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# Report of the Ultraviolet and Visible Sensors Panel

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## INTRODUCTION

The Ultraviolet and Visible Sensors Panel was originally chartered to review the advanced technology developments required for the wavelength range from 0.1 to 2.5 microns for astrophysics missions in the first part of the twenty-first century. The initial discussions of the panel centered on the designated wavelength range. It was agreed that the panel's considerations should be extended to cover the wavelength range from 0.01 to 0.1 microns in order to overlap with the deliberations of the X-ray and Gamma Ray Sensors Panel and not leave a gap in the extreme ultraviolet (EUV) spectral region at wavelengths below 0.1 microns. It was also decided, for reasons based on differing science goals and technologies, to split the wavelength range up into three domains; specifically, 0.01 to 0.3 microns, 0.3 to 0.9 microns, and 0.9 to 2.5 microns. A consensus was reached on the performance requirements and recommendations for technology development in all three wavelength ranges, as described in the next three sections of the report.

## 0.01 TO 0.3 MICRONS

### A. Technology Assessment

One of the primary requirements in the 0.01 to 0.3 μm wavelength range is to effectively reject visible-light radiation which, for many astrophysical objects, has an intensity many orders of magnitude greater than that of the ultraviolet and far-ultraviolet emissions. Because of this difficulty, and the relative immaturity of sensor technologies for the ultraviolet (UV), this wavelength range was considered the most demanding of development among those considered by this panel. Historically, photoemissive cathode technologies have offered the best performance across much of the UV range. However, the potentially superior imaging capabilities and sensitivity of CCDs offer inducement to extend their range into the UV, and CCDs may play a growing role in future missions, if efficient short-pass filters can be developed, the problems of contamination of cooled CCDs can be solved and an increase in sensitivity by back thinning can be achieved.

In the context of past and future NASA missions, Table IA summarizes existing and desired performance of photoemissive cathode technologies in the UV. The High Resolution Imager (HRI) on the Einstein Observatory is shown as an example of what has already been flown, and the Extreme Ultraviolet Explorer (EUVE) provides an example of technology already developed for an upcoming mission. In order to assess the capabilities currently under development and those desired for future astrophysics missions, the third column shows the performance that has been demonstrated to date in the laboratory for the Space Telescope Imaging Spectrograph (STIS), a refurbishment instrument for HST, and NGST is selected as an example of a more distant future mission. Equivalent information on CCD technologies is provided in Table IB. HST instruments WF/PC 1 and 2 are selected to represent an instrument already flown in space and one developed for an upcoming mission, respectively. NGST is again used as an example of a more distant future mission. Although a complete discussion of detector performance in the visible wavelength range is reserved for the following section, the CCD specifications are very similar, and have been included in Table IB for convenience.

TABLE IA. UV Capabilities for NASA Missions (Emissive Photocathodes)

| Development Status | Flown in Space | Developed for Space | Demonstrated in Laboratory | Desired for Future Mission |
|---|---|---|---|---|
| Sample Mission | Einstein Observatory | EUVE | HST II / STIS | NGST |
| Array size | 1850 x 1850 | 650 x 650 (2048 electronic bins) | 2k x 2k | 4k x 4k |
| Pixel size (μm) | 15 | 50 (circular) | 25 | 5 |
| Quantum efficiency for range (μm) | > 20% < 0.1 | > 30% < 0.1 | > 30% < 0.12 | > 50% 0.01 to ≥ 0.1 |
| Dark count ($cm^{-1}s^{-1}$) | 0.2 | < 0.3 | < 0.3 | < 0.3 |
| Read rate local ($s^{-1}pixel^{-1}$) and total ($s^{-1}$) | < 10 < $10^5$ | 40 > $10^4$ | 100 > 8 x $10^6$ | 1000 ≥ $10^8$ |
| Cosmic ray Discrimination | No | No | No | Discrimination |
| Tube Structure | Open | Open | Sealed & open | Sealed & open |

TABLE IB. UV and Visible Sensor Capabilities for NASA Missions (CCDs)

| Development Status | Flown in Space | Developed for Space | Demonstrated in Laboratory | Desired for Future Mission |
|---|---|---|---|---|
| Sample Mission | HST WF/PC 1 | HST WF/PC 2 | N/A | NGST |
| Visible blindness | < $10^{-4}$ | < $10^{-9}$ | < $10^{-9}$ with filter | < $10^{-9}$ for imaging |
| Array size | 800 x 800 | 800 x 800 | 4k x 4k | ≥ 15k x 15k |
| QE for 0.1 - 0.4 μm<br>QE for 0.4 - 1.0 μm | > 15%<br>> 15% | > 25%<br>> 25% | 30%<br>> 60% | > 80%<br>> 80% |
| Well capacity ($e^-$) @ pixel size (μm) | 30,000 @ 15 | 40,000 @ 7 | 40,000 @ 7 | 100,000 @ 5 |
| Read noise ($e^-$ rms) | 10 | 2 | 0.4 | 0.1 |
| Read rate (pixels $s^{-1}$) @ read noise ($e^-$ rms) | 50,000 @ 10 | 50,000 @ 2 | 50,000 @ 0.4 | 100,000 @ 0.1 |
| Operating temperature | - 95 °C | - 60 °C | - 20 °C | 20 °C |
| Mosaic capability | No | No | Buttable for line array | Buttable for 2-D mosaic |

## B. Development Plan

A number of technical advances are required, both for missions which have an immediate need, such as FUSE and HST, as well as for the advanced missions that will occur in the first part of the next century. A summary of the areas recommended for development is provided in Table II.

The primary requirement for this wavelength range is for simultaneous high-efficiency and "*solar-blind*", i.e. "*visible-blind*", response. There are three technology areas which the panel recommends for development. The first is high-quantum-efficiency ultraviolet photocathodes which have an inherently low sensitivity at wavelengths beyond 0.3 microns. These are required for the photo-emissive detector systems such as the imaging microchannel plate (MCP) detector systems.

**TABLE II. Technology Development Recommended for 0.01 to 0.3 Microns**

| Technology Development | First Mission Impacted | Program Dates | Program Size |
|---|---|---|---|
| • **High-efficiency "solar blind" detectors:** | | | |
| a. High QE photocathodes | FUSE | 91-93 | small/moderate |
| b. High QE CCDs | HST / ORI | 91-95 | large |
| c. High-transmission UV filters | HST / ORI | 92-95 | small/moderate |
| • **Improved MCPs:** | | | |
| a. New glass MCPs | FUSE | 91-93 | moderate |
| b. Advanced-technology MCPs | NGST | 93-98 | large/major |
| • **Advanced MCP readout systems:** | | | |
| a. Small pixel size | FUSE | 91-93 | moderate |
| b. Large format | HST / STIS | 91-95 | moderate/large |
| c. High dynamic range | HST / ORI | 91-95 | moderate/large |
| • **New materials:** | | | |
| a. Non-Si CCDs, high-bandgap sensors | NGST | 93-98 | large |
| b. Opaque negative-affinity photocathodes | NGST | 93-98 | moderate/large |
| • **Cryogenic 3-D detectors:** | | | |
| a. Simultaneous 2-D spatial, energy resolution | NGST | 93-00 | small |

The second recommended development area is for high quantum efficiency (QE) charge-coupled devices (CCDs) or other high-bandgap detector concepts. A number of means are being investigated for increasing the QE of CCDs in the UV, such as thinning, coating with down-converting phosphors, and ion implantation. Approaches such as SiC photodiodes or other novel high-bandgap intrinsic detectors are also promising approaches. The panel did not feel that it was its responsibility to discuss the relative merits or likelihood of success of the various approaches. Suffice to say, that any investigation in this area that shows promise should be investigated. The third requirement is for high-transmission UV filters that have a very low transmission at wavelengths longer than 0.3 μm, which will be required if inherently solar-blind detectors have not been demonstrated in time for future UV missions. A number of investigations into filters of this type are currently under way, but success to date has been relatively limited.

It was also felt that there was a need for improved MCPs to provide the basis for the imaging photo-emissive detector systems for this wavelength range. Improvements are required to the reduced lead silicate glass (RLSG) MCPs and there is a need to initiate now the development of advanced-technology MCPs (AT-MCPs), fabricated by lithographic semiconductor techniques. The requirements for these improved MCPs are listed in Table III.

Concurrent with this development, there is a need to develop advanced MCP read-out systems emphasizing small pixel size, large formats, and systems which can provide the high dynamic range that would be needed, for example, for a third-generation ultraviolet camera for HST. The requirements for these read-out systems are specified in more detail in Table IV.

Looking further ahead, it was felt that basic research in new materials technology was also required. For CCDs, investigations of large-bandgap non-silicon CCDs could produce a detector which has an inherently high level of rejection of visible light radiation, thereby bypassing the stringent requirements on visible-blocking filters. Similarly, the development of high-work-function opaque negative-affinity photocathodes would produce photoemissive detector systems with very high quantum efficiencies in the ultraviolet, and very low sensitivities at wavelengths longer than about 0.25 to 0.3 microns. The specific parameters desired for these CCDs (and negative-affinity photocathodes) are for large bandgaps (and work functions) ≥ 4 eV. There is currently no demonstrated capability for either technology, or any significant development already under way.

Finally, looking even further into the future, it was recommended that basic investigations into novel three-dimensional detector systems which can provide simultaneously two-dimensional spatial information and energy resolution should be initiated. Suggestions for these cryogenic detector systems have already been made, but obviously, at this point in

**TABLE III. Status and Requirements for High-Gain MCPs**

| | |
|---|---|
| Developed: | Diameter ~ 100 mm<br>Spatial uniformity ~ 25 to 50 μm (multi-fiber defects)<br>Channel diameter 10 μm<br>Dark count rate < 0.3 counts $cm^{-2}$ $s^{-1}$<br>Maximum count rate ~ 50 counts $channel^{-1}$ $s^{-1}$ (12-μm channels)<br>Lifetime ~ 10 C $cm^{-2}$ |
| Under development: | Channel diameter 8 μm<br>Square channels (60-μm to 25-μm channels)<br>Curved plates<br>Dark count rate < 0.03 counts $cm^{-2}$ $s^{-1}$<br>Maximum count rate ~ 100 counts $channel^{-1}$ $s^{-1}$ (12-μm channels)<br>Lifetime TBD |
| Required: | Diameter ~ 100 mm<br>No spatial distortion (AT-MCPs)<br>Square channels (6-μm channels)<br>Dark count < 0.01 counts $cm^{-2}$ $s^{-1}$ (anti-coincidence)<br>Maximum count rate > $10^3$ counts $channel^{-1}$ $s^{-1}$ (6-μm channels)<br>Lifetime > 30 C $cm^{-2}$ |

**TABLE IV. Status and Requirements for MCP Read-out Systems**

| | |
|---|---|
| Developed: | ~1 k x 1 k<br>Spatial resolution 14 μm to 25 μm<br>Position sensitivity ~ 1 μm<br>Maximum count rate ~ $10^6$ counts $s^{-1}$ |
| Under development: | ~ 2 k x 2 k<br>Spatial resolution 14 μm to 25 μm<br>Position sensitivity ~ 1 μm<br>Maximum count rate ~ 2 x $10^6$ - $10^7$ counts $s^{-1}$ |
| Required: | ~ 4 k x 4 k<br>Spatial resolution 10 μm<br>Position sensitivity < 1 μm<br>Maximum count rate >> $10^7$ counts $s^{-1}$<br>Buttable for mosaics |

time, studies are limited to conceptual analyses and fundamental laboratory investigations. The desired performance parameters for these detectors are for large-format arrays (~ 1k x 1k) with simultaneous energy resolution, E/ΔE > 10.

## 0.3 TO 0.9 MICRONS

### A. Technology Assessment

For the wavelength range from 0.3 to 0.9 μm, it was felt that the entire effort should be directed toward the further development of silicon CCDs because of their potentially very high quantum efficiencies in this wavelength range. It was also felt that a major effort should be made toward improving the packaging of these CCDs, since in many cases to date, the performance of the CCDs has been degraded by the undesirable aspects of their packaging. An overview in the context of NASA missions of the state-of-the-art and desired CCD performance in the visible was provided in Table IB in the previous section.

NASA has played a key role in the development of CCD technology. Starting in 1974, NASA recognized the potential of CCD arrays, which at that time were available in 100 x 100 formats and with ~ 100 e⁻ rms readout noise, and sponsored their further development. This initial program culminated in the CCD arrays which were flown on Galileo and the Hubble Space Telescope, with format and read noise of 800 x 800 and 10 e⁻ rms, respectively. This advance in technology is graphically demonstrated in figure 1, in which a modern 4096 x 4096 CCD array fabricated by LORAL is compared to the vidicon detectors used on the Voyager mission. Continuing NASA-sponsored work seeks to further improve format size and readout noise, as well as to increase the sensitivity, to extend the range across an unprecedented spectral range (1 Å - 11,000 Å), and to improve manufacturing yield and reliability, including radiation hardness.

### B. Development Plan

Future astrophysics missions require, simultaneously, a very high quantum efficiency, a deep full-well capacity, large format, low read noise at a high read rate, and a device that can be radiation hardened. It was felt by the panel that if a quantum efficiency of > 80% and a read noise of the order of, or less than, 1 e⁻ rms could be achieved, there would be no need for the development of photon-counting detectors for this wavelength range, since the CCDs could meet essentially all of the scientific requirements for the missions considered under the Astrotech 21 Program plan. Specific areas recommended by the panel for focused development of visible CCDs and CCD packaging are listed in Table V.

In the area of packaging, it was felt that the package should have low radiation emission, should be compatible with the flatness requirements of the optical system, should be compatible with the cleanliness requirements for the cooled CCD and, particularly, should be compatible with two-dimensional mosaicking of buttable CCDs. The possibility for cosmic ray discrimination, using anticoincidence counting of two CCDs mounted back-to-back, would also provide major advantages in observing efficiency, particularly for missions on the lunar surface.

## 0.9 TO 2.5 MICRONS

### A. Technology Assessment

The near infrared region from 0.9 µm to 2.5 µm is covered in detail by the Direct Infrared Sensor Panel. Consequently, the UV and Visible Sensor Panel decided to focus their efforts in this wavelength range on aspects of the technology that might particularly benefit from the heritage of shorter wavelength detectors. The great success of visible CCD detectors in providing the ultimate in sensitivity, as well as offering large-format arrays, leads this panel to support efforts to develop similar technologies for the near IR.

**TABLE V. Technology Development Recommended for 0.3 to 0.9 Microns**

| Technology Development | First Mission Impacted | Program Dates | Program Size |
|---|---|---|---|
| • **Si CCDs:** | | | |
| High Q.E. | HST II* / STIS | 91-94 | large |
| Deep full well | HST II / STIS | 91-94 | large |
| Large format | HST II / STIS | 91-94 | large |
| Low read noise | HST II / STIS | 91-94 | large |
| High read rate | LTT | 92-95 | moderate |
| Radiation hardened | LTT | 92-95 | large |
| • **CCD Packaging:** | | | |
| Low radiation | HST II / STIS | 91-94 | small |
| Thinned/flat | HST II / STIS | 91-94 | moderate |
| Cleanliness | HST II / STIS | 91-94 | moderate |
| Mosaic compatible | LTT | 92-95 | large |
| Cooling | LTT | 92-95 | moderate |
| Cosmic ray discrimination | LTT | 92-95 | large |

* Terminology II refers to 2nd generation instruments.

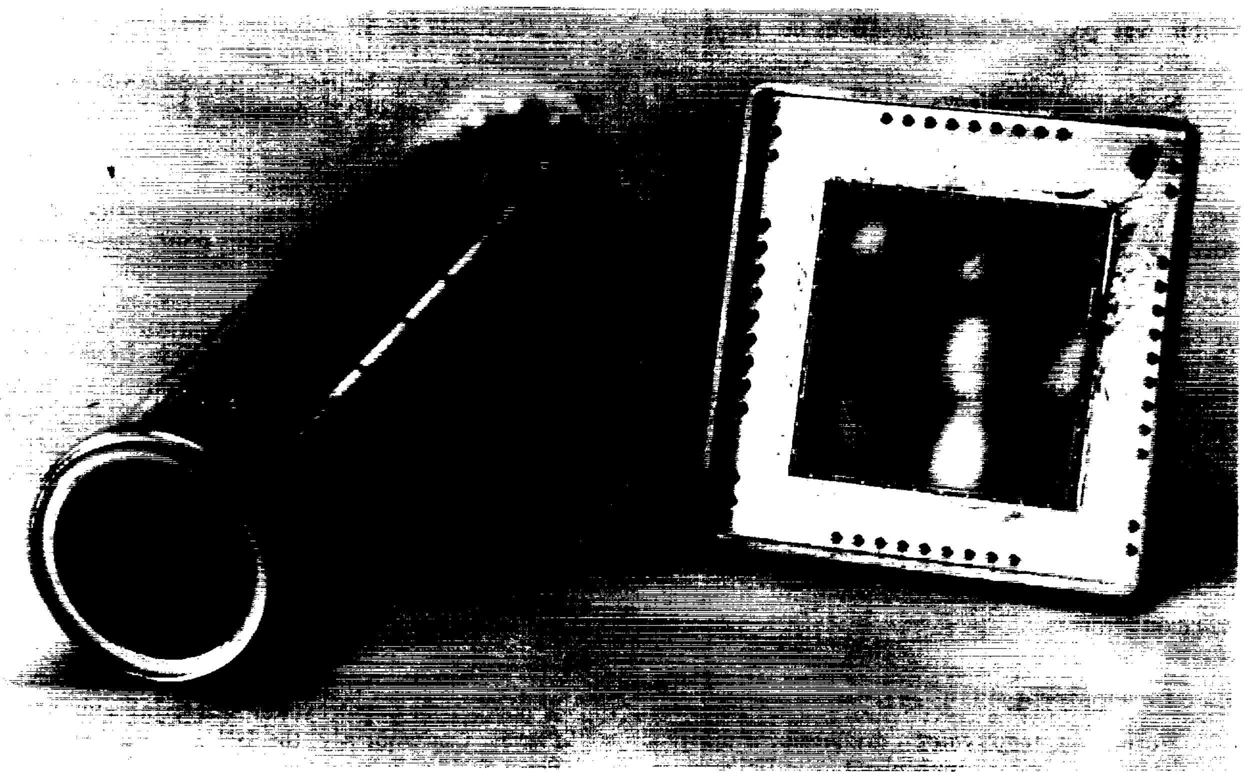

Figure 1. Comparison of a vidicon image tube developed in the early 1970's and used on the Voyager program with a state-of-the-art planar CCD array illustrating the advances in visible imaging technology during the last 20 years. The vidicon tube was scanned in an 800 x 800 array format with 15 x 15 μm pixels and was fabricated by the General Electrodynamics Corporation and has operated successfully for 15 years on the Voyager spacecraft. The CCD is a 4096 x 4096 array with 7.5 μm pixels fabricated by LORAL Corporation and has been demonstrated in the laboratory but is not yet qualified for flight.

### B. Development Plan

Specifically, the panel recommends investigations of novel CCD structures such as the Direct Shottky Injection Focal Plane Array where the first material could have a very high near-IR quantum efficiency such as Ge, InSb, or HgCdTe. It was also felt that an investigation into new materials for this wavelength range should be undertaken for advanced missions such as the NGST, where the lead time is sufficient for a longer term materials development effort. These recommendations are shown in Table VI. Some concern was also expressed that the technology in this wavelength range would be subject to classification by DoD because of its military applications.

## TECHNOLOGY DEVELOPMENT ISSUES

In its final discussions, the Panel felt that there were a number of additional issues that should be highlighted in the Astrotech 21 report. These issues are summarized in Table VII.

First, it should be clearly noted that there is no industrial or DoD requirement for CCDs with the performance characteristics required for astrophysics space missions. Consequently, NASA, as an agency, should be prepared to bear the full cost of developing these devices. Similarly, for the large-format MCPs, there is only a limited industrial requirement to meet the needs of the cathode ray tube industry. NASA must also be prepared to bear essentially the full cost of the development of these large-format MCPs. It was also noted that there are a very limited number of industrial sources for CCDs and MCPs with the performance characteristics required for astrophysics space missions, and that anticipated reductions in their funding as existing projects are completed may place their continued existence in jeopardy. Further, at this time, the development of large-format UV and visible-light detectors, specifically, silicon CCDs and MCPs, is currently funded almost solely by one NASA project; namely, the Second-Generation Hubble Space Telescope Imaging Spectrograph (STIS) being developed at the NASA Goddard Space Flight Center. Continuity of funding and level of

**TABLE VI. Technology Development Recommended for 0.9 to 2.5 Microns**

| Technology Development | First Mission Impacted | Program Dates | Program Size |
|---|---|---|---|
| **Monolithic Near-IR Arrays:** | | | |
| Si | HST-ORI | 93-96 | Small |
| Ge | HST-ORI | 93-96 | Small |
| InSb | LTT | 93-96 | Small |
| HgCdTe | MOI | 91-94 | Small |
| New materials | NGST | 93-96 | Small |
| Develop best option(s) | | 96-00 | Moderate |

**TABLE VII. Technology Development Issues**

- No industrial or DoD requirement for astrophysics quality CCDs.
- Limited industrial requirement for large-format MCPs.
- Limited number of industrial sources for CCDs and MCPs.
- Development of large-format UV and visible detectors (MCPs and CCDs) is currently funded almost solely by the HST / STIS instrument-development program.
- Continuity of funding and level of funding are critical to maintain these technologies.
- Very large arrays will require new data transmission and handling technologies which should be considered by the appropriate Astrotech 21 panel.

funding appropriate to attract the attention of the industrial corporations concerned is consequently critical to maintaining these technologies if they are to support the Astrotech 21 missions.

The final issue that was noted by this panel was that the very large array detectors will require new data-transmission technologies and new data-recording and data-handling technologies. While it is not the task of this workshop to review these technologies, it is hoped that an appropriate Astrotech 21 panel will review and report on the needs in this area.

## SUMMARY

After reviewing the Astrotech 21 mission set and the currently available sensor technology, the Ultraviolet and Visible Sensors Panel concluded that there are a number of areas in which additional development will be required in order to meet the science objectives of these missions. Within the wavelength range considered by this panel, 0.01 to 2.5 μm, requirements for the high-energy part of the UV spectrum, 0.01 to 0.3 μm, were judged to be farthest from existing sensor capabilities. In this region, the focus is on the need for large format high-quantum efficiency, radiation hard "solar-blind" detectors. Options recommended for support include Si CCDs with visible-rejecting filters, high-efficiency photocathodes with improved MCPs and readouts, and non-Si CCDs. Cryogenic, "3-D" detectors were also called out as meriting support. For the 0.3 to 0.9 μm range, it was felt that the entire effort should be directed towards the further development of Si CCDs, which were deemed to offer the best option for high quantum efficiencies for these wavelengths. Development of both the CCDs themselves, as well as advanced focal-plane packaging, was recommended for support. The panel also expressed concern over the precarious position of the CCD technology base, and the need for additional funding to sustain it as current sources of support are phased out. In the near IR, 0.9 to 2.5 μm, the panel recommended support for the investigation of monolithic arrays. Finally, the panel noted that the implementation of very large arrays will require new data-transmission, data-recording and data-handling technologies.