Radiometric Use of WorldView-3 Imagery

Technical Note

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Prepared by: Michele Kuester

This technical note discusses the radiometric use of WorldView-3 imagery. The first two sections briefly describe the WorldView-3 instrument and general radiometric performance including the WorldView-3 relative spectral radiance response and relative radiometric correction of WorldView-3 products. Section 3 covers conversion to top-of-atmosphere spectral radiance and conversion to top-of-atmosphere spectral reflectance. WorldView-3 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-3 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-3 mosaics with radiometric balancing because the generation of these products may apply non-linear transformations to the pixel DN values.

1 WorldView-3 Instrument

The WorldView-3 high-resolution commercial imaging satellite was launched on August 13, 2014, from Vandenberg Air Force Base. The satellite is in a nearly circular, sun-synchronous orbit with a period of 97 minutes, an altitude of approximately 617 km, and with a descending nodal crossing time of approximately 10:30 a.m. The revisit is 4.5 days at a greater than 20-deg off nadir angle. WorldView-3 acquires 11-bit data in 9 spectral bands covering panchromatic, coastal, blue, green, yellow, red, red edge, NIR1, and NIR2. An additional shortwave infrared (SWIR) sensor acquires 14-bit data in eight bands covering the 1100 to 2500 nm spectral region. See Table 1 for details. At nadir, the collected nominal ground sample distance is 0.31 m (panchromatic), 1.24 m (multispectral) and 3.7 m (SWIR). Commercially available products are resampled to 0.3 m (panchromatic), 1.2 m (multispectral) and 7.5 m (SWIR). The nominal swath width is 13.1 km (slightly less for the SWIR sensor). The WorldView-3 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-3 Relative Radiance Response

The spectral radiance response is defined as the ratio of the number of photo-electrons measured by the instrument system, to the spectral radiance [$W\text{-}m^{-2}\text{-}sr^{-1}\text{-}\mu m^{-1}$] 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 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. The curves for theWorldView-3 visible and near infrared multispectral bands are shown in Figure 1. The curves for the WorldView-3 SWIR bands are shown in Figure 2. The corresponding data are provided in *Attachement A.*

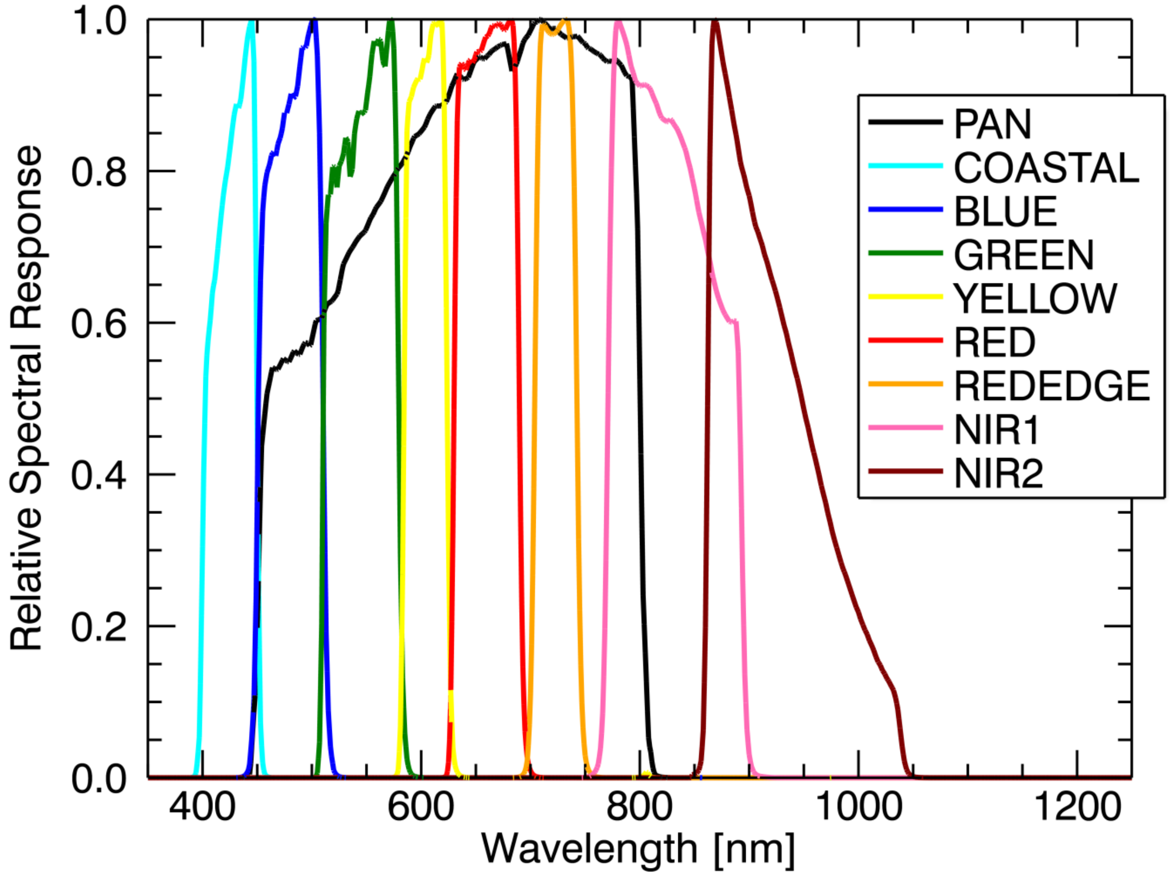


Figure 1: WorldView-3 Relative Spectral Radiance Response (nm) for the VNIR bands.

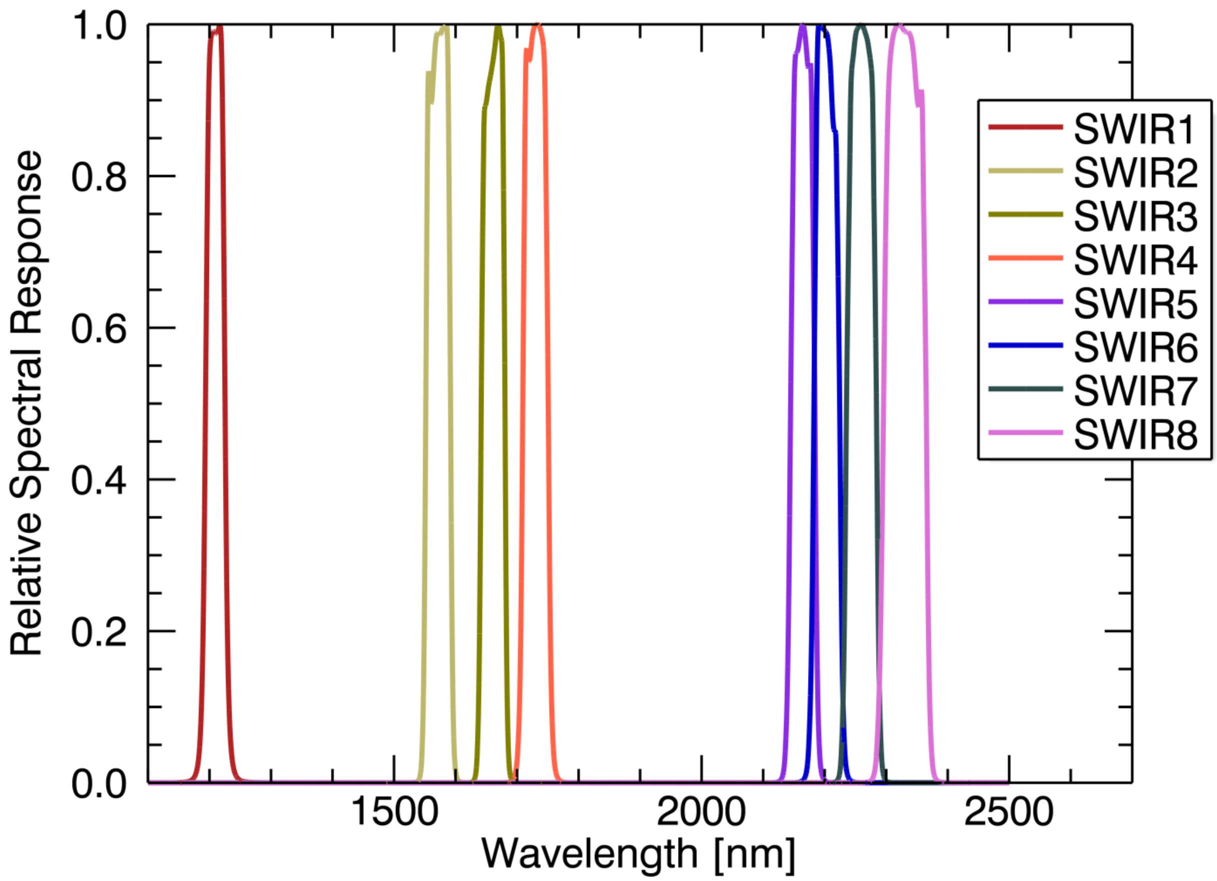


Figure 2: WorldView-3 Relative Spectral Radiance Response (nm) for the SWIR bands.

1.2 WorldView-3 Effective Bandwidth

The effective bandwidth for each band of the WorldView-3 system is defined as:

$$\Delta\lambda = \int_0^\infty R'(\lambda)d\lambda$$

where $\Delta\lambda$ is the effective bandwidth in μm for a given band, and $R'(\lambda)$ is the relative spectral radiance response for a given band. **The effective bandwidths should be used in the conversion to top-of-atmosphere spectral radiance for each band**

and are listed in Table 1. For reference, the center wavelength for each band is also given. The effective bandwidths are also included in the image metadata (.IMD file extension) accompanying the image product.

Table 1. WorldView-3 Effective Bandwidths

Spectral Band	Center Wavelength (nm)	Effective Bandwidth, $\Delta\lambda$ (µm)
Panchromatic	649.4	0.2896
Coastal	427.4	0.0405
Blue	481.9	0.0540
Green	547.1	0.0618
Yellow	604.3	0.0381
Red	660.1	0.0585
Red Edge	722.7	0.0387
NIR1	824.0	0.1004
NIR2	913.6	0.0889
SWIR1	1209.1	0.0330
SWIR2	1571.6	0.0397
SWIR3	1661.1	0.0373
SWIR4	1729.5	0.0416
SWIR5	2163.7	0.0389
SWIR6	2202.2	0.0409
SWIR7	2259.3	0.0476
SWIR8	2329.2	0.0679

2 Relative Radiometric Correction of WorldView-3 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-3 products.

A relative radiometric correction is performed on raw data from all detectors in all bands during the early stages of WorldView-3 product generation. This correction includes a dark offset subtraction and a non-uniformity correction (e.g. detector-to-detector relative gain).

It is important to note that, after radiometric correction, the corrected detector data are spatially resampled to create a specific WorldView-3 product that has relative radiometrically corrected image pixels. Once spatial resampling is performed, the radiometric corrections are not reversible. Data from all WorldView-3 detectors are relative radiometrically corrected and used to generate WorldView-3 products. To date, no detectors have been declared as non-responsive detectors. The WorldView-3 VNIR 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-3 products and for use with specific COTS tools that can only handle 8-bit data. The same is done for the 14 bit SWIR data. Whether the final bit depth is 16 or 8 bits, the goal of the relative 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.

3 Absolute Radiometric Correction of WorldView-3 Products and Conversion to Top-of-Atmosphere Spectral Radiance

WorldView-3 products are delivered to the customer as relative radiometrically corrected image pixels. 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 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-3 and should not be directly compared to imagery from other sensors in a radiometric/spectral sense. In addition, bands taken at different TDI levels may give misleading spectral information if left in digital number space. Image pixels should be converted to top-of-atmosphere spectral radiance at a minimum.

A pre-flight calibration has been performed and these data are provided in the .IMD metadata file that is delivered with the imagery. Since launch, DigitalGlobe has performed an extensive vicarious calibration campaign to provide an adjustment to the pre-launch values. The top-of-atmosphere radiance, L, in units of $W\mu m^{-1}\ m^{-2}\ sr^{-1}$, is then found from the DigitalGlobe image product for each band by converting from digital numbers (DN) using the equation,

$$L = GAIN * DN * \left(\frac{abscalfactor}{effectivebandwith}\right) + OFFSET$$

The TDI and scan direction specific *abscalfactor* and *effectiveBandwidth* are delivered with the imagery in the metadata file. The digital number, *DN*, is the pixel value found in the imagery. The *Gain* and *Offset* are the absolute radiometric calibration band dependent adjustment factors that are given in Table 2. Note that these are not necessarily static values and they are revisited annually.

Table 2. Absolute radiometric Calibration Adjustment Factors for WorldView-3 as of 1/29/2016. It is recommended that these values are used for more accurate at sensor radiance values. Updates will be made available to the public online alongside this technical paper or by request.

CAL VERSION	**2015v2**	
BAND	GAIN	OFFSET
PAN	0.923	-1.700
COASTAL	0.863	-7.154
BLUE	0.905	-4.189
GREEN	0.907	-3.287
YELLOW	0.938	-1.816

RED	0.945	-1.350
REDEDGE	0.980	-2.617
NIR1	0.982	-3.752
NIR2	0.954	-1.507
SWIR1	1.160	-4.479
SWIR2	1.184	-2.248
SWIR3	1.173	-1.806
SWIR4	1.187	-1.507
SWIR5	1.286	-0.622
SWIR6	1.336	-0.605
SWIR7	1.340	-0.423
SWIR8	1.392	-0.302

The absolute radiometric calibration factor and effective bandwidth values for each band are delivered with every WorldView-3 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), for example:

```
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 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 aggregration, 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.

4 Conversion to Top-of-Atmosphere Reflectance

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. In addition, techniques for removal of atmospheric effects range from a simple dark object subtraction or empirical line method, to more robust radiative transfer approaches. These methods require that first the imagery be normalized for solar irradiance and sensor radiance by conversion to top of atmosphere reflectance, $\rho(TOA)_\lambda$.

$$\rho(TOA)_\lambda = \frac{L_\lambda d^2 \pi}{E_\lambda \cos\theta_S}$$

where L_λ is the at-sensor radiance for the spectral band λ in W/m^2/µm/sr found in the previous section above, *d* is the Earth-Sun distance in astronomical units, E_λ is the band-averaged solar exoatmopsheric irradiance in W/m^2/µm, and θ_S is the solar zenith angle.

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 at a minimum to reduce atmospheric effects due to the upwelling path radiance (Richards, p. 46, 1999 or Schowengerdt, p. 315, 1997) followed by atmospheric modeling.

4.1 Solar Exoatmospheric Irradiance

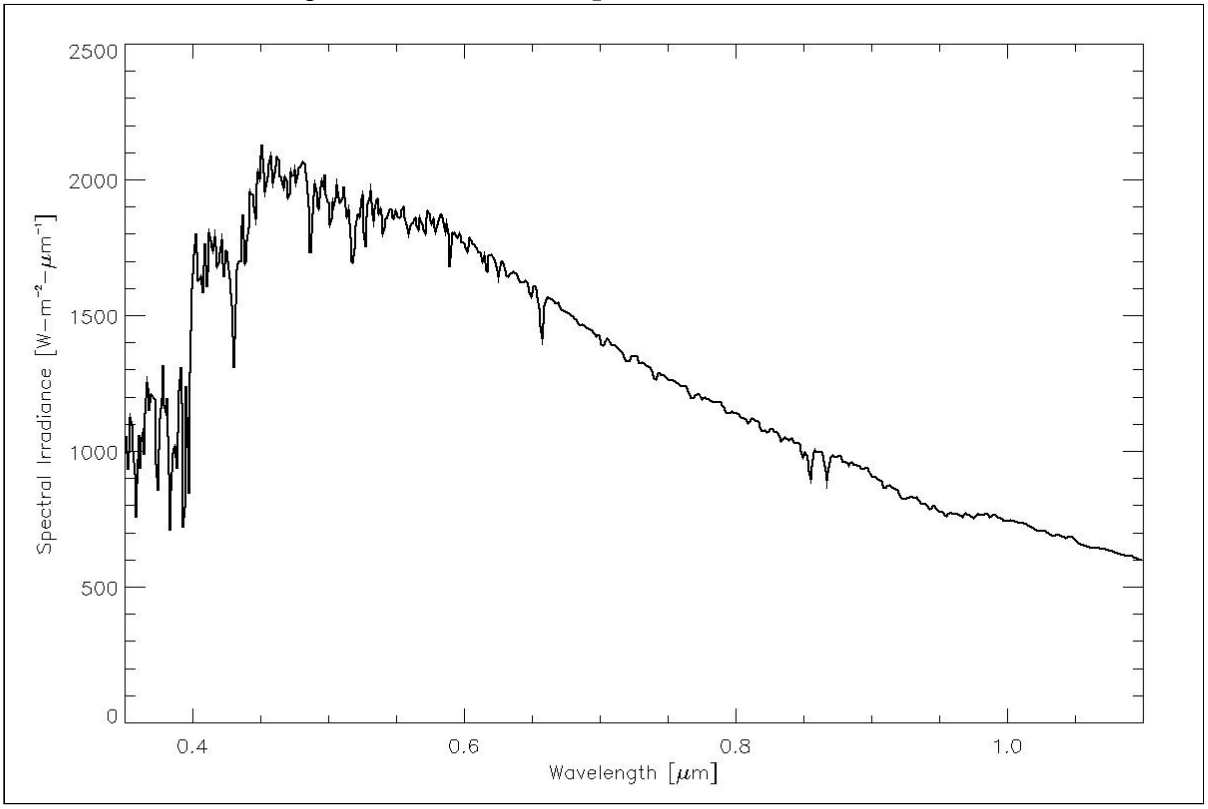
The WorldView-3 instrument is sensitive to wavelengths of light in the visible through shortwave-infrared portions of the electromagnetic spectrum as shown in Figure 1 and Figure 2. In this region, top-of-atmosphere radiance measured by WorldView-3 is dominated by reflected solar radiation. Spectral 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 is better used for this purpose. The solar spectral irradiance curve peaks around 450 nm in the coastal and blue bands and slowly decreases at longer wavelengths. The WRC Solar Spectral Irradiance Curve is shown in Figure 3 as an example. Thuillier 2003 is used for the vicarious calibration work at DigitalGlobe and is our recommended curve. The ChKur and WRC band averaged values are also given as they are also widely used and accepted in the remote sensing community. NOTE: the curves are given 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:

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

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

Figure 3: WRC Solar Spectral Irradiance Curve



Specific to WorldView-3, 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 3.

Table 3: WorldView-3 Band-Averaged Solar Spectral Irradiance

Spectral Band	**Spectral Irradiance [W-m^{-2}-μm^{-1}]**		
	Thuillier 2003	ChKur	WRC
PAN	1574.41	1578.28	1583.58
COASTAL	1757.89	1743.9	1743.81
BLUE	2004.61	1974.53	1971.48
GREEN	1830.18	1858.1	1856.26
YELLOW	1712.07	1748.87	1749.4
RED	1535.33	1550.58	1555.11
REDEDGE	1348.08	1303.4	1343.95
NIR1	1055.94	1063.92	1071.98

NIR2	858.77	858.632	863.296
SWIR 1	479.019	478.873	494.595
SWIR 2	263.797	257.55	261.494
SWIR 3	225.283	221.448	230.518
SWIR 4	197.552	191.583	196.766
SWIR 5	90.4178	86.5651	80.365
SWIR 6	85.0642	82.0035	74.7211
SWIR 7	76.9507	74.7411	69.043
SWIR 8	68.0988	66.3906	59.8224

4.1.2 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:

$$\mathrm{year} = \mathrm{YYYY}$$

$$\mathrm{month} = \mathrm{MM}$$

$$\mathrm{day} = \mathrm{DD}$$

$$\mathrm{UT} = \mathrm{hh} + \frac{\mathrm{mm}}{60.0} + \frac{\mathrm{ss.dddddd}}{3600.0}$$

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):

$$A = \text{int}\left(\frac{\text{year}}{100}\right)$$
$$B = 2 - A + \text{int}\left(\frac{A}{4}\right)$$
$$JD = \text{int}\left[365.25 \cdot (\text{year} + 4716)\right] + \text{int}\left[30.6001 \cdot (\text{month} + 1)\right] + \text{day} + \frac{UT}{24.0} + B - 1524.5$$

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.

4.1.2 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 13.4 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.

5 Radiometric Balancing for Multiple Scene Mosaics

For many customers, it may be desirable to create large area mosaics from multiple WorldView-3 scenes. Ignoring geometric effects, adjacent areas might appear to have different brightness values leaving a visible seam between scenes. As stated earlier, WorldView-3 pixel digital numbers are a function of the spectral radiance entering the telescope aperture at the WorldView-3 altitude of 617 km. 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 or simply converting to top-of-atmosphere solar reflectance as described in this technical document.

6 Summary

Raw WorldView-3 imagery undergoes a relative radiometric correction process to reduce visible banding and streaking in WorldView-3 products. The products are linearly scaled to absolute spectral radiance. Various types of spectral analysis can be performed on this radiometrically corrected WorldView-3 imagery. Depending on the application, WorldView-3 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, Top-of-atmosphere reflectance is recommended as a starting point. Additional radiometric balancing may help match the brightness of the scenes used in the mosaic. For customers interested in comparing WorldView-3 products with imagery from other sensors, keep in mind the spectral response curves and gain settings which are specific to WorldView-3. Many of the differences in analysis results can be explained by the differences in the sensors themselves.

7 References

Meuss, Jean. "Astronomical algorithms, 2nd Ed.." *Richmond, VA: Willmann-Bell*(1998).

Richards, John A. and Xiuping Jia. “Remote Sensing Digital Image Analysis: An Introduction 3rd ed.,” Springer, Berlin, 1999.

Schott, John R. “Remote Sensing: The Image Chain Approach,” Oxford University Press, New York(1997).

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Thuillier, G., et al. "The solar spectral irradiance from 200 to 2400 nm as measured by the SOLSPEC spectrometer from the ATLAS and EURECA missions." *Solar Physics* 214.1 (2003): 1-22.

Wehrli, C. “Extraterrestrial Solar Spectrum,” Publication 615, Physikalisch-Metrologisches Observatorium Davos and World Radiation Center, Davos-Dorf, Switzerland, pp. 23(1985).