SSA Modeling and Simulation with DIRSIG

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ABSTRACT

We describe and demonstrate a robust, physics-based modeling system to simulate time-varying ground and space-based observations of both LEO and GEO objects. With the DIRSIG radiometry engine at its core, our system exploits STK, adaptive optics modeling, and detector effects to produce high fidelity simulated images and radiometry. Key to generating quantitative simulations is our ability to attribute engineering-quality, faceted CAD models with reflective and emissive properties derived from laboratory measurements, including the spatial structure of such difficult materials as MLI. In addition to simulated video imagery, we will demonstrate a computational procedure implementing a "position-based dynamics" approach to "shrink wrap" MLI around space components.

1. INTRODUCTION

Lockheed Martin (LM) has collaborated for a number of years with the Rochester Institute of Technology (RIT) to develop an infrastructure for SSA phenomenology simulations using the DIRSIG modeling system. During this time, we have developed methods and procedures for simulating space objects in addition to building on a generalized spectro-polarimetric mathematical framework for characterizing RSO appearance as a function of object pose, illumination phase angle, wavelength, and polarization state. Key inputs to the modeling are high fidelity CAD models, accurate material properties, and illumination geometry from both direct and secondary sources. Techniques have been developed to produce polarimetric BRDF measurements at RIT, and were used to characterize solar panel materials provided by LM. We have also matured the ability to incorporate not only the surface BRDF, but introduce surface texture in the MLI wrapping technique to more accurately represent the wrinkles that invariably occur when installing MLI on spacecraft. These methods were then anchored against a GEO communication satellite in a test chamber at LM through an extensive campaign of high resolution imaging and lighting.

2. THE DIRSIG RADIOMETRIC ENGINE

The Digital Image and Remote Sensing Image Generation (DIRSIG) simulation model has been historically utilized to generate scene level data products for a variety of remote sensing modalities. The DIRSIG model is an image generation tool that utilizes a complex computational radiometry sub-system to predict absolute fluxes within a 3D scene description. The model uses [1 x 4] Stokes vector and [4 x 4] Mueller matrix calculus to propagate, reflect, and transmit fluxes within the simulated scene environment. The DIRSIG radiometry engine utilizes a single governing equation across all wavelength regions such that reflected and self-emitted contributions are always included unless explicitly disabled. The primary mechanism used to predict images is reverse ray-tracing where rays originate from the imaging detectors and are propagated into the scene. When a ray intersects the scene geometry, the associated radiometry solver is run to compute the surface leaving radiance. DIRSIG has a handful of radiometry solvers used for opaque surfaces and the most flexible is the generic radiometry solver. The generic radiometry solver computes the reflected radiance by sampling the hemisphere above the target. The distribution of these samples is based on the shape and magnitude of the associated BRDF. The nominal hemispherical sampling is cosine projected and has user-defined sampling parameters (e.g. total number of samples, etc.). The incident loads for those samples are determined by tracing higher generation rays which intersect other surfaces and trigger other instances of the radiometry solver. The fidelity of the sampling for higher generation bounces can be decreased using a bounce-dependent decay rate that modifies the sampling parameters. The total number of bounces that are tracked is also user controllable. The incident loads from the sampled hemisphere are numerically integrated using the geometry specific reflectance (BRDF) and the solid angle of the sample.

Although DIRSIG has been traditionally utilized to generate remotely sensed images of ground scenes, RIT, with funding and guidance from Lockheed Martin (LM), has over the past 7 years matured the model's capability to simulate radiometry maps of space-borne objects as viewed from a ground location, an air location, or another location in space. The model continues to rely on MODTRAN (either run in situ, or creates a look-up-table based atmospheric database input file prior to the main simulation) for incorporation of atmospheric contributions to the space object image generation process. The DIRSIG model has at least 10 different bi-directional reflectance distribution functions available to describe the spectral and directional nature of surface scattering properties. We are also currently in the process of incorporating support for ingesting and interpolating lab measured data that does not fit well to any existing BRDF models. Flexibility in material BRDF descriptions are key to radiometrically accurate modeling of space objects which often contain a variety of metal and thin-film surfaces not commonly found in ground based scene models. Additionally, the model supports a variety of file formats to describe target geometries such as Wavefront OBJ, MuSES TDF, and an openly documented DIRSIG specific file format that supports per facet level temperature attribution. Support for a variety of openly documented (non-proprietary) geometry descriptions provides a very flexible interface for simulation of most 3D CAD models of space objects. Incorporation of proprietary 3D geometry models is achieved typically by exporting to an open format, such as OBJ and providing that description to DIRSIG as input.

3. OPTICAL MEASUREMENTS

Lockheed Martin has a facility that measures multi-band BRDF of individual materials and small hardware models. The laboratory is specifically designed for optical measurements (e.g. large room, dark with low reflectance black walls in a clean room environment). The system is automated using in-house developed software and we have developed the post-processing code necessary to calibrate and ingest these lab measurements into our DIRIG based SSA modeling system.

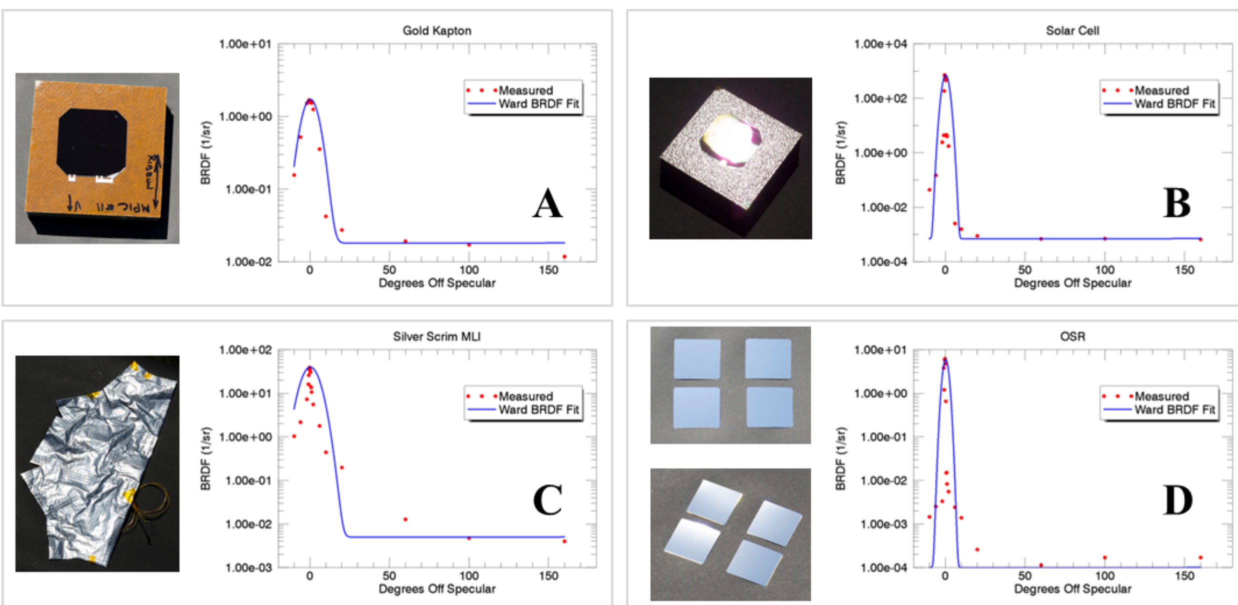

Figure 1. BRDF measurements and Ward BRDF model fit of four materials with associated photos. The photos in A and B are both of a solar cell on gold Kapton. The photo in A is the non-glinting reflection (off specular) and the photo in B is the glint orientation (at or near specular). C represents silver scrim MLI. The OSR in D is reflecting the blue sky. These materials are applied to the GEO COMM model shown later in the paper.

Each facet of the satellite model must be given a BRDF, and there are a number of ways to describe this to DIRSIG. Lambertian, where light reflects the same for any theta and phi; specularity, where light reflection varies only with theta, or the parameterized fit model, which is a mathematical estimation of BRDF shape, (i.e. Maxwell-Beard, Ward, etc.). Currently we use the parameterized fit model. This process starts with BRDF measurements in our optical measurement lab. We then adjust the fitting parameters for a given BRDF model (X and Y surface slope standard deviation, diffuse and specular weightings) to match the measured data, and then attribute each facet with the best fit BRDF. As illustrated in figure 1, some materials are not handled well by BRDF models. To overcome this, we are working toward using measurements directly without having to use a parameterized fit model.

4. CAD MODELS AND MLI WRAPPING

An accurate simulation of MLI blanket wrapping first depends on original engineering data. The CAD data serves as a basis from which all other simulation tasks will be based; this includes the creation of the collision mesh and the MLI mesh. The collision mesh is roughly the same shape and form as the CAD spline data. The exception is that 3D polygons make up the mesh; providing a barrier against which the MLI mesh will collide using position based dynamics (PBD). The MLI mesh, however, is a lower fidelity polygon mesh that fully envelopes the collision mesh that is going to be wrapped. Using the PBD solver in a series of stages and settings, the fidelity of the MLI mesh increases as it interacts with the collision mesh, until which point the overall flow of the mesh is continuous but tight against the collision object. The critical part of the process is to insure the mesh simulates a continuous blanket that wraps around corners neither too sharp nor too soft. Bend tolerances and rigidity of the simulation MLI are two key components of several parameters. The last stage introduces a small "micro" displacement to the overall MLI mesh. This displacement approximates small wrinkles that were not introduced into the initial wrap simulation. Adding this displacement breaks up large flat MLI areas that would otherwise be considered too smooth or uniform. The final spatially correct MLI mesh is then exported to OBJ format; allowing importation into DIRSIG for material assignment.

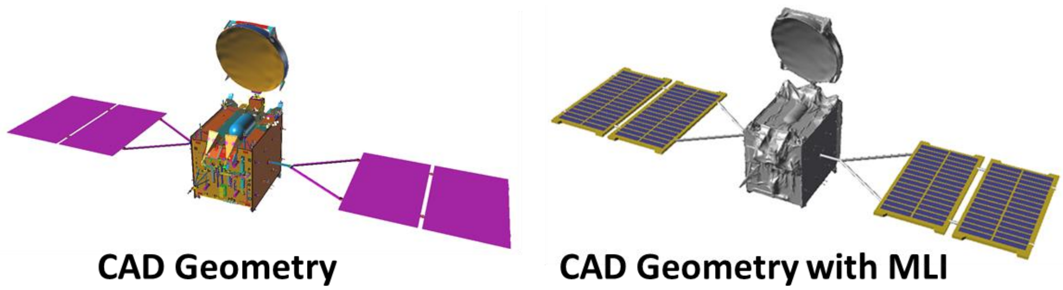

Figure 2. Graphic of engineering quality CAD model of a COMM satellite (left) and the same model after MLI blanket wrapping on the bus and COMM dish. The colors on the solar panels represent Gold Kapton and solar cell materials. The sides of the bus are OSR. There are no texture maps; the model is all faceted geometry.

5. COMPONENTS OF THE MODELING SYSTEM

5.1 CAD Modelling. There are several components to the modeling system that are essentially built around or run by DIRSIG. As mentioned above, CAD geometry and material measurements are key inputs. Another key component is the radiative transfer modeling that account for path radiance, atmospheric transmission, earth-shine etc. This component is handled by DIRSIG either with repeated Modtran runs during the simulation or via a lookup table prior to the image simulation. DIRSIG reads the input files containing the observer(s), target(s), time(s), etc. and sets up the appropriate Modtran calculations if desired.

5.2 Orbit geometry. Scenario and engagement geometry is handled with the STK to DIRSIG interface. This interface allows the user to ingest two line element (TLE) files for targets and observers and helps to visualize the simulation. The interface works for all DIRSIG imaging scenarios and handles ground to space, space to ground and space to space scenarios simultaneously. It can also generate the required files for component articulation (e.g. solar panels pointed toward sun and COMM dish pointed to downlink station). The interface is written in Java Script and HTML as an STK Plug-In and handles the coordinate conversion between STK and the DIRSIG scene coordinate system. The outputs are XML files directly ingested by the DIRSIG modeling system.

5.3 Telescope, AO, and detector. DIRSIG does have the ability to include optical and detector effects, but for more complex imaging scenarios, such as LEO satellite tracking with adaptive optics (AO), the user can apply telescope optics, detector, and AO effects in a post-processing step using radiance maps generated by DIRSIG. Figure 3 illustrates the major components, and how the user can use an off-line module to generate the required imagery or dataset.

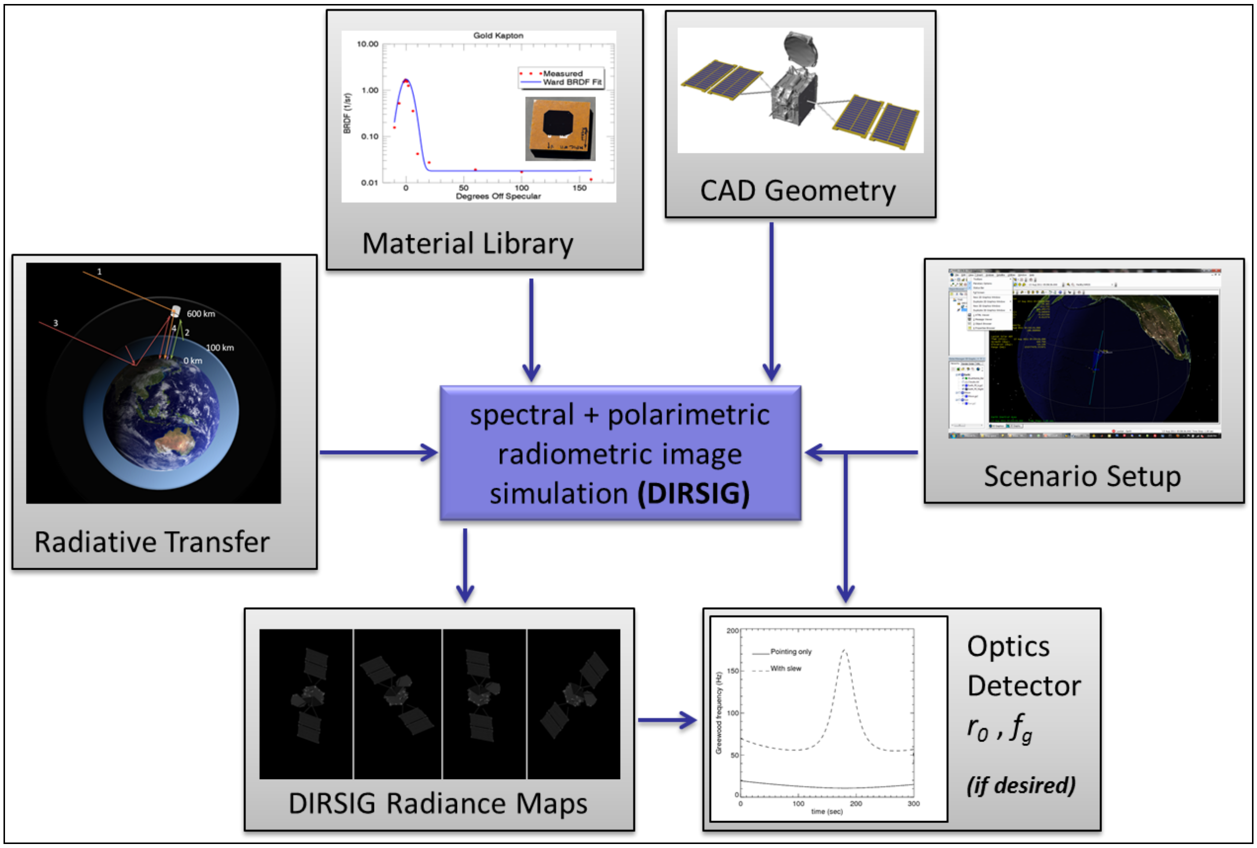

Figure 3. An overview of the modeling system illustrating the major components discussed in this paper.

In Fig. 4, we show the calculations needed to generate input files for the AO simulation. STK-generated telescope pointing angles as a function of time for the duration of the pass are key, since atmospheric seeing and transmission change as a function of pointing. From the time series of angles, we also calculate the telescope slew rate. For a wavefront sensor (WFS) reference, we use an off-line code to model photon flux from a 15 mJ/pulse, 5 kHz, 578 nm Rayleigh beacon as a function of elevation angle. The WFS is assumed to be range gated for a nominal 20 km range. We used a second off-line code to estimate the seeing and Greenwood frequency as a function of time, using a numerical model for the Mt Haleakala atmosphere. We modeled the deformable mirror (DM) and WFS geometry of the AEOS telescope AO systems and calculated the reconstructor matrix in yet another off-line code. Finally, we used simple IDL function to convert the time series of DIRSIG radiance maps to an equivalent series of photon flux maps using the AEOS aperture diameter along with the beam *f* number and pixel size at the VisIm camera.

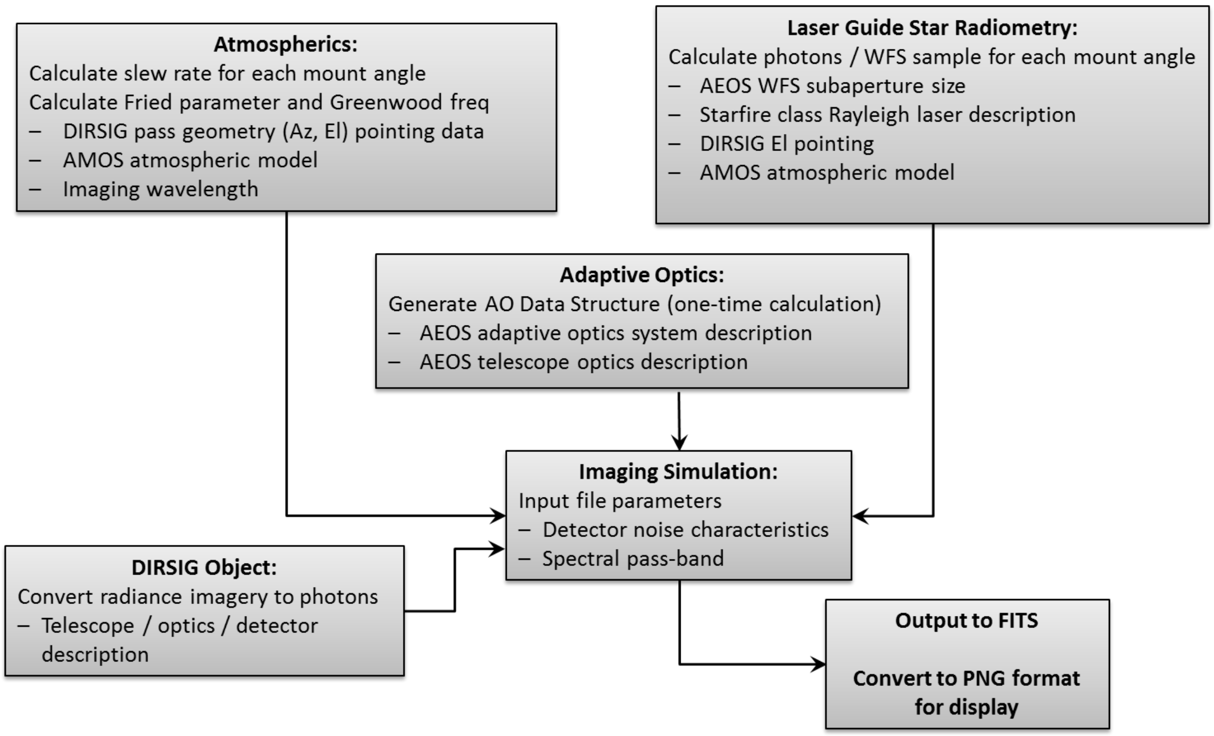

Figure 4. Diagram of the calculations required to create AO/imaging simulation inputs.

Finally, in Fig. 5, we provide additional detail for the AO / imaging simulation. The simulation doesn't model actual closed-loop control of the AO, but servo lag is modeled as wavefront measurement noise added to the WFS detector noise. The "loop bandwidth" can be changed during the pass to reflect the changing Greenwood frequency, which initially decreases due to the decreasing atmospheric path length, but then sharply increases near culmination due to the rapidly increasing slew rate. In our modeling, we attempted (while being realistic about the feedback available to an actual AO operator) to choose the bandwidth minimizing the sum of servo lag and wavefront measurement errors.

6. RESULTS

Simulation results are shown in this section to illustrate the radiometric quality of the simulations when using high fidelity models, BRDF measurements with rigorous ray tracing and radiative transport calculations. The Hubble Space Telescope was used for demonstration purposes for two reasons. One is that there are many photos of Hubble taken from the Space Shuttle during the servicing missions giving us the opportunity to make a qualitative comparison. Hubble has also been observed my Maui Space Surveillance System (MSSS) on more than one occasion, giving us the opportunity to make both a qualitative (images) and quantitative (intensity) comparisons.

For the simulation of the HST MSSS collection, we used actual collection parameters and the same HST model shown in figure 6. The pose of the satellite was estimated and we used models for the optics, detector and AO system consistent with the MSSS 3.6 meter at that time (circa 2007). We used the DIRSIG modeling system to generate the radiance maps and then ran the AO model as described above offline to produce the DIRSIG simulated *I* band imagery. The simulation produced 279 frames but only one is shown here.

There are important key differences limiting the fidelity of our simulated images. For example, we do not know the AO bandwidths used during the pass, and we do not simulate a separate tip-tilt control loop. Probably the biggest difference between our results and the actual observations is the use of a laser guide star (LGS) as a WFS reference. We chose to use an LGS reference to simplify modeling of the wavefront sensor error, which depends recursively on the AO compensation if the WFS reference is the satellite itself.

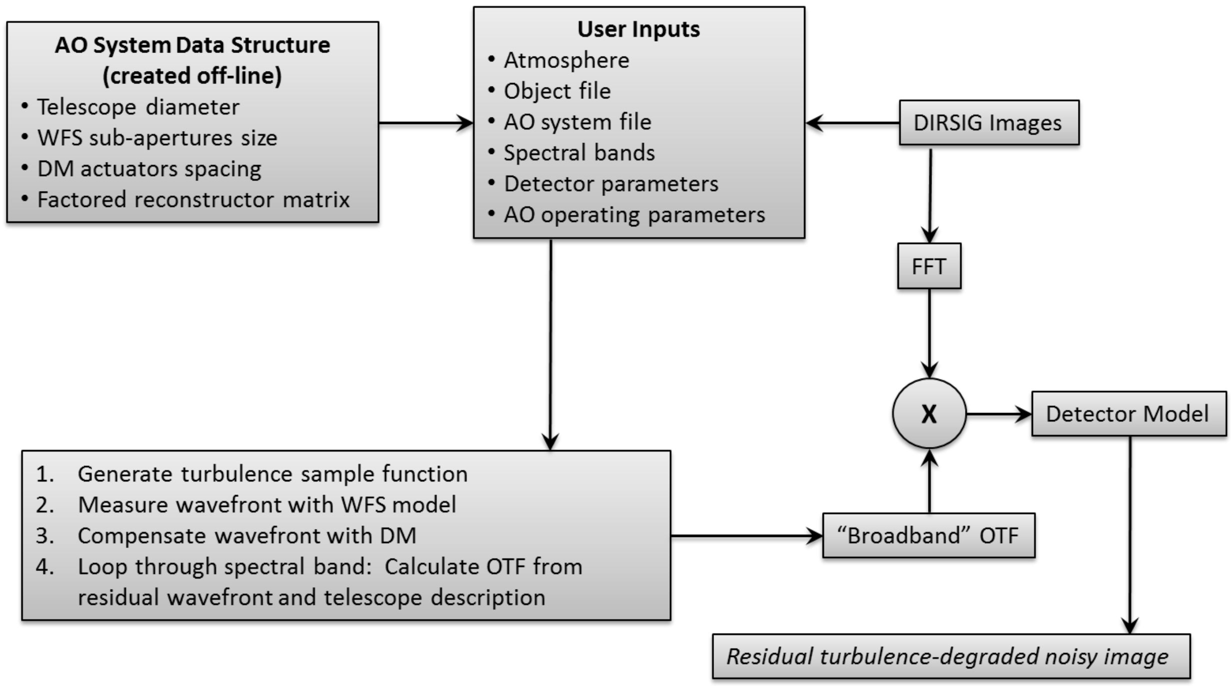

Figure 5. Diagram of the AO / imaging simulation inputs and calculations.

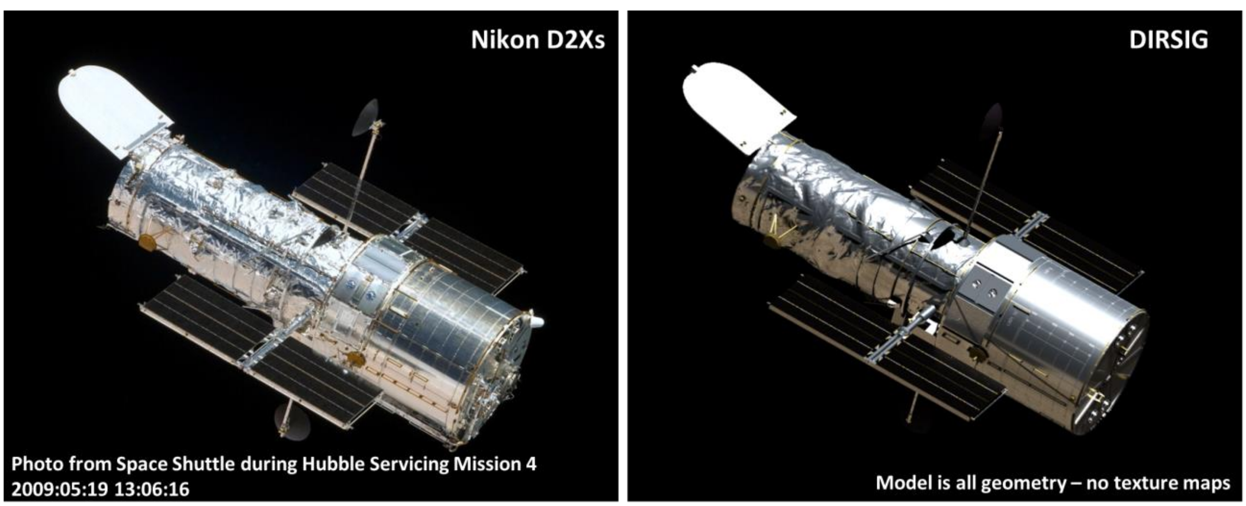

Figure 6. DIRSIG simulated color image of the Hubble Space Telescope compared to a photo taken from the Space Shuttle during the fourth Hubble Servicing Mission. There are no texture maps on the model. The MLI is all faceted geometry. Hubble photo from the NASA Hubble Servicing Mission 4 web site.

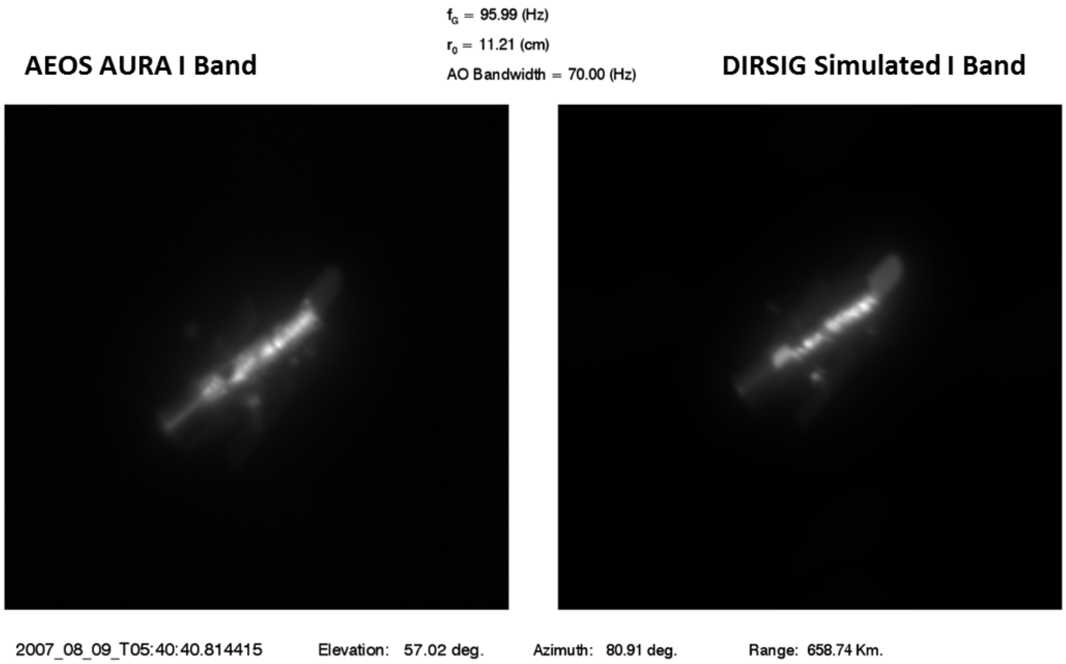

Figure 7. A comparison of one frame of the HST MSSS 3.6 meter AO simulation against the actual imagery.

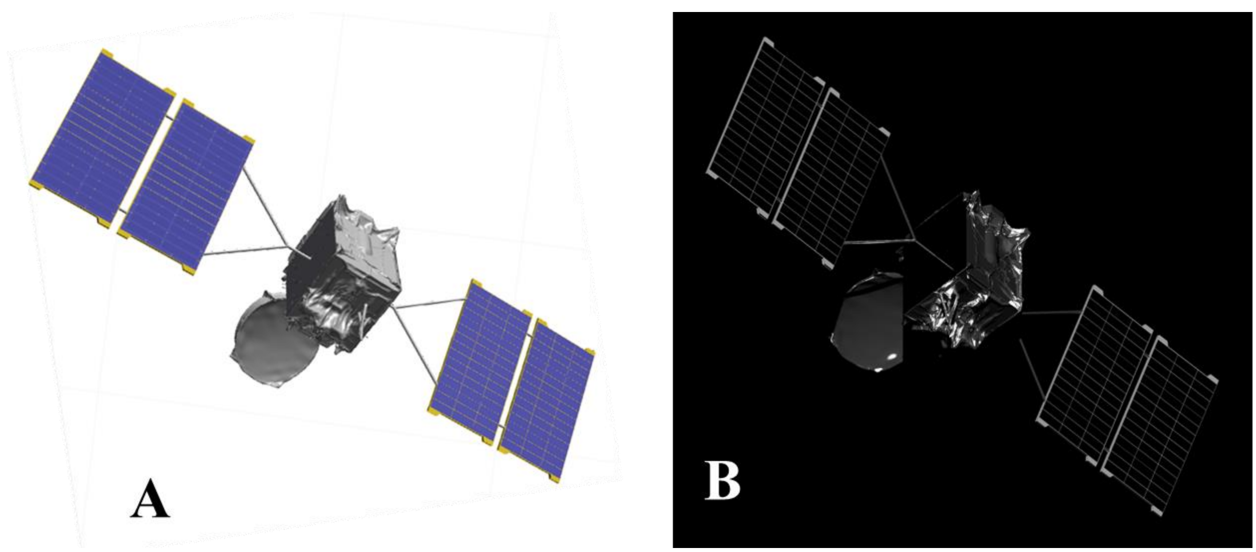

Figure 8. CAD geometry rendering showing a COMM satellite with MLI wrapping (A) and a DIRSIG radiometric image (B). The image in B has been stretched in a non-linear way to illustrate features. The glints would dominate in an un-stretched linear image. The solar illumination is from out of the page to the right. The solar panels are illuminated but are out of the specular lobe and part of the COMM dish is in the shadow of the bus.

7. CONCLUSION

We have demonstrated a physics-based modeling system to simulate ground and space-based observations of both LEO and GEO objects using the DIRSIG modeling system. The system exploits STK, Modtran, engineering-quality CAD models with reflective and emissive properties derived from laboratory measurements, including the spatial structure of such difficult materials as MLI.