Spatial Scanning with HST for Exoplanet Transit Spectroscopy and other High Dynamic Range Observations

P. R. McCullough & J. MacKenty (STScI)

Why would we do this?

SPACE TELESCOPE SCIENCE INSTITUTE
Operated for NASA by AURA

ABSTRACT

We are reviving an old technique of spatially scanning the telescope to improve observations, in this case with the Hubble Space Telescope's Wide Field Camera 3 (HST WFC3). Spatial scanning will turn stars into well-defined streaks on the detector, or, for example, spread a stellar spectrum perpendicular to its dispersion. There are at least two motivations for implementing such a capability: 1) reducing the fraction of overhead in observations of very bright stars such as those suitable for spectral characterization of transiting planets, and 2) enabling observations of very bright primary calibrators that otherwise would saturate the IR detector. We report results (McCullough & MacKenty 2011) from two engineering tests in which a star was imaged with WFC3 IR under various parameterizations of HST's scanning speed and orientation, and with or without a grism in place.

CONCLUSION: It works!

The re-introduction of spatial scanning to HST has been demonstrated for WFC3 IR and UVIS. We expect that the two primary motivations (see Abstract) are achievable.

TWO TESTS

We executed two on-orbit tests under HST program 12325, one on 2011-03-24 (IR imaging only) and the other 2011-04-18 (UVIS imaging & IR spectroscopy). The first test proved that we can scan a star across the IR detector in a straight line at a constant rate with well-defined starting and finishing positions. The second test demonstrated 1) the same capability for the UVIS detector (perhaps indicating an adjustment is needed in the synchronization with the UVIS channel), 2) that scanning works also for spectroscopy using the G141 grism with the IR detector, and 3) measured the operational overheads associated with a time series of scans.

SPECIFYING A SCAN

Referring to the figure below, the observer must define the scan rate, scan orient angle α, and scan direction (forward, meaning from a to b, or reverse, from b to a). Currently the scan rate must be less than 1 arcsec s^{-1} (limited by flight software parameters), but we are investigating if it can be increased to 7.84 arcsec s^{-1} (limited by gyros). For a given scan rate, the scan length on the detector is determined by the effective exposure time, which depends on both the commanded exposure time and whether the star is scanning "upstream" or "downstream" of the IR detector's raster-scanned readout.

The overheads per WFC3 IR exposure in a series in our tests were 19 s, 40 s, and 67 s, for nominal staring-mode, scanning mode (forward then reverse), and scanning mode (forward every time). The scans were at 1 arcsec s^{-1}.
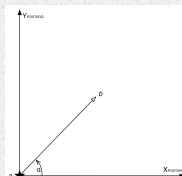
Scanned Imaging
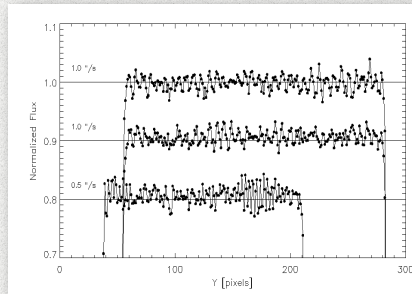
INFRARED: In one test, we trailed the star P330E across the WFC3 IR detector repeatedly, with rates of 1, 1, and 0.5 arcsec s^{-1} respectively. Photometry (above), integrated transverse to each of the three trails, show intermittent oscillations with ~3% amplitude at ~1.3 Hz, due to image motion or "jitter" during the scans. The 2nd and 3rd trails have been offset vertically by 0.1 and 0.2 for clarity.

According to Bradley (2011), at these scanning rates, the jitter measured by the Fine Guidance Sensor (FGS) in closed-loop guiding was not significantly different than that for nominal staring-mode operation of HST, ~0.0035 arcsec rms in each of two orthogonal axes. The power spectrum of the jitter contains peaks at 6.2, 3.3, 2.9, 1.3, and some less than 1 Hz, caused by the NICMOS cooling system, the high gain antenna, the aperture door, and the solar arrays.

The photometric oscillations are commensurate with the jitter. For example, consider the time-dependent position of the star

$$D(t) = V_0 \, t + A \sin \omega \, t,$$

where the first term is the uniform scan rate and the second term models the oscillatory jitter. The velocity is

$$V(t) = V_0 + A \, \omega \cos \omega \, t,$$

and hence the variability of the time for a star to cross a pixel, which determines the photometric variability along a scan, is sinusoidal with 3% amplitude, i.e. $A \omega \, / \, V_0 = 0.03$ for A = 0.0035 arcsec, $\omega = 2\pi(1.3 \text{ Hz})$, and $V_0 = 1$ arcsec s^{-1}.

For a detector well-calibrated to linearity, oscillations of the sort described above should not affect the photometric integral over the entire scan, in principle, except for the jitter's effect on the precise location (and hence time) of the start and finish of each scan. For IR imaging, the latter exception can be made negligible by scanning parallel to the fast-read direction of the IR readout., i.e. "horizontally."

Ultraviolet-visible (UVIS): In another test, we trailed the star GJ 1214 repeatedly across the same pixels of the UVIS detector at a rate of 1 arcsec s^{-1} for eight 5-s F814W exposures. Integrated over the entire 125-pixel long scan, the photometric repeatability was 4.0 mmag rms, or 40% greater than the quadrature sum of Poisson noise (1.1 mmag) and shutter noise (2.7 mmag). For the latter we adopted 12 milliseconds rms of shutter jitter per 5-s exposure (Hilbert 2009). The overheads per WFC3 UVIS-M512C-SUB exposure in our tests ranged from 58 s to 92 s; the 58 s value was the most common, and it was the same for staring mode or scans.

Scanned Spectroscopy
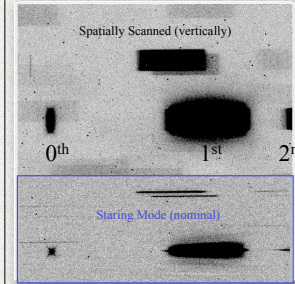
The spatially scanned spectrum of the star GJ1214 is labeled with its 0th, 1st, and 2nd order light and compared to a nominal staring-mode slitless spectrum of the same field (blue outlined inset). The images are 512 columns wide, of the detector's 1024. The scan was 40 pixels high. (4.8 arcsec).

In this test, we trailed the star GJ 1214 across the WFC3 IR detector repeatedly at a rate of 0.1 arcsec s^{-1} perpendicular to the dispersion of the G141 grism. By coincidence we observed for 15 minutes during the egress of the transiting extrasolar planet GJ 1214b.

The utility of scanning for the UVIS grism will be limited to 200 nm to 400 nm, due to order overlap longer than 400 nm.

POTENTIAL APPLICATIONS

We anticipate a number of potential applications for spatial scanning with HST. You are encouraged to discuss possibilities with us. Here are a few. For transit spectroscopy of exoplanets with WFC3, spatial scanning could increase the number of IR photons recorded by a factor of 10 for a star like GJ 1214 (H=9.09 mag), because spatial scanning reduces overheads considerably. For even brighter stars such as HD 189733, spatial scanning will enable observations that otherwise would be compromised by pre-exposure saturation of the IR detector that lacks a physical shutter. For a slitless stellar spectrum, one requires a wavelength-dependent flat field, but now we can get what we want directly, in orbit, using a spatially-scanned spectrum of a reference star for calibration. If we can increase the maximum scan rate to 2 arcsec s^{-1}, the primary calibrator star Vega will not saturate the IR detector pixels with the G141 grism in its -1st order, which is ~4.6 mag less efficient than the +1st order (Kuntschner et al. 2011). Similarly, in imaging mode, spatial scanning should permit unsaturated IR photometry of calibrators without concern that the star "burns in," i.e. gradually appears to brighten (by ~0.5%) with time due to its own electronic "after images." For example, a G2 V star, with H = 9.9 mag, scanned at 1 arcsec s^{-1} and imaged with the F125W filter will be marginally below saturation of the IR detector.

References

Bradley, A. 2011, Spacecraft System Engineering Services, private communication of unpublished report "FGS Vehicle Scan (#52 Command) On-Orbit Test of 2011:083"
Hilbert, B. 2009, WFC3 ISR 2009-25, "WFC3 SMOV Program 11427: UVIS Channel Shutter Shading"
Kuntschner et al. 2011, WFC3 ISR 2011-5, "Revised Flux Calibration of the WFC3 G102 and G141 grisms"
McCullough & MacKenty, J. 2011, WFC3 ISR 2011-NN, in preparation