Root Cause Analysis Report

Example_Hubble Space Telescope

sologic root cause analysis

Problem Statement

Report Number	N/A	**RCA Owner**	Brian Hughes
Report Date	12/7/2015	**RCA Facilitator**	Brian Hughes

Focal Point: Spherical aberration in Hubble Space Telescope (HST) images returned from orbit

When

Start Date: 1/1/1979	End Date: 4/25/1990
Start Time: N/A	End Time: N/A
Unique Timing	- Funding was granted in 1977. - Perkin Elmer completed the primary mirror in 1981. - The error was not discovered until routine image testing once the HST was on orbit in 1990.

Where

Component	Eight instrument packages, including 2 cameras, two spectrographs, one photometer, and three fine guidance sensors with wavefront sensors.
Company	NASA, Lockheed Martin, Perkin Elmer
Equipment	Hubble Space Telescope (HST) 2.4 m Ritchey-Chretien telescope, focal ratio f/24, optical range from 1,100 - 11,000 angstroms
Component	Primary Mirror - (2.4 m diameter concave hyperboloid)

Actual Impact

Safety	No safety impact	$0.00
Production Impact	Delay in operation of the Hubble Space Telescope - many different projects placed on hold during repair	$0.00
Cost	Shuttle mission to install repair (estimated)	$450,000,000.00
Reputation (External)	Loss in confidence in NASA, Perkin Elmer	$0.00
Quality	Quality escape, Hubble Space Telescope unusable in current state	$0.00
Cost	Design and build repair (estimated)	$20,000,000.00

Actual Impact Total: $470,000,000.00

Frequency	1 times Year
Frequency Note	This was the only project of this type.

Potential Impact

Revenue	Potential loss of entire project (estimated)	$2,500,000,000.00
Safety	Potential loss of future contracts (estimated)	$50,000,000.00
Cost	Potential Safety impact - repair required a separate shuttle mission, which is always risky	$0.00

Potential Impact Total: $2,550,000,000.00

Report Summaries

Executive Summary

Sometime after launch on 4/24/1990, engineers testing images from the Hubble Space Telescope (HST) noticed that the images were blurry. They were unable to focus the image through normal equipment adjustments. This was the result of spherical aberration that occurred after the primary mirror was ground too flatly at the edges. The mirror is ground based on data from a measuring device called a “reflective null corrector,” or RNC. The RNC was out of position due to an error in setup.

The error in the primary mirror went undiscovered. This is primarily due to the fact that both NASA and Perkin Elmer relied solely on the RNC for measurements. There were large gaps in Quality Assurance and Quality Control at Perkin Elmer. The project was wrought with challenges and threatened with cancellation by NASA. NASA also had gaps in their QA/QC process.

Corrective Actions:

Note: These corrective actions were originally suggested in the Allen Report, section 10.

1. Identify and mitigate risk.
2. Maintain good communication within the project.
3. Understand the accuracy of critical measurements.
4. Ensure clear assignment of responsibility.
5. Remember the mission during crisis.
6. Maintain rigorous documentation.

Cause and Effect Summary

Background:

Sometime after launch on 4/24/1990, engineers testing images from the Hubble Space Telescope (HST) noticed that the images were blurry. They were unable to focus the image through normal equipment adjustments. The blurry images were determined through testing to be a form of spherical aberration. Spherical aberration occurs when light reflected from the center of a mirror focuses at a different point than light reflected from the edges. In order to understand the causes of the spherical aberration in the HST, a brief description of how the telescope works is in order.

The HST is a 2.4 m Ritchey-Chretien telescope with a focal ratio of f/24 and an optical range from 1,100 - 11,000 angstroms. This type of telescope has two mirrors. In the HST, the primary mirror is concave and 2.4 meters in diameter. The secondary mirror is convex and much smaller at 0.3 meters in diameter. It works similar to a complex billiards shot. The light comes in from wherever the telescope is pointed, reflects off the primary mirror, then reflects again off the secondary mirror back through a hole in the center of the primary mirror to the focal plane where various instruments can process the image. It may be easier to understand how this works by viewing this diagram:

Click for picture of Ritchey-Chretien Telescope

This style is very common and used in many terrestrial telescopes. But in order to produce the image clarity required, each mirror must be produced to exact specifications. These mirrors are ground in way similar to creating lenses for eyeglasses. The main difference (besides scale) is the addition of a very thin layer of aluminum, which creates the reflective surface of the mirror. Material is removed with a polishing system until the surface has the desired curvature. If too much or too little is removed during the process, the mirror will not focus properly.

When the test engineers discovered the spherical aberration, they needed to identify what was causing it. After running several diagnostic tests, they determined that the problem was with the primary mirror. This report examines both how the error in the primary mirror occurred along with why this error was not caught at any point until on-orbit testing.

Error in Primary Mirror:

In short, the primary mirror was ground too flatly at the edges. Perkin Elmer Co. manufactured the primary mirror. Perkin Elmer won the bid in large part due to their successful completion of a smaller proof-of-concept mirror. The smaller mirror was constructed perfectly. The idea was to then simply scale up the process to make the larger mirror.

In order to achieve the proper lens specifications, Perkin Elmer required a measuring device that could mimic the desired final image perfectly. This device is called a Reflective Null Corrector (RNC). The RNC uses mirrors to determine how much material needed to be removed from the primary mirror. The process was to grind, test, and repeat until perfection was achieved. See this image:

Click for picture of Hubble Primary Mirror Polishing

The man in this image does not realize it, but the parameters controlling the massive grinding apparatus are incorrect. This is because the RNC measuring device was positioned 1.3 mm to far away from the mirror. This may not seem like a lot, but given the extremely tight tolerances required, it was enough to jeopardize the usability of the HST.

The RNC was out of position due to an error in setup. In order for the RNC to function properly, it must be perfectly positioned above the mirror. When Perkin Elmer built their prototype smaller mirror, they achieved this positioning by using a measuring rod cut to an exact length. This rod was fitted with cap on the end (called a “field cap”) that allowed engineers to achieve perfect alignment between the RNC and the primary mirror.

The end of the rod is reflective. Engineers reflect light off of the end of the rod to set the distance of the RNC. The problem was that they bounced the light off of the surface of the field cap instead of the end of the rod. A small amount of anti-reflective paint had chipped away from the end cap, exposing a reflective surface. The width of the field cap was 1.3mm – hence the reason the RNC was positioned 1.3mm too high off of the mirror.

Error Went Undiscovered:

The error in the primary mirror went undiscovered. This is primarily due to the fact that both NASA and Perkin Elmer relied solely on the RNC for measurements. They had complete trust in the RNC to properly and accurately direct the grinding process. This was because they supposedly “certified” the accuracy of the RNC (there is actually no documentation supporting how this was completed, or even that the certification was done). Other measuring devices were available and used. These were the Refractive Null Corrector (RvNC) and the Inverse Null Corrector (INC). Neither of these devices was as accurate as the RNC. Yet, the error was so great that they both actually were able to measure the spherical aberration in the primary mirror. However their measurements were discounted in deference to the supposedly “certified” RNC.

There were large gaps in Quality Assurance and Quality Control at Perkin Elmer. Quality was not allowed access to the metrology lab. And Quality reported directly to Project Management. This set up a conflict of interest between those trying to employ quality management systems and those trying to build the mirror.

The working environment in which this all took place was toxic. The project was wrought with challenges and threatened with cancellation by NASA. This created a stressful production environment in which QA/QC was considered an additional and unnecessary cost in light of the fact that the proof-of-concept project went so smoothly.

NASA also had gaps in their QA/QC process. The Defense Contractor Administration Service (now the Defense Contractor Management Agency) did not exist when the primary mirror was being built. Prior to that, NASA personnel accepted the Perkin Elmer process as satisfactory.

Final Testing:

There was no end-to-end final testing completed on the fully assembled OTA. This is because such a test would actually require two mirrors larger than the primary mirror, built to the same exacting standards. This would cost more than the telescope itself. Therefore, each of the components was tested individually. Final measurements on the primary mirror were actually extremely exact – even tighter than the specification required. The problem was that these final measurements were being compared to a standard that came from the flawed setup of the RNC.

-- END OF SUMMARY --

Solutions

SO-0001	**Solution**	Identify and mitigate risk (from Allen Report)	
	Cause(s)	RNC output was the sole data considered during manufacture	
	Note	The Project Manager must make a deliberate effort to identify those aspects of the project where there is a risk of error with serious consequences for the mission. Independent testing should be included to ensure that cost and schedule issues do not interfere with risk mitigation.	
	Assigned		**Criteria** Passed
	Due		**Status** Validated
	Term	medium	**Cost**
SO-0002	**Solution**	Maintain good communication within the project (from Allen Report)	
	Cause(s)	Error not discovered	
	Note	Proper delegation of responsibility and authority is important. But it must not restrict communication such that problems are not subject to review. The culture needs to change in a way that encourages reporting of issues, and that such reporting is not necessarily indicative of bad management.	
	Assigned		**Criteria** Passed
	Due		**Status** Validated
	Term	long	**Cost**
SO-0003	**Solution**	Understand the accuracy of critical measurements (from Allen Report)	
	Cause(s)	RNC had been 'certified' although there is no documentation of this	
	Note	The Project Manager must understand the accuracy of critical measurements. Terms such as "certified" and "not certified" need to be clearly defined with respect to critical measuring devices. Equipment that directly impacts flight hardware must be classified as such. Accurate records must be kept and audits conducted to ensure completeness. Key decisions, test results, and changes must be adequately documented.	
	Assigned		**Criteria** Passed
	Due		**Status** Validated
	Term	long	**Cost**
SO-0004	**Solution**	Ensure clear assignment of responsibility (from Allen Report)	
	Cause(s)	Error not discovered	

	Note	Project managers must ensure clear assignment of responsibility to QA and Engineering. Quality Assurance must have an independent reporting path to top management.	
	Assigned		**Criteria** Passed
	Due		**Status** Validated
	Term	long	**Cost**
SO-0005	**Solution**	Remember the mission during crisis (from Allen Report)	
	Cause(s)	Distractions due to project delays, etc.	
	Note	Challenging projects usually include periods of crisis in cost or scheduling. Mission Assurance must be maintained as the primary goal.	
	Assigned		**Criteria** Passed
	Due		**Status** Validated
	Term	long	**Cost**
SO-0006	**Solution**	Maintain rigorous documentation (from Allen Report)	
	Cause(s)	Error not discovered	
	Note	The Project Manager must ensure that documentation covering design, development, fabrication, and testing is rigorously prepared, indexed, and maintained.	
	Assigned		**Criteria** Passed
	Due		**Status** Validated
	Term	long	**Cost**

Team

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Evidence

EV-0001	**Evidence**	Hubble Independent Optical Review Panel (Final Version), NASA Goddard Space Flight Center
	Cause(s)	Conic constant design parameters = -1.0022985 Conic constant as-built parameters = -1.013236 Primary mirror ground "too much flattened away from the mirror's center"
	Location(s)	http://www.hq.nasa.gov/office/hqlibrary/documents/o173177366.pdf
	Attachment(s)	
	Contributor	Brian Hughes
	Type	Document
	Quality	★★★★★
EV-0002	**Evidence**	Hubble Space Telescope Optical Systems Failure Report (Allen Report), Jet Propulsion Laboratory
	Cause(s)	Primary mirror ground "too much flattened away from the mirror's center" Parabolic attributes determine focal points for the mirror Degree of error too great for adjustment Marginal focal point different location than paraxial focal point Could not adjust settings to compensate All points on the mirror need to focus in the same place Images experienced spherical aberration (blurry) HST on orbit - Successful launch and deployment HST was available to launch NASA launched it successfully Delivered to NASA by Lockheed Martin NASA accepted HST as complete Primary mirror delivered to Lockheed Martin by Perkin Elmer Lockheed Martin accepted primary mirror as complete Primary Mirror created by Perkin Elmer Perkin Elmer certified primary mirror as complete Perkin Elmer won the contract to construct the primary mirror Demonstrated competency by creating smaller mirror Amount bid by Perkin Elmer was acceptable to NASA Used a fixed length rod to measure proper distance Mirror polished based on measurements from Reflective Null Corrector (RNC) RNC was 1.3 mm too far away from the mirror RNC output was the sole data considered during manufacture Rod fitted with a field cap Top of field cap thickness = 1.3 mm Measurement occurred from top of the field cap, not the top of the rod

2 other measuring devices correctly identified the error
Wanted to ensure consistent accurate fit into measuring device
RNC had been 'certified' although there is no documentation of this
Auxiliary measuring devices were not certified
Reflected light used to set distance from top of bar
Multiple cycles
Anti-reflective paint on field cap damaged
Storage method of field cap?
Durability of paint allows for eventual chipping
Field cap material reflective
Unaware that reflection was from field cap and not measurement bar
Light reflected off of field cap, not top of bar
No secondary verification was performed on RNC position
Auxiliary measuring device data was discounted
By design, RNC was to be the sole measuring device
NASA agreed to the plan to use a single certified measuring device
Technical and supervisory limitations at Perkin Elmer
Project designed by skilled optical scientists at PE
Project build transferred to Optical Ops Division
Optical Ops Division insulated from review or technical supervision
Distractions due to project delays, etc.
RNC converts the aspherical image back to spherical
Spherical images are more easily testable by opticians
Aspherical mirrors produce higher quality images
Mirror design = aspheric
Measuring device needed to test the aspheric attributes
No final end-to-end test was performed
The test would have cost more than the project itself
Testing would require two mirrors, larger than the primary, and just as precise
Final exact end-to-end test possible
Met all checkpoints up to delivery
The fraction of the mirror tested was too small to give reliable results
OTA was mounted horizontally, causing gravity distortion
End-to-end focus test performed, did not use as check on accuracy
Test of exact specification not performed
Both mirrors exceeded individual specifications (on paper)
Rougher, less accurate test not performed
Template used as comparison was based on primary mirror error
Error in grinding the mirror
Error not discovered
QA limitations
RNC was a more precise measuring method
DCMC added to project after primary mirror had been ground
QA management system gaps not identified, questioned
QA limitations at NASA
QA personnel inexperienced
QA reported to Operations - not independent of production pressure
QA not allowed access to metrology
QA limitations at Perkin Elmer
Lockheed Martin assembled telescope, trusted PE and NASA
Could not adjust measuring rod

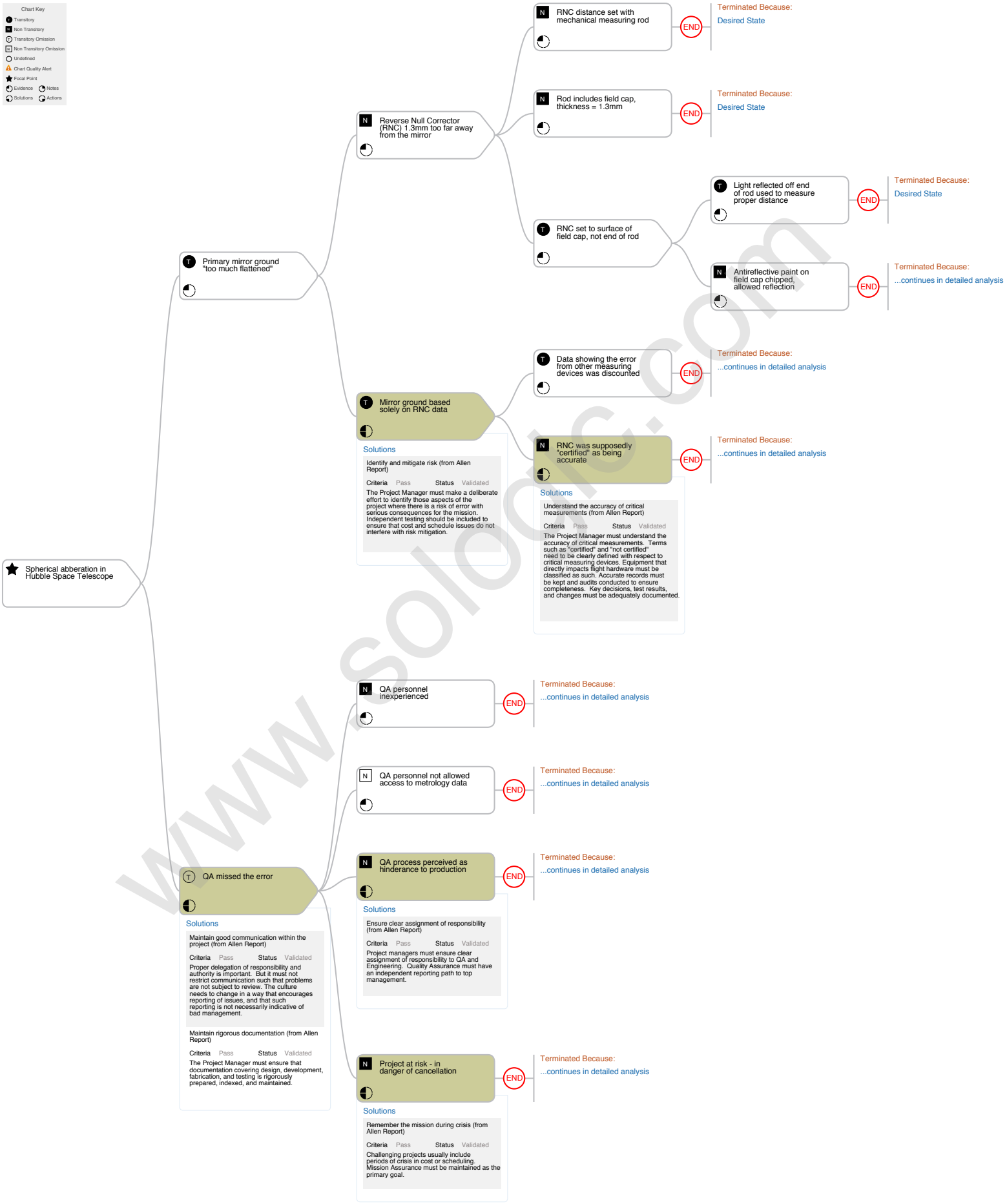
		Spacers added to measuring rod system Addition of spacers triggered MRB requirement No evidence that MRB was ever held Management of Change failure RNC as designed provided greater precision Previous method of test (Refractive Null Corrector) deemed insufficient RNC designed especially for this project
	Location(s)	https://www.ssl.berkeley.edu/~mlampton/AllenReportHST.pdf
	Attachment(s)	
	Contributor	Brian Hughes
	Type	Document
	Quality	★★★★★
EV-0003	**Evidence**	Hubble Space Telescope Timeline
	Cause(s)	
	Location(s)	http://www.spacetelescope.org/about/history/timeline/
	Attachment(s)	
	Contributor	Brian Hughes
	Type	URL
	Quality	★★★★★
EV-0004	**Evidence**	Brief History of Hubble Space Telescope, CBS News
	Cause(s)	Degree of error too great for adjustment
	Location(s)	http://www.cbsnews.com/network/news/space/125/125_HST_history.html
	Attachment(s)	
	Contributor	Brian Hughes
	Type	URL
	Quality	★★★★★

Actions

Notes

NO-0003	**Note**	No additional notes
	Cause(s)	

Summary Chart



Detailed Chart

Chart Key
- Transitory
- Non Transitory
- Transitory Omission
- Non Transitory Omission
- Undefined
- Chart Quality Alert
- Focal Point
- Evidence
- Notes
- Solutions
- Actions

Spherical aberration in Hubble Space Telescope (HST) images returned from orbit

HST on orbit - Successful launch and deployment

HST was available to launch

NASA launched it successfully
→ END
Terminated Because: Desired State

Delivered to NASA by Lockheed Martin

Primary mirror delivered to Lockheed Martin by Perkin Elmer

Primary Mirror created by Perkin Elmer

Perkin Elmer won the contract to construct the primary mirror

Demonstrated competency by creating smaller mirror
→ END
Terminated Because: Desired State

Amount bid by Perkin Elmer was acceptable to NASA
→ END
Terminated Because: Desired State

Perkin Elmer certified primary mirror as complete
Connects To: c RNC output was the sole data considered during manufacture

Lockheed Martin accepted primary mirror as complete

Lockheed Martin assembled telescope, trusted PE and NASA
→ END
Terminated Because: Other causual paths more productive

NASA accepted HST as complete

No final end-to-end test was performed

Rougher, less accurate test not performed

Both mirrors exceeded individual specifications (on paper)

Template used as comparison was based on primary mirror error
Connects To: e RNC output was the sole data considered during manufacture

Test of exact specification not performed

Final exact end-to-end test possible
→ END
Terminated Because: Other causual paths more productive

The test would have cost more than the project itself

Testing would require two mirrors, larger than the primary, and just as precise
→ END
Terminated Because: Other causual paths more productive

End-to-end focus test performed, did not use as check on accuracy

The fraction of the mirror tested was too small to give reliable results
→ END
Terminated Because: Other causual paths more productive

OTA was mounted horizontally, causing gravity distortion
→ END
Terminated Because: Other causual paths more productive

Met all checkpoints up to delivery
Connects To: d RNC output was the sole data considered during manufacture

Error not discovered

Solutions

Ensure clear assignment of responsibility (from Allen Report)

Criteria Pass Status Validated

Project managers must ensure clear assignment of responsibility to QA and Engineering. Quality Assurance must have an independent reporting path to top management.

Maintain rigorous documentation (from Allen Report)

Criteria Pass Status Validated

The Project Manager must ensure that documentation covering design, development, fabrication, and testing is rigorously prepared, indexed, and maintained.

Maintain good communication within the project (from Allen Report)

Criteria Pass Status Validated

Proper delegation of responsibility and authority is important. But it must not restrict communication such that problems are not subject to review. The culture needs to change in a way that encourages reporting of issues, and that such reporting is not necessarily indicative of bad management.

Technical and supervisory limitations at Perkin Elmer

Project designed by skilled optical scientists at PE
→ END
Terminated Because: Desired State

Project build transferred to Optical Ops Division

Optical Ops Division insulated from review or technical supervision

Distractions due to project delays, etc.
→ END
Terminated Because: SYSTEMIC LEVEL RISK

Solutions

Remember the mission during crisis (from Allen Report)

Criteria Pass Status Validated

Challenging projects usually include periods of crisis in cost or scheduling. Mission Assurance must be maintained as the primary goal.

QA limitations

QA limitations at Perkin Elmer

QA not allowed access to metrology

QA reported to Operations - not independent of production pressure
→ END
Terminated Because: Other causual paths more productive

QA personnel inexperienced
→ END
Terminated Because: Other causual paths more productive

QA limitations at NASA

QA management system gap: not identified, questioned

DCMC added to project after primary mirror had been ground
→ END
Terminated Because: Other causual paths more productive

Images experienced spherical aberration (blurry)

Marginal focal point different location than paraxial focal point

Could not adjust settings to compensate

Degree of error too great for adjustment
→ END
Terminated Because: Other causual paths more productive

Parabolic attributes determine focal points for the mirror
→ END
Terminated Because: Other causual paths more productive

All points on the mirror need to focus in the same place
→ END
Terminated Because: Other causual paths more productive

Primary mirror ground "too much flattened away from the mirror's center"

Conic constant design parameters = -1.0022985
→ END
Terminated Because: Desired State

Conic constant as-built parameters = -1.013236

Error in grinding the mirror

RNC was 1.3 mm too far away from the mirror

Measurement occurred from top of the field cap, not the top of the rod

Anti-reflective paint on field cap damaged

Storage method of field cap?

Durability of paint allows for eventual chipping

Field cap material reflective

Unaware that reflection was from field cap and not measurement bar

Light reflected off of field cap, not top of bar

Management of Change failure

Spacers added to measuring rod system

Could not adjust measuring rod
Connects To: f Measurement occurred from top of the field cap, not the top of the rod

Addition of spacers triggered MRB requirement
→ END
Terminated Because: Desired State

No evidence that MRB was ever held

No secondary verification was performed on RNC position

Used a fixed length rod to measure proper distance
→ END
Terminated Because: Desired State

Rod fitted with a field cap

Wanted to ensure consistent accurate fit into measuring device
→ END
Terminated Because: Desired State

Top of field cap thickness = 1.3 mm
→ END
Terminated Because: Desired State

Reflected light used to set distance from top of bar
→ END
Terminated Because: Desired State

Multiple cycles
→ END
Terminated Because: Desired State

Mirror polished based on measurements from Reflective Null Corrector (RNC)

RNC designed especially for this project

RNC as designed provided greater precision
→ END
Terminated Because: Other causual paths more productive

Previous method of test (Refractive Null Corrector) deemed insufficient
→ END
Terminated Because: Other causual paths more productive

Measuring device needed to test the aspheric attributes

RNC converts the aspherical image back to spherical
→ END
Terminated Because: Other causual paths more productive

Spherical images are more easily testable by opticlans
→ END
Terminated Because: Other causual paths more productive

Mirror design = aspheric

Aspherical mirrors produce higher quality images
→ END
Terminated Because: Other causual paths more productive

RNC output was the sole data considered during manufacture

Solutions

Identify and mitigate risk (from Allen Report)

Criteria Pass Status Validated

The Project Manager must make a deliberate effort to identify those aspects of the project where there is a risk of error with serious consequences for the mission. Independent testing should be included to ensure that cost and schedule issues do not interfere with risk mitigation.

2 other measuring devices correctly identified the error
→ END
Terminated Because: Desired State

Auxiliary measuring device data was discounted

Auxiliary measuring devices were not certified

By design, RNC was to be the sole measuring device

RNC had been 'certified' although there is no documentation of this

Solutions

Understand the accuracy of critical measurements (from Allen Report)

Criteria Pass Status Validated

The Project Manager must understand the accuracy of critical measurements. Terms such as "certified" and "not certified" need to be clearly defined with respect to critical measuring devices. Equipment that directly impacts flight hardware must be classified as such. Accurate records must be kept and audits conducted to ensure completeness. Key decisions, test results, and changes must be adequately documented.

RNC was a more precise measuring method
→ END
Terminated Because: Other causual paths more productive

NASA agreed to the plan to use a single certified measuring device