MISB — Motion Imagery Standards Board	MISB ST 0801.8
STANDARD	
Photogrammetry Metadata Set for Motion Imagery	**23 October 2019**

1 Scope

This standard presents the Key-Length-Value (KLV) metadata necessary for the dissemination of data for photogrammetric exploitation of Motion Imagery. The ability to geo-locate points on an image with known confidence is an important capability. The objective of this standard is to support precise geopositioning.

Metadata in this standard provides definitions and keys for individual elements. The intent is for other standards to reference the metadata elements in this document, and to include them in their respective data sets (e.g., truncation pack, floating length pack, Local Set, etc.). This document defines metadata specific to photogrammetry. This standard does not address metadata necessary for the primary exploitation of the Motion Imagery (including such elements as mission number, sensor type, platform type, etc.) and security metadata.

Populating photogrammetry metadata at the earliest point in the image workflow maximizes fidelity. In most cases, this will be on the platform hosting the Motion Imagery sensor, although the improved point-positioning accuracy afforded by differential GPS techniques may dictate populating these metadata at the receipt station for the Motion Imagery essence.

2 References

[1] MISB ST 0807.24 MISB KLV Metadata Registry, Oct 2019.
[2] SMPTE RP 210v13:2012 Metadata Element Dictionary.
[3] MISB ST 1201.4 Floating Point to Integer Mapping, Feb 2019.
[4] MISB ST 0107.4 KLV Metadata in Motion Imagery, Feb 2019.
[5] IEEE Standard for Floating-Point Arithmetic (IEEE 754).
[6] "Coordinate Systems," [Online]. Available: http://earth-info.nga.mil/GandG/update/index.php?dir=coordsys&action=coordsys.
[7] NIMA TR8350.2: Department of Defense World Geodetic System 1984, Its Definitions and Relationships with Local Geodetic Systems, 23 Jun 2004.
[8] MISB ST 1202.2 Generalized Transformation Parameters, Feb 2015.
[9] MISB ST 1010.3 Generalized Standard Deviation and Correlation Coefficient Metadata, Oct 2016.

3 Revision History

Revision	Date	Summary of Changes
0801.8	10/23/2019	• Added Section 5.1 – Frame Sensor Model Overview

4 Abbreviations and Acronyms

CSM	Community Sensor Model
ECEF	Earth-Centered, Earth Fixed
GPS	Global Positioning System
IMU	Inertial Measurement Unit
KLV	Key-Length-Value
LRF	Laser Range Finder
MISB	Motion Imagery Standards Board
NED	North-East-Down
RP	Recommended Practice
SI	International System of Units
SMPTE	Society of Motion Picture and Television Engineers
ST	Standard
WGS-84	World Geodetic System of 1984

5 Introduction

This standard provides definitions and keys for individual elements for the transmission of photogrammetric metadata values within Motion Imagery streams from the sensor to the end client for frame-accurate exploitation of the photogrammetric Motion Imagery.

5.1 Frame Sensor Model Overview

A Frame Sensor Model provides the mathematical relationship between an object of interest in the physical world and the image of the object taken with a frame-based camera or sensor. This Section defines terms the mathematical relationship uses for consistent application; Section 6 defines the actual metadata items, units, and data formats.

Figure 1 illustrates an ideal camera (i.e., sensor) imaging a *scene*, which is the space in the physical world that is "sensed" to form an Image. An ideal camera (and its model) does not have optical distortions or other adjustments. The illustration shows the sensor positioned above the scene looking downward. The Sensor Reference Point is an arbitrary point on or about the sensing device, which defines the position of the physical sensor. The Sensor Reference Point is measurable (e.g., GPS) and unambiguously identified with the physical sensor. Scene energy (e.g., reflected light) comes from the scene and enters the sensor, which records the image. The sensor model uses single perspective geometry when defining the mathematical relationship between the scene and image; therefore, the illustration shows the Perspective Center, which is the point all scene energy passes through before collection by the sensor's Detector Array. The illustration also indicates the four corners of the scene and their standard numbering order (upper-left, upper-right, lower-right, and lower-left).

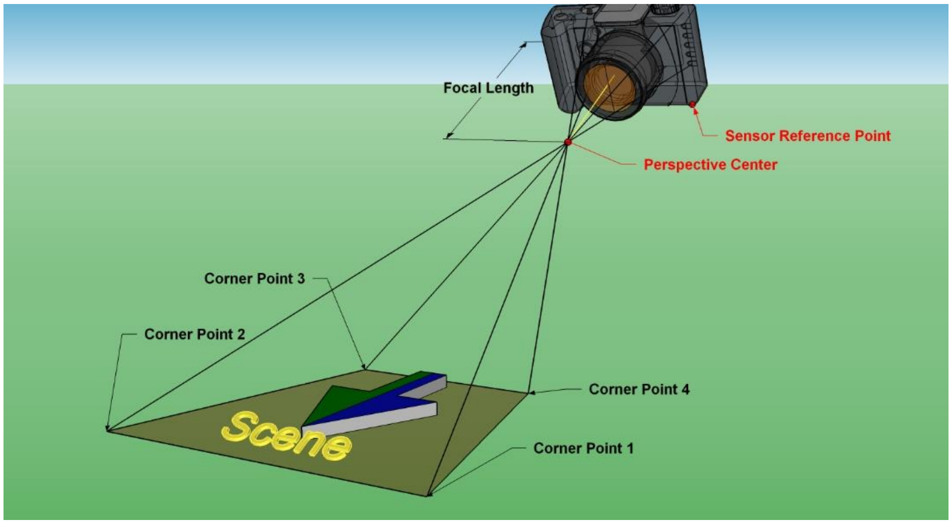

Figure 1: Overview of Sensor and Scene Relationship

Figure 2 shows the Detector Array inside the sensor. The Detector Array is a two-dimensional grid of individual detectors each measuring its local part of the scene energy; the combination of which becomes the image. With an ideal camera (e.g., no distortions), the line orthogonal to the Detector Array which passes through the Perspective Center is the Principal Axis (referred to in this document as the Boresight). The distance from the Perspective Center to the Detector Array is the Focal Length. Figure 2 shows the Sensor Reference Point is arbitrary and does not necessarily coincide with a specific point in the Detector Array nor the Perspective Center; additional metadata provides the relationship between the Sensor Reference Point's position and the Perspective Center. The Sensor Reference Point defines the position of the sensor system and is the reference point for its velocity.

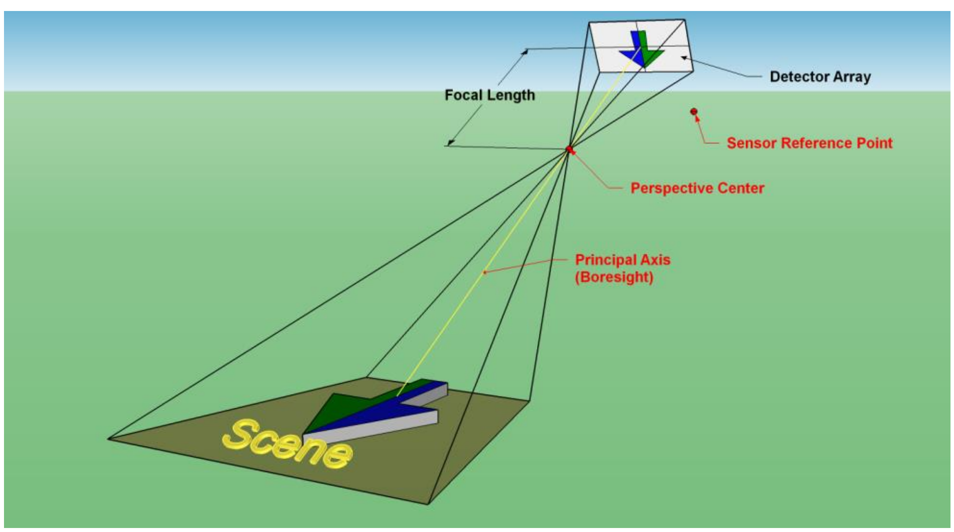

Figure 2: Sensor Detector Array

The Detector Array records a negative image (i.e., flipped top to bottom and left to right) because all scene energy passes through the Perspective Center. Figure 2 illustrates the negative image by showing the blue-green arrow inverted and flipped. Many sensor models use the positive image which is located the same distance (the Focal Length) from the Perspective Center but between the Perspective Center and scene. Figure 3 illustrates the positive image at an equivalent focal length away from the Perspective Center toward the scene; the blue-green arrow shows the positive image orientation matches the scenes orientation. The mathematics of using the positive image are equivalent to using the reflection of a negative image.

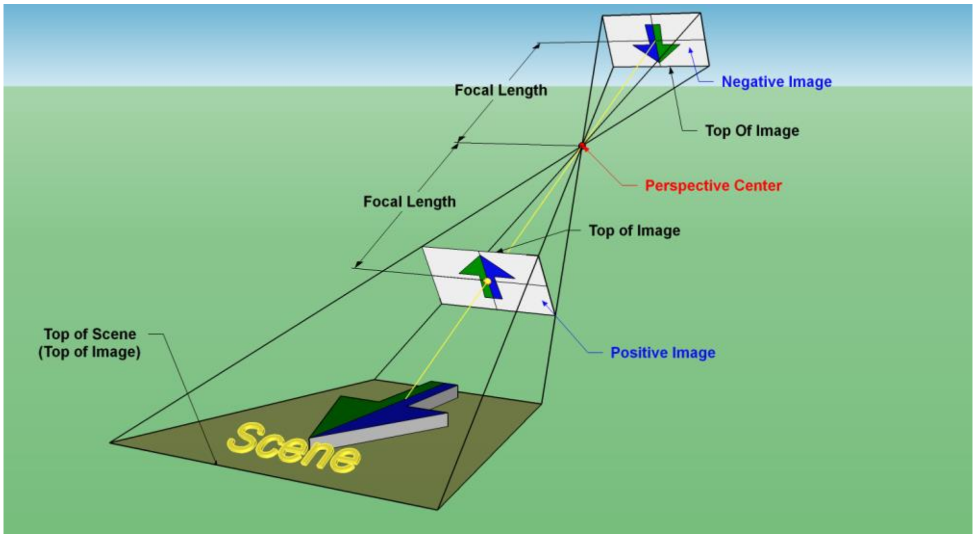

Figure 3: Negative and Positive Images

Figure 4 illustrates the model's points of interest, some which are the origin of a frame of reference (right-handed orientation). The red, green, and blue (RGB) vectors illustrate the x, y, and z axes, respectively, of each orientation. Each point uses a different frame of reference for their measurements, so normalizing the positions to the same frame of reference is part of the modelling process. The illustration shows the Target Vector, which is the vector from the Perspective Center to the Target Point.

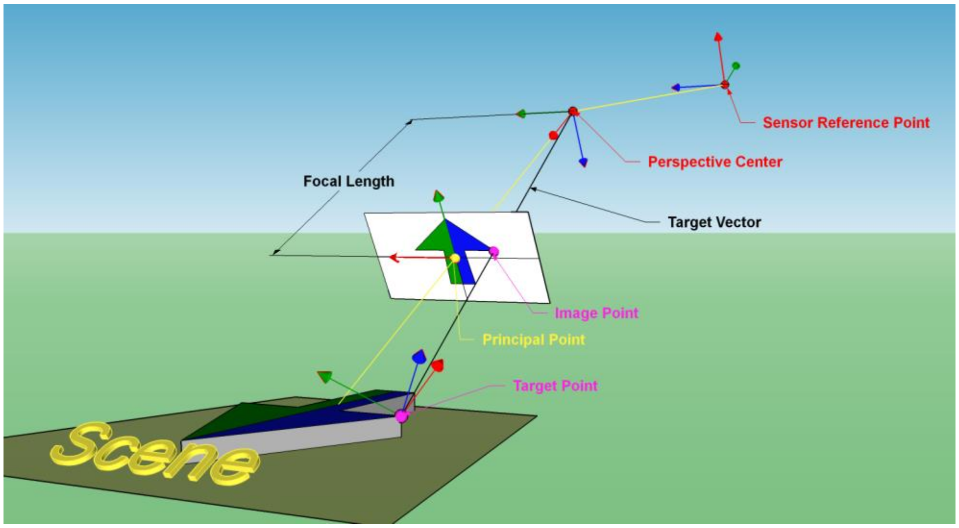

Figure 4: Model Frames of Reference

- The **Sensor Reference Point** is an absolute geodetic location (latitude, longitude, and height above ellipsoid). The Sensor Reference Point is the origin of a frame of reference having its orientation measured relative to North-East-Down (NED). The Sensor Reference Point provides the origin and orientation of the frame of reference for defining the position of the Perspective Center. Section 6.3 provides details for the Sensor Reference Point's position, velocity, orientation, and orientation velocities. Equation 4 uses the term *IMU* (Inertial Measurement Unit) as the name for this frame of reference.
- The **Perspective Center** is a position and orientation measured relative to the Sensor Reference Point's frame of reference. The orientation of the Perspective Center axes has the positive x-axis (red) aligning with the optical axis pointing toward the scene; the positive y-axis (green) pointing in the direction to the right side of the scene (as viewed by the image); and the positive z-axis (blue) pointing toward the bottom of the image, which completes a right handed coordinate system. Section 6.4.2 provides details for the Perspective Center's position, and axes orientations. Section 6.4.2 uses the term Boresight Offset to define location of the Perspective Center relative to the Sensor Position; additionally the term Boresight Delta Angle describes the orientation of the optical axes (or x, y, and z -axes) relative to the Sensor Reference Point and its axes. Equation 4 uses the term *LOS* (Line of Sight) as the name for this frame of reference.
- With an ideal camera the **Principal Point** (in yellow) is located at the center of the image and forms the origin of the Principal Point frame of reference. The orientation of the image's frame of reference has the positive x-axis (red) pointing toward the right side of the image, the y-axis (green) pointing towards the top of the image and the z-axis (not visible in the figure) orthogonal to the image plane, pointing out of the image toward the Perspective Center (completing a right-handed coordinate system). Section 6.4.4 provides details for the Principal Point Offset and Focal Length. Equation 4 uses the term *Frame* (Image-*Frame*) as the name for this frame of reference.
- The **Image Point** is the point of intersection between the Target Line and the focal plane. The Image Point position location is relative to the image's Principal Point.
- The **Target Point** is a position of an object in Earth Centered Earth Fixed (ECEF) coordinates. Figure 4 illustrates the ECEF x, y, and z axes for the given Target Point.

The ideal camera is the starting point for the mathematical relationship between an object of interest and the image. Adjustments to the model correct for real-world realities because of manufacturing and environmental impacts. One adjustment is the location of the Principal Point. The Principal Point is the intersection of the Principal Axis and the image. With an ideal camera the Principal Point is in the exact center of the image. Manufacturing imperfections and other issues may offset the Principal Point from the image's center. The location of the Principal Point is the **Principal Point Offset**. Figure 5 illustrates the Principal Point Offset shifted from the Center Of Frame; the Principal Axis (yellow line) intersects the image at the Principal Point, shown as the yellow dot on the frame.

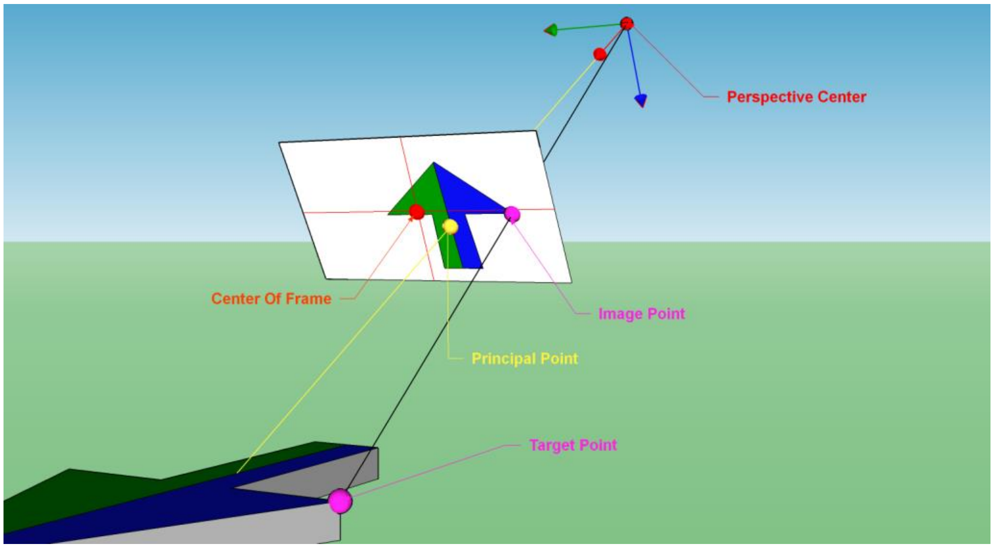

Figure 5: Principal Point Offset

6 Photogrammetry Metadata Sets

This document organizes photogrammetric metadata into three photogrammetric metadata sets: External Parameters, Internal Parameters, and Miscellaneous Parameters as listed below:

1) Photogrammetry External Parameters (see Section 6.3)
   a. Sensor Position
   b. Sensor Velocity
   c. Sensor Absolute Orientation
   d. Sensor Absolute Orientation Rate
2) Photogrammetry Internal Parameters (see Section 6.4)
   a. Boresight
   b. Image Size
   c. Focal Plane
   d. Radial Distortion
   e. Tangential-Decentering
   f. Affine Correction
3) Miscellaneous Parameters (see Section 6.5)
   a. Slant Range

6.1 Organization of the Photogrammetry Metadata

The metadata tables below describe in detail the parameters of Photogrammetry Metadata for digital Motion Imagery.

Each table of metadata elements has the following columns:

- Name – A descriptive name for the metadata item

- Key – The full 16-byte key value as defined in MISB ST 0807 [1] or SMPTE RP 210 [2]
- Units – Units of measure in SI units, if appropriate
- Format – Value encoding method, which can be one of the following:
    - UINT(<length>): Unsigned integer of <length> bytes
        - Example: UINT(8) is an unsigned integer of 8 bytes
    - IMAPB(<min float>, <max float>, <length>): MISB ST 1201 [3] notation for mapping ("packing") a floating point value into an integer value
        - Example: IMAPB(-1234,+1234,3) indicates that a floating-point value within the range from -1234.0 to +1234.0 mapped into 3 bytes
    - FLOAT(<length>): a floating-point value of <length> bytes
        - Example: FLOAT(4) is a 32-bit IEEE floating point number

6.2 Conventions

MISB ST 0107 [4] provides usage rules for metadata. IEEE 754 [5] provides guidance for floating point values.

Requirement(s)	
ST 0801.5-01	All KLV-encoded metadata shall be expressed in accordance with MISB ST 0107.
ST 0801.5-02	Floating point values shall comply with IEEE 754.
ST 0801.5-03	Measurements shall be expressed using the International System of Units (SI).

To promote bit efficiency, floating point values may be "packed" as integers, in accordance with MISB ST 1201.

All angle measurements are in half circles. To obtain the value of an angle in radians, multiply the number of half circles in the measurement by pi (π). Angle measurements are packed as integer representations of rational numbers.

pi (π) is defined as: $\pi = 3.1415926535\ 8979324$

This is the value of pi used in the coordinate conversion software developed and controlled by NGA; specifically, MSP GEOTRANS 3.0 (Geographic Translator) [6].

Requirement	
ST 0801.5-04	When converting values between radians and half circles, the value of pi (π) shall be 3.1415926535 8979324.

6.3 Photogrammetry External Parameters

The External Parameters relate the sensor to the "real world", using the World Geodetic System-1984 (WGS-84) coordinate frame. All the position coordinates and velocity elements are with respect to this coordinate reference.

This standard specifies the use of WGS-84 coordinates using a Cartesian, Earth-Centered, Earth-Fixed (ECEF) coordinate system. Figure 6 illustrates the earth's ellipsoid with the ECEF origin

(0, 0, 0) and axes in green. The ECEF's origin is the earth's center of mass. The ECEF x-axis points to the intersection of the equator and the IERS Reference Meridian (IRM) (Greenwich meridian), the z-axis points towards the North Pole (true North), and the y-axis completes the right-handed coordinate system [7]. An example ECEF position shows its x, y, and z coordinates. All ECEF measurements use the International System of Units (SI).

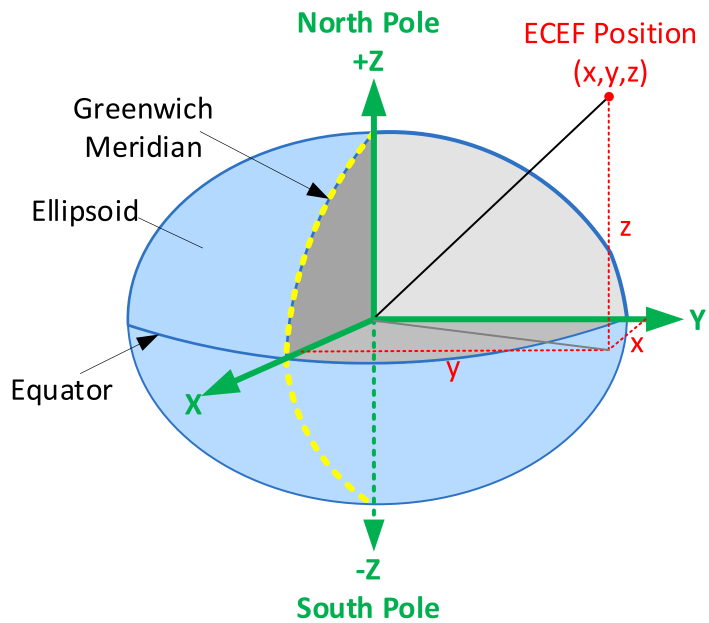

Figure 6: ECEF Coordinate System

Requirement	
ST 0801.5-05	Sensor position and velocity shall be expressed using the WGS-84 Earth-Centered, Earth-Fixed (ECEF) coordinate frame.

This coordinate system is consistent with the native coordinate format of the Global Positioning System (GPS). When transforming these coordinates to other systems system (e.g., Latitude, Longitude, and Height-Above-Ellipsoid) use techniques which minimize numerical errors.

This standard specifies the use of sensor orientation relative to a "local" coordinate frame, using a geodetic North-East-Down (NED) system at the ECEF location of the sensor. Figure 7 illustrates the NED local coordinate system which has the X-Y plane (yellow) parallel to a plane (blue) tangent to the ellipsoid; where the X-axis aligns with the longitudinal lines, with positive values going north; the Y-axis aligns with latitude lines, with positive values going east. The Z-axis of each plane is mutually orthogonal to the X and Y axes with positive Z values increasing in the downwards direction geodetically toward the earth's Z axis. The Z axes of both X-Y planes is collinear. Section 7 provides more detail of sensor position and orientation with corresponding figures and the rotation angles relative to the local coordinate system, where they are applied sequentially as heading-pitch-roll.

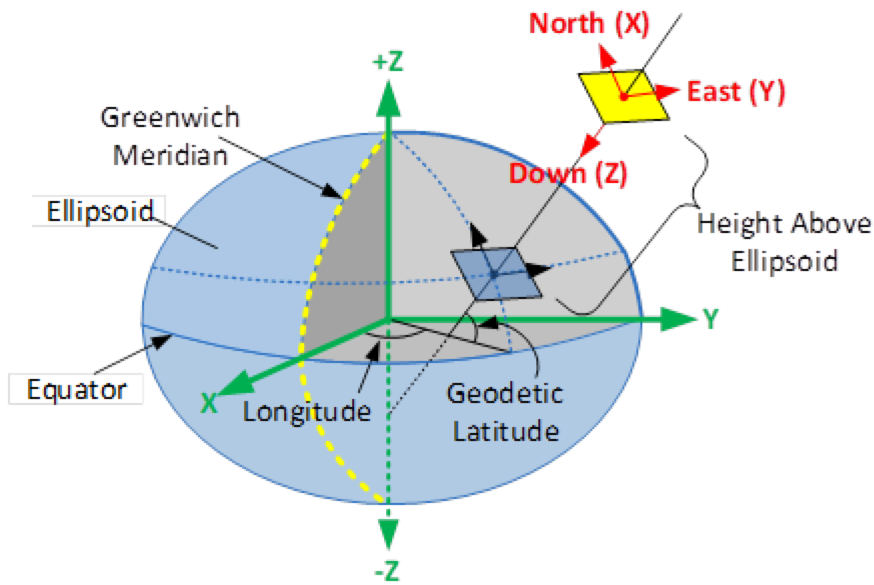

Figure 7: The NED Local Coordinate System

Requirement	
ST 0801.5-06	Sensor orientation shall be expressed using a North-East-Down (NED) coordinate frame located at the Earth-Centered, Earth-Fixed (ECEF) position of the sensor.

6.3.1 Sensor Position Metadata

Sensor position metadata set describes a reference point within a sensor. An example of this reference point is the center of rotation of the sensor (i.e., the point about which a two- or three-axis gimbal rotates). The center of rotation is a point of convenience, because its location does not change depending on the sensor orientation relative to the platform's reference frame. This metadata set includes elements for the ECEF position coordinates of the sensor. The intended use of this metadata set is to perform photogrammetric computations, which are based on the sensor perspective center. (The sensor perspective center is analogous to the pinhole of a pinhole camera.) This metadata set alone does not describe the sensor perspective center, but when used with the Boresight metadata set, described in Section 6.4.2, it gives the exact location needed in the photogrammetric computations. Table 1 lists the sensor position metadata.

Table 1: Sensor Position Metadata

Name	Key	Units	Format
Sensor ECEF Position Component X	06.0E.2B.34.01.01.01.01.0E.01.02.01.25.00.00.00 (CRC 25208)	m	IMAPB(-1e9, 1e9, 5)
Sensor ECEF Position Component Y	06.0E.2B.34.01.01.01.01.0E.01.02.01.26.00.00.00 (CRC 63908)	m	IMAPB(-1e9, 1e9, 5)

Sensor ECEF Position Component Z	06.0E.2B.34.01.01.01.01.0E.01.02.01.27.00.00.00 (CRC 36624)	m	IMAPB(-1e9, 1e9, 5)

6.3.2 Sensor Velocity Metadata

The sensor velocity metadata set includes the ECEF velocity components of the sensor. Table 2 lists the sensor velocity metadata.

Table 2: Sensor Velocity Metadata

Name	Key	Units	Format
Sensor ECEF Velocity Component X	06.0E.2B.34.01.01.01.01.0E.01.02.01.2E.00.00.00 (CRC 31847)	m/s	IMAPB(-25e3, 25e3, 3)
Sensor ECEF Velocity Component Y	06.0E.2B.34.01.01.01.01.0E.01.02.01.2F.00.00.00 (CRC 02771)	m/s	IMAPB(-25e3, 25e3, 3)
Sensor ECEF Velocity Component Z	06.0E.2B.34.01.01.01.01.0E.01.02.01.30.00.00.00 (CRC 50586)	m/s	IMAPB(-25e3, 25e3, 3)

6.3.3 Sensor Absolute Orientation Metadata

The Sensor Absolute Orientation Parameters are sensor Heading, Pitch, and Roll angles. (Heading may also be referred to as “azimuth”.) These parameters specify sensor orientation with respect to a North-East-Down frame of reference located at the sensor perspective center. These parameters describe the direction in which the sensor “Reference Axis” is pointing. The combination of the sensor Reference Axis and the Boresight metadata set described in Section 6.4.2 defines the sensor Principal Axis. This Principal Axis is also known as the sensor line-of-sight axis, or boresight. A detailed explanation appears in Section 7.

The Heading of a sensor is the angle from True North to the boresight vector projected onto the local horizontal plane. Range of values is 0 to (almost) 2 half-circles; North is 0, East is 0.5 half-circles; South is 1 half-circle, and West is 1.5 half-circles.

The Pitch of a sensor describes the angle its boresight vector makes with the horizontal, where the vertical is perpendicular to the ellipsoid; positive (negative) angles describe a nose up (down) orientation. Range of values is -1.0 half-circles to +1.0 half-circles.

The Roll of a sensor is the angle, defined as positive clockwise, that rotates the image about the boresight vector to complete the sensor orientation. This value is given in half-circles from -1.0 to +1.0.

The heading-pitch-roll transformation is customarily described using a rotation matrix, described in Section 7.

The azimuth-pitch-roll formulation of the rotation matrix has a known singularity point where the pitch angle is equal to +90 degrees or -90 degrees. During calculation, caution must be used to avoid errors as the sensor passes through these discontinuity points. This topic is discussed at the end of Section 7.

Note that heading, pitch, and roll must be applied in a strict sequence, as described in Figure 11, Figure 12, and Figure 13 of Section 7.

Requirement	
ST 0801.5-07	During coordinate system transformation calculations, sensor rotation angles shall be applied in the sequence (1) heading, (2) pitch, and (3) roll.

Table 3 lists the sensor absolute orientation metadata.

Table 3: Sensor Absolute Orientation Metadata

Name	Key	Units	Format
Sensor Absolute Heading	06.0E.2B.34.01.01.01.01. 0E.01.02.01.37.00.00.00 (CRC 38071)	half circles	IMAPB(0, 2,4)
Sensor Absolute Pitch	06.0E.2B.34.01.01.01.01. 0E.01.02.01.38.00.00.00 (CRC 16473)	half circles	IMAPB(-1, 1, 4)
Sensor Absolute Roll	06.0E.2B.34.01.01.01.01. 0E.01.02.01.39.00.00.00 (CRC 14061)	half circles	IMAPB(-1, 1, 4)

6.3.4 Sensor Absolute Orientation Rate Metadata

The definitions and sign conventions for the Sensor Absolute Orientation Rates (time rate of change) are the same as those given in Section 6.3.3.

The sensor absolute orientation rate metadata set includes the Sensor Absolute Orientation Rate components (in half-circles per second) of the sensor. Table 4 lists the sensor absolute orientation rate metadata.

Table 4: Sensor Absolute Orientation Rate Metadata

Name	Key	Units	Format
Sensor Absolute Heading Rate	06.0E.2B.34.01.01.01.01. 0E.01.02.01.40.00.00.00 (CRC 34799)	half circles /sec	IMAPB(-1, 1, 2)
Sensor Absolute Pitch Rate	06.0E.2B.34.01.01.01.01. 0E.01.02.01.41.00.00.00 (CRC 61787)	half circles /sec	IMAPB(-1, 1, 2)
Sensor Absolute Roll Rate	06.0E.2B.34.01.01.01.01. 0E.01.02.01.42.00.00.00 (CRC 27271)	half circles /sec	IMAPB(-1, 1, 2)

6.4 Photogrammetry Internal Parameters

Within photogrammetry, data values representing the configuration and orientation of optical sensor/detector systems behind a lens or aperture are commonly referred to as the internal parameters. These parameters represent a full and complete description of the internal sensor geometry.

In photogrammetry applications for digital Motion Imagery, these internal parameters enable transformation calculations between pixel coordinate systems and image space coordinate systems. The metadata definitions for the internal parameters described here provide representation of known systematic errors in the imaging system. The transformation between pixel and image space coordinate systems must use coordinates referenced to the full image resolution.

Requirement	
ST 0801.5-08	Transformation between pixel and image space coordinate systems shall use image coordinates at full image resolution.

6.4.1 Pixel Coordinate Transformation

This Standard uses three pixel-based coordinate systems for physical focal plane arrays and digital images: Row and Column; Line and Sample; and Measured (x, y). The first two use units of pixels, and the third uses physical measures, such as, millimeters. The Community Sensor Model (CSM) standard coordinate system is the Line and Sample coordinate system.

The Row and Column Coordinate system is an integer-based coordinate system which indexes individual pixels in the image. The Row and Column Coordinate System's origin (0,0) is at the upper left corner of the of the image with the positive Row axis pointing downwards and the positive Column axis pointing towards the right. Figure 8 illustrates the Row and Column Coordinate System overlaid on a five row by seven column (5 x 7) image; the Row and Column axes and the origin are blue. A sample coordinate at row 2, column 3 shows the coordinates are in the center of the pixel.

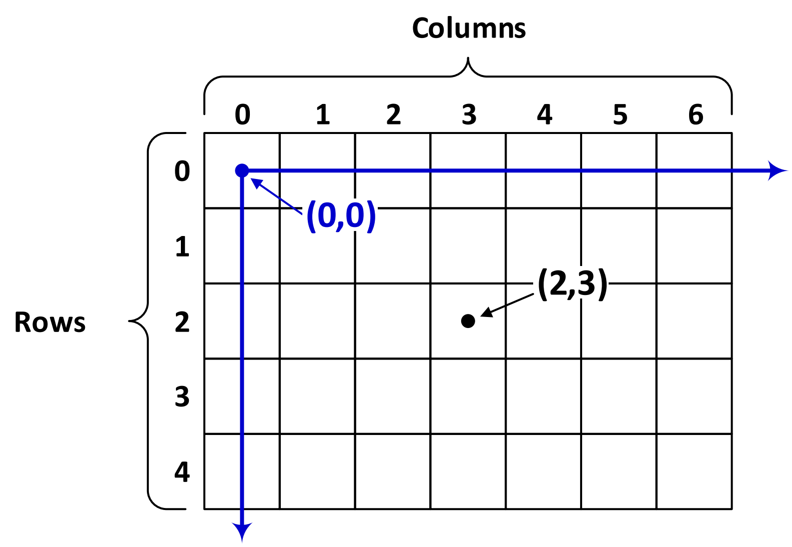

Figure 8: Row and Column Coordinates

The Line and Sample Coordinate System (CSM's Image Coordinate System) is a real-valued coordinate system which measures a position in the image in whole or fractions of pixels. The Line and Sample Coordinate System's origin (0.0, 0.0) is at the upper left corner of the upper left pixel of the image with the positive Line axis pointing downwards and the positive Column axis pointing towards the right. The center of each pixel is at half pixel high and wide in both the Row and Column directions. For example, the center of the upper left pixel has row, column coordinates of (0.5, 0.5). Figure 9 illustrates the Line and Sample Coordinate System overlaid on a five row by seven column (5 x 7) image; the Line and Sample axes and the origin are red. A sample coordinate in the same position as Figure 8 is at line 2.5, sample 3.5 which is in the center of the pixel.

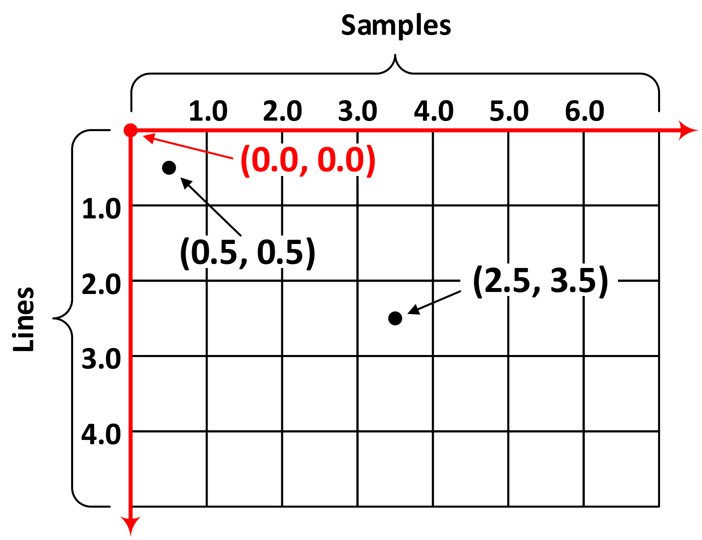

Figure 9: Line and Sample Coordinates

Figure 10 illustrates a real image with a Line and Sample axis overlay.

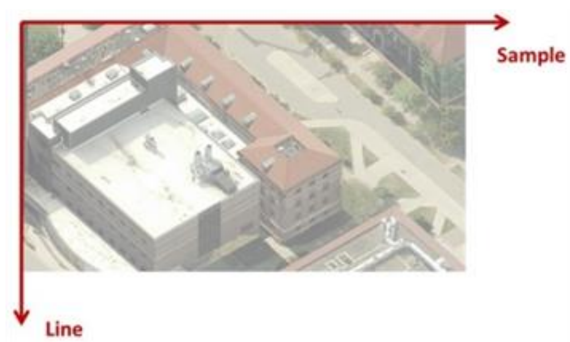

Figure 10: Line and Sample Axes Overlay on Real Image

The Measured Coordinate System (x, y) is a real-valued coordinate system which measures a position in the image in millimeters from using the same origin as the Line and Sample coordinate system.

MISB ST 1202 [8] defines additional forms of pixel to image mappings for chips, digitally zoomed images, or other types of general transformations.

6.4.2 Boresight Metadata

The Boresight Offset Delta X, Delta Y, and Delta Z parameters represent the mathematical translation from the origin of the sensor coordinate frame to the origin of the sensor perspective center. The rotational offsets Delta Angle 1, Delta Angle 2, and Delta Angle 3 are angular rotations applied to the sensor Reference Axes to align with the sensor Principal Axes. Delta Angle 1 represents the rotation about the twice-rotated x-axis of the sensor reference frame. Delta Angle 2 represents the rotation about the once-rotated y-axis of the sensor reference frame. Delta Angle 3 represents the rotation about the z-axis of the sensor reference frame.

The rotations are applied in the following order: (1) apply the Delta Angle 3 rotation about the z-axis of the sensor reference frame; (2) next apply the Delta Angle 2 rotation about the once-rotated y-axis of the sensor reference frame; and (3) finally apply the Delta Angle 1 rotation about the twice-rotated x-axis of the sensor reference frame. These sequential rotations will rotate the measured sensor reference frame to the sensor optical line of sight reference frame. If the sensor reference frame is aligned to the sensor optical axis, the three boresighting angles will be equal to zero.

See Section 7 for figures describing the rotations and for further information on the application of the boresight offsets. Table 5 lists the boresight metadata.

Table 5: Boresight Metadata

Name	Key	Units	Format
Boresight Offset Delta X	06.0E.2B.34.01.01.01.01. 0E.01.02.02.18.00.00.00 (CRC 39365)	m	IMAPB(-300, 300, 2)
Boresight Offset Delta Y	06.0E.2B.34.01.01.01.01. 0E.01.02.02.19.00.00.00 (CRC 61297)	m	IMAPB(-300, 300, 2)
Boresight Offset Delta Z	06.0E.2B.34.01.01.01.01. 0E.01.02.02.1A.00.00.00 (CRC 29869)	m	IMAPB(-300, 300, 2)
Boresight Delta Angle 1	06.0E.2B.34.01.01.01.01. 0E.01.02.02.1B.00.00.00 (CRC 00537)	half circles	IMAPB(-0.25, 0.25, 4)
Boresight Delta Angle 2	06.0E.2B.34.01.01.01.01. 0E.01.02.02.1C.00.00.00 (CRC 21300)	half circles	IMAPB(-0.25, 0.25, 4)
Boresight Delta Angle 3	06.0E.2B.34.01.01.01.01. 0E.01.02.02.1D.00.00.00 (CRC 09600)	half circles	IMAPB(-0.25, 0.25, 4)

6.4.3 Image Size Metadata

The image size metadata set provides the number of image rows (i.e. the image height), the number of image columns (i.e. the image width), the size of the pixels in the x-direction, and the size of the pixels in the y-direction. MISB ST 1202 provides the transformation from pixel coordinates to image-space coordinates. Table 6 lists the image size metadata.

Table 6: Image Size Metadata

Name	Key	Units	Format
Image Rows	06.0E.2B.34.01.01.01.01. 0E.01.02.02.06.00.00.00 (CRC 08248)	pixels	UINT(2)
Image Columns	06.0E.2B.34.01.01.01.01. 0E.01.02.02.07.00.00.00 (CRC 22156)	pixels	UINT(2)
Pixel Size X	06.0E.2B.34.01.01.01.01. 0E.01.02.02.82.00.00.00 (CRC 14321)	mm	IMAPB(1e-4, 0.1, 2)
Pixel Size Y	06.0E.2B.34.01.01.01.01. 0E.01.02.02.82.01.00.00 (CRC 00193)	mm	IMAPB(1e-4, 0.1, 2)

Requirement	
ST 0801.5-09	When the pixel size in the y direction is unspecified, it shall be assumed equal to the pixel size in the x direction indicating square pixels.

6.4.4 Focal Plane Metadata

The focal plane metadata set provides information about the sensor focal plane and imaging geometry. It contains the Principal Point offset and the effective focal length of the sensor. The principal point offset parameter $+x_0$ is defined as the Focal Plane Principal Point Offset X and the principal point offset parameter $+y_0$ is defined as the Focal Plane Principal Point Offset Y. Both x_0 and y_0 parameters represent principal point offset parameters in Section 6.4.5 Equation 1 and Section 6.4.7 Equation 3. Table 7 lists the focal plane metadata.

Table 7: Focal Plane Metadata

Name	Key	Units	Format
Focal Plane Principal Point Offset X	06.0E.2B.34.01.01.01.01. 0E.01.02.02.04.00.00.00 (CRC 52560)	mm	IMAPB(-25, 25, 2)
Focal Plane Principal Point Offset Y	06.0E.2B.34.01.01.01.01. 0E.01.02.02.03.00.00.00 (CRC 40061)	mm	IMAPB(-25, 25, 2)
Sensor Calibrated / Effective Focal Length	06.0E.2B.34.01.01.01.01. 0E.01.02.02.05.00.00.00 (CRC 48100)	mm	IMAPB(0, 10000, 4)

6.4.5 Radial Distortion Metadata

The radial distortion metadata set provides parameters needed to correct for barrel or pincushion distortions in the sensor optics. Radial lens distortion d_r for image coordinates x and y is modeled as a polynomial function of the radial distance r from the Principal Point. The radial distortion parameters are the k_0, k_1, k_2, and k_3 parameters of Equation 1.

$$d_r = k_0 r + k_1 r^3 + k_2 r^5 + k_3 r^7$$ **Equation 1**

where $\bar{x} = x - x_0$ $\bar{y} = y - y_0$ $r = \sqrt{\bar{x}^2 + \bar{y}^2}$

and x_0 and y_0 are the coordinates of the Principal Point.

This model of radial distortion has a limited range for which the residuals of the fit are considered acceptable. This "valid range" is a distance in image space (mm) radially from the principal point. Table 8 lists the radial distortion rate metadata.

Table 8: Radial Distortion Metadata

Name	Key	Units	Format
Valid Range of Radial Distortion	06.0E.2B.34.01.01.01.01. 0E.01.02.02.69.00.00.00 (CRC 44292)	mm	FLOAT(4)
Radial Distortion Constant Parameter	06.0E.2B.34.01.01.01.01. 0E.01.02.02.6A.00.00.00 (CRC 14040)	mm/(mm)	FLOAT(4)
First Radial Distortion Parameter	06.0E.2B.34.01.01.01.01. 0E.01.02.02.0A.00.00.00 (CRC 28426)	mm/(mm)^3	FLOAT(4)
Second Radial Distortion Parameter	06.0E.2B.34.01.01.01.01. 0E.01.02.02.0B.00.00.00 (CRC 06590)	mm/(mm)^5	FLOAT(4)
Third Radial Distortion Parameter	06.0E.2B.34.01.01.01.01. 0E.01.02.02.0C.00.00.00 (CRC 18579)	mm/(mm)^7	FLOAT(4)

6.4.6 Tangential-Decentering Metadata

The tangential-decentering metadata set provides tangential decentering parameters P_1, P_2, and P_3 to correct image coordinates x and y for these distortions using Equation 2.

$$\Delta x_{decen} = (1 + P_3 r^2)[P_1(r^2 + 2\bar{x}^2) + 2P_2\bar{x} \times \bar{y}]$$
$$\Delta y_{decen} = (1 + P_3 r^2)[2P_1\bar{x} \times \bar{y} + P_2(r^2 + 2\bar{y}^2)]$$ **Equation 2**

where Δx_{decen} and Δy_{decen} are the x and y components of the decentering effect.

$\bar{x} = x - x_0$ $\bar{y} = y - y_0$ $r = \sqrt{\bar{x}^2 + \bar{y}^2}$

where x_0 and y_0 are the coordinates of the Principal Point.

Table 9 lists the tangential-decentering metadata.

Table 9: Tangential-Decentering Metadata

Name	Key	Units	Format
First Tangential / Decentering Parameter	06.0E.2B.34.01.01.01.01. 0E.01.02.02.0D.00.00.00 (CRC 15911)	mm/(mm)^2	FLOAT(4)
Second Tangential / Decentering Parameter	06.0E.2B.34.01.01.01.01. 0E.01.02.02.0E.00.00.00 (CRC 42491)	mm/(mm)^2	FLOAT(4)
Third Tangential / Decentering Parameter	06.0E.2B.34.01.01.01.01. 0E.01.02.02.83.00.00.00 (CRC 16709)	1/(mm)^2	FLOAT(4)

6.4.7 Affine Correction Metadata

The affine correction metadata set provides affine correction parameters. Parameter b_1 is a differential scale correction parameter, and parameter b_2 is a skew correction.

$$\Delta x_{skew-scale} = b_1\bar{x} + b_2\bar{y}$$

where $\bar{x} = x - x_0$ and $\bar{y} = y - y_0$

Equation 3

x_0 and y_0 are the principal point offsets in the x and y directions, respectively; and x and y are the image coordinates in the frame coordinate system. Table 10 lists the affine correction metadata.

Table 10: Affine Correction Metadata

Name	Key	Units	Format
Differential Scale Affine Parameter	06.0E.2B.34.01.01.01.01. 0E.01.02.02.0F.00.00.00 (CRC 54095)	mm/mm	FLOAT(4)
Skewness Affine Parameter	06.0E.2B.34.01.01.01.01. 0E.01.02.02.10.00.00.00 (CRC 07174)	mm/mm	FLOAT(4)

Requirement	
ST 0801.5-10	If pixels are not square, the differential scale correction parameter b_1 shall be exactly zero.

6.5 Photogrammetry Miscellaneous Parameters

The following subsection describes parameters that are neither interior nor exterior orientation parameters; however, they are useful when describing the data collected from a Motion Imagery sensor.

6.5.1 Slant Range Metadata

Slant Range is defined in SMPTE RP 210 [2].

Requirement	
ST 0801.5-11	The definition of slant range shall be as defined in SMPTE RP 210.

Slant Range is the distance from the sensor to a point on the ground contained in the framed subject (image) depicted in the captured essence. When used in this metadata set, the position of the sensor is defined to be the position of its perspective center.

A pedigree component exists to describe the derivation of the slant range value. There are three options: (0) Other, indicated by a value of zero; (1) Measured, indicated by a value of 1; and (2) Computed, indicated by a value of 2.

Typically, a measured range value might be obtained using a laser range finder.

Requirement	
ST 0801.5-12	When the slant range pedigree value is absent from the metadata set, but a slant range value is specified, the pedigree value shall be assumed to be 1 (a measured range).

Included in this metadata set is a row and column coordinate for the slant range to indicate the coordinate within the scene for which the value applies. Typically, this will be at the center of the image.

For measurements obtained using a laser range finder, the metadata set includes a laser range finder (LRF) divergence value to quantify the divergence of the laser range finder. Table 11 lists the slant range metadata.

Table 11: Slant Range Metadata

Name	Key	Units	Format
Slant Range	06.0E.2B.34.01.01.01.01. 07.01.08.01.01.00.00.00 (CRC 16588)	m	FLOAT(4)
Slant Range Pedigree	06.0E.2B.34.01.01.01.01. 0E.01.02.02.87.00.00.00 (CRC 35764)	N/A	UINT(1)

SPRM Row Coordinate	06.0E.2B.34.01.01.01.01. 0E.01.02.05.07.00.00.00 (CRC 12632)	pixels	FLOAT(4)
SPRM Column Coordinate	06.0E.2B.34.01.01.01.01. 0E.01.02.05.08.00.00.00 (CRC 58806)	pixels	FLOAT(4)
LRF Divergence	06.0E.2B.34.01.01.01.01. 0E.01.02.05.09.00.00.00 (CRC 37634)	rad	FLOAT(4)

6.6 Error Propagation

This document provides a "library" of metadata elements for incorporating into aggregate KLV data structures (e.g., Local Sets) of other specifications (Standards and Recommended Practices). To comply with the objective that these metadata elements support precise geolocation, any containing specification must also include appropriate uncertainty information properly formatted as found in MISB ST 1010 [9].

Requirement(s)	
ST 0801.5-13	Specifications that include any of the photogrammetry parameters defined in this specification shall include related variance-covariance uncertainty information.
ST 0801.5-14	Uncertainty information regarding photogrammetry parameters defined in this specification shall be encoded in accordance with MISB ST 1010.

7 Appendix – Rotation Angle and Coordinate Systems Definitions

This appendix provides additional information for applying the information contained in this document.

As a means of providing an overview of the rotation angles and coordinate systems documented in this appendix and their relationships to one another, Equation 4 provides a mathematical description of the projection of ground coordinates (*e.g.* a target) in the ECEF system into the *Frame* image space coordinate system.

$$\begin{bmatrix} \tilde{x} \\ \tilde{y} \\ \tilde{z} \end{bmatrix} = \eta R_{LOS}^{Frame} R_{IMU}^{LOS} R_{NED}^{IMU} R_{ECEF}^{NED} \left(\begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} - \left(\begin{bmatrix} X_{SEN} \\ Y_{SEN} \\ Z_{SEN} \end{bmatrix} + (R_{NED}^{IMU} R_{ECEF}^{NED})^T \begin{bmatrix} b_{\Delta X} \\ b_{\Delta Y} \\ b_{\Delta Z} \end{bmatrix} \right) \right) \quad \textbf{Equation 4}$$

where $\tilde{x}, \tilde{y}$ are the idealized *Frame* image coordinates (in units of mm) that have undergone the photogrammetric internal parameter corrections documented in Section 6.4,

$\tilde{z} = -f$, where f is the Sensor Calibrated / Effective Focal Length,

η is a scale factor variable cancelled out by dividing the first and second rows by the third row of Equation 4 when exercising the collinearity equations defined by Equation 5, Equation 12 and Equation 7

$$R_{LOS}^{Frame} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & -1 \\ -1 & 0 & 0 \end{bmatrix}$$ **Equation 5**

X_T, Y_T, Z_T are the ECEF coordinates (in units of meters) of the target,

X_{SEN}, Y_{SEN}, Z_{SEN} are the "Sensor ECEF Position" coordinates (in units of meters) of the center of navigation of the sensor,

$b_{\Delta X}$, $b_{\Delta Y}$, $b_{\Delta Z}$ are the "Boresight Offset Delta" coordinates (in units of meters) in the IMU system,

$$R_{ECEF}^{NED} = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} \cos\lambda & \sin\lambda & 0 \\ -\sin\lambda & \cos\lambda & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$ **Equation 6**

where λ and ϕ are the Geodetic latitude and longitude, respectively, of the center of navigation of the sensor (*i.e.* corresponding to the ECEF coordinates X_{SEN}, Y_{SEN}, Z_{SEN}).

Establishing a convention for rotating a coordinate system to be parallel to another coordinate system requires choosing from a variety of methods that yield the same result. This ST uses the azimuth-pitch-roll sequence (termed "heading-pitch-roll" in the body of this document) for the rotations. To avoid errors in interpretation, the azimuth, pitch, and roll angles must be defined unambiguously with respect to the starting and ending coordinate systems.

This section of the appendix will describe the starting coordinate system, the ending coordinate system, and the prescription of the angles used to align the two systems.

The coordinate system in which the azimuth, pitch, and roll angles are referenced is a North-East-Down (NED) system, centered at the sensor perspective center. The NED reference frame is a right-handed coordinate system with North being analogous to the x-axis, East being analogous to the y-axis, and Down being analogous to the z-axis. The destination coordinate system is the Inertial Measurement Unit (IMU) coordinate system, which is a right-handed system with its origin at the center of navigation. For a system with zero boresight offset angles (assume for the remainder of this derivation), the line-of-sight axes will be aligned where the x-axis is pointing along the sensor line-of-sight vector, the y-axis is parallel to the rows in the image, and the z-axis is parallel to the columns in the image.

The first angle of rotation aligns the x-axis (North) with the projection of the sensor boresight vector into a horizontal plane by rotating about the NED z-axis (Down). This is illustrated below in Figure 11, where the x-axis is colored red, the y-axis is colored green, and the z-axis is colored blue. The magnitude of this angle is equal to the azimuth, where a positive angle is in the clockwise direction when looking in the "down" direction; in other words, positive moves the red-axis (x-axis) to the green-axis (y-axis). The angle labeled in the figure, A3, is equivalent to the azimuth.

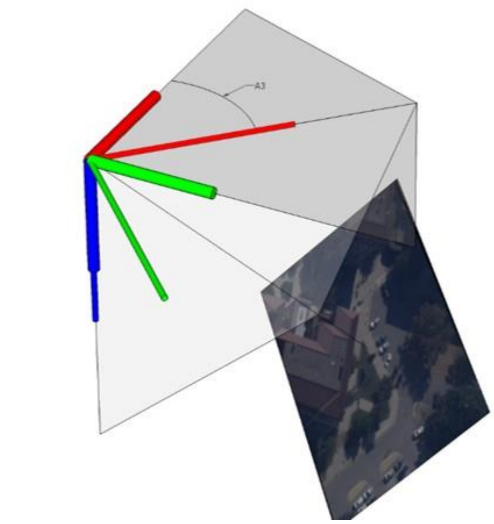

Figure 11: Description of the azimuth rotation

The second rotation points the once-rotated x-axis along the sensor boresight vector by a rotation about the once-rotated y-axis. The magnitude of this angle is the pitch, or a deflection from the local horizon shown in Figure 12. This angle is positive in the up-direction, where the blue-axis (once-rotated z-axis) moves towards the red-axis (once-rotated x-axis). Angle *A2* is equivalent to the sensor pitch and has a negative value when the sensor points towards the Earth.

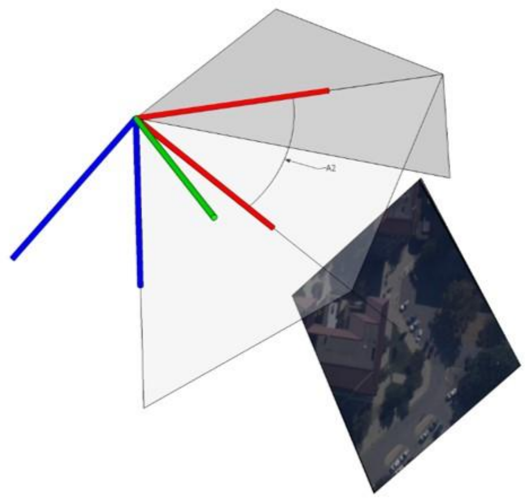

Figure 12: Description of the pitch rotation

The final rotation rotates the image about the sensor boresight vector by a rotation about the twice-rotated x-axis shown in Figure 13. The magnitude of this angle is the roll of the sensor, where it is positive clockwise when looking from the sensor along the boresight vector; in other words, the green-axis (y-axis) moves towards the blue-axis (twice-rotated z-axis). Angle *A1* is equivalent to the roll angle.

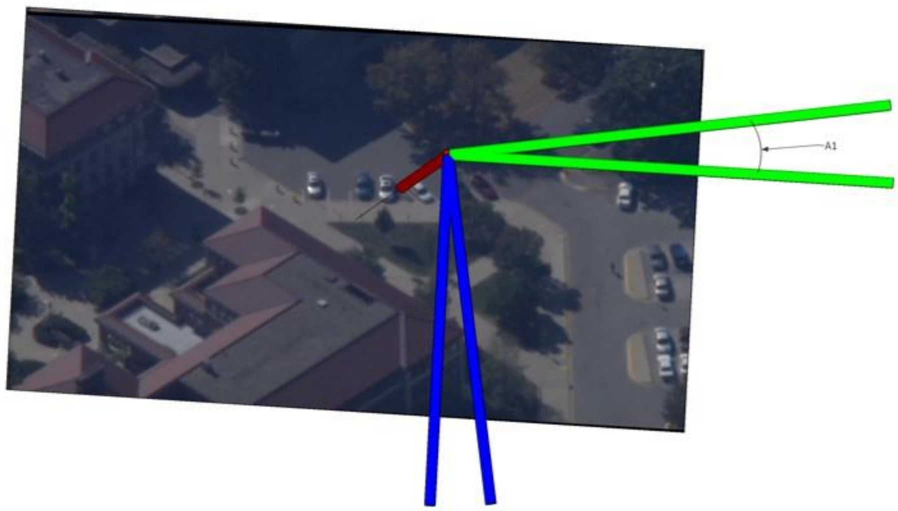

Figure 13: Description of the roll rotation

These rotations align the NED axes parallel to the IMU Axes. Equation 7 describes the total rotation matrix from the NED to the Inertial Measurement Unit (IMU) coordinate system. The IMU coordinate system represents the coordinate system for the senor's Reference Axes.

$$R_{NED}^{IMU} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos Ro & \sin Ro \\ 0 & -\sin Ro & \cos Ro \end{bmatrix} \begin{bmatrix} \cos Pt & 0 & -\sin Pt \\ 0 & 1 & 0 \\ \sin Pt & 0 & \cos Pt \end{bmatrix} \begin{bmatrix} \cos Az & \sin Az & 0 \\ -\sin Az & \cos Az & 0 \\ 0 & 0 & 1 \end{bmatrix}$$ **Equation 7**

The values used in this equation for the Azimuth (Az), Pitch (Pt), and Roll (Ro) angles can be derived from any rotation matrix that aligns a NED coordinate system with an IMU coordinate system. These values will be consistent regardless of how the initial rotations are defined provided the following prescription is followed. The rotation matrix is refined in Equation 8 through Equation 11 with each of its nine elements labeled.

$$R_{NED}^{IMU} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$ **Equation 8**

$$A_z = \tan^{-1}\left(\frac{r_{12}}{r_{11}}\right)$$ **Equation 9**

$$P_t = \sin^{-1}(-r_{13})$$ **Equation 10**

$$R_o = \tan^{-1}\left(\frac{r_{23}}{r_{33}}\right)$$ **Equation 11**

Using this formulation to define the angles allows the data provider to use *any* method of computing the rotation matrix that rotates the NED to the IMU coordinate system without loss of generality. In other words, this formulation does not have underlying assumptions that will cause a loss in computational accuracy.

An additional computational note is in dealing with arctangent functions. Since the data collected for the azimuth and roll angles can lie in any of the four quadrants of the unit circle, the two-argument form of the arctangent function (ATAN2) should be used. With the goal of this type of decomposition to obtain an identical rotation matrix, the results of the previously described algorithm satisfy this objective. However, the actual values for the azimuth-pitch-roll may be different. Differences typically occur when the pitch angle is less than -90 degrees or greater than +90 degrees. This condition will cause the azimuth to read 180 degrees different from the original angle, and the roll angle will also read 180 degrees different to account for the direction change. Again, the ATAN2 function of the decomposition will return identical results for the reconstructed rotation matrix. There is a possible discontinuity if the goal is to reconstruct the actual angles. Additional information is needed to determine the exact angles (*e.g.* adjacent frames or trajectory information).

Similarly, the rotation matrix for the boresighting offset angles which rotates the IMU coordinate system to the line-of-sight (Principal) coordinate system is formed using an identical sequence of rotations which rotate the NED system to the IMU system. Equation 12 describes this rotation matrix.

$$R_{IMU}^{LOS} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta_1 & \sin\beta_1 \\ 0 & -\sin\beta_1 & \cos\beta_1 \end{bmatrix} \begin{bmatrix} \cos\beta_2 & 0 & -\sin\beta_2 \\ 0 & 1 & 0 \\ \sin\beta_2 & 0 & \cos\beta_2 \end{bmatrix} \begin{bmatrix} \cos\beta_3 & \sin\beta_3 & 0 \\ -\sin\beta_3 & \cos\beta_3 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$ **Equation 12**

The order of rotations is applied similarly to the rotations from the NED to IMU rotations. The previously described Figure 11 through Figure 13 similarly describe the rotation of the IMU to line-of-sight coordinate systems.

After defining all the rotations and coordinate systems used to transform from ground to the image, the following defines how to model the errors in the angle values.

The uncertainty values associated with the “Sensor Absolute Heading”, “Sensor Absolute Pitch”, “Sensor Absolute Roll” and their associated correlation coefficients are all with respect to “small angle” errors δAz, δPt and δRo about the sensor coordinate system. These sigma’s represent uncertainties in rotation about Z, Y and X axes, respectively, of the sensor coordinate system shown graphically in Figure 14 and mathematically in Equation 13 as the error form of the rotation matrix that aligns the NED system to the IMU system, $R_{NED_{error}}^{IMU}$. As the figure and equation show, the sigmas are uncertainties in the Euler angles which define the orientation of the sensor coordinate system with respect to the North-East-Down coordinate system.

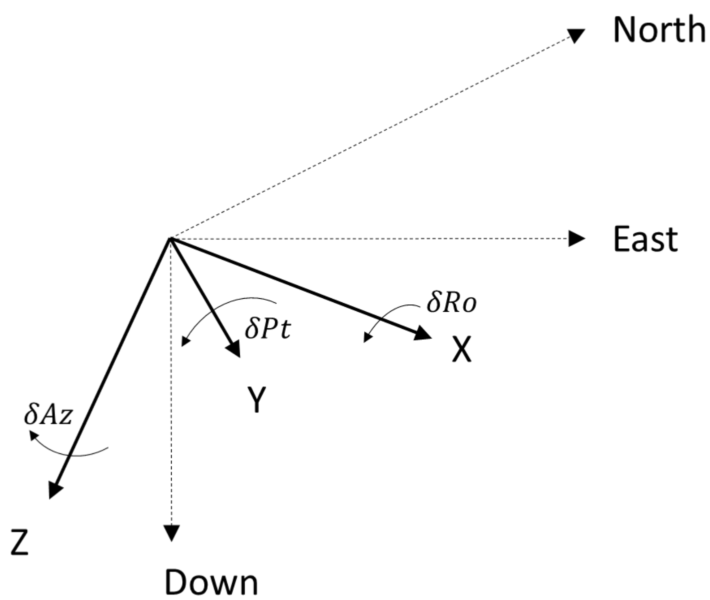

Figure 14: Small Angle errors about the IMU's X, Y and Z axes (North, East, Down axes are shown in dotted lines for context)

$$R_{NED_{error}}^{IMU} = \begin{bmatrix} 1 & \delta Az & -\delta Pt \\ -\delta Az & 1 & \delta Ro \\ \delta Pt & -\delta Ro & 1 \end{bmatrix} R_{NED}^{IMU} \qquad \textbf{Equation 13}$$

The convention for providing sigma and correlation coefficient values for the boresight offset angles is the same as described for sensor absolute angles. The error form of the rotation matrix that aligns the IMU to the LOS system, $R_{IMU_{error}}^{LOS}$, is summarized in Equation 14 where the "small angle" rotations are δb_1, δb_2 and δb_3.

$$R_{IMU_{error}}^{LOS} = \begin{bmatrix} 1 & \delta\beta_3 & -\delta\beta_2 \\ -\delta\beta_3 & 1 & \delta\beta_1 \\ \delta\beta_2 & -\delta\beta_1 & 1 \end{bmatrix} R_{IMU}^{LOS} \qquad \textbf{Equation 14}$$