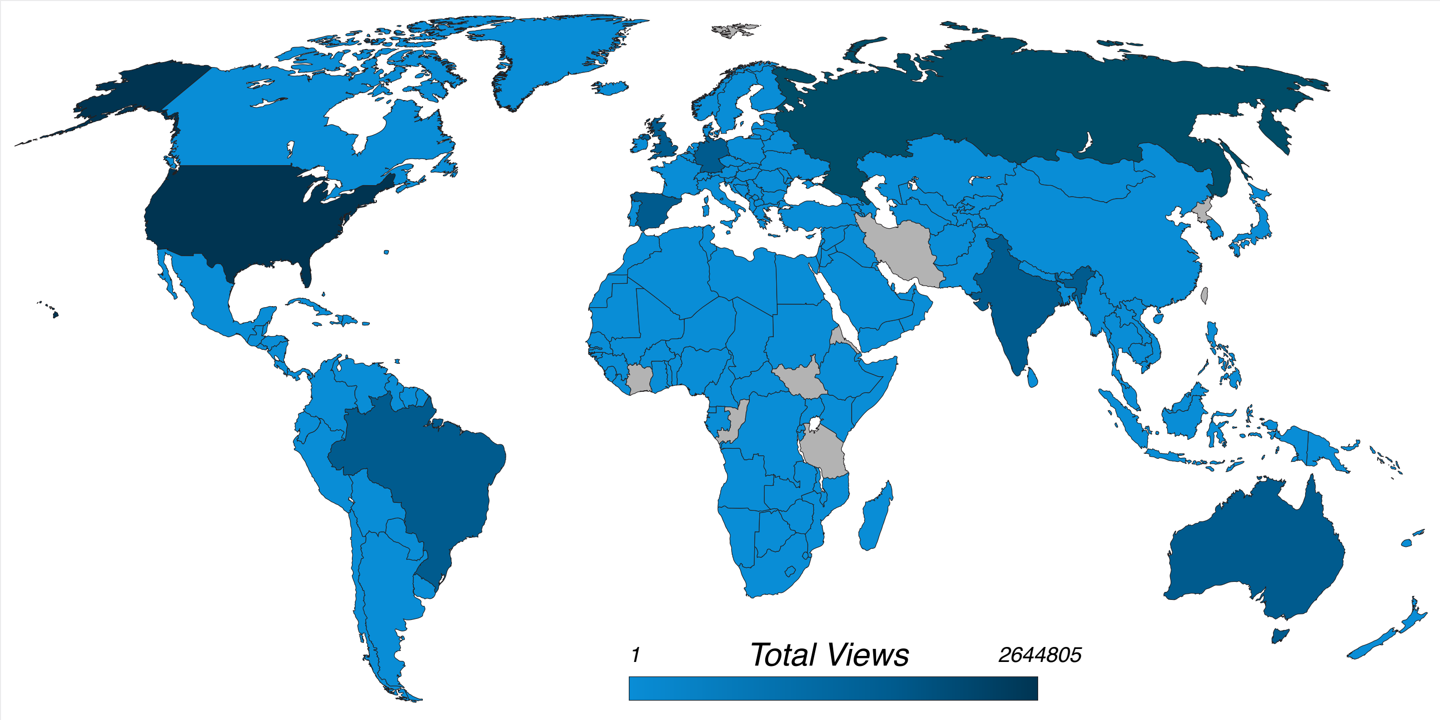


Figure 21
Map displaying relative concentration of views on the HDEV Ustream site from 226 countries/states around the world. Only the countries shown in gray either had zero views or the views were unidentifiable by country from any domain URL.

CONCLUSIONS AND NEXT STEPS

From what could be determined during the end-of life assessment, all of the cameras remained operational until the end when it is thought that the HDEV processor failed; cause is unknown. Several questions remain unanswered such as why weren't more damaged pixels apparent? Is the lack of bad pixels real or is imagery data being masked? Determining the answer may assist future space station and other mission program imagery planners in choosing camera hardware, equipment, communication mode or placement within or on a spacecraft depending on the purpose or level of quality required by the imagery user. Since HDEV hardware was not planned or designed to be returned for examination, alternative ways to approach finding answers are being pursued. An investigation and model of the radiation environment of HDEV on the CEPF and a more thorough understanding of the compression occurring along the video capture, conversion, and transmission pathway may explain why only 3 damaged pixels were visible in the nadir viewing camera at the end of its life.

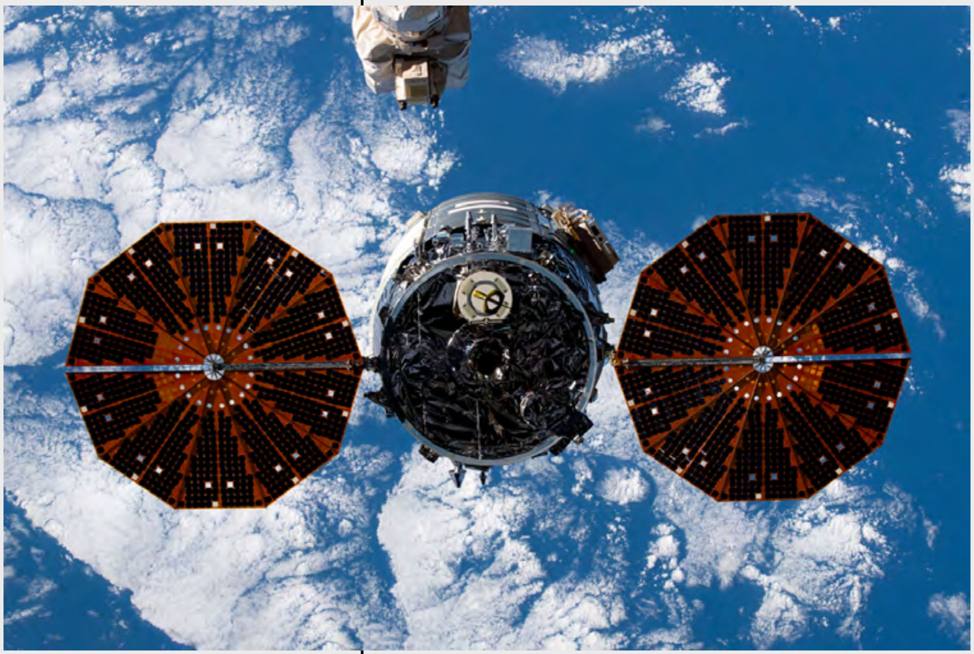


Figure 22
The Northrop Grumman Cygnus vehicle shortly after being released from the space station with HDEV attached (seen on upper right side of the vehicle). The vehicle was destined to be burned up as it entered the atmosphere over the South Pacific Ocean.

HDEV's streaming video of Earth [5], [6] expanded HDEV's contributions, beyond any expectations, to NASA and the space station program by reaching worldwide audiences and inspiring the next generation of space explorers to go on missions beyond low Earth orbit. HDEV raised the public's awareness of the station being in orbit, created awe from seeing the Earth from space, and provided imagery for numerous uses including developing educational material for STEAM engagement of learners across all ages. From peer reviewed educational curriculum to the musings of a traveling wooden Dr. Owl blog by an emeritus professor, to a quilt square, HDEV video has provided the inspiration to users around the globe, from all kinds of backgrounds and interests, to share their excitement of the video from the space station and will continue to do so as long as there is video of the Earth streaming from the space station. HDEV's live streaming video was viewed by more than 318 million viewers across the globe on Ustream alone, and had an average of 1333 viewers at any given moment from up to 237 countries and dependencies plus 54 US states and territories.

HDEV was disposed of on a Northrop Grumman Cygnus cargo vehicle on flight NG-13 in May 2020, as shown in Figure 22. Because of the public response and utilization of the HDEV imagery, different methods to continue the function of providing live streaming Earth views so the public can see what the astronauts see are being discussed. The streaming video will not only provide an amazing view from space but will also serve to bring awareness of the benefits of humans in space.

As a temporary solution to fill the void and provide Earth views from the station, an external high definition camera on Node 2, which is primarily for viewing visiting vehicles and situational awareness on the forward part of the station, is providing live imagery of the Earth on the prior HDEV Ustream site when the camera is available.

HDEV's scope grew to contribute so much more than the initial objectives of the technology demonstration experiment. It brought awareness and knowledge of NASA and the space station with over 318 million views, reached hundreds of thousands of students and teachers, and was present in numerous space, private, commercial, and educational establishments.

> "*...thank you for creating this...I think it is a beautiful and valuable thing to behold, and it brings serenity and perspective to my life every time I watch it.*
>
> Aileen Duffy

HDEV provided insights into impacts, engagement, and capabilities which would be beneficial in a future live streaming video system on the space station. The level of awareness and wide variety of applications cascading from HDEV's public, freely available, streaming video of the Earth demonstrated the concepts and potential impacts which a full-time, fully functional high definition streaming video could produce for the space station program and NASA overall.

As an example of video system capability, and mentioned in the Hardware Description section (page 5), HDEV was on a fixed mount and the cameras could not move. As a result many features passing just outside of the field of view could not be captured. One example is the 2017 solar eclipse shadow, which HDEV was unable to capture but the astronauts did with hand-held cameras. Using a system with a 360-degree camera or responsive cameras with low-light capability and adjustable settings, including aperture, zoom, pan/tilt, could provide the viewer control of what they want to observe.

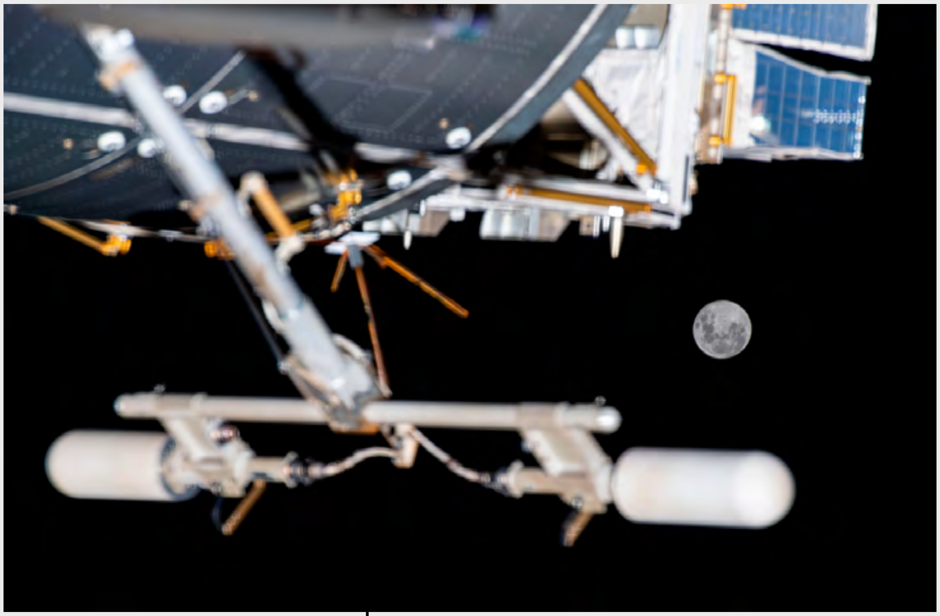
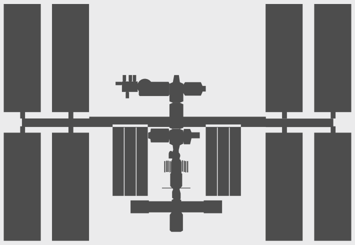


Figure 23
The Moon under the CEPF where HDEV was installed. The next generation of HDEV can expand the awareness of NASAs programs, including Artemis.

HDEV garnered public interest demonstrated by the 318 million views on Ustream over the life of HDEV with over 47000 to 81000 unique viewers every day. In addition, The ISS-Above and/or the Ustream feed is in nearly all the space operations centers around the world, 20 + science centers, and numerous classrooms. Losing this avenue for public interaction with the space station and NASA, loses a unique way to maintain a large support group. With better camera capabilities this number would likely grow as reflected in the larger numbers, during the first two (2) years, of unique users and domains which embedded the Ustream display into their sites. Also, more broadly distributing the streaming video once on the ground via multiple channels including distribution from JSC and various public outlets would enable even greater access and an increased interest in the space station and NASA programs to support our future mission as depicted in Figure 23.

In summary, this quote represents the feedback received from numerous individuals from around the world:

> *"HDEV Video encourages us space dreamers to keep on dreaming, non-believers to believe and the earthbound explorers to explore with our eyes. The images we see of our precious blue planet are mankind's medicine. I would like to thank you personally for that gift."*
> Allan J Gray,
> Westhoughton, Greater Manchester, UK



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APPENDIX A: HDEV TECHNICAL SPECIFICATIONS

	Hitachi HV-HD30	Toshiba IK-HR1S	Panasonic AG-HMC150	Sony FCB-EH4300
View from Columbus External Payload Facility (CEPF)	Forward	Nadir	Aft-1	Aft-2
Sensor / # of Sensors	1/3" CMOS / 3	1/3" CMOS / 1	1/3" CCD / 3	1/3" CMOS / 1
Format / Frame Rate	720p / 59.97	720p / 59.94	720p / 60p	720p / 60p
Lens	4 mm; Fujinon TF4DA-8 4mm F/2.2 C-mount Wide Angle Lens for 1/3 Inch 3-CCD Industrial Cameras, with Manual Iris and Focus. Lens secured with RTV 3145	4mm; Fujinon TF4DA-8 4mm F/2.2 C-mount Wide Angle Lens for 1/3 Inch 3-CCD Industrial Cameras, with Manual Iris and Focus . Lens secured with RTV 3145	3.9 mm; Included: 28mm-368 mm (35mm equivalent) Leica Dicomar lens w/13x zoom, O.I.S., motorized/ manual mode switching, F1.6-3.0 (f=3.9mm to 51mm/ 35mm equivalent: 28mm to 368mm)	4.7 mm
Focal Length Setting	Infinity	Infinity	Focus switch set to manual; focus ring set all the way to the left	Infinity
Horizontal Field of View	62.0 deg	45.1 deg	66.1 deg	36.6 deg
Vertical Field of View	37.3 deg	26.3 deg	40.2 deg	21.2 deg
HDEV Housing Angle of Camera	27 deg pitch	28 deg pitch	23 deg angle; no yaw	23 deg angle; no yaw
F-Stop / Aperture	f/16	f/16	f/16	f/16
Shutter	1/250 sec	Auto	1/2000	1/250
Gain	+0 dB	Off	Auto Gain Control = 6 dB	Set to "L" position
White Balance	5600 K	Auto WB; White Temp set to 5600K	Auto	Auto
Minimum Illumination Capability	10 Lux	8 Lux	3 Lux	0.5 Lux
Camera Mode	Manual			
Approximate Land Area Viewed by Camera	990 mi x 500 mi (1600 km x 800 km)	109 mi x 305 mi (490 km x 302 km)	620 mi x 427 mi (1000 km x 690 km)	

HDEV Total Dimensions

34” (86.40cm) X 46” (116.85cm) X 11.2” (28.45cm)X53.0” (134.62cm) X 19.27” (48.95cm), including EVA handrail and Columbus External Payload Adapter (CEPA) launch envelope.

HDEV Housing

HDEV Envelope: 40.0 in x 28.75 in x 11.5 in (1016 mm x 730.25 mm x 292.1 mm)

Internal volume: 37.0 in x 25.75 in x 10.62 in (939.8 mm x 654.05 mm x 269.75 mm)

Enclosure machined from 7050-T7451 AL plate with o-ring sealing at cover and viewing ports. All components are integral to hermetically sealed housing.

Enclosure filled with N2 at 1 atm. Individual isolation of COTS components. No active mechanical isolation of housing after study of launch load environment.

HDEV On-orbit Weight

On-orbit control weight, including adapter mounting hardware and cargo: CEPA 252.19 lbs (114.40kg) + HDEV 208.93lbs (94.76kg) = 461.12 lbs (209.16kg)

Mass Box Base and Box Cover: 66.6 lbs (30.2 kg) and 71.4 lbs (32.4 kg) respectively.

Window Information

Fused Quartz Cover glass; transmissivity of greater than 90% over the visible spectrum (390-750nm)

HDEV Communication Hardware

The Extron SW4 3G HD-SDI router detects the powered camera. It allows for multi-rate camera switching. Only one camera can be powered on and operating at a time.

Visionary Solutions’ AVN443 Encoder which enables H.264 compression and an MPEG-2 Transport Stream to be moved, via Real-time Transport Protocol (RTP), then formated by the Compact Reconfigurable Input/Output (CRIO) system, and delivered through the space station Columbus payloads communications system.

Compact RIO single board computer, and AJA HA5 HDMI to HD-SDI Converter.

All payload operations beyond initialization occurred via 1553 Transformer Coupled Interface and Ethernet communications with the US Operating Segment (USOS) Command and Data Handling (C&DH) System. Video data sent to the ground via Consultative Committee for Space Data Systems (CCSDS) packets over Ethernet. Real-time Transport Protocol (RTP) was used to send video from the encoder to the CRIO. RTP header was 12 bytes and was removed on the ground for data to be saved to a file for distribution.

Radiation Survivability

Aluminum Housing reduces total dose radiation.
Watchdog in CRIO
Over-current/Reset (SEC)
Redundancy in Input Power
No Redundancy: cRIO, Power Board, High Definition Multimedia Interface (HDMI) to Serial Digital Interface (SDI) Converter, Encoder, Router Component radiation testing.
Re-used circuit/components

Health & Status Software

Current & Voltage measured on cameras, encoder, router, and CRIO.
Temperature measured for general payload environment and specifically for CRIO.
Control/Status bits given for cameras, encoder, and router.
Command acknowledgment and validation, as well as last command executed and timestamp.
Four spare H&S messages were allocated for possible software status messages.

Thermal Range Constraints

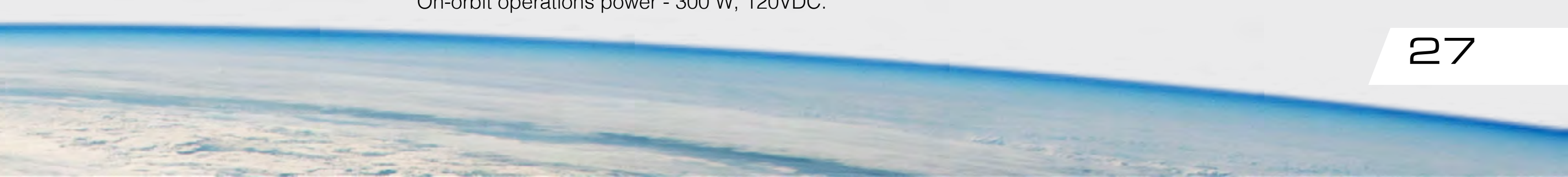
Camera Components: Operating Temperature Range* 0 to 40C (32 to 104F); Storage Temperature Range* -20 to 60oC (-4 to 140F)
*For COTS hardware this is based on a convective 1-G environment.
Space X Thermal Environment: -30 to 60C (-20 to 140F)
Space Station I/F (FRAM) Temperature Range: -72 to 48C (-98 to 118F)

End-of-Life Disposal

Predetermined definition of “End of Life” for payload operations was when no video data could be received from the ground. Upon completion of its science mission, HDEV was disposed on Cygnus NG-13, a vehicle with a FRAM interface configuration. Removed and attached to Cygnus NG-13 on May 7, 2020; NG-13 unberthed on May 11, 2020; Entered Earth’s atmosphere on a path to the South Pacific on May 29, 2020.

Power

At Launch for thermal control - 100W, 120VDC.
On-orbit operations power - 300 W, 120VDC.



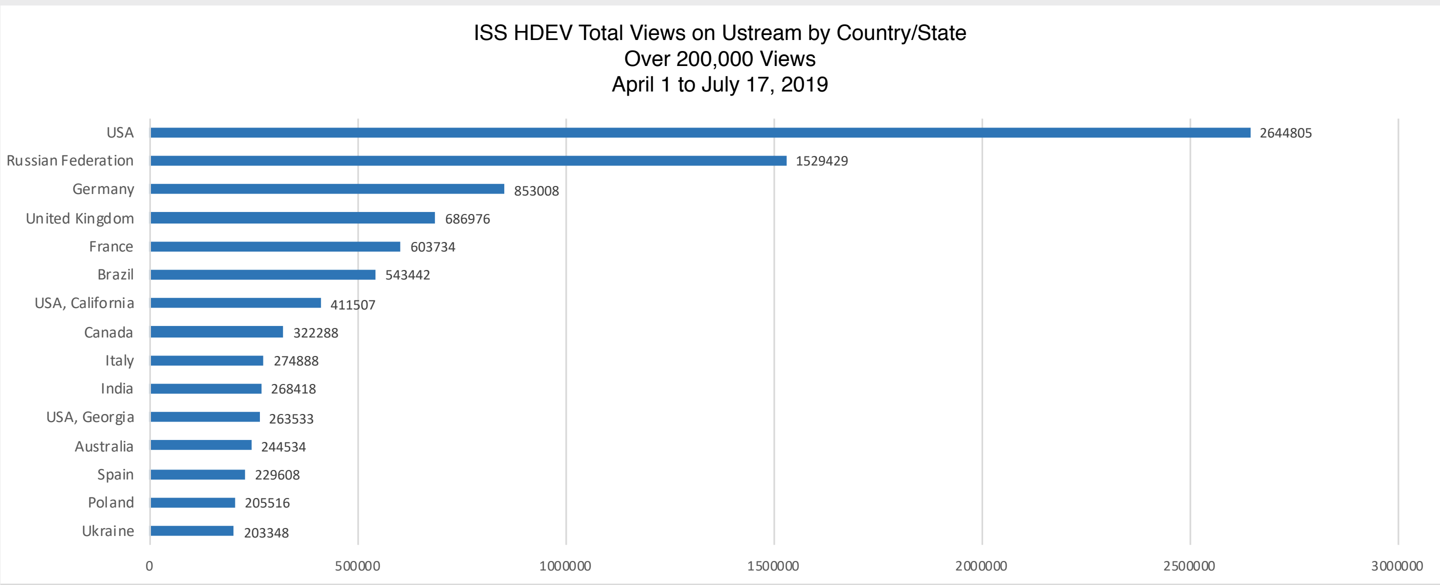
APPENDIX B:
HDEV PAYLOAD ANOMALY REPORTS

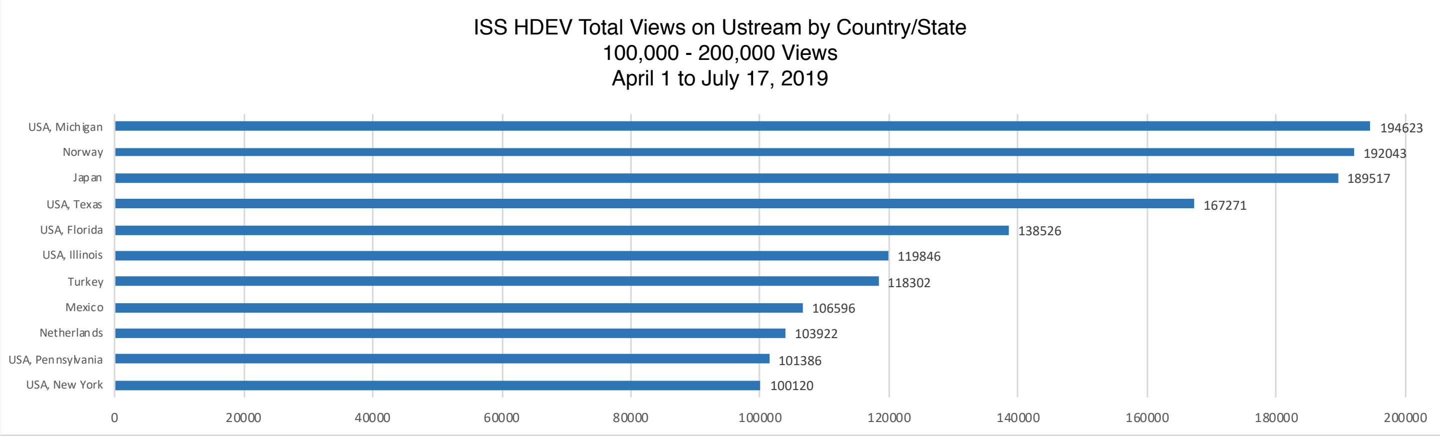
Payload Anomaly Report (PAR)	Symptom	Resolution	Date/Recurrence or Notes
HDEV-SW-0001	On Day 1 checkout, HDEV Did Not Accept STANDBY command following CYCLE and SELECT commands	A portion of the HDEV unique software was only calling the TReK API's uplink_command() function, which uses a default value from the POIC database to send commands rather than the correct MAC address. Minor correction to HDEV software solved the commanding issue.	1) May 2, 2014 2) July 18, 2019 - recurrence of not responding to commands. August 22, 2019 - determined that HDEV had reached its end of life. Suspected cause was failure of the processor or radiation event.
HDEV-SW-0002	Intermittent data then loss of HDEV Downlink video data. Commands weren't acknowledged, router encoder and a camera show overcurrent intermittently.	STANDBY and REBOOT not accepted; Power Cycle resolved the issue. Cause unknown. Later, color bars were evident in the video displayed on USTREAM ; this was related to a ground USTREAM issue and not to HDEV hardware or downlink. Other video data loss occurrences were solved by STANDBY, REBOOT, or Power Cycle.	1)July 9, 2015 2) Jan 28, 2019 Other video data downlink loss events occurred not documented on the PAR.
HDEV-SW-0003	HDEV only showing Gray Screen and STANDBY on screen	1) Because PEHG2 had a soft reboot the day before, resent MAC address; no change in data reception, STANDBY did not solve it; REBOOT solved the issue. Cause unknown. 2) It took a Power cycle to get the data to return. 3) Several instances of losing medium rate data; seemed related to switching to a specific camera in the rotation. Corrected by rebooting after going through the command cycle. Cause unknown.	1. Aug 7, 2014 2. Jun 15, 2018 3. Jun 23, 2018
HDEV-SW-0004	HDEV video appeared pixelated with a water-color effect and periodically alternated with the "Please Stand By" screen on USTREAM display.	HDEV data downlink was good. Resetting the ground system decoder resolved the issue.	1. Aug 17, 2014 Numerous instances occurred over the life of HDEV where the ground system feed to USTREAM was interrupted due to unplanned updates to the ground system computer and the HDEV ground software needed to be reinitiated. This had no impact on the HDEV downlink from the ISS.

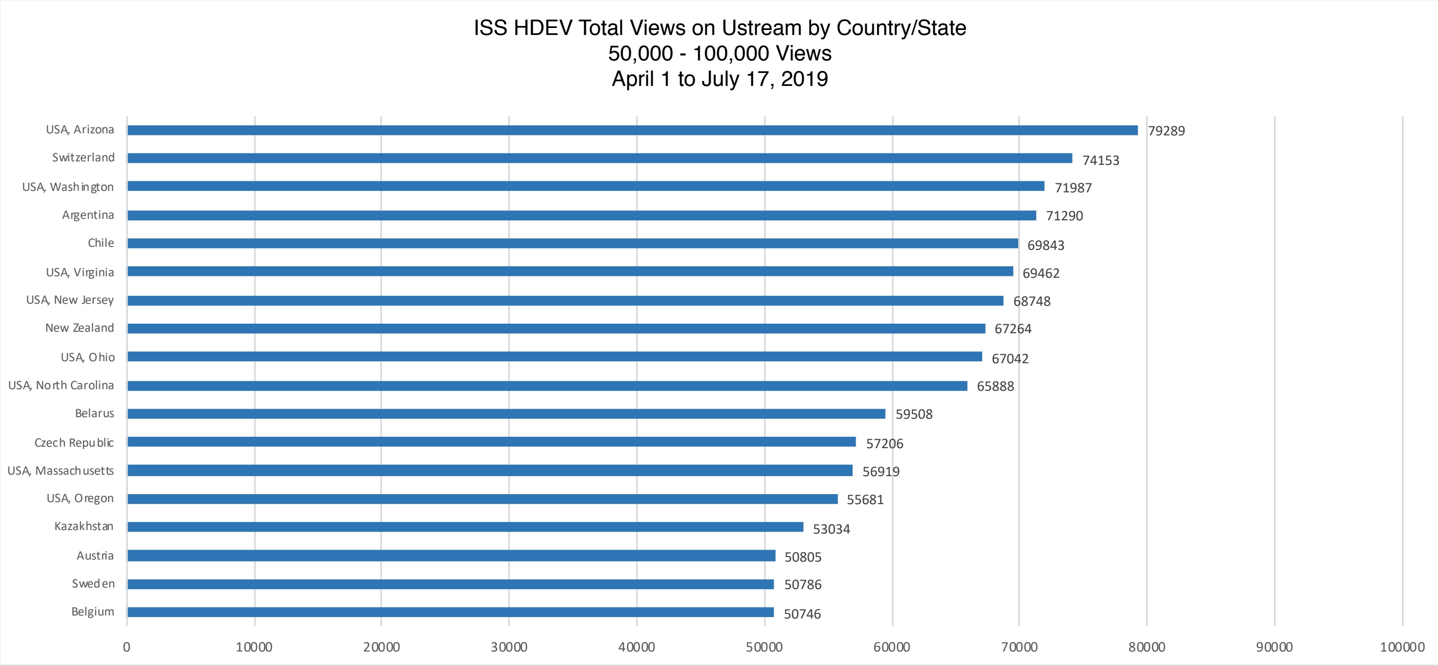
HDEV-SW-0005	HDEV had "stale" data where the various voltages, currents, and temperatures which are sent down in the health & status were not changing and the CRIO and encoder indicated overcurrent. As a result of this stale data, occasionally an incorrect overcurrent status bit may be set on a camera, encoder, or router.	Rebooting solved the issue. Cause unknown	1) Jun 23, 2015. Intermittent stale data started a few days before. There were several "stale" data incidents where a reboot or power cycle solved the issue.
HDEV-SW-0006	Recovery commands for Overcurrent Status on Encoder (EM) did not process. HDEV data rate reduced to 1 to 2 Mbps. DMC noticed COL PEGH HRDL: COL PEHG & PEHG2 showing rolling sequence errors	Overcurrent status not solved by reboots. Once PEHG issue noticed DMC sent PEHG reset commands which after 102 seconds the data flow became normal on PEHG. HDEV then required a power cycle to solve the issue. A power cycle was required for each encoder overcurrent indicator event.	1. Oct 13, 2015 2. Aug 2, 2017
HDEV-SW-0007	Gray screen on USTREAM, Camera views not cycling/ cycling function non-op	HDEV ground system and software reinitiated. Only one camera was put in the operational rotation.	1) Jan 05, 2016 Numerous instances occurred over the life of HDEV where the ground system feed to USTREAM was interrupted due to unplanned updates to the ground system computer and the HDEV ground software needed to be reinitiated. This had no impact on the HDEV downlink from the ISS.
HDEV-SW-0008	Momentary loss of Health & Status Data, also video board feed was static, frozen.	The Health & Status began on its own after 45 seconds. Once the H&S data started the video board data resumed normally	1) May 17, 2016 Numerous other momentary loss of H&S data events occurred. The events were logged at Marshall with no PAR report required.
HDEV-SW-0009	Loss of H&S	Solved by Power cycle, until July 18, 2019 when the downlink started to have major issues.	1. Oct 25, 2016 2) Nov 17, 2017 Numerous additional H&S loss events occurred through the life of HDEV. All solved by a power cycle except for the partial-then-total loss July 18-20, 2019.

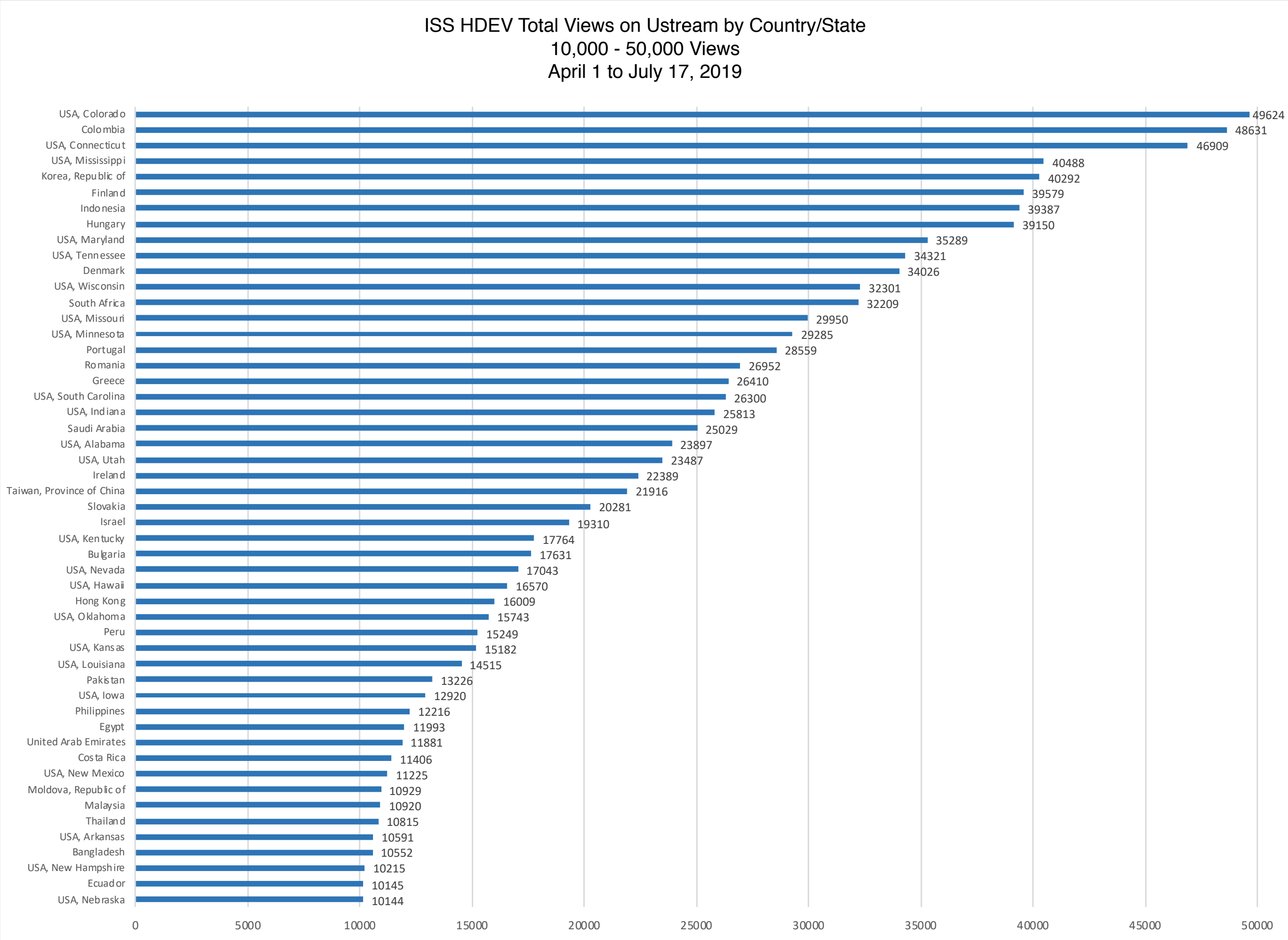
APPENDIX C:
USTREAM METRICS - TOTAL VIEWS BY COUNTRY AND US STATES FOR APRIL 1 - JULY 17, 2019 (FINAL 3.5 MONTHS)

The last 3.5 months of HDEV metrics for countries viewing Ustream are representative of the numbers of countries viewing HDEV for the last 5.2 years (226 countries over 3.5 months verses up to 237 countries in a year over the 5.2 years lifetime). The last 3.5 months were used for displaying data to reduce the magnitude of the numbers for charting purposes. These numbers do not include metrics from the 2372 websites which embedded the Ustream display during this time frame and were viewed but not "clicked on" to go to the Ustream website.

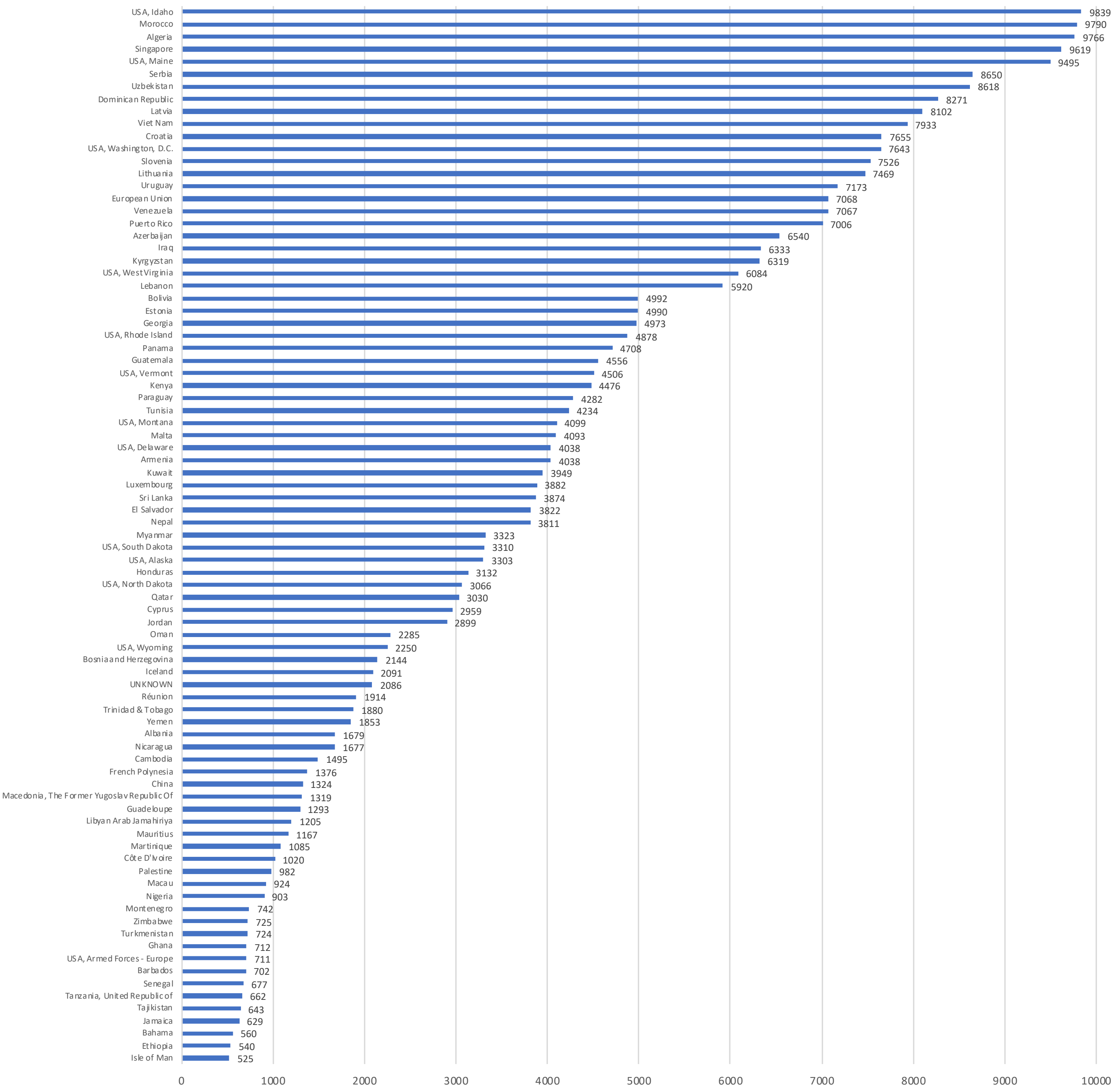




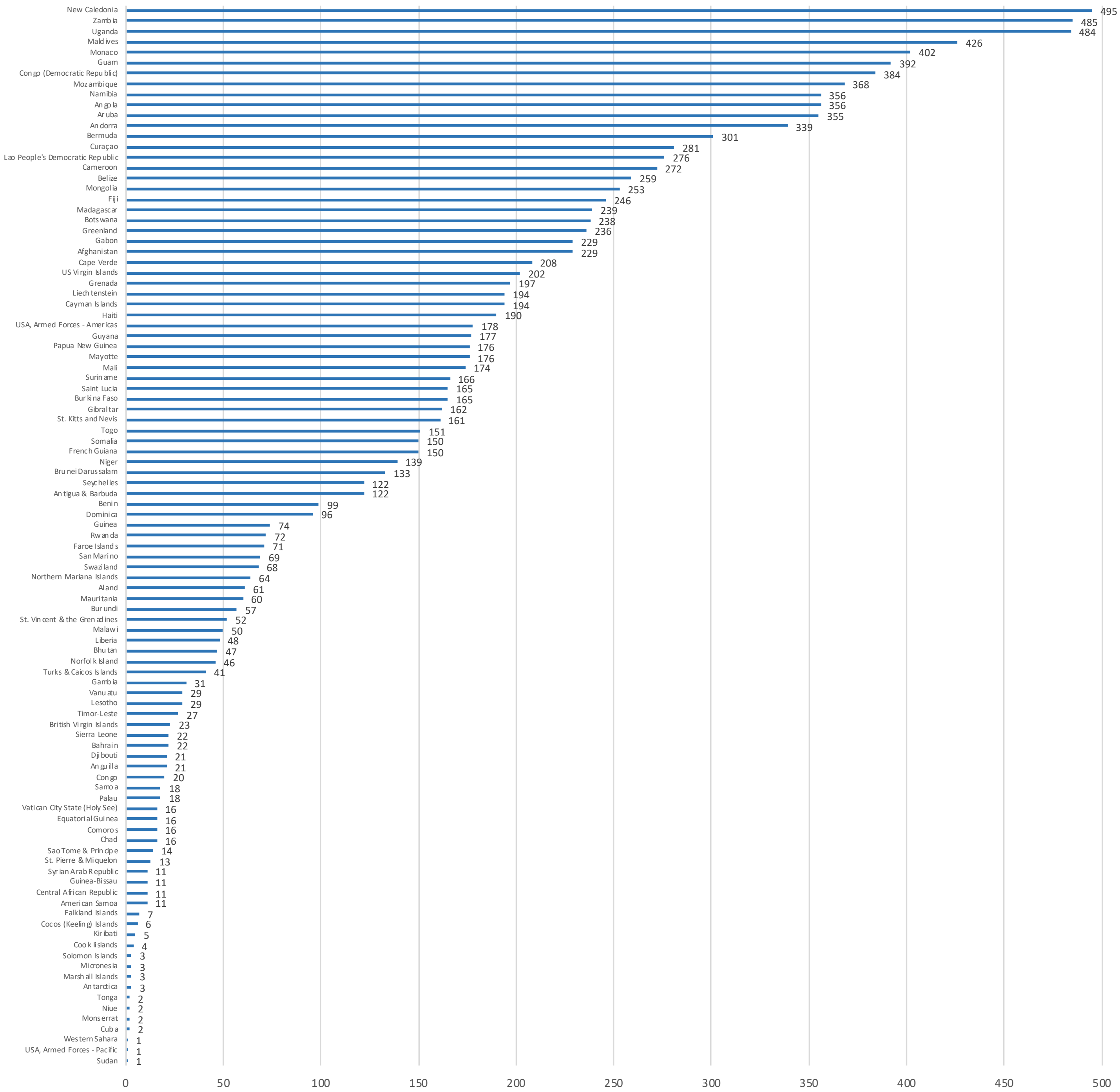

ISS HDEV Total Views on Ustream by Country/State
50,000 - 100,000 Views
April 1 to July 17, 2019
USA, Arizona 79289
Switzerland 74153
USA, Washington 71987
Argentina 71290
Chile 69843
USA, Virginia 69462
USA, New Jersey 68748
New Zealand 67264
USA, Ohio 67042
USA, North Carolina 65888
Belarus 59508
Czech Republic 57206
USA, Massachusetts 56919
USA, Oregon 55681
Kazakhstan 53034
Austria 50805
Sweden 50786
Belgium 50746
0 10000 20000 30000 40000 50000 60000 70000 80000 90000 100000


ISS HDEV Total Views on Ustream by Country/State
10,000 - 50,000 Views
April 1 to July 17, 2019
USA, Colorado 49624
Colombia 48631
USA, Connecticut 46909
USA, Mississippi 40488
Korea, Republic of 40292
Finland 39579
Indonesia 39387
Hungary 39150
USA, Maryland 35289
USA, Tennessee 34321
Denmark 34026
USA, Wisconsin 32301
South Africa 32209
USA, Missouri 29950
USA, Minnesota 29285
Portugal 28559
Romania 26952
Greece 26410
USA, South Carolina 26300
USA, Indiana 25813
Saudi Arabia 25029
USA, Alabama 23897
USA, Utah 23487
Ireland 22389
Taiwan, Province of China 21916
Slovakia 20281
Israel 19310
USA, Kentucky 17764
Bulgaria 17631
USA, Nevada 17043
USA, Hawaii 16570
Hong Kong 16009
USA, Oklahoma 15743
Peru 15249
USA, Kansas 15182
USA, Louisiana 14515
Pakistan 13226
USA, Iowa 12920
Philippines 12216
Egypt 11993
United Arab Emirates 11881
Costa Rica 11406
USA, New Mexico 11225
Moldova, Republic of 10929
Malaysia 10920
Thailand 10815
USA, Arkansas 10591
Bangladesh 10552
USA, New Hampshire 10215
Ecuador 10145
USA, Nebraska 10144
0 5000 10000 15000 20000 25000 30000 35000 40000 45000 50000

ISS HDEV Total Views on Ustream by Country/State
500 - 10,000 Views
April 1 to July 17, 2019

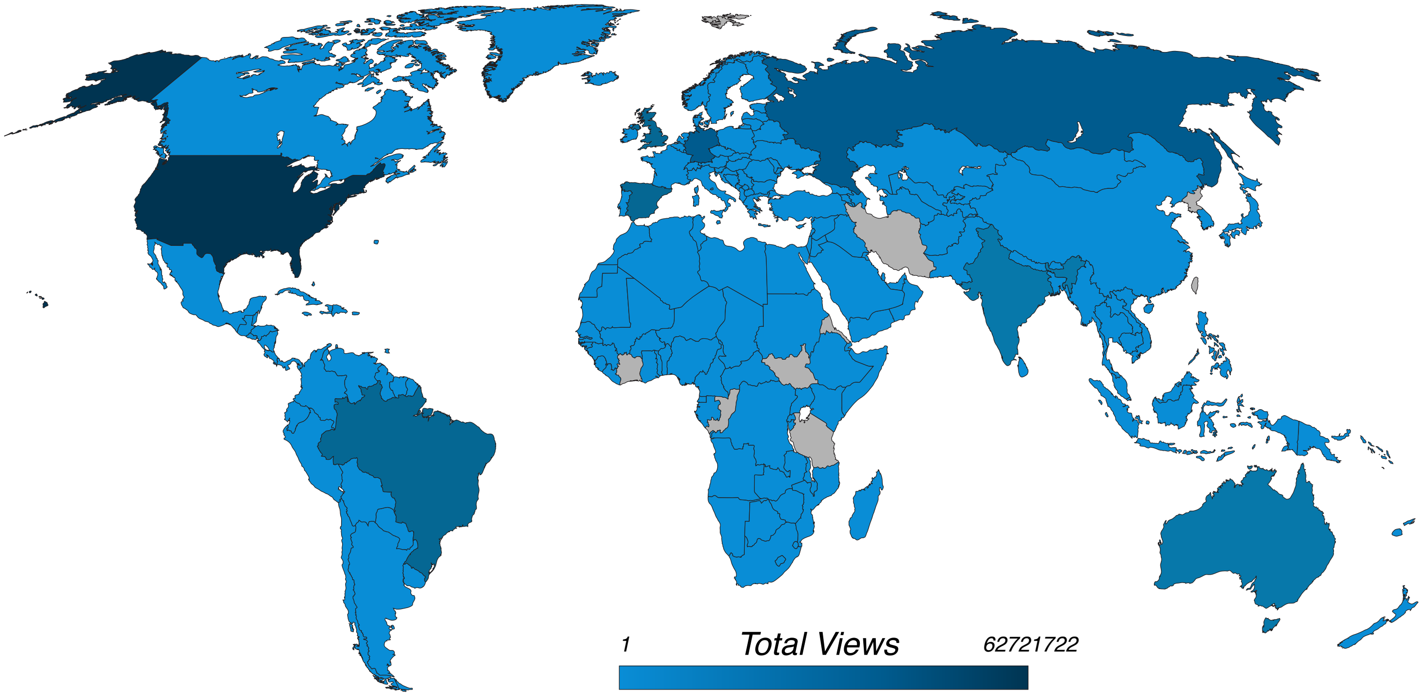


ISS HDEV Total Views on Ustream by Country/State
0 - 500 Views
April 1 to July 17, 2019

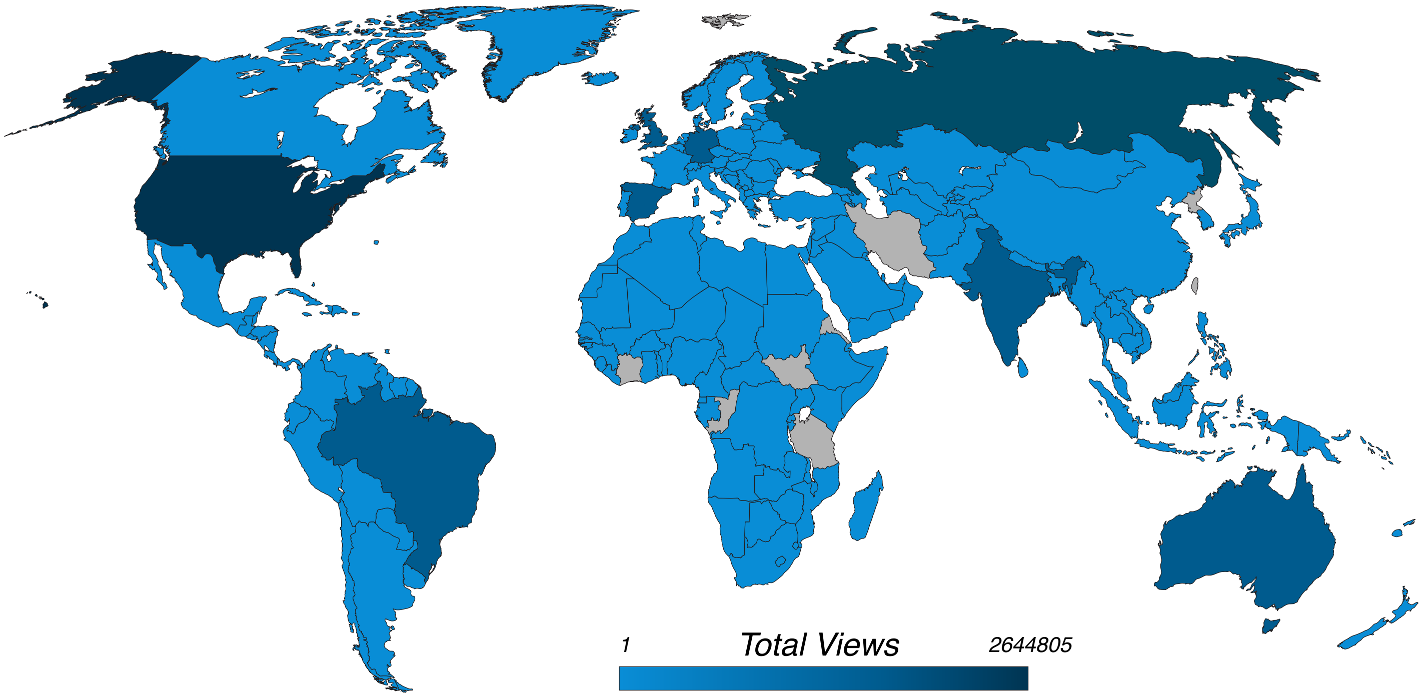


The world map depicting the Total Views by Country which USTREAM could determine over a 3.5 year period is shown to demonstrate that the data for the final 3.5 months is representative of the larger time period. The 3.5 month time period was used for metrics and graphics for the ease of depicting the data.

HDEV Total Views on Ustream by Country between Jan 1, 2016 & July 17, 2019 (3.5 years)



HDEV Total Views on Ustream by Country between April 1 & July 17, 2019 (final 3.5 months)



APPENDIX D:
USTREAM METRICS - LIST OF TOTAL VIEWS BY COUNTRY AND US STATES FOR APRIL 1 - JULY 17, 2019 (FINAL 3.5 MONTHS)

Afghanistan	229
Aland	61
Albania	1679
Algeria	9766
American Samoa	11
Andorra	339
Angola	356
Anguilla	21
Antarctica	3
Antigua & Barbuda	122
Argentina	71290
Armenia	4038
Aruba	355
Australia	244534
Austria	50805
Azerbaijan	6540
Bahama	560
Bahrain	22
Bangladesh	10552
Barbados	702
Belarus	59508
Belgium	50746
Belize	259
Benin	99
Bermuda	301
Bhutan	47
Bolivia	4992
Bosnia and Herzegovina	2144
Botswana	238
Brazil	543442
British Virgin Islands	23
Brunei Darussalam	133
Bulgaria	17631
Burkina Faso	165
Burundi	57
Cambodia	1495
Cameroon	272
Canada	322288
Cape Verde	208
Cayman Islands	194
Central African Republic	11
Chad	16
Chile	69843
China	1324
Cocos (Keeling) Islands	6
Colombia	48631
Comoros	16
Congo	20
Congo (Democratic Republic)	384
Cook Islands	4
Costa Rica	11406
Croatia	7655
Cuba	2
Curaçao	281
Cyprus	2959
Czech Republic	57206
Côte D’ivoire	1020
Denmark	34026
Djibouti	21
Dominica	96
Dominican Republic	8271
Ecuador	10145
Egypt	11993
El Salvador	3822
Equatorial Guinea	16
Estonia	4990
Ethiopia	540
European Union	7068
Falkland Islands	7
Faroe Islands	71
Fiji	246
Finland	39579
France	603734
French Guiana	150
French Polynesia	1376
Gabon	229
Gambia	31
Georgia	4973
Germany	853008
Ghana	712
Gibraltar	162
Greece	26410
Greenland	236
Grenada	197
Guadeloupe	1293
Guam	392
Guatemala	4556
Guinea	74
Guinea-Bissau	11
Guyana	177
Haiti	190
Honduras	3132
Hong Kong	16009
Hungary	39150
Iceland	2091
India	268418
Indonesia	39387
Iraq	6333
Ireland	22389
Isle of Man	525
Israel	19310
Italy	274888
Jamaica	629
Japan	189517
Jordan	2899
Kazakhstan	53034
Kenya	4476
Kiribati	5
Korea, Republic of	40292
Kuwait	3949
Kyrgyzstan	6319
Lao People’s Democratic Republic	276
Latvia	8102
Lebanon	5920
Lesotho	29
Liberia	48
Libyan Arab Jamahiriya	1205
Liechtenstein	194
Lithuania	7469
Luxembourg	3882
Macau	924
Macedonia, (Yugoslav Republic of)	1319
Madagascar	239
Malawi	50
Malaysia	10920
Maldives	426
Mali	174
Malta	4093
Marshall Islands	3
Martinique	1085
Mauritania	60
Mauritius	1167
Mayotte	176
Mexico	106596
Micronesia	3
Moldova, Republic of	10929
Monaco	402
Mongolia	253
Monserrat	2
Montenegro	742
Morocco	9790
Mozambique	368
Myanmar	3323
Namibia	356
Nepal	3811
Netherlands	103922
New Caledonia	495
New Zealand	67264
Nicaragua	1677
Niger	139
Nigeria	903
Niue	2
Norfolk Island	46
Northern Mariana Islands	64
Norway	192043
Oman	2285
Pakistan	13226
Palau	18
Palestine	982
Panama	4708
Papua New Guinea	176
Paraguay	4282
Peru	15249
Philippines	12216
Poland	205516

Portugal	28559
Puerto Rico	7006
Qatar	3030
Romania	26952
Russian Federation	1529429
Rwanda	72
Réunion	1914
Saint Lucia	165
Samoa	18
San Marino	69
Sao Tome & Principe	14
Saudi Arabia	25029
Senegal	677
Serbia	8650
Seychelles	122
Sierra Leone	22
Singapore	9619
Slovakia	20281
Slovenia	7526
Solomon Islands	3
Somalia	150
South Africa	32209
Spain	229608
Sri Lanka	3874
St. Kitts and Nevis	161
St. Pierre & Miquelon	13
St. Vincent & the Grenadines	52
Sudan	1
Suriname	166
Swaziland	68
Sweden	50786
Switzerland	74153
Syrian Arab Republic	11
Taiwan, Province of China	21916
Tajikistan	643
Tanzania, United Republic of	662
Thailand	10815
Timor-Leste	27
Togo	151
Tonga	2
Trinidad & Tobago	1880
Tunisia	4234
Turkey	118302
Turkmenistan	724
Turks & Caicos Islands	41
Uganda	484
Ukraine	203348
United Arab Emirates	11881
United Kingdom	686976
USA Total	2644805
USA, Alabama	23897
USA, Alaska	3303
USA, Arizona	79289
USA, Arkansas	10591
USA, Armed Forces - Americas	178
USA, Armed Forces - Europe	711
USA, Armed Forces - Pacific	1
USA, California	411507
USA, Colorado	49624
USA, Connecticut	46909
USA, Delaware	4038
USA, Florida	138526
USA, Georgia	263533
USA, Hawaii	16570
USA, Idaho	9839
USA, Illinois	119846
USA, Indiana	25813
USA, Iowa	12920
USA, Kansas	15182
USA, Kentucky	17764
USA, Louisiana	14515
USA, Maine	9495
USA, Maryland	35289
USA, Massachusetts	56919
USA, Michigan	194623
USA, Minnesota	29285
USA, Mississippi	40488
USA, Missouri	29950
USA, Montana	4099
USA, Nebraska	10144
USA, Nevada	17043
USA, New Hampshire	10215
USA, New Jersey	68748
USA, New Mexico	11225
USA, New York	100120
USA, North Carolina	65888
USA, North Dakota	3066
USA, Ohio	67042
USA, Oklahoma	15743
USA, Oregon	55681
USA, Pennsylvania	101386
USA, Rhode Island	4878
USA, South Carolina	26300
USA, South Dakota	3310
USA, Tennessee	34321
USA, Texas	167271
USA, Utah	23487
USA, Vermont	4506
USA, Virginia	69462
USA, Washington	71987
USA, Washington, D.C.	7643
USA, West Virginia	6084
USA, Wisconsin	32301
USA, Wyoming	2250
United States Virgin Islands	202
UNKNOWN	2086
Uruguay	7173
Uzbekistan	8618
Vanuatu	29
Vatican City State (Holy See)	16
Venezuela	7067
Viet Nam	7933
Western Sahara	1
Yemen	1853
Zambia	485
Zimbabwe	725

APPENDIX E: LIST OF FIGURES

Figure1 HDEV mounted on the nadir side of the CEPF. Visible are the windows for the two aft-viewing video cameras (rectangle and circle) and the nadir-viewing camera (semicircle in center of dark gray panel). NASA photo ID: ISS039e019134

Figure 2 The completed internal assembly of the HDEV hardware. The four cameras are identified in their respective locations inside the container.

Figure 3 The completed HDEV assembly. Visible are the two aft cameras (dark rectangle and circle on the left) and the nadir camera (dark circle inset on the right).

Figure 4 This distortion model or map shows the results of the camera/lens characterization of the Toshiba camera.

Figure 5 Left side of page: The SpaceX CRS-3 launch (NASA ID: KSC-2014-2191). Two views of the robotic operations during the HDEV installation activity.

Figure 6 HDEV is seen attached to the exterior of the Northrop Grumman Cygnus-13 vehicle shortly after unberthing from the space station. NASA ID: ISS063e010583

Figure 7 HDEV system design for default auto-cycle operations. The camera views were pre-planned and the cameras in the HDEV housing were mounted accordingly. The objective of the default camera rotation was to view and follow a feature in the forward-looking camera through the other cameras as it passed underneath the space station. The transition times for the cameras to switch broke the flow of viewing for most viewers, so the normal mode of operations changed to having each camera operate for one orbit then switch to the next camera.

Figure 8 HDEV Command and Data Handling flow diagram.

Figure 9 The only apparent damaged pixels occurred in the HDEV camera which looked nearly straight down on the Earth from the space station. The first damaged pixel appeared in August 2014 and remained for HDEV's operational life. The other two became apparent in July 2017 and are also shown in the 2018 view.

Figure 10 After only a few months on the space station, damaged pixels are very noticeable in images taken by on-board cameras. The same type of encoder (Visionary Solutions Inc. AVN443) used in the downlink process for this image was also used in HDEV. This image shows a selection of damaged pixels seen after approximately 1 year. Why did HDEV have only 3 apparent damaged pixels?

Figure 11 Demonstration of the Android App "The Eye of the Cyclone." (Image courtesy of Ortwein, A. et al. [12])

Figure 12 Columbus Eye Observatory. This screen shot from the Columbus Eye website [11] shows the location of the HDEV video and links to the associated teaching material and application to start the activity.

Figure 13 Pupils calculate the mean to correct image noise. (Image courtesy of Ortwein, A. et al. [12])

Figure 14 Specifications of the HDEV cameras and application in school lessons. (Image courtesy of Ortwein, A. et al. [12])

Figure 15 The Columbus Eye Augmented Reality app "The Earth Moon System" in a closed Alpha test in a school class. A celestial body and its companion revolve around their common barycenter in a 3D animation, fixated by the figure underneath. HDEV video was used to demonstrate using Moon rises and sets. [16]

Figure 16 An ISS-Above unit, with lights indicating when the space station passes overhead. (Photo courtesy of ISS-Above)

Figure 17 Left: ISS-Above curriculum, available to educators around the world. Right: Students at Barrett Elementary School react to the information displayed by ISS-Above. (Photo and image courtesy of ISS-Above)

Figure 18 ISS-Above's Founder and Inventor, Liam Kennedy, talks with a school about the space station and how they can see it pass overhead. (Photo courtesy of ISS-Above)

Figure 19 Prototype hardware design for the visual-inertial approach [19].

Figure 20 HDEV views inspired this "sunburst" quilt square which was used in a global community space quilt project initiated by Expedition 37 astronaut Karen Nyberg.

Figure 21 Map displaying relative concentration of views on the HDEV Ustream site from 226 countries/states around the world. Only the countries shown in gray either had zero views or the views were unidentifiable by country from any domain URL.

Figure 22 The Northrop Grumman Cygnus NG-13 vehicle shortly after being released from the space station with HDEV attached. The vehicle destined to be burned up as it enters the atmosphere over the South Pacific Ocean. NASA ID: ISS063E010644

Figure 23 The Moon under the CEPF where HDEV was installed. The next generation of HDEV can expand the awareness of NASAs programs, including Artemis. NASA ID: ISS063E009992

APPENDIX F: LIST OF ACRONYMS

ARISS	Amateur Radio on the International Space Station
AI	Artificial Intelligence
C&DH	Command and Data Handling
CCD	Charged Couple Device
CCSDS	Consultative Committee for Space Data Systems
CCT	Camera Calibration Toolbox
CEPA	Columbus External Payload Adapter
CEPF	Columbus External Payload Facility
CMOS	Complementary Metal-Oxide Semiconductor
Col-CC	Columbus Control Center
COTS	Commercial Off The Shelf
CRIO	Compact Reconfigurable Input/Output
CRS	Commercial Resupply Services
DLR	The German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt; DLR)
DMC	Data Management Coordinator
ESPE	Energetic Solar Particle Event
ESA	European Space Agency
FRAM	Flight Releasable Attachment Mechanism
GMT	Greenwich Mean Time
GSD	Ground Sample Distance
GSE	Ground Support Equipment (Packets Processed – real-time or stored)
HDEV	High Definition Earth Viewing
HDMI	High Definition Multimedia Interface
HUNCH	High Schools United with NASA to Create Hardware
IMMP	Intelligence Mapping and Monitoring
ISS	International Space Station
JSC	Johnson Space Center
LEO	Low Earth Orbit
MCOR	Medium-rate Communications Outage Recorder
MPEG	Motion Picture Experts Group
NASA	National Aeronautics and Space Administration
PAR	Payload Anomaly Report
PEHG	Payload Ethernet Hub Gateway
POIC	Payloads Operations and Integration Center
RTP	Real-time Transport Protocol
SDI	Serial Digital Interface
STEAM	Science, Technology, Engineering, Arts, and Mathematics
TReK	Telescience Resource Kit
URL	Uniform Resource Locator
USOS	United States Operating Segment

APPENDIX G:
LIST OF APPENDICES

Appendix A	HDEV Hardware Technical Specifications
Appendix B	List of the Payload Anomaly Reports (PARS)
Appendix C	Graphs of Total Views by Country during HDEV’s final 3.5 months
Appendix D	List of Total Views by Country during HDEV’s final 3.5 months
Appendix E	List of Figures
Appendix F	List of Acronyms
Appendix G	List of Appendices