Frame Sensor Model Metadata Profile Supporting Precise Geopositioning (FSMMG)

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Version 1.0

Prepared for the Community Sensor Model Working Group (CSMWG)
Established to serve the:
Geospatial Intelligence Standards Working Group (GWG)
Information Technology Standards Committee (ITSC)

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Revision History

Version Identifier	Date	Revisions/notes
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1. Introduction

1.1 Background/Scope

The National Geospatial-Intelligence Agency (NGA, formerly the National Imagery and Mapping Agency, (NIMA)) and Air Force Aeronautical Systems Center (ASC) have cooperated to standardize descriptions of the essential characteristics of imagery collection sensor systems by creating "sensor models". This information/guidance document will details the sensor and collector physics and dynamics that enable photogrammetry equations to establish the geometric relationship between sensor, image, and object imaged. A "*frame*" sensor model will be developed as the basis for establishing a process for development of additional sensor classes, e.g., synthetic aperture radar (SAR), pushbroom, whiskbroom, etc. This document will enable the validation and Configuration Management (CM) of geopositioning capabilities across the Distributed Common Ground/Surface System (DCGS) within the Imagery Intelligence (IMINT) Community.

1.2 Approach

This technical document details various parameters to consider when constructing a sensor model. A frame sensor is one that acquires all of the data for an image (frame) at an instant of time. Typical of this class of sensor is that it has a fixed exposure and is comprised of a two-dimensional detector or array; e.g., focal plane array (FPA) or Charge-Coupled Device (CCD) array.

"Sensor" usually refers to digital collections; the term "camera", if used, is typically used to denote use of film-based collectors. The focus of this report will be on those geometric sensor properties necessary for accurate and precise geolocation with electro-optical (visible) frame sensors and not on the spectral sensitivity of the sensor; although the definitions and development apply equally to film and infrared (IR) arrays.

1.3 Normative References

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO TC/211 211n1197, 19101 Geographic information – Reference model, as sent to the ISO Central Secretariat for registration as FDIS, December 3, 2001.

ISO TC/211 211n2047, Text for ISO 19111 Geographic Information - Spatial referencing by coordinates, as sent to the ISO Central Secretariat for issuing as FDIS, July 17, 2006.

ISO TC/211 211n2171, Text for final CD 19115-2, Geographic information - Metadata - Part 2: Extensions for imagery and gridded data, March 8, 2007.

ISO TC211 211n1017, Draft review summary from stage 0 of project 19124, Geographic information - Imagery and gridded data components, December 1, 2000.

ISO TC211 211n1869, New Work Item proposal and PDTS 19129 Geographic information - Imagery, gridded and coverage data framework, July 14, 2005.

Federal Geographic Data Committee (FGDC) Document Number FGDC-STD-012-2002, Content Standard for Digital Geospatial Metadata: Extensions for Remote Sensing Metadata.

Open Geospatial Consortium Inc. Transducer Markup Language Implementation Specification, Version 1.0.0, OGC® 06-010r6, December 22, 2006.

Open Geospatial Consortium Inc. Sensor Model Language (SensorML) Implementation Specification, Version 1.0, OGC® 07-000, February 27, 2007.

Community Sensor Model (CSM) Technical Requirements Document, Version 3.0, December 15, 2005.

North Atlantic Treaty Organization (NATO) Standardization Agreement (STANAG), Air Reconnaissance Primary Imagery Data Standard, Base document STANAG 7023 Edition 3, June 29, 2005.

National Geospatial-Intelligence Agency. National Imagery Transmission Format Version 2.1 For The National Imagery Transmission Format Standard, MIL-STD-2500C, May 1, 2006.

National Imagery and Mapping Agency. System Generic Model, Part 5, Generic Sensors, December 16, 1996.

Mikhail, Edward M., James S. Bethel, and J. Chris McGlone. Introduction to Modern Photogrammetry. New York: John Wiley & Sons, Inc, 2001.

1.4 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

1.4.1. adjustable model parameters

model parameters that can be refined using available additional information such as ground control points, to improve or enhance modelling corrections

1.4.2. area recording

“instantaneously” recording an image in a single frame

1.4.3. attitude

orientation of a body, described by the angles between the axes of that body’s **coordinate system** and the axes of an external **coordinate system** [ISO 19116]

1.4.4. attribute

named property of an entity [ISO/IEC 2382-17]

1.4.5. calibrated focal length

distance between the **projection center** and the **image plane** that is the result of balancing positive and negative radial lens distortions during sensor calibration

1.4.6. coordinate

one of a sequence of *n* numbers designating the position of a point in *n*-dimensional space [ISO 19111]

NOTE: In **a coordinate reference system**, the numbers must be qualified by units.

1.4.7. coordinate reference system

coordinate system that is related to the real world by a datum [ISO 19111]

NOTE: For geodetic and vertical datums, it will be related to the Earth.

1.4.8. coordinate system

set of mathematical rules for specifying how **coordinates** are to be assigned to points [ISO 19111]

1.4.9. data

reinterpretable representation of information in a formalised manner suitable for communication, interpretation, or processing [ISO/IEC 2382-1]

1.4.10. error propagation

determination of the covariances of calculated quantities from the input covariances of known values

1.4.11. fiducial center

point determined on the basis of the camera fiducial marks.

NOTE: When there are four fiducial marks, it is the intersection of the two lines connecting the pairs of opposite fiducials.

1.4.12. fiducial mark

one of four or more marks attached to the frame of a camera that are assigned **coordinates** when the camera is calibrated

NOTE: The **fiducial marks** are mechanical devices, which are firmly attached to the frame of the camera. During the exposure, the film is pressed from the back against the frame and the **fiducial marks**. The negatives of the **fiducial marks** appear on the exposed film. The **fiducial marks** allow for the establishment of an image coordinate system and their calibrated values assist in correcting for film distortion.

1.4.13. frame sensor

sensor that detects and collects all of the data for an image (frame / rectangle) at an instant of time

1.4.14. geodetic coordinate system

coordinate system in which position is specified by geodetic latitude, geodetic longitude and (in the three-dimensional case) ellipsoidal height [ISO 19111]

1.4.15. geodetic datum

datum describing the relationship of a **coordinate system** to the Earth [ISO 19111]

NOTE 1: In most cases, the **geodetic datum** includes an ellipsoid description

NOTE 2: The term and this Technical Specification may be applicable to some other celestial bodies.

1.4.16. geographic information

information concerning phenomena implicitly or explicitly associated with a location relative to the Earth [ISO 19101]

1.4.17. geographic location

longitude, latitude and elevation of a ground or elevated point

1.4.18. geolocating

geopositioning an object using a sensor model

1.4.19. geopositioning

determining the ground coordinates of an object from image coordinates

1.4.20. ground control point

point on the ground that has accurately known geographic location

1.4.21. image

coverage whose **attribute** values are a numerical representation of a remotely sensed physical parameter

NOTE: The physical parameters are the result of measurement by a **sensor** or a prediction from a model.

1.4.22. image coordinates

coordinates with respect to a Cartesian coordinate system of an image

NOTE: The image coordinates can be in pixel or in a measure of length (linear measure).

1.4.23. image distortion

deviation in the location of an actual image point from its theoretically correct position according to the geometry of the imaging process

1.4.24. image-identifiable ground control point

ground control point associated with a marker or other object on the ground that can be recognized in an **image**

NOTE: The ground control point may be marked in the image, or the user may be provided with an unambiguous description of the ground control point so that it can be found in the image.

1.4.25. image plane

plane behind an imaging lens where images of objects within the depth of field of the lens are in focus

1.4.26. image point

point on the **image** that uniquely represents an **object point**

1.4.27. imagery

representation of objects and phenomena as sensed or detected (by camera, infrared and multispectral scanners, radar and photometers) and of objects as **images** through electronic and optical techniques [19101-2]

1.4.28. metadata

data about **data** [ISO 19115]

1.4.29. object point

point in the object space that is imaged by a **sensor**

NOTE: In **remote sensing** and aerial photogrammetry an **object point** is a point defined in the ground **coordinate reference system**.

1.4.30. objective

optical element that receives light from the object and forms the first or primary **image** of an optical system

1.4.31. passive sensor

sensor that detects and collects energy that already exists (such as reflected energy from the Sun)

1.4.32. platform coordinate reference system

coordinate reference system fixed to the collection platform within which positions on the collection platform are defined

1.4.33. pixel

picture element [ISO 19101-2]

1.4.34. principal point of autocollimation

point of intersection between the **image plane** and the normal from the **projection center**

1.4.35. projection center

point located in three dimensions through which all rays between **object points** and **image points appear to pass geometrically**.

NOTE: It is represented by the rear nodal point of the imaging lens system.

1.4.36. remote sensing

collection and interpretation of information about an object without being in physical contact with the object

1.4.37. sensor

element of a measuring instrument or measuring chain that is directly affected by the measurand [ISO 19101-2]

1.4.38. sensor model

mathematical description of the relationship between the three-dimensional object space and the associated two-dimensional image plane

1.5 Symbols and abbreviated terms

1.5.1 Abbreviated terms

ASC	Aeronautical Systems Center
API	Application Program Interface
CCD	Charge-Coupled Device
CCS	Common Coordinate System
CM	Configuration Management
COTS	Commercial Off-The-Shelf
CSMS	Community Sensor Model Standard
CSMWG	Community Sensor Model Working Group
D	Down
DCGS	Distributed Common Ground/Surface System
DoD	Department of Defense
ECEF	Earth-centered, Earth-fixed
EGM	Earth Gravity Model
ENU	East-North-Up
EO	Exterior Orientation
FPA	Focal Plane Array
FR&T	Future Requirements and Technologies
GEOTRANS	Geographic Translator
GPS	Global Positioning System
GWG	Geospatial Intelligence Standards Working Group
IMINT	Imagery Intelligence
INS	Inertial Navigation System
IR	Infrared
ISO	International Organization for Standardization
ITS	Information Technology Standards Committee
MSL	Mean Sea Level
NATO	North Atlantic Treaty Organization
NED	North-East-Down
NGA	National Geospatial-Intelligence Agency (former NIMA)
NIMA	National Imagery and Mapping Agency
NITF	National Imagery Transmission Format
NCDM	National System for Geospatial Intelligence Conceptual Data Model
RSM	Replacement Sensor Model
S^2AG	Sensor Standards Acquisition Guide
SAR	Synthetic Aperture Radar
SenosrML	Sensor Markup Language
STANAG	Standardization Agreement (NATO)
TCPED	Tasking, Collection, Processing, Exploitation and Dissemination
TML	Transducer Markup Language
TRE	Tagged Record Extension
UTC	Coordinated Universal Time
WGS	World Geodetic System

1.5.2 Symbols

A	object, or ground point
a	image point
a_1, a_2, b_1, b_2	scale and skew coefficients
c_1, c_2	translation shift scalars
c	pixel column number (may be fractional)

C	number of columns (samples) on the collection array (unitless)
C_s	linear translations from CCS to collection array y-axis
C_ℓ	linear translations from CCS to collection array x-axis
d_x	pixel width, mm
d_y	pixel height, mm
E	East
f	sensor calibrated focal length, mm
H	sensor altitude, m HAE; also platform Heading
HAE	height above ellipsoid
H_{msl}	sensor altitude, km MSL
h_{msl}	object elevation, km MSL
h	object elevation, m HAE
K	refraction constant, micro-radians
k	arbitrary constant
k_1, k_2, k_3	first, second, and third order radial distortion coefficients, respectively
km	kilometer
L	sensor perspective center
ℓ	line
M	orientation (rotation) matrix
N	North
P	Platform pitch
p_1, p_2	decentering coefficients
r	radial distance, also pixel row number (may be fractional)
R	number of rows (lines) on the collection array (unitless); Platform Roll
s	sample
U	Up
X	X coordinates within Earth coordinate system
X_a	Platform longitudinal axis
x	various x coordinates defined by subscripts, collection array coordinate reference system x-axis, coordinate
x_0	x-coordinate of the foot of the perpendicular dropped from perspective center of the camera lens (mm)
x’	corrected image x coordinate
x_s	sensor coordinate reference system x-axis, at the sensor perspective center
Y	Y coordinates within Earth coordinate system
Y_a	Platform pitch axis
y	various y coordinates defined by subscripts, collection array coordinate reference system y-axis, coordinate
y_0	y-coordinate of the foot of the perpendicular dropped from sensor perspective center of the camera lens (mm)
y’	corrected image y coordinate
y_s	sensor coordinate reference system y-axis, at the lens center or perspective center axis
Z	Z coordinates within Earth coordinate system
Z_a	Platform yaw axis
z	various z coordinates, defined by subscripts
z_s	sensor coordinate reference system z-axis, at the lens center or perspective center axis
α	angle the refracted ray makes with local vertical
δr	radial optical distortion
Δd	atmospheric refraction angular displacement
Δx_{decen}	rotational symmetry, decentering, x component

Δy_{decen}	rotational symmetry, decentering, y-component
Δx_{lens}	total lens radial distortion and decentering, x-component
Δy_{lens}	total lens radial distortion and decentering, x-component
Δx_{radial}	atmospheric refraction, x-component
Δy_{radial}	atmospheric refraction, y-component
Δx_{ref}	radial optical distortion x-component
Δy_{ref}	radial optical distortion y-component
ϕ	latitude, pitch
λ	longitude
κ	yaw
σ	covariance matrix element
ω	roll
$\sum$	covariance matrix

2. Overview for Coordinate System Descriptions and Relationships

2.1 General Coordinate Reference System Considerations

The purpose of a frame model is to develop a mathematical relationship between the position of an object on the Earth's surface and its image as recorded by an overhead sensor. An image's spatial position may be given, at least initially or in its raw form, either in relation to a coordinate system locally defined or relative to an Earth reference. A horizontal (latitude and longitude) and a vertical (elevation) datum will be required to define the origin and orientation of the coordinate systems. Likewise, the corresponding object's position may be defined with respect to either the same coordinate system, or attached to any number of Earth-based datums. For purposes of this metadata profile, transformation between the various coordinate systems will be accomplished via a sequence of translations and rotations of the sensor's coordinate system origin and axes until it coincides with an Earth-based coordinate system origin and axes. An overall view of some of the coordinate system reference frames under consideration is shown in.Figure 1.

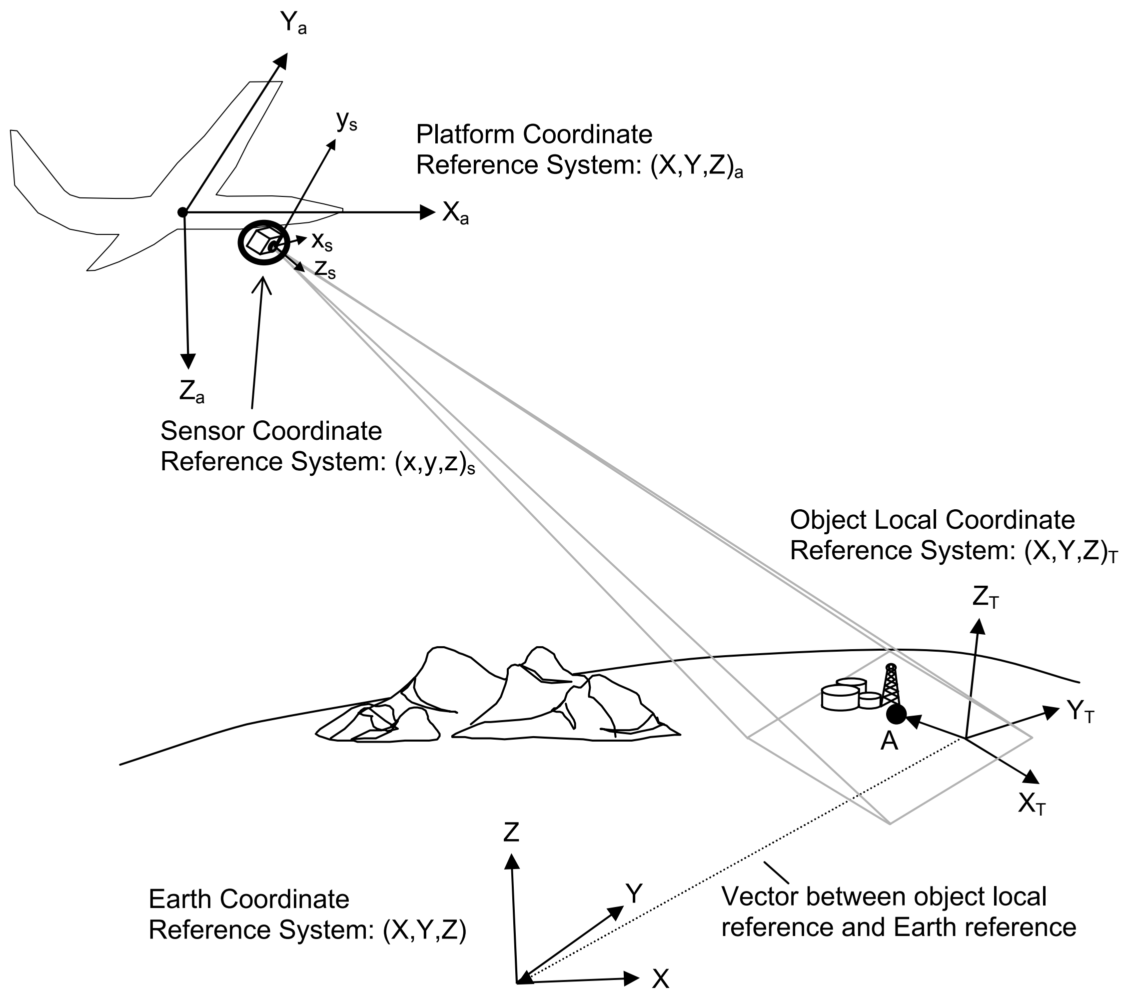

Figure 1. Multiple coordinate reference frames.

2.2 Earth Coordinate Reference System

To simplify the frame sensor model development, a stationary, non-time dependent coordinate reference frame is needed to which all other reference frames may be mathematically defined. We select a coordinate system (X,Y,Z) which is Earth-Centered, Earth-Fixed (ECEF), as shown in Figure 2; with the X-Y plane parallel to the equator, **X** intersects the Greenwich Meridian (from where longitude is measured; longitude equals 0-degrees at Y equal to zero), **Z** is parallel to the Earth's rotation axis and points toward the North pole, **Y** is in the equatorial plane and perpendicular to **X** and completes a right-handed coordinate system; i.e., the cross-product of **X** and **Y** is a vector in the direction of **Z**.

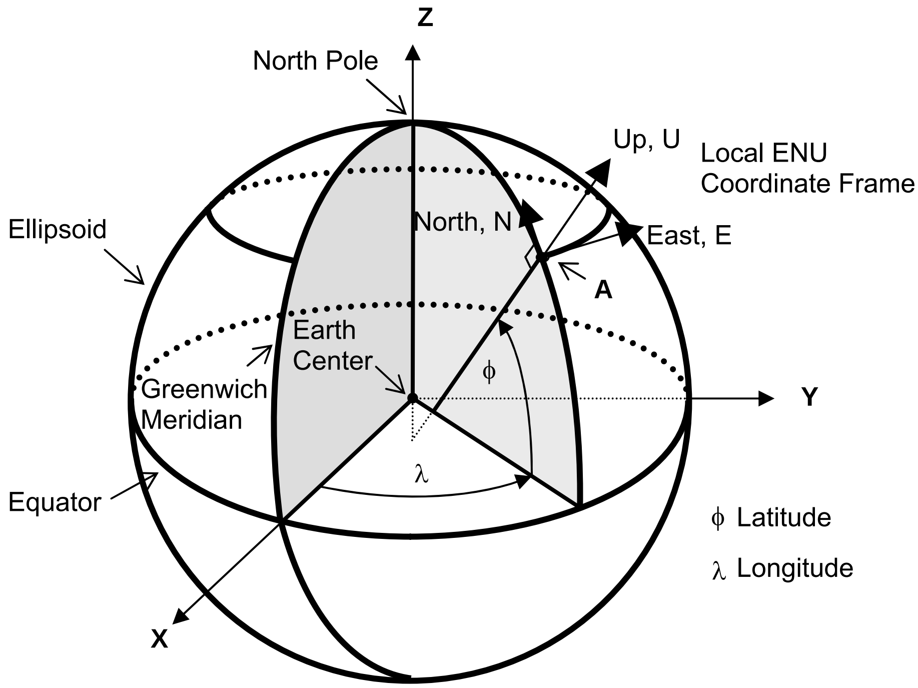

Figure 2. Earth-centered and local surface (ENU) coordinate frames (MIL-STD-2500C).

Therefore any point (A) on the reference surface may be described in (X,Y,Z) coordinates, or alternatively in the equivalent longitude, latitude, and elevation terms. Likewise, this point, the "object" point, can be described relative to a local reference system attached to the surface, specifically in an East-North-Up (ENU) orientation; where North is tangent to the local prime meridian and pointing North, Up vector pointing to the local zenith, and East completes a right-hand Cartesian coordinate system.

2.3 Platform Coordinate Reference System

A platform coordinate reference system is defined with respect to its center of navigation, fixed to the platform structure; e.g., the aircraft as shown in Figure 3. The axes are defined as: X_a positive along the heading of the platform, along the platform roll axis; Y_a positive in the direction of the starboard wing, along the pitch axis such that the X_aY_a plane is horizontal when the aircraft is at rest; and Z_a positive down, along the yaw axis. The platform coordinate reference system is also measured with respect to a North-East-Down (NED) reference system with its origin at the center of navigation. In horizontal flight, the platform Z_a axis is aligned with the Down (D) axis, and the North-East plane is parallel to the tangent plane to the Earth surface reference at the intersection of the D axis, Figure 4. Therefore, the platform reference system orientation defined in terms of its physical relation (rotation) about this local NED reference; Figure 5, are as follows:

Platform heading - horizontal angle from north to the NED horizontal projection of the platform positive roll axis, X_a (positive from north to east).

Platform pitch - angle from the NED horizontal plane to the platform positive roll axis, X_a-axis (positive when positive X_a is above the NED horizontal plane, or nose up).

Platform roll - rotation angle about the platform roll axis; positive if the platform positive pitch axis, Y_a, lies below the NED horizontal plane (right wing down).

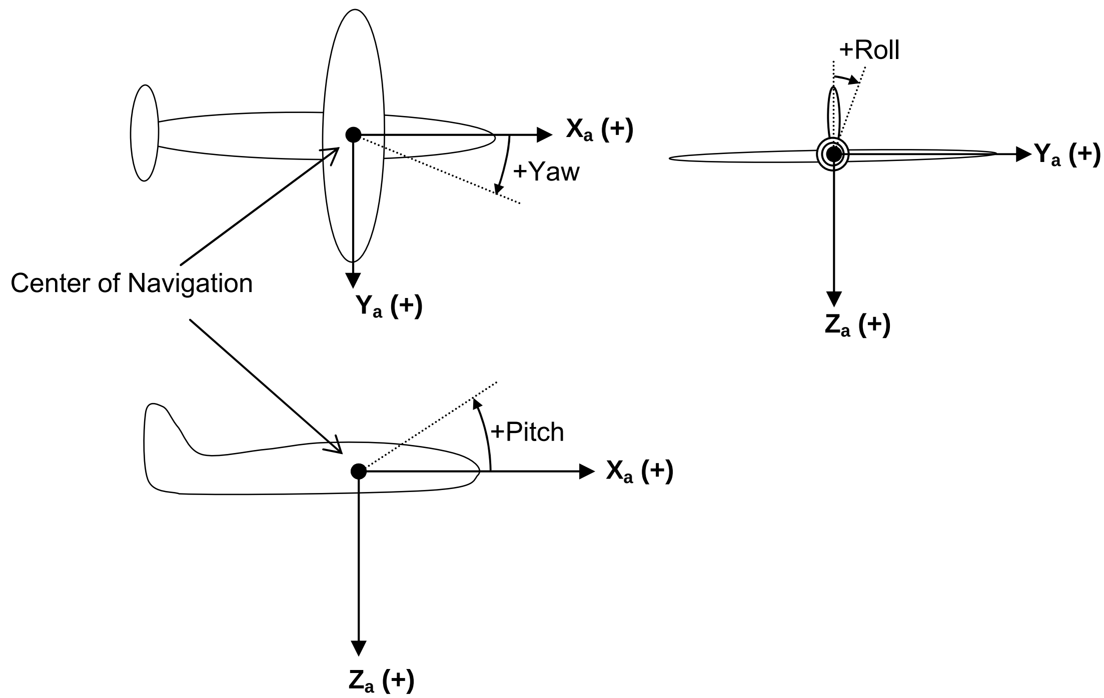

Figure 3. Platform coordinate reference system and local (NED) frame.

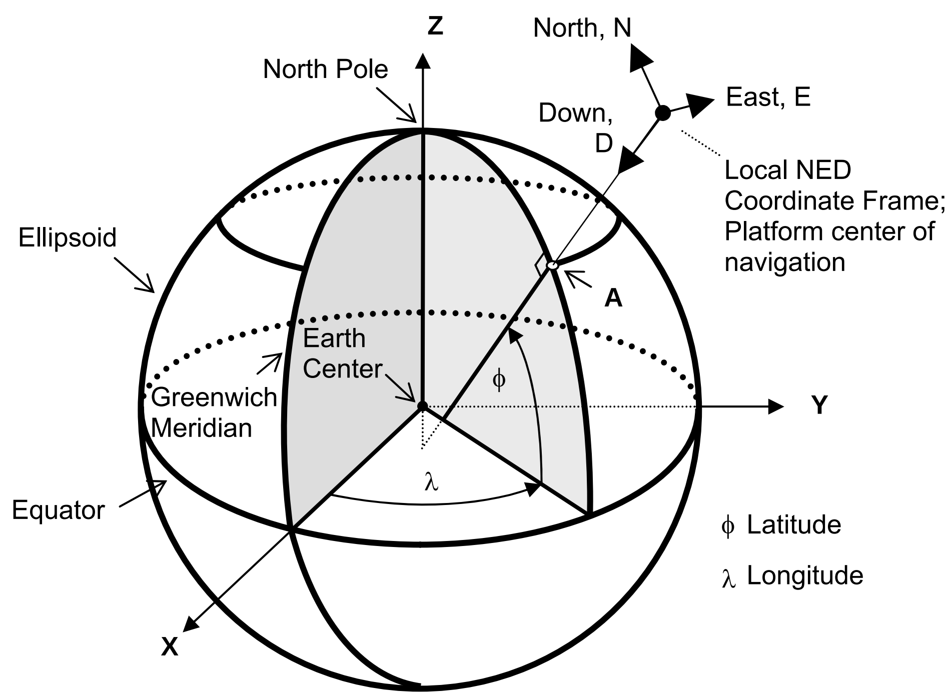

Figure 4. Earth and local platform (NED) coordinate frames.

The NED can be further defined to relate the local platform center of navigation through a sequence of angular rotations to the local Earth surface (ENU) reference; that is, the latitude, longitude and height, relative to an Earth-based ellipsoidal datum (e.g., WGS-84, Tokyo, etc.) and a vertical reference such as Mean Sea Level (MSL) or EGM-96. In turn, the local surface-based ENU reference can be translated and rotated into the ECEF frame; that is latitude, longitude, and gravity vector-based reference such as WGS-84, latitude (positive north), longitude (positive east), and gravity vectors relative to the Earth-based datum (i.e., WGS-84, EGM-96 ellipsoid).

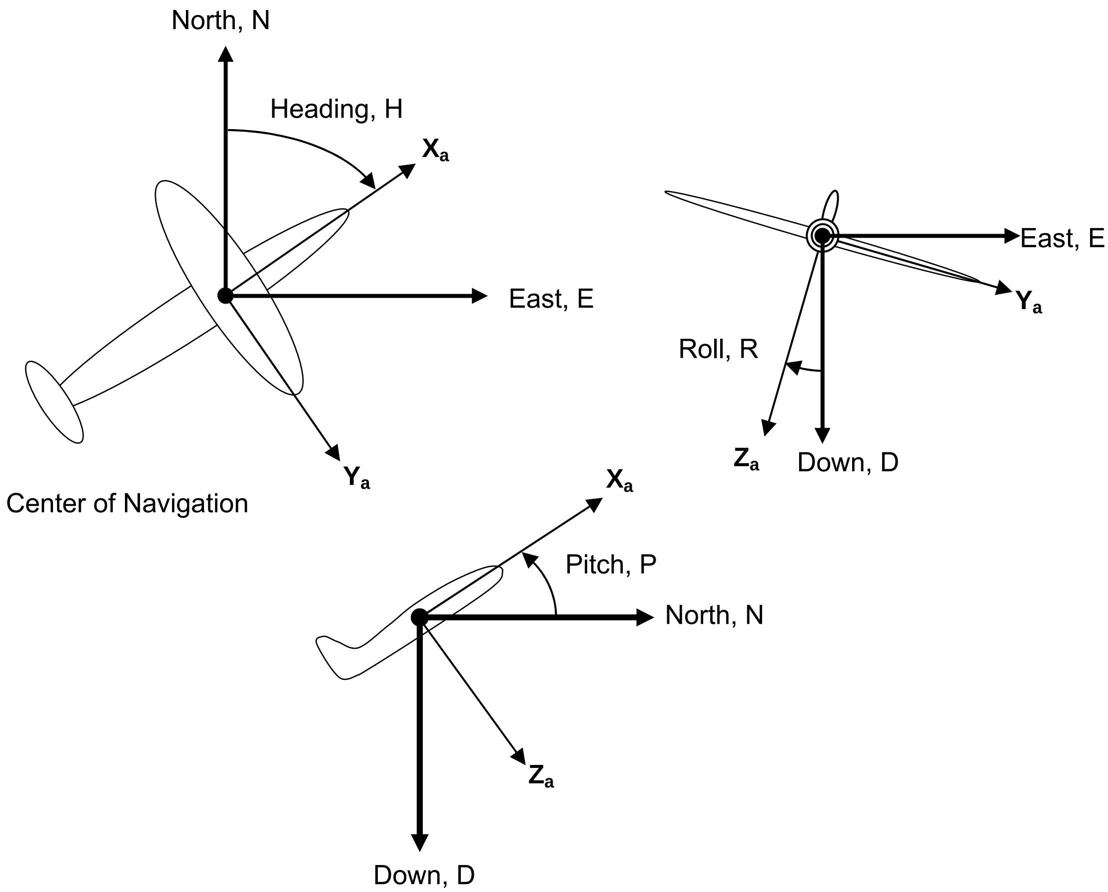

Figure 5. Platform coordinate reference system and local (NED) frame.

3. Frame Sensor Interior Descriptions

3.1 Sensor Coordinate Reference System

Define the origin of the sensor coordinate system to be centered on the frame sensor lens, its "lens center" or "perspective center" (x_s,y_s,z_s), with the positive *x*-axis aligned with the direction of flight of the platform, and the *z*-axis perpendicular to the lens and pointing away from the collection array. To establish an unambiguous alignment between the sensor and platform reference frames, at rest, the sensor axis (z_s) will be parallel to the platform Z_a–axis at nadir, and the x_s- and X_a-axes will be parallel and in the same positive direction. A positive image plane will be used as the reference in this frame model development of the image-to-ground transformation.

Depending on the sensor physical installation, the sensor coordinate system may be reported relative to one or more gimbal attachments, each with their own local coordinate system, to which the sensor is attached relative to the platform's center of navigation, which in turn may be referenced relative to the Global Positioning System (GPS) or other on-board inertial navigation system (INS). In practice, the center of navigation and the INS would likely be the same. Since gimbal information is unique to each sensor/platform design, intermediate rotations and translations required to align these specific components will not be addressed; NATO STANAG 7023 provides a detailed description of the influence of multiple gimbals. For consistency, however, transforming between coordinate systems is defined to follow a ZYX rotation sequence and x-, y-, z- offsets from the origin of each gimbal reference to subsequent gimbals, or platform and sensor reference systems to which they are attached. These rotation and offsets are defined as follows:

Sensor Position, X Vector Component - The x-axis measurement, mm, of the vector offset from the origin of the sensor mounting frame, e.g. Gimbal, Platform, or ECEF Coordinate System, to the origin of the sensor perspective centre, L. Similarly for the Y and Z vector components.

Sensor Rotation about Z-axis: Rotation of the sensor in the xy-plane of the sensor reference frame; measured as positive radians when positive +x-axis rotates directly towards +y-axis.

Sensor Rotation about Y-axis: Rotation of the sensor in the xz-plane of the sensor reference frame; measured as positive radians when positive +z-axis rotates directly towards +x-axis.

Sensor Rotation about X-axis: Rotation of the sensor in the yz-plane of the sensor reference frame; measured as positive radians when positive +z-axis rotates directly towards +y-axis.

Consider a frame sensor as a digital collector with a collection array made up of a matrix of detectors, or elements, at the focal plane, Figure 6. The sensor coordinate system is established such that when the sensor is pointing at nadir (z-down) then the sensor x-axis will be in the direction of travel, the y-axis parallel to the platform right wing, and z axis pointing at platform nadir. The focal plane array origin is located at the intersection of the sensor optical axis and image plane. Since reference is made to a positive image, the focal plane and sensor axes will be aligned. For collectors that are cameras, i.e., film-based, factors that may not pertain to a digital sensor must be accounted for, e.g., distortion factors associated with film deformation. These film distortions are accounted for within the mathematical modeling below. Although digital sensors may not suffer these same distortion factors, they may have their own unique distortions, such as unevenly spaced elements, which can be similarly accounted for. The transformation from line/sample to x,y coordinates will accommodate both media, as will be shown in section 3.3.

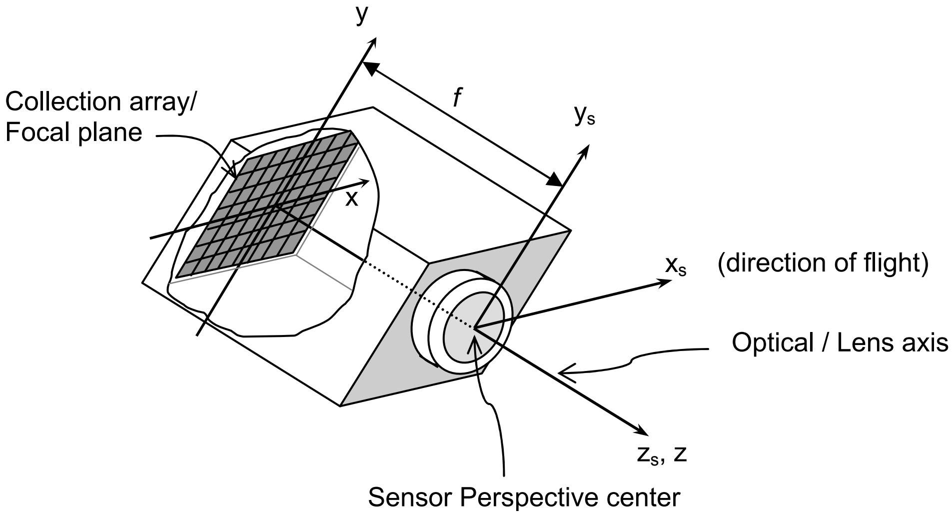

Figure 6. Sensor reference frame.

3.2 Typical Imagery Sensor Storage Layout

Typical of common imagery formats, and in particular ISO/IEC 12087-5, picture elements (pixels) are indexed according to placement within a “Common Coordinate System” (CCS), a two-dimensional array of rows and columns; as illustrated in the array examples in Figure 7. There are three commonly referred to coordinate systems associated with digital and digitized imagery: row, column (r,c), line, sample (ℓ,s), and x,y. The units used in the first two systems are pixels (and decimals thereof), while the x,y are linear measures such as mm (and decimals thereof), as will be introduced in following subclauses and Figure 7. The origin of the CCS, as shown in Figure 7, is the upper left corner of the first (or 0,0) pixel, which in turn is the upper left of the array. Because the CCS origin is the pixel corner, and the r,c associated with a designated pixel refers to its center, the coordinates of the various pixels, (0.4,0.5), (0.5,1.5), … etc., are as shown in Figure 7.

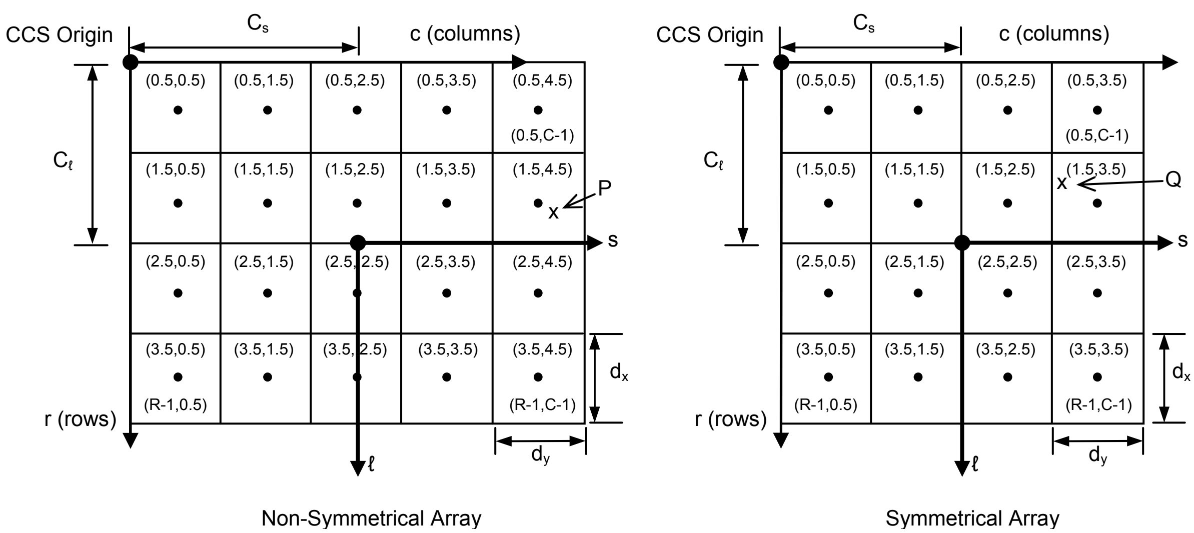

Figure 7. Pixel orientation within the frame sensor coordinate system.

3.3 Row, Column (r,c) to Line, Sample (ℓ,s) Coordinate Transformation

Since all mathematical development to follow are based on geometric center of the image as the origin, the (r,c) system is replaced by the (ℓ,s) system through two simple translations:

$$\ell = r - C_\ell$$
$$s = c - C_s \qquad \textbf{Eq. 1}$$

where C_ℓ and C_s are each half the image pixel array size, in pixels, in the row and column directions, respectively.

Examples.

Figure 7 (Nonsymmetrical Array): For C_ℓ = 4/2 = 2.0 C_s = 5/2 = 2.5 $r_p = 1.6\ pixel \quad c_p = 4.7\ pixel$

$$\ell_p = r_p - C_\ell = 1.6 - 2.0 = -0.4\ pixel$$
$$s_p = C_p - C_s = 4.7 - 2.5 = 2.2\ pixel$$

Figure 7 (Symmetrical Array): For C_ℓ = 4/2 = 2.0 C_s, = 4/2 =2.0 $r_Q = 1.4\ pixel \quad c_Q = 3.1\ pixel$

$$\ell_Q = r_Q - C_\ell = 1.4 - 2.0 = 0.6\ pixel$$
$$s_Q = c_Q - C_s = 3.1 - 2.0 = 1.1\ pixel$$

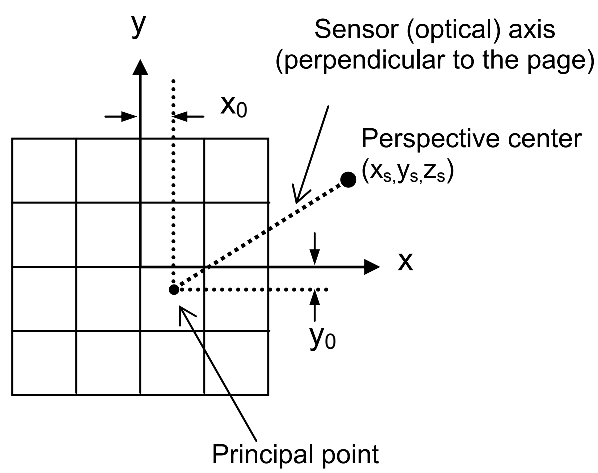

Figure 8. Placement of sensor axis.

Interior distortions or flaws, e.g., lens distortion errors, must be applied before the pixel-to-image transformation. Sensor developers may account for these imperfections as a part of calibration or through the use of other testing techniques to assess their sensor performance. In those cases, no adjustment by the exploitation tool may be necessary if lookup tables or automatic corrections are provided. Note that this paper will provide a simplified development and not attempt to model all of the possible influences; such as sensor array warping due to temperature changes, timing or dwell of image capture. Should applications require such advanced considerations, those influences, properly modeled, could be inserted into this basic model.

3.3.1 Array and Film distortions.

Deformations in the imagery are accounted for as follows:

$$x = a_1\ell + b_1 s + c_1$$
$$y = a_2\ell + b_2 s + c_2 \qquad \textbf{Eq. 2}$$

This transformation accounts for two scales, a rotation, skew, and two translations. The six parameters are usually estimated on the basis of (calibrated) reference points, such as camera fiducial marks, or their equivalent corner pixels for digital arrays. Here, the (x,y) image coordinate system, as shown in Figure 8, is used in the construction of the mathematical model, and applies to both film and digital sensors.

3.3.2 Principal point.

Ideally the sensor (lens) axis would, as in Figure 8, intersect the collection array at its center, (x,y) or (0,0). However, this is not always the case due to lens flaws, imperfections, or design, and is accounted for by offsets x_0 and y_0, as shown in the figure. Note that x_0 and y_0 are in the same linear measure (e.g., mm) as the image coordinates (x,y) and the focal length, *f*. For most practical situations, the offsets are very small, and as such there will be no attempt made to account for any covariance considerations for these offset terms.

3.3.3 Optical distortions.

Effects due to optical (lens) distortion are measured in terms of **radial** components. Assuming that calibration factors are not provided, the radial distortion can be approximated by a polynomial function applied to the x and y components; see Figure 9. The polynomial may take different forms; e.g., odd powers of the radial distance, or a scalar applied to the square of the radial distance. For purposes of this development, we follow a modified NGA Generic Sensor Model algorithm as follows.

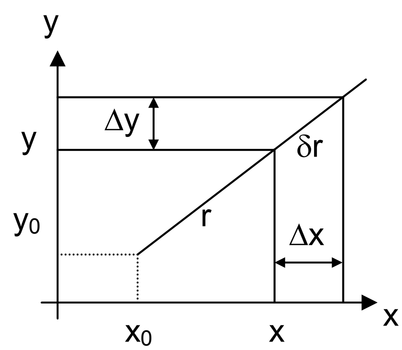

Figure 9. Radial optical distortion.

$$\delta r = k_1 r^3 + k_2 r^5 + k_3 r^7 \qquad \textbf{Eq. 3}$$

where:

$$r = \sqrt{\bar{x}^2 + \bar{y}^2} \qquad \bar{x} = x - x_0 \qquad \bar{y} = y - y_0 \qquad \textbf{Eq. 4}$$

and k represents the third, fifth, and seventh-order radial distortion coefficients. In most practical situations, the influence of the seventh-order term (k_3) is insignificant and can be ignored. This term will be included within the equations below, but not carried forward in the derivation of the collinearity equations. These k coefficients are obtained by fitting a polynomial to the distortion curve data from camera calibration using least squares. Contributions of first order terms may also be accomplished via adjustment to the focal length, but we have chosen to maintain attribution of distortion effects with their associated polynomials. The influence of this distortion is typically described as either a “pincushion” or “barrel” distortion, as shown in Figure 10.

The resultant x and y radial optical distortion components are then:

$$\Delta x_{radial} = \bar{x}\frac{\delta r}{r} = \bar{x}\frac{k_1 r^3 + k_2 r^5 + k_3 r^7}{r} = \bar{x}(k_1 r^2 + k_2 r^4 + k_3 r^6)$$
$$\Delta y_{radial} = \bar{y}\frac{\delta r}{r} = \bar{y}\frac{k_1 r^3 + k_2 r^5 + k_3 r^7}{r} = \bar{y}(k_1 r^2 + k_2 r^4 + k_3 r^6) \qquad \textbf{Eq. 5}$$

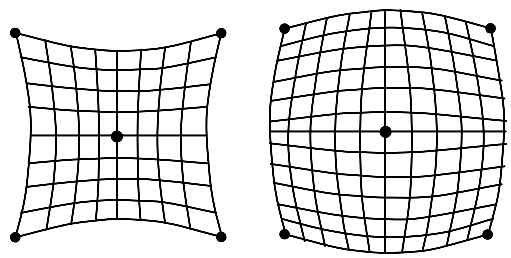

Figure 10. Optical radial distortion effects.

Another interior imperfection is described in terms of rotational symmetry, or “**decentering**.” While in general these effects may be assumed to be minimal, they may be more prominent in variable focus or zoom cameras. Consideration of this effect is given via the following (NIMA System Generic Model):

$$\Delta x_{decen} = p_1(2\bar{x}^2 + r^2) + p_2(2\overline{xy})$$
$$\Delta y_{decen} = p_1(2\overline{xy}) + p_2(2\bar{y}^2 + r^2) \qquad \textbf{Eq. 6}$$

where Δx_{decen} and Δy_{decen} are the x and y components of the decentering effect, respectively; p_1 and p_2 are decentering coefficients. Note that the referenced document included a third coefficient; however, for all practical purposes, this terms influence is so small that we choose to ignore it. Therefore, the contributions of lens radial distortions and decentering of x and y components are:

$$\Delta x_{lens} = \Delta x_{radial} + \Delta x_{decen} = \bar{x}(k_1 r^2 + k_2 r^4 + k_3 r^6) + p_1(2\bar{x}^2 + r^2) + p_2(2\overline{xy})$$
$$\Delta y_{lens} = \Delta y_{radial} + \Delta y_{decen} = \bar{y}(k_1 r^2 + k_2 r^4 + k_3 r^6) + p_1(2\overline{xy}) + p_2(2\bar{y}^2 + r^2) \qquad \textbf{Eq. 7}$$

3.3.4 Atmospheric Refraction. Adjustments may be required to account for bending of the image ray path as a result of atmospheric effects. These influences generally increase as altitude and look angles increase. Several methods, of varying complexity, are available to approximate the needed adjustments, including, for example, consideration of temperature, pressure, relative humidity, and wavelength. For purposes of this paper, we have chosen to adopt the following simple approximation

(Mikhail, 2001), where α is the angle the refracted ray makes with the local vertical, the angular displacement Δd (micro-radians) then becomes:

$$\Delta d = K \tan \alpha$$
$$where$$
$$K = \frac{2410 \times H_{msl}}{H_{msl}{}^2 - 6H_{msl} + 250} - \frac{2410 \times h_{msl}}{h_{msl}{}^2 - 6h_{msl} + 250}\left(\frac{h_{msl}}{H_{msl}}\right)$$
$$and$$
$$\alpha = \tan^{-1}(r / f) \qquad \textbf{Eq. 8}$$

H_{msl} is altitude (km, MSL) of the sensor, h_{msl} is the object elevation (km, MSL), and K is the refraction constant (micro-radians). This equation is a good approximation for collection parameters resulting when the optical axis coincides with the vertical axis ($\mathbf{Z}_T$,) from the ground object. Depending on the level of precision required, off-vertical collections may require more rigorous models. Note: Our parallel development of a "standard" sensor model proposes to use units of meters, referenced to height above ellipsoid (HAE), for sensor altitude and object elevation, thus the distinction between H_{msl}, h_{msl} (km, MSL) as used in the above equation and H, h (m, HAE) in the forthcoming standard is highlighted here.

Therefore, given image coordinates ($\bar{x}$, $\bar{y}$), the resulting coordinates (x'_{ref},y'_{ref}) are:

$$x'_{ref} = \bar{x}\frac{r'_{ref}}{r}$$
$$y'_{ref} = \bar{y}\frac{r'_{ref}}{r}$$

where

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

and

$$r'_{ref} = f \tan(\alpha + \Delta d) \qquad \textbf{Eq. 9}$$

It follows, then, that the refraction correction components (Δx_{ref}, Δy_{ref}) are:

$$\Delta x_{ref} = x'_{ref} - \bar{x} = \bar{x}\left(\frac{r'_{ref}}{r} - 1\right)$$
$$\Delta y_{ref} = y'_{ref} - \bar{y} = \bar{y}\left(\frac{r'_{ref}}{r} - 1\right) \qquad \textbf{Eq. 10}$$

Lastly, the corrections to the original image coordinates (x,y) are combined to establish the corrected image coordinates as follows:

$$\begin{aligned}
x' &= \bar{x} + \Delta x_{lens} + \Delta x_{ref} \\
&= \bar{x} + \bar{x}(\mathrm{k}_1 r^2 + \mathrm{k}_2 r^4 + \mathrm{k}_3 r^6) + \mathrm{p}_1(2\bar{x}^2 + r^2) + \mathrm{p}_2(2\overline{xy}) + \bar{x}\left(\frac{r'_{ref}}{r} - 1\right) \\
y' &= \bar{y} + \Delta y_{lens} + \Delta y_{ref} \\
&= \bar{y} + \bar{y}(\mathrm{k}_1 r^2 + \mathrm{k}_2 r^4 + \mathrm{k}_3 r^6) + \mathrm{p}_1(2\overline{xy}) + \mathrm{p}_2(2\bar{y}^2 + r^2) + \bar{y}\left(\frac{r'_{ref}}{r} - 1\right)
\end{aligned} \qquad \textbf{Eq. 11}$$

where *x'* and *y'* are the resulting corrected image coordinates.

Simplifying Equation 11:

$$\begin{aligned}
x' &= \bar{x}(\mathrm{k}_1 r^2 + \mathrm{k}_2 r^4 + \mathrm{k}_3 r^6 + \frac{r'_{ref}}{r}) + \mathrm{p}_1(2\bar{x}^2 + r^2) + \mathrm{p}_2(2\overline{xy}) \\
y' &= \bar{y}(\mathrm{k}_1 r^2 + \mathrm{k}_2 r^4 + \mathrm{k}_3 r^6 + \frac{r'_{ref}}{r}) + \mathrm{p}_1(2\overline{xy}) + \mathrm{p}_2(2\bar{y}^2 + r^2)
\end{aligned} \qquad \text{Eq. 12}$$

Therefore, given pixel coordinates (r,c), calculating the image coordinates, including correction factors considered, may be accomplished through the use of Equations 1, 2, 4, 8, 9, and 12. Therefore, (*x',y'*) are the coordinates required to establish the image-to-object transformation.

3.4 External Influences

Curvature of the Earth. Adjustments are required to account for curvature of the Earth if transforming between rectangular (Cartesian) coordinates to earth coordinates given in map projection (e.g., Lambert Conformal or Transverse Mercator). There are software programs available which provide the transformation between these differing formats, e.g., GEOTRANS; these will not be included in this development. Instead, we shall maintain use of Cartesian coordinates throughout.

This mathematical development applies to well calibrated metric cameras/sensors where all known systematic errors/distortions are corrected for before applying the fundamental imaging equations for central perspective applicable to frame imagery as introduced in the next section.

4. Collinearity Equations

Deriving the relation between image coordinates and the corresponding point on the Earth's surface they represent requires a common coordinate system, a process accomplished via translation and rotation from one coordinate system to the other. Extracting the object (***A***) from, the geometry is reduced to that shown in Figure 11.

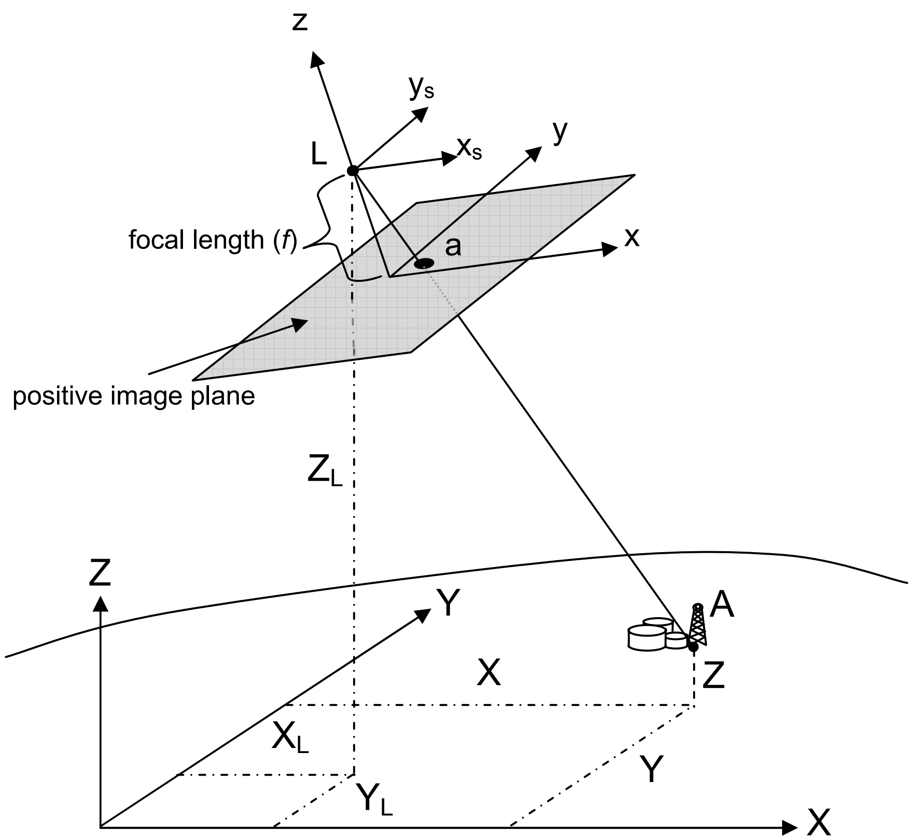

Figure 11. Collinearity of sensor perspective center, image, and corresponding object point.

Geometrically, the sensor perspective center (L), the "ideal" image point (**a**), and the corresponding object point (**A**) are collinear. Note that the "ideal" image point is represented by image coordinates *after* having been corrected for all systematic effects (lens distortions, atmospheric refraction, etc.), as given in the preceding section.

For two vectors to be collinear, one must be a scalar multiple of the other. Therefore, vectors from the perspective center (L) to the image point and object point, **a** and **A** respectively, are directly proportional. Further, in order to associate their components, these vector components must be defined with respect to the same coordinate system. Therefore, we define this association via the following equation:

$$\mathbf{a} = k\mathbf{MA} \qquad \text{Eq. 13}$$

where k is a scalar multiplier and **M** is the orientation matrix that accounts for the rotations (roll, pitch, and yaw) required to place the Earth coordinate system parallel to the sensor coordinate system. Therefore, the collinearity conditions represented in the figure become:

$$\left[\begin{pmatrix} x \\ y \\ 0 \end{pmatrix} - \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix}\right] = \mathrm{k}\mathbf{M}\left[\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} - \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}_L\right] \qquad \textbf{Eq. 14}$$

The orientation matrix **M** is the result of three sequence-dependent rotations:

$$\mathbf{M} = \mathbf{M}_\kappa \mathbf{M}_\phi \mathbf{M}_\omega = \begin{bmatrix} \cos\kappa & \sin\kappa & 0 \\ -\sin\kappa & \cos\kappa & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\phi & 0 & -\sin\phi \\ 0 & 1 & 0 \\ \sin\phi & 0 & \cos\phi \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\omega & \sin\omega \\ 0 & -\sin\omega & \cos\omega \end{bmatrix} \qquad \textbf{Eq. 15}$$

Where the rotation ω is about the X-axis (roll), ϕ is about the once rotated Y-axis (pitch), and κ is about the twice rotated Z-axis (yaw), the orientation matrix **M** becomes:

$$\mathbf{M} = \begin{bmatrix} \cos\phi\cos\kappa & \cos\omega\sin\kappa + \sin\omega\sin\phi\cos\kappa & \sin\omega\sin\kappa - \cos\omega\sin\phi\cos\kappa \\ -\cos\phi\sin\kappa & \cos\omega\cos\kappa - \sin\omega\sin\phi\sin\kappa & \sin\omega\cos\kappa + \cos\omega\sin\phi\sin\kappa \\ \sin\phi & -\sin\omega\cos\phi & \cos\omega\cos\phi \end{bmatrix} \qquad \textbf{Eq. 16}$$

Note that although the earlier derivation expressed coordinates with regard to the image plane ("negative" plane), the image point **a** in Figure 11 is represented by coordinates (x,y), whose relation is simply a mirror of the image plane. Thus the components of **a** will have opposite signs of their mirror components (x,y) as follows:

$$\begin{aligned} \bar{x} &= -(x - x_0) \\ \bar{y} &= -(y - y_0) \end{aligned} \qquad \textbf{Eq. 17}$$

Therefore, for any given object, its "World" coordinates (X,Y,Z) are related to coordinates (x,y) via:

$$\begin{aligned} x &= -f\left[\frac{\cos\phi\cos\kappa(X - X_L) + (\cos\omega\sin\kappa + \sin\omega\sin\phi\cos\kappa)(Y - Y_L) + (\sin\omega\sin\kappa - \cos\omega\sin\phi\cos\kappa)(Z - Z_L)}{\sin\phi(X - X_L) - \sin\omega\cos\phi(Y - Y_L) + \cos\omega\cos\phi(Z - Z_L)}\right] \\ y &= -f\left[\frac{\cos\phi\sin\kappa(X - X_L) + (\cos\omega\cos\kappa - \sin\omega\sin\phi\sin\kappa)(Y - Y_L) + (\sin\omega\cos\kappa + \cos\omega\sin\phi\sin\kappa)(Z - Z_L)}{\sin\phi(X - X_L) - \sin\omega\cos\phi(Y - Y_L) + \cos\omega\cos\phi(Z - Z_L)}\right] \end{aligned} \qquad \textbf{Eq. 18}$$

Note that (x,y) above represent "corrected" pair, (*x'*,*y'*), from Equation 12. Note that the equations above also rely upon the positional and orientation information of the sensor. Unfortunately, the ability to accurately measure the sensor position, e.g., system latency, GPS/INS errors, can be the source for a substantial amount of uncertainty. The recent shift in interest from simply providing an "image" and the visual information it encompasses, to exploitation of the image to provide highly accurate coordinates serves to highlight this difficult challenge. The degree to which the accuracy of these results is required will determine the degree to which modeling of the collection system parameters is required.

5. Application of Sensor Model

5.1 Adjustable Parameters

The frame sensor model is represented by the two pairs of equations in Equations 12 and 18. The parameters involved in Equation 12 pertain to various sources of systematic errors that affect the image coordinates. On the other hand, the parameters in Equation 18 represent the elements of the geometric model that describe the central, or perspective, projection that is the basis of frame sensor imaging. For the case of calibrated cameras, the image coordinates, (x,y*)* in Equation 18, are in fact the coordinates (*x',y')* in Equation 12 that would have been corrected for all the systematic errors. For this case, the adjustable parameters are those six exterior orientation (EO) parameters associated with the position and attitude of the camera during the image exposure; X_L, Y_L, Z_L, ω, ϕ, and κ appearing in Equation 18. In some cases, the camera focal length, *f*, may also be allowed to adjust, making a total of seven adjustable parameters.

For the cases where the camera is not fully metric, or when calibration is not possible/available, then a so-called self-calibration is performed during the "image adjustment" through either single image resection or multiple image triangulation. In such cases, the mathematical model is extended to include several more parameters, in addition to the six EO elements, sometimes up to a total of 22 parameters. These situations must be treated very carefully, as a high correlation between parameters (some approaching perfect correlation resulting in total functional dependence) can occur, leading to numerical instability resulting from singular matrices. The camera angular coverage (more problems with narrow angles) geometric arrangement of the imagery (near nadir present increased problems) character of the imaged terrain (difficulties when flat or nearly flat), etc., all contribute to high correlation. The following extended collinearity equations present a compromise for self-calibration. Note that as stated earlier, due to the relative influence of the k_3 term, it has been deleted from the following equations.

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

$$x = \bar{x} + \Delta x$$

$$y = \bar{y} + \Delta y$$

$$\Delta x = \frac{\bar{x}}{f}\Delta f + \bar{x}(\mathrm{k}_1 r^2 + \mathrm{k}_2 r^4) + \mathrm{p}_1(2\bar{x}^2 + r^2) + \mathrm{p}_2(2\overline{xy}) + b_1\bar{x} + b_2\bar{y} \qquad \textbf{Eq. 19}$$

$$\Delta y = \frac{\bar{y}}{f}\Delta f + \bar{y}(\mathrm{k}_1 r^2 + \mathrm{k}_2 r^4) + \mathrm{p}_1(2\overline{xy}) + \mathrm{p}_2(2\bar{y}^2 + r^2)$$

In this equation, there are 9 added parameters for self-calibration: x_o, y_o, Δf, k_1, k_2, p_1, p_2, b_1, b_2. The additional symbols, to those already given and defined earlier, are:

Δf — correction to the focal length, which will also accommodate a uniform scale change

b_1, b_2 — two parameters to accommodate a differential scale in one axis compared to the other, and a skew between the two axes.

The full pair of equations used in estimating all the adjustable parameters are obtained by substituting the fully expanded form of x,y of Equation 19 into Equation 18. The total number of adjustable parameters then is 15, as listed in the following table.

Grouping	Number of Parameters	Parameters
a	3	X_C, Y_C, Z_C
b	3	ω, ϕ, κ
c	3	x_o, y_o, Δf
d	2	k_1, k_2
e	2	p_1, p_2
f	2	b_1, b_2
Total	15	

The way that these various sets of parameters are handled depends on the sensor type, imaging mission, and the application and use of the resulting imagery.

The degree to which the sensor adjustable parameters are known depends upon whether the imaging is performed by a fully calibrated, partially calibrated, or uncalibrated sensor. For example, if the imagery is acquired using a metric (or cartographic) aerial camera, then all the internal sensor parameters will be known from the proper laboratory calibration common to such cameras. The other extreme is when the imagery is obtained by a frame sensor, the characteristics of which are totally unknown. In such cases, some or all of the 9 sensor parameters (in groups c through f above) become what are called *self-calibration parameters*. The number of parameters to be adjusted, and the identity of those parameters, depends upon the kind of sensor and the intended application.

The six parameters in groups a and b define the location and orientation of the sensor at the time of acquiring a frame image. In order to extract any positional information from such an image, numerical values for these six parameters are required. The quality of these values directly impacts the accuracy of the derived positional information. The more accurate and reliable these six parameters are, the higher is the accuracy of the extracted geopositioning information. For a high quality metric (cartographic) camera they are, in a sense, treated in an opposite manner to the sensor group of parameters. Whereas the sensor parameters are usually determined quite accurately a priori through careful calibration, the exterior (platform) parameters cannot be that well determined in advance. It is usual to carry such six elements as adjustable parameters in order to refine their initial values derived from GPS and INS. For less precise work, the GPS- and INS-provided data are usually adequate.

To summarize, for a frame image one may associate a set of adjustable parameters, the values of which are updated through a least squares adjustment. The number of such parameters can vary from as many as sixteen to as few as three; i.e., only ω, ϕ, κ when the GPS-provided (X_L,Y_L,Z_L) are of sufficient accuracy for the purpose of supporting precise geopositioning.

5.2 Covariance Matrices

In all the metric applications of imagery, the quality of the extracted information is considered as important as the information itself. This is particularly true for geopositioning applications which require high levels of accuracy and precision. The location of an object in the three-dimensional ground space is given either by its geodetic coordinates of longitude (λ), latitude (ϕ), and height (above the ellipsoid, h), or by a set of Cartesian coordinates (X,Y,Z). Although there are many ways to express the quality of the coordinates, the most fundamental is through the use of a *covariance matrix*. For example:

$$\Sigma = \begin{bmatrix} \sigma_X^2 & \sigma_{XY} & \sigma_{XZ} \\ \sigma_{XY} & \sigma_Y^2 & \sigma_{YZ} \\ \sigma_{XZ} & \sigma_{YZ} & \sigma_Z^2 \end{bmatrix} \quad \textbf{Eq. 20}$$

in which σ_X^2, σ_Y^2, σ_Z^2 are the marginal variances of the coordinates, and σ_{XY}, σ_{XZ}, σ_{YZ} are covariances between the coordinates, which reflect the correlation between them. The practice is often to reduce these six different numbers to only two: one expressing the quality of the horizontal position and the other the quality in the vertical position. The first is called *circular error*, or CE, and the second *linear error*, or LE. Both of these can be calculated at different probability levels, CE50 for 0.5 probability, CE90 for 0.9 probability, etc. Commonly used measures, particularly by NGA under "mapping standards," are CE90 and LE90. The CE90 value is derived from the 2-by-2 submatrix of Σ that relates to X*,Y*, or

$$\begin{bmatrix} \sigma^2{}_X & \sigma_{XY} \\ \sigma_{XY} & \sigma^2{}_Y \end{bmatrix} \quad \textbf{Eq. 21}$$

The LE90 is calculated from σ_Z^2 . In these calculations, the correlation between the horizontal (*X,Y*) and vertical (*Z*) positions, as represented by σ_{XZ}, σ_{YZ}, are ignored (i.e., assumed to be zero). The X,Y,Z system in these equations usually refers to the local coordinate system where Z represents elevation.

In order to have a realistic and reliable value for the estimated covariance matrix, Σ, of the geoposition, all the quantities that enter into calculating the coordinates *X,Y,Z* must have realistic and dependable variances and covariances. These latter values present the image sensor modelers and exploiters with the most challenge. Sensor designers frequently do not provide any reasonable estimates of the expected errors associated with their sensor parameters. For well-calibrated sensors, it is usually reasonable to have the values of the needed sensor parameters as well as their quality. Note however, as stated earlier, for most practical situations, the principal point offsets and distortional parameters have such small magnitudes with regard to the other terms, no attempt will be made to account for any covariances of these terms.

By contrast, the quality of the six exterior orientation parameters is not usually reliably known. If such parameters are carried as adjustable parameters, then it is not critical to have good prior error estimates. These prior values can be approximate since, through the adjustment process, they would be refined through rigorous error propagation associated with least squares adjustment. These updated parameter covariances are, in turn, used in a rigorous propagation to produce the final covariance matrix, Σ, associated with each object.

The most difficulty is encountered when no adjustability is allowed and the information is based solely on the mission support data. In this case, if the input values for the quality of the parameters are either grossly in error, or non-existent, the propagated geolocation covariance matrix, Σ, can be considerably in error.

6. Frame Sensor Metadata Requirements

A compilation of the frame model parameters is given in the following tables. Table 1 provides the fundamental metadata that the sensor must provide such that an exploitation tool will recognize the sensor, and, therefore, those parameters specifically required to define image geometry. Distinction between what the sensor and the entire collection system (including the platform and other external sources of data) provides is important, because exploitation tools must be designed to retrieve the appropriate data from the appropriate source. For example, a sensor may not be expected to provide its orientation with respect to WGS-84, but rather to the platform from which it operates; which would presumably produce data with respect to WGS-84. Table 2 lists the parameters required of the platform to support orientation of the sensor such that conversion between image and object coordinates is possible.

Table 1. Frame sensor model type definition and parameters. (Requirement: M - Mandatory, C - Conditional, O – Optional, TBR – To be resolved.)

ID	Parameter	Definition	Obligation/ condition	Comments	TRE (when applicable)	Name/Role Name
1	Sensor Type	Classification indicative of the characteristics of the collection device.	M	Although this paper specifically addresses non-mosaiced framing EO-IR sensors, for completeness in sensor model development this field is listed as mandatory as it is anticipated to become part of a recommended metadata "core" elements list. STANAG 7023 further defines types (e.g., $01 FRAMING, $02 LINESCAN", etc.).	STANAG 7023 (A-9.1, table, Field 1)	SENSOR_TYPE
2	Number of Columns in sensor array	C, the number of columns in the sensor array. (unitless)	C	Conditional because can be derived from sensor array width, y-direction, divided by column spacing (d_y), if that information is available in lieu of number of columns. Note that for sensor modeling, the size of the original imaging operation must be provided; that is, the original image size before chipping (if any).		NCOLS
3	Number of Rows in sensor array	R, the number of rows in the sensor array. (unitless)	C	Conditional because can be derived from sensor array width, x direction, divided by row spacing (d_x)., if that information is available in lieu of number of rows. Note that for sensor modeling, the size of the original imaging operation must be provided; that is, the original image size before chipping (if any).		NROWS
4	Collection Start Time	The date and time at the start of the sensor activation.	O	Future iterations of this table should include the ability to measure image acquisition as an interval, not an instantaneous event, e.g., as permitted in STANAG 7023. Though optional for frame sensors, likely will be mandatory for others.	STANAG 7023 (A-9.11, table, Field 1)	COLLECTION_START_TIME
5	Sensor Position, X Vector Component	The x-axis measurement, mm, of the vector offset from the origin of the sensor mounting frame, which must be stated, e.g. gimbal, platform, or ECEF coordinate system, to the origin of the sensor perspective center, L.	C	Offset vector describes the position of the sensor perspective center relative to a gimbal position (if any), which, in turn may be referenced to the platform coordinate system; or the offset may be given directly to the platform coordinate system, if known. Conditional in the case where a sensor may provide position information directly referenced to, say, an ECEF system.	STANAG 7023 (A-9.5, table, Field 1)	X_VECTOR_COMPONENT
6	Sensor Position, Y Vector	The y-axis measurement, mm, of the vector offset from the origin of	C	See Sensor Position, X Vector Component	STANAG 7023	Y_VECTOR_COMPONENT

ID	Parameter	Definition	Obligation/ condition	Comments	TRE (when applicable)	Name/Role Name
	Component	the sensor mounting frame, which must be stated, e.g. gimbal, platform, or ECEF coordinate system, to the origin of the sensor perspective center, L.			(A-9.5, table, Field 2)	
7	Sensor Position, Z Vector Component	The z-axis measurement, mm, of the vector offset from the origin of the sensor mounting frame, which must be stated, e.g. gimbal, platform, or ECEF coordinate system, to the origin of the sensor perspective center, L.	C	See Sensor Position, X Vector Component	STANAG 7023 (A-9.5, table, Field 3)	Z_VECTOR_COMPONENT
8	Sensor Rotation about Z-axis	Rotation of the sensor in the xy-plane of the sensor reference frame; positive when positive +x-axis rotates directly towards +y-axis. (radians)	M	Reference may be made to gimbal mounting or to platform reference system; but must be specified. If these rotation angles are gimbal mounting angles, this development transforms them into the required sequential Euler angles.	STANAG 7023 (A-9.6, table, Field 1)	SENSOR_ROTATION_Z
9	Sensor Rotation about Y-axis	Rotation of the sensor in the xz-plane of the sensor reference frame; positive when positive +z-axis rotates directly towards +x-axis. (radians)	M	See Sensor Rotation about Z-axis.	STANAG 7023 (A-9.6, table, Field 2)	SENSOR_ROTATION_Y
10	Sensor Rotation about X-axis	Rotation of the sensor in the yz-plane of the sensor reference frame; positive when positive +z-axis rotates directly towards +y-axis. (radians)	M	See Sensor Rotation about Z-axis.	STANAG 7023 (A-9.6, table, Field 3)	SENSOR_ROTATION_X
11	Sensor Focal Length	*f*, lens focal length; effective distance from optical lens to sensor array.	C	Conditional that the sensor calibrated focal length is not sent. Similar to STDI-0002 TRE ACFTB, Focal_length, page 79, Table 8-6; "effective distance from optical lens to sensor element(s), used when either ROW_SPACING_UNITS or COL_SPACING_UNITS indicates µ-radians. 999.99 indicates focal length is not available or not applicable to this sensor." For pushbroom/whiskbroom, used as the initial condition.		FOCAL_LENGTH
12	Sensor	Lens calibrated focal length, *f*,	C	Conditional that the sensor uncalibrated focal length is		FOCAL_LENGTH_CAL

ID	*Parameter*	*Definition*	*Obligation/ condition*	*Comments*	*TRE (when applicable)*	*Name/Role Name*
	Calibrated Focal Length	(mm); corrected effective distance from optical lens to sensor array.		not sent in lieu of a calibrated value. Similar to STDI-0002 TRE ACFTB, Focal_length, page 79, Table 8-6; "effective distance from optical lens to sensor element(s), used when either ROW_SPACING_UNITS or COL_SPACING_UNITS indicates µ-radians. 999.99 indicates focal length is not available or not applicable to this sensor." Where "precise" positioning (as defined by the user) is not important, this adjustment is not necessary.		
13	Principal point off-set, x-axis	x_0, x-coordinate within the sensor array coordinate system of the foot of the perpendicular dropped from sensor perspective center of the camera lens onto the collection array. (mm).	C	As a coordinate, this term includes magnitude and direction (i.e., positive/negative x). Conditional when this is replaced with calibration, measured, or look up table data. NITF and STDI do not specifically address point off-sets.		PRIN_OFFSETX
14	Principal point off-set, y-axis	y_0, y-coordinate within the sensor array coordinate system of the foot of the perpendicular dropped from sensor perspective center of the camera lens onto the collection array. (mm).	C	As a coordinate, this term includes magnitude and direction (i.e., positive/negative y). Conditional when this is replaced with calibration, measured, or look up table data. NITF and STDI do not specifically address point off-sets.		PRIN_OFFSETY
15	Principal Point offset covariance data	Covariance data of principal point offsets.	O	In practice, of such small magnitude so as can be ignored.		
16	Sensor Coordinate Reference Orientation	Origin at sensor perspective center; positive z-axis aligned with optical axis and pointing away from sensor. Sensor axes will be parallel to and in the same directions as the platform center of navigation axes at nadir.	M			
17	Sensor position and altitude accuracy variance data	$\sigma^2_{X_L}, \sigma^2_{Y_L}, \sigma^2_{Z_L}$ $\sigma^2_{\omega}, \sigma^2_{\phi}, \sigma^2_{\kappa}$ Variance (sigma^2) data for position (X_L,Y_L,Z_L), and attitude (roll, pitch, yaw.	M	Usually estimated on the basis of (calibrated) reference points, such as camera fiducial marks, or their equivalent corner pixels for digital arrays. Conditional if standard deviations are provided instead.		

ID	Parameter	Definition	Obligation/ condition	Comments	TRE (when applicable)	Name/Role Name
18	Focal length accuracy variance data	σ_f^2	C	Variance parameter. Conditional if standard deviation provided instead.		
19	Column Spacing	Column spacing, d_y, measured at the center of the image; distance in the image plane between adjacent pixels within a row.	M	NITF definition, STDI-0002, ACFTB, "COL_SPACING", includes angular and linear measurement methods.		COL_SPACING
20	Row Spacing	Row spacing, d_x, measured at the center of the image; distance in the image plane between corresponding pixels of adjacent columns.	M	d_x, NITF, STDI-0002 ACFTB, "ROW_SPACING", includes angular and linear measurement methods.		ROW_SPACING
21	Various distortions a_1,b_1,c_1,a_2,b_2,c_2	representing 2 scales, rotation, skew, and 2 shifts	M		n/a	
22	Distortion $(a_1,b_1,c_1,a_2,b_2,c_2)$ covariance data	Covariance data of scales, rotation, skew, and shift distortions.	O	In practice, of such small magnitude, so as can be ignored.		
23	Column axis offset	C_ℓ, linear translation from the image upper-left corner pixel to the collection array origin (mm), s-axis	C	Conditional, as can be derived if other physical properties are known; number of rows and row spacing. Not to be confused with NITF (Tables A-3, A-5, etc.) which defines column offsets to specify an Image Location (ILOC); the location of the first pixel of the first line of the image relative to the CCS origin.	n/a	COL_AXIS_OFFSET
24	Row axis offset	C_s, linear translation from the image upper-left corner pixel to the to collection array origin (mm), ℓ-axis	C	Conditional, as can be derived if other physical properties are known; number of columns and column spacing. Not to be confused with NITF (Tables A-3, A-5, etc.) which defines column offsets to specify an Image Location (ILOC); the location of the first pixel of the first line of the image relative to the CCS origin.	n/a	ROW_AXIS_OFFSET
25	Lens radial distortion coefficients	k_1 (mm^-2), k_2 (mm^-4), k_3 (mm^-6), lens radial distortion coefficients	C	Conditional when replaced with calibration, measured, or look up table data. NITF and STDI-0002 do not specifically address distortion factors. This Frame paper described these based on the "NIMA System Geometric Model Part 5 Generic Sensors" document.	n/a	DISTOR_RAD1 DISTOR_RAD2 DISTOR_RAD3

ID	Parameter	Definition	Obligation/condition	Comments	TRE (when applicable)	Name/Role Name
26	Lens radial distortion (k_1,k_2,k_3) covariance data	Covariance data of lens radial distortion.	O	In practice, of such small magnitude, so as can be ignored.		
27	Decentering lens correction coefficients	$p_1(mm^{-1})$, $p_2(mm^{-1})$	C	Conditional when replaced with calibration, measured, or look up table data. NITF and STDI-0002 do not specifically address distortion factors. The Frame paper described these based on the “NIMA System Geometric Model Part 5 Generic Sensors” document.	n/a	DECEN_LENS1 DECEN_LENS2 (Eq 5)
28	Decentering lens correction (p_1,p_2) covariance data	Covariance data of decentering lens correction coefficients.	O	In practice, of such small magnitude, so as can be ignored.		

Table 2. Collection platform parameters (Requirement: M - Mandatory, C - Conditional, O – Optional, TBR – To be resolved.)

ID	Parameter	Definition	Rqmt	Comments	TRE	Proposed Field Name
29	Platform Time	Time at which data was collected.	O	Provides data to correlate platform location to sensor acquisition. Optional for “frame”, **Mandatory** if location not simultaneously collected with image data, to provide necessary orientation of sensor/platform/Earth reference for other sensor types.	STANAG 7023 (A-6.1, table, Field 1)	PLATFORM_TIME
30	Platform geo-location	The position of the platform given as latitude and longitude given in radians.	C	Not required for image-to-ground calculations if sensor location data available directly. Center of navigation defined wrt the local NED coordinate frame, and then related to an ECEF reference. However, rather than mandating a single reference system, consideration should be given to allowing the reference system to be defined when the location values are provided. This would be consistent with the Transducer Markup Language OpenGIS® Implementation Specification (OGC® 06-010r6), which requires the source, values, and all associated information to be provided to uniquely define location data, instead of mandating a specific reference system.	STANAG 7023 (A-6.1, table, Field 2)	PLATFORM_GEOLO C

ID	*Parameter*	*Definition*	*Rqmt*	*Comments*	*TRE*	*Proposed Field Name*
31	Platform altitude	Platform altitude, feet or meters, above a specified reference at image acquisition time.	C	See platform location. STANAG 7023 designates MSL, AGL, and GPS; those left as options under this development. Conditional on sensor altitude at scan time being sent.	Similar to STANAG 7023 (A-6.1, table, Fields 3, 4, and 5)	PLATFORM_ALT
32	Platform true heading at scan line time	Platform heading relative to true north. (positive from north to east)	C	Conditional on sensor position and rotation data available directly when given within an absolute reference. Added to STANAG definition, "(positive from north to east)". Alternatively, true heading not required if platform yaw is given,	Similar to STANAG 7023 (A-6.1, table, Field 9)	PLATFORM_TRUEHDG
33	Platform pitch	Rotation about platform local y-axis (Y_a), positive nose-up; 0.0 = platform z-axis (Z_a) aligned to Nadir, limited to values between +/-90degrees.	C	Conditional on sensor position and rotation data available directly when given within an absolute reference. Consistent with STANAG 7023, paragraph A-6.1; added "limited" values.	Similar to STANAG 7023 (A-6.1, table, Field 10)	PLATFORM_PITCH
34	Platform roll	Rotation about platform local x-axis (X_a). Positive port wing up. (degrees)	C	Conditional on sensor position and rotation data available directly when given within an absolute reference. Consistent with STANAG 7023, paragraph A-6.1.	STANAG 7023 (A-6.1, table, Field 11)	PLATFORM_ROLL