Report of the Hubble Space Telescope Senior Review Panel
Submitted March 28, 2014

ABSTRACT

The Hubble Space Telescope (HST) Senior Review Panel conducted site visits at the Space Telescope Science Institute (STScI) and the Goddard Space Flight Center (GSFC) from March 10 – 13, 2014. Both institutions were cordial hosts. Their briefings to the panel and responsiveness to our questions were thorough, informative and transparent. The findings and conclusions contained in this report represent a consensus of all panel members. The panel's impressions of the current state of the Hubble Observatory were very positive. Following the major overhaul of the spacecraft and the introduction or repair of four state-of-the art scientific instruments during Servicing Mission 4, Hubble is operating at or near the highest level of performance and scientific productivity in its history. Its stakeholders have been generous in their financial and moral support of Hubble over the years. The scientific return to the American people per dollar spent on Hubble is higher today than it has ever been. The collective brainpower of the worldwide scientific community that openly competes to utilize Hubble is responsible for extraordinary scientific gains that would not have been envisioned even a decade ago. We find no evidence that this trend of frontier-bending scientific achievement is likely to falter anytime soon. The GSFC/STScI operations staff has undergone a factor-of-two reduction in size over the past decade while maintaining or enhancing the efficiency of their functions. Hubble operations have become very cost-effective. Expert statistical analyses of the projected lifetimes of Hubble subsystems indicate that the spacecraft and its instruments can reasonably be expected to continue to operate at a high level for the foreseeable future – likely to 2020 and beyond. The large oversubscription in scientific demand for observing time on Hubble, indicates that there remains far more important and exciting science to be done than the observatory can accommodate. If appropriately funded, the Hubble observatory will in all likelihood continue at its present level of achievement and productivity for years to come. The Senior Review Panel strongly and unanimously recommends its continued long-term operation

FINDINGS AND CONCLUSIONS

1. Hubble remains a critical facility in advancing our knowledge of the cosmos. Hubble continues to expand the frontiers of astronomy and astrophysics and addresses the strategic objectives of the Decadal Review and the Astrophysics Division Roadmap.

2. Hubble is currently at or near its peak in terms of scientific impact, data quality and productivity. It is returning exceptional value to the U.S. taxpayer for the dollars invested and is likely to continue doing so for the foreseeable future. We see the continuation of HST for the next few years at its present level of capability as a highly cost effective investment in NASA's astrophysics portfolio.

3. New observing techniques and dramatic increases in calibration precision are enabling scientific investigations with Hubble that would have been inconceivable a decade ago. These include measurement of the Hubble constant to 1% precision and the associated determination of the dark energy density parameter, w; and the detection of water vapor in the atmospheres of transiting exoplanets.

4. Demand for Hubble observing time by the global astronomical community continues at a very high level and it is expected to remain so for the foreseeable future.

5. The Hubble spacecraft and its scientific instruments are in excellent operating condition, and are projected to function well for many years. The current suite of instruments is reaching its peak productivity.

6. Impressive improvements in operational cost efficiency were achieved during the "prime" phase of the post-SM4 mission. Operations manpower has been reduced to a level approximately one half of what it was a decade ago. Most notably the Space Telescope Control Center at Goddard has transitioned from full-time, 24/7 staffing, to a highly automated mode with 8/5 staffing, and the planning and scheduling functions at STScI have been similarly streamlined. The GSFC/STScI operations staff is to be commended for being responsive to budgetary pressures and maintaining the functionality and efficiency of a legacy ground system. We are confident that the project will continue to demonstrate excellent stewardship in pursuing additional efficiencies.

7. In the brief span of this review we were unable to determine reliably additional areas where efficiency could be significantly improved. Identification of any further reductions that would clearly not adversely affect scientific quality or productivity would require a more in-depth study. There seem to be some areas where continuous process improvement might be possible. We believe savings realized in this way are likely to be small.

8. The scientific productivity of HST has been due not just to the remarkable capabilities of the observatory, but also to the consistent and adequate funding of the general observers and archival researchers. We believe the STScI has demonstrated good stewardship in administering this program. We applaud and strongly endorse the project's determination to maintain this precious resource. We would recommend that before any significant cuts to the GO/AR funding are contemplated, further attention be given to additional efficiencies throughout the program.

9. HST is unique in its ability to inform and inspire the public about humanity's place in the universe. The committee is impressed by the important public engagement work that HST EPO has done over the years, and expresses its support that resources be programmed that allow that work to continue at STScI.

In conclusion, the panel was very impressed with the strong evidence that, if the HST program is appropriately funded, the Hubble hardware will enable a highly productive observatory for many more years, and there are scientifically compelling reasons to do so. Further, we recognize that the community's next flagship program, JWST, is not without risk. In the interest of prudent stewardship of the nation's investment in NASA's astrophysics program, it would not be wise to terminate the HST program, nor to significantly diminish its performance capabilities, until JWST is fully operational. The Senior Review Panel strongly and unanimously recommends the continued long-term operation of the Hubble Space Telescope observatory.

BASIS FOR FINDINGS

1. **Hubble remains a critical facility in advancing our knowledge of the cosmos. Hubble continues to expand the frontiers of astronomy and astrophysics and addresses the strategic objectives of the Decadal Review and the Astrophysics Division Roadmap.**

2. **Hubble is currently at or near its peak in terms of scientific impact, data quality and productivity. It is returning exceptional value to the U.S. taxpayer for the dollars invested and is likely to continue doing so for the foreseeable future. We see the continuation of HST for the next few years at its present level of capability as a highly cost effective investment in NASA's astrophysics portfolio.**

3. **New observing techniques and dramatic increases in calibration precision are enabling scientific investigations with Hubble that would have been inconceivable a decade ago. These include measurement of the Hubble constant to 1% precision and the associated determination of the dark energy density parameter, w; and the detection of water vapor in the atmospheres of transiting exoplanets.**

The Hubble Space Telescope has been exploring the universe for 24 years and remains a key facility in advancing our knowledge of the cosmos. Historically some of Hubble's great accomplishments include: resolving Cepheid variables in external galaxies which led to a determination of the Hubble constant to 10%, imaging of proto-planetary disks and the identification of thousands of galaxies in the Hubble Deep Fields, precipitating a revolution in our understanding of galaxy evolution.

In 2009 the crew of the Space Shuttle Atlantis installed two new instruments onboard HST, the Cosmic Origins Spectrograph (COS) and the Wide Field Camera 3 (WFC3), and they repaired two instruments, the Advanced Camera for Surveys (ACS) and the Space Telescope Imaging Spectrograph (STIS). They also replaced a Fine Guidance Sensor, six gyroscopes, the instrument command and data handling computer and six batteries. The new instruments and upgraded spacecraft systems have performed superbly, allowing Hubble to remain at the forefront of astrophysical research.

Quantitative metrics – namely refereed scientific publications based on Hubble observations – demonstrate conclusively that the latest servicing mission has left HST in its most scientifically capable state since launch. Publications continue to increase every year, and by multiple metrics HST is the most significant observational facility in astronomy. Further, HST data archive metrics demonstrate the continuing and lasting value of Hubble results to the entire worldwide

astronomical community. Downloads from the archive now greatly exceed the data ingest rate from new observations, indicating that the value of even older HST data remains paramount.

Some recent highlights from Hubble observations include the following:

The CANDELS program (Cosmic Assembly Near Infrared Deep Extragalactic Redshift Survey) has used the WFC3 and the Advanced Camera for Surveys to detect 250,000 galaxies in the redshift range z=1.5 to z=8, encompassing a range in look-back time from about 8.5 to 13.0 billion years in a universe that is 13.8 billion years old. This includes the discovery of the most distant spectroscopically confirmed galaxy with z=7.51 and a population of star forming galaxies at z=1.7

The Panchromatic Hubble Andromeda Treasury (PHAT) program is surveying the northeastern quadrant of the Andromeda galaxy, M31, in the UV, IR and optical with the WFC-3 and Advanced Camera for Surveys. PHAT has made > 1 billion photometric measurements of > 150 million stars. This survey requires astrometric and photometric calibration far beyond that needed for previous programs, and has pushed the instruments to their limits.

A new program is underway to measure the Hubble constant (H0), the rate at which the universe is expanding at the present time, to a precision of 1%. The Hubble constant is currently known to 3%, largely due to observations by HST. However, improving the precision to which H0 is known will allow a tighter constraint on the dark energy equation of state density parameter, w. This will be achieved through a newly developed WFC3 spatial scanning mode, which will make it possible to measure the relative positions of stars to within 40 micro arc-seconds (millionths of an arc second). This in turn will allow for accurate parallax (distance) measurements for stars out to 1 to 8 kpc (3200 to 26,000 light years) within our Milky Way galaxy, including many long period classical Cepheid variable stars. An improved accuracy in our knowledge of the distance to these “standard candle” Cepheids lays the foundation for a more accurate calibration of other “standard candles” that can be observed to far greater distances out across the universe, such as Type Ia supernovae.

Never within the dreams of the people who originally conceived of Hubble many decades ago was the fact that Hubble would be used to detect and characterize the atmospheres of planets around other stars. Hubble was the first observatory to detect an organic molecule (methane) in an exoplanet atmosphere. Hubble has now detected water in the atmospheres of two transiting exoplanets, HD209458b and HAT-P-1b, using the WFC3 spectroscopic grism and the same spatial scanning technique developed originally the for the high precision parallax measurements described above. In this case, the scanning mode enables very high signal-to-noise spectroscopy of the 1.4-micron water vapor absorption bands.

It is quite extraordinary for a piece of highly technical space hardware to become significantly more capable and productive with increasing age. Yet both summary metrics and also specific case studies (as above) show quite conclusively that this is the case with Hubble.

4. **Demand for Hubble observing time by the global astronomical community continues at a very high level and it is expected to remain so for the foreseeable future.**

The panel reviewed the statistics for the demand of Hubble observing time over the last 10 cycles. The demand remained broadly constant and certainly does not show any downward trend. In fact, the average over-subscription in orbits increased from ~5 in the five cycles before the servicing mission 4 (SM4) to ~7 in the five cycles since SM4, perhaps as expected due to the significantly increased capabilities of the observatory. These steady over-subscription rates are among the highest recorded at any major ground- or space-based observatory. HST remains in high demand as an observatory enabling forefront science.

The panel notes that the retrieval of archival data has doubled since SM4 and continues to increase. Correspondingly, the number of publications from archival research is continuously increasing, now roughly matching the number of publications from General Observer (GO) programs. The latter is happening despite the number of publications from GO programs steadily increasing as well, although at a slower rate.

5. **The Hubble spacecraft and its scientific instruments are in excellent operating condition, and are projected to function well for many years. The current suite of instruments is reaching its peak productivity.**

In 2013 the NASA Engineering and Safety Center (NESC) conducted a 6- month review of the projected probable lifetimes of Hubble's spacecraft subsystems and scientific instruments. The NESC is an independent organization within NASA established after the Columbia tragedy to bring to bear the best expertise from across the Agency on critical engineering and safety problems regarding NASA's most important missions. The NESC is empowered to draw upon the staffs of all 10 NASA field centers, as well as academia and industry, in putting together "tiger teams" to focus on specific problems. In the case of the independent assessment of Hubble failure probabilities, the NESC team consisted of over 20 experts drawn from six NASA centers.

The probabilities calculated for Hubble's subsystems and instruments indicate a high likelihood that the observatory can continue doing science as it is today at least until 2020, though admittedly with the possibility of reduced observational efficiency in some failure scenarios. The projected normalized reliability of all four science instruments exceeds 85% out to about 2021. The normalized reliability of all the critical subsystems, except the Fine Guidance Sensors and Fine Guidance Electronics exceed 80% out to 2021. The latter two subsystems have projected reliabilities in excess of 75% to 2021.

We appreciate the expertise of the NESC in providing an independent assessment of the lifetime that can reasonably be expected for Hubble, on which our conclusions are in part based.

There are no single-point failure modes on Hubble that could take down the entire observatory. It has ample redundancy. Planned mitigations for numerous possible sub-system failures or degraded performance have been developed in advance via the project's Life-Extension Initiatives campaign. Hubble will likely degrade gracefully, with loss or degradation of individual science instrument modes and individual sub-system components. It is under such circumstances that it becomes imperative to retain highly qualified and experienced engineers and scientists who, if past space observatories (OAO, IUE, FUSE, et al.) are any guide, will become ever more clever in mitigating problems, enabling Hubble to proceed with world-class scientific research.

Of course there are no absolute guarantees in this business. But we're encouraged with how nearly perfectly the observatory continues to operate nearly five years after it was last serviced. One of six gyros finally failed on March 6, 2014, nearly five years after Servicing Mission 4. Gyros have been treated as "consumable" components of Hubble's Pointing Control System over the years, and this loss of Gyro 5 was surprising only in how long it took to occur. Hubble could continue to do world-class science with only one gyro.

6. **Impressive improvements in operational cost efficiency were achieved during the "prime" phase of the post-SM4 mission. Operations manpower has been reduced to a level approximately one half of what it was a decade ago. Most notably the Space Telescope Control Center at Goddard has transitioned from full-time, 24/7 staffing, to a highly automated mode with 8/5 staffing, and the planning and scheduling functions at STScI have been similarly streamlined. The GSFC/STScI operations staff is to be commended for being responsive to budgetary pressures and maintaining the functionality and efficiency of a legacy ground system. We are confident that the project will continue to demonstrate excellent stewardship in pursuing additional efficiencies.**

This critical portion of the HST operations support has benefited from a joint exercise in continuous process improvement conducted as a team effort by personnel at GSFC and STScI stretching back at least 15 years. The results of this effort have been a marked decrease in personnel required to conduct these activities with a simultaneous increase of HST observing efficiency from the initial target of 35% to approximately 50%. This is all the more impressive when one realizes that in the period immediately following HST launch it was questionable whether a sustained 35% would be achievable.

Over the years a suite of software tools was developed to both ease the preparation of observing proposals and to improve the long- range planning, in order to present the schedulers a pool of observations from which they can build an efficient schedule for each week's activity. At the same time this team maintained the process for response to schedule changes driven by targets of opportunity, observations initiated with Director's Discretionary Time, and last-minute changes by observers to optimize science. Similarly impressive economies have been achieved in the areas of spacecraft monitoring and communications management without any apparent risk to either scientific productivity or spacecraft health. Automated operations have allowed staffing of this function to be reduced from 24 hours 7 days a week to 8 hours 5 days a week by implementing computer monitoring of critical telemetry points and instant text messaging to virtually the entire operations team when any telemetry exceeds pre-set limit violations. The system is sophisticated enough to allow judgment to be exercised as to whether the violation needs urgent attention, or can wait until normal working hours to be addressed. The instant messaging enables much faster and more widespread communication within the project, than the old-fashioned telephone calling trees used previously.

At the present time, each week of HST operations serves 53 principal investigators and contains 138 target visits encompassing 900 to 1000 separate exposures. Every activity must be completely specified in advance, step by step in a unique command load for the onboard computers which is uplinked each day. On very rare occasions, Hubble places itself into a safe mode, until the operations team on the ground can assess some on-board anomaly. This has happened only twice since Servicing Mission 4. The planning and scheduling teams have become very proficient in re-intercepting the science observation time line with new command loads that minimize losses of science data and observing time, following resolution of an anomaly. The project is to be commended for achieving this overall remarkably high level of efficiency in virtually all aspects of operations, and the corresponding improvements in science productivity, with a far smaller staff size than ever before.

7. **In the brief span of this review we were unable to determine reliably additional areas where efficiency could be significantly improved.**

Identification of any further reductions that would clearly not adversely affect scientific quality or productivity would require a more in-depth study. There seem to be some areas where continuous process improvement might be possible. We believe savings realized in this way are likely to be small compared to those achieved previously.

In addition to the proposal, supplemental materials were made available to the panel: the organization chart of both GSFC/HST and STScI, the high level work breakdown of the project (for both GSFC and STScI), the full Work Breakdown Structure (WBS) for the STScI, the WBS dictionary providing the content of each work package, and the detailed FTE breakdown associated with each work package. Further, the project manager at GSFC and the project lead at STScI openly answered all the panel's questions on these documents. The panel had the opportunity to question on site, during two full days at GSFC and STScI, the various group leads. The panel was impressed by and grateful to the project for the displayed transparency and for having readily provided the panel with the information necessary to identify any potential improvements in efficiency.

Some areas within the Hubble project were identified as places where the potential for further increase in efficiency could be investigated, but in these cases the following caveats apply. Given the short time that was available to the panel, we cannot guarantee that higher efficiencies could truly be realized in these areas, nor can we reliably evaluate what the impact on science would ultimately be if changes were made. The panel stresses that none of the identified areas is likely to produce large amount of savings compared to those already realized over the last five years. The overall operations at GSFC and STScI appear already lean to the panel. The current Hubble mission is certainly perceived by the panel as providing an excellent return on investment, with operation costs not higher than those for the largest ground-based observatories (ESO, ALMA). Given the complexities of operation of a low earth orbit satellite, it is a true testament to the cost-cutting measures of the HST leadership that the current operations cost is comparable to major ground facilities.

8. **The scientific productivity of HST has been due not just to the remarkable capabilities of the observatory, but also to the consistent and adequate funding of the general observers and archival researchers. We believe the STScI has demonstrated good stewardship in administering this program. We applaud and strongly endorse the project's determination to maintain this precious resource. We would recommend that before any significant cuts to the GO/AR funding are contemplated, further**

attention be given to additional efficiencies throughout the program.

Throughout the HST mission the observatory's user community has received significant financial support for HST science data analysis and interpretation, and dissemination of the results. HST datasets can be large and complex, and this financial support has been key in bringing in-depth HST research findings and discoveries forward to the science community and general public in a timely manner. In FY14 roughly 1/3 of the HST operating budget is distributed to the HST user community as such support. NASA and the HST project are to be commended for supporting the analysis of both new HST data in the General Observer (GO) program, and older data in the Archival Research (AR) program (thus extending the scientific utility and return on investment of these older data). Further, STScI is to be commended for the responsible and transparent administration of these resources. The panel has no doubt that user community financial support has been important in making HST research more thorough, timely, scientifically impactful, and broadly accessible to scientists and the US taxpayer alike.

During the review the HST Project presented a plan for the continuation of GO/AR user funding for the next several years at roughly the FY14 level (with some modest reductions starting in FY17); the panel appreciates the project's ongoing commitment to it's astronomy community partners in difficult budget circumstances. In subsequent discussion the panel was advised that the scope of HST GO/AR funding is defined by NASA Headquarters, and we strongly support NASA's cognizance in this area as important for program transparency.

Going forward the panel appreciates that significant budgetary pressures in FY15 and out years may lead NASA to consider reducing the scope of HST research grant support. We acknowledge that modest reductions HST GO/AR funding would likely be an acceptable trade against significant loss of HST technical capability, as long as such reductions would leave HST productivity and scientific impact at a high level. The panel would also advise NASA that HST user support will remain critical to a productive mission; in this way we join with the HST Project in supporting a strong ongoing GO/AR program. We would recommend that additional project efficiencies (i.e. Finding 7) be pursued before significant reductions are adopted in the HST GO/AR program.

9. **HST is unique in its ability to inform and inspire the public about humanity's place in the universe. The committee is impressed by the important public engagement work that HST EPO has done over the years, and expresses its support that resources be programmed that allow that work to continue at STScI.**

Although we were not charged to look at the Education and Public Outreach activities at STScI, at our request we received an excellent presentation from several members of the Office of Public Outreach (OPO). Essentially all astronomers are aware of the success of HST outreach efforts, as their effective programs are evidenced in numerous forums. The evidence for the success of this work is clear: an overwhelming fraction of our nation's citizens are familiar with Hubble, a situation unique among NASA's varied space and earth science programs.

The presentation concentrated on how OPO is moving with current trends in media and education, for example, dissemination to mobile devices and touch screen hardware. It is clear that OPO monitors and effectively responds to these changing trends. They also continue to nurture and improve their mature and proven systems such as *ViewSpace*. The ubiquity of broadband connectivity throughout the US, even to quite rural areas, now permits any institution with a basic computer and monitor to receive and autonomously display instantaneously-updated content that is completely equivalent to that available to the most sophisticated science museums.

In summary, OPO continues to evolve with changing media technology. Hubble's hugely significant contribution to public science literacy and enthusiasm is largely due to STScI OPO and its government partners. It stands as a clear example of the effectiveness of imbedding outreach directly within the science program. We urge continued support of this extremely valuable part of the HST program.

REVIEW PROCESS

The 2014 HST Senior Review Panel was composed of:

- A. Boden – California Institute of Technology, Palomar Observatory -- co-chair
- D. Leckrone – Goddard Space Flight Center (retired) – co-chair
- R. Humphreys – University of Minnesota
- M. Kissler-Patig – Gemini Observatory
- B. Margon – University of California at Santa Cruz
- R. Milkey – American Astronomical Society (retired)
- A. Prestwich – Chandra X-Ray Science Center, Harvard/Smithsonian Center for Astrophysics
- A. Trivelpiece – Oak Ridge National Laboratory (retired)

Preparatory Material – Project Proposal

As context for the panel work, roughly three weeks before the panel convened in Baltimore NASA provided us with the SR proposal submitted by the HST project. That proposal did an excellent job of summarizing HST's recent history, scientific accomplishments, and impact; scientific prospects going forward (and how those prospects are traceable to the Decadal Survey and NASA Astrophysics Roadmap); observatory operations, and project budget. This proposal served as the initial basis for the panel work, and the HST project is to be commended for providing the complete and articulate program summary contained in the proposal.

NASA Charge – P Hertz

During the morning session on 10 March NASA Astrophysics head Dr. Paul Hertz addressed the panel, summarizing the state of the 2014 NASA Astrophysics Portfolio, and issuing the review charge to the panel. Dr. Hertz' review charge summary to this panel is presented here for completeness:

- Perform an assessment that includes
    - scientific merit and expected science return
    - how the science addresses the strategic objectives
    - effectivness of the observatory and science center in enabling new science, archival research, and theory
    - any obvious technical obstacles in the next two to four years
    - overall quality of observatory stewardship

- Provide any relevant recommendations that would enhance the science return of the mission within its available resources

- Provide any relevant recommendations that would reduce the operation cost with acceptable impact on the science return
    - aspects of operation and stewardship that do not provide good return on investment
- Identify PMOs and other proposed activities/goals that would be appropriate metrics at the next review.

- Make a recommendation on whether or not to extend the mission

Unique to the charge to the panels reviewing the two Great Observatories, Hubble and Chandra, (relative to other panels within the 2014 Senior Review process) was the instruction that the FY15 and FY16 project allocation had been set by NASA, and Senior Review input was solicited primarily on project priorities, responsiveness to the difficult budget situation, and whether additional efficiencies were apparent that might reduce costs with "acceptable" impacts on operations.

The afternoon of 10 March the project briefed the panel. The panel briefing covered material on HST science, operations, and management. Representatives of all major HST project elements were in attendance, and discussions were open and cordial.

On Tuesday 11 March the panel visited the HST Operations facility at the Goddard Space Flight Center (GSFC). The panel received briefings on GSFC HST Operations from GSFC personnel, and toured the Mission Operations Center, Mission Support Center, and the GSFC-resident ground system support facilities. All the facilities appeared in excellent condition, and discussions were open, cordial, and thorough.

The morning of 12 March the panel visited with several groups from the Space Telescope Science Institute (STScI). Included in our tour of STScI were presentations and discussions with HST User Support, and Long- and Short-Range Planning Teams; the HST Instrument Support Group; the Mikulski Archive for Space Telescopes (MAST – which manages data ingest, calibration pipeline, and user data access for HST), and the HST/JWST Education and Public Outreach Team. These visits were pleasant, informative, and cordial – the panel acknowledges and appreciates the hospitality and transparency of the various teams in these discussions.

At both Goddard and STScI the panel posed some questions designed to penetrate more deeply into the details of staffing levels and budgets. While there was the possibility that such queries might be interpreted as "hostile," the GSFC and STScI staffs representing the HST project were invariably cordial, professional, and

transparent. We thank them for their helpful spirit, and constructive engagement in and support for this review.

For the afternoon of 12 March and morning of 13 March the panel met in Executive Session to discuss the panel's perceptions, reactions, and findings. After considerable discussion the panel came to a high degree of unanimity on its conclusions, and briefed NASA HQ the afternoon of 13 March on its consensus findings.

RECOMMENDATIONS FOR THE CONDUCT OF FUTURE REVIEWS

Given the scope, complexity, and longevity of the HST mission the panel members felt that the review process could be fine-tuned to improve the panel's insight into critical areas and to limit the impact of the review preparation on the project. While such reviews are frequently beneficial to the party being reviewed, they do produce a substantial impact, one that can divert effort from other productive activities. For a mission with as high a profile and long-term stability as HST, it would seem that the review process could be narrowed to take advantage of both of these factors.

In fact, a two-year cycle for reviews appears to be too frequent for a Great Observatory with these characteristics. At least, this is the case in the absence of major changes to the operational status of the observatory resulting from failures on board the spacecraft. However, as it may be required to conduct such reviews on a two-year cycle, we offer the following suggestions to improve the efficacy of this process.

In the absence of major changes in observatory performance or resources alternate reviews should be considered as "delta" adjustments on the prior review. Attention should be focused on any areas that were identified as areas of interest by the prior review. And the specific elements of the charge to the panel could be adjusted as follows

1. *Assess the scientific merit and expected science return of HST*. This should be visited each meeting, however, given the profile of HST in astrophysical research it should be expected that the panel will have familiarity with the science produced by HST and the discussion could focus more on future capabilities and risks than on summarizing the present state of affairs.
2. *Review how the science produced by HST addresses the strategic objectives of the Astrophysics Division.* In the absence of revisions to the documents defining these objectives this topic could be omitted from the "delta" review cycle.
3. *Assess the effectiveness of HST and its associated operations center and infrastructure in enabling new science, archival research, and theory.* In the "delta" review cycle this area should focus on changes from the previous

review. Given the longevity of the mission and the substantial resource provided by the HST archive, we do not expect this to change rapidly.

4. *Assess the effectiveness of the science and mission operations processes, and identify any obvious technical obstacles to achieving HST's science objectives in the next two to four years*. This area should be visited in detail in each review, but with concentration on only those areas which are identified by the management teams of STScI and the Project at GSFC as risks to the science program. By doing so, the review will be able to give a much more detailed assessment of the impact of such risks, should they be realized, as a guide to management's response.
5. *Assess the overall quality of observatory stewardship, and review usage of the allocated funds, in light of overall limited financial resources, to maximize science quality, observational efficiency, and return on investment.* Given the complexity and size of the operational support for HST, this is a daunting challenge for a short-duration review. We suggest that areas of concentration could be selected for each review to allow more in-depth understanding by the review panel.
6. *Provide any relevant recommendations that would enhance the science return of the mission within its available resources.* This is similarly a challenge for any review panel for the same reasons. Taking that into consideration, we suggest that within the scope of the "delta" reviews this be concentrated on those areas identified as being of such interest by prior reviews.

In the presence of major changes in observatory performance or resources, the review should be entirely concentrated on the impact of those changes and the plans to maximize the science return from both the observing program and the archival program.