Landsat 7 on-orbit modulation transfer function estimation

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ABSTRACT

The Landsat 7 spacecraft and its Enhanced Thematic Mapper Plus (ETM+) were launched on April 15, 1999. Pre-launch modeling of the ETM+ optical system predicted that modulation transfer function (MTF) performance would change on-orbit. A method was developed to monitor the along-scan MTF performance of the ETM+ sensor system using on-orbit data of the Lake Pontchartrain Causeway in Louisiana. ETM+ image scan lines crossing the bridge were treated as multiple measurements of the target taken at varying sampling phases. These line measurements were interleaved to construct an over-sampled target profile for each ETM+ scan direction. Corresponding profiles were simulated using analytical models of the bridge and of the ETM+ system transfer function. Model parameters were adjusted to achieve the best fit between the simulated profiles and the image measurements. The ETM+ modulation at the Nyquist frequency and the full width at half maximum of the point spread function were computed from the best-fit system transfer function model. Trending these parameters over time revealed apparent MTF performance degradation, observed mainly in the 15-meter resolution ETM+ panchromatic band. This confirmed the pre-launch model prediction that the panchromatic band was the most sensitive to changes in ETM+ optical performance.
Keywords: Landsat 7, ETM+, MTF, Point Spread Function

1. INTRODUCTION

The Landsat 7 Enhanced Thematic Mapper Plus (ETM+) sensor continues the Landsat series of multispectral, space-borne Earth remote sensing instruments that began with the launch of Landsat 1 in 1972. Launched on April 15, 1999, Landsat 7 acquires high-resolution (15-meter panchromatic, 30-meter multispectral, 60-meter thermal) imagery of Earth's land areas from a near-polar, Sun-synchronous orbit. Prelaunch testing, analysis, and modeling of the ETM+ optical system by engineers at Santa Barbara Remote Sensing (SBRS), the instrument builders, predicted that optical performance, as measured by the modulation transfer function (MTF), could be expected to change on-orbit as a result of exposure to the space environment. This prediction motivated the development of techniques to estimate the ETM+ on-orbit MTF performance using images of ground targets. These techniques were needed so that the Landsat 7 system operators could measure MTF performance over the course of the mission to validate the prelaunch predictions and to monitor data quality. This paper describes the methodology used to monitor ETM+ on-orbit MTF performance and presents the results obtained since launch.

1.1 Landsat 7 ETM+ overview

The basic sensor technology used in the ETM+ is similar to that of the Thematic Mapper instruments on Landsats 4 and 5 and the Enhanced Thematic Mapper built for Landsat 6. The ETM+ instrument detectors are aligned in parallel rows on two separate focal planes: the primary focal plane, containing the visible (including panchromatic) and near infrared spectral bands, and the cold focal plane, containing the short wave and long wave (thermal) infrared bands. The primary focal plane is illuminated by the ETM+ scanning mirror, primary mirror, secondary mirror, and scan line corrector mirrors[1]. In addition to these optical elements, the cold focal plane optical train includes the relay folding mirror and the spherical relay mirror, as shown in figure 1. The ETM+ scan mirror provides a nearly linear cross-track scan motion that covers a 183-km-wide swath on the ground. The scan line corrector compensates for the forward motion of the spacecraft and allows the scan mirror to produce usable data in both scan directions. An image data set is built as a time sequence of cross-track scans, acquired as the spacecraft orbit carries the ETM+ over the target area. The original Landsat 7 MTF performance specifications called for all ETM+ bands to exhibit modulation greater than 0.275 at the Nyquist frequency, in both the along- and across-scan directions[2]. The remainder of this paper will focus on along-scan performance. As noted in section 4 below, the ETM+ across-scan MTF performance is an area of active study. Corresponding methods for across-scan MTF estimation are currently under development.

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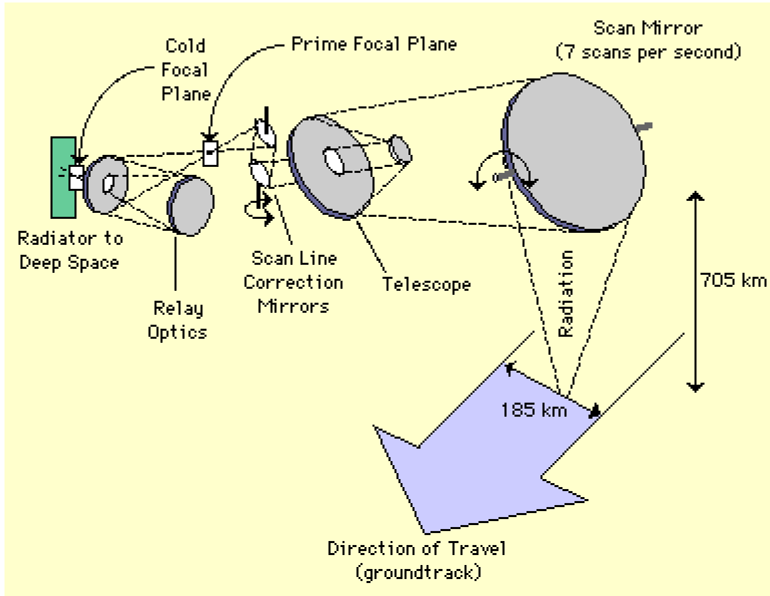

Figure 1: ETM+ Optical Path

1.2 Motivation for on-orbit MTF performance monitoring

Prelaunch analysis of the ETM+ optical system indicated that a slight change in focal properties was to be expected on orbit as residual water slowly outgassed from the ETM+ telescope structure. If uncompensated this would result in a small misfocus that would be most noticeable at the primary focal plane. To account for this, a shim was designed to adjust the primary focal plane into the fully outgassed zone of optimum focus. This would result in gradually improving on-orbit MTF performance over time. Unfortunately, the shim was installed improperly such that the benefits of this adjustment would not be realized. This error was detected too late in the Landsat 7 program to take corrective action. Instead, the effect on optical performance was evaluated through additional modeling and analysis and deemed to be acceptable. The new models predicted that on-orbit MTF performance would degrade somewhat with time with the most significant effects being observed in the 15-meter panchromatic band[3, 4]. Having the smallest detectors, the panchromatic band is most sensitive to optical effects. The model predictions indicated that this band would exhibit modulation below the 0.275 specification limit at Nyquist, once the system was fully outgassed. As a result, the specification limit was reduced to a value of 0.17 modulation at Nyquist for the panchromatic band only.

The expectation of degrading performance and the uncertainties inherent in the model predictions led to a strong desire on the part of those charged with operating, calibrating, and characterizing the Landsat 7 system: the USGS EROS Data Center and the NASA Landsat Project Science Office, to develop the capability to routinely monitor actual ETM+ on-orbit MTF performance. The data processing and analysis methods developed as a result are the topic of section 2.

2. MTF ESTIMATION METHODOLOGY

Two common approaches to the problem of measuring sensor MTF performance using images of natural (Earth) targets are: 1) to attempt to locate natural edge or line features that can be used as observations of the system's edge/line response, and 2) to compare imagery from the sensor under study with corresponding data from a higher resolution sensor[5]. The former approach is hampered by the difficulty in locating edge/line targets of sufficient size to provide a good representation of the system response. The latter method works best if the two sets of imagery are acquired at or near the same time, or at least under similar conditions, to avoid the problems associated with temporal variations in target conditions. A primary goal of the ETM+ estimation method is to provide consistent measurements of the MTF over time in order to observe and characterize performance trends. This would have led to practical difficulties in acquiring the repeated tandem ETM+ and high-resolution data sets needed for comparison using the second approach. This consideration, coupled with the identification of a ground target suitable for use in determining the line response at the ETM+ 15-meter and 30-meter resolutions, led to the adoption of the first approach in the ETM+ MTF estimation methodology.

2.1 Test target

The Lake Pontchartrain Causeway in Louisiana is a 24-mile long double span bridge that happens to be nearly aligned with the Landsat 7 ground track. The bridge is near the center of Lake Pontchartrain in the Landsat 7 browse image shown in figure 2. The bridge dimensions are such that the 15-meter panchromatic band can just resolve the two spans, whereas they appear as a single line target in the 30-meter multispectral bands. The bridge is not a usable target in the 60-meter thermal band. Although they are the same width, the two spans were constructed at different times (1956 and 1969) and exhibit slightly different reflectance. The two spans are joined by a series of seven crossovers, used as turn-around areas by emergency vehicles. In addition to the crossovers, there are two locations on the bridge where the surface material changes causing short segments of much lower than normal reflectance. Other than these dark gaps and the bright crossovers, the bridge and its water background are reasonably uniform.

Figure 2: Lake Pontchartrain Causeway target area

2.2 Data preparation

Landsat 7 acquires the Lake Pontchartrain scene (Worldwide Reference System path 22 and row 39) every 16 days. Cloud-free acquisitions of the Causeway become candidates for MTF characterization. The selected test scenes were processed to Level 1R on the Landsat 7 Image Assessment System[6]. At this processing level the data have been radiometrically corrected to scaled (16-bit integer) at-aperture radiance but have not been geometrically resampled. Thus, each image pixel represents the calibrated output of a single imaging detector. Since the Level 1R data are geometrically unprocessed, the effects of the ETM+ cross-track scanning pattern are readily visible. Figure 3 shows several scans of panchromatic band data surrounding one of the bridge crossovers. The ETM+ scanning pattern, coupled with a slight rotation of the bridge relative to the Landsat 7 ground track, leads to variations in the phase at which the detectors intersect the bridge. This makes the image scans containing the bridge appear as a sequence of samples of a cross-scan line target acquired with varying phases.

A 64-scan image window containing the bridge was extracted from each of the seven reflective bands: the five visible and near infrared (VNIR) bands from the primary focal plane, and the two short wave infrared (SWIR) bands from the cold focal plane. A 16-sample window surrounding the bridge was then automatically extracted from each image line by centering the window on the peak of a three-point moving average across the line. The resulting collection of image data (16 samples by 1024 lines for the 30-meter bands, and 16 samples by 2048 lines for the 15-meter panchromatic band) constituted the fundamental observations used in all subsequent analyses.

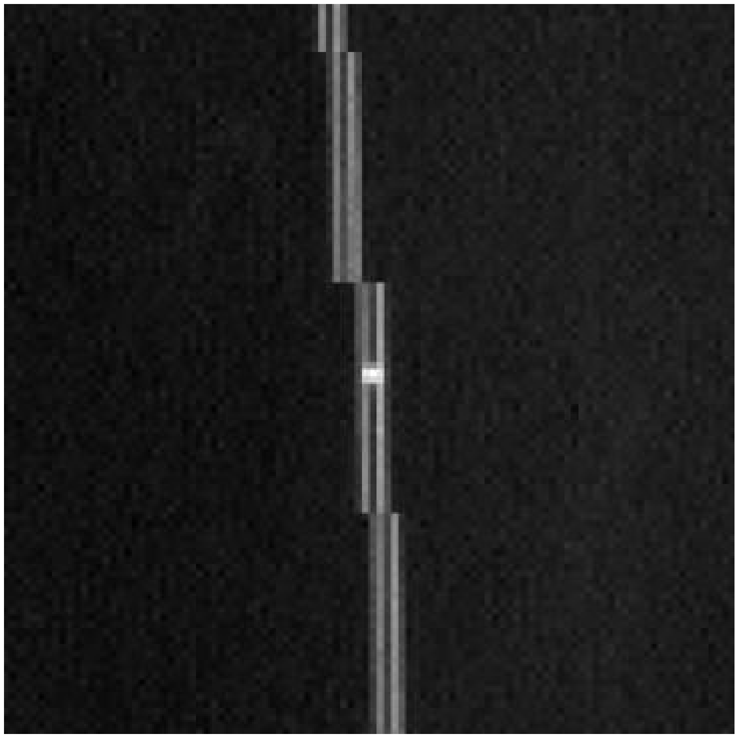

Figure 3: Bridge crossover detail (panchromatic band)

The next step in reducing the radiometrically corrected imagery of the bridge was to remove the anomalous samples created by the seven bridge crossovers and the two apparent gaps mentioned above. The image lines containing these features were deleted from the data set. The remaining image lines were then sorted by scan direction to separate the forward (west-to-east) and reverse (east-to-west) scan data. Each line was then classified according to the phase at which it intersected the bridge, by correlating the image data with a set of templates representing ideal cross sections of the bridge at phase angles varying in $1/8^{th}$ pixel increments. Thus, each image line was assigned to one of eight phase bins.

The image line segments were sorted by phase and the lines in each phase bin were averaged to construct a set of eight 16-point mean representations of the bridge cross section at $1/8^{th}$ pixel increments for each scan direction. The eight mean bridge profiles were then interleaved to construct a single 128-point profile, oversampled by a factor of eight. This pixel interleaving approach is described in more detail elsewhere[7] and is similar to the method used to analyze the prelaunch ETM+ MTF test data[8]. The net result is a single image data line of the bridge cross section, effectively sampled at eight times the actual ETM+ sampling rate. This measurement of the ETM+ response to the bridge target can be compared to a theoretical response constructed from analytical models of the target and the ETM+ system transfer function (STF). An estimate of the effective ETM+ STF can be derived by varying the parameters of the analytical models to best fit the observed data profile.

2.3 Target model

The analytical target and STF models were constructed in the frequency domain and transformed to the spatial domain, via an inverse fast Fourier transform (IFFT), for comparison to the image data. The target model treats the double span bridge as a pair of rectangular pulses, of unequal amplitude, against a constant background. Assuming a coordinate system origin midway between the two bridge spans, the three components of the target model can be expressed in the frequency domain:

Left Span: $$l(\omega) = d \ \mathrm{sinc}(\frac{\omega d}{2}) \ e^{j\omega\frac{d+g}{2}} \qquad j = \sqrt{-1} \qquad (1)$$

Right Span: $$r(\omega) = d \ \text{sinc}(\frac{\omega d}{2})\ e^{-j\omega \frac{d+g}{2}} \quad (2)$$

Water: $$\delta(\omega) = \begin{cases} 1 & \text{if } \omega = 0 \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

where: ω = spatial frequency in radians per meter,
d = bridge span width = 10.0 meters,
g = gap between spans = 24.4 meters,
sinc(x) = sin(x)/x.

The terms "left" and "right" span are used to apply to the first and second, respectively, span seen by the ETM+ detectors during a scan. Thus, during forward scans, the westernmost span is on the "left" and the easternmost span is on the "right", while during reverse scans the easternmost span is on the "left" and the westernmost span is on the "right". This formulation puts the forward and reverse scan target models in time-order. In the subsequent data analysis, the observed reverse scan data profiles were also inverted to put them in time order to make it easier to use a single STF model for both scan directions. The target model components are used to construct the target models for forward and reverse scans as:

Forward Scan: $$\text{fwd}(\omega) = A_W\ l(\omega) + A_E\ r(\omega) + A_B\ \delta(\omega) \quad (4)$$

Reverse Scan: $$\text{rev}(\omega) = A_E\ l(\omega) + A_W\ r(\omega) + A_B\ \delta(\omega) \quad (5)$$

where: A_W = western bridge intensity,
A_E = eastern bridge intensity,
A_B = background water intensity,
$l(\omega),\ r(\omega),\ and\ \delta(\omega)$ are as defined above in (1), (2), and (3).

In applying this target model, the three target component intensities: A_W, A_E, and A_B, were taken to be scene specific variables while the target dimensions: d and g, which were obtained from the Louisiana State Department of Transportation and Development and from the Lake Pontchartrain Causeway internet site, were held fixed.

2.4 System transfer function model

The system transfer function model adopted for the ETM+ is the same as that used by Markham[9] in his analysis of the Thematic Mapper (TM) instruments' spatial response. This transfer function model has three components: 1) an optics model that treats the effects of the ETM+ optical system as a Gaussian blur, 2) a detector model that assumes the detector spatial response is a rectangular pulse, and 3) an electronics model that treats the ETM+ electronic prefilter circuitry as a four pole (two real and two imaginary) low pass Goldberg filter. Although the TM and ETM+ electronics were designed as a three pole (one real and two imaginary) low pass filter, prelaunch tests with the TM showed that the actual filter response was better characterized by a four pole model[9]. The frequency domain representations of these STF model components are:

Optics: $$O(\omega) = e^{-\frac{\omega^2 \sigma^2}{2}} \quad (6)$$

where: σ = optical blur parameter.

Detector: $$D(\omega) = \text{sinc}(\frac{\omega\, r}{2}) \quad (7)$$

where: r = detector dimension.

Electronics: $$E(\omega) = \frac{1}{\left(1 + j\frac{f}{f_1}\right)\left(1 + 2Lj\frac{f}{f_2} - \left(\frac{f}{f_2}\right)^2\right)\left(1 + j\frac{f}{f_3}\right)} \quad (8)$$

where: $f = \omega / 2\pi$,
f_1, f_3 = real pole frequencies,
f_2 = complex pole frequencies,
L = complex pole pair damping coefficient.

The STF model parameters were initially specified in at-sensor angular units. They were converted to units of ground meters using the Landsat 7 orbital altitude as a scaling factor. This produced a system transfer function model scaled to match the target model and the image data. A scan direction dependent phase shift is included along with the STF model components from equations (6), (7), and (8) to construct the composite STF models for forward and reverse scans:

Forward STF: $$STF_F(\omega) = O(\omega)\ D(\omega)\ E(\omega)\ e^{-j\omega X_F} \quad (9)$$

where: X_F = scene dependent forward scan phase shift.

Reverse STF: $$STF_R(\omega) = O(\omega)\ D(\omega)\ E(\omega)\ e^{-j\omega X_R} \quad (10)$$

where: X_R = scene dependent reverse scan phase shift.

The magnitude response of the composite STF is plotted in figure 4 along with the magnitudes of the optics, detector, and electronics components. The plot is based on nominal values for the STF parameters.

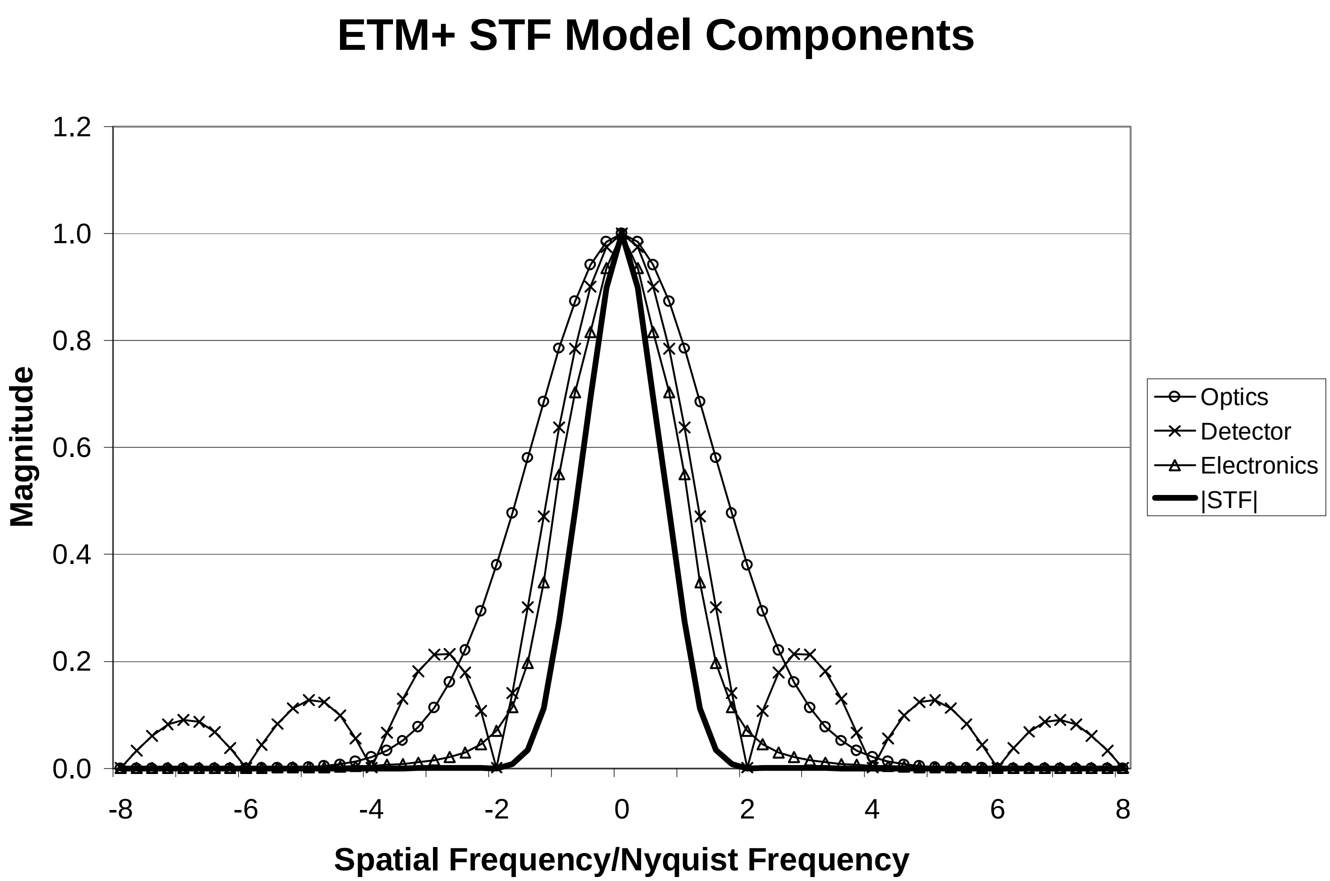

Figure 4: System transfer function model components

The composite STF model includes a total of eight parameters: the optical blur (σ), the detector dimension (r), the four electronic filter parameters (three frequencies plus the damping coefficient), the forward scan phase angle (X_F), and the reverse scan phase angle (X_R). The optical blur parameter is the key unknown, believed to be subject to change over time due to telescope outgassing. Prelaunch measurements of the effective detector dimensions[10] allowed this parameter to be held fixed. Ideally, the same would be true of the electronic filter parameters. Only the values for the three pole design filter frequencies were available for the ETM+. Since the analysis of the TM prelaunch test data demonstrated that the actual filter performance deviated somewhat from the design values[9], the ETM+ filter parameters were treated as unknowns. The phase parameters are scene specific offsets used to align the analytical model to the measured image data and must be uniquely determined for each data set.

2.5 Estimation procedure

ETM+ MTF performance estimates for the VNIR, panchromatic, and SWIR bands of each target area scene were derived by computing values for the ten variable model parameters (the three target model intensity parameters and seven STF model parameters defined in sections 2.3 and 2.4) to best-fit the oversampled forward and reverse scan data profiles (described in section 2.2) for each band. This process involved iteratively generating model profiles by multiplying the forward and reverse scan frequency domain STF models by the corresponding frequency domain target models, and applying inverse fast Fourier transforms to convert the results to the spatial domain. The root-mean-square (RMS) difference between these model profiles and the oversampled data profiles was the metric used to evaluate the fit between the model and the data. The iterative solution process used a gradient search method to minimize the RMS difference. As noted above, the sample sequence for the reverse scan data profile was inverted to put the data in temporal, rather than spatial, order prior to computing the fit, to simplify the generation of the corresponding reverse scan model profile. Figures 5 and 6 show example plots of the model fit for the near infrared (NIR) and panchromatic bands acquired on December 22, 2000.

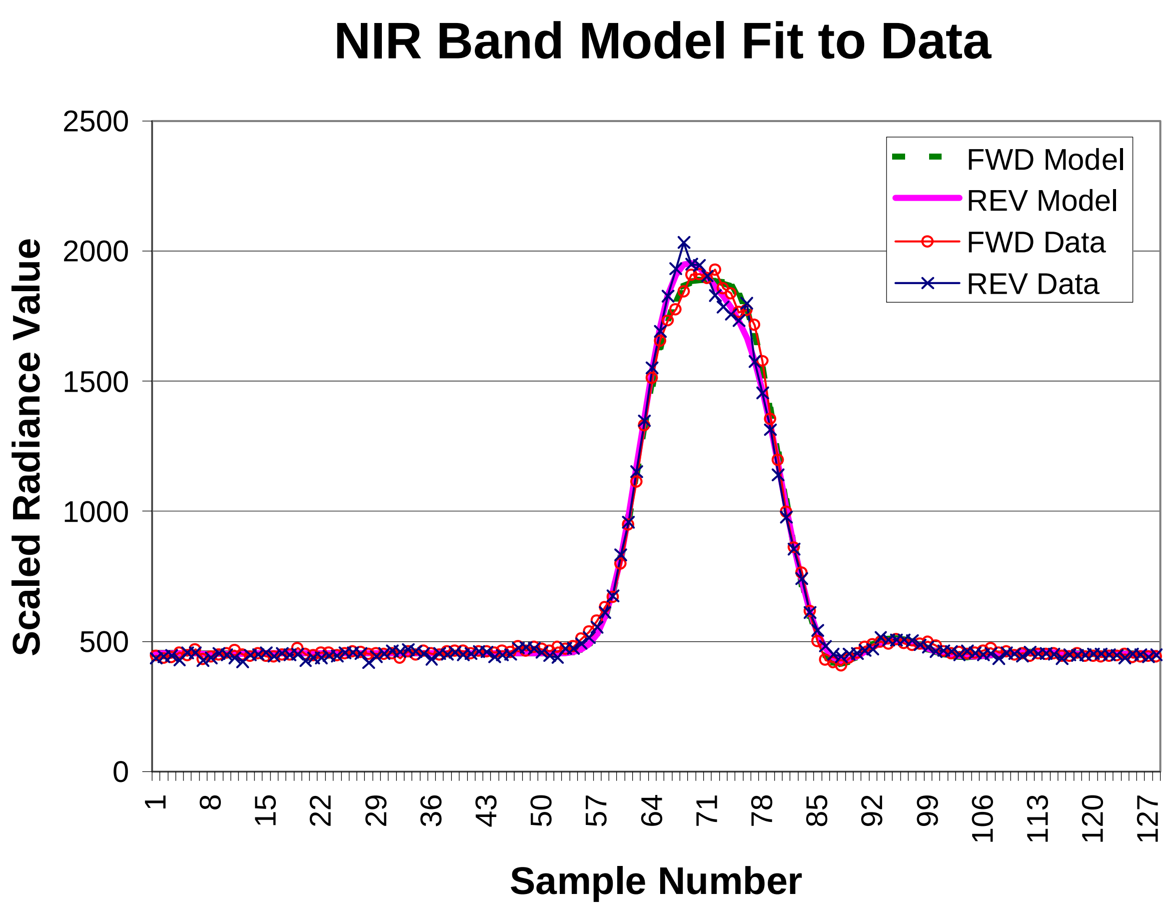

Figure 5: Near infrared band model fit to image data

The iterative solution method requires reasonable beginning values for the model parameters to converge to a valid result. Adopting the best-fit values from the previous scene analyzed set the initial STF model parameters. Nominal values were used for the first scene processed. This approach takes advantage of the fact that the STF parameters, with the exception of the scene dependent phase angles, are expected to be constant or varying slowly with time. Initial values for the target intensity parameters and for the STF forward and reverse phase angles were computed using a preliminary fit to the data in which only those five parameters were allowed to adjust. All ten parameters were then adjusted to best fit the model to the data. Several of the STF model parameters are highly correlated leading to slow convergence or, in extreme cases, even divergence of the iterative solution. In particular, the correlation between the optical blur parameter and the electronic filter parameters can lead to poorly determined solutions in which optical effects are difficult to distinguish from electronics effects. This was a more significant problem for the 15-meter panchromatic band than it was for the 30-meter bands.

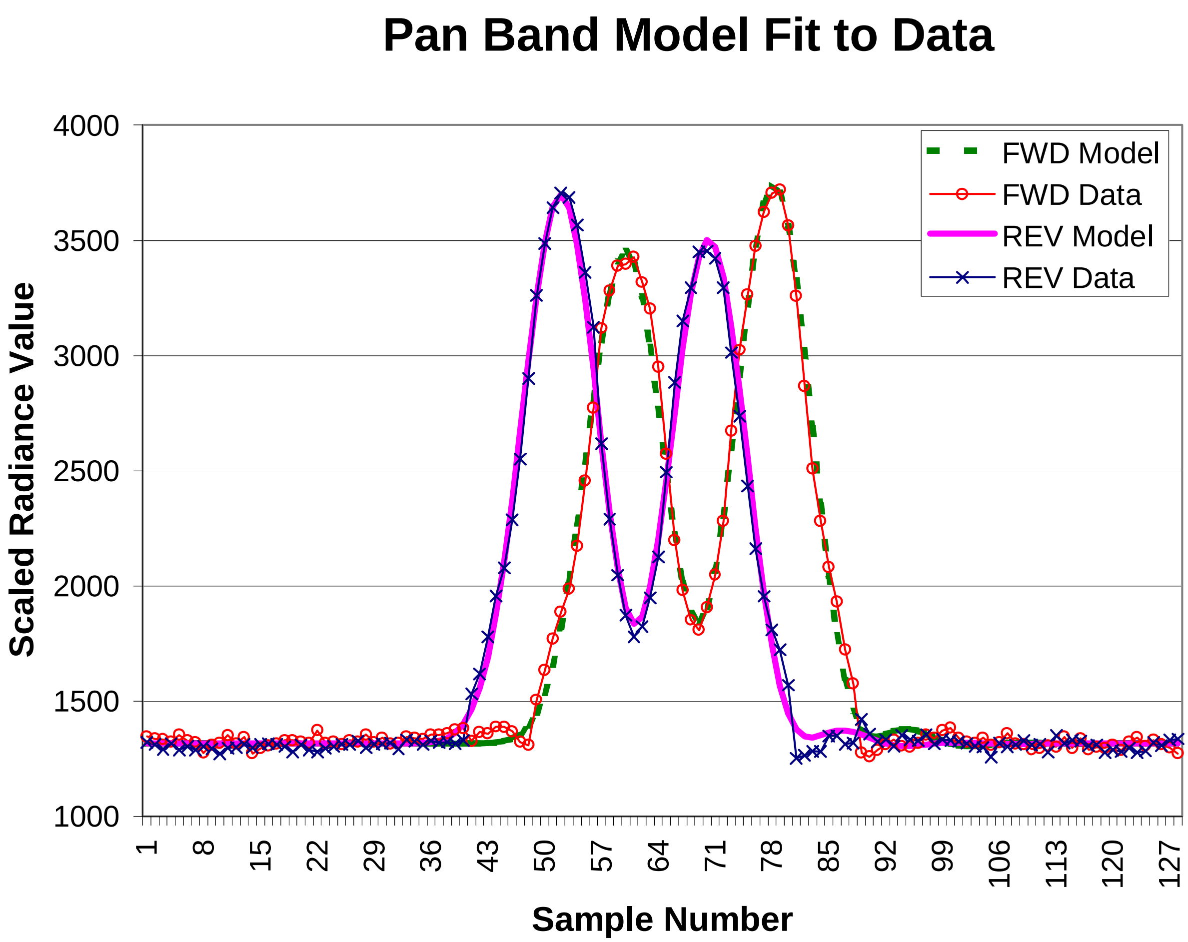

Figure 6: Panchromatic band model fit to image data

The plots in figures 5 and 6 show that the bridge target dimensions are such that the two spans can be distinguished by the 15-meter panchromatic band while they appear as a single feature in the 30-meter bands. A comparison of the two plots also reveals that the electronic filter's overshoot or "ripple" effect following the bridge target is more pronounced in the 30-meter band. This is probably due to the optical blurring effect (which is similar for all bands) more significantly suppressing the electronic filter effects (which scale with the band resolution) at the higher resolution. This seems to make the electronic filter parameters more difficult to estimate using the panchromatic band data. In fact, the STF parameter solution diverged for a few panchromatic band data sets making it necessary to hold the electronic filter parameters fixed. Average values from other data sets that did not have convergence problems were used in those cases.

3. RESULTS

A total of seventeen scenes of the Lake Pontchartrain test area were acquired, processed, and analyzed over the first two years of the Landsat 7 mission. These data sets span the time period from June 3, 1999 through June 16, 2001. Best-fit STF parameters were computed for the panchromatic band, and for the six 30-meter VNIR and SWIR bands, for each of these scenes, using the methods described in section 2. After the best-fit STF model parameters were computed they were used to generate MTF and point spread function (PSF) models by taking the magnitude and IFFT of the STF, respectively[11]. The MTF model was used to evaluate the MTF at the Nyquist frequency, providing a simple characteristic parameter for trending purposes. Similarly, the full width at half the maximum (FWHM) value of the PSF was computed to characterize the system's performance in the spatial domain. All of the target and STF model parameters as well as the RMS model fit metrics and the derived MTF at Nyquist and PSF FWHM parameters, were recorded and tracked over time.

3.1 Data sets analyzed

The initial goal of the ETM+ MTF analysis program was to evaluate the system performance monthly, if possible based on the availability of cloud free target scenes. Suitable data sets were acquired and processed for five of the seven months from June through December 1999 and for nine of the twelve months in 2000. An additional scene from the first week of January 2000 was used to partially fill the data gap caused by a lack of scenes in December 1999. Excessive cloud cover prevented successful acquisitions of Lake Pontchartrain for the first four months of 2001 but usable scenes were available for May and June. Other than the gap in early 2001, data availability has not been a serious problem for monitoring the ETM+ MTF.

3.2 Point spread function characterization

For each image band, the width of the point spread function was computed using the analytical STF model. The STF phase parameter was varied to maximize the central value of the corresponding point spread function. Starting from the maximum value, the phase was first increased until the PSF value was half the maximum value, and then decreased until the PSF was halved. The difference between these two half maximum phase values, converted to ground meters, was taken to be the PSF FWHM. The PSF parameters computed in this way are shown in figures 7 and 8.

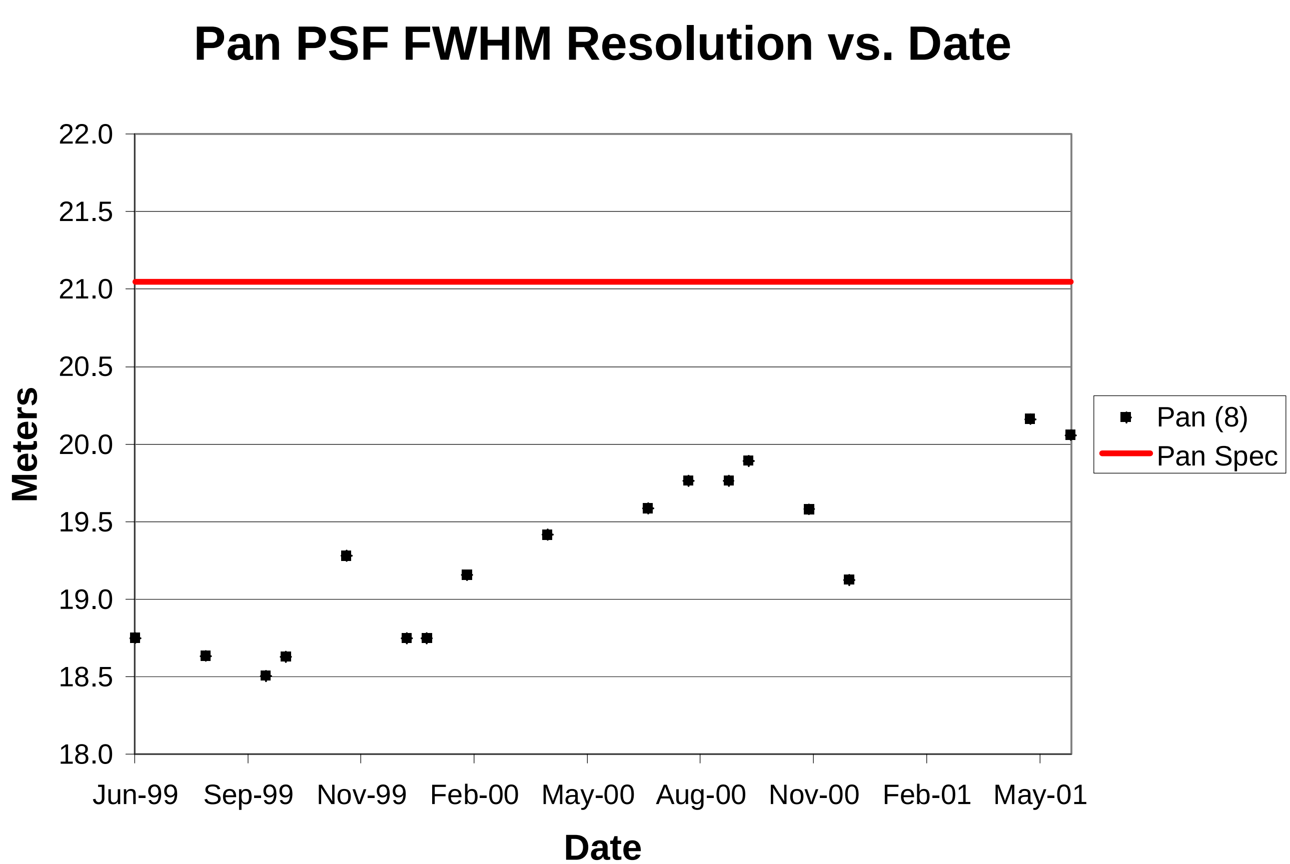

Figure 7: Panchromatic band PSF full-width at half maximum over time

The PSF width plots in figures 7 and 8 both show specification reference lines to place the measured data in context. These values were computed by adjusting the STF model parameters to best fit the Landsat 7 MTF performance specifications. ETM+ MTF performance was originally specified as greater than or equal to 0.275 at Nyquist, 0.551 at two-thirds Nyquist, and 0.692 at half Nyquist[2]. The STF model that best fit these values yielded the PSF FWHM thresholds plotted as the "Spec" line in figure 8. As noted in section 1.2, this specification was relaxed to 0.170 modulation at Nyquist, 0.461 at two-thirds Nyquist, and 0.627 at half Nyquist for the panchromatic band. This is reflected in the "Pan Spec" line in figure 7.

Figure 8 shows that the SWIR bands, located on the cold focal plane, generally exhibit narrower PSFs than the VNIR bands on the primary focal plane. Of the VNIR bands, the NIR band appears to have the poorest performance. This also bears out the prelaunch model predictions, which indicated that the bands at the edges of the primary focal plane: the panchromatic band and the NIR band, would be the most seriously affected by any optical degradation. Both figures 7 and 8 show a slight trend of increasing PSF width over time for all bands suggesting that the predicted on-orbit optical degradation has occurred.

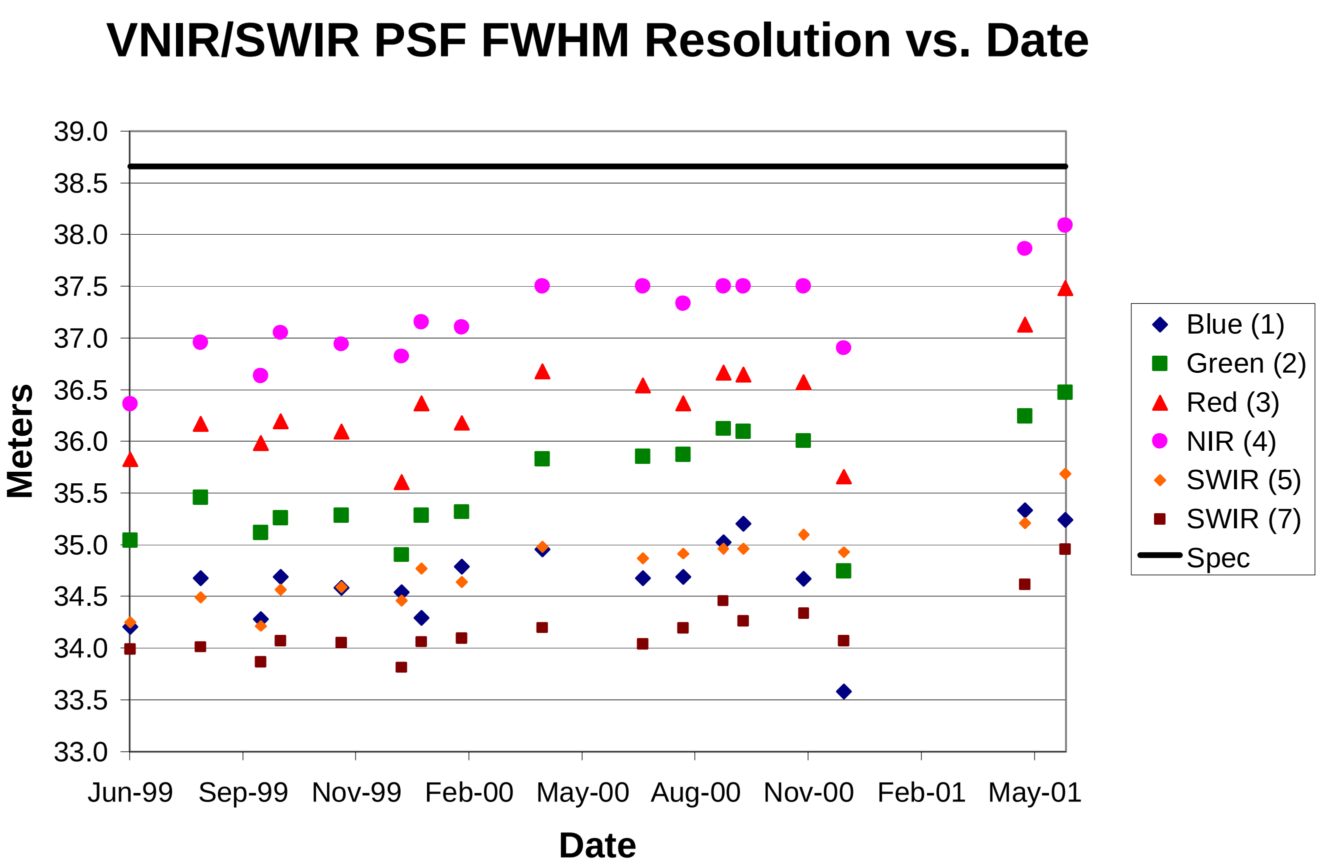

Figure 8: VNIR/SWIR PSF full-width at half maximum over time

3.3 MTF at Nyquist frequency characterization

The ETM+ MTF at Nyquist for each band in each test scene was evaluated directly from the best-fit STF models by evaluating the magnitude of the model at the Nyquist frequency. Figure 9 shows the resulting performance trends for all bands over time. In addition to the 0.275 modulation at Nyquist specification threshold, this plot also includes the panchromatic band performance trend predicted using the prelaunch optical models[3]. The MTF performance plots for the 30-meter bands show the frequency domain representation of the information presented in figure 8. Figure 9 shows that the panchromatic band performance, while below the original 0.275 modulation at Nyquist specification has remained above the relaxed 0.17 modulation threshold. It is also reasonably consistent with the prelaunch model prediction. The prediction and the data fall within the same range and were very close through much of 2000. Further, the results suggest that the actual performance was poorer than expected at launch but that it has degraded at a somewhat slower rate than predicted.

All of the plots also demonstrate that there is substantial variation from date to date. In most cases, all of the bands tend to fall above or below the general trend for certain dates. The consistently higher values from the December 2000 scene are a good example of this. These excursions are probably due to variations in atmospheric and target conditions. The data also suggest that there may be a seasonal component to this, with winter scenes typically yielding better performance than summer scenes, possibly due to lower atmospheric humidity or more uniform surface water conditions.

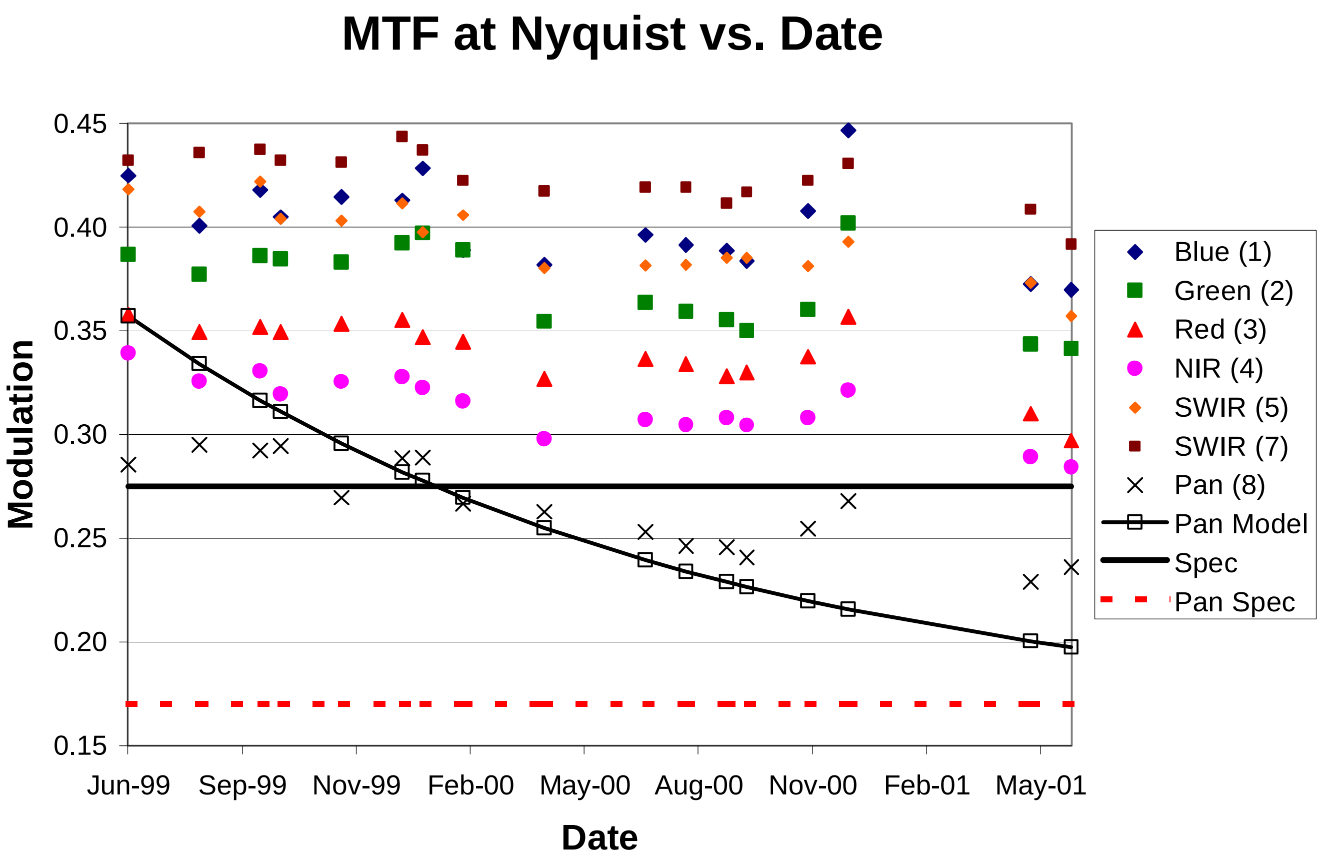

Figure 9: MTF at Nyquist frequency over time

4. CONCLUSIONS AND FUTURE WORK

The results for the first two years of the Landsat 7 mission, produced by the on-orbit MTF estimation method described above, are consistent with the prelaunch model predictions for ETM+ along-scan performance. In particular, the on-orbit data confirm the presence of the predicted gradual MTF performance degradation. In quantitative terms, after two years the panchromatic band MTF performance, as measured by the modulation at the Nyquist frequency, has been measured to be approximately midway between the original 0.275 modulation specification and the relaxed 0.17 modulation specification value, decreasing at a rate slightly slower than the model prediction. The consistency between the prelaunch model and the on-orbit measurements and the relative stability of the on-orbit measurements across the spectral bands and from date to date, suggest that the MTF estimation method is yielding useful results, and is achieving the goal of providing a means of monitoring the changing ETM+ MTF performance.

Work is continuing to improve the estimation method, particularly by deriving better estimates of the electronics filter parameters from prelaunch test data. This would make it possible to remove these variables from the model fit to on-orbit data, yielding more stable and rapidly converging solutions.

Techniques for estimating ETM+ MTF performance in the across-scan direction are also under development. Initial experiments using ground targets rotated away from the Landsat 7 ground track have produced promising results.

The STF estimates produced from on-orbit data analysis are also being used to derive reconstruction filter parameters for use in MTF compensation processing. MTF compensation is a user-selectable option available for resampling Landsat 7 Level 1G image products. The new reconstruction parameters would be available for use in, at least partially, compensating for the ETM+ optical blurring effects during Level 1G product generation.

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