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DIRSIG LIDAR CAPABILITIES

Prepared for LaSen, Incorporated

Digital Imaging and Remote Sensing Laboratory
Chester F. Carlson Center for Imaging Science
Rochester Institute of Technology
54 Lomb Memorial Drive
Rochester, New York 14623
(585) 475-6380
(585) 475-5988 (FAX)

http://dirs.cis.rit.edu/

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1. Introduction

Recent advances in tunable lasers and infrared detectors have allowed much more sophisticated and accurate work to be done, but a comprehensive spectral LIDAR model has yet to be developed. This paper briefly describes the first principles based elastic LIDAR model being developed at Rochester Institute of Technology (RIT) by the Digital Imaging and Remote Sensing (DIRS) Laboratory.[1]

1.1. *DIRSIG Model Overview*

The Digital Imaging and Remote Sensing Image Generation (DIRSIG) model is an integrated collection of independent first principles based submodels which work in conjunction to produce radiance field images with high radiometric fidelity in the 0.3 – 30.0 μm region.[2] This modular design creates a high degree of flexibility and interchangeability within the model that was used to our advantage in the implementation of the hybridized model. The following sections briefly describe the various aspects of the image generation model.

1.1.1. Scene Geometry Submodel

The scene geometry submodel provides the mechanism through which collections of three-dimensional objects are incorporated into the SIG environment. The 3D-wireframe models can be built in a CAD environment or purchased from commercial drawing providers. The wireframe models are then facetized, and thermodynamic and optical properties are attached on a facet-by-facet basis. Terrain elevation maps can be directly incorporated into the scene and attributed using pure class maps or material mixture maps. Collections of attributed models are then assembled to create complex scenes that can be used for simulated image acquisitions.

1.1.2. Ray-Tracing Submodel

The DIRSIG model can be generalized as a radiometrically and thermally rigorous rendering tool that is built around a non-uniform subdivision (octree) ray tracer. The ray tracer searches the scene geometry database to generate lists of surfaces along a given ray path which may include conventional opaque surfaces as well as several obscuring transmissive surfaces (i.e. clouds, gas plumes, vegetation, etc.). The ray tracer is also utilized to establish solar shadowing histories required for reliable temperature predictions and for current lunar and man-made source shadowing conditions at the simulation time.

1.1.3. Sensor Submodel

At the core of the DIRSIG model is the sensor submodel, which directs the computations made for each pixel. This submodel includes a sophisticated geometric description of the simulated sensor's focal plane, which allows it to generate the rays to be traced for each pixel on the focal plane. In addition to the common framing camera geometries supported by most image simulation environments, the DIRSIG sensor model can also simulate scanning geometries such as line scanners or pushbroom scanners. For scanning platforms, a flight profile including platform location and orientation on a line-by-line basis can be specified by the user. In addition to describing larger sources of geometric distortions (i.e. rolling, pitching, etc.), the flight profile can also be used to introduce pixel or sub-pixel geometric distortions from platform jitter.[3]

In addition to the geometric description of the focal plane and acquisition platform, the sensor model includes the spectral description of the sensor's detectors. This includes the channel bandpasses and spectral response functions. In addition to supporting discrete channels with individual response functions, the model also provides mechanisms for the user to describe spectrometer systems using a list of channel centers and widths. The model is also able to produce spectral radiance image cubes over a user defined spectral range and user defined spectral resolution.

1.1.4. Thermal Submodel

Temperature predictions are currently determined by a forward chaining differential model called THERM, (written by DCS Corporation as part of the Air Force Infrared Simulated Image Model (AIRSIM)). This model takes into account material properties (i.e. heat capacity, thickness, density, etc.), meteorological histories (i.e. insolation, wind speed, air temperature, etc.) and a solar shadow history of the previous 24-hours. Since many inputs to the model vary on a pixel by pixel basis (shadowing history, sky obscuration, etc.) the output imagery exhibits a high degree of temperature variation characteristic of actual MWIR and LWIR imagery. Temperature predictions can also be overridden at the facet level with a fixed temperature (possibly generated by a more sophisticated offline model). Temperature predictions for the target and backgrounds are handed to the radiometry model for incorporation into the self-emission components of the radiance computation.

1.1.5. Radiometry Submodel

The radiometry model is responsible for computing the spectral radiance incident from a given path. Depending on the path geometry, the radiance computation for a given path might include the incorporation of direct sky light or sun light (for a clear path to the sky) or the reflected and emitted components from one or more surfaces along the path. All of these radiometric calculations are performed on a spectral basis at a resolution specified by the user. The details of various aspects of the model are discussed in the following sections.

1.1.6. Atmospheric Modeling

DIRSIG uses the MODTRAN[4] radiation propagation model to generate a complex set of look-up tables to characterize the exoatmospheric irradiance, emitted and scattered radiances (upwelled and downwelled) and path transmission. MODTRAN imposes a 2 cm^{-1} upper limit on the user defined spectral resolution that the model can operate at. This limit can be alleviated by utilizing FASCODE[5] for atmospheric predictions, however, the FASCODE model does not feature the mature multiple-scattering models currently available with MODTRAN and the time required to create the atmospheric database can increase by orders of magnitude.

1.1.7. Surface Reflectance Modeling

Surface reflected radiances from opaque surfaces at the end of a path or from transparent surfaces along a path are computed utilizing a simplified bi-directional reflectance model.[6] When well-populated surface reflectance databases are available, the model can be easily modified to utilize full bi-directional reflectance distribution functions (BRDFs). For directly viewed opaque surfaces, the ray tracer and the radiometry model are used in conjunction to sample the incident radiance from the entire hemisphere above the surface. More rays are cast into the specular direction to insure that the shape of the specular lobe is effectively represented. The incident radiation from each sample is then modified by the reflectance for the given geometry, weighted by the sampled solid angle and added to the total reflected radiance term.

1.1.8. Texture

To simulate texture in targets, DIRSIG utilizes a large database of reflectance curves for a given material (presumed to represent the variations from inhomogeneities) and the bi-directional reflectance model to introduce variations due to orientation and surface structure. Each material class is assigned a texture image that represents that spatial variation of reflectance in a known spectral region. During the rendering process, a mapping mechanism identifies a pixel in the texture image that is then used to drive the selection of a reflectance curve from the database for that material. For instance, if the selected pixel's digital count is n standard deviations from the mean of the texture image, then a curve that is n standard deviations from the mean in the spectral region of the texture image is selected from the database. The selected curve is utilized in all spectral computations involving that surface for the pixel currently being processed. This process allows the model to introduce spatial-spectral variations using a mechanism that attempts to enforce the wavelength depended mean, variances, covariances and contrast ranks.

1.1.9. Transparent Surfaces and Volumes

The model also allows the user to include plate-type transmissive surfaces that can be used to model glass, camouflage, vegetation, etc. Transparent volumes such as clouds or water bodies can also be included and will exhibit path length dependent reflectance, extinction and emission properties.[7] The plate-type surfaces are heavily utilized to simulate trees, which exhibit a significantly high near-IR transmission. This increased near-IR transmission is responsible for effects including "leaf-stacking" within the canopy and "tree-shine" on objects near a tree line.

1.1.10. Auxiliary Image Data

In addition to producing radiance images for the bandpasses specified, DIRSIG is also capable of producing per-pixel "ground truth" data in the form of image maps. The user can select from the following list of available images:

• Material/Class	Primary hit, first opaque hit and first transparent hit
• Sun/Shadow Mask	Sunlit or shaded map for primary surface
• Temperature	Primary hit, first opaque hit and first transparent hit
• Hit Information	Hit point X,Y,Z coordinates and surface-to-sensor angle
• Path Angles	Zenith and azimuth angle of path
• Emissivity	Average emissivity of hit surface in each band
• Upwelled Radiance	Integrated upwelled (path) radiance in each band
• Downwelled Radiance	Integrated downwelled (incident) radiance in each band
• Path Transmission	Average atmospheric and object transmission in each band
• Plume Information	Concentration by gas, temperature and dilution

These auxiliary image maps can be utilized to debug unexpected phenomenology or as truth data for algorithm developers utilizing the synthetically generated data for algorithm testing.

1.2. LIDAR Capabilities

In order to provide a tool to assist in LIDAR development, a first principle based elastic LIDAR model was incorporated into the DIRSIG model. It calculates the irradiance onto the focal plane on a spectral basis for atmospheric and topographic returns, based on user-defined system characteristics and atmosphere descriptions. The *geometrical form factor (GFF)*, a measure of the overlap between the sensor and receiver field-of-view, is carefully modeled for both the monostatic and bistatic systems. The model includes the effect of multiple bounces from topographical targets. At this time, only direct detection systems have been modeled. Several sources of noise are extensively modeled, such as speckle from rough surfaces. Additionally, atmospheric turbulence effects including scintillation, beam effects, and image effects are accounted for. To allow for future growth, the model and coding are modular and anticipate the inclusion of advanced sensor models and inelastic scattering. Figure 1 illustrates many of the physical processes which the model takes into account. The pulse begins at some user defined point in the atmosphere, a certain height above the ground, and pointing in a certain direction.

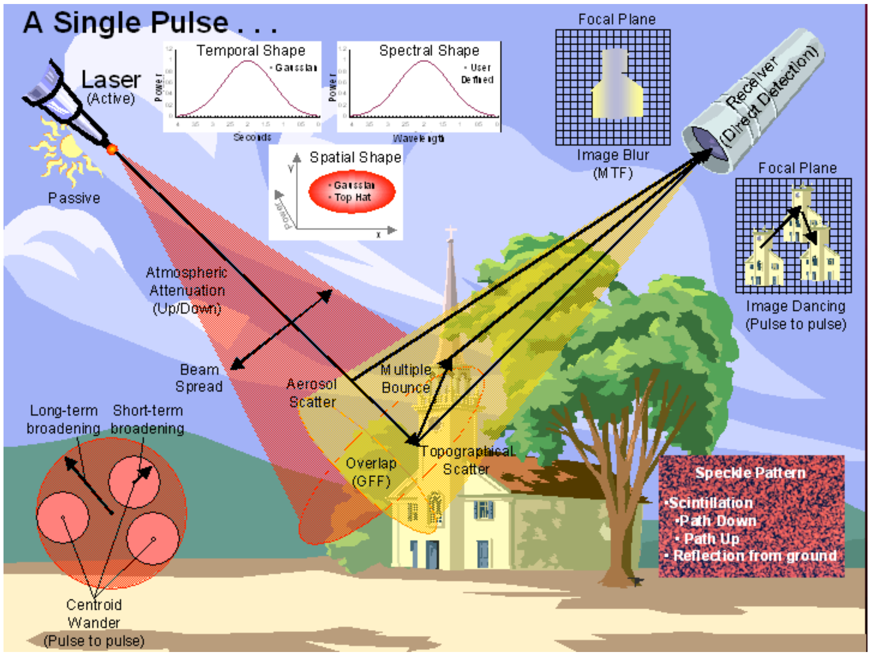

Figure 1: Schematic description of the DIRSIG LIDAR modeling chain.

1.2.1. *Pulse Modeling*

The pulse is modeled with spatial, spectral and temporal dimensions. The spatial density of the pulse can be modeled as either Gaussian or Uniform from a user-supplied beam width. The pulse spreads spatially as a function of distance from the source using either a user-supplied divergence or based on spreading due to the user-defined atmospheric turbulence. The spectral shape of the pulse is assumed to be Gaussian about a user-supplied mean wavelength and width and using a user-supplied power (pulse energy). The temporal pulse shape is also assumed to be Gaussian using a user-supplied pulse width. At this time, multiple pulse acquisitions cannot be modeled but this feature could be incorporated thereby allowing the user to specify a pulse repetition rate.

1.2.2. *Source-Receiver Overlap*

The geometric overlap of the beam field-of-view with the receiver field-of-view is commonly referred to as the *geometric overlap factor* or the *geometric form factor* (GFF). The DIRSIG model accounts for this source-receiver overlap as an integral element of the propagation-detection problem that allows the model to be utilized for both monostatic (range independent beam-receiver overlap) and bistatic (range dependant beam-receiver overlap) systems. The plot in Figure 2 illustrates how a system with a fixed offset between the source and receiver can be tuned to produce returns from specific ranges by adjusting the relative angle between the source and receiver. Utilizing a bistatic system allows the system designer and operators to geometrically eliminate the ground return for gas plume studies using geometric gating rather than electronic time gating. The inclusion of this important system characteristic allows the DIRSIG model to be used to explore system design trades and data tasking issues.

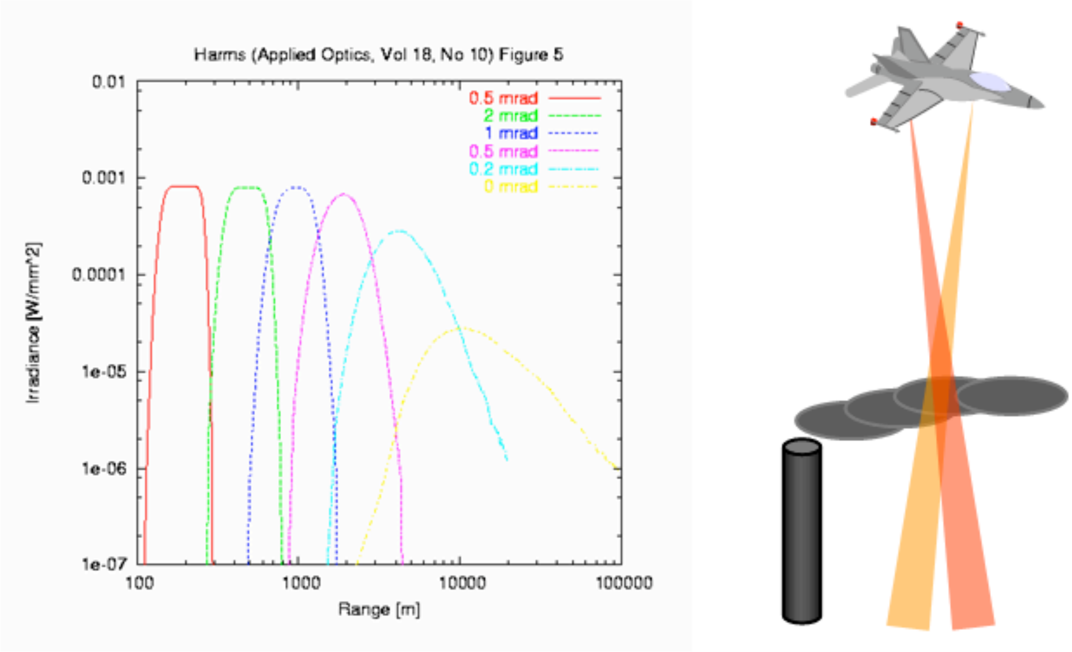

Figure 2: Modeling of Source-Receiver Overlap.

1.2.3. *Pulse Propagation and Backscatter*

As the pulse is propagated through the atmosphere it is attenuated by both molecular absorption and Mie and Rayleigh scattering. The atmosphere also introduces additional effects due to turbulence, including a broadening of the pulse both spatially and temporally. Additionally, the beam will be randomly deflected from its initial propagation direction. This deflection will cause the position of the beam centroid to vary from one pulse to the next. Atmospheric turbulence also causes random spatial and temporal fluctuations in the beam intensity (scintillation) which results in a speckle type pattern onto the beam. Some of the scattered energy will make it back to the receiver and create an atmospheric return, referred to as the aerosol return. The amount of energy retro-reflected back to the receiver depends upon the atmospheric volume backscatter coefficient and the overlap of the beam and the receiver field-of-view at the given range. Unscattered photons continue along the propagation path to be potentially scattered at a later time by the atmosphere or other elements in the scene. If the scene is complicated, portions of the beam may be reflected by several surfaces before being retro-reflected back into the receiver.

1.2.4. *Additional Absorption and Scattering*

In addition to atmospheric absorption and scattering, the user can include geometric elements in their simulation that have absorption and elastic scattering characteristics. For example, the model has been used to demonstrate Differential Absorption LIDAR (DIAL) applications on a simple gas plume that was assigned gas specific spectral absorption and scattering properties. The same elements of this generalized radiative transfer approach are used to model the pulse propagation through thin transmission elements including tree leaves.

1.2.5. Pulse Reflection

The magnitude of the reflected pulse is dependant on the GFF at the surface and the surface geometry specific spectral reflectance model. The reflectance can be varied across material using the existing DIRSIG spatial-spectral (texture) mechanisms and higher-frequency surface deflections can be modeled using existing DIRSIG "bump mapping" approaches.

Reflection by a topographical ("hard") surface also can impose a speckle pattern onto the beam due to the surface roughness. This aspect of the model is a hybrid of a first principles and empirical approach and is currently undergoing further development.

1.2.6. Pulse Detection

As the beam propagates back to the receiver, it undergoes the same atmospheric effects that were previously described. The broadening of the pulse field due to turbulence results in a blur at the focal plane and the varying deflection of the beam from pulse to pulse causes the image to move about the focal plane. The receiver model uses the existing DIRSIG sensor model which allows the user to specify the detector size (pitch) and the optical focal length. Sensor noise can be added to the produced radiance/irradiance data products or modeled at run-time using user-supplied noise parameters.

The receiver model in its current implementation uses direct detection and is only sensitive to the intensity of the beam. Future consideration is being given to coherent detection modes.

2. Summary

The DIRSIG model could be used to model the Airborne LIDAR Pipeline Inspection System (ALPIS). The model is capable of modeling the specific tuning range, line width, line shape, pulse energy and field-of-view of the ALPIS instrument. Simulation of the ALPIS instrument would incorporate the suite beam propagation effects (wavelength specific absorption/transmission and backscatter) and surface effects (absorption/transmission, scattering/reflection, and speckle) described in this paper. The instrument could be simulated over a variety of scenes containing various elements including tree canopies and gas plumes.

The current implementation of the LIDAR modeling in the DIRSIG model is preliminary at this time and will need to be enhanced with a basic user interface to be used by the general user community. The addition of new modeling approaches for inelastic (Raman) scattering and coherent detection schemes may need to be addressed in order to model the ALPIS system more accurately.

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