JOINT ISPRS/CEOS-WGCV TASK FORCE ON RADIOMETRIC AND GEOMETRIC CALIBRATION

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ABSTRACT:

A draft *Resolution* passed by the Committee on Earth Observing Satellites (CEOS) Plenary in 2002 recommended that a task force be established with joint membership by the Working Group on Calibration and Validation (WGCV) and ISPRS. This resolution formed the basis for subsequent ISPRS *Resolutions* (I.1, I.2, and I.3) adopted by the General Assembly at the XIXth Congress in Amsterdam. The idea originated from the CEOS WGCV Terrain Mapping Subgroup, which recognized that a standard format for sensor parameters should be established. There is a demand for consistent practices in measuring the radiometric and geometric calibration of satellite sensor data because of: (1) the rapid increase in numbers of orbital and Earth-oriented platforms, (2) the variety of digital sensors now taking Earth and environmental measurements across the EM spectrum, (3) the wide array of angular and multi-angular measurements and fields-of-view being employed, (4) the desire for measurements and observations to be fused into complex products for specific applications, and (5), the growing interest by Ordinary Members of ISPRS to contribute high quality calibration test fields for global sensors that embrace all of the world's ecological and climate zones. ISPRS Working Groups I/1, I/2 and I/5 have responsibility for task force activities. In January 2001, the WGs developed a profile of expertise and skills required by the task force. In November 2002, the first joint task force meeting was held in Denver at the Commission-I midterm symposium to identify its Chair and membership. Most recently, in December 2003, the Task Force convened its first International Workshop to identify, define, and review best practices for measuring the radiometric and geometric properties of infrared and visible optical sensors (IVOS). This paper is a summary of the workshop findings and recommendations. For further information on calibration methods, techniques, and best practices, a peer-reviewed book in the ISPRS Book Series titled *Post-launch Calibration of Satellite Sensors* contains articles by most of the Workshop presenters. It is scheduled for release in summer 2004.

1. BACKGROUND

1.1 Rationale

Digital aerial and satellite image data are acquired as raster (gridded) data. For optical systems, the dimensions of a picture element are defined by the: (a) altitude of the sensor, (b) milliradian field-of-view, (c) number and arrangement of detectors, and (d) system's instantaneous-field-of-view. Digital values for each picture element are determined by the radiance recorded for given spectral bands and the radiometric resolution (bit rate).

On a global scale, images derived from digital systems are useful for studying Earth processes because they reveal synoptic patterns that would otherwise never be observable in a timely fashion to capitalize on their content. Science and user communities are well trained to make visual interpretations of synoptic images related to terrestrial vegetation, geomorphology and digital elevation models, ocean patterns (temperature, chlorophyll), ice, and many atmospheric constituents. Experience and expanded data availability from an increasing number of sensors operated by both national governments and commercial firms, have expanded applications requiring electronic fusion of many data sets for use at local and regional scales.

Trends in the New Millennium are to fuse data from several sensors designed to measure different phenomena of the Earth's physical and cultural systems. To perform their individual Missions, these sensors have a variety of system designs, spectral bandwidths, and spatial resolutions. These various data sets are being fused into digital composites, and applied in a modelling framework to local and regional needs. Interpretation of multi-layered and multi-theme natural and cultural processes requires a comprehensive understanding of the radiometric and geometric properties of each of the input data sets forming the composite because misinterpretation of the modelled results can carry critical social, economic, and political implications.

1.2 Actions Undertaken

In anticipation of the greater depth of understanding required to interpret fused images and modelled results from sensor data, the Committee on Earth Observing Satellites (CEOS) recognized a need for consistency in terminology and definitions for radiometric and geometric calibration parameters. The International Society for Photogrammetry and Remote Sensing (ISPRS) likewise recognized this need, especially on behalf of global data users who might otherwise misinterpret data products, or interpret them in inconsistent fashion. The two organizations therefore formed a joint Task Force on Radiometric and Geometric calibration to review the maze of engineering and sensor design terminology in hopes of developing a list of terms, definitions, and best practices for measuring calibration parameters.

The Joint Task Force met in Denver in November 2002, and held its first International Workshop in December 2003. The group met for four days to hear a variety of presentations, participate in discussions, and deliberate on calibration terminology for optical mechanical scanners and digital aerial frame-cameras. Overall the focus was on in-flight and post-launch calibration procedures, but pre-launch calibration procedures were reviewed heavily to emphasize the need for a systems approach. What is designed and measured in laboratories before launch must be re-measured and verified throughout the sensor's operational life. For two reasons, the group elected to approach calibration in terms of "image quality." First, because sensor performances reported by commercial aerial and satellite data providers must be verified by the quality of images delivered to national and international government agencies who purchase such imagery; and second, because imagery, not fusions of modelled output, represent the lingua franca for illustrating and describing sensors and making inter-sensor comparisons.

A subsidiary theme of the Workshop focused on calibration test sites and ranges. It is well recognized by the professional calibration community that much of the world's experience with vicarious calibration measurements is based on a few arid zone sites. One way to engage a broader community of calibration experts and develop greater understanding of atmospheric affects on detected radiances is to expand the distribution of test ranges into all primary Earth ecosystems, including the open oceans and coastal zones. It is believed that many nations might contribute to a calibration test range network to both better understand image quality in their own environs, and to participate in the global community of space-faring nations.

This report contains a list of terms in the optical region, provides some provisional definitions, and identifies resources for further reference and deliberation. Some of the many terms identified have already been defined by international organizations like ISO, and CIE, and are in common agreement and use. Some are in process of being defined, or are proposed for future Standards by international bodies; and some have variable definitions depending on engineering and applications contexts. The on-going roles for the Task Force are to: (a) complete the list of terms for optical-mechanical scanners; (b) expand the dialogue to include sensors from other electromagnetic regions (ultraviolet, thermal, and microwave spectra); and (c) broaden the community of scientist, engineer, and application stakeholders to build consensus.

This report addresses only a fraction of the complexity of calibration terms and definitions. In the 2004-2008 Congress quadrennium, it is hoped that Commission-I will continue this important joint activity through incremental improvements, and perhaps by expanding the Task Force scope to include active sensors.

1.3 Task Force Resolution and Terms-of-Reference

Noting the disparate way in which Earth observing sensor parameters are specified and quoted, and that the extra terrestrial community adopts a standard format, and

Recognizing that proper use, understanding and inter-comparison of sensor parameters depends on clear unambiguous definition, WGCV

Recommends that a task force be established with ISPRS to formulate a plan for standardization of radiometric and geometric parameters of sensors.

Draft Terms of reference

1. Collect and collate lists of parameters used to describe Earth observing sensors.
2. Make an analysis of these and recommend a standard list of parameters for presenting descriptions of EO satellites.
3. Identify ambiguity and confusion within these terms and recommend methods and means of clarifying these issues
4. Prepare a document that sets out standard methods of describing EO sensors
5. Communicate and consult widely with the user community

2. 2003 WORKSHOP

2.1 Field Tour

On December 2, 2003 attendees of the Workshop were invited on a tour of the NASA Stennis Space Centre (SSC) remote sensing verification and validation facility. Laboratories and infrastructure represented at the facility were developed to support the Centre's activities for in-flight characterization of primarily high-spatial resolution remote sensing systems and data products. Approximately 50 persons attended the tour.

The tour included an overview presentation to introduce the in-flight characterization site. The site is approximately 25 square miles in size, is relatively flat, and includes a variety of land-cover types, targets, and instrumentation to support reflective and thermal radiometric characterization, spatial resolution characterization, and geopositional accuracy assessments. Attendees were then escorted on a tour of the site, including visits to various targets and instrumentation. Targets visited included geodetic targets that are part of a network of approximately 200 targets ranging in diameter from less than 1 meter to nearly 3 meters. Spatial resolution targets at SSC consist of a 150-meter painted concrete radial target to estimate system spatial resolution and two 20x40-meter painted concrete edge targets to characterize edge response and estimate Modulation Transfer Function (MTF). The tour also included a first-hand look at a sample of SSC's 20x20-meter deployable radiometric tarps. The tarps, which are of four different reflectance values, support radiometric characterization as well as edge response characterization. In addition, tour attendees viewed a field spectroradiometer, sun photometer, weather station, and goniometer, all of which support in-flight radiometric characterizations.

The SSC sensor characterization laboratory was also visited. This laboratory primarily supports characterization of field instruments, but also can support airborne sensor and component-level characterizations. This lab is equipped with NIST-traceable standards. In the lab, tour attendees viewed a laser-illuminated integrating sphere setup used to characterize hyperspectral pushbroom systems. This capability is used to characterize the radiometric properties of SSC's field spectroradiometers. The spectroradiometers are also characterized in an environmental chamber within the lab; this allows for the generation of calibration coefficients corresponding to in-field temperature conditions that cause drifts in spectroradiometer performance. The lab also includes a capability to characterize spatial response of digital framing systems using small-scale edge targets. In addition, the tour included a description of an SSC-developed system for the radiometric and spatial characterization of cross-track airborne sensors. The lab consists of several NIST-traceable blackbodies for thermal infrared radiometric characterization including water bath blackbodies observed by tour attendees. Other capabilities viewed in the lab included an SSC-developed active field target for in-flight spectral characterization and the testing of light emitting diodes, which have potential to be the next-generation of radiometric calibration sources.

2.2 Technical and Discussion Sessions

The Workshop was conducted entirely in plenary as a sequence of seven technical sessions:

- Identifying and describing sensor parameters
- Standards and guidelines
- Methods and approaches for radiometric calibration
- Methods and approaches for geometric calibration
- Inter-sensor calibration
- Examples of sensor and image characterization programs
- Test sites and ranges.

Interspersed with the technical sessions were four discussion sessions focused on the Task Force terms-of-reference. After concluding the formal technical and discussion sessions, the Task Force assembled to further discuss plans and strategies for follow-on activities. It was generally agreed that "image quality" is the pervasive attribute of interest to most data and imagery users, and that the basis of image quality resides in documenting both pre-launch and post-launch calibration parameters.

3. FINDINGS

3.1 Available Resources

A variety of documents and standards already exist upon which to build calibration terms, definitions, and measurement methodologies. While the results of the task force meeting in Gulfport began its work, as set forth in the CEOS Resolution, it is clear that this should not be pursued in a vacuum. Among the pre-existing available materials are the following:

1 Prokhorov, A.V., V.I. Sapritsky, O.M. Mikhaylov, V.P. Zakharenkov, V. Privalsky, T.Humphreys, R. Datla, and L.K. Issaav (in technical review): Spaceborne Optoelectronic Sensors and Their Radiometric Calibration: Terms and Definitions (Part 1) Calibration Techniques. This work is a joint effort between Vega International, Inc.; Vavilov State Optical Institute, St. Petersburg, Russian Federation; and, Space Dynamics Laboratory, Utah State University, USA; Editorial support is being provided by NIST and the Russian Institute of Metrological Service, Russian Federation. The work is very comprehensive in both Russian and English. Status: Undergoing 2nd editorial revisions, expected release 2005.

2.International Standards Organization (ISO), Technical Committee 211 (TC211), Working Group 6 is the forum for ISO 19130 and ISO 19101-2. Both are in draft stages, but utilize definitions either in common use, or already formally agreed upon internationally in source documents such as the International Vocabulary of Basic and General Terms in Metrology (VIM), various CIE publication, Geospatial One-Stop, and other published ISO standards.

3. Several ISO, either completed or in draft stages should be reviewed by the task force and used as sources of definitions. Among the known standards are the following:
a 19101.2 Geographic Information-Reference Model-Imagery
b 19115 Geographic Information-Metadata
c 19115.2 Part-2-Metadata for Imagery and Gridded Data
d 19121 Geographic Information-Imagery and Gridded Data
e 19124 Geographic Information-Imagery and Gridded Data Components
f 19130 Geographic Information-Sensor and Data Models for Imagery and Gridded Data
g 19130 (project team) Proposed standard on radiometric calibration and validation. WG6 of TC211 has approved the project, which must now be approved by US INCITS-L1 as a U.S. Contribution to ISO TC211.

4 CIE. 1987. The International Lighting Vocabulary, 4th edition.

5 Several Russian Federation and Former USSR publications
a GOST 7601-78 Physical Optics: Terms, Symbols, and Definitions of Basic Optics
b GOST 26148-84: Photometry: Terms and Definitions
c GOSTs 8.417-81, 16263-70, 27176-86

6 Several United States Standards:
a ANSI Standard Z7.1-1967: Nomenclature and Definitions for Illuminating Engineering
b ASTM Standard E284-99a: Standard Terminology of Appearance
c International Union of Pure and Applied Chemistry. Names, Symbols, Definitions, and Units of Quantities in Optical Spectroscopy. Spectrochimica Acta, 1987, 43A91):1-9.
d Military Standard on Infrared Terms and Definitions AD-784 341, December 1971.
e Shapiro, I.J. 1975. Reference Book of Radiometric Nomenclature, John Wiley and Sons.

7 Wyatt, C.L., V. Privalsky, and R. Datla. 1998. Recommended Practice: Symbols, Terms, Units and Uncertainty Analysis of Radiometric Sensor Calibration. NIST Handbook 152

8 Wyatt, C.L. and V. Privalsky. 1996. Recommended Practice: Symbols, Terms and Units for Space-based Infrared Sensor System Calibration and Uncertainty Analysis. Space Dynamics Laboratory, Utah State University, Logan, UT.

9 Prokhorov, A., V. Sapritsky, and V. Privalsky. 2001. *Ground-based Radiometric Calibrations of Space-borne IR Sensors. Terms and Definitions, Part 1. Calibration Techniques,* New York.

10 Dinguirard, M. and P.N. Slater. 1999. Calibration of Space Multispectral Imaging Sensors: A Review. *Remote Sensing of Environment* 68(3): 194-205.

11 Light, D. 2004. A Basis for Estimating Digital Camera Parameters. *PE&RS* 70(3): 297-300.

12 American Society for Photogrammetry and Remote Sensing. 1994. *Glossary of the Mapping Sciences*. Co-published by the American Congress on Surveying and Mapping and the American Society of Civil Engineers. 594 pp.

3.2 Terms and Definitions

3.2.1 Standard Definitions: Terms and definitions provided in the resources cited above are not included in this paper, but there is overlap between some of those terms and those discussed at the Task Force Workshop. These will have to be reconciled in future deliberations.

3.2.2 Task Force Workshop Terms:

absolute geolocational accuracy: the closeness of the agreement between image-defined location of a point or feature with respect to ground coordinates and the true location of that feature, typically expressed as a circular error or linear error. See also **systematic error**, and **random error**, both of which affect absolute accuracy.

absolute radiometric accuracy: the difference between the radiance measured by the sensor and the true radiance of a source. Radiometric accuracy is determined by comparing a calibrated source that can be traced to a radiometric standard. Absolute radiometric accuracy depends on stability, polarization, stray light, linearity and other components [pk1][pk2].

band-to-band registration: refers to how well the same scene is recorded in different spectral bands (Kramer 2001). It is the relative geometric registration between bands, usually specified in terms of a fraction of a pixel.

bidirectional reflectance distribution function: the ratio of radiance leaving a target to the irradiance incident upon the target

calibration: the process of quantitatively defining the system responses to known, controlled signal inputs.

central wavelength: For a given spectral band, the central wavelength is the wavelength at the centre of the spectral bandwidth.

circular error-90 (CE90): a metric to describe horizontal accuracy (X and Y coordinates) in map or image products at the 90% confidence level (that is, 90% of well-defined points tested fall within a certain radial distance). CE90 defines the radius of a circle that encompasses 90% of the points.

combined standard uncertainty: combination of the uncertainty components considering their interdependence or correlation.

contrast transfer function (CTF): a 2-dimensional measure of a system's sensitivity to detect rectangular patterns of diminishing spatial width.
a) Edge target = difference between the dark and bright area pixel values measured in digital numbers (DNs), divided by the 1-sigma standard Deviation (SD) noise level.

cross-talk (optical & electronic): In an imaging system, spectral cross-talk is a measure of electromagnetic energy leakage from one spectral band (spectral response for a given band) to another.

dynamic range: the ratio of the maximum observable energy and the minimum still useful energy (max signal/min signal); it is defined as 10 log. The maximum signal is the signal at which the system saturates while the minimum signal is usually defined as the noise floor. All radiant energy less than the minimum vanishes into noise, while the energy above the maximum disappears into the saturation of the detector. (Kramer, 2001) The dynamic range of an imaging system refers to the range of radiance or reflectance values (and digital numbers) that can be measured (recorded). Systems with low dynamic range will saturate when measuring bright (highly reflective) targets or not be able to resolve features at low radiance levels. The dynamic range, or range of brightness values, is also often defined by the system quantization, or the number of bits. An 8-bit system will allow for 28 = 256 brightness levels, while a 16-bit system will allow for 216 = 65536 brightness levels.

edge spread function (ESF): the image signal corresponding to an edge as an input signal (CCRS 2004). a measure of a system's ability to distinguish a straight, high contrast edge.

effective instantaneous field-of-view (IFOV): the resolution corresponding to a spatial frequency (ground resolution) for which the system MTF is 50%.

emittance: the ratio of a target's radiance to the radiance emitted from an ideal blackbody at the same thermodynamic temperature of the sample

expanded uncertainty: the product of the combined standard uncertainty and a coverage factor (k) whose value is chosen based on a desired level of confidence (usually k = 2).

general image quality equation (GIQE): Leachtenauer et al. (1997) provide a mathematical relationship between GSD, RER, image enhancement, and SNR to estimate image quality objectively. The GIQE also includes ringing and edge sharpness effects associated with an edge response. One commonly accepted form of the GIQE expresses this relationship in terms of the National Imagery Interpretability Rating Scale (NIIRS).

Geo-locational accuracy (circular error-90 [(CE90]): a standard metric to describe horizontal accuracy in map or image products at the 90% confidence level (that is, 90% of well-defined points tested must fall within a certain radial distance).

ground sample (ing) distance (GSD): the distance between the center of adjacent pixels in an intrinsic sensor image (that is, not a re-sampled image); the distance between the centres of adjacent pixels. See also **instantaneous field-of-view**.

instantaneous field of view (IFOV): the (angular) aperture within which the sensor is sensitive to electromagnetic radiation. It may be expressed either as a small solid angle or as a unit area (Kramer 2001). When expressed in degrees or radians (solid angle), this is the smallest plane angle over which an instrument is sensitive to radiation. When expressed in linear or area units such as meters or hectares, it is an altitude dependent measure of the ground resolution of the sensor (CCRS, 2004). Often, GSD is equated with the spatial resolution of a pixel, or simply with IFOV. However, this need not be the case. If the radiometric and electronic performance of a sensor allow, GSD can be made smaller than IFOV to achieve better image quality because of the reduction of smear (Kramer, 2001).

instantaneous geometric field-of-view (IGFOV): the geometric size of the image projected by the detector on the ground through the optical system ("pixel footprint).

interpretability: the ability to identify and distinguish objects, features, patterns, and textures within a remote sensing image, and determining their significance. It refers to the ability to visually examine the image, including object relative locations and extents, for a given application (Wolf, 1983). Interpretability is related to GSD, SNR, and PSF/MTF, but is also subjective in that it is dependent on the judgment/opinion of the user and the application. Some methods have been developed to evaluate interpretability.

irradiance: radiant flux per unit area.

length distortion: the accuracy of distance measures on images using a geometric model.

line spread function (LSF): (a) the 1-dimensional PSF orthogonal to the length of a thin wire smaller than the system pixel size; (b) the derivative of the edge spread function with respect to position (Schott 1997). The Fourier Transform of the LSF is the OTF in one of the spatial frequency directions.

linear error-90 (LE90): defines a line which encompasses 90% of the points, typically used as an expression of vertical accuracy (Z coordinates).

linearity: the relationship between two variables so that when plotted on a graph they yield a straight line (Photonics Dictionary 2004) For an imaging system, linearity refers to the relationship between the systems digital numbers (DNs) and the radiance values measured by the system. The digital number recorded by the system should be linearly related to the amount of radiance measured by the system. Linearity (or non-linearity) is characterized by measuring the system's response to varying radiance levels spanning the system's full dynamic range.

modulation transfer function (MTF): (1) a measure of an imaging system's ability to recreate the spatial frequency content of the scene. It is the magnitude of the Fourier Transform of the "point spread" and "line spread" functions (PSF and LSF); (2) a measure of the spatial quality of an imaging system. The modulus of the Optical Transfer Function (OTF), normalized such that the first value is unity; (3) the reduction in contrast in the image compared to the contrast of the objects imaged. MTF is the ratio of the amplitude (peak intensity difference) of a signal, as seen by the sensor, to the true sinusoidal target amplitude as a function of the spatial frequency of the target (CCRS 2004).

modulation transfer function compensation (MTFC): a post-processing image restoration technique that enhances image sharpness and increases image noise.

national image interpretability rating scale (NIIRS): a 10-level rating scale that defines the ability to identify certain features or targets within an image. The NIIRS defines and measures the quality of images and performance of imaging systems. Through a process referred to as "rating" an image, the NIIRS is used by imagery analysts to assign a number that indicates the interpretability of a given image. For example, the ability to identify trains or strings of standard rolling stock on railroad tracks (not individual cars) would receive a NIIRS rating of 3, while the ability to identify individual spikes in railroad ties would receive a rating of 9. The NIIRS concept provides a means to directly relate the quality of an image to the interpretation tasks for which it may be used (Pike 1998). The NIIRS is traditionally used to evaluate panchromatic imagery. The Multispectral Image Interpretability Rating Scale (MSIIRS) has been developed to rate multispectral imagery.

noise: the unwanted and unpredictable fluctuations that distort a received signal and hence tend to obscure the desired message. Noise disturbances, which may be generated within the remote sensing system, or which may enter the system from the outside, limit the range of the system and place requirements on the signal power necessary to produce useful data/information (Photonics Directory 2004). See also signal-to-noise ratio, noise equivalent delta radiance, noise equivalent delta temperature, and systematic noise as key related parameters.

noise equivalent delta radiance (NEDL, NEΔT): the root mean square, or standard deviation of the mean, that produces a SNR of 1 reported in radiance (or irradiance) units. This assumes that all known systematic errors are first removed. This measurement represents the lowest signal that can be measured by an instrument, just before the signal falls below the level of the noise. (Analytical Spectral Devices). NEDL is also referred to as noise equivalent radiance (NEL). This can also be reported as the Noise Equivalent Irradiance (NEI), which is the radiant flux density (W/cm2) required for a system to produce an output signal equal to the noise, or the input irradiance at which the signal-to-noise ratio is unity (Photonics Directory 2004).

noise equivalent delta temperature (NEDT, NEΔT): in thermal imaging systems, the change in temperature that yields a signal-to-noise ratio of unity (Photonics Directory 2004).

optical transfer function (OTF): an equivalent measurement of the "point spread function" (PSF) obtained through a two-dimensional Fourier Transform consisting of the magnitude and phase terms. Like the PSF, it is a measure of the spatial performance of an optical system. It includes phase relationship between the target and measured signals as well as the amplitude change as a function of frequency (CCRS 2004). The phase component of the OTF is called the Phase Transfer Function (PTF).

point spread function (PSF): a direct 2-dimensional measure of a system's ability to reproduce an infinitely narrow source of radiance; thus, the response of a system to a point source of radiance. Mathematically: the response to a delta function (Schott 1997). PSF defines the apparent shape of a point target as it appears in the output image. It is a plot of illuminance of the image as a function of distance in the image plane (CCRS, 2004). See also **optical transfer function**, **modulation transfer function**, **edge transfer function**, **relative edge response**, **line spread function** and **spatial out-of-field**.

polarization: the partial orientation of the electric (and magnetic) fields of an electromagnetic wave. Horizontal (H)/Vertical (V) polarization refers to the electronic filed (magnetic field) vector's being parallel/normal to the surface of the medium that the wave is incident upon. Polarization knowledge offers an additional capability in detecting object characteristics and in discriminating between them, especially in the microwave region of the electromagnetic spectrum (Kramer 2001). See also **polarization sensitivity** and **Stokes**

parameters as important adjunct attributes for characterizing polarization in remote sensing systems.

polarization sensitivity: the magnitude of change in performance of the remote sensing system as a result of polarization effects.

precision error: see **random error.**

presence of artifacts and flaws: artifacts and flaws within imagery can include items such as line drop outs, bad pixels, banding, distortion, etc. that appear within an image and affect its usefulness.

pulse target: difference between maximum average value and background area brightness level divided by the 1-sigma SD noise estimate of the background areas.

quantization: the process of converting continuous values of information to a finite number of discrete values. It is expressed as a number of bits. A 10-bit quantization means that the measured signal can be represented by a total of 210=1024 digital values, say from 0 to 1023. (Kramer, 2001) The quantization level of an imaging system should be sufficient to meet the SNR requirements of the application.

radiance: radiant flux per unit area per unit solid angle.

radiant flux (radiant power): the total amount of power in a defined optical beam, measured in watts

radiometrically accurate IFOV (RAIFOV): the resolution for which the MTF is higher than 0.95.

random error: refers to the unpredictable, non-correlated component of the total error (Coleman and Steele 1999), calculated using mathematical laws of probability (Wolf, 1983). Also known as precision error.

relative edge response (RER): (a) a measure of a system's ability to distinguish a straight, high contrast edge; (b) special case of the ESF, where the ESF is normalized. (c) a geometric mean of normalized edge response differences, between zero and 1 (the dark side of the edge at zero and the bright side at unity), measured in two directions of image pixels (X and Y) at points distanced from the edge by -0.5 and 0.5 GSD.

relative geo-locational accuracy: (a) a measure of the integrity of angular and distance relationships of point features within an image; (b) the placement of point features relative to other points, sometimes called point-to-point accuracy. Relative accuracy is often computed as a function of distance. By accounting for relative error, an image having a large systematic error, or bias, may be shown to conserve positional relationships among features and thus, can be shown to have value for some applications (Ager 2002).

r**elative radiometric accuracy**: the difference between measured radiometric values from pixel-to-pixel and/or from band-to-band. It is the accuracy that is internal to the instrument, and not relative to an absolute standard.

signal-to-noise ratio (SNR or S/N): (a) the amount of contrast between the bright and dark points of a 2-dimensional target divided by the variance in the homogeneous regions; (b) the ratio of the level of information-bearing signal power to the level of noise power (Kramer 2001). SNR can also be defined as the ratio of the power in a desired signal to the undesirable noise present in the absence of a signal (Photonics Directory 2004).

spatial out-of-field: The response of a system to radiation outside the field-of-view of the system, which is usually associated with stray light. This is often a measure of the wings of the PSF.

spatial resolution: ability of a sensor to resolve spatial objects
spectral bandwidth: For a given spectral band, the spectral bandwidth is the width of the spectral response curve at the full-width at half maximum (FWHM) value of the spectral response.
spectral responsivity: a measure of a system's response to a known electromagnetic radiation field at a specified wavelength. The spectral response depends on the spectral characteristics of the detector, filters, telescope, and other components. Spectral response as a function of wavelength can be modeled as the spectral product of the response of the components, such as the detector, with the spectral transmission of all filter components, and the diffuser (National Physics Laboratory, 2004). See also **spectral bandwidth**, **central wavelength**, and **cross-talk** as additional key parameters related to responsivity.

standard uncertainty: an estimated standard deviation.

Stokes parameters: the parameters, relative to polarized light, that are usually represented as: I, the intensity of the light beam; M, that part of the beam polarized in the horizontal plane; C, that part polarized in the +45° direction; and S, that part circularly polarized (Photonics Directory 2004).

subjective parameters: when evaluating image quality, there are often attributes that are not traceable to SI Units. See **interpretability**, **general image quality function**, and **national image interpretability rating scale**, **presence of artifacts and flaws**, and **suitability to applications**.

suitability to applications: an image's suitability to various research and operational applications must ultimately be considered. Suitability refers not only to quantitative radiometric, spatial, and geometric performance of a sensor, but also to the overall ability of the acquired data (imagery) to address the needs of users for specified application. This can also be referred to as validation.

systematic error: a measurement error that follows some mathematical or physical law; also known as correlated error, or bias. If the conditions causing the error are measured, a correction can be calculated and the systematic error eliminated. Systematic errors will remain constant in magnitude and algebraic sign if the conditions producing them remain the same (Wolf 1983). In this case the systematic error is the fixed or constant component of the total error (Coleman & Steele 1999).

systematic noise: noise created by non-random sources such as non-uniformity in the detector response caused by dead detectors or noisy pixels. This type of noise can produce image artifacts such as striping and banding in the image.

transmittance: the ratio of the incident to transmitted flux. Type A = evaluated statistically; Type B = evaluated using models or other external information; Type B = one standard deviation.

validation: the process of assessing, by independent means, the quantity of the data products derived from the system outputs.

4. RECOMMENDATIONS

1. Create a list of Radiometric and Geometric parameters and poll the task force members for their additions and deletions;

2. Working face-to-face or via email reach consensus on the list of parameters, prioritize the list, review the range of existing definitions, and develop provisional standard definitions, citing references;

3. Work ISO TC211 to translate Task Force definitions into the ISO process;

4. The EO community should consider establishing an MRA-like database similar to one created by the National Metrology Institutes (NMIs) of EO-specific quantities populated by information from the calibration teams around the world about their measurement capabilities, but with the quality of the data underwritten by formal comparisons/audits from independent NMIs;

5. Engage in a total systems approach to measuring pre-launch and post-launch calibration, using best practices, materials and equipment; and over time to share and test these technologies among sensor designers in a variety of laboratories and Earth environments;

6. In-flight and on-orbit calibration of radiometric and geometric parameters would benefit from expanding the global distribution of test sites and ranges to include many more of Earth's ecosystems. To date, the predominance of vicarious test sites have been located in arid regions characterized by high frequency of relatively clear sky conditions and large areas of uniform, spectrally flat, radiance;

7. Techniques for lunar and stellar calibration are promising and deserve further trials and experimentation;

8. Traceability to SI Units is required to ensure that calibration metadata are comparable between sensors (e.g., internal and external calibration, comparison of spectral bandwidths, geopositional accuracies, etc.).

5. REFERENC PUBLICATION

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