On-orbit management of contaminants within the HST Wide Field Planetary Camera and their effect on instrument performance

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ABSTRACT

The Wide Field Planetary Camera (WF/PC) onboard the Hubble Space Telescope contains contaminants which condense on the windows in front of each CCD detector. These contaminants are UV opaque and increase with time to the extent that after several months they block 50% of the flux at 300 nm. Also, when the contaminants are warmed above -40°C and then returned to the normal CCD operating temperature of -87°C, particles form and severely degrade the image quality. The windows may be temporarily cleaned by raising their temperature to 0°C. However, this results in a change in the structure of the flat field due to the partial removal of the UV flood which was applied after launch to suppress Quantum Efficiency Hysteresis in the CCDs. Repeated decontaminations will reintroduce the QEH and necessitate another time consuming UV flood and recalibration of the instrument. After 22 months of on-orbit operation, the contaminants could no longer be fully removed by the decontamination procedure. This paper describes the current state of the contaminants, what has been deduced concerning their properties and sources, the results of our efforts to remove them, and some lessons for future space-based instruments using cryogenic UV sensitive detectors.

1. THE WIDE FIELD PLANETARY CAMERA

The WF/PC was built by the Jet Propulsion Laboratory (JPL) with Prof. J.A. Westphal of the California Institute of Technology as Principal Investigator. The WF/PC was installed in the *Hubble Space Telescope* (HST), launched aboard the Space Shuttle *Discovery* in April 1990. The WF/PC is a general purpose camera equipped with 8 Texas Instruments 800 x 800 pixel CCD detectors and 48 filters and related optical components.[1,2] The CCD detectors are arranged into two sets of four detectors which view the facets of a reflective, nearly infocus pyramid through Cassegrain repeater optics. The focal ratios of these repeaters are such that one set of 4 detectors creates a 2.57 x 2.57 arcminute field of view (f/12.9) and the second set creates a 66 x 66 arcsecond (f/30) field of view. The CCD detectors are individually packaged with a MgF_2 window (which serves as a field flattener) in 0.1 atmospheres argon (which serves as a thermal conductor). Each package is coupled to a 6 stage thermoelectric cooler (TEC) which is in turn coupled to a liquid ammonia filled heat pipe connected to a radiator on the external surface of the HST spacecraft. This side of HST normally is never exposed to direct sunlight. The CCDs are normally operated at -87°C; because of the argon atmosphere, the MgF_2 windows are at nearly same temperature as the CCD detectors.

2. INTERNAL CONTAMINANTS

During thermal-vacuum ground testing of the WF/PC, prior to the launch of HST, contaminants intrinsic to the instrument were discovered which seriously limit its UV performance especially at wavelengths shorter than 200 nm. A quasi-exponential decline in the sensitivity at 150 nm with an 1/e time on the order of a few days was observed. It was also determined that warming the CCD camera heads to ~+20°C for several hours would restore the UV sensitivity.

On-orbit experience has shown that these contaminants, when permitted to accumulate for several months, reduce sensitivity at wavelengths from 120 nm to longwards of 500 nm as can be seen in Figure 1 (vertical lines indicate the instances when the camera heads were warmed). The sensitivity decline over time is monotonic and fairly repeatable. The decline in short wavelength sensitivity is accompanied by an increase in the scattered light in the images (see Figure 2).

The contaminants appear to be deposited uniformly and do not significantly degrade the image quality. The only possible site

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for these contaminants along the optical path which is consistent with their behavior (and the features discussed in Section 3) is the front (external) side of the cold MgF_2 windows. This surface is located 6 mm in front of the CCD detectors and therefore an equal distance from the focal plane.

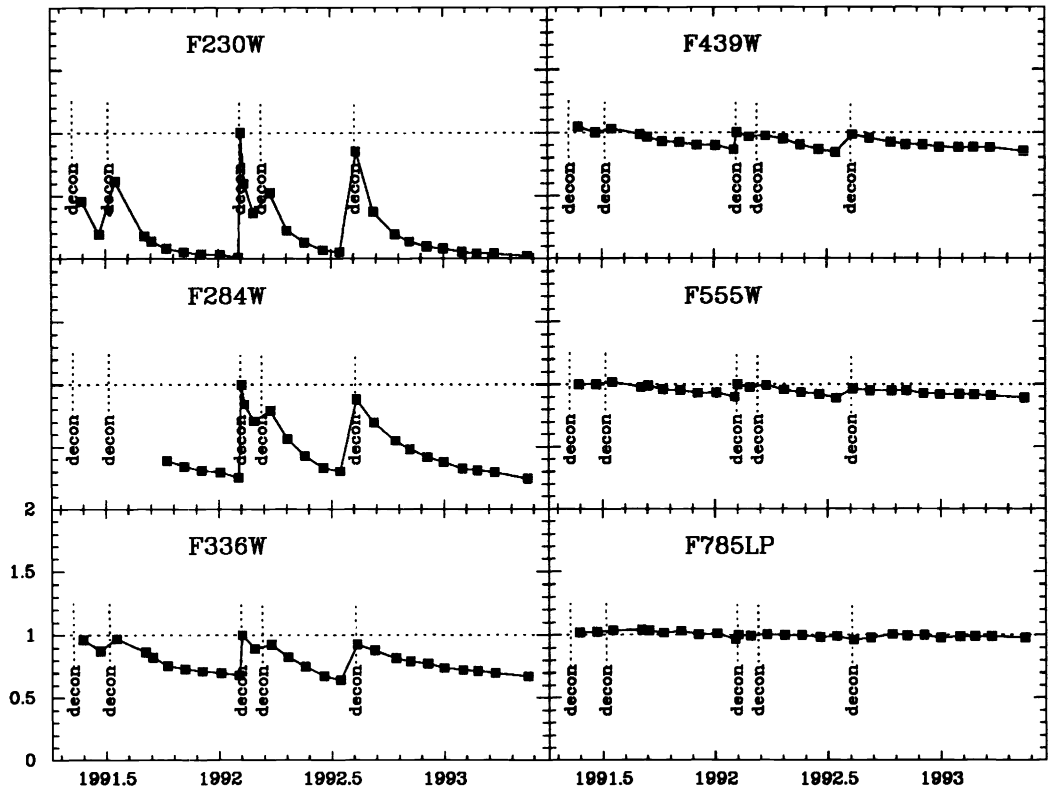

Figure 1. The observed instrumental response, normalized to observations obtained on 1992 February 5, at approximately monthly intervals. The vertical dotted lines indicate times at which the WF/PC was decontaminated (each of the decontaminations in early 1992 actually represents two decontaminations separated by a few days). Each panel is labeled with the name of the filter used for the observations. The names reflect the central wavelength in nanometers except for F785LP where the central wavelength is approximately 885 nm.

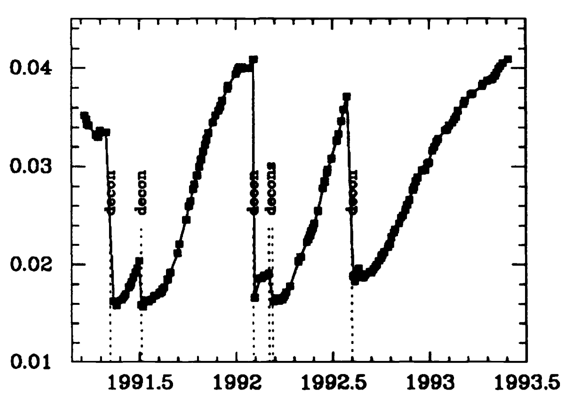

Figure 2. The change in the scattered light is shown as the fraction of light at 555nm observed at the CCD detector off of the edge of the pyramid compared to the intensity at the center of the CCD detector. The decontaminations are indicated as in Figure 1.

3. STATE CHANGES OF THE CONTAMINANTS

On-orbit operational experience has shown that these contaminants can achieve states other than the uniform layer which develops when they are slowly deposited during normal operation. Loss of power to the TECs results in the camera heads warming to an equilibrium temperature of approximately -35°C in about 1 hour. This may occur when the WF/PC itself or the HST spacecraft enters certain protective safe modes. Although only limited imaging is possible with the CCD detectors at this relatively warm temperature, the scattered light is observed to decrease considerably leading to the conclusion that a significant fraction of the layer of contaminants evaporates at this temperature. Such measurements have only been made after tens of hours at -35°C.

Returning the camera heads to their nominal -87°C operational temperature leaves a residual contamination in the form of small particles on the MgF_2 windows. When seen in internal and external (bright earth) images which illuminate the entire field of view (i.e. flat field images), this contamination has the appearance of "measles." The WF/PC is basically unusable with the degree of measles present following a period during which the CCD were warmed only to -35°C. Therefore procedures have been developed to "decontaminate" WF/PC by raising the CCD temperatures to higher levels for a controlled period of time. This is accomplished by a carefully timed sequence of commands sent from the ground to switch heaters on the heat pipes and the camera heads on and off. The standard procedure is to elevate the CCD temperatures to 0 $^{\circ}$C (± 2 $^{\circ}$C) for 1 to 1.5 hours with fairly rapid warm-up and cool down rates (~ 1 hour each).

4. QEH AND UV FLOOD

The Texas Instrument CCD detectors used in the WF/PC camera have a problem in that their sensitivity, especially in blue light, is dependent upon their recent (~hours) exposure history. This effect, known as quantum efficiency hysteresis (QEH), depends upon the intensity of the previous exposure(s) and varies considerably with location on the CCD detectors. QEH was recognized as a problem for the WF/PC after its original construction. A means of exposing the CCD detectors to sufficient solar UV light to create a surface charge capable of quenching the QEH effect was provided with the addition of a multi-element optical relay ("light pipe") and a small mirror attached to the WF/PC radiator that looks aft along the side of the HST spacecraft.

The first, and to date only, conditioning of the CCD detectors using this light pipe (a process known as a "UV Flood") was performed in December 1990 and was successful in suppressing the QEH effect. The procedure requires nearly 2 days of HST time during which few, if any, other observations can be performed. Since a side effect of the UV Flood is to increase the quantum efficiency (QE) of the CCD detectors in a very position and wavelength dependent fashion, a recalibration of the WF/PC flat field and photometric calibrations is necessary after each UV flood.

Warming the CCD detectors during decontaminations or during periods when the TECs are turned off, results in a decline in the surface charge introduced by the UV Flood. While the amount of charge needed to suppress QEH in most locations on the CCD detectors is a small fraction of the amount deposited by the UV Flood, the QE as a function of both location and wavelength will change with any change in the amount of surface charge. If too much charge is lost, then the UV Flood will need to be repeated to avoid QEH. The rate of charge loss is a strong function of CCD detector temperature. There appears to be essentially zero loss at the nominal operating temperature. The "routine" decontamination procedure (see Section 3 above) leads to a loss of 2 to 5 percent of the UV Flood. Since December 1990, nine decontaminations (of varying degrees) plus approximately 1 week at ~ -35°C have not resulted in a return of QEH. Efforts to determine the fraction of the UV Flood remaining from measurements of changes between locations with relatively large and relatively small changes in QE as a result of the UV Flood suggest that somewhat less the 50% of the December 1990 UV Flood remained as of December 1992.

Since the UV Flood procedure is costly both in its execution and in its demand for additional calibration observations, the preservation of the UV Flood is a significant operational goal. The HST spacecraft safing procedures were modified during the first year of flight to permit the WF/PC TECs to remain powered on during most of the simpler safe modes (those during which the HST power budget was satisfactory and the primary spacecraft computer was active and able to monitor the safety of the WF/PC). The decontamination procedures have been empirically adjusted to minimize the loss of UV Flood while still removing the "measles" form of the contaminants. Decontamination induced QE changes in the flat fields are compensated for by periodic observations of internal lamps (which do not compete with time for scientific observations) whose ratios are then used to update the primary flat field calibrations which were obtained from exposures of the sunlit earth.

5. PERSISTENT MEASLES

After a relatively long period of uninterrupted buildup of the contaminants (July 1991 to February 1992), a routine decontamination was carried out on 3 February 1992. This procedure was successful in restoring the UV throughput and in decreasing the level of scattered light but left a residue of measles. Three additional decontaminations, with some procedural modifications suggested by JPL and STScI staff, did not remove these "persistent measles". In both quantity and amplitude the persistent measles are much less severe than the measles which remain after a period with the TECs off (see Figure 3). From an autocorrelation analysis, the persistent measles represent a 1.1% rms modulation of a fully illuminated image (i.e. flat field) with a 4 to 5% peak amplitude in their cores.

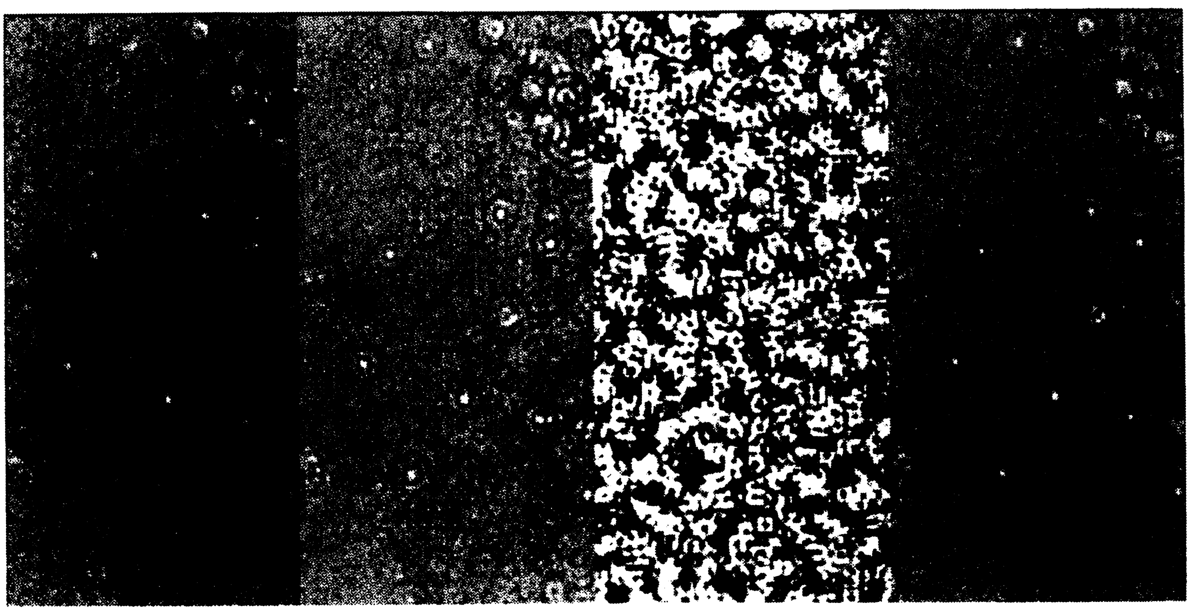

Figure 3. A 100 x 200 pixel region (4.3 x 8.6 arcseconds on the sky) of the PC 5 CCD detector is shown at four epochs. The leftmost region shows the state of the measles in February 1992 immediately after the development of the persistent measles. The next region shows the same region in June 1992 and the subsequent region shows the dense coating of measles which were present following a period in July 1992 with the TECs off. The rightmost region shows the same region following a decontamination in August 1992.

There is significant variation in both the amount and appearance of the persistent measles between the eight cameras in the WF/PC. This is partially correlated, but not in all cases, with the variations in the maximum temperatures reached by each camera head during the decontamination procedure. The persistent measles have been found to be extremely stable over time (~1 year) and are essentially unchanged by decontaminations reaching, on the warmest camera head, +10°C for approximately 1 hour. Optical modelling finds the persistent measles to be consistent with the presence of 10 - 15 μm sized particles on the cold external surfaces of the field flattening windows discussed in Section 1.

The origin of the persistent measles is most likely the stepper motor which rotates the reflective pyramid. The motor was operated for several months in late 1991 with short (~10 to 20 minute) intervals between motions. It had not previously been operated in that mode other than very occasionally. An operations limitation requiring a wait of 30 minutes or more between motions of the pyramid has been established. Other than the coincidence between the period in which the persistent measles species of contamination was produced (July 1991 through January 1992) and the period of short interval motions of the pyramid, this theory is supported by thermal modeling which indicates that the core temperature of the pyramid motor exceeds +50°C and by considerable outgassing during high temperature baking of similar motors at JPL as part of the construction of the WFPC2 camera (which will replace the WF/PC during the first HST Servicing Mission). No other operational differences have been identified during the July 1991 through January 1992 period.

6. SCIENCE IMPACT OF PERSISTENT MEASLES

The persistent measles cannot be fully corrected with post-observation calibration because they are on an out of focus surface (the same is true of dust particles on field flattening windows and on the nearly infocus pyramid faces). Some improvement is possible by using flat fields with measles present (or ratios of internal lamp exposures taken before and after February 1992). This appears to work best with sources whose illumination of the optical system is similar to flat fields (i.e. large extended objects). Objects with steep gradients (e.g. stars) are less well corrected. Observations in which the signal to noise ratio (S/N) of the targets is low (e.g. faint targets) are relatively unaffected since a few percent modulation is within the photon shot noise.

The most significantly impacted programs include high S/N observations of extended structures (e.g. planetary atmospheres), large field-of-view observations (since the density of the persistent measles varies considerably over the field of view), and precision photometry and astrometry (which had already been limited by the HST primary mirror's spherical aberration). An additional difficulty is that the majority of WF/PC science programs have relied, at least somewhat, on deconvolution of the HST point spread function. Since deconvolution tends to emphasize features of stellar dimension, which includes the persistent measles (as well as cosmic ray events), this further limits the quality of the observations and complicates the analysis of the images. However, it appears from both an Space Telescope Science Institute (STScI) assessment of the ongoing science program and from comments from the community, that while some science programs are seriously limited by the persistent measles, the majority of WF/PC science programs are only slightly affected.

7. EFFORTS TO REMOVE PERSISTENT MEASLES

Following the failure of both the routine and modified low temperature decontamination procedures to remove the persistent measles, a study was begun by Goddard Space Flight Center (GSFC), JPL, and STScI personnel to determine the appropriate response. It appeared likely from the start, and has now been established, that removal of the persistent measles would require a high temperature decontamination that would also remove the surface charge on the CCD detectors and therefore require a UV Flood procedure. Efforts to remove the persistent measles started with analysis of two questions: (1) what was the probability of successfully removing the persistent measles and, (2) what was the probability of subsequently restoring the UV Flood. Both the risks inherent in these questions and the costs in HST observing time were weighed against the expected improvements in the science observations.

Available analysis of the likely behavior of the contaminants indicates that removing all or most of the persistent measles appears to be possible with 10 to 30 hours of decontamination at ~ +20 to +25°C. Such a decontamination results in the total loss of the UV flood. There is no certainty as to the exact composition of the contaminants (more than 100 possible materials have been identified when the lower temperature contaminants are included). Because the UV light on the field flattening windows during the UV Flood procedure might polymerize the contaminants and potentially create a greater problem (e.g. they might darken), polymerization test were made with the most probable contaminants. WF/PC spare motors and cable assemblies was baked in vacuum at GSFC and outgassed contaminants were collected onto MgF_2 windows; the windows were then exposed to a simulated UV Flood and examined. These experiments, while unable to prove the absolute safety of the UV Flood in the event that the persistent measles could not be removed, tend to provide confidence that the measles would not become worse.

Successfully restoring the UV Flood would require repeating the procedure carried out in December 1990. A concern in doing so was that possible degradation of the UV throughput of the lightpipe assembly might prevent a successful UV Flood. When theoretical analysis of possible contamination and optical surface reflectance was inconclusive, a test procedure was developed and planned for execution in October 1992. Further preparation for a UV Flood involved careful thermal modeling of the WF/PC to create the optimum decontamination procedures.

In August 1992, problems with the HST magnetometers resulted in an anti-sun pointing exclusion that precludes executing a UV Flood. The exclusion was necessary because shadowing by the aft shroud of the HST spacecraft in an anti-sun attitude results in severe cooling of the magnetometers which have begun to produce unreliable outputs when so cooled. The magnetometers are required for control of momentum dumping (particularly when HST is under control of the backup flight computer). This situation currently precludes further efforts to remove the persistent measles since the risks are thought to far outweigh the potential benefits, especially as WF/PC is currently scheduled to be replaced with the WFPC2 instrument (which includes both an optical fix for the spherical aberration and CCD detectors which do not require a UV Flood).

As a contingency against loss of the UV Flood due to a prolonged period with the TECs off, a partial UV Flood procedure (to charge only the four CCD detectors for the Wide Field configuration) which might satisfy the magnetometer thermal constraints is being developed. However, the failure of the primary solar array drive electronics has further complicated this issue since it creates an additional anti-sun pointing restriction.

8. LESSONS LEARNED

Ultimately, the science output of the WF/PC has been compromised by the persistent measles contamination for three underlying reasons. First, a significant amount of contaminant material was incorporated into the WF/PC during its construction. During construction both selection of materials and bake-out to temperatures well above possible operating levels is necessary. JPL has carried out such a program during the construction of WFPC2 and their experiences have been valuable in understanding the behavior of the WF/PC's contaminants. Second, decontamination of the WF/PC is difficult both due to the necessity of retaining or subsequently restoring the UV Flood. Since the UV Flood capability was added after the initial design and construction of the WF/PC, its limitations are understandable but the interdependence with other HST subsystems has rendered the UV Flood capability unusable. Further, confidence in successfully removing the persistent measles would be higher if provision had been made for heating optical surfaces likely to collect contaminants to temperatures well in excess of those which might be reached in any other part of the instrument. Third, the optical and thermal design of the WF/PC created cold optical surfaces close to the focal plane; artifacts on such surfaces are particularly difficult to correct by flat fielding.

9. ACKNOWLEDGMENTS

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10. REFERENCES

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