The Hubble Space Telescope (HST) Advanced Camera for Surveys Repair (ACS-R)

Integrating Commercial Products in the Flight Software Environment

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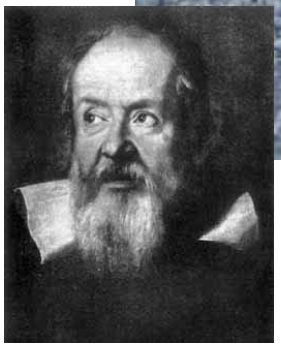
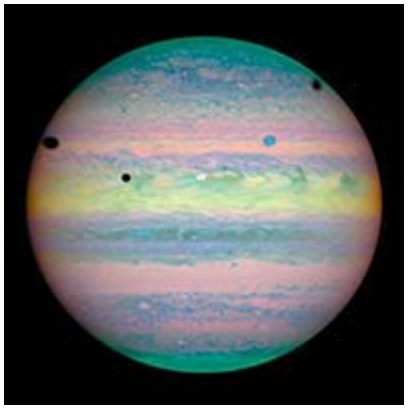
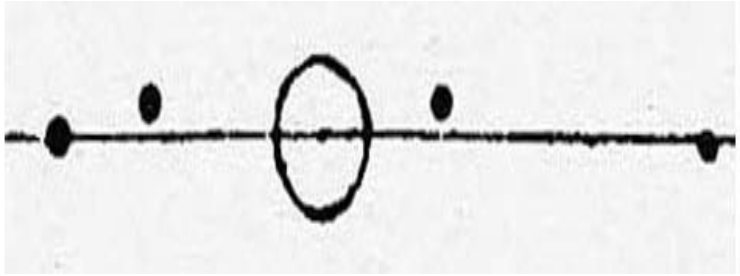
Introduction – Hubble Space Telescope



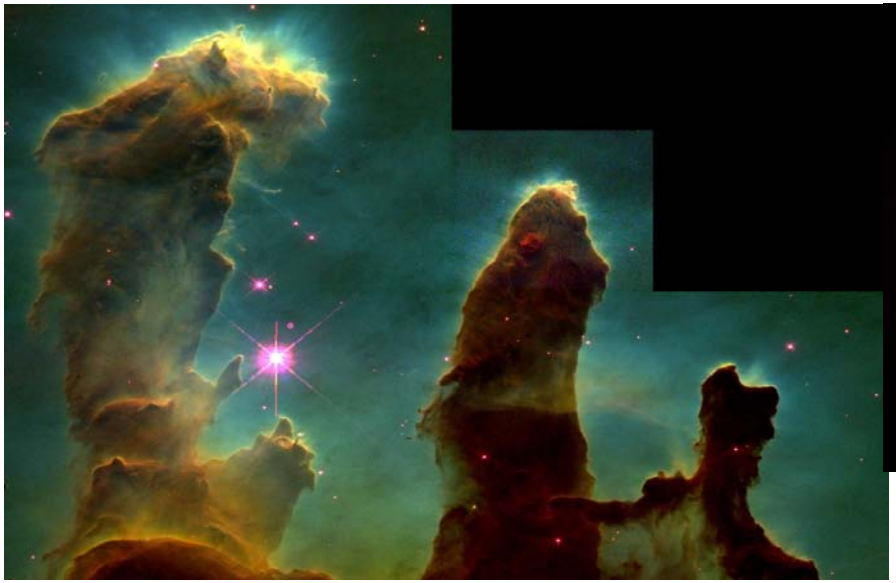




- Galileo first to point a telescope toward the heavens
- Changed mankind's view of the universe
- Hubble Space Telescope has again changed our view of the heavens
- Hubble brings the universe into our homes.

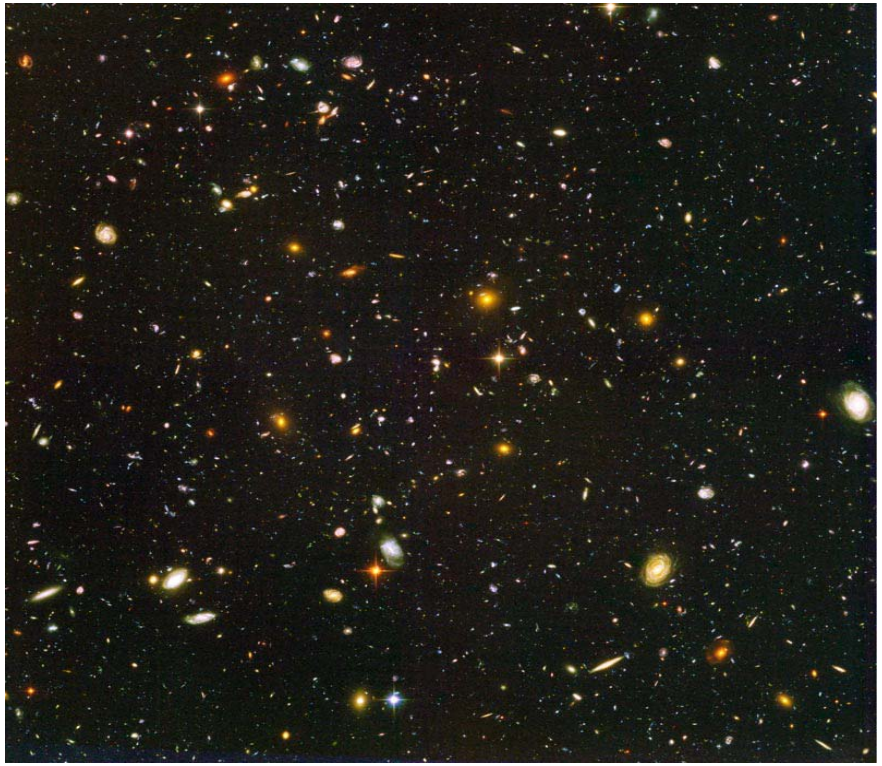
Introduction - HST Facts

- Launched in 1990
- More than 300,000 citations in scientific papers since launch
- No other scientific instrument has had such an impact on mankind's understanding of the universe
- Widely distributed science images maintain prominence of scientific research in the public eye
- Images are huge public relations tool for NASA.



"The Hubble Space Telescope is truly an icon of American life. I maintain that if the average American knows only one science project, one science instrument, I bet it's Hubble."
Ed Weiler, Associate Administrator Science Missions Directorate, NASA

Introduction – HST Servicing Mission

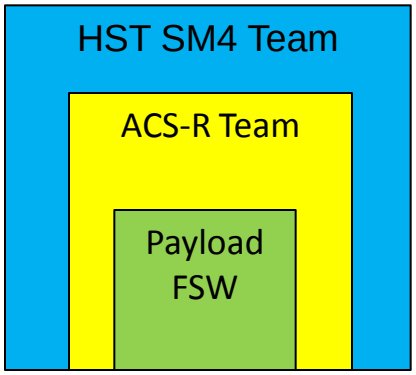


Hubble Ultra Deep Field (HUDF) Image Showing Thousands of Galaxies in Small Portion of the Sky

- HST has now been serviced by astronauts five times to correct initial problems and maintain and upgrade science instruments
- January 2004 – NASA cancels planned HST Servicing Mission 4 (SM4) as being too risky
- February 2004 – NASA embarks on robotic repair mission design to accomplish SM4 objectives
- October 2006 – New NASA Administrator reverses decision, sets new shuttle SM4 launch date for October 2008
- January 2007 – Hubble's flagship camera, the Advanced Camera for Surveys (ACS), responsible for 2/3 of Hubble's science data, suffers irrecoverable power failure prior to planned SM4 launch
- March 2007 – Momentum gathers for addition of ACS Repair to SM4
- April 2007 – ACS Repair (ACS-R) Team put together.

"NASA engineers reported today that most of the Advanced Camera for Survey's capabilities — including the ability to take the sort of deep cosmic postcards that have inspired the public and to track the mysterious dark energy splitting the universe to the ends of time — have probably been lost for good." New York Times, January 29, 2007

Introduction – ACS-R



- "A unique aspect to mission was attempt to repair two instruments: STIS, which failed in 2004, and ACS, which failed in 2007, in both cases because of electronic short circuits. A bold effort was undertaken to attempt to repair both instruments." *David Leckrone NASA Hubble Senior Project Scientist*.
- The effort was "bold" because neither the ACS nor Space Telescope Imaging Spectrograph (STIS) was ever intended to be repaired in orbit. The repair of ACS required the installation of a new power supply on the outside of the instrument
- Embedded in the new avionics was a vendor-supplied Application-Specific Integrated Circuit (ASIC) with no flight heritage
- The Advanced Camera for Surveys Repair (ACS-R) Operations Team was formed at Goddard Space Flight Center (GSFC) and included the Code 440 Payload Flight Software Team
- 35 new software requirements identified
- Unprecedented schedule of 8 months from design to integration with no room for error
- Two new instruments being installed as part of the servicing mission had been designed to complement ACS, elevating importance of the need for a flawless successful ACS repair.

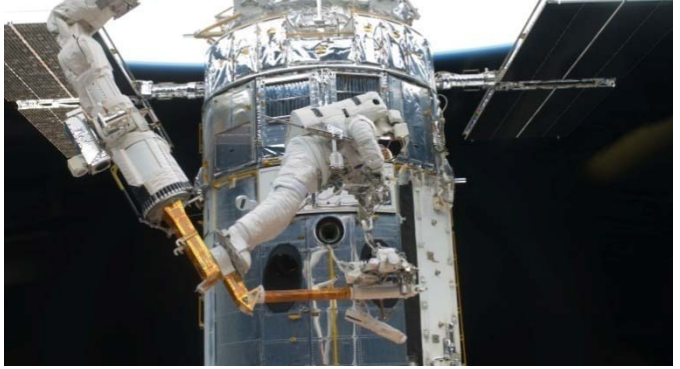
Introduction – ACS-R

Background

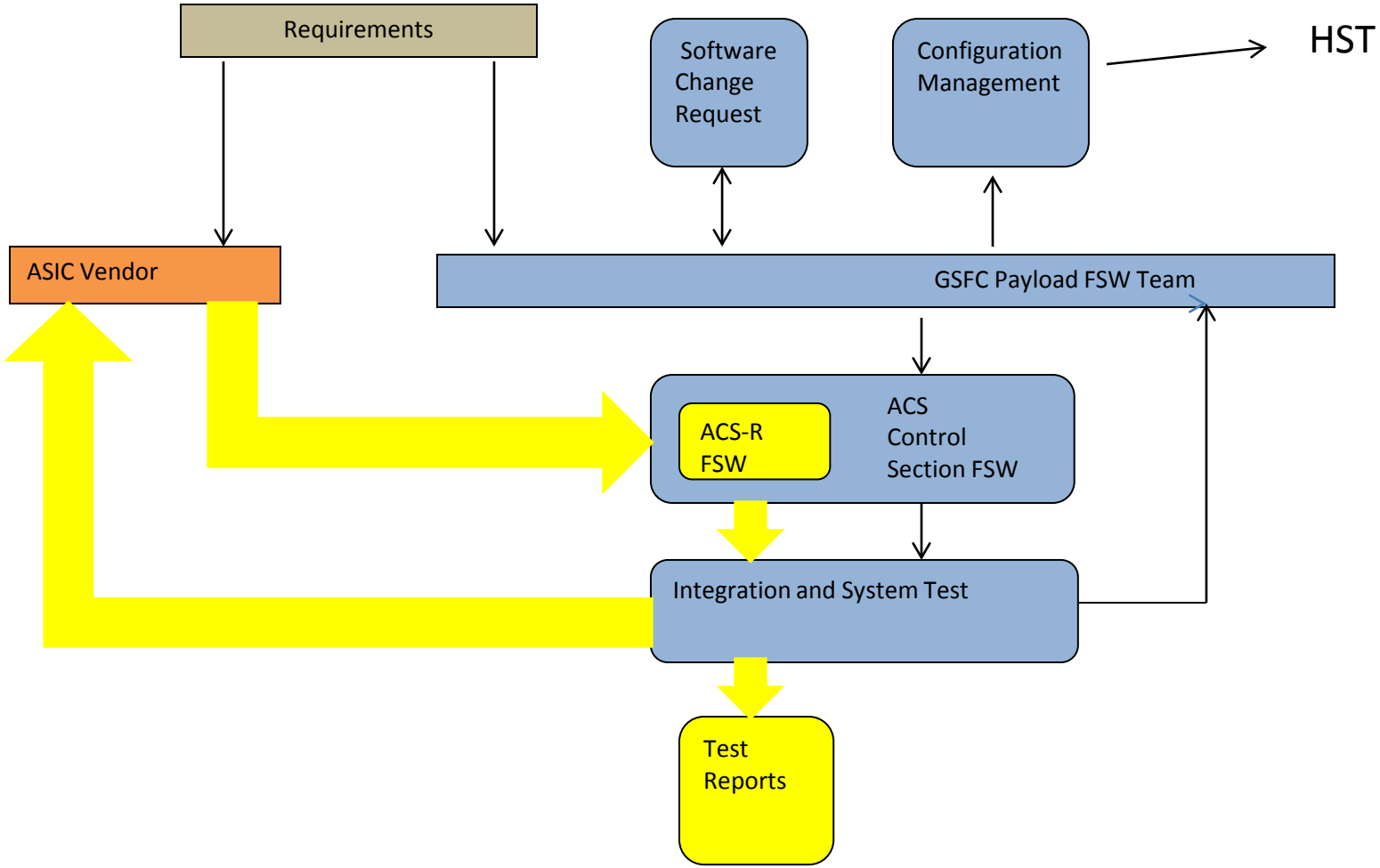
- In order to interface ACS to the ASIC we had to:
  - Create new flight software
  - Modify existing flight software
  - Update tools used to verify flight software applications.
- Flight software has four distinguishing characteristics
  - Embedded and only accessed via communication links to orbiting spacecraft
  - Interfaces with numerous hardware devices on spacecraft
  - Executes on radiation hardened processors that are slow and memory limited
  - Performs real time processing that must satisfy numerous timing constraints and inability to meet those constraints can potentially result in mission failure.
- All flight software changes are subjected to rigorous spaceflight standards
- We had benefit of proven flight software methodology, ASIC vendor did not
- By treating separate ASIC product as flight software change we were able to raise ASIC integration effort to spaceflight standards in time for delivery.

Innovation

- **Type:** Our innovation was a process innovation
- **Business Need:** Tight schedule and performance criteria demanded innovative approach be used in place of traditional design, develop and integrate life cycle
- **Process Innovation:** Enable concurrent software development through novel software testing approach
  - Include the component level test requirements in the higher level software and system integration process
  - Significantly reduced error propagation
  - Parallel, independent development efforts
    - Saved time which allowed the team to meet the schedule
    - Minimized the errors traditionally associated with parallel software development.



Process Schematic



Processes for ACS and ASIC FSW effort

Task:

- To successfully integrate and test a new FSW image for the ASIC from a hardware vendor, in addition to updating the ACS FSW to support loading, control, and telemetry interfaces within a fixed schedule.
  - The ASIC FSW was tasked to replace the function of the control electronics for the Wide Field Channel CCD.
- The ACS Repair effort was a highly visible GSFC project and underwent independent reviews, as if it were new: Concept, Requirements/PDR, FSW Peer Review, CDR, PER. The FSW Flight Readiness Review was conducted prior to the servicing mission.
- The FSW Requirements definition phase documented requirements for command/control, engineering/science data, loading/dumping, diagnostics, and error reporting.
  - Early and frequent communications with ACS-Repair hardware , software, and system engineers helped to establish requirements. It was a learning experience for GSFC and for the hardware vendor on how the ASIC FSW needed to perform. Design technical interchange meetings followed ; on-going weekly meetings helped resolve issues for FSW and Operations.
- The ASIC FSW requirements were also established but continued to evolve.
  - ASIC FSW was to be managed as an additional ACS FSW image to be maintained . The ASIC image was to reside in the EEPROM of ACS's existing flight processor and transferred upon command to the ASIC.
  - The ASIC FSW vendor was inexperienced in software process, but worked with us well to resolve issues as they came up. They independently followed their own software configuration and held release content reviews with GSFC.
  - Early baseline software drops to GSFC and an Formal Qualification Test were completed.
  - However, it was an on-going process as the ASIC requirements became refined, and the new hardware simulator test units evolved and matured.

Processes for ACS and ASIC FSW effort

Approach:

- Treat as “new” ACS FSW implementation with mature maintenance process
- Scope the work to fit:
  - FSW release plan and schedule developed to produce early builds having as much functionality as possible
  - On-going builds expected to support integration
  - FSW schedule had to keep up with early integration efforts, environmental testing, and be complete before final Operations level testing
  - Established FSW configuration management and build processes made this easier.
- The FSW requirements were functionally mapped to 22 Software Change Requests (SCR). Our web based software change forms were then used to document the FSW design, implementation, and testing for particular component-like grouped requirements. Our HST FSW Configuration Control Board reviewed and approved the changes (FSW, System Eng, and Science reps).
- Design reviews and code reviews were held for each SCR with system engineers and science staff.
- The implementation of the ACS and ASIC FSW produced initial baseline releases prior to system integration level testing.

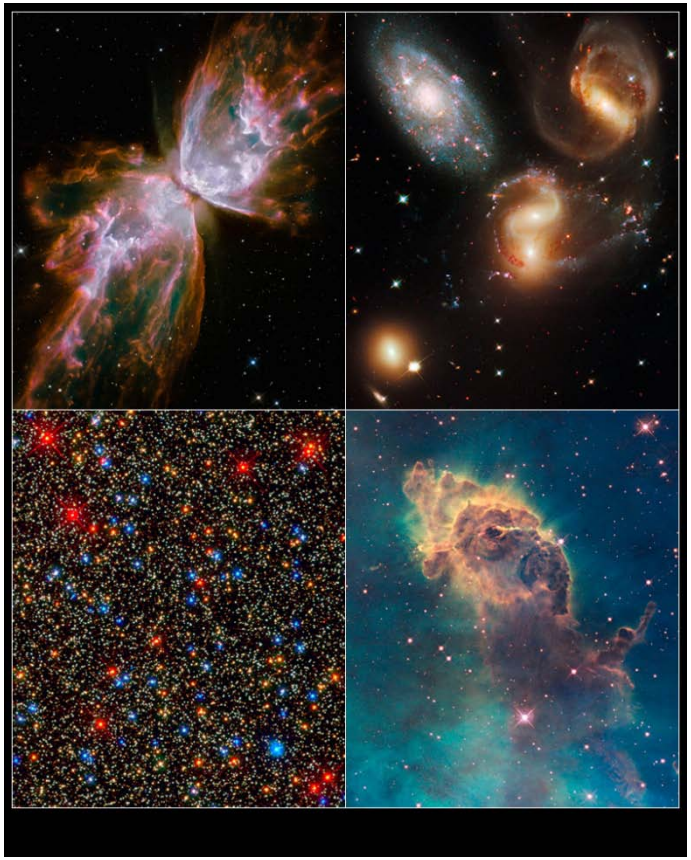
Processes for ACS and ASIC FSW effort

Integration Testing - new commands, new interface

- Configured FSW builds were used by the developers to perform SCR level testing to save time, and get the most out of an integrated test level. Test scripts were established per SCR and used for requirement verifications and regression testing for each subsequent build as needed, especially if there were modifications on the ASIC FSW side. Test products and results were also reviewed per release.
- Early integration testing with preliminary ASIC "test units"
  - proved to be valuable in uncovering details, corrections, and re-thought plans. This allowed the ACS FSW to continue to test while the ASIC FSW staff was working on builds and testing in parallel.
- A more mature ASIC engineering model soon followed and allowed FSW integration test to start rolling through an iterative testing process. The ASIC FSW drops were incorporated into the ACS FSW products and a new build was loaded to the test environment. Established tests were executed and new ASIC or ACS SCRs documented identified issue/change as needed. New releases were generated after CCB approval.
- The instrument experience of the software and operation team in already knowing how the exposures and readouts were expected, facilitated greatly in identifying these issues early.
- An established team, with known processes, and high-fidelity software environment eased the potential loss of time to make the effort all come together in the end on time.

Innovation

- Treat separate ASIC product as a flight software change in order to verify its compliance within proven spaceflight system integration processes in use at Goddard Space Flight Center
- Extensive experience of Payload FSW Team members helped pinpoint potential problem areas - several design problems found as a result
- The team's analysis consistently provided solutions to complex problems, and helped project meet schedule
- Approach dramatically shortened the system integration life cycle while ensuring quality
- ACS was the first instrument to successfully pass all of its calibration criteria following the repair.



Post servicing mission images

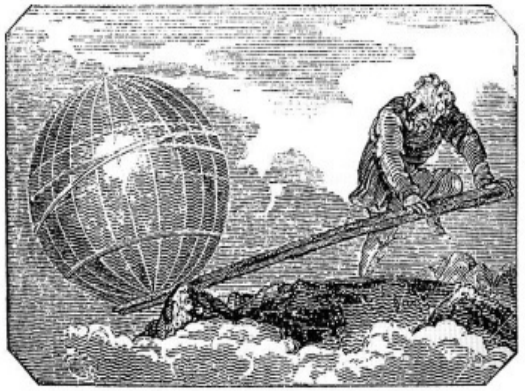
Innovation

- Innovative approach enabled the successful integration of a commercial part to spaceflight requirements in limited time from concept to launch
- The repair was flawless and the new code and interface have exceeded expectations
- Contributions of Payload FSW Team members helped return ACS to leading edge scientific research
- This achievement has strengthened NASA's reputation for creative innovation within the international science community.

Leverage – Mission Critical System Integration

Schedule Constraints,
Multiple Vendors,
Changing Requirements

FSW
Processes



Archimedes lever

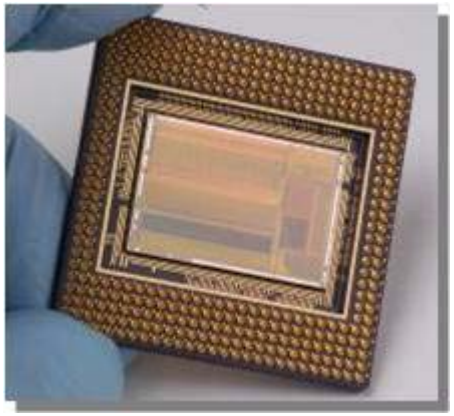
- ACS-R success demonstrates the high level of FSW capabilities and readiness to support mission critical system integration for space and Earth science observing systems
- Enhances the reputation of FSW in the science and engineering disciplines for its role in spaceflight solutions
- Provides proof of concept for JWST
- Strengthens relationships with NASA, the Space Telescope Institute, and within the HST Team.

Leverage – ASIC Applications

- Team has now acquired experience in the successful integration of a programmable part for spaceflight systems.
- Success of ACS-R repair has given NASA validation for using ASICs to reduce the size and weight of space-borne science instruments
- The successful integration of the ASIC on HST provides a reference for other projects facing similar mission critical scenarios
- The experience gained from the ACS repair should translate into a better understanding of costs and project requirements for others preparing for or facing similar situations.

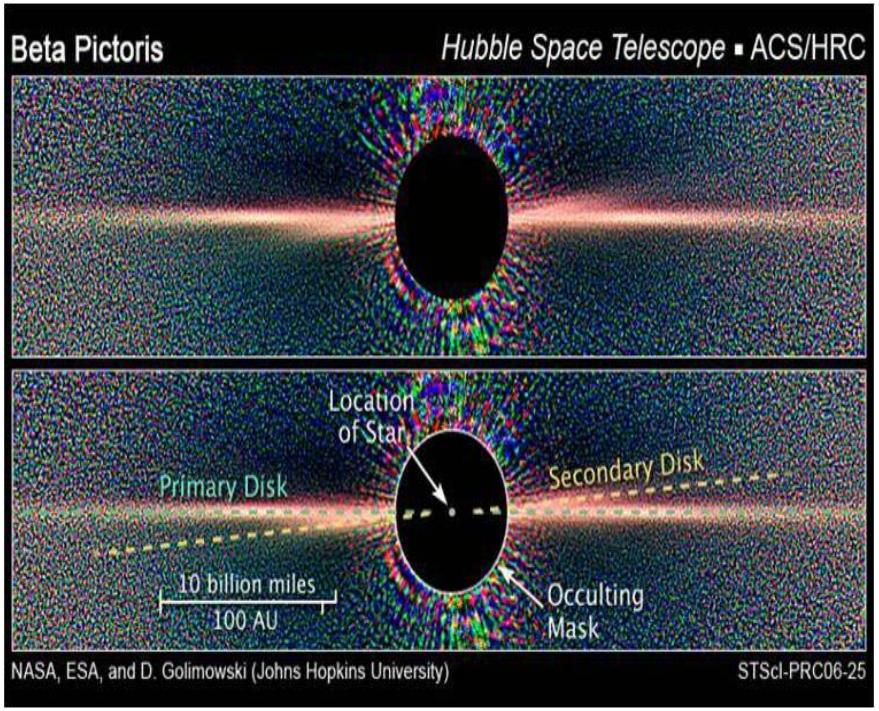
From this:

To this:



Proven – Software Performs!

- The Hubble Advanced Camera for Surveys, previously inoperable, is working once again
- Is now being used to:
  - obtain mosaic observations of large astronomical objects in parallel with newly installed Wide Field Camera 3 (WFC3)
  - or deep field observations in parallel with either WFC3, Cosmic Origins Spectrograph (COS) or Space Telescope Imaging Spectrograph (STIS)
- Images released by NASA following repair are positive proof of success.



ACS Coronagraphy Probes Extrasolar Protoplanetary Systems

"With all the instruments on board Hubble now working, we can look forward to a period of great scientific productivity, and even more breathtaking images."
Mario Livio, Author and Astrophysicist

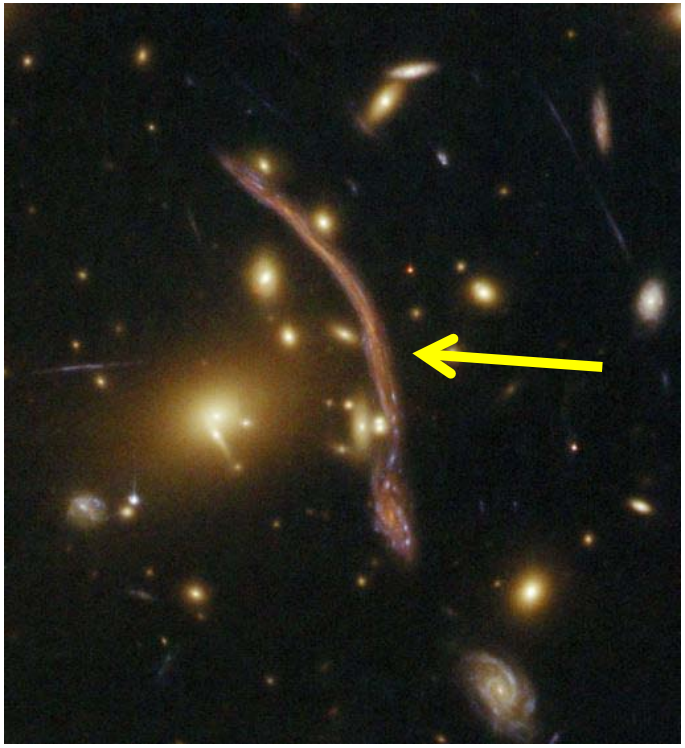
Proven – 1st Images

Barred Spiral Galaxy NGC 6217

- First image of a celestial object taken with the newly repaired Advanced Camera for Surveys (ACS)
- Photographed on June 13 and July 8, 2009, as part of the initial testing and calibration of Hubble's ACS
- The barred spiral galaxy NGC 6217 lies 60 million light-years away in the north circumpolar constellation Ursa Major.

"Prior to this mission, we were down to three operating channels…Today we have thirteen, on six fully operating instruments. I am not able to report any failure or problem on the spacecraft itself."
Dave Leckrone, NASA Hubble Senior Project Scientist

Proven – 1st Images

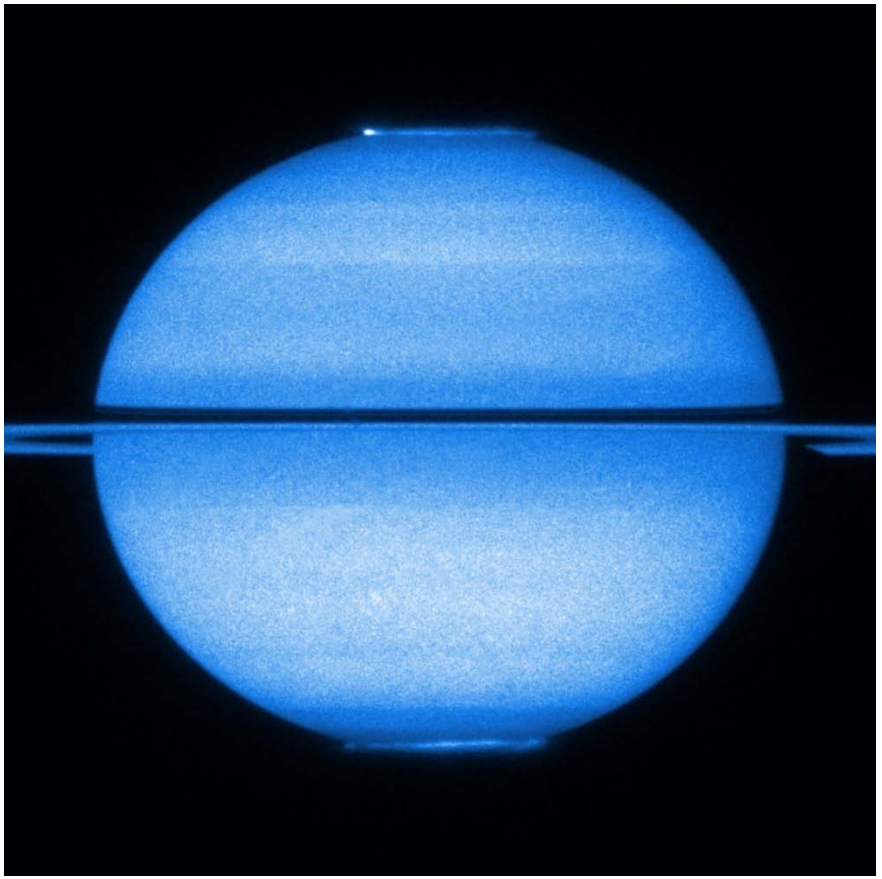


Hubble ACS image: Galaxy cluster Abell 370 (orange ellipses) serves as a gravitational lens, magnifying the images of background galaxies. A background galaxy (red with bright blue stars) is visible in numerous lensed images. One, below center, is relatively undistorted, but a long "tail" above it consists of three or four separate lensed images of the same galaxy.

- Image taken July 16, 2009, with the newly repaired ACS camera
- Galaxy cluster Abell 370 lies 5 billion light years away
- One of the first observations of gravitational lensing predicted by Einstein's theories
- Provides astronomers a vital tool for measuring distribution of dark matter
- It is currently believed that dark matter makes up approximately 1/4 of the known universe.

Value

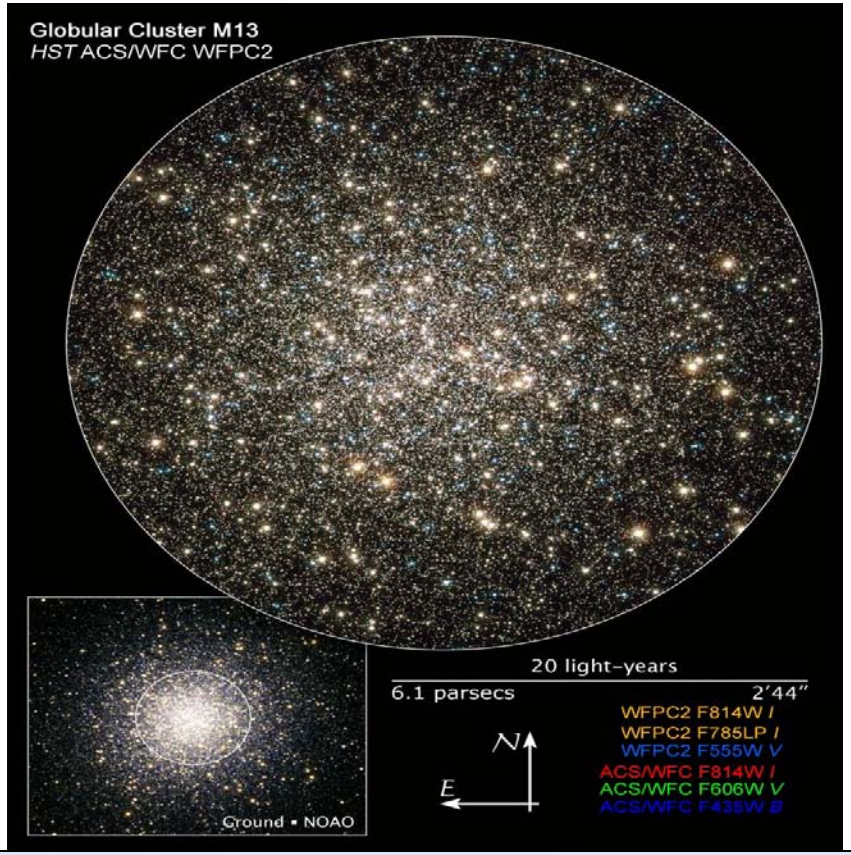
- ACS again able to tackle some of the most fundamental problems in astrophysics, including Dark Energy, Dark Matter, Galaxy Formation, Star Formation and Extrasolar Planets
- ACS can help fulfill the international scientific communities expectations for extending the frontiers of science
- Successful repair provides return on taxpayers' investment in technology
- ACS observations will help to further mankind's quest to understand the universe.



ACS image of Saturn

Value

- Our team has now successfully worked side by side with our customers in support of Hubble for over two decades
- This accumulated experience and expertise combined with that of the HST community was perhaps the most significant factor in the success of the repair.



Globular Cluster M13 in Hercules resolved by ACS

"We're so used to talking about extraordinary things at NASA – we do them so often that the word seems to lose some of its meaning. But in the case of the team that has been responsible for operating and servicing Hubble for the past 20 years, there really is no other word that fits – they are truly an extraordinary group of women and men." Robert Strain, Goddard Space Flight Center Director

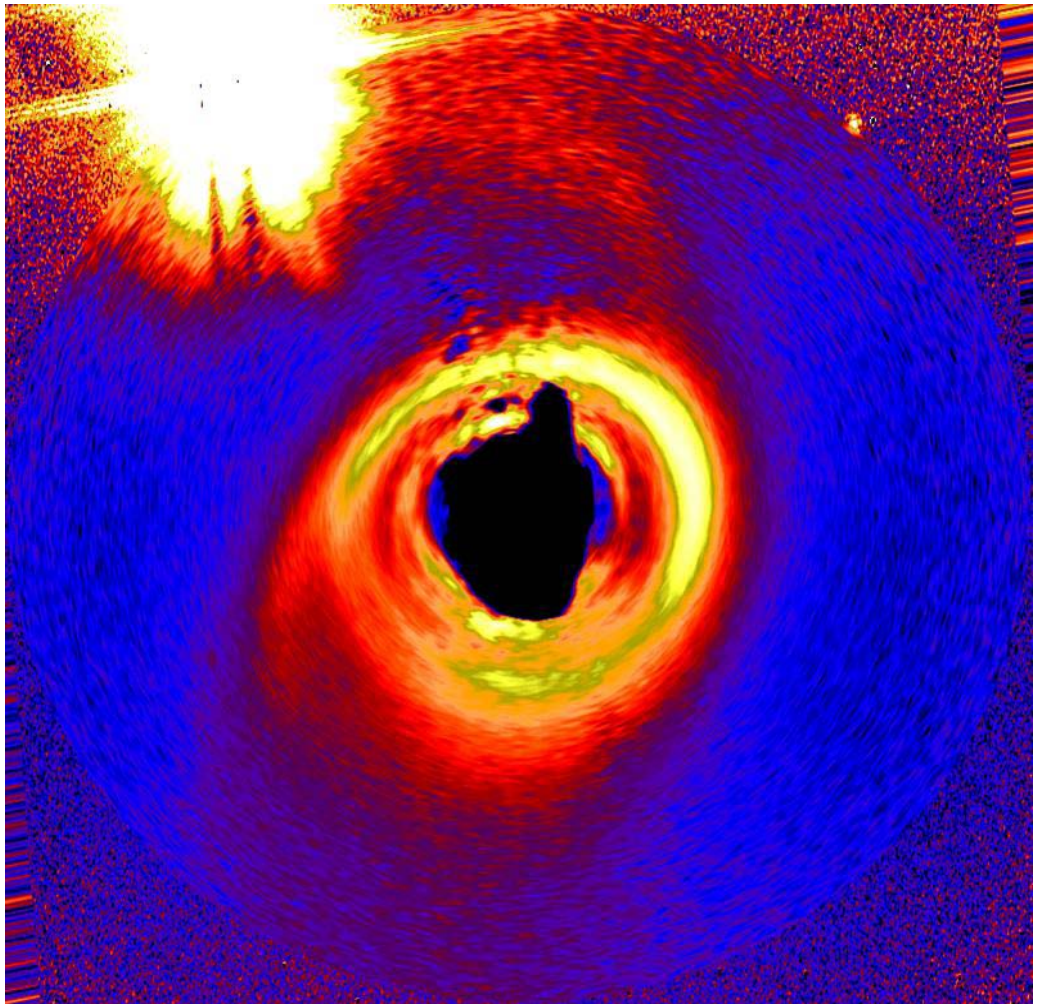
Summary

- Innovation
  - Novel Testing Approach
    - Markedly shortened development time
    - Reduced risk to science instrument
    - Improved long term reliability.
- Leverage
  - Enhances reputation of Flight Software in science and engineering
  - Extends our knowledge base in support of other missions
  - Approach is transferable to other industries.

Summary

- Proven track record of customer satisfaction
- Success of repair effort within schedule constraints shows that innovative use of software and methodology can shorten system integration life cycle
- Shortened life cycle adds value both quantitatively (budget, schedule) and qualitatively (reliability).

The possibilities are endless …



"We often frame our understanding of what the space telescope will do in terms of what we expect to find, and actually it would be terribly anticlimactic if in fact we find what we expect to find. ... The most important discoveries will provide answers to questions that we do not yet know how to ask and will concern objects we have not yet imagined." John Bahcall

Dust Disk Around Star HD 141569A, Expected Birthplace of Planets