2022 Astrophysics Senior Review
Hubble Space Telescope

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PANEL

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EXECUTIVE SUMMARY

HST continues to be a scientific powerhouse, unique in its breadth and depth; it enables cutting edge science across the entire landscape of astrophysics and

planetary science. The key intellectual role of Hubble and its archive, delivering discoveries at the frontiers of knowledge, is reflected in its exceptional productivity (at the rate of over 1000 papers/year; over 19,000 since launch). The GO/AR/TH grant program is a vital component of the scientific success of Hubble and is the driver for discovery.

The project performed admirably and delivered excellent science and seamless operations in spite of the unprecedented challenges of the pandemic. Prompt responsiveness to spacecraft instrumentation technical issues, and proactive efforts to extend its lifetime, have maintained the health of the mission during the review period.

HST continues to be exemplary in terms of education and public outreach, with press releases, stunning images, and other legacy products that have an unparalleled and broad impact in society.

The HST project is actively and successfully improving diversity, equity, access and inclusion in the profession, principally with its introduction and continuation of the Dual Anonymous Peer Review process for time allocation on Hubble. Pioneering this intervention, and demonstrating its impact, the HST project has catalyzed adoption of it across other NASA facilities and beyond.

HST is expected to continue its leadership role - befitting a great observatory - in the proposed period, providing synergy with the James Webb (JWST) and Roman (NGRST) Space Telescopes , and other NASA missions through its unique ultraviolet (UV) capabilities. HST's capabilities are vital to addressing most of the key scientific questions identified by the Astrophysics Decadal 2020 report.

The scientific impact of HST and its archive is expected to remain excellent during the period 2022-2027, provided that operations and investigator support are funded at the level of the proposed over-guide budget and that the observatory and its instruments stay healthy. The in-guide budget would severely undermine the scientific return from the observatory.

Looking forward, as HST ages, community stewardship and broader community engagement have to inform a fundamental shift in approach in order to maximize innovative scientific usage of the facility during a contingency event of catastrophic failure and or gradual degradation. This will enable harnessing the collective wisdom of the broader community beyond the currently acknowledged stakeholders (investigators that are awarded time) and, in preparation for failures,

help address and tackle needs beyond the immediate horizon.

In this spirit, the senior review committee recommends the following studies be conducted with wider community involvement, and the results be made available to the next senior review committee, with the goal of maximizing scientific return of the mission:

1) An external analysis of possible changes to the operation model to further optimize the science return per dollar
2) An external process to imagine the future of Hubble both in terms of operations and scientific capacities in case of major hardware failures

The committee also strongly recommends that NASA preserves long term dedicated grant support for archival work even in the event of a complete loss of the spacecraft.

ADJECTIVAL RATING FOR SCIENCE MERIT: **Excellent**

ADJECTIVAL RATING FOR RELEVANCE & RESPONSIVENESS: **Excellent/Very Good**

ADJECTIVAL RATING FOR TECHNICAL CAPABILITY AND COST REASONABLENESS: **Very good**

OVERALL ADJECTIVAL RATING: **Excellent/Very Good**

Introduction

The scientific impact of HST and its associated archive have fundamentally transformed our understanding of the near and far Universe, from the earliest galaxies to exoplanets to bodies in the solar system. One metric to quantify its remarkable impact is citation indices: both by number of citations and intellectual influence of its papers, HST continues to rank as an unrivaled science machine.
Despite its age, the suite of instruments on HST continues to provide unparalleled access to the ultraviolet and blue/optical region of the electromagnetic spectrum

with a telescopic aperture far larger than on any other current NASA operating flight mission. The project and the scientific community have leveraged these unique capabilities to initiate various UV Legacy programs (e.g., ULLYSES) that will create an extensive archive that will enhance the impact of the mission long after operations have been suspended. The scientific use of HST archival data continues unabated on a steep trajectory, with roughly ~1000 papers published per annum, of which more than 60% rely on archival data. This growing community uses and mines the Hubble archive, through its enhanced interfaces and high level data products.

Science relying on HST has helped Nobel Prize teams in the past; and it is proving to be pivotal in revealing the existence of a new crisis in cosmology wherein multiple methods to provide precision measurements of the Hubble constant are presently in tension. Continued study in these fields, combined with upcoming JWST observations, will undoubtedly open up new discovery frontiers.

Hubble's discoveries and the visually arresting images it captures are extremely well communicated to a global audience. This deep and continuing engagement with the public has strong returns on investment in terms of public support of NASA's exploration portfolio. HST has captured the imagination of the younger generation of STEM learners; it has advanced science literacy and informed the public imagination on our current understanding of fundamental questions of our role and place in the Universe.

CRITERION A: SCIENTIFIC MERIT

Factor A-1: Overall scientific strength and impact of the mission.
Factor A-2: Expected scientific output and science productivity given the costs over the requested funding period.
Factor A-3: Quality of data collection, archiving, distribution, and usability.

A1:

Strengths:

Major: Hubble continues to be an extraordinarily productive science mission. It is producing high impact results in virtually every area of astronomy, including many unexpected ones. This is a major achievement for a 32-year old mission and a testament to the versatility of the telescope and instruments; the quality of science and mission operations and user support; the engagement and creativity of the community; and the importance of the GO/AR/TH funding. The panel expects this excellence to continue in coming years, if the spacecraft and instruments remain healthy, and the over-guide budget is awarded to support the mission and external grants.

Major: Recent Science Results — we briefly outline major recent science discoveries and results across domains in astronomy, astrophysics and planetary science.

Solar System — Hubble has provided important scientific opportunities to advance understanding of bodies in the solar system, and is well-aligned with NASA SMD science priorities of exploration and scientific discovery and the strategic objective to further our knowledge of the origin and history of the solar system. Studies of the first interstellar comets, 'Omuama, and 2I/Borisov, tracking of ever-evolving storms and rich atmospheric phenomena in Saturn's and Neptune's atmospheres, and detection of salts on Europa have contributed to the transformation of our state of knowledge in cross-cutting themes at the core of Planetary Science, including building new worlds, planetary habitats, and workings of the solar system. The continuing Outer Planet Atmospheres Legacy (OPAL) program and the production of high-level science products (HLSPs) (e.g., planetary maps) contribute to legacy archives for future mission development and assessment. Hubble has provided observations that enable enhanced return of mission science from NASA assets such as JUpiter ICy moons Explorer (JUICE), acquisition of early ultraviolet observations of Europa and Ganymede ice plumes, the Double Asteroid Redirection Test (DART), affording contemporaneous observation windows for remote sensing experiments of the impactor event, and New Horizons, providing target astrometry for outer Kuiper-belt objects of interest, including Arrokoth. These efforts enhance the impact factor of Hubble as a contributor to the overall portfolio of NASA mission assets that are cross-disciplinary in nature.

Exoplanets — HST continues breaking ground in exoplanet science using its unique UV capabilities. It is worth highlighting that HST UV spectroscopy provides

a powerful tool to constrain models of exoplanet atmospheres and also characterize properties of transiting planet host stars, such as those discovered by TESS. The combination of accuracy and UV spectrophotometry capabilities of HST play a key role in the characterization of exoplanet atmospheres. The observations that form part of the Panchromatic Comparative Exoplanet Treasure (PanCET) will provide a long lasting legacy in this area, providing spectroscopic observations from the UV to the IR permitting current and future studies of exoatmosphere composition and mass loss. Going forward, the combination of UV capabilities from Hubble and the IR capabilities of JWST will continue on this important quest.

Stellar physics — UV spectroscopy provided by HST traces stellar processes such as stellar winds and coronal mass ejections. The on-going ULYSSES program will highly impact our understanding of stellar evolution of young stars over a range of masses and metallicities. ULLYSES data address science topics such as accretion physics in low mass T Tauri stars as well as photosphere and wind characterization in young massive stars. ULLYSES, with its comprehensive library of UV spectra, is a powerful example of HST legacy data, which will allow ample opportunities for archival research, as well as providing templates for studies of integrated stellar populations at high redshifts.

Supernovae - Once again with the on-going interest in the use of supernovae as standard candles, HST has played the defining role in validating the significance of the so-called Hubble tension. The gap between the determination of the Hubble constant from near and distant probes of the Universe now stands at 5-sigma and is calling our fundamental cosmological model into question. The implementation and potential science output of the rapid response ToO has been demonstrated with the observation of the Type II core-collapse supernova SN2020fqv. This innovation has the potential for Hubble to play a key role in time domain astronomy helping track transient phenomena.

Stellar populations and interstellar medium — HST continues to revolutionize our understanding of stars, resolved stellar populations, and the interstellar medium. Impact has derived from studies of stars, star clusters, and nebulae in the Milky Way (Hubble's color portraits of nebulae must rank among its most iconic images – e.g., the pillars of creation in the Eagle Nebula M16) to resolved stellar populations in Local Group galaxies – where individual galaxies are used as laboratories to study groups of stars at a common distance to study the various phases of stellar evolution and the effects of reddening and extinction by

interstellar dust. The facility has provided some of the deepest optical imaging ever obtained of stellar fields in nearby galaxies, allowing us to directly detect stars that are approximately half the mass of our Sun but located as far away as the Andromeda galaxy at ~0.8 Mpc. The tremendous sensitivity, calibration, and precision of the ACS and WFC3 have revolutionized our understanding of our Local Group – its formation, evolution, and future. For example, the Panchromatic Hubble Andromeda Treasury (PHAT), one of the three original multi-cycle treasury programs, produced the largest Hubble mosaic image ever, in six filters ranging from the ultraviolet to the near infrared, and has become a gold standard for stellar population studies. Hubble recently discovered an elusive, free-floating black hole and has tracked the intricate motions of stars in the dense cores of globular clusters. The creative use of the pure parallel mode is permitting imaging the full range of interstellar environments in the Magellanic Clouds while ULYSSES is collecting its reference stellar atlas of UV spectra. The telescope continues to provide observations required to answer critical questions in this field, and requests may well increase as JWST reaches full operations.

Galaxies — The Hubble Ultra Deep Field, the deepest image of the Universe ever taken, revealed a Universe full of beautiful galaxies with intricate internal substructure. This iconic image has been seen by millions of people around the world. Building on this signature achievement, Hubble has continued to push the frontier of galaxy formation in the early Universe out to z ~ 9–10, only ~500 Myr after the Big Bang, and deep into the era of cosmic reionization, thanks to the infrared capabilities of WFC3 and the exploitation of Nature's telescopes - cluster lenses. Hubble will continue to increase the samples of these extremely young galaxies, samples that serve as pathfinders for JWST studies. The ability to probe both the nearby and distant Universe has enabled many scientific breakthroughs. One recent example is that compact star-forming galaxies observed at z ~ 2 were the direct progenitors of compact, quiescent galaxies which evolved into today's giant elliptical galaxies. Closer to the present epoch, Hubble's imaging of the resolved stellar populations of Local Group and Local Volume galaxies has provided great insight into their star formation history, chemical enrichment history, and dynamical/assembly history, and, importantly, the complex interrelationships among these histories. In summary, the facility has revealed the broad arc of galaxy formation and evolution over cosmic time, from the best glimpses to date of the early Universe, to a detailed understanding of the galaxies we see at the present day.

Supermassive Black Holes and Active Galactic Nuclei — HST has revolutionized our understanding of the growth of supermassive black holes by measuring their masses, revealing the properties of their host galaxies, and by offering glimpses of the feeding accretion disks for local AGN. Our current understanding of the accretion history of black holes over cosmic time relies on empirical correlations derived from HST data. This is an area where the synergy with Chandra has been very productive. Recent HST science results pertain to the discovery of black holes in low-mass dwarf galaxies, and the counter-intuitive and puzzling discovery of star formation in the vicinity of these black holes, which are typically believed to inhibit gas cooling and star formation. HST has carried out UV reverberation mapping campaigns revealing new insights into the physics of accretion and of the surrounding broad line region, demonstrating once again the impact of its unique capabilities.

Intergalactic and circumgalactic medium — Hubble's UV spectroscopic capabilities continue to be a vital resource for addressing the question, as posed by the Decadal Survey Astro 2020 panel on galaxies, "How do gas, metals, and dust flow into, through, and out of galaxies?" The capability will remain unique for the foreseeable future and it is a major strength of Hubble. Highlights since the most recent review include the mapping of the CGM of Andromeda, the mapping of diffuse baryonic structures via the CUBS survey, and the current prominence of inflow over outflow in the Milky Way and its effect on the local metallicity.

Large Scale Structure of the Universe — Hubble remains a transformative facility for gravitational lensing studies, and the scientific breakthroughs achieved with observations of galaxy and cluster lenses has greatly enhanced our ability to derive astrophysical constraints on the nature of dark matter and the high redshift Universe. The unknown nature of dark matter remains one of the big open questions in cosmology today. HST observations of individual lenses have provided new insights into the range of inner density profile shapes for the dark matter halos and the amount of substructure, and revealed tension between cosmological numerical simulations and observations. These discrepancies present a challenge for the standard paradigm, and thus could potentially lead to the discovery of new physics. The capabilities of HST for lensing studies will remain unique even with the availability of the new suite of instruments and wavelength coverage offered by JWST and NGRST. HST lensing observations bringing fainter background galaxies into view have served as critical pathfinders for JWST observations of the highest redshift galaxies probing cosmic dawn.

Fundamental Physics and Cosmology — Hubble continues to deliver key results in this area. The so-called "Hubble tension", the tension between the Hubble constant measured in the local Universe and that inferred from early Universe probes extrapolated to present time under standard cosmological assumptions, has been at the forefront of cosmology and it is expected to remain a focal point for the 2022–2025 period. Showcasing its versatility, HST contributes not only via major improvements to the traditional local distance ladder method, but also by enabling high precision strong gravitational time delay measurements, and by playing a crucial role in the identification of optical counterparts to gravitational waves. Hubble provides unique insights into the nature of dark matter via cosmological microlensing and milli-lensing measurements, e.g., by setting limits on the dark matter free-streaming length and on the fraction of dark matter that is composed of primordial black holes.

Weakness: **NONE**

A2:

Strengths:

Major: It is expected that the scientific output and productivity of the mission will remain extremely high over the requested funding period, commensurate with its cost as proposed in the over-guide budget, if the spacecraft and instruments remain healthy. Ensuring sustained funding of the GO/AR/TH programs at the current level is critical to ensuring the expected science returns from HST going forward. Future scientific aspirations for HST are only consistent with the over-guide budget proposal and full funding of the GO/AR/TH grants. Conversely, the in-guide budget would imply a dramatic reduction in scientific output of the mission.

Weakness:

Minor: Hubble's role and leadership in the all-sky, time-sensitive, multi-messenger events domain, a new grand challenge identified in the Decadal Survey Astro2020, is ill-defined in the proposal, yet is alluded to be a new challenge in the FY23–FY27 funding period. Regardless, the in-guide budgetary profile proposed

over the future requested funding period cannot effectively support this new programmatic direction. Moreover, maintaining the current overall efficiency of scheduled operational goals (scheduling efficiencies ~52%) while pursuing the new out year project goal of integrating HST to rapidly respond to gravity-wave event triggers from LIGO-VIRGO-KAGRA and other transient phenomena driven by alerts from platforms like ZTF, Rubin, etc. appears infeasible and unlikely. Further, programmatic strain will be amplified by growing community demand for time-constrained observations (e.g., exoplanet transit requests, currently trending at 20% of all scheduled observations); simultaneous HST-JWST observations, and time-critical NASA mission support. Collectively, the 2022 Science PMO#1 as presented in the proposal opens substantial risk to the integrated science productivity of Hubble operations in a great observatory mode, further illustrating the need for the over-guide budget.

A3:

Strengths:

Major: The Hubble team continues to achieve very high standards in data collection, archiving, distribution, and usability. They have provided a number of novel science-enabling tools and high level data products to the community. This investment has resulted in a continued increase of archival data, with ~60% of the roughly 1000 Hubble-based papers now published each year using archival data. This growing use of the Hubble archive, through its enhanced MAST interface, fulfills the objective of 2019 Scientific PMO#2.

Weakness:

Minor: HST's efforts in the areas of archive and cloud-computing services that will need to integrate into the overall interoperable archive infrastructure architecture currently being developed by NASA SMD were not mentioned within the proposal, including in the Data Management Plan. As use and impact of the archive continues to grow on a steep trajectory, innovation in this area in a coordinated fashion with Agency-wide initiatives will be needed to enhance the distribution and usability of HST data holdings while decreasing costs.

Minor: The impacts of sophisticated open-source theoretical modeling codes, large-scale data science initiatives associated with artificial intelligence efforts utilizing the HST archive as well as other NASA and ground-based archives, and migration of HST pipeline and analysis algorithms development into python environments for broad public utilizations, pose a sustained resource and FTE commitment that was not adequately considered in the narrative of 2022 PMO#3. Collectively, these data science pathways provide a roadmap for innovation in scientific capabilities of HST. The Projects' exploration of engagement balance and leadership, in consultation with a wide community of stakeholders, was not sufficiently discussed. In the future, the inclusion of goals and objectives, combined with limitations of activity and support horizons, would enhance the overall impact of the Data Management Plan and position the Project to more effectively address policy within the evolving NASA SPD-41 directives.

CRITERION B: RELEVANCE & RESPONSIVENESS

Factor B-1: Relevance to research objectives and focus areas described in the SMD Science Plan and the 2020 Astrophysics Decadal Survey.

Factor B-2: Relevance to NASA's core value of Inclusion and alignment to SMD Science Plan Strategy 4.1. Specifically, the quality of plans and likelihood of success for nurturing the diversity of thought and background represented a diverse community and an inclusive environment.

Factor B-3: Progress made toward achieving PMOs in the 2019 Senior Review proposal (for missions included in the 2019 SR). Performance of addressing any findings in the 2019 Senior Review (for missions included in the 2019 SR).

B1:

Strengths:

Major: Hubble continues to provide key insights into the three major scientific themes of astrophysics research: (1) "How does the Universe work?", (2) "How did

we get here?", and (3) "Are we alone?" It is expected to contribute mightily in the proposed period, providing vital synergy with JWST, Roman, and other NASA missions through its unique capabilities. Hubble will also contribute significantly to addressing the key scientific questions identified by the National Academy of Sciences Decadal Survey Astro2020, provided that it stays healthy and the over-guide budget is awarded.

Minor: Other science directorates within NASA SMD have utilized Hubble to enhance the scientific return of flight missions to a variety of solar system bodies, to mitigate risk associated with rendezvous and close encounter navigation, and to advance Planetary Defense through the detection and identification of hazardous populations. In this respect, Hubble supports the broader 2020-204 NASA SMD vision for scientific excellence that relies on creative collaborations to unlock new opportunities while providing inputs for informed risk-taking to improve operations.

Weakness:

Minor: The response to Scientific 2022 PMO#3 provides scant insight into future strategic use of Hubble's capabilities, stating no planning has been forthcoming. For a mature observatory looking forward to the next potential 5 years of operation, one would expect some potential activities to be enumerated, as the Decadal Survey Astro2020 has been public for some time. Pivoting to respond to community aspirations as detailed in the Astro2020 survey will likely require difficult choices, impacting Hubble operations. Optimization planning likely to be required soon needs full engagement of the community.

B2:

Strengths:

Major: Hubble's pioneering development of the dual-anonymous proposal reviews (DAPR) process is an achievement showing progress via concrete action to fulfill the goals of the 2019 Scientific PMO#1. This core restructuring and enhancement of the peer scientific review process dramatically advances NASA's core value of inclusion. Outcomes to date have demonstrated better inclusivity and access in the scientific use of Hubble by new segments of the community (mid-career women and early career scientists). This process was initiated by the Hubble

team, and is being widely adopted by other NASA facilities as well as by NSF and even more broadly by other scientific disciplines. The appointment of a new diversity equity inclusion and accessibility (DEIA) officer into the senior management structure at STScI, with a level of autonomy and ability to drive and guide policy in this area, speaks to the sincere commitment to these important goals. These changes will help incorporate best practices and philosophies into the very fiber of the organization consistent with NASA's new 5th pillar core value. The recent full 360 review of the flagship Hubble Fellowship Program to transform and bring it into better alignment with the goals of equity, access, inclusion and diversity is an important step forward.

Weakness:

Minor: A regular internal audit and sharing of the information on the demographics and diversity of STScI staff, including critical examination of promotion and retention practices is warranted. The aspiration for DEIA extends to and needs to be embraced both internally and externally. It is recommended that this information be made available to the next senior review.

B3:

Strengths:

Major: The 2019 Senior Review identified three Programmatic Prioritized Mission Objectives (PMOs). The Hubble team has performed very well in keeping the observatory healthy and safe (Programmatic PMO#1). Highlighted activities in this area include active monitoring of the spacecraft, telescope, and instruments, anomaly identification and response, updates to operation modes and acquisition algorithms. The Hubble team continues to be proactive in mitigating observatory degradation (Programmatic PMO#2). The movement of the COS far-UV spectra to Lifetime Position 5 is an outstanding example of the mitigation strategies of the Hubble team. This activity alone has extended the lifetime of the COS UV spectroscopy to approximately 2030. The combination of the activities associated with PMO#1 and PMO#2 has kept the scheduling efficiency at a consistent all time high average of about ~52% in the last three years.

Major: The Hubble team made good progress with respect to all the scientific PMOs. The results of the activities associated with these PMOs are reflected in the

outstanding science Hubble continues to achieve, the competitiveness of the science program, the high publication record of Hubble new and archival data, and the overall capitalization on the unique UV capabilities of Hubble and its synergies with other ground based and space facilities.

Weaknesses:

Major: The proposal does not sufficiently describe the implementation of operational efficiencies and cost reduction measures, responding to 2019 Programmatic PMO#3. During the presentations and Q&A sessions, the Project showed that cost efficiencies have been realized as a result of a fixed dollar budget during the 2019–2022 period, and that a budget increase is necessary for Mission Services (Appendix B, 2b), Other Mission Operations (Appendix B, 2c), and Science Operations Functions (Appendix B, 3). Anticipating the next Senior Review, the Project is challenged to more carefully articulate and quantify outcomes assessment against this programmatic goal of implementing operational efficiency at costs that are commensurate with the maximization of community science return. The panel recommends to NASA a full and detailed external review of Hubble operations (both at GSFC and at STScI) to be completed before the next Senior Review, so that its results can be taken into account. A possible outcome of this external review may include a trade off between the operational model and scientific priorities.

CRITERION C: TECHNICAL CAPABILITY & COST REASONABLENESS

Factor C-1: Overall operating cost and cost efficiency of the mission's operating model for proposed scientific goals.

Factor C-2: Health of the spacecraft and instruments, and suitability of the mission's operating model (e.g., governance, science team, instrument team, inclusion, diversity of thought and backgrounds represented) to maximize its scientific return.

C1:

Strengths:

Major: Responses to spacecraft and instrumental glitches in operations have been efficient, expedient, and cost effective to date. The operating model has increased in efficiency due to the fixed budget and inflationary pressure, while continuing to deliver excellent scientific results. During the proposed period, it is noted that the over-guide budget is required to maintain scientific impact and productivity by retaining excellence in operations and support for GO/AR/TH programs. Retaining support for these programs at the current level in terms of purchasing power, with yearly increases to account for non-negligible inflation, is vital to the realization of the discovery potential of the observatory. Funding at the in-guide level would result in a dramatic loss of scientific output.

Weakness:

Major: While some efficiencies have been realized due to inflationary pressure on a fixed budget, the project has not been fully responsive to the recommendation of the previous senior review to examine cost saving measures. The case has been made that operations are efficient within the current model but it has not sufficiently demonstrated that further cost savings cannot be obtained via innovative changes. A full review of the operations is beyond the scope of this committee. However, a dedicated and extensive external review seems necessary to provide a fresh new perspective on the operations. Therefore, as noted above, during the 2022–2025 period, the committee recommends a full and detailed external review of the operations with the goal of further increasing the scientific output per dollar. Having the results of this external evaluation available to the next Senior Review would be very valuable for optimizing the scientific output of the mission beyond 2025.

C2:

Strengths:

Major: The flight and science operations teams have tirelessly and effectively addressed the goals articulated in 2019 PMO#1. The HST is 32 years in space and still operating near its peak capabilities. The GSFC mission operation and STScI science operation continue to execute a superb science program. The science efficiency, when averaged over periods of a month or longer (while excluding

significant anomalies), is as high as it has ever been. The aging spacecraft has suffered some degradations but remains fully capable. Thorough, largely automated trending of engineering data continues to enable early detection of degrading operational modes and permits development of operations workarounds ahead of future potential failures. (Workarounds already exist for a degraded MA transmitter, degraded FGSs and another gyro failure.)

The only single failure that threatens potential loss of science (permanent or long period) is a failure in the currently single-string SI C&DH-Side A. As the original C&DH-A operated for 19 years, and the current Side B hardware operated for 12 years (after first spending 19 years in space), the units have proven highly reliable. The Committee was informed during the presentation and Q&A that there is some potential for a future Side B hardware recovery and was given an estimated development time of 12–18 months – unless perturbed by other problems. The Panel believes that HST may well continue to operate at or near its present high science efficiency for the next 3–5 years, and perhaps much longer. Nevertheless, by October 2023, the probability of continued C&DH-A operation will have dropped to ~78%, so work on the Side B recovery is critically important.

HST mission console staffing was reduced to a 2 staff, 8 hours, 5days/week operation some years ago, and has functioned very successfully. The systems engineering and flight software staff are likewise far smaller than originally envisioned. The current mission operation (MOSES) staff size is significantly smaller than the size independently anticipated by different Project Management personnel more than a decade ago, and should be maintained. The anomalies addressed in 2021 were resolved relatively rapidly (despite very thorough and cautious investigations) because of the size and expertise of the remaining staff. [HST subsystems often demand multiple engineers with complementary (non-redundant) skills. The Pointing Control Subsystem is just one example.] The Panel believes that no staff reduction large enough to significantly reduce the out-year HST Project over-guide requests is tenable unless NASA's risk-tolerance to mission failure is very substantially lowered and HSTs designation as a Great Observatory is abandoned. Still, the Project appears fully committed to achieving economies as they are identified.

Appropriately, the STScI devotes significant resources to scientific instruments (SI) trending, and to detector maintenance and calibration maintenance. Although the electronics of two SIs (ACS and STIS) are single-string, WFC-3 and

COS electronics still have redundancy. Effective measures are being used to address and successfully manage each SI's detector sensitivity and performance. The creation of additional science modes as needed by the community is an important service. The present availability of up-to-date data calibrations and re-calibrations is a commendable improvement over historical practices. Altogether, the science operation at STScI is very broad in scope and provides many services to the user community.

Science planning and scheduling of a low-earth-orbiting astronomical observatory is complex, partly manual and time-consuming. The increase in science efficiency from the original requirement of 30% to ~50% is entirely attributable to the expertise and creativity of the science staff, working both on its own and sometimes in tandem with proposers. Fast turnaround and scheduling of targets of opportunity is challenging. The process improvements STScI has made are highly commendable and responsive to the evolving needs of the community.

However, future community desires may saturate HST's ability to respond and maintain a high level of science efficiency requiring the Project to carefully balance commitments. The future use of one-gyro science mode (to which STScI will transition after the next gyro failure) will place even more demands on planning and scheduling processes and staff (in part because of the reduced instantaneous field-of-regard). One-gyro mode and two-gyro mode are very similar in efficiency and performance. The former will preserve the last gyro for use after a subsequent failure and prolong the science mission.

Weakness:

Major: Future failures and associated long safe-mode periods constitute a potential risk to achieving full observatory science objectives over the next 3-to-5-year period. SI C&DH reliability drops to 78% by the end of FY23 on a single string and this warrants immediate attention. (Reliability is only 40% by the end of FY27.) This has single-point failure potential. Partial recovery of the Side B unit may require 12 to 18 months to fully implement the system fix (including vetting flight software, I&T, etc). Thus, the Observatory could be unable to execute science for an extended period.

Reduced gyro operations will significantly reduce (by about 25%) the current science field of regard, affecting the efficiency of science and mission operations

processes. This operational mode will significantly constrain Target-of-Opportunity scheduling and fast response to time-sensitive science. Further, transition to less-than-three-gyro operations will lower the science efficiency of the mission by about 25% (to ~35% from the current ~50% absolute). It will also limit fast-moving-target science inside the orbit of Mars. Gyro loss is identified as an obvious technical obstacle to achieving the observatory's science objectives as driven by the community.

In light of the above weaknesses, it is recommended that the Project engage the community to prioritize time critical observations that need to happen before potential failures, via director discretionary time or special scheduling initiatives.

Minor: The slow loss of Solar Array output will require additional attention to SI power management and increase mode cycling. This could affect component reliability. Off-nominal roll orientations will be further limited, occasionally impacting guide star availability and science with strict orientation requirements. In addition, loss of a Solar Array panel to meteorite impact would accelerate the need for power management which may degrade science efficiency. The single-string electronics for ACS and STIS – instruments operating on repaired electronics for intervals longer than the operations-hours accumulated prior to the failures addressed and repaired in SM4 – comprise a risk to the breadth of HST's science program. Spectroscopic use of Hubble, especially its unique ultraviolet capability, warrants proactive engineering and operational modalities to be developed as contingencies. Over the next 3–5 years the Project may need to rigorously examine more active management of subsystems, and assess the operations risk more thoroughly to keep the full complement of Great Observatory capabilities robust.

Other potential but unexpected failures might require a significant change in HST's operations profile. For example, loss of an S-band transmitter or an S-band antenna gimbal freeze would sharply affect science data downlink and likely require a significant change in the mission's science data acquisition profile. Although S-band usage and antenna gimbals are trended and were not identified as current high risk items, unforeseen anomalies happen. Advanced planning and broad community input may reap benefits that preserve Hubbles's scientific productivity and observatory's science objectives in the next three to five years even in the event of constricted operations.

ADDITIONAL FINDINGS

In summary, the main conclusions of the 2022 Senior Review of the Hubble Space Telescope, based on careful review of the proposal and subsequent deliberations, are:

1. With its current funding, including that for GO/AR/Legacy Teams, HST is at its maximum rate of scientific return. For HST to continue to function as a Great Observatory and continue to provide cutting edge science returns, the Panel strongly believes that funding for the GO/AR/TH programs needs to be maintained at the current levels in terms of purchasing power (with yearly increases accounting for non-negligible inflation), while also preserving the quality and efficiency of operations within the current model. The over-guide budget is required and recommended.
2. In order to ensure maximal future science returns for the aging HST, the panel recommends that a full and detailed external review of operations at GSFC and STSCI be conducted, with the goal to identify possible innovative changes that could lead to an increased science per dollar value. The panel recommends that the report and findings of this review be included in the materials made available to the next senior review committee to help guide the future of Hubble beyond 2025.
3. The panel recommends setting up an external committee to mine the collective expertise of the larger astronomy community to develop scientific plans for HST in the event of catastrophic instrumentation failures or gradual degradation. The panel strongly recommends the expansion of the stakeholders for this crucial task beyond just the investigators who have scheduled time on HST and staff at STScI. The panel recommends that the report and findings of this study be included in the materials made available to the next senior review committee to help guide the future of Hubble beyond 2025.
4. Hubble is an aging spacecraft. As anomalies continue to increase in frequency and severity, leaving little contingency margin, the committee recommends that the 2022 Science PMOs be expanded to examine what absolute science imperatives ought to be addressed while HST is fully functional. In practice, the panel recommends swift development of science

plans to prepare for potential failures of the spacecraft (e.g. SI C&DH) or instruments. The mitigating actions could include expediting legacy and JWST coordinated programs, introducing appropriate new initiatives as part of the time allocation process, or soliciting ideas for Director Discretionary Time programs.

5. The panel strongly recommends the continuation of healthy and dedicated funding for the AR/Th programs based on Hubble data beyond the life of the spacecraft and its instruments.