NPOESS VIIRS: Design, Performance Estimates and Applications

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Abstract

This paper summarizes design, performance estimates and applications of the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Visible Infrared Imager Radiometer Suite (VIIRS). VIIRS is progressing toward Engineering Development Unit (EDU) integration and flight model assembly for launch on the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP) satellite. Applications of VIIRS are anticipated to represent dramatic improvements over heritage capability from the Defense Meteorological Satellite Program (DMSP) Operational Line-scanning System (OLS) and the National Oceanic and Atmospheric Administration (NOAA) Polar-orbiting Operational Environmental Satellite (POES) Advanced Very High Resolution Radiometer (AVHRR). VIIRS draws heavily on the NASA Earth Observing System (EOS) MODerate resolution Imaging Spectroradiometer (MODIS) currently operating aboard the Terra and Aqua satellites, offering similar spectroradiometry at better spatial resolution. VIIRS on-orbit performance simulations based on MODIS data illustrate the dramatic improvements VIIRS will offer compared to current operational satellites for meteorology.

Background and VIIRS Design

The National Polar-orbiting Operational Environmental Satellite System (NPOESS) will replace the current military and civilian operational polar-orbiting environmental systems and provide supplemental data to the earth sciences community based on Environmental Data Records (EDRs) defined by the NPOESS Integrated Operational Requirements Document (IORD). The NPOESS Integrated Program Office (IPO) contracted with Raytheon from November 1997 to September 2002 to develop the Visible Infrared Imager Radiometer Suite (VIIRS) design, based on the VIIRS Sensor Requirements Document (SRD). Raytheon had responsibility for VIIRS EDR performance as well as sensor design and development to meet the sensor specification. In September 2002, the Raytheon contract was transferred to Northrop-Grumman Space Technology (NGST), and the EDR responsibility was also transferred to NGST, with Raytheon under contract to NGST to supply the sensor. The first VIIRS will fly on the joint NASA-IPO NPOESS Preparatory Program (NPP) for NPOESS risk reduction.

Figure 1 shows different views of the VIIRS design layout; a functional block diagram is provided in Figure 2. Sensor performance is predicted using models developed by Raytheon. VIIRS collects radiometric and imagery data in 22 bands from 0.4 to 12.5 μm to support worldwide DoD and civilian operations. With direct heritage to the MODerate resolution Imaging Spectroradiometer (MODIS) now flying on NASA's Terra and Aqua Earth Observing System (EOS) (Schueler and Barnes 1998), VIIRS data will support EDRs such as sea surface temperature (SST) and soil moisture; atmospheric aerosols and suspended matter; cloud base height, cover and layers, particle size, and optical depth; land EDRs such as surface temperature, snow cover and vegetation; and ocean EDRs including net heat flux and chlorophyll concentration. Many of the required VIIRS data products have been generated by the MODIS

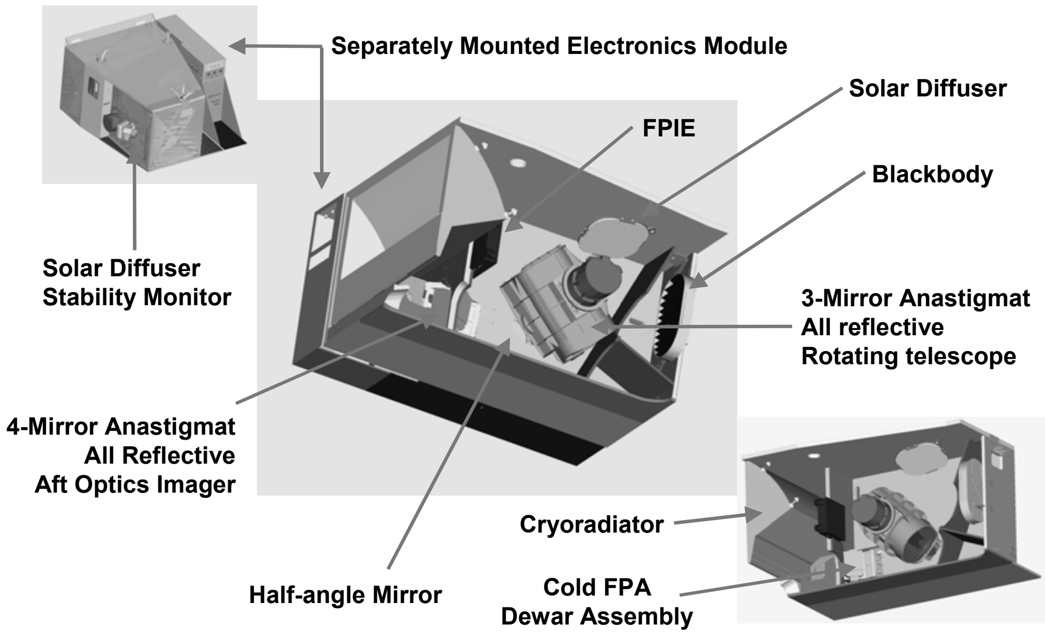

Figure 1: Single sensor design contains substantial flight hardware heritage.

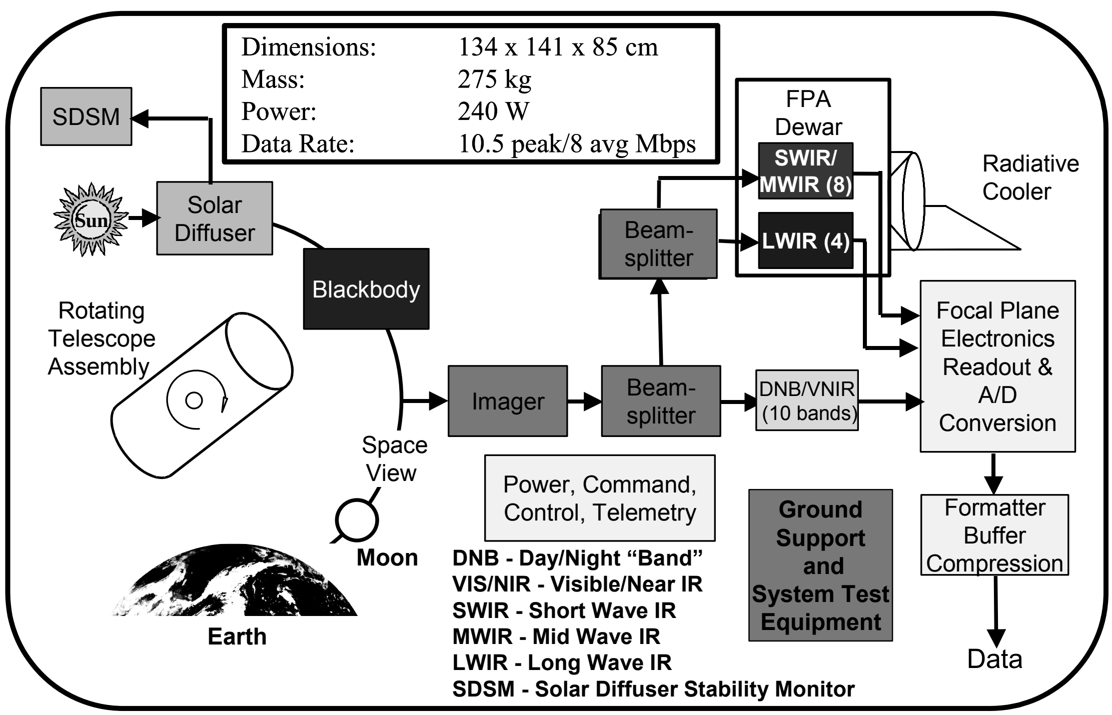

Figure 2: VIIRS block diagram traces photons from the Earth scene or internal calibration mechanisms to the focal plane arrays (FPA) and data output.

science team demonstrating VIIRS expected performance. In particular, with relevant performance comparable to VIIRS sensor requirements, MODIS has demonstrated SST, one of three key NPOESS EDRs, meeting VIIRS SST EDR accuracy and precision requirements. This provides confidence that so long as VIIRS meets its sensor performance requirements, the EDRs will also be met.

VIIRS Predicted Performance

VIIRS sensor performance is predicted using a comprehensive range of models and simulations for signal-to-noise ratio (SNR), modulation transfer function (MTF), radiometric accuracy, polarization performance, structural and thermal design and performance and many other performance characteristics. Some models are VIIRS-specific, such as the Microsoft Excel SNR and dynamic-range model and the reflective and emissive band absolute radiometric error Mathcad models. Inputs to these models are derived from other modeling and simulation programs such as the optical transmission, MTF, forward and reverse ray tracing, and polarization models in Code V, advanced sensor applications program (ASAP) and the SINDA thermal model. SNR, spectral radiance dynamic range, spatial MTF, polarization, radiometric accuracy, and structural and thermal performance under operational environments represent the primary sensor performance parameters that determine VIIRS overall environmental data record (EDR) performance success.

VIIRS performance requirements in each of the 22 spectral bands are largely derived from driving EDR requirements for each channel that include horizontal sample interval (HSI), SNR and “typical” radiances or scene temperatures at which SNR is specified. VIIRS meets required performance with margin in all bands.

HSI is not the same as horizontal spatial resolution (HSR), although for most spectral bands the two are very close in value. HSR is defined as half the inverse of the spatial frequency at which the MTF equals 0.5. The imagery EDR’s fine HSR requirements were met with balanced optical and focal plane MTFs. The detector field stops in the moderate resolution (radiometry) bands were sized to provide improved HSI for coarser horizontal cell size (HCS) non-imagery EDRs, which also improves detector yield and SNR. VIIRS offers HSI <1.3 km nearly to edge-of-scan (EOS) in all bands, though this HSI is required only to 43.6 degrees off-nadir. VIIRS offers finer nadir HSI than the Polar-orbiting Operational Environmental Satellite (POES) Advanced Very High Resolution Radiometer (AVHRR) and the NASA Earth Observing System MODIS instruments, and with better nadir SNR via 3:1 aggregation following a patented design approach (Schueler 1997) as illustrated in Figure 3. At edge of scan (EOS), indicated as “@3000km” in Figure 3, the HSI (and spatial resolution) is 4:1 finer in the cross-track dimension compared to AVHRR and MODIS, yet with comparable SNR, and better than the DMSP OLS. Diverse civil and DoD requirements therefore support one another through an integrated single-sensor design that balances improved imagery and spectroradiometry.

VIIRS is required to meet sensitivity requirements over a broad range in scene radiance that is defined by two typical radiances or temperatures in “dual-gain” bands. In seven bands the saturation radiance and SNR requirements at low radiance made it impractical to meet both the dynamic range and sensitivity requirements with a single detector-channel gain setting. In these cases, Raytheon could have designed two separate detector arrays to meet the EDRs, one with high gain and excellent low radiance sensitivity, and another with lower gain and high saturation radiance. MODIS uses this approach for several spectral bands because when MODIS was designed in 1990, similar conflicting dynamic range and sensitivity requirements could not be met with one detector array. Raytheon since developed a readout integrated circuit (ROIC) capacitive transimpedance amplifier (CTIA) unit-cell with automatic gain control to cover the dynamic range, called “dual-gain.” This allows the data necessary for the wide range of VIIRS EDRs to be accommodated with fewer detector arrays, reducing cost, data rate, and electronics mass, power, and volume.

The predicted SNR for all bands except the Day/Night Band (DNB) from nadir to EOS for both single and dual-gain bands have margin of better than 20%. The DNB CCD array provides a minimum SNR greater than 5.7 at EOS under its minimum radiance condition. The models used to predict SNR have been updated to take into account the most recent estimates of optical transmission based on tests of silver mirror witness samples, measured dichroic and spectral filter performance and a reduction in optical aperture resulting in an f/6.2 system. Data from on-orbit MODIS and Enhanced Thematic Mapper (ETM) instruments were used to predict end-of-life optical transmission degradation due to long-term exposure to Earth-reflected ultraviolet radiation. Additionally, measured Noise Equivalent Irradiance (NEI) data from Engineering Development Unit (EDU) focal planes indicate that the associated noise allocations in the SNR model will generally be achievable and with significant margin for many bands.

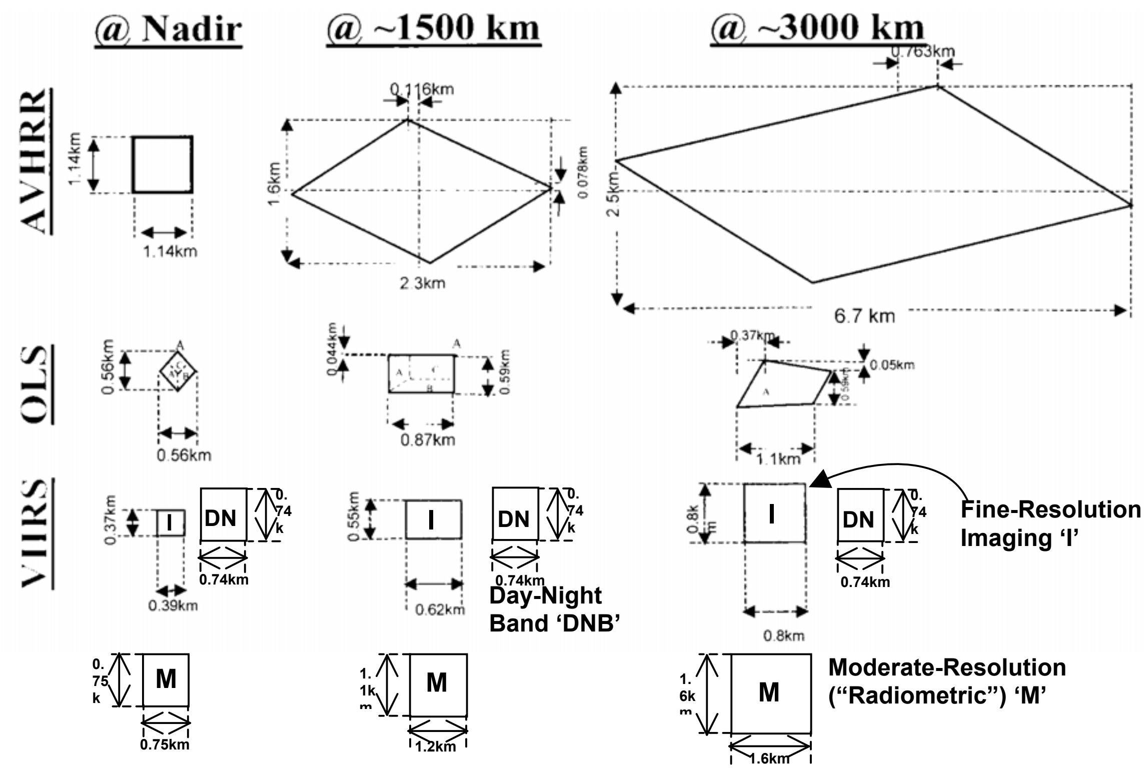

Figure 3: VIIRS provides finer spatial resolution and sampling than AVHRR or MODIS in the moderate-resolution bands, as well as improved sampling compared to OLS.

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In parallel, the sensor thermal model was updated to provide higher fidelity predictions of internal sensor surface temperatures as a function of time in orbit (representative thermal data shown in Figure 4). These updated thermal predictions were used in the emissive band radiometric uncertainty model to verify that the design will achieve the excellent emissive band radiometric performance predicted at CDR.

A modest band-to-band registration improvement was possible by optimizing the location of the S/MWIR and LWIR detector field stops so that their locations better compensate residual pin cushion distortion in the overall sensor optical system. The updated band-to-band registration model predicts that the areas associated with spatially overlapping instantaneous fields of view (IFOVs) of specified moderate resolution S/MWIR and LWIR bands will be matched to better than 82%.

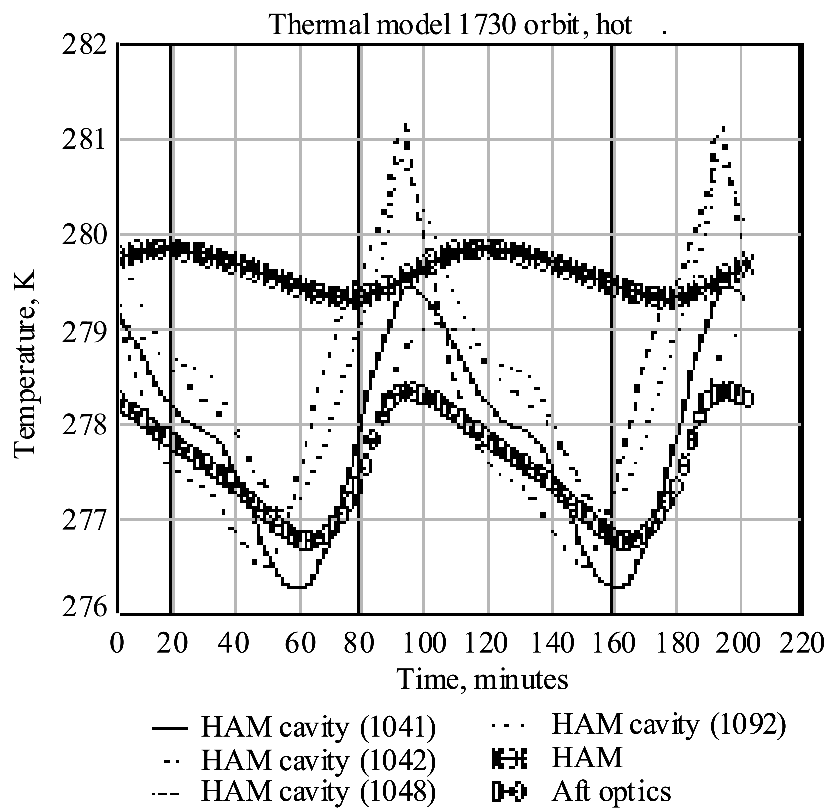

Figure 4: VIIRS thermal modeling provides details of internal time-varying temperatures.

MODIS Similarity to VIIRS Allows Realistic Simulations

While MODIS does not precisely emulate VIIRS, particularly in terms of spatial resolution over the entire swath, MODIS is the key heritage that led to the VIIRS design. Most of the MODIS bands offer 1km spatial resolution similar to AVHRR, and therefore, near nadir, comparable spatial resolution to VIIRS moderate resolution bands as illustrated in Figure 3. Moreover, MODIS has a few bands at 250 and 500 m nadir spatial resolution, comparable to the VIIRS imagery bands. Therefore, by applying near-nadir MODIS data to algorithms based on VIIRS-equivalent spectral bands, it is possible to create rather realistic VIIRS data simulations that illustrate the anticipated VIIRS on-orbit performance from a visual user perspective. NRL has done this type of simulation work in an effort to provide field users with direct insight into the benefits of VIIRS data. As users have become familiar with MODIS data through actual application, these exercises have been more than academic in nature.

Simulated VIIRS Performance Based on Landsat Data

As shown in Figure 3, VIIRS restricts pixel growth with increasing scan angle, improving the sharpness and accuracy of EDRs. Figures 5 and 6 show examples of the improvement. Using Landsat data, Figure 5 simulates AVHRR visible image degradation. The image, especially this high-resolution zoom, is practically unusable at the edge. In simulating VIIRS in the same way (Figure 6), the degradation is practically not noticeable. The result will be a greatly increased ability to use VIIRS in high-resolution forecasting situations.

Simulated VIIRS Performance Based on DMSP OLS Data

The VIIRS DNB (Lee et al., 2004) can be anticipated by viewing DMSP OLS (Johnson et al., 1994), but the DNB images are likely to be far superior. Unfortunately, it is difficult to simulate this improvement due to the lack of higher-resolution data. However, some reasonable appraisals of likely changes with VIIRS can be made. The IFOV of DMSP OLS at nadir is 2.2 km; with VIIRS DNB it will be 0.74 km. Thus, lights (including cities) that one can see in images (e.g., Figure 7) are likely to be far more numerous, allowing much more effective use of the data for energy assessment, economic development and population studies. VIIRS will also eliminate a number of image artifacts such as the solar glare shown in the upper portions of Figure 8. The “constant contrast” feature of VIIRS DNB will also eliminate the uneven transition from day to night along the day/night terminator seen in many DMSP OLS images (not shown).

Summary

The NPOESS VIIRS is a 22-band single sensor design employing a cross-track rotating telescope assembly (RTA) and offering dramatically improved spatial resolution, spectral coverage, and radiometry compared to POES AVHRR and DMSP OLS. VIIRS performance has been modeled via an extensive set of commercial ray tracing and structural and thermal design programs, as well as VIIRS-specific radiometric models developed by Raytheon. These models have been validated against flight hardware measurements on earlier programs and on VIIRS engineering development hardware. The predicted performance based on these models shows margin against the sensor specification. To provide users with a clearer perspective on what these performance predictions mean in terms of real applications capability, NRL used MODIS data to simulate VIIRS performance in a number of applications scenarios. These simulations have been compared to current capability to illustrate the dramatic operational improvements that VIIRS will offer.

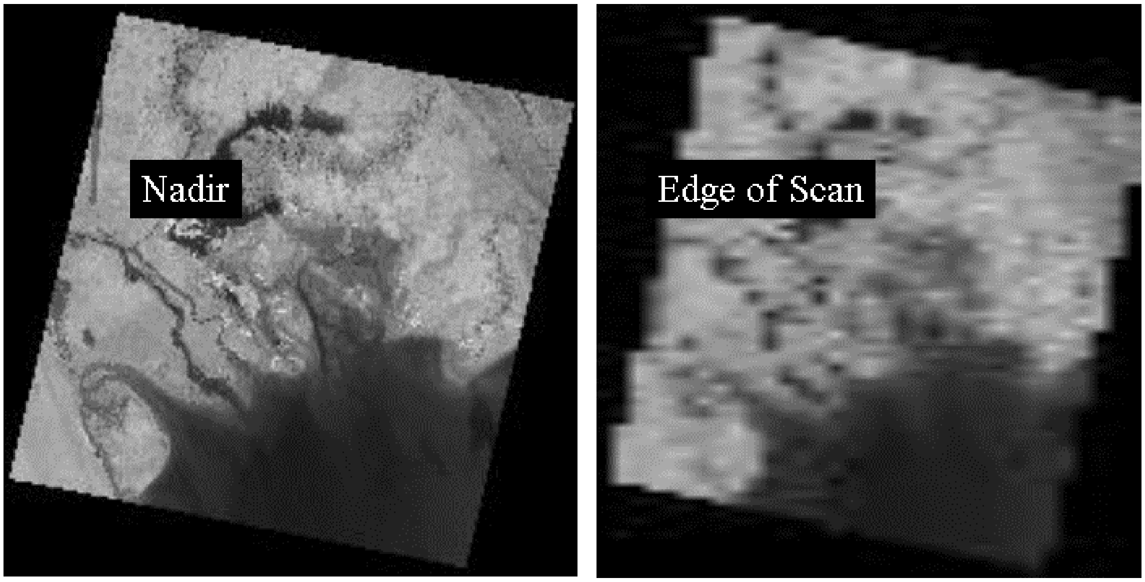

Figure 5: Landsat Simulation of AVHRR image shows degradation from nadir to the edge of scan. Location: northern Persian Gulf.

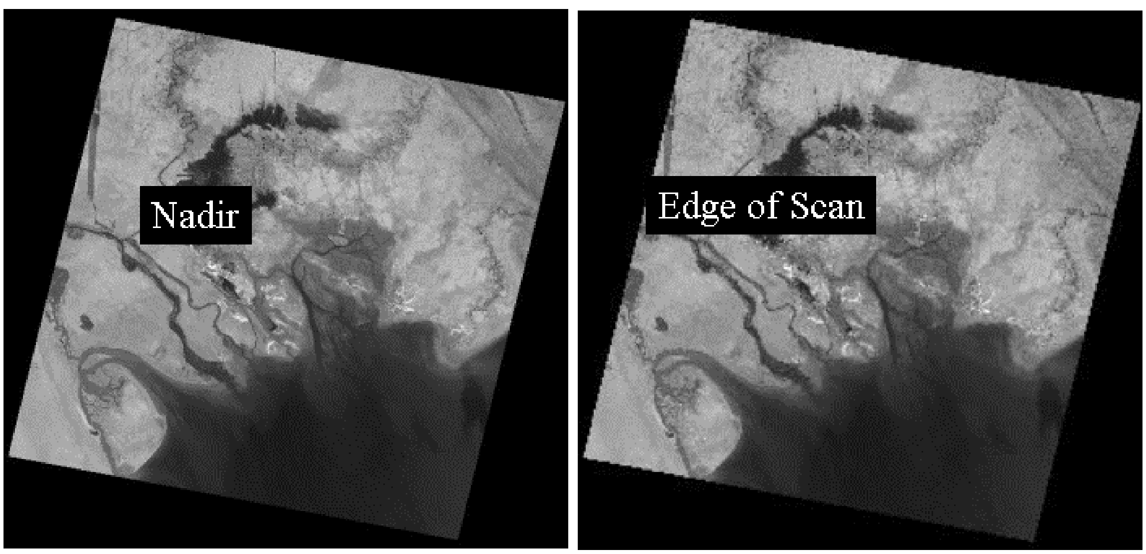

Figure 6: Landsat Simulation of VIIRS imager resolution shows minor degradation from nadir to the edge of scan.

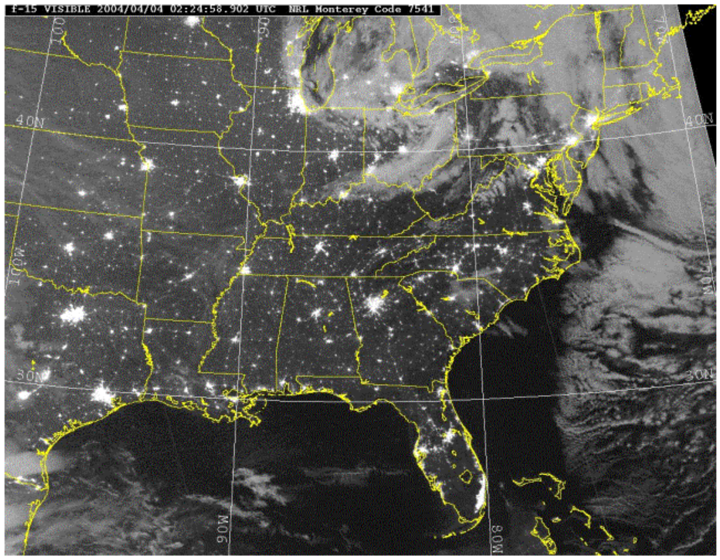

Figure 7: OLS nighttime visible showing cities and moonlit clouds.

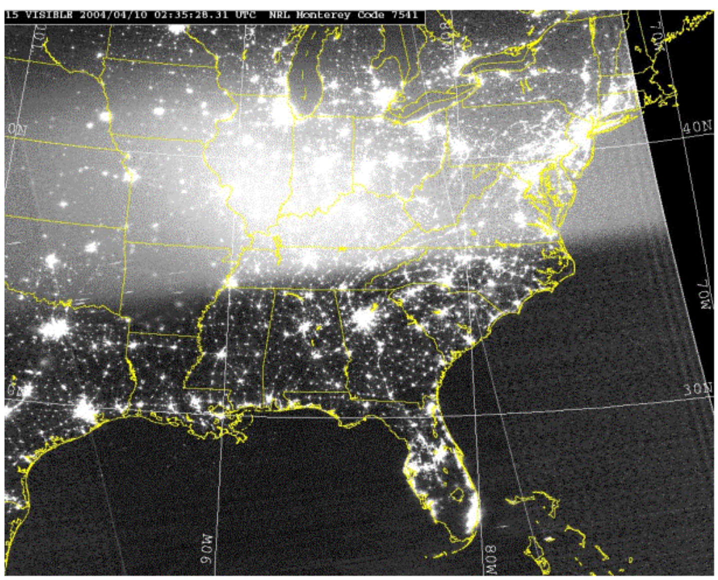

Figure 8: Nighttime visible without moonlight. Glare (upper portion of image) will be eliminated with VIIRS.

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