INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps.

ProQuest Information and Learning
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
800-521-0600

UMI®
OCEAN SUN GLINT ALBEDO ESTIMATION FROM GEOSTATIONARY SATELLITE DATA

by

Kenneth Edward Kehoe

A Thesis Submitted to the Faculty of the
DEPARTMENT OF ATMOSPHERIC SCIENCES
In Partial Fulfillment of the Requirements
For the Degree of
MASTER OF SCIENCE
In the Graduate College
THE UNIVERSITY OF ARIZONA

2002
2002

STATEMENT BY AUTHOR

This thesis has been submitted in partial fulfillment of requirements for an advanced degree at The University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of quotation from or reproduction of this manuscript in whole or in part may be granted by the head of the major department of the Dean of the Graduate College when in his interests of scholarship. In all other instances, however, permission must be obtained from the author.

SIGNED: Kenneth Reho

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

Roger Davies
Professor of Atmospheric Sciences

Date 8/16/02
ACKNOWLEDGEMENTS

I would like to express my gratitude to Roger Daves for his knowledge and guidance throughout this project. I also would like to thank Mike Garay for his wonderful work with the GOES-10 system software and helpful insights.

This thesis was made possible with the help of many others, but I would like express thanks to Akos Horvath, Michael Barlage, Catherine Moroney, Iliana Genkova, and Paquita Zuidema for their wisdom and wonderful suggestions throughout my masters studies.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF ILLUSTRATIONS</td>
<td>5</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>6</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>7</td>
</tr>
<tr>
<td>Chapter 1 INTRODUCTION</td>
<td>8</td>
</tr>
<tr>
<td>1.1 What is Sun Glint</td>
<td>8</td>
</tr>
<tr>
<td>1.2 Data Source</td>
<td>13</td>
</tr>
<tr>
<td>1.3 Motivation</td>
<td>17</td>
</tr>
<tr>
<td>Chapter 2 THEORY AND PREVIOUS WORK</td>
<td>19</td>
</tr>
<tr>
<td>2.1 Smooth Surface Reflection</td>
<td>19</td>
</tr>
<tr>
<td>2.2 Past Work</td>
<td>22</td>
</tr>
<tr>
<td>Chapter 3 DATA AND TECHNIQUES</td>
<td>26</td>
</tr>
<tr>
<td>3.1 Converting Radiance Into Albedo</td>
<td>26</td>
</tr>
<tr>
<td>3.2 Sorting and Binning</td>
<td>28</td>
</tr>
<tr>
<td>Chapter 4 RESULTS</td>
<td>37</td>
</tr>
<tr>
<td>4.1 Model Estimates</td>
<td>37</td>
</tr>
<tr>
<td>4.2 Results</td>
<td>40</td>
</tr>
<tr>
<td>4.3 Errors</td>
<td>52</td>
</tr>
<tr>
<td>Chapter 5 DISCUSSION</td>
<td>56</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>62</td>
</tr>
</tbody>
</table>
**LIST OF ILLUSTRATIONS**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>False Color Image of Sunglint.</td>
<td>11</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Cross Section of Earth Including Sun Glint</td>
<td>14</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Fresnel Reflection as a Function of Incident Angle</td>
<td>21</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Illustration of Angular Definitions</td>
<td>24</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Illustration of Glint Mask</td>
<td>32</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Graph of Model Prediction of Spherical Albedos</td>
<td>39</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Graph of Plane Albedo of Ocean Surface</td>
<td>47</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Graph of Angular Bins Used</td>
<td>50</td>
</tr>
</tbody>
</table>
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1</td>
<td>GOES-10 Channel Values</td>
<td>17</td>
</tr>
<tr>
<td>Table 2</td>
<td>Spherical Albedos</td>
<td>44</td>
</tr>
</tbody>
</table>
ABSTRACT

Specular reflection off the ocean surface has been used to derive ocean wave heights and surface wind speeds, but the effect that waves have on ocean surface reflection of incident solar radiation is not fully understood. This study focussed on measuring how sun glint affects the Earth’s radiation budget, by including the previously ignored specularly reflecting region. Measurements collected by the GOES-10 geostationary satellite were used to produce an effective sun glint albedo to characterize the accuracy of omitting the glint region from the radiation budget. Estimations were made using the Cox/Munk statistical distribution model. These results varied slightly as a function of wind speed where a 6 m/s surface wind speed produced an effective clear sky sun glint albedo of 1.9%. This value was less than the satellite measured value of 2.2 +/- 0.1% for measurements in the cloud free region. Estimates including clouds show a smaller glitter effect of 1.7 +/- 0.1%. These values were then extrapolated to the full Earth value by including ocean fraction resulting in global values of 1.6 +/- 0.1% and 1.2 +/- 0.1% for clear sky and cloudy respectively.
Chapter 1  INTRODUCTION

1.1 What is Sun Glint

Oceans cover about three quarters of the Earth's surface, and play a substantial role in the radiation budget. For this reason, studying visible sunlight reflections off the ocean surface is essential to understanding the Earth's radiation balance. Previous studies have looked at ocean reflectance, but ignored the poorly understood region where the Sun's image is reflected (Gregg and Patt 1994). This provides an incomplete understanding of ocean surface reflection in the visible wavelengths. This study focuses on the troublesome area of sun glint, and its associated radiative properties.

Glint is a geometrical phenomenon occurring when a source (e.g. the Sun) and a detector (e.g. a satellite) are aligned in specular reflection producing a mirrored image of the source on the ocean surface. The region outside of this specular area is observed by diffuse reflection. Perfectly calm ocean conditions create a spherical reflective surface, similar to a convex mirror, with an image of the Sun appearing approximately 150 km in diameter (from
a geostationary orbit), and centered at the specular point of sun glint (SPG). However, water waves create a distorted surface forming a diffuse sun image with an approximate diameter of 3000 km. The relative area covered by glint varies according to surface conditions, which in turn correlate with wind speed. The glint image, also described as glitter, covers a vast portion of the ocean which may be comprised of many different surface conditions. The change in roughness from calm, flat water to choppy, wind-driven waves has the effect of converting the outer glint boundary from a crisp edge to irregular border (Figure 1).

The main purpose of this study was to quantify the contribution of sun glint to the Earth’s radiation budget. Past work with satellite data avoided sun glint areas by using methods that minimize contaminated pixels by avoiding the solar zenith angles which satisfy the requirements for glint to appear (Gregg and Patt 1994, Kosik and Paci 1981). This reduces the available data set, and can produce incorrect results for albedo calculations.
Deeper investigations into the specular reflections provided methods to passively study the ocean surface conditions. Cox and Munk (1954a, 1954b) elaborated on this idea by deriving surface wind speed by modeling properties of sun glint. Their method has been shown to produce promising results from aircraft measurements (Borrego 1993), as well as when translated to satellite remote sensing (O’Brien and Mitchell 1988, Breon 1993b).

There have been numerous other studies based on deriving wind speeds and ocean wave heights, but few studies have focused on the increase in reflected radiative energy associated with sun glint. For low Earth orbiting satellites, radiation pressure from reflections off the Earth can produce long term orbital perturbations. These effects are subtle, but measurable. A study by Vokrouhliky and Farinella (1995) suggested the excess radiation from glitter to play a substantial role in the “albedo effect” which may produce satellite orbit perturbation.
(Figure 1) False color image of sun glint at satellite noon. Clouds appear blue and the relative edge of glint is shown in dark yellow. The glitter area represents approximately 3000 km on each side.
A good way to understand why the relative area of glitter and intensity changes is to imagine the ocean surface as being made up of infinitesimally small mirrors. The shape of the wave, and where the reflection occurs determines the orientation of the mirror in relation to the incoming beam of light from the Sun. Waves in the central glint region use the "mirrors" on the tops of the waves (and valleys for high solar angles) to specularly reflect incoming light. Reflections farther from the SPG, shifts the reflections from the top to the side "mirrors". These reflections become increasingly more complicated farther from the SPG, and only allow part of the incoming radiation to reflect completely. As the waves move, the individual "mirrors" move along with them so that only a fraction of the water's surface is orientated correctly to reflect light into the satellite's detector. This creates bright spots intermixed with shadowed regions, and gives the water a sparkling appearance. The rest of the light is either reflected in a direction not correlated with the optical path of the satellite or absorbed by the water's surface.
With fine enough resolution, each individual wave could be seen, but from satellite distances the resolution does not allow single waves to be discerned. Instead, a satellite observation of the sun glint area is made up of an average of the contributions of many small surface waves. The intensities of neighboring values do not show a dramatic change in radiance values, but a gradual non-linear slope that increases to a maximum at the SPG. These slowly changing values do not define a sharp edge that outlines the affected area, thereby making it difficult to determine where the diffuse ocean reflection ends and specular reflection begins (Figure 2).

1.2 Data Source

Data from the western Geostationary Operational Environmental Satellite (GOES-10) stationed over the Pacific ocean has provided a platform to continuously study the vast ocean glitter. These observations of glint from a geostationary altitude (35,000 km) may differ from polar orbiting satellites (1500 km or less) by covering greater ocean area (McClain and Strong 1969). This is purely a consequence of the difference in satellite distance from the surface creating the illusion of a larger area. The flux values derived from
(Figure 2) An east-west cross section of the Earth at satellite noon through the glint affected area. Spikes are clouds not removed.
radiance measurements are not dependent on satellite orbital distance, and will produce the same flux densities.

GOES-10 has been involved in relatively few radiation studies since its launch, but the full disk coverage that the satellite provides is ideal for studying the large glitter features. The satellite orbits at 35,786 km over the equator at 135° west longitude, centrally located over the Pacific ocean. Operation started on May 13, 1997 (GOES online). It is maintained by the National Oceanic and Atmospheric Administration with a twin satellite, GOES-8, monitoring the eastern United States and Atlantic Ocean. These two satellites provide information about the vertical temperature and moisture profile of the atmosphere, surface and cloud top temperatures, and ozone distribution. By scanning almost a third of the Earth at one time, the array of five cameras sensitive at varying wavelengths (Table 1) simultaneously produce five different full disk images. One image requires 26 minutes to capture the full Earth starting with the most northern point and scanning west to east. This is short enough to neglect any small scale changes that may occur in the atmosphere or the ocean surface. The five full disk
images were archived at the University of Arizona every three daylight hours since April of 1998 producing a total of seven images per day. This study used the 0.65 μm visible channel for its radiance measurements while the 10.7 μm infrared (IR) channel was converted into effective temperatures to be used for cloud screening.

The visible detector-channels are not calibrated in orbit, but calibration coefficients were measured by ITT Aerospace/Communication Division before launch and are used in the data conversions. These values can be found in Weinreb and Han (2000). Background values are subtracted off the raw counts and the visible calibration coefficients for each of the eight detectors are used for the conversion. Although a detailed analysis of the degradation of the satellite’s detectors has not been officially published, a study by a fellow colleague (Garay, personal communication, 2002) found it to be within a few percent per year. This reduction in detector efficiency should have a minimal effect on the albedo estimations for the one year analyzed, and any change in the calibration coefficients are believed to be small.
Table 1: GOES-10 Channel Values

<table>
<thead>
<tr>
<th>Channel Number</th>
<th>Central Wavelength</th>
<th>Wavelength Range</th>
<th>Nadir Field of View</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.65 μm</td>
<td>0.55-0.75 μm</td>
<td>1 km</td>
</tr>
<tr>
<td>2</td>
<td>3.90 μm</td>
<td>3.80-4.00 μm</td>
<td>4 km</td>
</tr>
<tr>
<td>3</td>
<td>6.75 μm</td>
<td>6.50-7.00 μm</td>
<td>8 km</td>
</tr>
<tr>
<td>4</td>
<td>10.70 μm</td>
<td>10.20-11.2 μm</td>
<td>4 km</td>
</tr>
<tr>
<td>5</td>
<td>12.00 μm</td>
<td>11.50-12.50 μm</td>
<td>4 km</td>
</tr>
</tbody>
</table>

1.3 Motivation

The sun glint observed from satellites can provide an abundance of information about the ocean surface. Perhaps the greatest characteristic of glint is its large size. This combined with the fact that it will always be present somewhere on the ocean surface suggest careful consideration in omitting it from atmospheric models. This study's primary focus is to see what effects would ensue by not including glitter, and if the current predictions of specular reflection of a rough surface can be correctly modeled. This study focuses on describing sun glint through two simple methods, the plane albedo and spherical albedo. The next chapter describes some of the previous work dealing with sun glint including the simplest
possible expressions to predict the relationship between solar angle and intensity. Chapter 3 will explain how the measurements are transformed into albedo, and how this study chose to separate the smaller glint signal from diffuse ocean reflection. Finally, in Chapter 4, the albedos acquired through satellite measurements are compared to modeled predictions. The thesis concludes with a discussion of how well the surface characteristics are understood, and under what circumstances glint needs to be included into calculations of shortwave reflections off the surface of the Earth.
2.1 Smooth Surface Reflection

The Fresnel equations quantify the amount of incident radiation reflected when radiation strikes a smooth surface of a known index of refraction, and subsequently travels in the specular direction. The reflection coefficient, \( r \), depends on the orientation of the electric field vector, the incidence angle, \( \theta_i \), and the refraction angle, \( \theta_r \). If the electric field vector is parallel to the incident plane, the reflection coefficient is given by equation (1), and by equation (2) if the electric field vector is perpendicular to the incident plane (Jerlov 1976). If the incident angle is known, the refraction angle can be easily derived through Snell’s law, \( \sin \theta_i = \frac{n_2}{n_1} \sin \theta_r \). Where \( n_2 \) is the index of refraction of the medium the light is propagating into. The index of refraction for sea water was assumed to equal 1.33 (Jerlov 1976, Cogley 1979) referenced to a vacuum. This index of refraction can change as a function of both salinity and temperature, but the range of values are less than a percent different (Jerlov 1976) and not substantial point of error. The minimum reflection for the sum of the two reflection coefficients occurs at
normal incidence where \( \theta_i \) is equal to zero, and is on the order of 2\%. Most of the energy reflected occurs directly at the air-water interface, while a small portion penetrates and subsequently back scatters out. This small portion accounts for 0.005 to 0.02 of the total albedo of water (Katsaros et al. 1985). This suggests that the water surface is a highly non-Lambertian reflector, and is strongly variable depending on the incoming solar angle.

\[
r_{\parallel} = \left( \frac{\tan(\theta_i - \theta_r)}{\tan(\theta_i + \theta_r)} \right)^2
\]

\[
r_{\perp} = \left( \frac{\sin(\theta_i - \theta_r)}{\sin(\theta_i + \theta_r)} \right)^2
\]

Figure 3 plots the reflections as a function of angle of incidence for light polarized parallel (\( \parallel \)) and perpendicular (\( \perp \)) to the plane of incidence. This shows how the reflection largely responds to incident angles greater than 30°.

Ocean surfaces are never perfectly smooth, but are composed of multiple waves of differing frequencies. Waves change the smooth surface and the specular reflections, creating a series of complicated reflections. This can
Graph of specular reflection off a smooth salt water surface as predicted by the Fresnel equations.
have the affect to reduce the glitter reflectance. These rough conditions are formed by winds and produce white caps and sea foam which have a higher albedo. The amount of sea composed of white caps and sea foam is small, and therefore, even with much higher reflections, is presumed to not show a significant contribution to regular ocean reflectance.

2.2 Past Work

Accurate estimations of albedos are important in understanding the Earth’s radiation budget, for they play a major role in forecasting, and climate modeling. These albedos usually cannot be measured directly, but are calculated from measurements of radiances. A standard technique in deriving albedos consists of creating an angular distribution model (ADM), which is necessary when using relatively few independent angular measurements. These models introduce anisotropy factors which model the effects of varying solar ($\theta_o$), view ($\theta$), and azimuth ($\phi$) angles (Figure 4), and can produce the greatest amount of uncertainty into estimations of albedos. Therefore, this analysis chose a simpler method adapted from Taylor and Stowe (1984) of sampling as many angles as possible and sorting into angular
bins (SAB), to reduce the need to make modeling assumptions. Taylor and Stowe also studied the reflectance patterns for water over the full range of solar zenith angles from NIMBUS-7 ERB data, for the purpose of creating ADM. They showed a general increase in the plane albedo as the solar angle became more oblique.

Prakash et al. (1994) derived an algorithm for precisely locating the central glitter point from geometrical considerations of the curvature of the Earth. They showed predictability in calculation of the specular point of sun glint through daily and seasonal cycles of the Earth. However, the relative size and shape of the glitter pattern was not predictable because it depends on current sea surface conditions. Generally, the glitter pattern is circular in shape, but closer inspection of the radiances reveal internal structure and jagged edges dependent on the local conditions. A reduction in wind speed, oil slicks, or material floating on the surface could cause a decrease in wave activity, which would then alter the intensity of specular reflection to the satellite, and produce what is referred to as a dark patch. McClain and Strong (1969) used these dark patches to further refine the wind speed retrievals originally
Figure 4) Definition of angles
modeled by Cox and Munk. This natural variability in surface conditions produces fluctuations in size, radiance intensity, and general appearance of the glint area.
3.1 Converting Radiance Into Albedo

The satellite detectors on GOES-10 measure the number of counts of photons, and convert these values into radiances for the pixel area on the surface. These values are not a true representation of the flux reflected off the Earth when the scanner is focused off-nadir. As the imager scans toward the limb of the Earth, the surface area increases with the same angular range of view. This can be accounted for by dividing by the $\cos(\theta_o)$ (The following equations are derived from Lenoble 1993). Therefore all radiance values were first normalized by

$$L = \frac{L_\lambda(\theta, \theta_o, \phi)}{\mu_o} \left( \frac{r}{r_o} \right)^2,$$

where $r/r_o$ is the ratio of current Earth-Sun distance over the annual average, and $\mu_o = \cos(\theta_o)$ (Figure 4). The range of values measured by the detector can be more clearly understood by comparing them to the incoming radiation. For a specified incident solar angle, a ratio, called bidirectional reflectance (BRF) is created to describe how the surface reflects light,
The BRF is a measure of how the surface reflects when compared to a Lambertian reflector for a specific incident angle. In this case, the incident radiation, $F_0$, can be assumed to be a constant striking the top of atmosphere,

$$F_0 = \frac{\pi}{\kappa}$$  \hspace{1cm} (5)

with $\kappa=0.00198808 \text{ (m}^2 \text{ sr} \text{ m})/\text{W}$ calculated for the visible channel on GOES-10, and integrated over the response function of the detector (Weinreb and Han). This produces a solar constant of around 1580.2 W/(m$^2$ μm). This value was derived from the solar irradiance tables of Neckle and Labs (1984).

Replacing $F_0$ in equation (4) with equation (5), the GOES-10 BRF can be calculated as

$$\text{BRF} = \kappa L$$  \hspace{1cm} (6)

The total reflected flux is then obtained by an integral over both view and azimuthal directions of the BRF in equation (6) to form the plane albedo,

$$\rho(\theta_0) = \frac{\kappa}{\pi} \int_0^{2\pi} \int_0^1 (L) \mu d\mu d\phi ,$$  \hspace{1cm} (7)
with \( \mu = \cos(\theta) \), and \( \pi \) is introduced for normalization purposes. Equation (7) represents the plane albedo, or reflectance, for a specific solar angle, but this must be integrated over all solar angles to find the true spherical albedo,

\[
A = \frac{2K}{\pi} \int_0^{2\pi} \int_0^1 (L) \mu \mu_n d\mu d\mu_n d\phi
\]  

(8)

3.2 Sorting and Binning

The values of specularly reflected radiances retrieved by the satellite within the glint region are mixed with diffuse values of ocean reflectance. Some of the specularly reflected light originated by means of diffuse sources, but this is most likely a second order contribution. Therefore the glitter source is understood to be comprised of almost entirely direct solar radiation.

Separating glint from the diffuse reflection required finding a background state to which the specular reflection was added. Because the non-specular reflections could not be quantified well enough to simply subtract, two independent sets of measurements were maintained. The first set contained all ocean pixels, including those in the glint region. A second set excluded the pixels containing any specular reflection, creating the background ocean
values. The difference between the two resulted in extra contribution to total ocean reflection from sun glint.

As previously mentioned the SAB method was used in acquiring radiance values over the full range of angles. This was accomplished by sorting the top of atmosphere radiance measurements into corresponding angular intervals (bins) of view, solar, and relative azimuth angle for each pixel over the full hemisphere. The view and solar values were placed into bins equal in cosine space of 0.025 and 0.05 respectively. Each relative azimuth bin consisted of 10°, spanning all 360°, for a total of 28,800 total bins. A single image would only contribute to a small portion of these bins depending on time of day as well as year, but the bins were gradually filled throughout one full year. The numerous values in each bin were averaged to eliminate natural variability from constantly changing sea conditions.

A geostationary orbit allows the satellite to concentrate on one fixed position constantly, but limits the variety in viewing angles. The SAB method requires a full range of angles in the measurements for complete coverage.
This was accomplished by assuming the general characteristics of water reflection did not depend on temperature or location. In order to maximize the number of filled angular bins, a single daily complement of seven images was analyzed. The complements were spaced one week apart throughout one year. The images were generally separated by three hours, although a few days included images differing by only 2 hours. This allowed the natural North-South precession of the Sun to vary the solar angles at the surface. Initial investigations showed small shifts in the view, azimuth, and solar zenith angles for a single pixel from one day to the next, whereas 6-7 days showed enough deviation to contribute to previously empty bins.

Calculating the albedo requires data from the full range of angles, but a geostationary satellite produces fewer measurements at large view angles. Because this method used the difference between two sets of measurements, a large portion of the bins do not contain glitter. This resulted in negligible values for the bins at off-forward scattering azimuthal angles. Multiple measurements throughout the year produce a large number of bins where direct measurements of both glint-free and glint-included are possible. This
was a result of the shifting specular region as the year progressed. Values were obtained around the outer edge of the glint, but no pixels located near the SPG are able to be seen without glitter contamination.

Critical to this study was the identification of glitter contaminated pixels. This was not a trivial task to accomplish with simple analysis of the direct radiance values. Because no defining outer edge of the glint area exists, an algorithm could not be created to ensure minimal infiltration of specularly reflected pixels. Therefore a geometrical mask was used to block out a circular region on the globe where pixels had a high probability of containing glitter (Figure 5). This was done by defining a cone centered on the specular reflection direction described by equation (9) (Diner et al. 1999).

\[
\cos \zeta = uu_o + (1 - u^2)^{1/2} (1 - u_o^2)^{1/2} \cos \phi
\]  

\text{note: } u_o = \cos \theta_o, u = \cos (180-\theta)

\cos \zeta \text{ is the dot product between the specular vector reflecting off the SPG and the corresponding vector between observed pixel and detector. If } \zeta \text{ was}
(Figure 5) Illustration of glint mask
less than $37^\circ$, the pixel was considered contaminated and not used in the glint free case.

Also critical to this study was the identification of cloud contaminated pixels. Initially a method was attempted to use a visible cloud detection algorithm by measuring the differences between neighboring pixels as an edge detection scheme. This method worked well for high sun angle images, even in the sun glint region, but removed important glitter pixels when the solar angle became more oblique and Fresnel reflection became as bright as the surrounding clouds. Difficulty was also discovered using this procedure because it required extensive computer memory for the large files produced by GOES-10. By using the IR channel-4 image converted into effective temperatures, both difficulties were overcome. The IR full disk scan size is sixteen times smaller than the visible, hence reducing the amount of memory required for cloud screening. Because the channel 4 band is centered at 10.7 $\mu$m emission, there is no glitter reflection off the ocean. This allowed the detection of clouds at the limb even when Fresnel reflections approached 90%. Originally, a threshold sea surface temperature was chosen to discern
between clouds and ocean surface, but the naturally varying Pacific surface temperatures made it difficult to correctly choose an effective threshold. A large percentage of the clouds obscuring the ocean surface were low cumulus and stratus, and emitted at temperatures only a few degrees lower than the surface. A second scheme found the threshold temperatures by retaining the warmest sea surface temperatures for each scan line and subtracting 2.0 K. The 2.0 K was found through several studies of temperatures to provide the most water-only pixels while removing a majority of the clouds. Some small scale cloud structures were not detected by this cloud removal algorithm, but were believed to not pose a major problem when averaged with the large number of other pixels from the many other images throughout the year.

GOES-10 is an operational satellite primarily used for forecasting. This made it difficult to compare IR and visible images for the purpose of cloud clearing. The visible channel provides extra information to produce latitude and longitude coordinates, where coordinate information is not provided for the other four channels. It was also discovered that random lines in the IR image would occasionally not be received by the ground receiver, where the
next line in the image would take its place. This was not a major issue for creating images, but became a problem when matching pixels later in the image. This issue was resolved with an algorithm to locate missing lines and flag the missing line of data. Even though the algorithm works quite well there were some cases where pixel matching was imperfect. A study to test the effect of this possible cloud contamination revealed little to no effect on the overall averaged values, most likely due to the immense number of pixels averaged together.

The SPG only appears in the GOES-10 images between +/- 20° latitude. Therefore a latitudinal restriction was place on the data set to only analyze the pixels between +/- 45° latitude to eliminate any sea ice or difficulties distinguishing clear from cloudy pixels. This restriction made it possible to use a simpler cloud identifying algorithm while still focussing on glitter. The majority of the images are focused on the Pacific Ocean, but a substantial part of North America and the western coast of South America were included. This study’s focus on water albedo required the removal of the large land mass. Although using the greatest amount of water area was a priority, the
large number of pixels taken each three hour interval meant it was possible to reject a reasonable number of water values to ensure no land was included. Therefore a cutoff was established at $85.5^\circ$ west to remove South America. A circle was created to remove North and Central America centered at $65^\circ$ north and $80^\circ$ west with a radius of $53^\circ$. This created a boundary where no values were used if they resided within the circle or east of the cutoff.

The large continental land masses are well filtered, but smaller islands are still included into the radiance measurement. Due to the copious amount of ocean pixels analyzed, the influence of small land masses are minimal, and do not pose a noticeable difference in the albedo calculations.
Chapter 4 RESULTS

4.1 Model Estimates

Most studies of sun glint have focused on obtaining wind speeds from the specular reflections. A statistical representation of the wave slopes can be created by assuming a Gaussian distribution of the slopes of the water waves, where the size and shape of the wave is highly dependent on the surface wind speed. By measuring the reflectance of a known location, an estimate of the necessary wind speed is calculated to produce the sea conditions. This is the basic idea Cox and Munk (1954a) used to derive their inverse method of determining sea surface wind speed by measuring the reflectance from the sea surface in the sun glint region. A model created by Breon (1993a) derived from the original Cox/Munk technique was used in this study to estimate the albedo of a roughened water surface with varying wind speeds. Figure 6 shows how the albedo of the water surface changes as a function of wind speed. The low wind values are not truly represented because the model does not have the adequate resolution at small winds, and large winds would produce white caps and sea foam. These white caps have a much
higher reflection (Nicolas et al 2001) and are not included in the model. Working within the model's wind speed range, a change of ~8\% in albedo between the largest and smallest value is possible depending on the corresponding wind speed. The maximum glitter albedo of 1.93\% occurs with a surface wind speed of 5 m/s. This is slightly less than the yearly average ocean wind speed of 6 to 7 m/s. The difference in albedo as a function of wind appears to be minor, so that an estimate of 1.9\% is reasonable for the range of typical ocean surface wind speeds.

Initial investigations of the model revealed uncharacteristically low values at oblique solar angles of 80° or more where the Fresnel equations predicted the most intense reflections. This was first assumed to be a consequence of the initial intentions of the Cox/Munk distribution model, which was originally developed for higher solar angles. Also, at grazing incident angles, shadowing effects may become important, and these are not included in the model. Analysis of the satellite data, however, showed a similar trend of decreasing reflections at grazing solar angles, suggesting the model is realistic even at very large solar zenith angles.
(Figure 6) Graph of spherical albedos as a function of wind speed as calculated by the Cox/Munk (1954b) model.
4.2 Results

One full year of data containing a total of 350 images at varying times of the day was processed, producing a data set structured by date, time of day, and the three geometrical angles. This was further stratified into four different cases: all pixels, all pixels except the glint region, cloud-free ocean, and cloud-free plus glint-free ocean values. The two cloud covered data sets were intended to be used as a check against the full Earth albedo. The values of each pixel were normalized to overhead sun and placed in the appropriate bins. Initial intentions included a study of the glint albedo as a function of season, but the angular coverage was not as evenly distributed as previously expected. Therefore any albedo calculations must use the full year complement of processed images. To increase the coverage, angular symmetry about the azimuthal plane was assumed. This produced an increase of about 10% greater coverage, resulting in 60% bins filled for the cloudy cases, and 40% for the cloud free cases (The cloud-free case is shown in Figure 8). To ensure good sampling, these values were also screened by
using only bins containing more than 1000 different samples. This reduced the likelihood of inadequate statistics producing an outlier.

A comparison between the with-glint and without-glint analysis revealed a number of empty bins in the case without-glint. These bins corresponded with bins in the with-glint case which contained measurements. The purely diffuse ocean radiance values for the glint-free cases were inferred with a linear interpolation between values on either side of the affected region. For overhead sun, endpoint values could not be attained for both sides to make an interpolation, so the last measured values were taken to be a constant through the glitter region. This provided the diffuse ocean surface values and made it possible for the subsequent subtraction of radiance values. However, this method still left a large number of bins unfilled.

Specular reflection, the focus of this study, only required filled bins $\pm 20^\circ$ off forward scattering in the azimuthal direction for low sun cases. At large solar angles, the specular reflections were predominantly only in the forward direction, and gradually increased the range of affected azimuthal angles as
the solar zenith angle tended to zero. This suggested a large number of bins would not be necessary for this study’s focus on specular reflection. The limited azimuthal range of glint-affected pixels was seen in the radiance values, as well as the comparison of filled bins to bins where glint was expected. Even though the full data set showed a low number of samples, the main area of focus was well covered.

Accounting for missing bins in the spherical integration was accomplished through normalizing the incident radiation. To produce the fully integrated albedo, the partial albedo was first obtained by summing all filled bins. Evaluating equation (8) required a transformation where the integrals were replaced by summations producing equation (10). A partial albedo provided a low estimate which could then be converted to the true albedo by accounting for the reduced incident radiation.

\[
A = \frac{2\kappa}{\pi} \sum_{0}^{20} \sum_{0}^{40} \sum_{0}^{36} (L)\mu\mu_0\Delta\phi\Delta\mu\Delta\mu_0
\]

The amount of emphasis placed on the normalization could be reduced by filling in empty bins. Initial investigations used a third degree polynomial
spline routine from the IDL software package with tension restrictions. When ample number of samples existed the routine worked well, but with large data gaps the spline produced mathematical interpolations with large oscillations. This prompted the use of a simple linear interpolation between two corresponding values. Due to the large number of bins in both view and solar angles, the curves remained smooth and differences between the two methods proved to be small. Therefore all interpolations were carried out with the simpler method. This greatly increased the number of usable bins, and was improved upon by performing the interpolation as a function of view angle, followed by a second pass as a function of solar angle. This method was also used in the opposite manner interpolating as a function of solar angle first then view. The end result produced close to full coverage in the region where glint was expected, and above 80% over all. Table 2 shows the ensuing results with all three methods. Attempts were made to also use the azimuthal component, but sparser sampling and less consistent values produced unreasonable results.
Table 2: Spherical Albedos

<table>
<thead>
<tr>
<th></th>
<th>Earth $^\pm$ 45° Lat. (%)</th>
<th>Clear Sky Ocean $^\pm$ 45° Lat. (%)</th>
<th>Clear Sky Sun Glint (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Data</td>
<td>24.6 $^\pm$ 0.1</td>
<td>13.4 $^\pm$ 0.1</td>
<td>2.2 $^\pm$ 0.1</td>
</tr>
<tr>
<td>First View then</td>
<td>25.9 $^\pm$ 0.1</td>
<td>14.7 $^\pm$ 0.1</td>
<td>2.2 $^\pm$ 0.1</td>
</tr>
<tr>
<td>Solar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First Solar then</td>
<td>26.0 $^\pm$ 0.1</td>
<td>14.3 $^\pm$ 0.1</td>
<td>2.3 $^\pm$ 0.1</td>
</tr>
<tr>
<td>View</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The Earth is not an aqueous planet, but has on its surface continents covering about a quarter of the spherical surface. A first guess based on present ocean coverage would produce an increase in spherical ocean albedo of 1.6% by including sun glint. This number came from analysis of a current land mask which produce an ocean coverage estimate of 0.73. This estimate was attained by assuming the Sun at equinox, and predicting the change in reflected energy weighted by incident angle.

Figure 7 plots the plane albedo versus the center value of each solar zenith angle bin. The spacing between bins is not consistent in degrees because the bins were chosen to be equal in cosine space. This method of bin sizing focused on the larger solar angles where the Fresnel equations predicted more
of a dependence (Figure 3). The general increase in albedo as the solar angle became more oblique was noted in both ocean cases, but pure sun glint albedo did not show the predicted increase in albedo with larger solar angles. An increase in incident angle on the ocean surface does show an increase in the plane albedo, but the glint portion remained constant up to 60° with a peak at 70°. Unexpectedly, the glint reflectance then decreased reaching minimal reflectance by 85°. Using the two interpolation methods described previously, similar results were found for all three graphs.

This very small reflectance at large solar zenith angles could be explained for both the model and satellite data by understanding the shape of the water wave. First, the model uses a Gaussian distribution to describe the general shape of the wave. This turns out to reproduce the average ocean wave shape well. For overhead sun, the crests and valleys are orientated correctly to reflect light vertically back to the source. The total water valley area used for vertically reflecting light entails a substantial portion of the total surface area, and has almost no azimuthal dependence. Even though the surface area reflecting back to the source is large, the reflectance is at a minimum and
reduces the total reflected flux. As the solar zenith angle increases, the
reflectance increases, but correctly orientated wave surface area decreases.
These two processes work together to allow the total plane albedo to increase
only slightly, reaching a maximum around 70°. At this point, the amount of
wave surface area used to specularly reflect primarily in the forward direction
decreases faster than the increase in reflection coefficient. By 85° only the
very crest of the wave is specularly reflecting, but the tiny area only allows a
small amount to reflect. The same process can be used to describe real ocean
reflections, but wave shape is not exactly Gaussian. Analysis of Figure 7
suggests the crest area to be even smaller, for the minimal reflectance is
reached by 85°.

Both the ocean outlier at 88° and the decrease in plane albedo of glint at
oblique angles suggested low sampling. Figure 8 shows the number of bins
filled out of a possible 1440 for each solar angle bin. This showed an even
distribution of angular bins even at large angles, thereby suggesting the
decrease in plane albedo at large solar angles is accurate and matched the
prediction of the model.
(Figure 7) Plane albedo of ocean surface as a function of solar zenith angle. All data points are raw data only.
The ocean surface is influenced by waves of different amplitudes and
frequencies. Most of the surface activity that causes the difference between
regular Fresnel reflections and the diffuse reflection is caused by smaller
ocean waves. A second component to the undulation of the surface comes
from ocean swells, which have a much longer wavelength, on the order of
kilometers, and a greater amplitude. When a swell is present the average
ocean surface plane tips causing the location on the wave where specular
reflection occurs to shift up or down the wave slope. This could produce a
localized region of more intense reflection, or conversely a dark spot. For
this to occur, the orientation of the swell would need to correctly align with
the forward scattering direction to change the incident angle on the wave
"mirror". If the swell is not correctly aligned, the wave would only change
its position to sea level, but not its wave slope direction. These swells may be
detectable in the imagery as dark spots, but do not produce any net change in
albedo as a whole. Any change the swells cause will be small since Figure 7
shows how little the plane albedo changes as a function of solar zenith angle.
The most noticeable change occurs when the incident angle is shifted from a lower reflectance to the maximum reflectance region centered around 70°.

The Earth albedo is lower than other estimations because of the latitudinal restrictions, and the primarily focus on the Pacific Ocean. The ocean typically appears darker than land, and eliminating the high latitude regions where highly reflecting snow or ice covered areas have a large contribution, reduces the observed reflection. The value of 24.6% for the Earth falls within expected values, and provides reassurance in the sun glint estimations. Conversely, the ocean albedo is not affected by the latitudinal restrictions. Even though the ocean reflectance is a function of latitude, the spherical albedo represents an integration over the changing solar angles, so the latitudinal restrictions are not a factor. The spherical ocean albedo was higher than expected, but this value contains the glint region as well.

The model used in this study does not contain clouds, and the data used to produce the glitter albedo was screened for clouds before using the values. This results in an estimation of sun glint albedo on a cloud free planet, or the
(Figure 8) The number of bins where a measurement was possible vs. solar zenith angle. Model curve represents number of bins where non-zero values were expected.
maximum extra reflection off the ocean surface. In fact, a vast majority of the ocean surface is covered by clouds reducing the incident light upon the surface. These clouds fluctuate thickness and position over the surface. This complicates what effect glitter can have on the radiation budget. If the region over the glint area were mainly covered with clouds, only a small fraction of incident radiation could be specularly reflected, possibly small enough to be neglected. The placement of the clouds within the glint region dictates how much of an affect the glitter will have. By only covering the outer edge and leaving the central (more intensely reflecting) region, the clouds would produce only a small change to the spherical albedo. It is a reasonable assumption that the amount of cloud cover outside the geometrical glint region corresponds to the amount of cloud coverage over the ocean surface within the glint region. Therefore, the same subtraction process was performed to create a sun glint albedo with the clouds included. By subtracting the glint-free case containing clouds from the full cloudy case before the integration, an estimation for glint albedo of 1.7% was obtained as it would be influenced by clouds. The cloudy glint albedo was then adjusted
for the ocean fraction of the Earth weighting by incident angle, resulting in an albedo of 1.2%.

4.3 Errors

In deriving these albedos a number of assumptions had to be made that affect the understanding of the results. In order to view the ocean’s surface at all possible angles, it was assumed that any clear ocean pixel was analogous to a completely separate ocean pixel with the same viewing geometry. The real difference may be a physical distance or a period of time. This results in values that change because of fluctuating local winds, causing the surface to increase or decrease wave activity. This may produce an instance where glint was believed to appear, but did not have the current conditions for specular reflection to the satellite. Therefore, these results are an average sun glint albedo over the Pacific Ocean for one year.

To make the subtraction of binned data without-glint from data containing glint, the missing data were filled in with a linear assumption. Without direct measurements this method could not be disproven. Most gaps requiring the
linear interpolation were small and substituting a more complicated routine would not have made a drastic change to the calculated albedos.

The spline function used to fill in missing data, as opposed to only using raw data, was intended to reduce the emphasis placed on normalizing the integration, and maximizing the amount of information pulled from the data set. The original raw data represented a small sample of the full range of angles, and could have been further filled in by reducing the difference between days analyzed. Due to the computational time limitations, only one day out of a week was chosen. Unfortunately doubling the number of analyzed days would not have doubled the number of filled bins. This was due to the limitations of a geostationary satellite. Processing all 365 days in a year would still leave angular gaps, resulting in less than full coverage. Results from this study suggested the maximum specular reflection does not occur at the largest solar angles as was predicted by the initial study of the Fresnel reflection off a smooth water surface. The two methods used to fill in breaks in the analysis showed similar results suggesting greater coverage would not show a significant increase in glitter albedos. This leads to the
belief that the present sun glint albedo may represent a low value, and with
the capability of resolving more angles the glitter albedo would increase only
slightly.

Along with the direct radiance measurements normalized to overhead sun,
the squares of the values were retained for producing the standard deviation
(SD), and standard error of the mean (SEM). A large SD for the ocean with-
clouds data set was discovered, which was an expected result for the intense
difference in ocean versus cloud reflectance. The clear-sky case provided a
SD reduced by a factor of six, which was taken to show an effective cloud
clearing algorithm. The SEM was used to check upper and lower limits of
the albedo calculations, and produced a range of values varying less than 5%
for all four sets of measurements. Due to the great number of pixels averaged
for each bin, a 5% error for each angle bin is within the expected range of this
technique, and primarily a result of using one full year of images where the
surface conditions could vary throughout the year. By using a large data set
the random errors due to natural variability have been greatly reduced. The
large number of bins used in the final albedo calculations reduced the errors
to +/- 0.1 percent albedo. However, there may be errors due to sampling effects setting the limits of uncertainty. When the albedo estimates are extrapolated to the globe, an assumption is made about the statistical similarity of clouds over all ocean surfaces. There may be differences in cloud statistical distributions over other non-Pacific oceans, but this should only produce small deviations from the global influence predicted in this paper.

These small range of values also suggested the integrated solar reflection off the water’s surface has a small dependence on current conditions even with the glitter region changing size and intensity. A decrease in wave activity will reduce the relative size of the glint region, but an increase in intensity compensates for the smaller reflecting area. This result was predicted by the small range in values as a function of wind speed from the Cox/Munk distribution. The model does suggest a big change in albedo associated with large wind speeds, but these greater winds are usually accompanied with storms of sufficient cloud cover, reducing direct surface reflections.
Chapter 5  DISCUSSION

Through a simple method of sorting into angular bins, and geometrical considerations of where glint was to appear, the average ocean sun glint albedo was calculated. The results from satellite data showed a similarity to the predicted statistical Cox/Munk model for obtaining surface wind speed measurements. Both methods show a maximum sun glint reflectance at 70°, followed by a quick reduction to the overall minimal value at oblique angles. The model values show a smooth trend as a function of solar zenith angle, while the satellite data suggest other outside influences on the plane albedos. One main difference results from the changing sea surface from one geographical region to another. These separate locations in the Pacific Ocean have different mean wind speed and direction which influence the glitter producing surface conditions. Due to the geostationary satellite chosen for this study, the dominant view and solar angle changes with the time of year. This may produce a bias for some of the solar angles where a more intense sun glint was observed for different segments of the curve (Figure 7). The satellite data also contained small gaps which were corrected by normalizing
the incident radiation. This may have overlooked some important regions, but the final results represent a good estimate of the sun glint albedo. With proper tuning of the model's wave shape and surface conditions, the two methods could show better agreement.

The model and GOES data results show similar values, but differ greatly in their technique in obtaining the reflection values. The statistical model focused on specular reflection off a wavy surface, and produced these results with constant surface conditions and no clouds. This varies dramatically from the satellite measured results, which required the subtraction of two cloud free independent data sets containing missing values. All attempts possible were made to eliminate the effects of clouds on reflectance values, but inevitably some small amount of cloud contamination did occur. The clouds were also capable of influencing neighboring pixels of clear ocean. The IR channel used for cloud clearing was used to look at each pixel from above to decide if it was contaminated, but large solar angles allow clouds to obscure solar radiation from striking a neighboring clear pixel area. This reduction of incident radiation was then measured as a decrease in reflec-
tivity, and subsequently reducing the plane albedo. This effect primarily occurs at large incident angles and may account for the difference between the model and satellite retrieved plane albedos at large solar angles.

This study also set out to better understand what influence systematically ignoring sun glint has on planetary albedo calculations. First estimates of the sun glint albedo as modeled by the Cox/Munk distribution produced an albedo of 1.9%. This corresponds well with the GOES clear sky albedo of 2.2 \pm 0.1\% . When the influence of clouds was analyzed the glint albedo decreased to 1.7 \pm 0.1\%. These results were then extrapolated to include ocean fractional coverage of the Earth and incident angle influences. The net albedo of sun glint was reduced by a factor of 0.73, resulting in a clear sky global albedo of 1.6 \pm 0.1\% and 1.2 \pm 0.1\% for the case including clouds. This percent change represents a substantial difference in absorbed radiation.

These albedo values represent the narrow-band albedo calculated from the channel one detector with a wavelength range of 0.55 - 0.75 \mu m, and typically would not represent the full broad-band albedo (0.2 - 4.0 \mu m).
Other techniques incorporate spectral bands with land and atmospheric models to transform the narrow-band albedo into a broad-band albedo (Laszlo et al 1988). These studies require scene identification as part of the transition process. While land surfaces have varying albedos for different solar angles as well as time of year, ocean albedos typically do not depend on wavelength. A study by Laszlo et al (1988), and Pinker and Ewing (1987) showed the GOES channel one albedo for ocean closely predicts the full broad-band albedo with an error of about 1%. This can be explained by the basic understanding of specular reflection off a water's surface as predicted by the Fresnel laws. Equations (1) and (2) do not depend on wavelength, and therefore closely approximate the broad-band albedo with a narrow-band sampling.

One of the major issues global meteorological models face for precise forecasting has been a better understanding of radiative transfer. Recent advances with better prioritizing of both short and long wave energy have given these models the capability to produce more accurate forecasts further into the future. Typically these models have used ADM's to simulate how the
solar radiation will react with the surface. A 1% change in albedo would have a large effect on the model’s energy exchange. Current estimations of doubling the carbon dioxide concentrations reduces the outgoing longwave radiation by 3 to 4 W/m$^2$ (Hartmann 1994). A 1% change in reflected radiation due to including sun glint would produce a similar change in energy of around 3 W/m$^2$. Also important to the ADM’s capability to correctly describe the magnitude of reflected light, is the angular dependence on the incident solar zenith angle. Water is a great demonstrator of a non-Lambertian surface where changes in orientations show measurable differences. This applies for both underestimating as well as overestimating the reflectance of the ocean surface. Directly applying Fresnel predictions to a water’s surface would produce overly intense reflections at oblique angles. The specular reflection at glancing angles does not produce the near perfect reflection as predicted, but a near zero reflection. Not accounting for such a change overestimates the true reflected energy.

With a large fraction of the Earth covered with water, inclusion of the poorly understood glitter region is important in understanding the true full Earth
albedo. Although the actual amount of excess radiation reflected out of the glint region may be considered small, the grand scale of the feature requires accounting for the extra reflected radiation. This study found a value of 2.2 $^{+/-}$ - 0.1% for the clear sky spherical albedo and a maximum at 70° for the plane albedo. This maximum was also correctly predicted by the statistical model. Unlike clouds or vegetation, the spherical albedo of glint does not show large fluctuations depending on time of year, and can be depended upon to always appear in the satellite imagery. If the final goal of radiative transfer studies is to precisely characterize how the planet reflects incoming solar radiation, this large but subtle feature should be taken into consideration.
REFERENCES


GOES online, Available online at: http://www.oso.noaa.gov/goes/index.htm

Hartmann, D. L., Global Physical Climatology, Academic Press, San Diego, California, 1994


