Radiometric Use of WorldView-2 Imagery

Technical Note

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This technical note discusses the radiometric use of WorldView-2 imagery. The first four sections describe the WorldView-2 instrument and general radiometric performance including the WorldView-2 relative spectral radiance response, solar spectral irradiance, gain settings, and radiometric correction of WorldView-2 products. Sections 5-7 cover more advanced topics: conversion to top-of-atmosphere spectral radiance, radiometric balancing for multiple scene mosaics, and conversion to top-of-atmosphere spectral reflectance. WorldView-2 imagery MUST be converted to spectral radiance at a minimum before radiometric/spectral analysis or comparison with imagery from other sensors in a radiometric/spectral manner. The information contained in this technical note applies to the raw WorldView-2 sensor performance and linearly scaled top-of-atmosphere spectral radiance products. Caution is advised when applying the equations provided here to pan-sharpened products, dynamic range adjusted (DRA) products, or WorldView-2 mosaics with radiometric balancing because the generation of these products may apply non-linear transformations to the pixel DN values.

1   WorldView-2 Instrument Description

The WorldView-2 high-resolution commercial imaging satellite was launched on October 8, 2009, from Vandenberg AFB, and was declared to be operating at Full Capability on January 4, 2010. The satellite is in a nearly circular, sun-synchronous orbit with a period of 100.2 minutes, an altitude of approximately 770 km, and with a descending nodal crossing time of approximately 10:30 a.m. WorldView-2 acquires 11-bit data in nine spectral bands covering panchromatic, coastal, blue, green, yellow, red, red edge, NIR1, and NIR2. See Table 2 for details. At nadir, the collected nominal ground sample distance is 0.46 m (panchromatic) and 1.84 m (multispectral). Commercially available products are resampled to 0.5 m (panchromatic) and 2.0 m (multispectral). The nominal swath width is 16.4 km. The WorldView-2 instrument is a pushbroom imager, which constructs an image one row at a time as the focused image of the Earth through the telescope moves across the linear detector arrays, which are located on the focal plane.

1.1   WorldView-2 Scan and Focal Plane Concept

Images are generated from the WorldView-2 instrument by using the spacecraft attitude determination and control system (ADCS) to scan a set of overlapped linear detector arrays across an image of the Earth produced by the WorldView-2 telescope.   This is accomplished by pointing the entire spacecraft, carrying a rigidly affixed instrument, without the use of internal scanning devices

The WorldView-2 system has panchromatic (Pan) and multispectral (MS) sensors. The focal plane has a detector pitch of 8 micrometers for Pan and 32 micrometers for the MS arrays. The system supports multiple line rates and combinations of operating modes. Bi-directional scanning is also supported so that the scan direction for any acquired image strip is either forward or reverse.

The WorldView-2 system has a total of 8 MS bands arranged in two arrays of 4 MS bands each. Imaging options on the WorldView-2 system are: PAN Only, PAN + 4 MS (MS1: NIR1, Red, Green, Blue) and PAN + 8 MS bands (MS1and MS2: RedEdge, Yellow, Coastal, NIR2). Pixels may also be aggregated by combining the charges of two adjacent pixels in the same column into a double-height pixel (1x2 mode), or by combining charges of a 2x2 square of four pixels into a double-width and double-height pixel (2x2 mode).

Both Pan and MS bands of the WorldView-2 focal plane employ a technique called time-delayed integration, or TDI, which effectively increases the exposure over that provided by the basic line rate. The available TDI settings

for Pan are: 8, 16, 32, 48, 56, and 64. The available TDI settings for the MS bands are: 3, 6, 10, 14, 18, 21, and 24. Due to hardware limitations, the MS TDI settings are paired such that NIR1 and Red must have the same TDI, Green and Blue must have the same TDI, Red Edge and Yellow must have the same TDI, and Coastal and NIR2 must have the same TDI.

The various combinations of line rates, aggregations, and TDI levels are categorized by operating modes, and are summarized in Table 1 below. The "C" mode, with pan compression of 2.4 and MS compression of 3.2, is the nominal operating configuration for WorldView-2.

Table 1: WorldView-2 Focal Plane Operating Modes

Mode	PAN Line Rate† (lines/sec)	MS Line Rate† (lines/sec)	Aggregation	TDI Rates	Compression Levels (bpp)
A	24,000	N/A	PAN = 1x1	PAN = 8, 16, 32, 48, 56, 64	2.75, 2.4
B	24,000	3,000	PAN = 1x1, MS = 1x2	PAN = 8, 16, 32, 48, 56, 64 MS = 3, 6, 10, 14, 18, 21, 24	PAN: 2.75, 2.4 MS: 4.3, 3.2, 2.4
C	20,000	5,000	PAN = 1x1, MS = 1x1	PAN = 8, 16, 32, 48, 56, 64 MS = 3, 6, 10, 14, 18, 21, 24	PAN: 2.75, 2.4 MS: 4.3, 3.2, 2.4

† - line rate at pixel level, not at detector level

The WorldView-2 focal plane is comprised of fifty panchromatic staggered Detector Sub-Arrays (DSAs), and two sets of ten MS, staggered Detector Sub-Arrays (DSAs), as shown in Figure 1. The two sets of staggered MS arrays are positioned on either side of the Pan array, one for the MS1 bands (MS1: NIR1, Red, Green, Blue), and the other for the MS2 bands (MS2: RedEdge, Yellow, Coastal, NIR2) . Each DSA contains four parallel rows of detectors, each with a different color filter. For each DSA, the individual bands are collected by a separate readout register. The Pan array uses two separate readout registers for each of its fifty DSAs. Each readout register has its own analog-to-digital converter.

Figure 1: The WorldView-2 Focal Plane Layout (not drawn to scale)
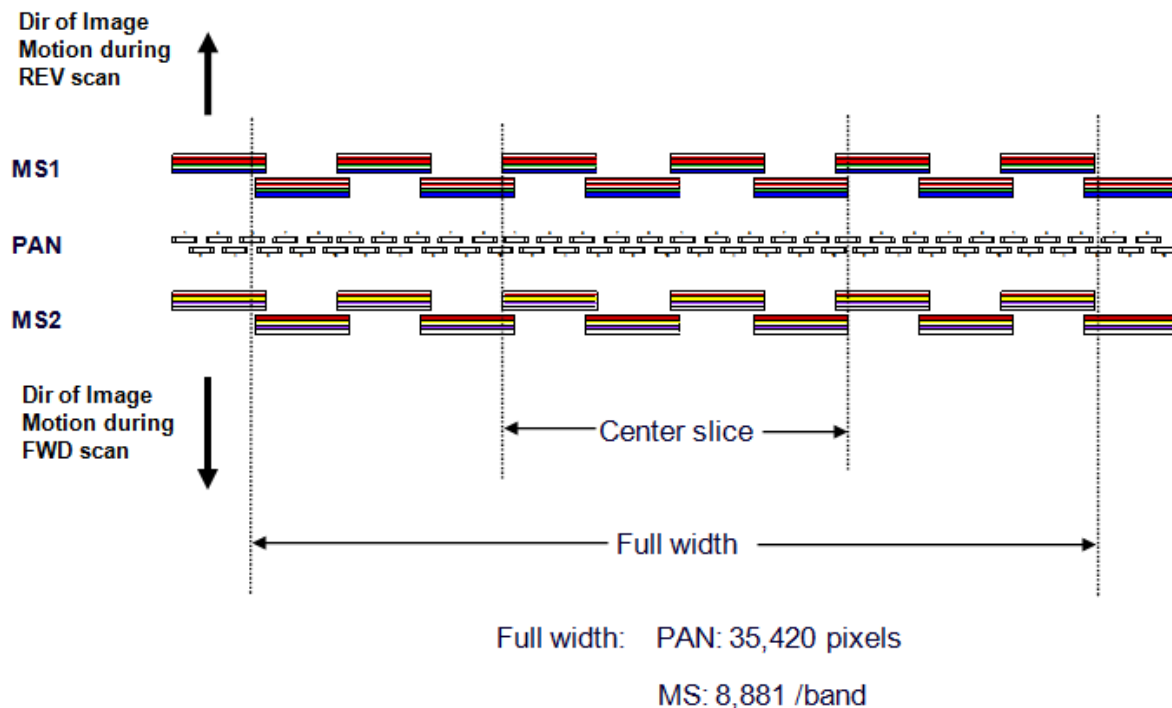
1.2 WorldView-2 Relative Spectral Radiance Response

The WorldView-2 spectral radiance response is defined as the ratio of the number of photo-electrons measured by the system, to the spectral radiance [W-m^{-2}-sr^{-1}-μm^{-1}] at a particular wavelength present at the entrance to the telescope aperture. It includes not only raw detector quantum efficiency, but also transmission losses due to the telescope optics and MS filters. The spectral radiance response for each band is normalized by dividing by the maximum response value for that band to arrive at a relative spectral radiance response. These curves for the WorldView-2 panchromatic and MS bands are shown in Figure 2.

Figure 2: WorldView-2 Relative Spectral Radiance Response (nm)

WW02 Relative Spectral Radiance Response
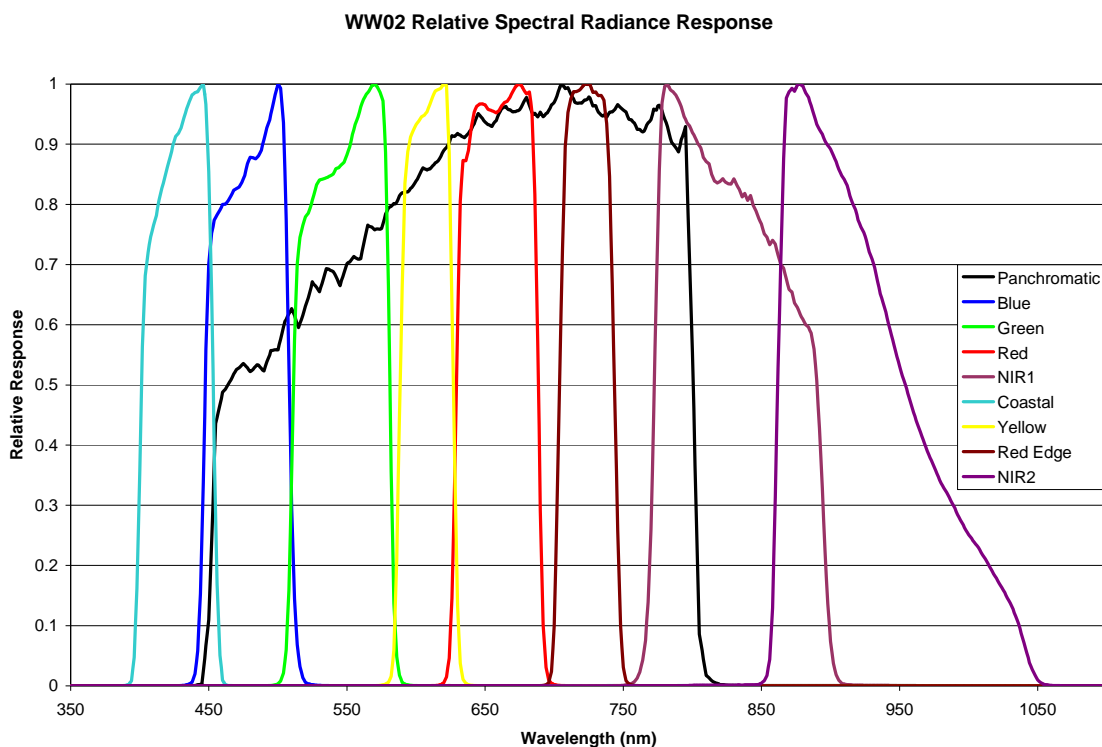
Various band passes for the WorldView-2 system are listed in Table 2. The 50% and 5% (of peak) band passes are found from the actual system response curves from Figure 2. Note that the actual data values used to create these plots are available as digital files, upon request from DigitalGlobe.

Table 2: WORLDVIEW-2 Band Passes [μm]

Spectral Band	Center Wavelength, um	50% Band Pass	5% Band Pass
Panchromatic	0.632	0.464 – 0.801	0.447 – 0.808
Coastal	0.427	0.401 – 0.453	0.396 - 0.458
Blue	0.478	0.448 – 0.508	0.442 – 0.515
Green	0.546	0.511 – 0.581	0.506 – 0.586
Yellow	0.608	0.589 – 0.627	0.584 - 0.632
Red	0.659	0.629 – 0.689	0.624 – 0.694
Red Edge	0.724	0.704 – 0.744	0.699 - 0.749
NIR 1	0.831	0.772 – 0.890	0.765 – 0.901
NIR 2	0.908	0.862 – 0.954	0.856 - 1.043

The effective bandwidth for each band of the WorldView-2 system is defined as:

$$\Delta\lambda_{Band} = \int_0^\infty R'(\lambda)_{Band} \cdot d\lambda$$

where $\Delta\lambda_{Band}$ is the effective bandwidth [μm] for a given band, and $R'(\lambda)_{Band}$ is the relative spectral radiance response for a given band as shown in Figure 2. The effective bandwidths should be used in the conversion to top-of-atmosphere spectral radiance for each WorldView-2 band and are listed below in Table 3. The effective bandwidths are also included in the image metadata (.IMD file extension) accompanying the image product.

Table 3. WorldView-2 Effective Bandwidths

Spectral Band	Effective Bandwidth, $\Delta\lambda$ [μm]
Panchromatic	0.2846
Coastal	0.0473
Blue	0.0543
Green	0.0630
Yellow	0.0374
Red	0.0574
Red Edge	0.0393
NIR1	0.0989
NIR2	0.0996

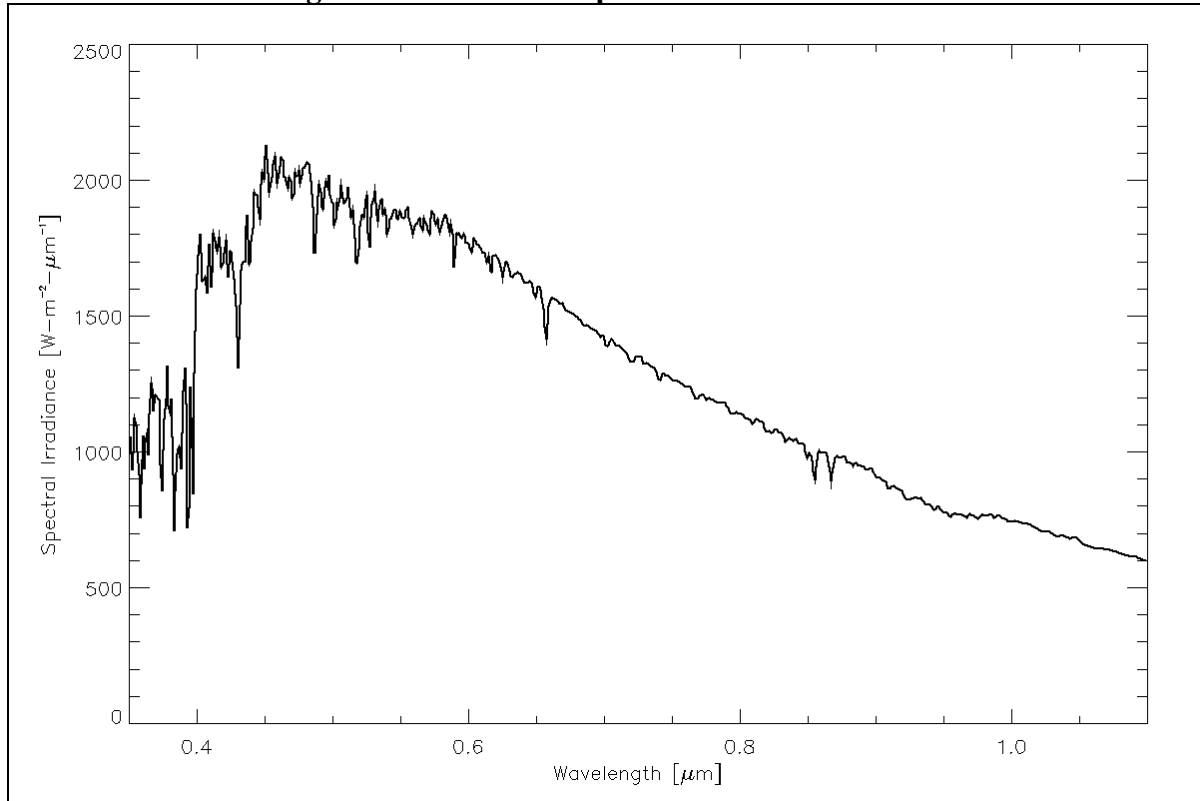## 2   Solar Spectral Irradiance

The WorldView-2 instrument is sensitive to wavelengths of light in the visible through near-infrared portions of the electromagnetic spectrum as shown in Figure 2. In this region, top-of-atmosphere radiance measured by WorldView-2 is dominated by reflected solar radiation. Spectral irradiance is defined as the energy per unit area falling on a surface as a function of wavelength. Because the Sun acts like a blackbody radiator, the solar spectral irradiance can be approximated using a Planck blackbody curve at 5900 degrees Kelvin, corrected for the solar disk area and the distance between the Earth and the Sun (Schowengerdt, pp. 36-37, 1997). However, a model of the solar spectral irradiance was created by the World Radiation Center (WRC) from a series of solar measurements (Wherli, 1985) and will be used for WorldView-2 conversions to surface reflectance and radiometric balancing of multiple scene mosaics. As shown in Figure 3, the WRC solar spectral irradiance curve peaks around 450 nm in the coastal and blue bands and slowly decreases at longer wavelengths. NOTE: the WRC curve is for an Earth-Sun distance of 1 Astronomical Unit (AU) normal to the surface being illuminated.

In general, band-averaged solar spectral irradiance is defined as the weighted average of the peak normalized effective irradiance value over the detector bandpass as shown in the following equation:

$$Esun_{\lambda Band} = \frac{\int_0^\infty Esun(\lambda) \cdot R'(\lambda)_{Band} \cdot d\lambda}{\int_0^\infty R'(\lambda)_{Band} \cdot d\lambda}$$

where $Esun\lambda_{Band}$ is the band-averaged solar spectral irradiance [W-m^{-2}-μm^{-1}] for a given band, $Esun(\lambda)$ is the WRC solar spectral irradiance curve [W-m^{-2}-μm^{-1}] shown in Figure 3, and $R'(\lambda)_{Band}$ is the relative spectral radiance response for a given band.

Figure 3: WRC Solar Spectral Irradiance Curve

Specific to WorldView-2, the band-averaged solar spectral irradiance values for an Earth-Sun distance of 1 AU, normal to the surface being illuminated, are listed in Table 4.

Table 4: WorldView-2 Band-Averaged Solar Spectral Irradiance

Spectral Band	Spectral Irradiance [W-m^{-2}-μm^{-1}]
Panchromatic	1580.8140
Coastal	1758.2229
Blue	1974.2416
Green	1856.4104
Yellow	1738.4791
Red	1559.4555
Red Edge	1342.0695
NIR1	1069.7302
NIR2	861.2866

3 Gain Settings

Assuming the detectors have a linear response as a function of input radiance, the equation of a straight line can be used for the camera equation:

$$DN_{Det,Band} = L_{Det,Band} \cdot Gain_{Det,Band} + Offset_{Det,Band}$$

where $DN_{Det,Band}$ is the raw image digital number value[counts], $L_{Det,Band}$ is the target spectral radiance [W-m^{-2}-sr^{-1}-μm^{-1}], $Gain_{Det,Band}$ is the absolute gain [counts / W-m^{-2}-sr^{-1}-μm^{-1}], and $Offset_{Det,Band}$ is the instrument offset [counts]. Rather than calibrate an absolute gain for each individual detector, a single gain is determined for each band, and then each detector is scaled relative to the other detectors in the same band. Separating the absolute and relative gain as described, one arrives at the following expression:

$$DN_{Det,Band} = L_{Det,Band} \cdot Gain_{Band} \cdot B_{Det,Band} + Offset_{Det,Band}$$

where $Gain_{Band}$ is the absolute gain [counts / W-m^{-2}-sr^{-1}-μm^{-1}] for each band and $B_{Det,Band}$ is the relative detector gain [unitless]. By definition, the average relative gain equals one. To conform to the nomenclature carried out through the rest of this technical note, $DN_{Det,Band}$ will be redefined as $p_{Det,Band}$, $L_{Det,Band*}Gain_{Band}$ will be redefined as $q_{Det,Band}$, and $Offset_{Det,Band}$ will be redefined as $A_{Det,Band}$. The above equation then takes the form:

$$p_{Det,Band} = q_{Det,Band} \cdot B_{Det,Band} + A_{Det,Band}$$

where $p_{Det,Band}$ are raw detector data [counts], $q_{Det,Band}$ are radiometrically corrected detector data [counts] which are linearly scaled to spectral radiance, $B_{Det,Band}$ is the detector relative gain, and $A_{Det,Band}$ is the dark offset [counts].

The gain settings for WorldView-2 Pan and MS bands are dependent on the following conditions: band, TDI exposure level, line rate, pixel aggregation, and bit depth of product. The appropriate absolute gain values, taking into account the combination of these parameters, are provided with each product in the image metadata (.IMD file extension).

The product image bands, line rate, and aggregation, are set based on the operating mode (see Table 1). The bit depth for WorldView-2 products can be 8 or 16 bits. The TDI setting for a given image is selected using a look-up table based on the estimated solar elevation angle for the image acquisition. No land cover information is taken into account in setting the TDI level. The values in the look-up table were chosen to maximize the radiometric resolution of WorldView-2 while minimizing the number of saturated pixels in an image.

4 Radiometric Correction of WorldView-2 Products

Relative radiometric calibration and correction are necessary because a uniform scene does not create a uniform image in terms of raw digital numbers (DNs). Major causes of non-uniformity include variability in detector response, variability in electronic gain and offset, lens falloff, and particulate contamination on the focal plane. These causes manifest themselves in the form of streaks and banding in imagery. In the case of a pushbroom system focal plane containing linear arrays, the data from every pixel in a given image column comes from the same detector. Any differences in gain or offset for a single detector show up as a vertical streak in raw imagery. Differences in gain and offset for a single readout register show up as vertical bands as wide as the number of detectors read out by the register. Relative radiometric correction minimizes these image artifacts in WorldView-2 products.

A relative radiometric correction is performed on raw data from all detectors in all bands during the early stages of WorldView-2 product generation. This correction includes a dark offset subtraction and a non-uniformity correction

(e.g. detector-to-detector relative gain).   Isolating the radiometrically corrected detector data in the last equation of Section 3, this is accomplished using the following equation:
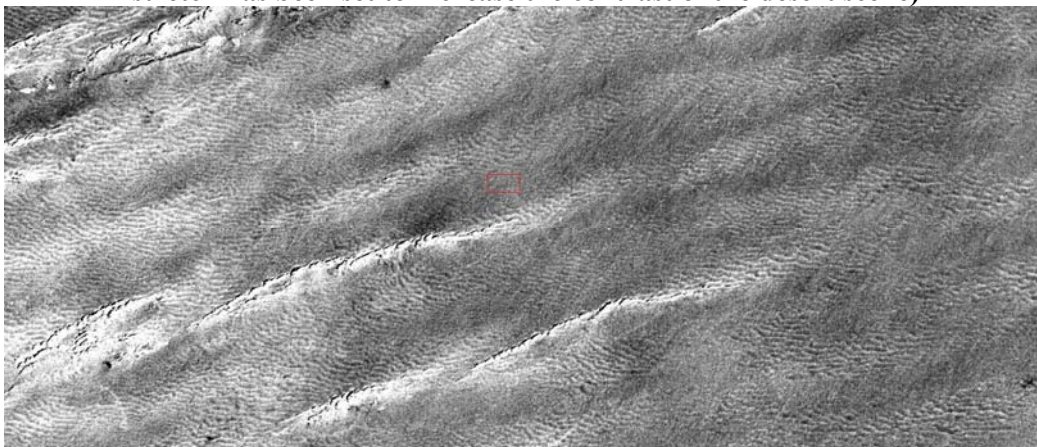
$$q_{Det,Band} = \frac{p_{Det,Band} - A_{Det,Band}}{B_{Det,Band}}$$

where $q_{Det,Band}$ are radiometrically corrected detector data [counts], $p_{Det,Band}$ are raw detector data [counts], $A_{Det,Band}$ is the dark offset [counts] for a specific image acquisition, and $B_{Det,Band}$ is the detector relative gain.

Figure 4: Raw desert image (visual stretch has been set to highlight banding and streaking)
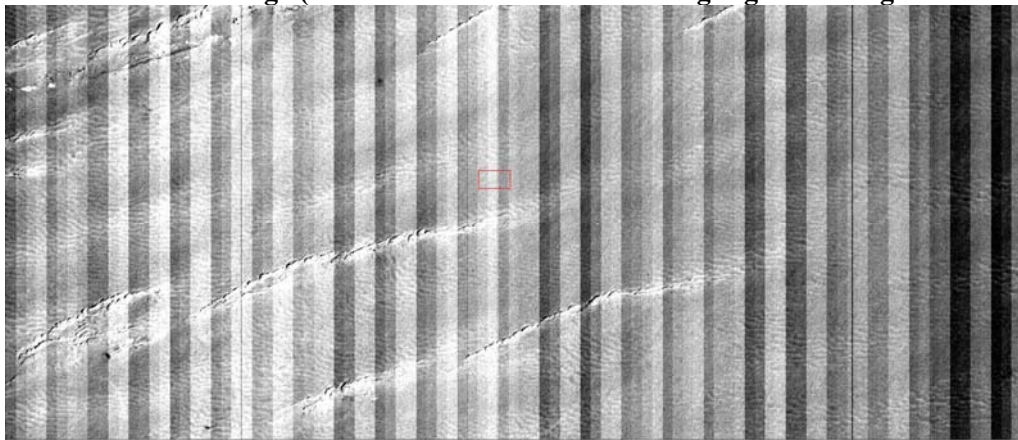
To illustrate the concept of radiometric correction, Figure 4 is a raw desert image from the WorldView-2 Pan band. Gain and offset differences between readout registers result in banding. Non-uniformities can be seen as both dark and light vertical streaks. Application of radiometric correction causes the banding and streaking to virtually disappear, as shown in Figure 5. Figures 4 and 5 each have a different visual stretch based on the minimum and maximum brightness of the pixels (not including masked and invalid detectors). The raw image stretch is set by the streaks so the detail of the desert has less contrast in the figure and the streaks are exaggerated.

**Figure 5: Radiometrically corrected desert image (visual
stretch has been set to increase the contrast of the desert scene)**

It is important to note that, after radiometric correction, the corrected detector data ($q_{Det,Band}$) are spatially resampled to create a specific WorldView-2 product that has radiometrically corrected image pixels ($q_{Pixel,Band}$). Once spatial resampling is performed, the radiometric corrections are not reversible. Data from all WorldView-2 detectors are radiometrically corrected and used to generate WorldView-2 products. To date, no detectors have been declared as non-responsive detectors. The WorldView-2 instrument collects data with 11 bits of dynamic range. These 11 bits are either stored as 16 bit integers or are scaled down to 8 bits to reduce the file sizes of WorldView-2 products and for use with specific COTS tools that can only handle 8-bit data. Whether the final bit depth is 16 or 8 bits, the goal of the radiometric correction, other than minimize image artifacts, is to scale all image pixels to top-of-atmosphere spectral radiance so that one absolute calibration factor can be applied to all pixels in a given band.

5 Conversion to Top-of-Atmosphere Spectral Radiance

WorldView-2 products are delivered to the customer as radiometrically corrected image pixels ($q_{Pixel,Band}$). Their values are a function of how much spectral radiance enters the telescope aperture and the instrument conversion of that radiation into a digital signal. That signal depends on the spectral transmission of the telescope and MS filters, the throughput of the telescope, the spectral quantum efficiency of the detectors, and the analog to digital conversion. Therefore, image pixel data are unique to WorldView-2 and should not be directly compared to imagery from other sensors in a radiometric/spectral sense. Instead, image pixels should be converted to top-of-atmosphere spectral radiance at a minimum.

Top-of-atmosphere spectral radiance is defined as the spectral radiance entering the telescope aperture at the WorldView-2 altitude of 770 km. The conversion from radiometrically corrected image pixels to spectral radiance uses the following general equation for each band of a WorldView-2 product:

$$L_{\lambda Pixel, Band} = \frac{K_{Band} \cdot q_{Pixel, Band}}{\Delta \lambda_{Band}}$$

where $L\lambda_{Pixel,Band}$ are top-of-atmosphere spectral radiance image pixels [W-m^{-2}-sr^{-1}-μm^{-1}], K_{Band} is the absolute radiometric calibration factor [W-m^{-2}-sr^{-1}-count^{-1}] for a given band, $q_{Pixel,Band}$ are radiometrically corrected image pixels [counts], and $\Delta\lambda_{Band}$ is the effective bandwidth [μm] for a given band. Offset subtraction is unnecessary at this point because it has already been performed in the radiometric correction step during product generation.

The absolute radiometric calibration factor for each band, or K factors, are determined pre-launch by illuminating the focal plane with a known radiance source in a controlled laboratory environment. The K factors are in units of band-integrated radiance per count and calculated using the following equation:

$$K_{Band} = \frac{\int_{0}^{\infty} L(\lambda)_{Source} \cdot R'(\lambda)_{Band} \cdot d\lambda}{\langle q_{Source} \rangle_{Band}}$$

where $L(\lambda)_{Source}$ is the spectral radiance of the calibration source, $R'(\lambda)_{Band}$ is the relative spectral radiance response for a given band, and $\langle q_{Source} \rangle_{Band}$ is the mean value of radiometrically corrected image data taken while viewing the calibration source for a given band.

Conversion to top-of-atmosphere spectral radiance is a simple two step process that involves multiplying radiometrically corrected image pixels by the appropriate absolute radiometric calibration factor, or K factor, to get band-integrated radiance [W-m^{-2}-sr^{-1}], and then dividing the result by the appropriate effective bandwidth to get

spectral radiance [W-m^{-2}-sr^{-1}-μm^{-1}]. This will be described in more detail in the subsections to follow. First the usage of correct parameters for a given product will be explained.

The absolute radiometric calibration factor and effective bandwidth values for each band are delivered with every WorldView-2 product and are located in the image metadata files (extension .IMD). An excerpt from a product .IMD file shows the absolute radiometric calibration factor (`absCalFactor`) and the effective bandwidth (`effectiveBandwidth`):

```
BEGIN_GROUP = BAND_C
    …
    absCalFactor = 9.295654e-03;
    effectiveBandwidth = 4.730000e-02;
END_GROUP = BAND_C
```

This example is for the coastal band. There are sections for each MS band, in particular: `BAND_C` = Coastal; `BAND_B` = Blue; `BAND_G` = Green; `BAND_Y` = Yellow; `BAND_R` = Red; `BAND_RE` = Red Edge; `BAND_N` = NIR1; `BAND_N2`= NIR2. Note that the values are provided in scientific notation.

The absolute radiometric calibration factor is dependent on the specific band, as well as the TDI exposure level, line rate, pixel aggregation, and bit depth of the product. Based on these parameters, the appropriate value is provided in the .IMD file. For this reason, care should be taken not to mix absolute radiometric calibration factors between products that might have different collection conditions.

In general, conversion equations are to be applied on all pixels in a given band of a WorldView-2 image and should use 32-bit floating point calculations. At the option of the customer, the resulting floating point values of band-integrated radiance or spectral radiance may be rescaled into a desired 16-bit or 8-bit range of brightness as may be required for handling by an image processing system. When doing this, it is recommended that the customer keep track of subsequent conversions so that there is a known relationship between any new image DNs and the band-integrated radiance or spectral radiance of the pixel for the given band.

5.1 Band-Integrated Radiance [W-m^{-2}-sr^{-1}]

Band-integrated radiance is defined as the peak normalized effective radiance value over the detector bandpass (Schott, p. 59, 1997) as shown in the following equation:

$$L_{Band} = \int_{0}^{\infty} L(\lambda) \cdot R'(\lambda)_{Band} \cdot d\lambda$$

where L_{Band} is the effective band-integrated radiance [W-m^{-2}-sr^{-1}] of a target to be imaged for a given band, $L(\lambda)$ is the spectral radiance of a target to be imaged, and $R'(\lambda)_{Band}$ is the relative spectral radiance response for a given band as shown in Figure 2.

In practice, conversion of WorldView-2 products from radiometrically corrected image pixel values to band-integrated radiance is achieved with the following formula:

$$L_{Pixel,Band} = absCalFactor_{Band} \cdot q_{Pixel,Band}$$

where $L_{Pixel,Band}$ are top-of-atmosphere band-integrated radiance image pixels [W-m^{-2}-sr^{-1}], $absCalFactor_{Band}$ is the absolute radiometric calibration factor [W-m^{-2}-sr^{-1}-count^{-1}] for a given band as provided in the .IMD files, and $q_{Pixel,Band}$ are radiometrically corrected image pixels [counts].

5.2 Band-Averaged Spectral Radiance [W-m^{-2}-sr^{-1}-µm^{-1}]

Band-averaged spectral radiance is defined as the weighted average of the peak normalized effective radiance value over the detector bandpass as shown in the following equation:

$$L_{\lambda_{Band}} = \frac{\int_0^\infty L(\lambda) \cdot R'(\lambda)_{Band} \cdot d\lambda}{\int_0^\infty R'(\lambda)_{Band} \cdot d\lambda}$$

where $L\lambda_{Band}$ is the band-averaged spectral radiance [W-m^{-2}-sr^{-1}-µm^{-1}] of a target to be imaged for a given band, $L(\lambda)$ is the spectral radiance of a target to be imaged, and $R'(\lambda)_{Band}$ is the relative spectral radiance response for a given band shown in Figure 2.

The second step in conversion to top-of-atmosphere spectral radiance is to divide the band-integrated radiance by an effective bandwidth as follows:

$$L_{\lambda_{Pixel,Band}} = \frac{L_{Pixel,Band}}{\Delta\lambda_{Band}}$$

where $L\lambda_{Pixel,Band}$ are top-of-atmosphere band-averaged spectral radiance image pixels [W-m^{-2}-sr^{-1}-µm^{-1}], $L_{Pixel,Band}$ are top-of-atmosphere band-integrated radiance image pixels [W-m^{-2}-sr^{-1}], and $\Delta\lambda_{Band}$ is the effective bandwidth [µm] for a given band as provided in the .IMD files (also listed in Table 3 in this document).

6   Radiometric Balancing for Multiple Scene Mosaics

For many customers, it may be desirable to create large area mosaics from multiple WorldView-2 scenes. Ignoring geometric effects, adjacent areas might appear to have different brightness values (counts) leaving a visible seam between scenes. As stated earlier, WorldView-2 counts are a function of the spectral radiance entering the telescope aperture at the WorldView-2 altitude of 770km. This top-of-atmosphere spectral radiance varies with Earth-Sun distance, solar zenith angle, topography (the solar zenith angle is calculated for flat terrain so topography adds an extra geometry factor for each spot on the ground), bi-directional reflectance distribution function (BRDF-the target reflectance varies depending on the illumination and observation geometry), and atmospheric effects (absorption and scattering).

Topography, BRDF, and atmospheric effects can be ignored for simple radiometric balancing. Consequently the major difference between two scenes of the same area is the solar geometry. The solar spectral irradiance values listed in Table 4 correspond to the values for the mean Earth-Sun distance, normal to the surface being illuminated. The actual solar spectral irradiance for a given image varies depending on the Earth-Sun distance and the solar zenith angle during the individual image acquisition. This variation will cause two scenes of the same area (or adjacent areas) taken on different days to have different radiances and hence different image brightnesses. The difference can be minimized by correcting imagery for Earth-Sun distance and solar zenith angle. Before applying this correction, the solar geometry must be determined for each scene to be used in the mosaic.

6.1 Determination of Solar Geometry

The variations in solar spectral irradiance are dominated by the solar geometry during a specific image acquisition. The Sun can be approximated as a point source since the Earth-Sun distance is much greater than the diameter of the Sun. The irradiance of a point source is proportional to the inverse square of the distance from the source. Therefore the irradiance of a point source at a desired distance can be calculated given the irradiance of the source at a specified distance (Schott, p. 64, 1997):

$$E_2 = \frac{E_1 r_1^{\ 2}}{r_2^{\ 2}}$$

where E_2 is the sought after irradiance at the desired distance r_2, and E_1 is the known irradiance of the source at specified distance r_1. The average Earth-Sun distance is 1 Astronomical Unit (AU), hence the equation becomes:

$$E_2 = \frac{E_1}{r_2^{\ 2}}$$

which can be rewritten as:

$$Ees_{\lambda_{Band}} = \frac{Esun_{\lambda_{Band}}}{d_{es}^{\ 2}}$$

where $Ees\lambda_{Band}$ is the band-averaged solar spectral irradiance [W-m^{-2}-μm^{-1}] at a given Earth-Sun distance, $Esun\lambda_{Band}$ is the band-averaged solar spectral irradiance [W-m^{-2}-μm^{-1}] at the average Earth-Sun distance as listed in Table 4, and d_{es} is the Earth-Sun distance [AU] for a given image acquisition. As the Earth orbits the Sun throughout the year, the variation in Earth-Sun distance leads to a change of irradiance of around ± 3.4%.

The solar spectral irradiance is defined normal to the surface being illuminated. As the solar zenith angle moves away from normal, a projected area effect is introduced and the same beam of light illuminates a larger area (Schott, pp. 66-67, 1997). This effect is a function of the cosine of the illumination angle and is represented by:

$$E\theta_{\lambda_{Band}} = Esun_{\lambda_{Band}} \cdot \cos(\theta_s)$$

where $E\theta\lambda_{Band}$ is the band-averaged solar spectral irradiance [W-m^{-2}-μm^{-1}] at a given solar zenith angle, $Esun\lambda_{Band}$ is the band-averaged solar spectral irradiance [W-m^{-2}-μm^{-1}] normal to the surface being illuminated as listed in Table 4, and θ_s is the solar zenith angle. The two solar geometries can be combined to solve for $E\lambda_{Band}$, the band-averaged solar spectral irradiance for a given image acquisition:

$$E_{\lambda_{Band}} = \frac{Esun_{\lambda_{Band}}}{d_{es}^{\ 2}} \cdot \cos(\theta_s)$$

6.1.1 Earth-Sun Distance

In order to calculate the Earth-Sun distance for a given product, the customer must first use the image acquisition time to calculate the Julian Day. The acquisition time for a product is contained in the image metadata file (.IMD file extension). Acquisition time uses the UTC time format and in the relevant section of the .IMD files looks like:

Basic Product:

```
BEGIN_GROUP = IMAGE_1
    …
    firstLineTime = YYYY_MM_DDThh:mm:ss:ddddddZ;
    …
END_GROUP = IMAGE_1
```

Standard (projected) Product:

```
BEGIN_GROUP = MAP_PROJECTED_PRODUCT
    …
    earliestAcqTime = YYYY_MM_DDThh:mm:ss:ddddddZ;
    …
END_GROUP = MAP_PROJECTED_PRODUCT
```

From the UTC time format, retrieve the year, month, day and calculate the Universal Time (UT) from the hours, minutes, and seconds:

$$\text{year} = \text{YYYY}$$
$$\text{month} = \text{MM}$$
$$\text{day} = \text{DD}$$
$$\text{UT} = \text{hh} + \frac{\text{mm}}{60.0} + \frac{\text{ss.dddddd}}{3600.0}$$

If the customer has an algorithm that can calculate the Julian Day, that value can also be used. Otherwise use the equations listed below (Meeus, p. 61, 1998). The word "int" listed in the equations means to truncate the decimals and only use the integer part of the number. If the image was acquired in January or February, the year and month must be modified as follows:

$$\text{year} = \text{year} - 1$$
$$\text{month} = \text{month} + 12$$

Next, calculate the Julian Day (JD):

$$A = \text{int}\left(\frac{\text{year}}{100}\right)$$

$$B = 2 - A + \text{int}\left(\frac{A}{4}\right)$$

$$JD = \text{int}[365.25 \cdot (\text{year} + 4716)] + \text{int}[30.6001 \cdot (\text{month} + 1)] + \text{day} + \frac{UT}{24.0} + B - 1524.5$$

As an example, the WorldView-2 launch date of October 8, 2009 at 18:51:00 GMT corresponds to the Julian Day 2455113.285. Once the Julian Day has been calculated, the Earth-Sun distance (d_{ES}) can be determined using the following equations (U.S. Naval Observatory):

$$D = JD - 2451545.0$$

$$g = 357.529 + 0.98560028 \cdot D$$

$$d_{ES} = 1.00014 - 0.01671 \cdot \cos(g) - 0.00014 \cdot \cos(2g)$$

NOTE: g is in degrees but most software programs require radians for cosine calculations. Conversion may be necessary for g from degrees to radians. The Earth-Sun distance will be in Astronomical Units (AU) and should have a value between 0.983 and 1.017. For the WorldView-2 launch date, the Earth-Sun distance is 0.998987 AU. At least six decimal places should be carried in the Earth-Sun distance for use in radiometric balancing or top-of-atmosphere reflectance calculations.

6.1.2 Solar Zenith Angle

The solar zenith angle does not need to be calculated for every pixel in an image because the sun angle change is very small over the 16.4 km image swath and the along-track image acquisition time. The average solar zenith angle for the image is sufficient for every pixel in the image. The average sun elevation angle [degrees] for a given product is calculated for the center of the scene and can be found in the .IMD files:

```
BEGIN_GROUP = IMAGE_1
    …
    meanSunEl = 68.7;
    …
END_GROUP = IMAGE_1
```

The solar zenith angle is simply:

$$\theta_S = 90.0 - sunEl$$

This example is for a sun elevation angle of 68.7 degrees, which corresponds to a solar zenith angle of 21.3 degrees.

6.2 Applying Geometry to data

For both of the equations in this section, imagery from multiple dates can be scaled to remove geometry factors associated with the solar spectral irradiance during those image acquisitions. The scaling can be performed without calculating the actual solar spectral irradiance. After either equation has been applied, the solar geometry values associated with the imagery are: $d_{ES} = 1$ AU and $\theta_S = 0$ degrees.

Once the Earth-Sun distance and solar zenith angle are known, WorldView-2 imagery from different dates can be modified to remove the scene specific solar conditions. In the case of 16-bit products, and assuming the same absolute radiometric calibration factors are used, radiometrically corrected pixels can be modified directly using:

$$q'_{Pixel,Band} = \frac{q_{Pixel,Band} \cdot d_{ES}^2}{\cos(\theta_S)}$$

where $q'_{Pixel,Band}$ are solar geometry corrected image pixels [counts] for a given band, $q_{Pixel,Band}$ are radiometrically corrected image pixels [counts] for a given band, d_{ES} is the Earth-Sun distance [AU] during the image acquisition, and θ_s is the solar zenith angle [degrees] during the image acquisition. The solar geometry is independent of wavelength, so the same geometry factors are applied to each band.

If the absolute radiometric calibration factors are different between products, or the bit depth is different (8 vs 16 bits), the imagery must first be converted to top-of-atmosphere band-averaged spectral radiance following the instructions in Section 5. Top-of-atmosphere spectral radiance imagery may then be modified to account for solar geometry using the following equation:

$$L'_{\lambda Pixel,Band} = \frac{L_{\lambda Pixel,Band} \cdot d_{ES}^2}{\cos(\theta_S)}$$

where $L'_{\lambda Pixel,Band}$ are solar geometry corrected top-of-atmosphere band-averaged spectral radiance image pixels [W-m^{-2}-sr^{-1}-μm^{-1}] for a given band, $L_{\lambda Pixel,Band}$ are top-of-atmosphere band-averaged spectral radiance image pixels [W-m^{-2}-sr^{-1}-μm^{-1}] for a given band, d_{ES} is the Earth-Sun distance [AU] during the image acquisition, and θ_s is the solar zenith angle [degrees] during the image acquisition. Be advised that scenes scaled with these solar geometry corrections may not perfectly match due to topographic, atmospheric, BRDF, and other temporal differences.

7 Conversion to Top-of-Atmosphere Reflectance

The shape of the top-of-atmosphere spectral radiance curves, as a function of WorldView-2 wavelengths, are dominated by the shape of the solar curve. For many multispectral analysis techniques such as band ratios, Normalized Difference Vegetation Index (NDVI), matrix transformations, etc., it is common practice to convert multispectral data into reflectance before performing the analysis. The top-of-atmosphere spectral radiance in the solar reflected portion of the spectrum can be modeled as the sum of three major contributors of radiation (Schowengerdt, p. 38, 1997):

$$L^s_\lambda = L^{su}_\lambda + L^{sd}_\lambda + L^{sp}_\lambda$$

where L^s_λ is the total top-of-atmosphere spectral radiance, L^{su}_λ is the unscattered surface-reflected radiation, L^{sd}_λ is the downwelling surface-reflected skylight, and L^{sp}_λ is the upwelling path radiance. Expanding the unscattered surface-reflected radiation, and assuming a Lambertian reflecting target, results in the expression (Schowengerdt, p. 44, 1997):

$$L^{su}_\lambda = \rho_\lambda \cdot \frac{\tau_{v_\lambda} \cdot \tau_{s_\lambda} \cdot E_\lambda \cdot \cos(\theta_S)}{d_{ES}^2 \cdot \pi}$$

where L^{su}_λ is the unscattered surface-reflected radiation, ρ_λ is the target diffuse spectral reflectance, τv_λ is the view path atmospheric spectral transmittance, τs_λ is the solar path atmospheric spectral transmission, and E_λ is the solar spectral irradiance, θ_s is the solar zenith angle, and d_{ES} is the Earth-Sun distance. Follow the directions in Section 6 to calculate the solar zenith angle and Earth-Sun distance. The top-of-atmosphere band-averaged spectral radiance for a WorldView-2 image band can be defined as:

$$L_{\lambda_{\text{Pixel,Band}}} = \rho_{\lambda_{\text{Pixel,Band}}} \frac{\tau_{v_\lambda} \cdot \tau_{s_\lambda} \cdot \text{Esun}_{\lambda_{\text{Band}}} \cdot \cos(\theta_S)}{d_{ES}^2 \cdot \pi} + L_\lambda^{sd} + L_\lambda^{sp}$$

Ignoring atmospheric effects gives the general equation:

$$L_{\lambda_{\text{Pixel,Band}}} = \rho_{\lambda_{\text{Pixel,Band}}} \cdot \frac{\text{Esun}_{\lambda_{\text{Band}}} \cdot \cos(\theta_S)}{d_{ES}^2 \cdot \pi}$$

Rearranging the equation to solve for the surface reflectance results in the top-of-atmosphere band-averaged reflectance equation for a WorldView-2 image band:

$$\rho_{\lambda_{\text{Pixel,Band}}} = \frac{L_{\lambda_{\text{Pixel,Band}}} \cdot d_{ES}^2 \cdot \pi}{\text{Esun}_{\lambda_{\text{Band}}} \cdot \cos(\theta_S)}$$

Top-of-atmosphere reflectance does not account for topographic, atmospheric, or BRDF differences. Consult the references by Schott or Schowengerdt for further discussion on correction for topographic or atmospheric effects. Typically a dark object subtraction technique is recommended to reduce atmospheric effects due to the upwelling path radiance (Richards, p. 46, 1999 or Schowengerdt, p. 315, 1997) followed by atmospheric modeling.

8 Summary

Raw WorldView-2 imagery undergoes a radiometric correction process to reduce visible banding and streaking in WorldView-2 products. The products are linearly scaled to absolute spectral radiance. Various types of spectral analysis can be performed on this radiometrically corrected WorldView-2 imagery. Depending on the application, WorldView-2 products may need to be converted to top-of-atmosphere spectral radiance or spectral reflectance. These transformations are performed using the equations listed in this technical note. In the case of large area mosaics, data conversions may not be necessary but radiometric balancing will help match the brightness of the scenes used in the mosaic. For customers interested in comparing WorldView-2 products with imagery from other sensors, keep in mind the spectral response curves and gain settings which are specific to WorldView-2. Many of the differences in analysis results can be explained by the differences in the sensors themselves.

9 References

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