Assessment of Tilt Capability for Spaceborne Global Ocean Color Sensors
Watson W. Gregg and Frederick S. Patt

Abstract—The importance of tilt capability for sun glint avoidance for future global ocean color missions was analyzed. The analyses focused on Sea-viewing Wide Field-of-view Sensor (SeaWiFS) mission, because its radiometric, orbital, and sensor characteristics are well defined. The analyses concentrated on two major questions: 1) does tilting to avoid sun glint increase or decrease the total ocean coverage, and 2) at high latitudes far from the region of maximum sun glint, should the sensor be tilted or untilted?

For ocean coverage maximization, if the sensitivity of ocean color algorithms to sun glint is of the same order as the error in the atmospheric correction algorithms, then a tilted sensor produces nearly 20 percent better coverage than an untilted one after 2 d in the absence of clouds, and 12 percent after 4 d including clouds. Thus, the tilt capability can improve the ocean coverage of future ocean color missions.

At high latitudes differences in transmitted water-leaving radiance between tilted and untilted sensors were well within the algorithm errors. Furthermore, sun glint radiances exceeding the algorithm errors occurred at high wind speeds as far as 70° from the solar declination, suggesting that sensors should remain in the tilted mode up to this limit.

I. INTRODUCTION

The tilt capability of the Coastal Zone Color Scanner (CZCS) must be partially credited for the success of the sensor. The concern before launch was that excessive sun glint (radiance specularly reflected off the ocean surface toward the sensor) would interfere with the spectral signal emanating from the ocean and preclude the determination of derived chlorophyll concentrations [13], [19]. The ability of the CZCS to tilt fore and aft of nadir by 20° enabled avoidance of sun glint such that chlorophyll concentrations could be quantified to ±35 percent in clear ocean waters [8].

The overall success of the CZCS led to several proposals for follow-on ocean color sensors. All of these proposed sensors are intended to make global observations of ocean color. A tilt capability is often included as part of the design of these sensors.

While the tilt capability was clearly important to a limited-duty sensor like the CZCS, which was usually only turned on for 2-min durations over specific regions, it is unclear whether such capability is necessary for a sensor routinely operating and monitoring the Earth on a global scale. This is because sun glint is a bidirectional reflectance phenomenon, and multiple observations of the ocean's surface over many orbits and many days will produce many viewing angles of a given location on the ocean that do not meet the conditions for receiving sun glint contributions in contaminating amounts.

The purpose of this paper is to examine the importance of the tilt capability in a simulated global ocean color mission. The results are of considerable importance to the design of future global ocean color sensors, since the tilt capability is expensive to build, because it is a perturbing influence to spacecraft control on orbit, and finally because it requires significant on-board power to operate. Substantial savings can potentially be gained if the tilt mechanism is not necessary. Conversely, if the tilt capability is necessary to improve global observations of ocean color, it must be included early in the design of the sensor. Second, it is important to know exactly how to use the tilt capability to produce the most complete and scientifically useful observations possible.

The focus in this paper is on SeaWiFS, which has the tilt capability, and which is due for launch in 1994 in a private venture by the Orbital Sciences Corporation. The SeaWiFS mission is emphasized because it is well defined, it serves as a model for future global ocean color missions, its wavelength complement is considered a minimum set to achieve the goals of ocean color remote sensing, and because it will fly in an orbit typical for future ocean color missions. Thus, the results here may be extrapolated to other proposed missions at least qualitatively, if not quantitatively, and the methods may be applied quantitatively to other missions.

II. METHODS

The analysis proceeds in two major parts. In the first part the question addressed is: does the use of tilt to minimize sun glint increase or decrease global coverage of ocean color? These analyses are called the coverage analyses. In the second part of the analysis the question addressed is: if it is used, where should the tilt be used at high latitudes to produce the highest-quality scientific data? A tilted sensor views the same location on the Earth as an untilted sensor, but at a larger spacecraft zenith angle. Thus, the tilt increases the path length of radiance...
through the atmosphere, possibly degrading the water-leaving radiance retrievals. This component is called the high-latitude tilt analysis.

A. Coverage Analyses

For the coverage analysis section, simulation models of the orbit, geolocation, and radiative transfer must be built and coupled. Limits of sun glint radiance must be selected to determine useful coverage. These limits are set initially as two extremes: 1) when sun glint radiance exceeds the noise equivalent radiance (NER) of the sensor in question, and 2) when the sum of the sun glint radiance, scattered radiance from the atmosphere, and upwelling radiance emanating from beneath the ocean exceeds the sensor saturation radiance. For SeaWiFS, the NER and saturation radiances are defined (Table I).

1) Orbit Model: The orbit model used in these analyses is a Brouwer-Lyddane general perturbations model with a fifth-order Earth gravity field [16]. The orbit characteristics of SeaStar (the spacecraft carrying SeaWiFS on orbit) used in the model are given in Table II. They were selected to produce a consistent equator crossing at near-noon local time (actually 9 min after noon) for a year at a nominal altitude of 705 km. SeaStar is in a descending node daylight equator crossing (as indicated by the right-ascension ascending node). Most analyses here were performed for the northern hemisphere spring equinox. However, sensitivity tests were performed for the northern hemisphere summer and winter solstices, and the autumnal equinox, using right-ascension ascending node parameters appropriate for the season (Table II).

2) Geolocation Model: Location of points on the Earth requires knowledge of the sensor characteristics. These characteristics are known for SeaWiFS (Table III). SeaWiFS acquires data at two different resolutions, known as local area coverage (LAC), which is the full spatial resolution taken in limited amounts due to data recorder limitations, and global area coverage (GAC) which is merely the LAC subsampled every fourth pixel along-scan and along-track. The tilt can occur in three increments: nadir, 20° forward along the velocity vector of the spacecraft, and 20° aft of the velocity vector.

The geolocation algorithms used here were developed by Patt and Gregg [18] and provide an exact solution for an ellipsoidal Earth. They produce the longitude and latitude of the pixel being viewed by the sensor as a function of scan and tilt angles. The algorithms also produce the local solar zenith and azimuth angles (θs and φs) and spacecraft zenith and azimuth angles (θ and φ) needed for the radiative transfer calculations. Zenith is defined as the angle measured from the local vertical vector to the sun or spacecraft, and azimuth is defined as the angle from local north to the sun or spacecraft, measured clockwise.

3) Radiative Transfer Model: The radiative transfer model is used to calculate sun glint radiance, and the atmospheric and oceanic contributions to the total radiance. Sun glint radiance at the sea surface is computed using the Cox and Munk [4] relation

\[ L_s(\theta, \phi, \theta_s, \phi_s, W, \lambda) = T_s(\lambda, \theta_s)F_s(\lambda)\rho_s(\theta, \phi, \theta_s, \phi_s, W)/(4 \cos \theta \cos \theta_s) \]  

(1)

where \( F_s(\lambda) \) is the extraterrestrial spectral irradiance corrected for Earth–sun distance [8], \( \rho_s \) is the Fresnel reflectance of the sea surface for normal incidence, \( p_s(\theta, \phi, \theta_s, \phi_s, W) \) is the probability of seeing sun glitter in the di-
rection $\theta, \phi$, given the sun in position $\theta_s, \phi_s$ as a function of wind speed ($W$), and $\theta_s$ is the angle between nadir and the normal to the sea-surface slopes required to produce a reflection angle to the spacecraft [22].

The term $T_d(\lambda, \theta)$ represents the total downward transmittance of irradiance as a function of the $\theta_n$, the absorbing gases in the atmosphere, and scattering by molecules and particles. It is expressed as the sum of the direct and diffuse transmittances

$$T_d(\theta_n) = t_d(\theta_n) + t_s(\theta_n)$$  \hspace{1cm} (2)

where the subscripts $d$ and $s$ represent direct and diffuse components. The direct transmittance $t_d$ represents simply the transmittance of the direct solar beam after absorption by the gaseous components of the atmosphere, scattering and absorption by aerosols, and scattering by molecules (Rayleigh scattering):

$$t_d = t_r t_a t_o t_w(1 - t_o)$$  \hspace{1cm} (3)

($\lambda$- and $\theta_d$-dependencies have been dropped) where the subscripts refer to Rayleigh, aerosol, ozone, water vapor, and oxygen transmittances, respectively. Definition of the transmittance terms for each component in (3) can be found in Bird and Riordan [3]. Solution of (3) requires knowledge of the Rayleigh optical thickness, aerosol scattering and absorption properties, and absorption coefficients are taken from Gregg and Carder [11] for the wavelength region 400–700 nm (Table IV). Mean extraterrestrial irradiance is computed from Neckel and Labs [17], weighted with a full-width half-maximum (FWHM) Gaussian response curve for the SeaWiFS bands (Table IV). For the two SeaWiFS bands $>700$ nm, the Rayleigh optical thickness is computed from Hansen and Travis [12], and oxygen and water vapor absorption coefficients are derived from Tanre et al. [21]. Aerosol absorption and scattering characteristics are derived as a function of wind speed, relative humidity, visibility, and air mass type using the Gregg and Carder [11] model.

Some of the irradiance from scattered Rayleigh and aerosol components continues forward and contributes to the total irradiance at the surface. This is accounted for by the diffuse transmittance

$$T_d = t_r t_a t_o t_w[0.5(1 - t_o^{0.95}) + t_r^{1.5} F_o(1 - t_o)]$$  \hspace{1cm} (4)

where $t_{sn}$ is the aerosol transmittance after absorption

$$t_{sn} = \exp[-(1 - \omega_a) \tau_a M]$$  \hspace{1cm} (5)

and $t_{sn}$ is analogously the transmittance after scattering

$$t_{sn} = \exp[-\omega_a \tau_a M]$$  \hspace{1cm} (6)

[14]. In (4)–(6), $F_o$ is the forward scattering probability of the aerosol [3], $\omega_a$ is the single scattering albedo of the aerosol, $\tau_a$ is the aerosol optical thickness (both from [11]), and $M$ is the atmospheric path length, expressed by

$$M = 1/[(\cos(\theta_n) + 0.15(93.885 - \theta_n))^{1.25}]$$  \hspace{1cm} (7)

[15]. Note that this expression accounts for curvature of the atmosphere at large zenith angles, which is important in determining Earth coverage for global ocean color sensors.

If $L_s(\lambda)$ is the sun glint radiance at the sea surface, $T(\lambda, \theta) L_s(\lambda)$ is that received by the sensor, where $T(\lambda, \theta)$ is the total transmittance (direct plus diffuse) from the Earth to the satellite. It is defined as in (2)–(7) with $\theta$ substituted for $\theta_n$. This total transmittance accounts for radiation transmitted directly from the sea surface as well as radiation from nearby pixels scattered into the field of view of the sensor. The quantity $T(\lambda, \theta) L_s(\lambda)$ is the parameter of interest here, since it represents the actual sun glint radiance sensed by the sensor.

Computed sun glint is sufficient to determine the ocean coverage when NER is used as the threshold. However, when saturation is used as the threshold, the entire complement of atmospheric and oceanic constituents must be included. For remote sensing of ocean color, these constituents are represented by

$$L_s(\lambda) = L_r(\lambda) + L_o(\lambda) + T(\lambda, \theta) L_s(\lambda)$$

$$+ T(\lambda, \theta) L_o(\lambda)$$  \hspace{1cm} (8)

where $L_r$ is the total radiation received at the sensor, and the quantity that must be below the saturation value to qualify as a valid pixel for quantitative ocean color analyses, $L_s$ is the Rayleigh radiance, $L_o$ is the aerosol radiance, and $T L_s$ is the water-leaving radiance diffusely transmitted from the ocean to the spacecraft. The Rayleigh radiance $L_r$ was computed using the exact multiple scattering method of Gordon et al. [9].

The aerosol radiance $L_o$ must be determined. According to Gordon and Castano [7], the aerosol radiance may be determined by

$$L_o = \omega_s \tau_s F_o p_o M/4\pi$$  \hspace{1cm} (9)

($\lambda$-dependence dropped) where $\omega_s$ is the single scattering albedo of the aerosol, $\tau_s$ is the optical thickness, and $p_o$ is a factor to account for the probability of scattering to the spacecraft for three different paths from the sun (see [7]). The term $F_s$ is the extraterrestrial irradiance attenuated by two trips through the ozone layer [7] and one trip through the atmospheric water vapor and oxygen as a modification for the SeaWiFS bands. In (9), $M$ has been
substituted for $1/\cos \theta$ to allow calculations on a curved Earth/atmospheric system.

The factor $p_a$ is computed by

$$p_a = \frac{[P(\theta_+ - 1 - g_1]}{[1 + g_1^2 - 2g_1 \cos \theta_+]^2} + (1 - a) \frac{1 - g_2^2}{[1 + g_2^2 - 2g_2 \cos \theta_+]^2}$$

where $a = 0.983$, $g_1 = 0.82$, and $g_2 = -0.55$ [7]. The term $\cos \theta_+ - \cos \theta_+ \sin \theta \sin \phi + \phi_3)$.

The last term in (8) $TL_m$ is computed as

$$TL_m(\lambda) = [1 - \rho \lambda \theta_0)] [L_m(\lambda)]_N \cdot \cos \theta_0 T(\lambda, \theta_0) T_e(\lambda, \theta_0)$$

where $\rho \lambda \theta_0$ is the total surface reflectance, weighted as a function of the relative proportions of direct and diffuse irradiance impinging at the surface (and thus providing the $\lambda$-dependence) and taking into account wind-speed roughness effects and foam [11]. The term $[L_m(\lambda)]_N$ is the normalized water-leaving radiance

$$[L_m(\lambda)]_N = \frac{1 - \rho \lambda \theta_0)}{(1 - \rho \lambda \theta_0)] F_o(\lambda) R(\lambda)}$$

where $\rho \lambda \theta_0$ is a normalized mean value of surface reflectance for direct and diffuse irradiance for a flat sea. It differs from $\rho_0$ in that wind-speed–surface roughness effects are not included, and we assume a constant value of 0.043 [10]. The term $R(\lambda)$ is the irradiance reflected just below the sea surface, $m$ is the index of refraction for seawater, $Q$ is the irradiance-to-radiance ratio (equals $\pi$ for totally diffuse radiance), $r$ is the water-air reflectance for totally diffuse irradiance, and other terms are described earlier. The refractive index $m$ is taken to be 1.341 [1], and $r$ is taken to be 0.48 [10]. The ratio $R(\lambda)/Q$ is wavelength dependent:

$$R(\lambda)/Q = 0.110 \frac{b_0(\lambda)}{K(\lambda)}$$

where $b_0(\lambda)$ is the spectral backscattering coefficient and $K(\lambda)$ is the spectral attenuation coefficient. $K(\lambda)$ is determined from

$$K(\lambda) = K_w(\lambda) + K_p(\lambda) + K_g(\lambda)$$

[2], where $K_w(\lambda)$ is the attenuation coefficient of pure seawater, $K_p(\lambda)$ is that for phytoplankton, and $K_g(\lambda)$ is that for gelbstoffe, or yellow substances.

Use of this model for a SeaWiFS simulation requires that values for wavelength-dependent parameters be chosen for SeaWiFS bands. Values for $K_w(\lambda)$ are taken from Baker and Smith [2] (Table V). $K_p(\lambda)$ is computed from

$$K_p(\lambda) = k_p(\lambda) C \exp \left\{ - [k_p(\lambda) \log_{10} (C/C_0)]^2 \right\} + 0.001 C^2$$

[2], where $C$ is chlorophyll concentration, $C_0$ is a reference chlorophyll value (0.5), and where $k_p(\lambda)$ and $k_g(\lambda)$ are spectral fit coefficients determined over the SeaWiFS bands (Table V). For this simulation, $K_g(\lambda)$ is assumed to be zero.

The backscattering coefficient $b_0(\lambda)$ may be deconvolved into components similar to $K(\lambda)$ [3]:

$$b_0(\lambda) = 0.5 b_w(\lambda) + b_p(\lambda)$$

where $b_w(\lambda)$ is the total scattering coefficient for pure seawater [20] and $b_p(\lambda)$ is the backscattering coefficient of phytoplankton. The coefficient 0.5 is the backscattering-to-total scattering ratio for pure seawater. The term $b_w(\lambda)$ is determined from an empirical relationship developed by Gordon et al. [10]:

$$b_w(\lambda) = A(\lambda) C^{B(\lambda)}$$

$A(\lambda)$ and $B(\lambda)$ are computed for SeaWiFS bands as shown in Table V. The only remaining unknown for the model, then, is $C$, which is assumed to be the global mean of eight years of CZCS observations, or 0.33 mg · m$^{-3}$.

4) Wind Speeds, Clouds, and Other Atmospheric and Oceanic Parameters: Wind speeds are necessary to compute sun glint magnitudes and aerosol optical properties. They were obtained from six years of data from the Fleet Numerical Oceanography Center (FNOC), made available from the NASA Climate Data System (NCDS). The mean wind speeds over these six years at 2.5° by 2.5° spatial resolution were used.

Global cloud cover data from the International Satellite Cloud Climatology Project (ISCCP), also available from the NCDS, were used to determine the effect of clouds on the coverage analyses. The data used here were the global mean over six years, from 1983 to 1988, and were reported in percent. Cloud obscuration was determined using a random number generator, reporting values between 0 and 1. If the random number exceeded the cloud fraction, then the pixel was taken to be clear. The random numbers were recalculated on a daily basis on the assumption that major changes in cloud cover occur on approximately this time scale. Global distributions of mean wind speeds and cloud cover as used in this paper are shown in Fig. 1.

Several other atmospheric parameters are required for
of the radiative transfer models. These are surface pressure, water vapor, ozone concentration, relative humidity, air mass type, and visibility. In addition, the chlorophyll concentration is required to produce radiance values from the semianalytic ocean radiance model. Global mean values for all of these parameters are used in all coverage analyses (Table VI).

5) Sun Glint Contamination: Coverage analyses involve determining the ocean area covered by the SeaWiFS sensor after removal of areas contaminated by sun glint. Sun glint contamination is determined in two ways: 1) when the transmitted sun glint radiance $T_L$ is greater than NER and 2) when the total radiance $L_t$ including sun glint, atmospheric contributions, and transmitted water-leaving radiance, equals or exceeds the sensor saturation value. If the condition is met in any of the eight bands, the pixel is considered contaminated. Swath widths are limited to $\pm 45^\circ$ (GAC width) under the assumption that this represents the useful maximum for quantitative ocean color observations.

6) The Tilt Strategies: Three tilt strategies are employed in this analysis. The first strategy involves no tilt throughout the SeaWiFS orbit, and serves as the basis for comparison. In the second strategy, the sensor begins each orbit tilted aft (toward the North Pole), changes tilt from aft to fore near the solar declination latitude, and remains in this configuration throughout the remainder of the orbit. In this operation sequence, a substantial gap in ground coverage occurs when changing tilt from aft to fore. For SeaWiFS, this change requires about 30 s, which includes some delay to allow spacecraft control to properly recover. The tilt location is chosen to take this delay into account and minimize total sun glint radiance.

In the third tilt strategy, a method is employed to reduce the overall long-term loss of coverage near the solar declination. This method is called the staggered tilt operation, and involves changing the tilt from aft to fore some distance before the optimum tilt location on 1 d (northward of the optimum tilt location for a descending node orbit), then some distance after this point (southward) on the next. Examination of the ground tracks for a 705 km altitude orbit such as SeaWiFS (Fig. 2) shows that tracks come within proximity every 2 d. The nearest tracks have a separation of $2.27^\circ$ in longitude (about 250 km) between days 1 and 3, and between days 2 and 4. This is in contrast to the interorbit separation of $24.75^\circ$ in longitude (2700 km) for two consecutive orbits. Thus, it was determined that changing the location of the tilt change every 2 d would reduce the loss in coverage near the solar declination from a sun glint avoidance optimization strategy. A great deal of trial and error was required to determine the best locations above and below the declination latitude for this staggered tilt strategy. For SeaWiFS, the best locations were found to be about 50 s north for the first 2 d (corresponding to approximately $3.4^\circ$ of latitude) and about 70 s south for the next 2 d (corresponding to approximately $4.8^\circ$ latitude). Thus, for all coverage analyses, three tilt strategies are assessed: untilted, tilted about the solar declination latitude, and the staggered tilt. In all cases, a 40 min/orbit duty cycle is employed, as per design specifications for SeaWiFS.

Simulations were run for 16 d, which is the ground-track repeat time for orbits at the 705 km altitude, as planned for SeaWiFS and the Earth Observing System (EOS), which is in a similar orbit. Percent coverage is determined by comparison with the maximum coverage obtained in a 16-d run where no sun glint and no clouds

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**TABLE V**

<table>
<thead>
<tr>
<th>$\lambda$ (nm)</th>
<th>$k_a$</th>
<th>$k'$</th>
<th>$b_a$</th>
<th>$a$ (METERS$^{-1}$)</th>
<th>$b$ (METERS$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>410</td>
<td>0.0194</td>
<td>0.208</td>
<td>0.077</td>
<td>0.0067</td>
<td>0.0031</td>
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<tr>
<td>443</td>
<td>0.0169</td>
<td>0.175</td>
<td>0.081</td>
<td>0.0054</td>
<td>0.0050</td>
</tr>
<tr>
<td>490</td>
<td>0.0212</td>
<td>0.121</td>
<td>0.091</td>
<td>0.0051</td>
<td>0.0040</td>
</tr>
<tr>
<td>510</td>
<td>0.0370</td>
<td>0.100</td>
<td>1.006</td>
<td>0.0026</td>
<td>0.0036</td>
</tr>
<tr>
<td>555</td>
<td>0.0663</td>
<td>0.076</td>
<td>1.144</td>
<td>0.0019</td>
<td>0.0050</td>
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<td>670</td>
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<td>1.463</td>
<td>0.0008</td>
<td>0.0038</td>
</tr>
<tr>
<td>765</td>
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<td>0.060</td>
<td>1.852</td>
<td>0.0005</td>
<td>0.0020</td>
</tr>
<tr>
<td>865</td>
<td>3.4000</td>
<td>0.010</td>
<td>1.752</td>
<td>0.0003</td>
<td>0.0020</td>
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**TABLE VI**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
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<td>Surface Pressure</td>
<td>1013.25 mb</td>
</tr>
<tr>
<td>Water Vapor</td>
<td>1.5 cm</td>
</tr>
<tr>
<td>Ozone</td>
<td>340 Dobson units</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>80%</td>
</tr>
<tr>
<td>Air-Mass Type</td>
<td>1 (oceanic aerosol origin)</td>
</tr>
<tr>
<td>Visibility</td>
<td>15 km</td>
</tr>
<tr>
<td>Chlorophyll Concentration</td>
<td>0.33 mg m$^{-3}$</td>
</tr>
</tbody>
</table>
Fig. 2. SeaWiFS descending node orbit tracks for four days, showing how the third and fourth day tracks approach the first and second day. Labels next to the orbit tracks indicate which day in the sequence the orbit track belongs to.

occur, and for a 40-min duty cycle (corresponding to a solar zenith angle maximum of 72.7° at the northern and southern extremes for SeaWiFS). For a simulation beginning at the vernal equinox, this maximum coverage corresponds to 98 percent of the total ocean area.

B. High Latitude Tilt Analyses

In the second part of the analysis, where optimal locations for tilt change at high latitudes are assessed, the differences in transmitted water-leaving radiance [13] for a tilted and untilted sensor are examined. In this analysis, it is necessary to ensure that both the tilted sensor and untilted sensor are viewing the same point on the Earth to eliminate the bias associated with a backward-looking tilted sensor. Here we utilize an inverse location method involving simple spherical trigonometry. The method is derived from Wilson et al. [23] for the CZCS, and reformulated for a descending node spacecraft to simulate SeaWiFS.

For the high-latitude tilt analyses, extreme atmospheric and oceanic conditions are sought, rather than the global mean values used in the coverage analyses, in order to maximize the difference between tilting and nontilting sensors. These conditions occur when chlorophyll concentration is set to 0.05 mg · m⁻³, air-mass type to 10 (continental-type prevailing aerosol), visibility to 6 km, relative humidity to 100 percent, wind speeds to 4.75 m · s⁻¹ (global mean over the six years of FNOC data), and other conditions as in Table VI. Furthermore, bidirectional shadowing effects [24] are incorporated into sun glint analyses because of their importance at high latitudes (low solar zenith angles), in contrast to the global coverage analyses.

III. Results and Discussion

A. Coverage Analyses

When the sun glint contamination threshold is total radiance ≥ saturation for SeaWiFS, ocean coverage by an untilted sensor exceeds that by a tilted sensor, both with and without clouds (Fig. 3), at the spring equinox using climatological cloud cover and wind speeds. However, the differences in the coverages in the presence of clouds are very small (<3 percent). Coverage by the staggered tilt approximately equals that by the untilted sensor, except on the second day without clouds, when the difference is 6 percent. Conversely, ocean coverage by the tilted sensors always exceeds coverage by untilted when the contamination threshold is sun glint radiance > NER (Fig. 3). Differences are as large as 21 percent without clouds after 2 d, and > 15 percent with clouds after 6 d. The staggered tilt produces only a small increase in coverage.

The decision to tilt therefore rests upon the sensitivity of the algorithms used to retrieve quantitative ocean color. The saturation threshold represents a completely insensitive algorithm to sun glint, i.e., sun glint is correctable up to the maximum sensor radiance capability. The NER threshold represents a hypersensitive algorithm, i.e., one for which any sun glint exceeding the noise limit of the sensor is assumed to preclude the use of that pixel for chlorophyll retrievals. In the CZCS atmospheric correction algorithms, sun glint was ignored. The question here is which threshold better represents the algorithm sensitivity for the modern capability.

Marine aerosols typically contain large particles, generally have wavelength-independent scattering characteristics, and are also generally nonabsorbing [5], [11]. When the dominant aerosol in the field-of-view is marine, sun glint "looks" like a marine aerosol, and the atmospheric correction methods of the CZCS [8], [9], remove sun glint nearly completely. However, when the aerosol is of a continental source, it is typically composed of smaller particles and is spectrally absorbing and scattering, resulting in spectral effects on the retrieved radiance that differ greatly from sun glint. In this case, even small...
amounts of sun glint will interfere with the characterization of the aerosol and result in error in the retrieved water-leaving radiance and consequently pigment estimates.

More refined algorithms with more sophisticated approaches to removing aerosols are expected for future ocean color sensors, relying upon information provided in the near-infrared bands, where the ocean is nearly totally absorbing [6]. For these future algorithms, the sensitivity to sun glint should be considered to be on the order of the accuracy of the atmospheric correction algorithms, which is approximately 3-4 times the SeaWiFS NER at 443 nm (H. R. Gordon, personal communication). This corresponds to approximately one CZCS digital count.

Although the atmospheric correction accuracy of other SeaWiFS bands is unknown at this time, particularly at 765 and 865 nm, we assume a sun glint sensitivity of 3.5 NER for all bands. Considering this as the sun glint threshold, it is clearly advantageous to tilt (Fig. 4). Quicker and more complete coverage is obtained for a tilted sensor whether clouds are included or not. Increases of 20 percent in ocean coverage are noted for the tilted sensor at 2 d in the absence of clouds, and 12 percent after 4 d with clouds. A small exception is that an untilted sensor exceeds the coverage of the tilted sensor after 10 d for a cloudless Earth, but only by 2 percent, and the tilted coverage equals the untilted at 16 d. Global maps of ocean coverage for the three tilt strategies at the 3.5 NER threshold, including clouds, show the geographic distribution of these results (Figs. 5-7).

These results are confirmed using monthly mean cloud cover and wind speeds for 4 seasons, at the northern hemisphere spring equinox, summer solstice, autumn equinox, and winter solstice (Fig. 8), rather than the annual mean conditions used before. Increases in coverage due to use of tilt ranged from 11 to 13 percent after 4 d, at the 3.5 NER limit. Larger increases in coverage at the winter solstice are probably due to higher wind speeds in the southern hemisphere, producing more widespread sun glint, and thus increasing the benefit of tilting.

Considering the uncertainty associated with the sun glint threshold, it is useful to assess the differences in coverage at various thresholds. This can provide a means to determine the importance of the tilt capability as algorithm sensitivities to sun glint differ or change with time. The thresholds span the range from 1 NER to 1000 NER, and show that coverage differences decrease with increasing NER thresholds (Fig. 9). At a threshold > 10 NER, the coverage difference drops below 10 percent maximum, but a threshold of 500 NER is necessary to decrease the coverage difference below 5 percent. This threshold means that the algorithm is insensitive to sun glint radiance up to 2.1 mW · cm⁻² · μm · sr⁻¹ at 865 nm. For SeaWiFS and the Moderate Resolution Imaging Spectrometer (MODIS), which use a bilinear gain response, this much sun glint will place ocean observations in the second gain mode, where the signal-to-noise ratio is greatly reduced. For other sensors that use a constant linear gain, such as the Ocean Color and Temperature Sensor (OCTS), this sun glint value will exceed the saturation limit when added to the other atmospheric and oceanic radiative contributions.

The staggered tilt strategy produces only a minor increase in global ocean coverage when clouds are included (Figs. 4 and 7). This small increase in percent coverage by the staggered tilt on global scales translates to a substantial increase in coverage near the solar declination latitude over that obtained by the optimal sun glint avoidance tilt strategy (Fig. 10). (The strong peak in coverage after 1 d near 75° S latitude is an artifact of the slightly greater coverage produced by a tilted sensor even for the same operational duration.) After 4 d, the staggered tilt produces 35 percent more coverage near the equator than does the tilt without clouds, and 18 percent more coverage including clouds. After 16 d, the staggered tilt increases coverage by about 10 percent with and without clouds. The staggered tilt strategy nearly eliminates one of the largest deficiencies of the optimum sun glint avoidance tilt strategy: the lack of coverage near the solar declination. It retains all of the advantages of tilting, including greatly increased coverage near midlatitude (Fig. 10).
Fig. 5. Global coverage for an untilted sensor, with a 3.5 NER sun glint contamination threshold.

Fig. 6. As in Fig. 5 for a tilted sensor.
Fig. 7. As in Fig. 5 for a sensor utilizing the staggered tilt operation.

A sensor with a shorter tilt change time than SeaWiFS will produce a smaller loss of coverage at the equator, and consequently the staggered tilt strategy will produce a smaller increase in coverage. Even in these circumstances, however, the staggered tilt will produce better coverage at the solar declination latitude and a better distribution of coverage throughout the global oceans.

Future algorithm improvements may include corrections for sun glint, or the algorithms may be less sensitive to glint. The 3.5 NER threshold used here represents an estimate of the current state of accuracy of atmospheric correction algorithms. Any significant decrease in sensitivity to sun glint, either through direct correction or through indirect, methods, will shift the balance more favorable to non-tilting sensors. However, the improvements must be substantial, as seen in Fig. 9. Nevertheless, small differences in coverage might be sufficient justification to avoid the expense of designing, manufacturing, testing, and operating a tilt mechanism, depending upon the actual costs.

It should be noted that the analyses presented here are impractical to confirm in the flight of an actual sensor. The periods of time required to determine the differences in coverage between tilted and untilted sensors (4–16 d) are too long to expect a constant distribution of cloud cover. Consider also the effects of changing solar decli-
Fig. 9. Coverage differences as a function of different sun glint thresholds, ranging from NER to 1000 NER. All computations were for the spring equinox, using mean annual cloud cover and wind speeds.

Fig. 10. Depiction of ocean coverage by latitude, with 3.5 NER as the sun glint contamination threshold. The three diagrams on the left-hand side show the coverage in the absence of clouds for one day, four days, and 16 days, respectively, from top to bottom. The three diagrams on the left are similar except that clouds were included.

nation. It might take years of experimentation with an actual sensor to prove the case of tilting versus nontilting in order to achieve reasonably reliable and unbiased results. Even then, one is left with possibly gigabytes of data at the wrong tilt; either overly contaminated with sun glint or missing. These are valuable data about oceanic processes that can never be recovered.

B. High Latitude Tilt Analyses

It is now necessary to assess whether tilting at high latitudes produces a degradation in the quality of the radiometric signal emanating from the ocean. For this analysis we examine the effects of the transmitted water-leaving radiance $T_{w}(\lambda)$ for tilted and untilted sensors. We normalize the same viewing location and vary the orbit position using an inverse geolocation method to ensure observation of the same Earth location. The effects of tilting on $T_{w}(\lambda)$ are then reduced to the difference in spacecraft viewing geometry, and are not coupled with the difference in solar geometry.

Only wavelengths between 412 and 555 nm are assessed for this analysis since the assumption for atmospheric correction is that the ocean is nearly totally absorbing for wavelengths $\geq 670$ nm. The results clearly indicate that the difference in transmitted water-leaving radiance delta $T_{w}$ between tilted and untilted sensors is well within the 3.5 NER limit of atmospheric correction accuracy, and is consequently insignificant (Fig. 11). The largest differences occur for the westernmost pixel (defined as 45° scan angle) and for lower latitudes (55° and 60° from the solar declination latitude). At higher latitudes ($\geq 65°$ from solar declination) the difference is within or very near the SeaWiFS NER. These results suggest that the transmitted water-leaving radiance signal will not be degraded if a sensor is left in the tilted mode (up to $\pm 20°$ tilt angle), far from the solar declination latitude. Recall that these results were derived using atmospheric and oceanic conditions that maximized the differences between tilting and nontilting.

The transmitted water-leaving radiance represents the component of the radiometric signal received by the satellite emanating from the ocean and thus containing information about the ocean. Significant differences (i.e., exceeding 3.5 NER) in the quality of the water-leaving radiance signal by tilted versus untilted sensors can occur if atmospheric correction errors increase nonlinearly with increasing viewing geometry, but the results shown here suggest that these differences are small. At high latitudes, solar zenith angles are large and the irradiance penetrating the ocean is small. Thus, any difference due to a small difference in viewing geometry is necessarily small, as well. The magnitudes of the differences in spacecraft zenith angle are shown in Table III for the 45° scan angle, which is approximately 4°. At the center pixel, the difference is about 22°, which is a difference of only 8 percent in path length ($1/cos \theta$). These results suggest that tilting does not make a difference at high latitudes in terms of derived radiometric quality.

These results assume a perfect atmospheric correction. Errors associated with atmospheric correction should be
assessed by considering the "retrieved" water-leaving radiance. This is the residual radiance after all atmospheric contributions to the total radiance are subtracted. To assess the magnitude of this error as relevant to tilted and untitled sensors, we assume that the exact Rayleigh scattering computations are correct, and that any atmospheric correction error is due to the characterization of the aerosol. The aerosol is assumed to follow the Angstrom spectral dependence, as used in the CZCS, except that determination of the Angstrom exponent (the indicator of this spectral dependence) is determined using the Rayleigh-corrected total radiance at 670 and 865 nm, as described in Gordon [6]. The retrieved $TL_w$ using this method produces differences for tilted and untitled sensors similar to the transmitted differences described and shown in Fig. 11.

Actually, there is an advantage to remaining tilted even at high latitudes. This is because substantial sun glint can occur at even at high latitudes if the wind speed is high enough. Nearly 30 percent of the pixels in a scan contain sun glint in amounts exceeding 3.5 NER for SeaWiFS at a 20 m·s$^{-1}$ wind speed as far as 70° away from the solar declination latitude (Fig. 12). Monthly mean wind speeds were observed in the FNOC six-year mean record as high as 18 m·s$^{-1}$, suggesting that these speeds are not unrealistic. Nearly 10 percent of the pixels in a scan are contaminated up to about 72° from the declination. Thus, if sun glint minimization is an important criterion for successful future ocean color missions, the tilt should be used as far away as 72° from the solar declination latitude (Fig. 12).

At distances greater than 72° from the solar declination latitude, the difference in transmitted water-leaving radiance is small, but it is always larger in the untitled case. Nadir-pointing, nontilted strategies should be considered if sufficient power is available, the radiance levels are sufficient to be considered usable, and the accuracy of the atmospheric correction algorithms is improved.

**Fig. 11. Differences in transmitted water-leaving radiance $TL_w(\lambda)$ between a tilted and an untilted sensor. Solid bars indicate the NER. Left-hand side: difference for the westernmost pixel in the SeaWiFS scan, where the scan angle is 45°. Right-hand side: difference for the center pixel.**

**Fig. 12. Percent loss of pixels in a scan as a function of wind speed and latitude of the subsatellite point. Computations were performed for the spring equinox, and so latitude corresponds to the angular distance from the solar declination latitude.**

### IV. Conclusion

The advantages and disadvantages of the tilt mechanism for sun glint avoidance for future global ocean color missions were examined. The analyses focused on the SeaWiFS mission, because its radiometric, orbital, and sensor characteristics are well defined. The analyses concentrated on two major questions: 1) does tilting increase or decrease the total ocean coverage, and 2) at high latitudes far from the region of maximum sun glint, where should the sensor change tilt?

Regarding the first question, the decision to tilt depends upon the sensitivity of atmospheric correction algorithms to sun glint. If they are completely insensitive, better coverage is obtained in fewer days for a nontilting sensor. If they are highly sensitive, better coverage is obtained for a tilting sensor. Inclusion of clouds changed the conclusions only slightly: if the algorithms are insensitive to sun glint, tilted and untilted sensors obtain about the same ocean coverage in the same amount of time; whereas in the sensitive case, the coverage obtained by a tilted sensor is greater than that by an untilted one.

Atmospheric correction algorithms for ocean color are expected to have an error on the order of 3-4 times the NER of SeaWiFS (corresponding to one CZCS digital count). If this is used as the threshold for coverage, then a tilted sensor produces 12 percent greater coverage than an untilted one. Thus the tilt capability can improve the ocean coverage of future ocean color missions.

The largest drawback in a tilting sensor is the uneven distribution of coverage: greater coverage at latitudes away from the solar declination latitude is obtained at the cost of reduced coverage near the declination. This bias in coverage can be nearly eliminated using a staggered tilt strategy. This strategy involves changing tilt from aft to fore some distance prior to reaching the declination latitude for a few days and then shifting the tilt location to some distance away from the declination. The exact lo-
cations to change tilt depends upon the orbital and scanning characteristics of the sensor in question, but in essence is a trade-off of increased glint for better coverage. Increases in coverage at the solar declination latitude are as much as 18 percent after 4 d for SeaWiFS under climatological cloud conditions. Increases up to 35 percent can be achieved if no clouds are present in this region.

At high latitudes it is found that differences in transmitted water-leaving radiance between tilted and untilted sensors are well within the atmospheric correction algorithm errors. Furthermore, sun glint radiances exceeding the algorithm errors can occur at high wind speeds even as far as 70° from the solar declination latitude. Thus, if sun glint minimization is an essential goal for global ocean color missions, the tilt mechanism should be operated to avoid sun glint throughout the range of orbital positions corresponding to this limit. At distances greater than 72° from the solar declination latitude, the difference in transmitted water-leaving radiance is small, but it is always larger in the untilted case. Nontilted strategies should be considered if sufficient power is available, the radiance levels are sufficient to be considered usable, and the accuracy of the atmospheric correction algorithms is improved.

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