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Observing the Moon

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ABSTRACT

The Hubble Space Telescope (HST) was not designed to support observations of a target as close as the Moon. Nevertheless, ways have been found to make lunar observations work within certain limitations. These limitations are explained, and guidelines are provided for Phase 1 proposals and for Phase 2 observing programs.

1 Misconceptions

There are some common misconceptions about HST's ability to observe the Moon.

- *The Moon is too bright.* While there are some instrument/mode/filter combinations for which the Moon is too bright, there are many others for which the Moon presents no brightness problem. For details on the brightness limitations of a particular configuration, consult the Instrument Handbooks at http://www.stsci.edu/hst/HST_overview/instruments. The Moon **is** too bright for the Fine Guidance Sensors (FGSs). As a result, the sub-arcsecond level pointing possible for fixed targets cannot be achived. This situation is explored in section 2.
- *The Moon moves too rapidly.* HST can track moving targets up to a rate of 5 arcseconds/second under FGS guidance and up to 7.8 arcseconds/second under gyro guidance. The Moon's maximum apparent angular rate as seen from HST is 4.9 arcseconds/second. The high apparent rates of motion between HST and the Moon are **not** linear. HST can compensate for the linear portion of the apparent rates, but the residual apparent motion is large compared to the typical resolution element that makes HST observations attractive in the first place. Limiting image smearing requires a trade-off of exposure duration and number. This situation is explored in sections 4 and 5.
- *HST has never observed the Moon.* HST's previous lunar observations are:

- 1996: GO 6513 (PI A. Stern) observed the lunar atmosphere 1 degree from the Moon's limb with the Faint Object Spectrograph and the High Resolution Spectrograph.
- 1998: GTO/OS 7717 (PI J. Caldwell) observed the Moon with the Space Telescope Imaging Spectrograph (STIS) and the Wide Field Planetary Camera 2.
- 1999: GO/DD 8539 (PI E. Barker) observed the impact of Lunar Prospector with STIS.
- 2005: NASA 10719 (PI J. Garvin) observed the Moon with the Advanced Camera for Surveys (ACS).
- 2009: GO/DD 11806 (PI A. Colaprete) observed the impact of the Lunar Crater Observation and Sensing Satellite with STIS and Wide Field Camera 3 (WFC3).
- 2012: GO 12537 (PI D. Ehrenreich) used ACS, STIS, and WFC3 to observe the transit of Venus as reflected on the Moon.
- 2019: GO/DD 15674 (PI A. Youngblood) used STIS to observe Earthshine reflected off of the Moon during a lunar eclipse as an analog to observing Earth as a transiting exoplanet.

2 Gyro Guiding

HST observations are normally conducted under FGS guidance, which provides high pointing accuracy (<1 arcsecond) and high pointing stability (< few milliarcseconds/orbit). However, the FGSs cannot be used for lunar observations. First, the Moon itself will block a substantial portion of the FGS fields of view. Worse, scattered light from the Moon, even from a small sunlit portion, will overwhelm any stellar guiding signal and prevent proper operation of the FGSs. For normal guiding, the HST must be pointing further than 9 degrees from the Moon in order to use the FGSs. Consequently, lunar observations must rely on using gyro guiding.

The absolute pointing accuracy at the start of a gyro guiding episode is limited to ~15 arcseconds (1-sigma). The errors in the initial pointing are determined by the size of the slew from the prior target and by the accuracy limits of the Fixed Head Star Trackers (FHSTs). For observing the Moon, the slew error can be minimized by acquiring guide stars just outside the 9 degree Moon avoidance angle, and then slewing to the science target on the Moon. The absolute pointing accuracy is larger, 20-30 arc-seconds, if HST simply slews from the prior science target, without accomplishing an update near the Moon. This pointing error needs to be considered when designing lunar observations. This error is relatively small compared to the size of the large aperture cameras, but is non-negligible when using small aperture cameras. In the latter case, a mosaic of observations may be necessary to guarantee that a specific target is captured.

Once the initial pointing in gyro mode has been established an additional error will accumulate (in a random direction) at the rate of ~1.4+/-0.7 milliarcseconds/second, or about 4 +/- 2 arc-second over an orbital visibility period. This error is due to drift in the gyros. It usually is possible to remove this error at the start of each new observing orbit, possibly at the loss of some observing windows.

3 Parallax Correction

The Moon's apparent angular rate as seen from HST varies from 0.002"/s to 4.9"/s. Of this, only 0.5-0.6"/s is due to the Moon's motion. The rest is due to the parallax induced by HST's orbit around the Earth. Normally when HST observes a moving target, a geocentric target ephemeris is computed and provided to the telescope. HST's on-board software then computes a correction for the parallax induced by the telescope's orbit.

Due to limitations of HST's original flight computer, certain approximations were necessary in the on-board parallax correction algorithm. While these approximations work well for most solar system targets, the algorithm begins to fail for targets closer than about 3.8 million kilometers. Although the original flight computer was replaced with more capable hardware during Servicing Mission 3A, the on-board parallax correction algorithm was not changed because no need to do so was perceived at the time.

Since the on-board parallax correction cannot be used for the Moon, lunar observations must be implemented using an HST-centric target ephemeris. This ephemeris includes the effect of the orbital motion of HST as well as the motion of the Moon. Uncertainties in the ephemeris of the HST around the Earth will contribute additional pointing errors. Extra effort is required of STScI operations staff to ensure that the HST ephemeris is updated shortly before final scheduling to reduce these errors.

An HST-centric target ephemeris can be specified by setting the Ephemeris Center field to HUBBLE in the APT Phase 2 solar system target definition.

4 Linear Tracking

HST's capability to track moving targets is limited to constant rate linear slews. For most solar system bodies, a constant rate linear track works well over the duration of one HST orbit. However, the apparent motion of the Moon as seen from HST varies significantly in both rate and direction. Figure 1 shows an example of the changing angular rate of a lunar target as seen from HST. This example is for a specific pointing on the Moon at a specific observing time. Other pointing/time combinations may yield different angular rates. Figure 2 uses the Tycho crater as an example lunar target and shows its path on the sky as seen from HST. The generally elliptical target path is dominated by HST's orbital motion (~7 km/s). However, the ellipse does not close because of the Moon's orbital motion (~ 1 km/s).

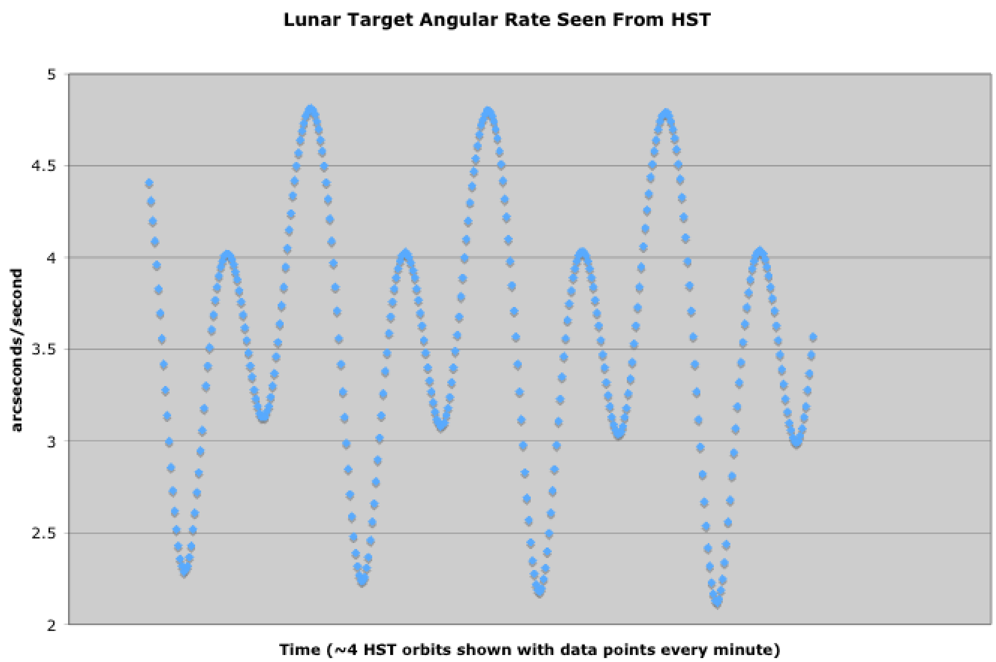

Figure 1. A target and observing time specific example of the Moon's angular rate as seen from HST.

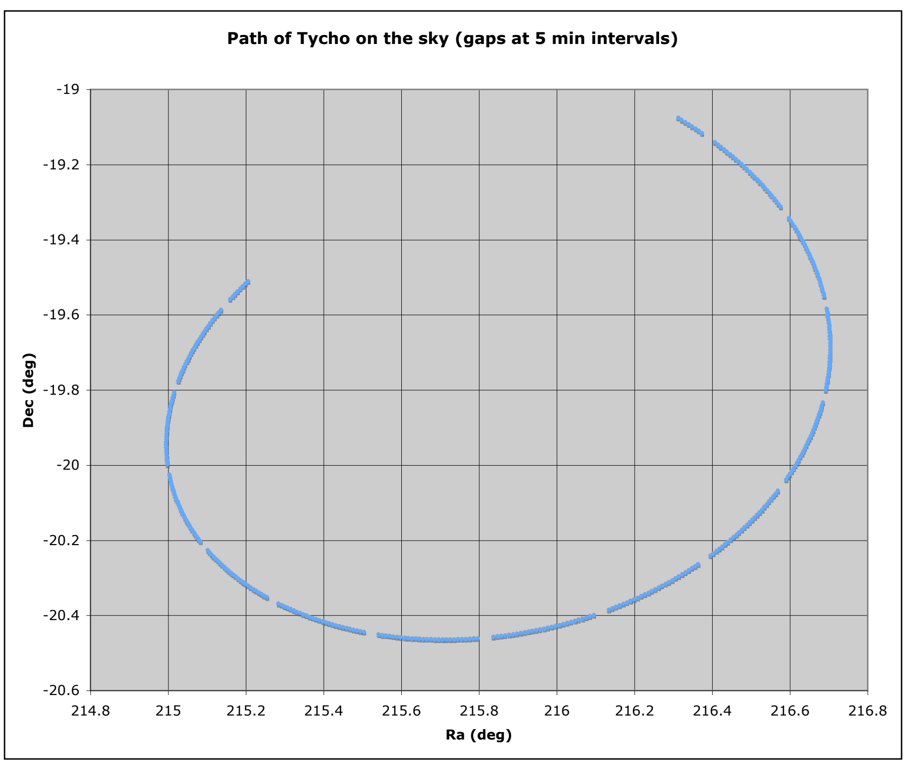

Figure 2. Apparent path of Tycho on the sky as seen from HST.

Mismatches between HST's tracking and the actual motion of the Moon can be minimized by using multiple target tracking slews per HST orbit. Figure 3 shows linear tracking slews overlaid on the actual target motion.

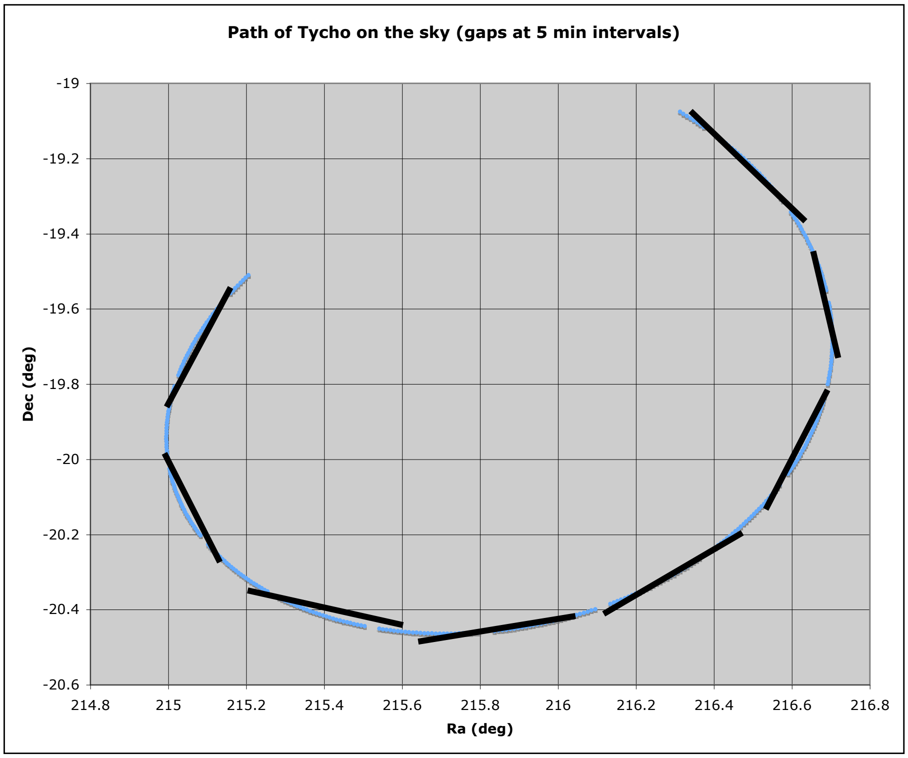

Figure 3. Linear tracking slews overlaid on actual target motion.

Increasing the number tracking slews in the orbit improves the fit to the path of the Moon's motion.

Even with multiple tracking slews per orbit, there will still be some error in each track with the start and end of the track exhibiting the best matches to the actual target motion. If the best possible accuracy is required, a separate tracking slew can be employed for each exposure. It is important to note, however, that each track will not begin at exactly the same time as the science exposure itself, but will instead be synchronized to start with the activities associated with the exposure. Those activities may include various overheads (e.g. filter wheel motion) that happen before the exposure itself. Depending on the instrument, configuration, and mode, it may be possible to move some of these overhead activities to take place before the start of the track and thus move the actual exposure closer to the start time of the track when the match to the Moon's motion is the best.

It is important to note that some overhead is involved in starting and stopping each tracking slew, so while using multiple slews per orbit will improve pointing accuracy, it will also decrease observing efficiency. Please contact your program coordinator to discuss the details of multiple tracking slews with respect to your specific observing requirements.

While multiple tracking slews can address the issue of fitting to the curve of the Moon's motion, there still remains the issue of the constant HST tracking rate vs. the Moon's changing rate. This might not be a serious issue if short exposures are used and if maximum resolution is not required; but in cases where it does matter, observing can be limited to the times when the Moon's apparent rate is closest to linear. Figure 4 shows the problem of trying to track with constant velocity segments. While tracking can be done at any time, it becomes clear that the optimal velocity match will occur at the minimum and maximum points of the velocity curve, of which there are three such points (not occulted by the Earth) per HST orbit.

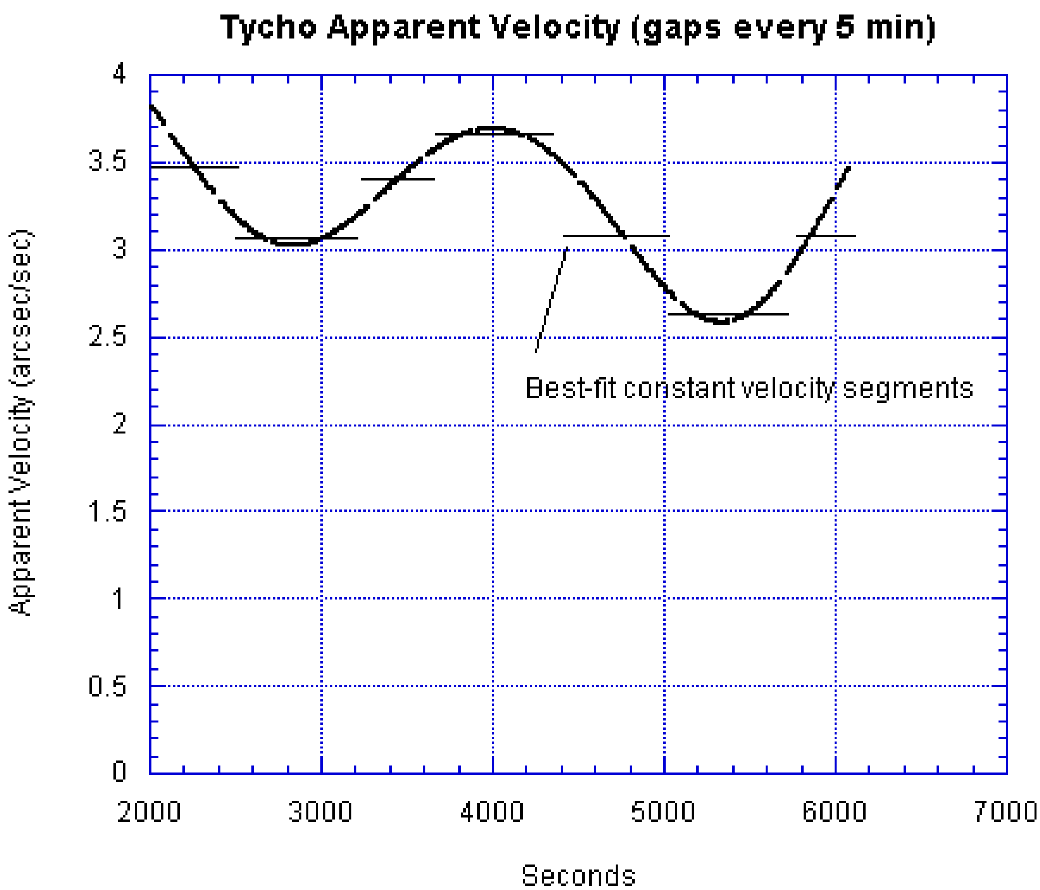

Figure 4. Target velocity on the sky

If observing is limited to the few minutes around these velocity extrema, then the match to the Moon's angular rate is maximized, but observing efficiency is dramatically reduced. Depending on the observation's pointing requirements, it may or may not be necessary to limit observing to times near the velocity extrema.

To limit observing to these points, specify an angular velocity window in the phase 2 solar system target definition.

5 Image Smear Estimate

Even the best efforts to match the Moon's motion will not be completely successful, and most exposures will experience some smearing. The amount of smear will depend on the duration of the track and the placement of exposures within that track. Minimum track duration and exposure placement vary based on science instrument configuration and on the number of exposures done per target track. A 1 second WFC3/UVIS expsoure can expect a smear of 0.10" to 0.24". ACS/HRC exposures in HST's most recent Moon observing program, NASA 10719 had an average smear of 0.076"/s. (Note that 1" translates to 1.7-2.0 kilometers on the Moon.) Figure 5 is an example which shows the change in separation between telescope pointing and target location for the case of a short WFC3/UVIS exposure which does not share its track with any other exposures.

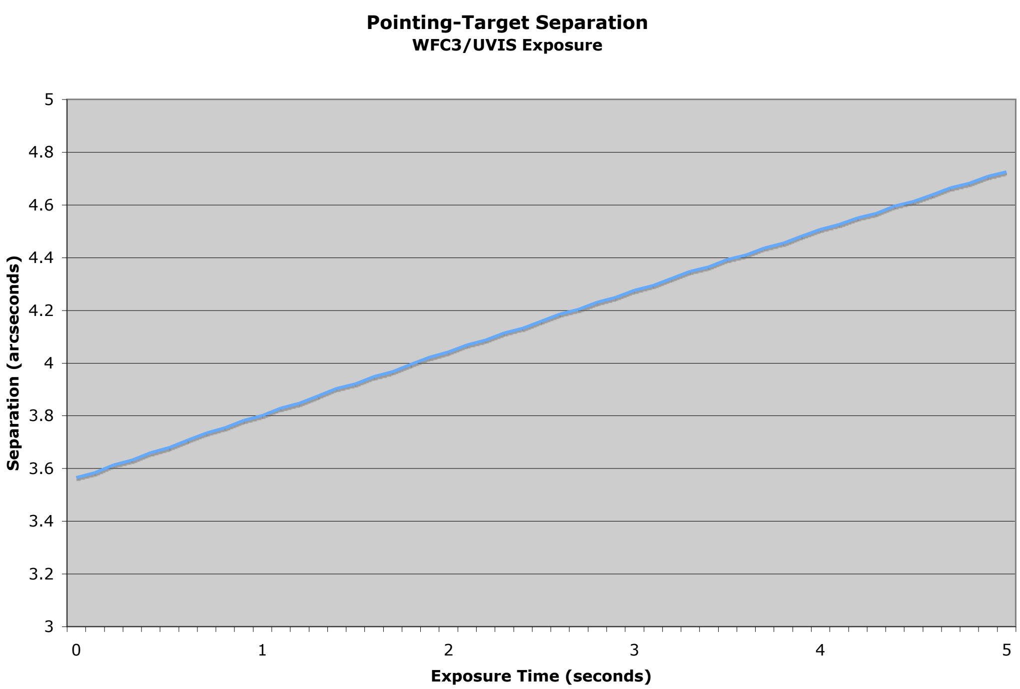

Figure 5. Image smear estimate for a WFC3/UVIS exposure.

Observers who would like smear estimates for other science instrument configurations should contact STScI.

6 Observation Examples

Depending on an observation's pointing requirements, it may or may not be necessary to employ each of the mitigation strategies mentioned above. An observation which can tolerate a fair amount of pointing uncertainty may need little to no mitigation. GTO/OS 7717 and GO 8539 are examples of such programs. On the other hand, when the absolute best possible pointing accuracy is required, then all possible mitigation of HST's limitations can be employed albeit at a high impact to observing efficiency. NASA 10719 is an example.

7 Conclusion

Observing the Moon with HST is possible but not routine. While this document covers the broad issues, each potential lunar observation may have its own specific considerations. When developing a proposal to observe the Moon, proposers are encouraged to contact the STScI (Help Desk in phase 1, program coordinator in phase 2) for detailed and specific advice. Any accepted programs to observe the Moon will require a detailed evaluation to determine if they can be carried out within the available resources.