Radiometric modelling of a satellite remote sensing system used for image generation

L van der Westhuizen

CSIR Defence, Peace, Safety and Security, PO Box 395, Pretoria, South Africa, 0001

E-mail: `lvdwesthuizen@csir.co.za`

Abstract. A mathematical model that defines the signal output of passive sensors, used to view the surface of the Earth, is developed. The mathematical model describes the different solar and self-emitted thermal energy paths that contribute to the radiance reaching the sensor of an Earth observation satellite. The different solar and self-emitted thermal energy paths were defined by identifying the radiometry pertaining to image generation of optical satellites viewing the surface of the Earth. This was done by studying the physical real world model of a satellite remote sensing system used in image generation. It was found that the mathematical model must include expressions to describe the sensor to be mounted on satellites, the target that is being viewed by the sensor and the effects of the medium through which the sensor views the target. The total radiance reaching the sensor must therefore include thermally emitted radiance, atmospheric path radiance and reflected radiance terms. The reflected radiance terms are due to sources such as the target, sun, sky and ambient environment. A mathematical model which includes these terms describes the signal output of sensors used in satellite remote sensing systems. This mathematical model aids in the prediction and study of the output of a multi-spectral space remote sensing image generation system, before the actual system is manufactured. The mathematical model can be implemented in software in order to develop a detailed image simulation process that is capable of producing an accurate representation of the image data obtained from a satellite remote sensing system. The capability to simulate the signal output of these sensors is of great value, as it reduces the dependency on extensive field tests when developing, testing and calibrating space remote sensing cameras.

1. Introduction

Remote sensing is the process of collecting data that describes the properties of an object of interest without coming into physical contact with that object [1, p. 1], [2, p. 2], [3]. Earth observation is a common remote sensing application, where images of the surface of the Earth are generated by means of sensors mounted on airborne platforms or satellites [3].

Satellites used for overhead Earth observation, provide a repetitive and consistent view of the Earth and allows the Earth to be viewed in different spectral regions in order to extract different information about a scene [1, p. 2], [2, p. 2]. Data acquired from a satellite remote sensing system can be used to answer questions with regard to the conditions of water quality, vegetation health and pollutant levels and how these conditions change over time [1, p. 2].

Sensors that are integrated into satellite remote sensing systems are designed to meet specific image requirements and image quality is evaluated according to the application [4]. Simulations are used to reduce the dependency on extensive field tests when developing, testing and calibrating space remote sensing cameras or optical instruments that are to be mounted on satellites or airborne platforms. A radiometric model is used in a simulation environment to predict the output of a satellite remote sensing system accurately before the actual system is manufactured. The radiometric model must include a signature rendering equation, an atmospheric model and models of the objects being viewed by the sensor. Accurate simulations of the signal output of sensors viewing the surface of the Earth or the atmosphere of the Earth allow for more versatile and flexible simulation tests [5], [6].

2. Earth observation using satellite remote sensing

A satellite remote sensing system has a range of different input variables. The state of the system is affected by all the elements that make up the system. This includes the position of the Sun in the sky, the properties of the atmosphere, the sensor response and the scene being viewed by the sensor [7]. The collection of data of the Earth surface or atmosphere can be divided into steps which include image capture (data acquisition) through remote sensing using a satellite, transmission of the data recorded by the satellite, reception of the data by a satellite receiving station, the processing, interpreting and analysing of the received data and the application of the acquired information from the processed data [3], [8, p. 3].

The main steps in collecting data of the Earth surface or atmosphere using a passive sensor mounted on a satellite, is depicted in figure 1.

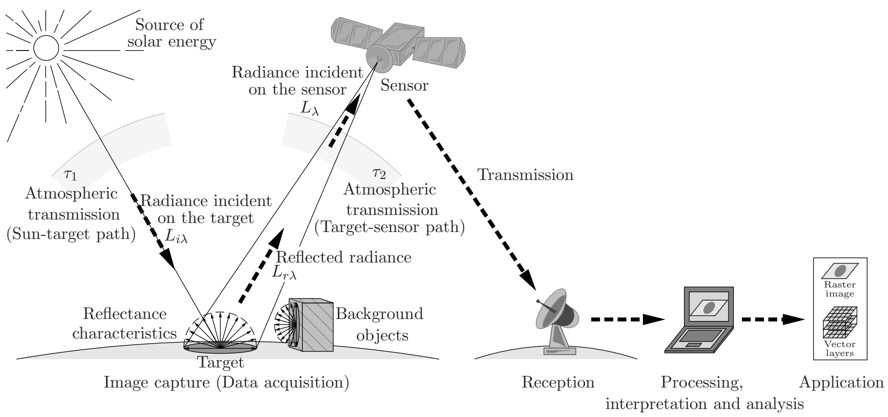

Figure 1. Satellite remote sensing used in the process of data acquisition and analysis (Image adapted from [3] and [8, p. 3]).

A satellite remote sensing system collects the target signature data by means of a sensor mounted in a satellite and is modelled by the signature rendering equation. A satellite remote sensing system consists of a source of illumination such as the Sun, the interaction of propagating flux with particles in the atmosphere, the target, the ambient environment and the sensor. Each component in the satellite remote sensing system must be included in the signature rendering equation [3], [4], [7], [9]. The signature rendering equation is used in a simulation environment to predict the output of a satellite remote sensing system accurately.

In order to simulate an accurate representation of the scene being viewed by the sensor mounted on a satellite, the reflected, emitted and transmitted radiance components of all the objects modelled in the scene must be calculated. Both the spectral and directional emittance and reflectance properties of an object are important and must be considered when modelling the target [10, p. 61]. In the case of semi-transparent objects the spectral and directional transmittance properties of the target must also be considered.

The irradiance incident on the surface of the target is dependent on the properties of the atmosphere [11]. The propagating flux is significantly affected by the atmosphere [1, p. 93]. The atmosphere causes the propagating flux to attenuate and adds path radiance to the radiance leaving the target surface [6]. As flux propagates through the atmosphere it may be absorbed or scattered by the particles in the atmosphere which cause a change in the intensity, direction and possibly the optical wavelength of the propagating flux. Atmospheric turbulence causes the propagating wavefront to distort [3], [12, p. 156]. Radiative transfer codes can be used to include the atmospheric effects on the propagating flux when calculating the at-sensor flux [11].

The sensor will have limitations that result in an imperfect measurement of the target signature [2, p. 110]. The sensor model must take into account the sensor architecture and the spatial, spectral, temporal and radiometric resolution of the sensor. Factors that cause geometric image distortion in the sensor output must be included when modelling the satellite remote sensing system. The scanner properties of the sensor, the orbit and altitude of the platform on which the sensor is mounted and the rotation and geometry of the Earth all contribute to geometric image distortion [2, pp. 75-76].

A signature rendering equation that describes the flux measured at the sensor in a satellite remote sensing system is developed.

3. The signature rendering equation

The signature rendering equation is a mathematical model that describes the flux measured at the sensor and the effects of the sensor on the collected flux. Terms typically used in the signature rendering equation to describe the total flux collected by the sensor include the radiance terms for self-emitted thermal energy from objects in a scene, reflected sunlight, reflected skylight and atmospheric path radiance [1, pp. 58-62], [2, pp. 47-49 and 63], [6], [8, p. 24]. Terms to account for the adjacency effect and semi-transparent objects in a scene should be included in the signature rendering equation to further improve the accuracy with which the signature rendering equation models the flux measured at the sensor.

Figures 2 to 8 represent the energy paths followed by flux as it propagates from a source to the sensor. In figures 2 to 8 the solid lines represent the solar energy paths and the dashed lines represent self-emitted thermal energy paths. The total radiance leaving the surface of an object is represented by a solid line leaving the surface of an object. The total radiance leaving an object includes all the solar radiance components and self-emitted thermal radiance components of that object. Semi-transparent targets are represented by a cloud in figures 2 to 8.

Each energy path in figures 2 to 8 is translated into a mathematical expression. The signature rendering equation describing the flux measured at the sensor of an Earth observation satellite remote sensing system is derived by summing the mathematical expressions for all the energy paths. A suggested signature rendering equation, that descibes the flux measured at the sensor of an Earth observation satellite remote sensing system and that can be implemented in a simulation environment, is given in equation (1).

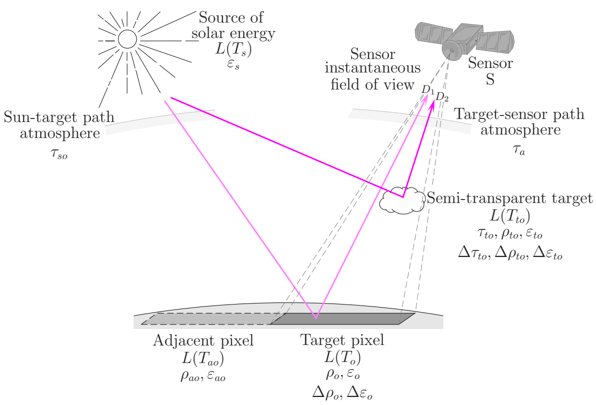

Figure 2. The direct reflected sunlight radiance component.

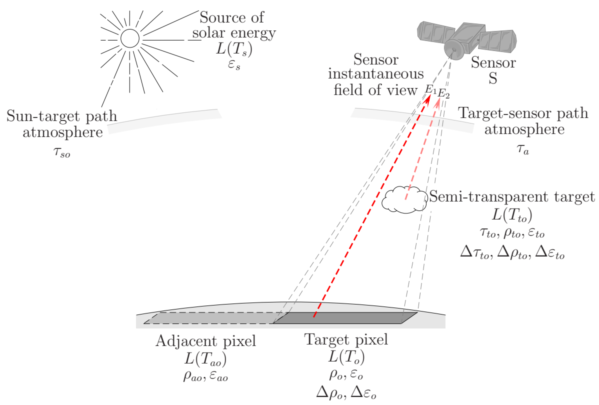

Figure 3. The self-emitted thermal radiance component.

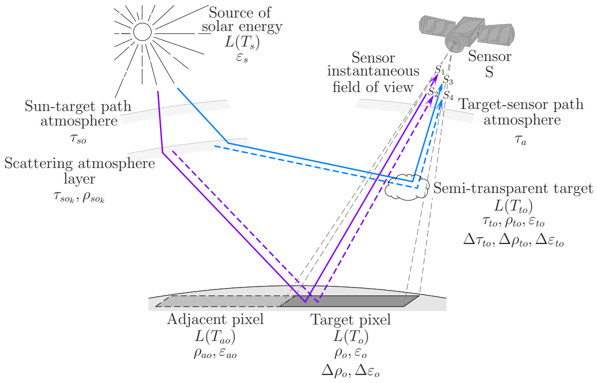

Figure 4. The solar scattered and self-emitted thermal skylight radiance component.

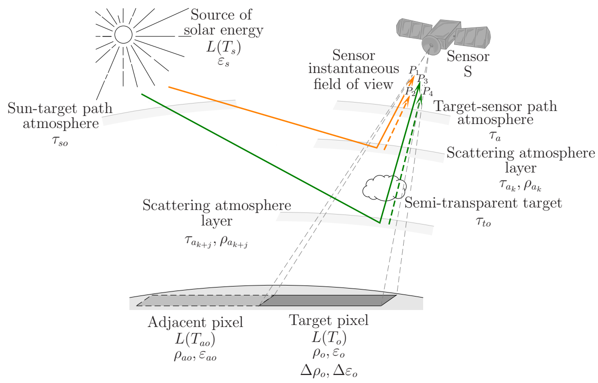

Figure 5. The path radiance component.

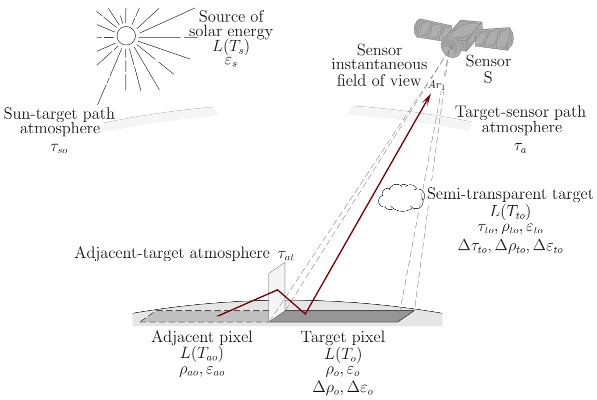

Figure 6. The adjacent object reflected radiance component.

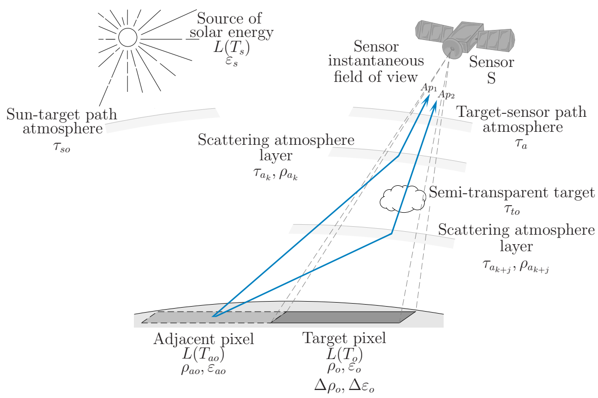

Figure 7. The adjacent path radiance component.

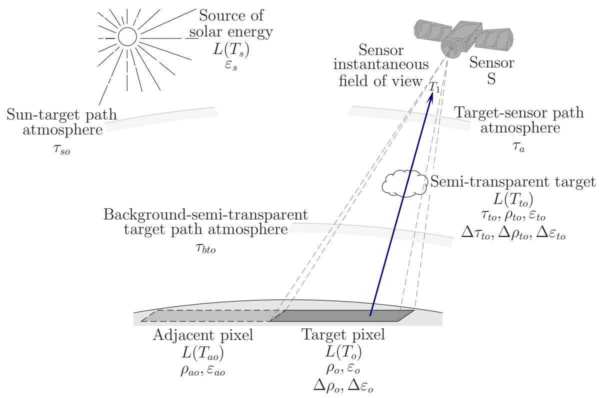

Figure 8. The transmitted radiance component.

$$
\begin{aligned}
L_{\Delta\lambda} = \; & \overbrace{\Delta\rho_o \, \frac{A_s}{R_s^2} \int_\lambda \varepsilon_s \; L(T_s) \; \cos\theta_i \; \tau_{so} \; \rho_o \; \tau_a \; S \; d\lambda}^{Direct\ reflected\ sunlight} \; + \; \overbrace{\Delta\varepsilon_o \int_\lambda L_{target_\lambda} \; \tau_a \; S \; d\lambda}^{Self-emitted\ thermal\ radiance} \\
& + \; \overbrace{\Delta\rho_o \int_{\Omega_{sky}} \int_\lambda L_{sky_\lambda} \; \cos\theta_i \; \rho_o \; \tau_a \; S \; d\lambda \; d\Omega_{sky}}^{Skylight} \; + \; \overbrace{\int_\lambda L_{pathSE_\lambda} \; S \; d\lambda}^{Path\ radiance} \\
& + \; \overbrace{\Delta\rho_o \int_{\Omega_{ao}} \int_\lambda L_{adjacent_\lambda} \; \cos\theta_i \; \rho_o \; \tau_{at} \; \tau_a \; S \; d\lambda \; d\Omega_{ao}}^{Adjacent\ object\ reflected\ radiance} \; + \; \overbrace{\int_\lambda L_{pathA_\lambda} \; S \; d\lambda}^{Adjacent\ path\ radiance} \\
& + \; \overbrace{\Delta\tau_{to} \int_\lambda L_{behind_\lambda} \; \tau_{bto} \; \tau_{to} \; \tau_a \; S \; d\lambda}^{Transmitted\ radiance}
\end{aligned}
\tag{1}
$$

The signature rendering equation in equation (1) accounts for the characteristics of the target being viewed, the atmosphere through which the flux propagates and the sensor spectral response. The target viewed by the sensor can either be non-transparent or semi-transparent. Semi-transparent objects found in a scene include clouds, smoke and the foliage of trees.

The direct reflected sunlight term in equation (1) describes solar radiance reflected directly off the target. The self-emitted thermal radiance term describes radiance emitted by a target. The skylight term describes atmospheric scattered radiance reflecting off the target. The path radiance term describes radiance reflected towards the sensor without reflecting off the target.

The adjacency effect describes the effect that objects outside the sensor Instantaneous Field of View (IFOV) have on the total radiance recorded by the sensor. The radiance of the objects outside the sensor IFOV can be reflected into the sensor IFOV either as upwards path radiance or as incident flux onto the target in the IFOV, which is then reflected towards the sensor [1, pp. 59-61], [2, p. 49], [9], [13]. The adjacency effect is described in equation (1) by the adjacent object reflected radiance and the adjacent path radiance terms.

The transmitted radiance term in equation (1) addresses semi-transparent targets in a scene. This term describes flux transmitted through the semi-transparent target towards the sensor. The transmitted flux originates from objects located behind the semi-transparent object in a scene. If the semi-transparent target is being viewed then the symbols for the non-transparent target in equation (1) must be replaced by the equivalent semi-transparent symbols. For example ρ_o should be replaced by ρ_{to}.

The orientation of the target being viewed also has an effect on the radiance received by the sensor. If the object is tilted, then the hemisphere above the object is divided into two portions, a portion filled by the background objects and a portion filled by the sky. The orientation of the target will play a part in determining the portion of radiance reflected due to the irradiance from the sky and the portion of radiance reflected due to the irradiance from the background objects. This can be represented by a shape factor or by integrating over the solid angle filled with the sky, Ω_{Sky}, or background objects, Ω_{ao} [1, pp. 117-121], [13]. Equation (1) uses integration to describe the portion of radiance reflected due to the irradiance from the sky or background objects, as shown in the skylight term and the adjacent object reflected radiance term.

The reflectance, ρ_o, in equation (1), represents the Bidirectional Reflectance Distribution Function (BRDF) of the target and should be substituted with an appropriate BRDF model. The atmospheric transmittance of the paths followed by the propagating flux are represented by τ_a between the target and sensor, τ_{so} between the sun and target, τ_{at} between the adjacent object and target, τ_{bto} between the background object and semi-transparent target. τ_{to} is the transmittance of the semi-transparent object. The symbols $\Delta\rho_o$, $\Delta\tau_{to}$ and $\Delta\varepsilon_o$ represent the spatial texture properties of a target. The symbol S is the sensor response and must be substituted with the sensor model. Other symbols used include the temperature of the Sun T_s, the spectral emissivity of the Sun ε_S, the area of the Sun A_s, the distance from the Sun to the Earth R_s and θ_i which is the angle of incidence of the flux to the surface normal of the target.

4. Simulation models and future work

There are several exisiting models used to simulate satellite remote sensing systems. Examples of simulation models are the Digital Imaging and Remote Sensing Image Generation (DIRSIG) simulation environment [1, p. 626], the Optronics System Simulator (OSSIM) simulation environment [6], the model suggested by J. Zhang, X. Zhang, B. Zou and D. Chen [9], the model suggested by J. Choi and T. Kim [11] and the simulation model Software Environment for the Simulation of Optical Remote Sensing Systems (SENSOR) [13]. Future work includes the implementation of the suggested signature rendering equation in a simulation environment.

5. Conclusion

A signature rendering equation radiometrically models a satellite remote sensing system by describing the total radiance reaching the sensor mounted on a satellite or airborne platform. In order to simulate a satellite remote sensing system accurately, the signature rendering equation implemented in a simulation environment should include terms to describe the radiance terms for self-emitted thermal energy from the objects in the scene, reflected sunlight, reflected skylight, atmospheric path radiance, adjacency effects and the transmittance of radiance through semi-transparent objects in a scene.

Acknowledgments

The author wishes to acknowledge assistance from C.J. Willers, D. Griffith and M.Lysko at the CSIR and Prof. J. du Preez at the University of Stellenbosch.

References

[1] Schott J R 2007 *Remote Sensing: The Image Chain Approach* 2nd ed (New York, NY: Oxford University Press)

[2] Schowengerdt R A 2006 *Remote Sensing: Models and Methods for Image Processing* 3rd ed (Burlington, MA: Academic Press) [Online]. Available: `http://www.sciencedirect.com/science/book/9780123694072`

[3] Department of the Army, US Army Corps of Engineers 2003 *Engineering and Design: Remote Sensing, EM 1110-2-2907* [Online]. Available: `http://140.194.76.129/publications/eng-manuals/em1110-2-2907/entire.pdf`

[4] Fiete R D 1999 *J. Imaging Sci. Techn.* **51** 103 – 9

[5] Willers C J and Willers M S 2011 *OSSIM: Optronics System Simulator* (Pretoria, SA: Council for Industrial and Scientific Research) CSIR White Paper 6700-PG-103400-01 RPT Rev 4 (svn-r1203)

[6] Willers C J, Willers M S and Lapierre F 2011 Signature modelling and radiometric rendering equations in infrared scene simulation systems *Proc. of SPIE Security and Defence 2011* vol 8187 (Prague, Czech Republic)

[7] Kerekes J P and Landgrebe D A 1991 *IEEE Trans. Syst., Man, Cybern.* **21** 125 – 133

[8] Lillesand T M, Kiefer R W and Chipman J W 2008 *Remote Sensing and Image Interpretation* 6th ed (Wiley)

[9] Zhang J, Zhang X, Zou B and Chen D 2010 *IEEE Trans. Geosci. Remote Sens.* **48** 3889 – 3902

[10] Palmer J M and Grant B G 2010 *The Art of Radiometry* (Belligham, WA: SPIE Press)

[11] Choi J and Kim T 2008 Study on spectral transmission characteristics of the reflected and self-emitted radiation through the atmosphere *Multisensor Fusion and Integration for Intelligent Systems, 2008. MFI 2008. IEEE International Conference on* (Seoul, Korea) pp 354 – 9

[12] Thomas M E, Duncan D D, Beland R R, Gilbert K G, Otten III L J, Rose W C and Gebhardt F G 1993 Atmospheric propagation of radiation *The Infrared and Electro-Optical Systems Handbook* vol 2 ed Smith F G (Environmental Research Institute of Michigan and SPIE Optical Engineering Press)

[13] Börner A, Wiest L, Keller P, Reulke R, Richter R, Schaepman M and Schläpfer D 2001 *ISPRS Journal of Photogrammetry and Remote Sensing* **55** 299 – 312