OPTICAL REMOTE SENSING IMAGING SYSTEM MODELING AND DESIGN

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ABSTRACT

Earth observation using space borne imaging system have advantage over any other terrestrial means as it offers global coverage of earth and its environ in wide spectral range and unprecedented spatial & temporal scales for host of remote sensing applications such as agriculture, forestry, oceanography, cartographic etc. These applications demands accurate measurements of the upwelling earth radiation by the imaging system for retrieval of various physical parameters of interests. The achievable accuracy depends on characteristics of various participating elements in a remote sensing chain including source of radiation, atmospheric effects on down-welling and upwelling radiation, target of reflectance, adjacency effects, path radiance, background signal, sensor spectral, geometric and radiometric response, data processing and product generation process, data interpretation methods etc. Hence, it is imperative to develop suitable mathematical models for estimation of EO parameters to aid in design, development and characterization of imaging systems.

Keywords* – *Remote Sensing, Imaging System, Electro Optical, Mathematical model.

I. INTRODUCTION

Spaceborne imaging systems are precision instruments for accurately measuring upwelling radiation from earth surface carrying spectral signature of various ground objects. Based on these measurements, application specific parameters are retrieved for quantitative assessment of underlying physical processes affecting earth and it’s environ. This whole process of remote sensing from spaceborne platform is treated as a coupled system, whose major constituent elements are; source of radiation, reflective properties of the scene, atmospheric effects on downwelling and upwelling radiation, scene sensor geometry, Imaging system (sensor) response and ground based image processing chain [1]. It is important to understand the complex interplay of these elements for proper interpretation of the remotely sensed data.

When we observe the Earth from space, the intervening atmosphere does not transmit all parts of EM spectrum. Thus, the atmosphere is transparent only to certain portions of the EM radiation, which are called “atmospheric window” regions. Earth observation is carried out in these windows of the EM spectrum. The EM energy transmitted from the source (sun, transmitter carried by the sensor) interacts with the intervening atmosphere and is spectrally and spatially modified before reaching the Earth’s surface. The EM radiation falling on the Earth interacts with the Earth surface resulting in part of the energy being sent back to the atmosphere. In addition, self-emission from the surface due to its temperature also takes place. This is the "signature" of the target, which is detected by sensors placed on suitable platforms, such as aircraft, balloons, rockets, satellites, or even ground-based sensor-supporting stands. The sensor output is suitably manipulated and transported back to the Earth; it may be telemetric as in the case of unmanned spacecraft, or brought back through films, magnetic tapes, and so on, as in aircraft or manned spacecraft systems. The data are reformatted and processed on the ground to produce photographs or stored in a computer compatible digital data storage medium. The photographs/digital data are interpreted visually/digitally to produce thematic maps and other information. The interpreted data so generated need to be used along with other data/information, and so on, to arrive at a management plan. This is generally carried out using a geographic information system [2].

Based on this motivation, we report here development of a mathematical model for scene and sensor of IRS imaging systems at finer abstraction level by accounting for all possible signal transformation processes in the remote sensing chain including scene effects and sensor's signal transformation and noise effects. The model enables estimation of realistic sensor output in DN and MTF which directly impacts the sensors measuring capability.

II. OVERVIEW OF IMAGING SYSTEM

The satellite program in India started with the design and development of a scientific satellite, which was launched using a Soviet rocket from a cosmodrome in the erstwhile USSR on April 19, 1975. The satellite after launch was named Aryabhata, after the fifth century Indian astronomer. Encouraged by the success of Aryabhata, it was decided to develop an application satellite that could be a forerunner to meet the goal of providing services for national development. Since the Aryabhata was a low Earth orbiting satellite, developing a remote sensing satellite was the most appropriate choice. In view of the complexities of realizing an operational remote sensing satellite in the first mission, it was decided to go for an experimental system that can provide the necessary experience in the design, development, and management of a satellite-based remote sensing system for an Earth resources survey. The satellite carried a two-band TV camera system with a spatial resolution of about 1 km and a multiband microwave radiometer. The satellite was launched on June 7, 1979 from the erstwhile USSR. The satellite was named Bhaskara, after the twelfth century Indian mathematician Bhaskaracharya. The follow-on satellite Bhaskara 2 was also launched from the USSR on November 20, 1981.

The Bhaskara missions provided valuable experience in a number of interrelated aspects of satellite-based remote sensing systems for resource survey and management. The next logical move was to embark on a state-of-the-art operational Earth observation system. Way beyond the 1 km camera system used in the learning phase, India has successfully launched a series of remote sensing satellites—the IRS satellites—starting with IRS-1A in 1988. When IRS-1C was launched in 1995, with its PAN camera providing 5.8 m resolution, it had the highest spatial resolution among civilian Earth observation satellites in the world and retained its number one position until the advent of IKONOS in 1999, with 1 m resolution capability. Since then a number of Earth observation satellites have been launched for land, ocean, and meteorological studies including a series of cartographic satellites, which can be used for updating of topographic maps. Another milestone is the launch of the Radar Imaging Satellite in 2012—a state-of–the-art microwave remote sensing satellite carrying a SAR payload operating in the C-band (5.35 GHz). These are low Earth orbiting satellites. In addition, the Indian Space Research Organization (ISRO) has a constellation of geostationary satellites carrying Earth observation cameras to provide information for meteorological studies and forecast.

Although IRS satellites were developed strongly on the basis of meeting national development needs, the excellence that they promoted in technology, applications, and capacity building enabled them to play a significant role in the international arena. The data from the IRS satellites are available globally through Antrix Corporation Limited (Antrix), the marketing arm of the ISRO.

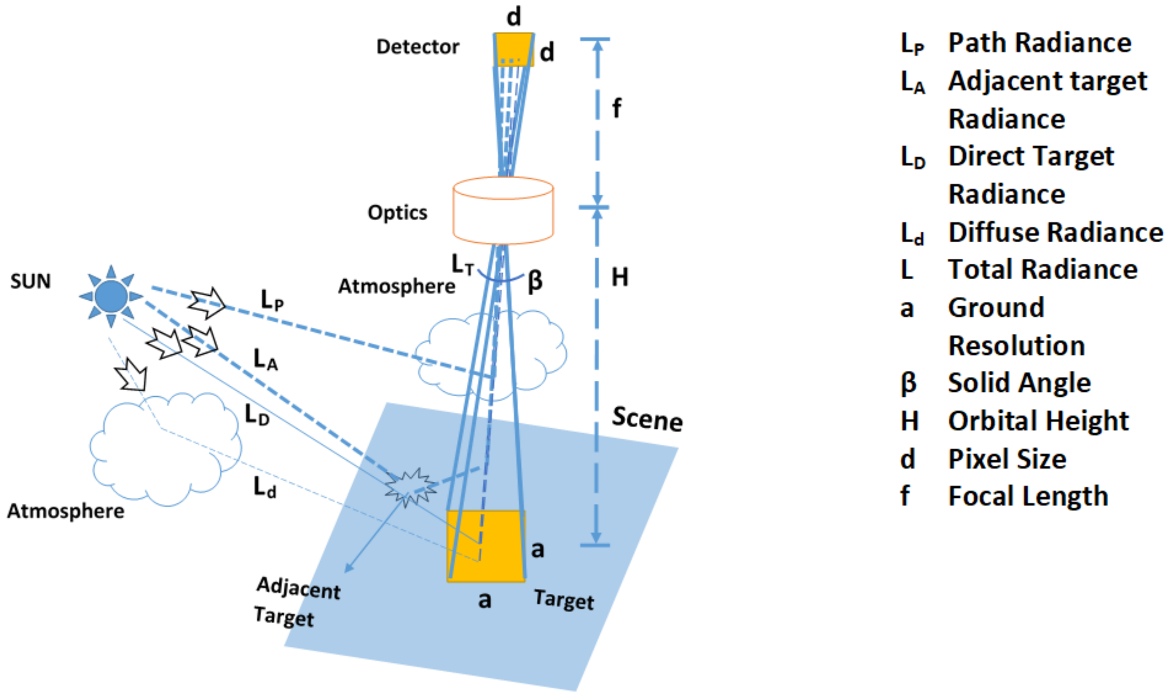


Fig.1 Typical Signal transformation process in Remote Sensing Imaging Chain

Various IRS missions chronicled in preceding section carried state-of-the-art imaging systems meeting stringent spectral, spatial, and radiometric requirements of the user community. Imaging system design is dictated by the user requirements and availability of technological elements at that time. Typically, an IRS imaging system comprises of a focusing optics, detector, electronics and mechanical systems. Each of these elements are described in detail below along with technological challenges involved [2].

III. MODELING OF IMAGING SYSTEM

Remote sensing imaging systems measures the upwelling radiance filling the optical aperture and provides its output in digital counts through various signal transformation process within the imaging chain. The Signal transformation process in a remote sensing chain is shown in Figure 1.3 [3], [1], and [5]. The radiometric response of any imaging system depends on its signal transformation process and overall noise generation in the chain. This modeling helps in quantifying contributions of each element in the image generation process. A-priory knowledge of these contributions helps in optimizing system performance during actual imaging system development. In this section both signal and noise modeling are discussed.

A. Signal Modeling

Solar radiation illuminates the target on the earth surface and based on the target characteristics, part of the radiation is directed towards the sensor. The imaging sensor collects the signal falling on its aperture and transforms it into measurable counts based on optical, detector and electronics characteristics. As such this process can be split into two models at lower abstraction level i.e. scene model and Imaging system model. At higher abstract level, this signal flow can be modeled as shown in Figure 5.1.

The scene model should be able to predict the top of atmosphere (TOA), at sensor radiance values to which an imaging system model will respond. Although a scene in remote sensing term can be very complex and no model as such can accurately predict the scene output. However, known processes are well documented in the literature and with some level of approximation this can be modeled. The main element in the scene model is solar illumination, atmospheric effects, target reflectance, adjacency effects, scene-sensor viewing geometry etc. Considering all these aspects, scene models for IRS sensors are well documented in references [4], [1]. Mathematical transformation process in a remote sensing imaging system is provided in [3]. In the current work, we adopt the mathematical expressions provided in these references, wherever required.

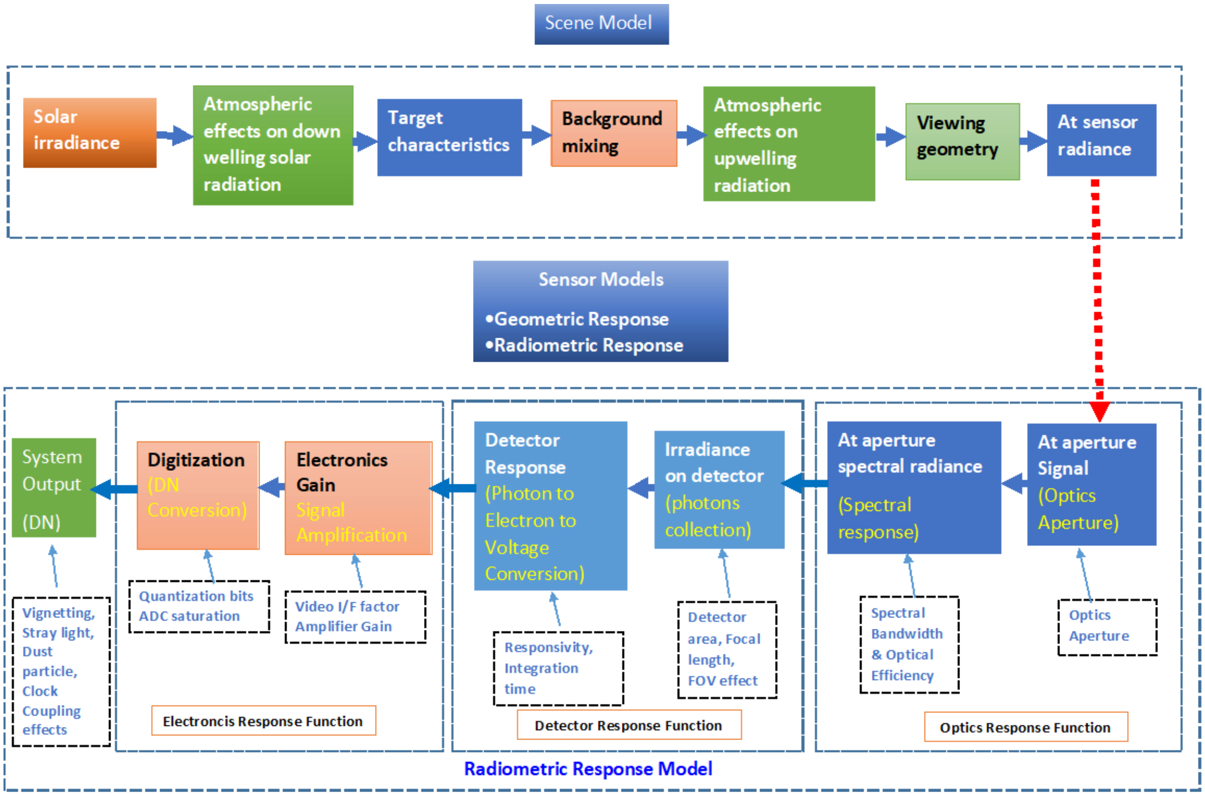


Fig. 2 Signal Model for IRS Imaging System

The imaging system has two major response function i.e. Geometric and radiometric. In the current work we model only the radiometric response function. The main element in the Imaging system's radiometric response model is focusing optics, which collects the incident radiation on its primary aperture and concentrates the energy on a detector placed in its focal plane. One of the important parameters of optics system is its transmission efficiency. The Transmission efficiency has cascading effects, where more number of elements reduces the efficiency. The large field of view leads to gradual energy fall off towards the extreme filed. Pass band of the filter dictates the amount of energy collected in the spectral band. Smaller bandwidths results in lower signal values. The baffling systems incorporated to reduce the stray light effects. Overall optomechanical configuration realization aspects lead to vegetating of incident radiation in the image plane. Signal gathering capability of the optical system is governed by its primary aperture size, focal length, spectral bandwidth, optical signal transmission efficiency etc. The detector converts this energy into a measurable electrical signal with the help of associated electronics chain. Dwell time, responsively, pixel size, quantum efficiency etc are some of the detector parameters, which determine the optical to electrical signal transformation efficiency. The electronics system contributes in signal transformation process with two important function, first it generates bias and clock levels for CCD operation, second, he video processor circuit suitably amplifies and digitizes the analog electrical signal for further transmission and image generation. During these transformation processes, various elements in the imaging chain causes signal dependent and fixed pattern noise, limiting the measurement capability. In the signal transformation process, the imaging system should ensure acceptable spectral, geometric and radiometric fidelity. Any degradation in the imaging sensor function can jeopardizes the earth observation mission objectives. Higher abstraction levels in models are achieved by further decomposing the imaging system response into optical, detector and electronics response functions. It is important to understand the each of these elements characteristics, which contribute in signal transformation process.

In an ideal system, the imaging chain elements do not interfere with each other in signal transformation process, ensuring linear response of the system. However, in real world, complex interplay of these elements results in Opt mechanical vegetating, stray light effects, dust particles, clock coupling etc, which affect the signal transformation process.

Also, unaccounted or uncontrolled noise sources results in integrated system SNR performance degradations. These effects can be added as further abstraction levels. Some of these effects such as vegetating, stray light etc are difficult to model. Approach adopted for accounting their contributions are described during simulation studies.

In a remote sensing imaging geometry, the sensor receives this upwelling radiance within the solid angle subtended by the ground target on the image plane corresponding to one resolution element.

$$\Omega = \frac{x^2}{H^2} = \frac{a^2}{f^2} = \beta^2$$

This collected radiance by optical aperture (A0) is modified by the optical efficiency of the optical system (τ_e) and filter's spectral response (τ_f). This signal in the form of radiant flux falls on the detector placed in the focal plane of the optics. This signal transformation is expressed in the equation below:

$$\Phi = \int_{\lambda 1}^{\lambda 2} L_\lambda \Omega A_0 \tau_e \tau_f d\lambda$$

Considering circular aperture optics of diameter D and expressing solid angle in terms of detector pixel area and focal length the equation transforms to:

$$\Phi = \frac{\pi}{4} \int_{\lambda 1}^{\lambda 2} L_\lambda D^2 \tau_e \tau f \frac{A_d}{f^2} d\lambda$$

This irradiance is converted proportionately to number of electrons by the detector based on it's responsively and charge integration time. Based on the readout rates, these charges are dumped onto the sense node and are converted into equivalent electrical voltage for measurements. So, detector level signal transformation is expressed in mathematical form as per equation:

$$V = \frac{\pi}{4} T_i \int_{\lambda 1}^{\lambda 2} \frac{L_\lambda \tau_e \tau_f R_\lambda \cos^4 \theta}{f_{no}^2} d\lambda$$

The voltage generated by the detector is interfaced with the external electronics chain for further processing. This interface matches the detector output impedance with the electronics load for maximum signal transfer. Subsequently electronics chain amplifies the signal to match the ADC input dynamic range for conversion to digital numbers (DN). Analog signal at ADC input can be expressed as:

$$V = \frac{\pi}{4} T_i G_I G_A \int_{\lambda 1}^{\lambda 2} \frac{L_\lambda \tau_e \tau_f R_\lambda \cos^4 \theta}{f_{no}^2} d\lambda$$

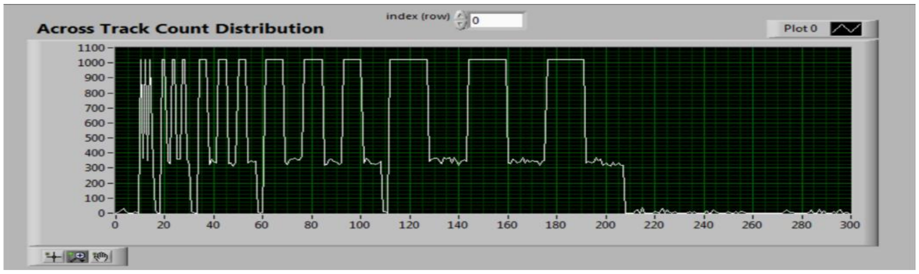
Where GI = [RL/RL+RP] (Voltage across the termination resistor) and GA is Video amplifier gain. The voltage signal at ADC input is transformed into a digital count based on number of quantization bits.

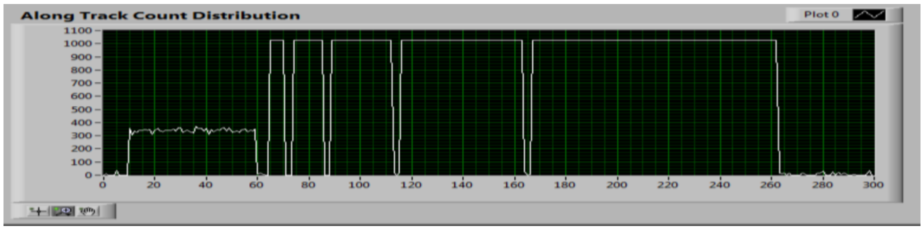
$$DN = \frac{2^n - 1}{V_{Sat}} [\frac{\pi}{4} T_i G_I G_A \int_{\lambda 1}^{\lambda 2} \frac{L_\lambda \tau_e \tau_f R_\lambda \cos^4 \theta}{f_{no}^2} d\lambda]$$

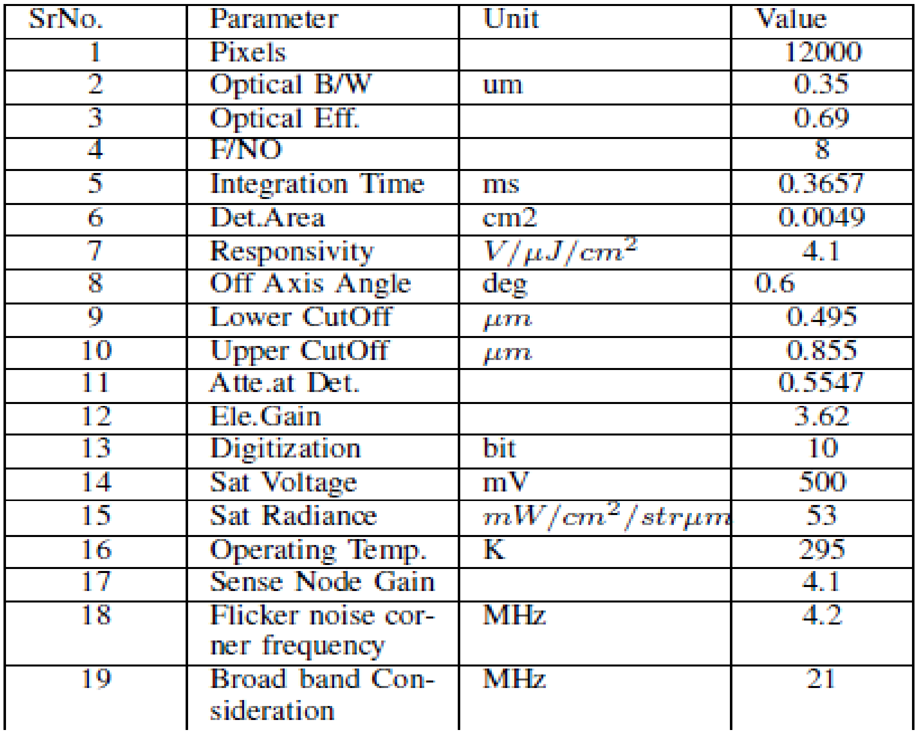
Where ρT will be derived from Equation provides direct relation between ground reflectance and the Imaging system output in DN. All the input parameters related to input scene can be derived from various models and sensor parameters can be taken from design of the imaging system. The Imaging system output in DN is derived for a single pixel. However, detectors used in the IRS missions are linear detectors.

IV. SIMULATION STUDIES AND RESULTS

The developed model was implemented in MATLABT for simulation studies. For testing the model, Cartosat-2 imaging system configuration is selected. This system is designed to provide submeter (0.8 m GSD) class imageries from spaceborne platform for cartographic applications. The imaging system's telescope is an RC type telescope with 700 mm primary mirror aperture with f-number fno/8. The focal plane comprises of two 12k element CCD detectors for redundancy purposes with 7 _m pixel pitch [6]. Analog video data of the 12K pixels are throughput 8 ports, with 1500 pixels each. Port wise modular Electronics system is designed to provide very low noise so that photon noise limited performance can be achieved.







SrNo.	Parameter	Unit	Value
1	Pixels		12000
2	Optical B/W	um	0.35
3	Optical Eff.		0.69
4	F/NO		8
5	Integration Time	ms	0.3657
6	Det.Area	cm2	0.0049
7	Responsivity	$V/\mu J/cm^2$	4.1
8	Off Axis Angle	deg	0.6
9	Lower CutOff	μm	0.495
10	Upper CutOff	μm	0.855
11	Atte.at Det.		0.5547
12	Ele.Gain		3.62
13	Digitization	bit	10
14	Sat Voltage	mV	500
15	Sat Radiance	$mW/cm^2/str\mu m$	53
16	Operating Temp.	K	295
17	Sense Node Gain		4.1
18	Flicker noise corner frequency	MHz	4.2
19	Broad band Consideration	MHz	21

Table 1 Simulation Input Parameters

For two radiance level, overlapping profiles are shown in Figure 10 for assessment of pixel to pixel variations. For quantitative analysis, Pixel by pixel difference is taken between simulated and measured signal output profiles. The difference is expressed in percentage of measured data to bring out closeness of match as shown in 11. We observed a very close match of <_5% for all radiance levels (Figure 9) except for one lower level as shown in Figure 12, where slightly higher estimation error of the order of <10% has been observed. The residual profile has some kind of fixed pattern noise. This indicates that the error is due to specific fixed pattern noise present in the measured data, which could not be accounted for in the model.

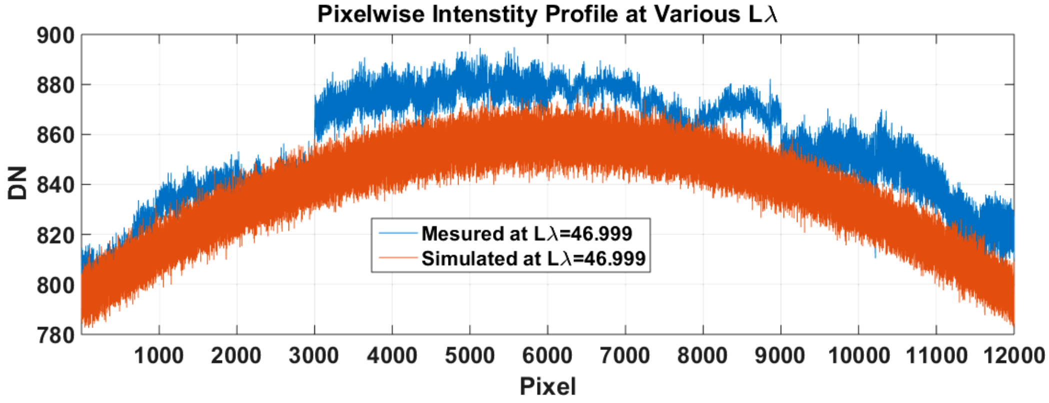


Fig. 3 Comparison of Measured Vs Estimated Spatial illumination profile for higher radiance

This FPN could be due to the complex noise environment arising due to electronics chain, EMI emanating from interconnection harness etc, whose impact on signal level is difficult to model. Attempts need to be made to improve the model to account for these behaviors in signal and noise modeling. However, this error is not very large and mostly it gets corrected in radiometric correction process.

V. CONCLUSION

Developed a generic model and can be applied to other IRS imaging systems. The model incorporates scene elements and can provide direct conversion of ground target's reflectance to sensor output in terms of digital counts for quantitative assessment of retrieval parameters. Developed model is also useful for simulating system behavior for newer proposed imaging systems and can provide realistic assessment of sensor performance in various scene conditions and for variety of ground objects. The model can be integrated with geometric response model of the system so as to get end-to- end system performance. The developed model has lot of scope for simulating system response for upcoming imaging systems to be flown on various IRS missions.

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