Light Reflection from Water Waves: Suitable Setup for a Polarimetric Investigation under Controlled Laboratory Conditions

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ABSTRACT
The reflection of sunlight from a wavy water surface, often referred to as sun glint, is a well-known phenomenon that presents challenges but also hitherto untapped opportunities in remote sensing based on satellite imagery. Despite being extensively investigated in the open ocean, sun glint lacks a fundamental characterization obtained under controlled laboratory conditions. A novel apparatus is presented, which is suitable for highly time-resolved measurements of light reflection from different computer-controlled wave states, with special emphasis on the detection of the polarization components. Such a system can help establish a link between the evanescent “atomic glints” from a single wave facet and the familiar sunglint pattern obtained by time averaging over a surface area containing many facets.

1. Introduction
Sun glint has bedeviled remote sensing from its very inception, because data in sunglint regions were unusable for retrieving surface or atmospheric properties. Lacking a nearly perfect theory of glint, it proved almost impossible to subtract it and thereby recover the typically small signal buried in glint “noise.” Add to this the fact that glint often saturated the sensor, or pushed it outside its linear calibration range into a nonlinear regime, and it is easy to understand why glint became the remote sensor’s nemesis.

The experimental apparatus presented here is designed to improve the description of glint by going back to basics—specifically, by measuring the reflectance of a laser beam from a computer-controlled wavy water surface at a time resolution high enough to capture individual (“atomic”) glints, the fundamental quantities of which all glint patterns are composed (Fig. 1). We assembled the apparatus, a suspended goniometer, to adapt to the unusual conditions of measuring bidirectional reflectance from a surface that is rapidly changing and also unable to support the weight of the apparatus. The wave state, consisting of any desired mixture of capillary and gravity waves, is created and monitored by the advanced controls of an indoor wave tank facility.

No natural phenomenon except for Rayleigh scatter-
A good description of glint relies upon an accurate model of the surface geometry. The most frequently cited references in this respect remain the pioneering investigations carried out over 50 yr ago by Cox and Munk (1954a,b, 1956). They deduced surface properties from glint measurements in real-world situations, assuming that the only forcing giving rise to a certain wave-slope distribution was the wind speed. However, this approach relies on assumptions about surface conditions that could not be controlled or fully verified as statistically stationary. The setup provides independent and repeatable measurements of surface statistics. As surface reflectance is strictly related to the surface geometry, glint measurements can be exploited to verify slope distributions and perfect surface models.

Wave slope and its relation to wave breaking coverage have also been shown to be directly connected to the exchange of heat flux and greenhouse gases across the air–sea interface (Zappa et al. 2001, 2004). Glint data may offer an alternative approach to such measurements.

The following section introduces the wave tank and its capabilities. Section 3 describes the experimental apparatus setup designed for our measurements: the support, the source, and the detector. Section 4 describes the calibration of the instrument. The selection of results begins with reflectance measurements for the flat water surface (section 5a). We then discuss the retrieval of wave-slope distributions from the surface imaging data (section 5b) and finally give examples of atomic glints generated by gravity and capillary waves (section 5c). Conclusions are given in section 6.

2. The Wallops wave tank

We surveyed several wave tanks, and by far the best for our purposes was the Air–Sea Interaction Research Facility at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) Wallops Flight Facility in Virginia (Long 1992). A schematic illustration of the facility is provided in Fig. 2. Its primary objectives are to test theoretical results and to collect empirical data for the development of remote sensing techniques, in support of microwave remote sensor development and algorithms for air–sea interaction studies.

Controlled wave states can be created by means of three separately controllable dynamic forcings: a hydraulic pusher unit at one end of the tank to create gravity waves that are then absorbed at the other end, a wind generator to create capillary waves, and a subsurface current to improve the simulation of real-world situations. The tank’s main test section for studying
wind–wave current interactions is 18.29 m long, 1.22 m high, and 0.91 m wide. It is filled to a water depth of 0.76 m, with 0.45 m remaining for airflow. Winds up to 18 m s\(^{-1}\) can be reproduced, along with water current in either direction of about 0.5 m s\(^{-1}\) generated by pumping 380 L s\(^{-1}\) through the facility’s 0.4-m pipes. Electronically controlled hydraulic units at both ends of the tank can generate any wave frequency or pattern up to 10 Hz. Computer control of the wind, current, and hydraulic units allows complete hands-off automation of research runs and accurate repetition of unsteady situations for statistical studies. The tank water can be heated and maintained at warm temperatures, and the overwater airflow can be cooled and humidity controlled.

The facility provides, as infrastructure, an advanced system for measuring instantaneous wave slopes (Long and Klinke 2002). At the heart of the system is a Silicon Mountain Design 1M-60 digital camera, capable of 1024 \(\times\) 1024 pixel resolution and capturing 12-bit images at up to 60 frames per second, sufficient to “freeze” even the fastest-evolving wave slopes without smearing. The system also includes a large light box that illuminates the water surface from below. Both parts are illustrated in Fig. 3, together with the mirror that allows the camera to image the surface from the side of the tank.

Each pixel in the image corresponds to a fixed point on the water surface but, as a result of refraction by the local slope, to a variable point on the light box. If the light box provided uniform illumination, the brightness of a point on the surface would remain the same regardless of its slope. The box is therefore masked to produce a linear gradient of intensity along the down-tank direction: in this way, measured intensity is a function of the component of surface slope along the same direction. The calibration is performed by measuring the brightness of each pixel in response to a set of known slopes on a plastic barge (see section 5b). By interpolation we are then able to define a one-to-one relationship that links grayscale intensity to local slope.

Vertical capacitance-wire probes partially immersed in the tank are also used to measure surface elevation and, from differences in elevation between pairs of wires, the longitudinal and transverse slope components. The wire and surrounding tank vessel can be considered a pair of capacitor plates. As the elevation of the water surface changes, the effective capacitance between the plates varies. The detector circuit measures a voltage that is proportional to the water surface elevation. The voltage is low-pass filtered to remove 60-Hz interference, and high-pass filtered to provide self-zeroing of very slow changes in the mean water elevation (such as when the tank is filled or drained). Because the wires are 1 cm apart, and because a meniscus forms where the water touches each wire, this method only works for waves having wavelengths longer than the meniscus diameter near the flat water surface.

3. Experimental apparatus and setup

A block diagram of the apparatus is drawn in Fig. 3. The subsections below describe the single components and their role in the overall structure.

a. Design considerations

The design presented several challenges. Water waves are dynamic and can neither be generated with a compact apparatus nor tilted at pleasure to realize different illumination conditions, as is done in many reflectance experiments on solid samples to avoid the repositioning of the light source and/or the detector. The mechanical suspension had to be designed around the geometrical constraints of the wave tank, on the one hand providing stiffness and a convenient, quick positioning method while, on the other hand, remaining as lightweight and nonobstructive as possible.

The design of the detector exploits the size of the optical components as much as possible. A small field of view (FOV) is required to avoid seeing several glints at once (always possible when several capillary waves
are in the field of view); furthermore, optical elements for measuring polarization should be illuminated very near the normal direction to ensure proper performance. On the other hand, a small field of view reduces the signal-to-noise ratio (SNR). It also limits the choice of wave heights because it is not possible to capture the reflection originating from waves with amplitudes greater than the linear dimension of the field of view at the surface. Figure 4 illustrates this latter problem for a value of the aperture diameter equal to the aperture stop (AS). The projection of AS on the surface varies with the angle of incidence $\theta$ according to $\text{FOV}_{\text{calm}} = \text{AS sec } \theta$. If the surface elevation raises or falls, it can be shown that the (reflected) axial beam exits the field of view when the vertical surface displacement exceeds $\pm \Delta z = \frac{1}{2} \text{AS csc } \theta$. Thus, glints originating from portions of a wave lying outside this range cannot be detected even though the reflected beam travels parallel to the optical axis of the detector.

The mechanical advantages (e.g., finer angular positioning, negligibility of effects linked to surface curvature) in having the detector far from the surface had to be balanced with the limitations brought by the finite

**Fig. 3.** Block diagram of our glint measurement apparatus. Wave states in the tank are created using any combination of the tank control units for wind, wave, and current. The 1-m-radius, rainbow-shaped rail with source and detector is here rendered with AutoCAD, and shows the instrumentation positioned at the “Brewster configuration” (source and detector both at 53.1° from the vertical). The 8-channel datalogger records the polarization (3 channels), reference detector signal, and wave elevation on capacitance wires spaced 1 cm apart near the glint area (3 channels). Images of the portion of surface under investigation are captured by an imaging system (support not shown for simplicity) and stored in a separate PC. Water and air temperatures and wind speed are also monitored in each experiment.

**Fig. 4.** Effect of surface elevation on the field of view.
size of the optical elements. The detector field of view is not a cylinder as shown in Fig. 4 but a cone; thus, for a given instrument aperture, the portion of the surface that is observed depends on its distance to the detector. Moreover, the greater this distance, the faster the tangential velocity of the reflected beam. This requires higher sampling rates (tens of kilohertz), which reduce the signal-to-noise ratio because the signal tends to be lost between the high-frequency components of the instrumental and background noise. Also, capturing a statistically meaningful amount of glints can require long run times. These factors all together translate into very large data volumes.

b. Supporting structure

A special semicircular rail (radius 1.05 m), dubbed “Black Rainbow,” has been assembled to allow accurate positioning of the source and the detector over the water surface at a range of polar angles spanning the principal plane (parallel to the long axis of the tank). The rail is cut at its ends and spans an arc of approximately 160° to prevent interference with the surface. The structure is suspended from an I-beam over the long axis of the tank, about 1 m above the top of the tank itself. The rail is aligned with the long axis of the tank and firmly clamped in place. Special care was taken to minimize torques and vibrations by reducing the weight of each component including the instrumentation.

Two carriages mounting Manfrotto finely tunable geared heads are used to move the source and detector along the arc. The heads enable high-precision, final positional adjustments because of the virtual absence of backlash in the control knobs. Angles are measured within 0.2° accuracy by means of a digital protractor (PRO 3600, Applied Geomechanics, Inc.) placed in dedicated positions on the source and the detector. This gravity-based reading of the angle, through the variation of capacitance of liquid-filled sensors, allows the flat water surface rather than the rainbow to be used as a reference (defining as “flat” a water surface at rest).

The source mount also features a sliding plate for fine adjustment of the distance of the incident beam from the plane of the rainbow. The incident and the reflected beams define the plane of incidence. The electric vector of a light beam can be decomposed into \( p \) and \( s \) components (parallel and perpendicular to the plane of incidence, respectively).

c. The source

The source of light is a fiber-coupled laser diode working at 638 nm with a maximum output power of 3 mW. Fiber-optic delivery of the beam lightens the source carriage and reduces torque on the rainbow, thereby keeping the laser electronics away from the water. The diameter of the collimated beam can be adjusted with interchangeable collimators, within a range of 3–10 mm. At the lower end of this range, it is possible to illuminate only a small part of a single capillary wave to fulfill the “tangent plane approximation” (see section 5c), where the diameter of the reflected beam is equal to that of the incident beam. This condition is essential for the study of atomic-glint dynamics. The collimator is mounted on a kinematic plate. The plate is the first element of a cage system (see Fig. 5), a solid yet light frame that facilitates alignment with the rest of the embedded optical components. The polarization state of the incident beam is selected with a linear polarizer mounted on a micrometric rotating stage. The direction of the transmission axis is determined by the position that minimizes the reflection at the Brewster angle, corresponding to incident \( p \)-polarized light (light polarized in a direction parallel to the plane of incidence). Even though the radiation emitted by the diode is intrinsically polarized parallel to the \( p-n \) junction, stress-induced birefringence in the fiber cable leads to a rotation of the plane of vibration. The angle of rotation depends on the coiling of the cable and is, for all practical purposes, random. The polarizer, the next element in the optical train, transmits only the component along the selected direction (azimuth); as a result the transmitted intensity varies arbitrarily with slight motions of the cable. The most
A convenient way to circumvent this nuisance is to employ a reference detector, which collects the portion of the incident beam reflected off a “beam sampler” made of plain fused silica glass, placed as the last element in the optical train. All the intensities measured by the detector are normalized by this reference. To minimize the sensitivity to the incident polarization state, it is desirable to illuminate the beam sampler as close to normal incidence as possible. Mechanical constraints prevented us from lowering this angle below 10°, at which point the reflectance curves for s- and p-polarized light on fused silica glass depart slightly from each other. For this reason, the voltage measured by the reference detector was found to increase linearly with incident power, but the coefficient is 5.00 for p-light and 5.54 for s-light. These coefficients must be taken into account when calibrating the detector’s response.

d. The glintometer

The glintometer is a custom-built photopolarimeter based on a division-of-amplitude photopolarimeter (DOAP) design (Azzam 1982, 1985). A basic DOAP consists of a coated beam splitter and two polarizing beam splitters, so the incident beam is split into four different paths. If properly constructed (Azzam 1985; Azzam and De 2003; Savenkov 2002), each path is a linearly independent projection of the Stokes vector. Thus, the incident-beam Stokes vector can be found at any instant by a linear transformation of the measurement vector. We chose to measure only the first three components of the Stokes vector both because this leads to a simpler design and because, with a linearly polarized incident beam, we expect no circular polarization in the reflected beam. Figure 6 depicts the optical design of the glintometer; as with the source, the components are mounted within a cage system (Fig. 7). A nonpolarizing beam-splitter cube splits the incoming beam into two roughly equal parts. One is detected as is and is used to retrieve the scalar intensity, whereas the other travels to a polarizing beam splitter that transmits the component polarized in the plane of incidence and reflects that perpendicular to the same plane. Both beam splitters are from Edmund Optics. A note of caution must be observed when indicating s and p components, which are always defined relative to a plane of incidence. Since the beam splitters are mounted in a horizontal layout, the plane of incidence of light on the splitter cubes is tilted at 90° with respect to the plane of incidence on the water. Therefore, light that is parallel (perpendicular) to the plane of the page in Fig. 6 is s-polarized (p-polarized) if referenced to the source polarizer, but p-polarized (s-polarized) if referenced to the plane of incidence on the beam splitters.

Three focusing lenses with short focal length (25.4 mm), placed after the beam splitters, collect the three portions of the beam and focus them onto three detector modules. Each module consists of a monolithic photodiode and transimpedance amplifier (Burr Brown, P/N OPT101). These modules are compact because the photodiode and amplifier are integrated into a single 8-pin dual inline package (DIP). This design avoids problems such as leakage current, noise pickup, and gain peaking due to stray capacitance. The photodiode
Table 1. For two incident states of polarization, the transmittance of the scalar-intensity ($T_{sc}$), p-polarization ($T_p$), and s-polarization ($T_s$) channels; $T_{tot}$ is the total transmittance of the system.

<table>
<thead>
<tr>
<th>Incident polarization</th>
<th>$T_{sc}$</th>
<th>$T_p$</th>
<th>$T_s$</th>
<th>$T_{tot}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>46.6%</td>
<td>40.9%</td>
<td>0%</td>
<td>87.5%</td>
</tr>
<tr>
<td>$s$</td>
<td>46.3%</td>
<td>0%</td>
<td>36.2%</td>
<td>82.5%</td>
</tr>
</tbody>
</table>

The nonpolarizing beam splitter showed little dependence of its transmittance on the incident state of polarization: 47.5% for the $p$ component (relative to the beam splitter; see above) as compared to 48.3% for the $s$ component. Its reflectance exhibits twice as much variation, going from 45.4% ($p$) to 47.2% ($s$). The polarizing beam splitter transmits $p$-polarized light with 93.4% efficiency and reflects 81.7% of $s$-polarized light. Each focusing lens exhibited a constant, polarization-independent transmittance of 97.5%.

The total losses of the glintometer, with the beam splitters and the focusing lenses mounted, are given in Table 1. For $p$-polarized incident light, 46.6% of the incident intensity reaches the scalar-intensity detector and 40.9% reaches the $p$ detector, giving a total transmittance value equal to 87.5%. This provides a ratio of 0.88 between the two signals. For $s$-polarized incident light, the percentages reaching the scalar-intensity and the $s$ detectors are 46.3% and 36.2%, respectively, giving a ratio of 0.78. The total optical transmittance in this case is 82.5%. These values, determined as specified above from the readings of the power meter, are in agreement with those retrieved during the calibration [see section 3d(4)]. Thus, the glintometer detects $p$-polarized incident light more efficiently (better SNR) than $s$-polarized light. This behavior is mainly due to the polarizing beam splitter element.

2) FIELD OF VIEW

Consider the intensity photodiode and its corresponding focusing lens. The photodiode has a square active area 2.3 mm on a side, placed at a distance equal to the lens focal length (25.4 mm). Referring to Fig. 6, we see that the photodiode–lens pair has an intrinsic field of view given by $\text{FOV} = 2 \tan^{-1} \left( \frac{d}{2L} \right) \sim 5^\circ 2'$. An adjustable iris on the front of the glintometer baffle determines the FOV, controlling the cone of light reaching the detector as shown in Fig. 6. With the iris fully open, the intrinsic field of view (cone A) is protected against room-light contamination by the baffle. Cone B shows the field of view with the iris partially closed. Table 2 gives theoretical values for the field of view and the diameter of the area intercepted on a flat water surface 1 m away as a function of the aperture diameter.

Consider now the fields of view of the detectors for the polarization channels. They receive light that has gone through two beam splitters. Their distances to the instrument aperture are the same by design. Thus, they have the same FOV, slightly different than that of the scalar-intensity detector because of the extra optical path (which is equal to the distance between the centers of the two beam splitters). A further complication for the $p$-polarization detector is that, to reach it, the rays must undergo two reflections. Because of the complex geometry, the field of view was determined experiem-
tally. The glintometer was mounted on a rotating table (capable of arc-minute angular resolution) and aligned with the source. The rotation takes place about an axis that goes through the focusing lens of the scalar-intensity detector, corresponding to the vertex of the cone defining the field of view (see Fig. 6). The polarizer is then set so as to have a beam polarized at 45° (and thus detectable signals in all channels), and the response of the photodiodes is recorded as the table is manually rotated. The signal from each channel rises to a plateau and then falls as the incoming beam moves into and out of the field of view of the sensors. The field of view is the width of the plateau. The procedure is repeated for different diameters of the aperture stop. When no aperture stops are placed in front of the optics, the response of the photodiodes covers different angular ranges. The polarization channels have a larger width and are also found in a mirrored position relative to the curve of the scalar-intensity photodiode: this is believed to be the effect of the number of reflections the beam undergoes before reaching each photodiode and seems to indicate good mechanical alignment within the cage system holding the optics.

Given the chosen center of rotation, this procedure provides a measure of the FOV of the scalar-intensity photodiode only. The determination of the actual field of view of the polarization channels would require “straightening” the optical path, mounting the polarization photodiodes in place of the scalar-intensity photodiode, and increasing the length of the optical path to make up for that in between the two beam splitters. Since this configuration does not correspond to the normal operational conditions, we use the iris to limit the aperture and have the signals from the three photodiodes rising simultaneously. In the situation where the iris is closed to a point where the cone matches the intrinsic field of view, the system is considered optimized in a throughput sense against stray light. Closing the iris even further leads us closer to the paraxial approximation at the expense of a reduction of the field of view and a worse signal-to-noise ratio.

4. Calibration of the instrument

The calibration of the glintometer loosely follows the procedures outlined by Azzam and Lopez (1989) and Krishnan (1992). The purpose is to determine the polarization state and the intensity (and therefore the Stokes vector) of a beam from the readings of the photodiodes. To this end, light with known polarization states is selected on the source (accurately aligned with the glintometer). The glintometer response is then interpolated to a characteristic instrumental function, which enables the determination of the parameters of any incident beam. Errors are estimated with conventional techniques of error propagation (Taylor 1997).

The intensity of the beam leaving the source is determined from the linear relation between optical power and reference voltage \( I = V_{\text{ref}} c(\alpha) \), where \( V_{\text{ref}} \) is the voltage measured by the reference detector. As explained in section 3c, the coefficient of proportionality \( c(\alpha) \) depends slightly on the angle of polarization because of the difference between \( s \) and \( p \)-reflection coefficients on the fused-silica beam sampler at 10° incidence, where \( \alpha \) is the angle between the plane of polarization and the reference direction. (Note that \( \alpha = 0^\circ \) corresponds to \( p \)-polarized light and \( \alpha = 90^\circ \) to \( s \)-polarized light.) The value of \( c(\alpha) \) is therefore calculated by combining the retrieved limiting coefficients \( c(0^\circ) = 5.00 \) and \( c(90^\circ) = 5.54 \) with weights equal to the contribution of each polarization component to the resulting intensity. Let \( I = I_s + I_p \) be the intensity (square of the electric field amplitude \(|E|^2\)) incident on the beam sampler. The reference detector will respond with a voltage

\[
V_{\text{ref}} = c(\alpha)I = c(90^\circ)I_s + c(0^\circ)I_p = c(90^\circ)E\sin\alpha|E|^2 + c(0^\circ)E\cos\alpha|E|^2 = c(90^\circ)I\sin^2\alpha + c(0^\circ)I\cos^2\alpha,
\]

from which we find

\[
c(\alpha) = c(90^\circ)\sin^2\alpha + c(0^\circ)\cos^2\alpha.
\]

This dependence on the square of sinusoidal functions relates to the Malus law (Hecht 2002), which describes the intensity transmitted by a linear polarizer. Since the system is designed to measure reflectances, the reference detector mounted on the source is optimized to respond to a different range of radiant energies than the glintometer. As a rule of thumb, the beam sampler picks about 4% of the energy (3 mW at maximum at the exit of the laser unit, minus the variable loss due to the fiber-polarizer pair; see section 3c). Because of this low value, the effect of the polarization-dependent reflectance on the transmitted beam can be neglected. Reflection on water introduces a polarization-dependent attenuation that goes from about 98% at normal incidence to a few tens of a percent for “reasonable” angles (100% of reflectance is approached only at grazing incidence). Since a power of 0.2 mW is enough to saturate the glintometer photodiodes, neutral density filters are used to attenuate the incoming beam during calibration. This stack of filters has been characterized with a polarization-independent transmittance \( T_p = 0.0486 \pm 0.0006 \); the actual intensity
entering the glintometer during calibration is therefore $I_{\text{in}} = I_T R$.

The response of the polarization channels as the source polarizer is rotated is proportional to the polarization components. The collected data points, normalized against the incident intensity $I_{\text{in}}$, can therefore be fitted to expressions of the kind $C_1 \cos^2 \alpha$ for the $p$-polarization channel and $C_2 \sin^2 \alpha$ for the $s$-polarization channel (Fig. 8). A least squares regression provided the values $C_1 = 163 \text{ V}$ and $C_2 = 144 \text{ V}$.

Several sources of error have to be considered when estimating the uncertainty in the measured reflectance values. The uncertainty in the incident intensity can be derived from the estimates of the relative errors in the power meter reading ($\delta_p = 2\%$ from technical specifications), the coefficient $c$ ($\delta_c = 1\%$), and the transmittance of the filters used during the calibration ($\delta_T = 1\%$). The error in selecting $\alpha$ ($\delta_\alpha = 0.35\%$) is derived instead by combining the errors in the determination of the direction of the transmission axis of the polarizer ($\delta_\alpha = 1' / 360' = 0.3\%$) and in the positioning of the same ($\delta_\alpha = 0.5' / 360' = 0.15\%$).

The error in the determination of the fitting parameters is $\delta_x = 1\%$. Any unknown incident intensity $I$ illuminating the glintometer will cause a response $I_p = I C_1 \cos^2 \gamma$ in the $p$-polarization channel and $I_s = I C_2 \sin^2 \gamma$ in the $s$-polarization channel. The angle $\gamma$ is retrieved from $\gamma = \sqrt{\tan^{-1}(I_p/I_s)}$.

Suspecting that the performance of the optical power meter was poorer than specified, we relied on repeatability tests to compute the total uncertainty rather than carrying out a rigorous error propagation analysis.

These tests suggest that a reasonable estimate for the relative errors on incident intensity and the intensity detected by the glintometer are both close to 5%. Taking the quadratic sum (Taylor 1997), we obtain $\delta_R = 7\%$. This value determines the error bars of the measured reflectances (see, e.g., Fig. 9).

### Datalogging

A versatile datalogger from National Instruments (CompactDAQ series) was chosen to digitize the collected signals. The modular nature of the chassis-based system allows an easy expansion of the number of available channels. Data can be simultaneously sampled with a frequency up to 100 kilosamples per second, and logged with 16-bit resolution into a computer.

5. Results

a. The flat surface

Before introducing waves, the apparatus was tested by reproducing the Fresnel equations from measurements of the specular reflection from the flat surface at a range of angles. As seen in Fig. 9, the experimental points (representing the polarization components of the reflected intensity) show good agreement with the theoretical curves. The error bars are assigned as discussed in section 4. Somewhat surprisingly, an extensive literature search did not reveal any other reported attempt to experimentally confirm the Fresnel equations over a flat water surface.
b. Surface data

We considered several wave states ranging from gravity to capillary waves. The wave amplitudes were bounded within values favorable to the detection of glints; for example, for source and detector in specular geometry the reflection of a crest or a trough falls into the field of view [see section 3d(2)]. Gravity waves were produced with the hydraulic unit at a frequency of 1.25 Hz and a peak-to-peak amplitude of 1.3 V, set on the function generator. With these values the unit shows a horizontal linear displacement of 2.6 cm. The resulting wave profile is close to sinusoidal (with an average total wave height of 1.5 cm) although, even at low amplitude, water waves in the gravity range tend to have sharper crests and flatter troughs than sinusoids (Phillips 1977). Three capillary wave states were also generated, corresponding to wind speeds of 1.1, 3.2, and 6.3 m s$^{-1}$ (measured by an anemometer placed in the measurement area), classified as light to moderate winds in the open ocean. Since two of the covering panels of the wave tank had to be removed to mount the rainbow structure, the wind field inside the tank could not be controlled as precisely as usual. The setup nonetheless worked surprisingly well and the horizontal wind fluctuated very little.

We image the surface in the area of the illuminated spot for approximately 60 s before and 60 s after each set of reflectance measurements, at a rate of 60 frames per second. The data collected with the imaging system are meant to provide the statistics of the wave slopes. Simultaneous detection of glints and surface images is avoided to eliminate the risk of damaging the charge coupled device (CCD) detector with the reflected laser beam. Each image can be thought of as a 2D array of slope values. A subset image of approximately 200 × 400 pixels is extracted from the original 1024 × 1024 image. The resolution at the water surface is 0.35 mm per pixel, so the surface area covered by the subset image is roughly 6 cm × 12 cm.

The imaging system and its calibration have been described by Long and Klinke (2002). A Plexiglas calibration barge, with 11 slopes evenly distributed in the positive and negative domain, is floated across the field of view on the still water surface. The light-box gradient introduces a variation in intensity along the down-tank direction (the row direction in the image). Snel’s law ensures a one-to-one correspondence between each pixel’s intensity and the component of surface slope along the same direction. The response of each pixel to the series of known slopes on the barge is recorded. A polynomial fit applied to these data points enables the retrieval of the slope values corresponding to any intensity measured in the columns of cross-tank pixels.

Once the calibrated slope images are obtained, they can be analyzed further with the Hilbert–Huang transform (HHT) method established for nonlinear and non-steady data (Huang et al. 1998, 1999, 2003). The application of this method to images has been discussed by Long (2005). Each row of pixels in a calibrated image gives the instantaneous component of the local slope along the down-tank direction. The HHT separates these slope data into scale components, from the shortest (noiselike) to the longest (offsets or slow trends), giving a detailed view into the scales present within the surface dimension covered by the images. By analyzing a time series of images, the slope distribution during the time of measurement can be obtained, as well as any temporal changes of the water waves’ wavelength and frequency.

The image statistics are also important for potential future simplifications of our experiment. Proving that the time average taken over a single pixel equals the spatial average obtained over various portions of the image of increasing size will allow us to embed the imaging system in a more compact fashion and reduce data volumes, and furnish precious information about wave dynamics in general. Since high sampling rates for images can quickly generate many gigabytes of data, it is also important to assess how long a run is required to get reasonably stationary statistics.

Figure 10 compares different data taken at the nadir with the imaging system, associated with gravity and capillary wave states. The first panels in each row show sample snapshots, selected from the gravity wave (top panel) and capillary wave (bottom panel) datasets. Recalling that the images represent slope rather than surface elevation, we note that slopes vary in a much smoother way in the case of gravity waves, as opposed to the bursts observed for capillary waves. The brighter and darker areas of the images represent extreme slopes, whereas the crests or the troughs are to be found in the middle of the grayscale color map (zero slope value). For each wave state, the wave-slope distributions (rightmost panels) are computed following the slope evolution at one pixel location throughout the time sequence of images (central panels). Repeating the calculation for different pixels, we established that the distributions overlap within the experimental noise and therefore can be considered spatially stationary. Here the results are for a pixel close to the center of the field of view in the datasets containing the presented snapshots. It has also been confirmed that 1 min of data is enough to generate temporally stationary statistics.

The application of the HHT technique revealed the
presence of a nonoscillating component in both time series. This offset was believed to be introduced during the measurements by an increase in the brightness of the bulbs in the light box, and was therefore subtracted to guarantee that the average slope of each time series be zero.

The two typical peaks of a probability distribution of a pseudosinusoidal function are visible in the gravity waves data. The higher and narrower peak in the positive region shows that these waves rise with a more constant slope than they fall. This fact could be partly attributed to waves that are incompletely developed because of their relatively small distance from the paddle. Gravity waves also exhibit a rich content of zero-slope values mainly coming from their flat troughs. The total range of slopes is smaller than for capillary waves, whose more uniform distribution has tails stretching to values up to $\pm 0.3$.

**c. General facts about glints**

The reflected beam will follow trajectories determined by the slopes of the underlying waves. A crucial consideration is that glints are observed only when the reflected beam is observed through a limited aperture (in our case, the instrument entrance window, ultimately determined by the iris placed in front of the baffle). The full-width at half-maximum of the glint peaks, which is connected to their linear velocity, depends on the observation distance. Within the *tangent plane approximation*, glints are observed every time the surface slope is oriented so as to realize the specular geometry between the source and the detector. If the source and detector are positioned at polar angles $\theta_S$ and $\theta_D$, the reflected beam will hit the center of the field of view when the incident beam illuminates a portion of surface tilted at an angle $\beta = \frac{1}{2}(\theta_D - \theta_S)$.

As an example of how glints are generated, we show the output of the channels as the flat water surface is disturbed by a train of gravity waves driven down the tank by the hydraulic paddle (Fig. 11). By combining the output from the capacitance wires and the three detectors, we obtain an actual representation of the wave state with the glint intensities overlapped with the slopes at which they occur. Here the source illuminates
the water surface at the Brewster angle (53.1° from the vertical). The constant signal of the Fresnel reflectance on the flat surface is broken down in glints as the first gentle, small-amplitude waves modify the surface tilt at the location of the illuminated spot. As expected, glints appear at the same position for each cycle (i.e., only at that particular slope that exactly realizes the specular reflection conditions between source and detector). Missing glints are due to the physical impossibility of generating perfect 1D waves traveling down the tank, a situation that occasionally leads to reflect the incident beam off the plane containing the source and the glintometer.

The investigation was extended to a wider range of wave states. Gravity waves (1–3 Hz in frequency) have smaller slopes than capillary waves, and therefore the reflected beam spans a smaller angular range. The slope evolution in time is also slower and the profile of atomic gravity glints looks smoother, as can be observed in Fig. 12. On the other hand, steeper slopes and faster time evolution, typical of capillary waves, direct the reflection in a more random fashion. Atomic capillary glints are 5–10 times shorter lived, consistent with their typical frequency of 14–15 Hz. The repeated, high-speed grazing of the reflection in and out the field of view, with a considerable portion of time spent at its edge, accounts for the finer modulation of their profile (Fig. 13).

A spot size of 3 mm covers an area that in the case of capillary waves is comparable to the wavelength of some of the waves. Therefore, the blooming of the reflected beam as an effect of surface curvature can also be partially responsible for a decrease in the peak intensities of the glints. For wavelengths greater than the spot size, the distance of the glintometer from the water surface guarantees that surface curvature effects are, to a good approximation, negligible.

6. Conclusions

We have described an experimental apparatus designed to collect polarimetric measurements of light re-
reflection off controlled wave states created in the wave tank at the Air–Sea Interaction Research Facility at NASA GSFC Wallops Flight Facility. The relatively inexpensive system was assembled from scratch, and consists of a suspended semicircular rail on which a laser source and a detector can be precisely locked in position to point at a small area of the water surface at specified polar angles, yet moved quickly to new angular positions. Movement along the rail is accomplished with carriages equipped with geared heads developed for the film industry, which allow fine positional and angular tuning of the source and/or detector.

The detector is a custom-built photopolarimeter. It splits an incoming beam to measure the first three components of its Stokes vector, digitizing them with a fast datalogger.

The setup also includes a separate imaging device to capture snapshots of the surface around the illuminated spot, developed as part of the wave tank infrastructure by S. Long. The images are collected at a repetition rate fast enough (60 Hz) to freeze any wave state created in the tank. Using a gradient-intensity light source at the bottom of the tank, the images can be transformed to wave-slope images, providing vital context for our glint measurements. An ancillary system of capacitance-wire probes provides an independent measure of surface elevation and slope, but it is useful only for gravity and not capillary waves.

The overall system enables the study of atomic glints, the basic elements of which the familiar sunglint patterns are composed. It is capable of collecting billions of glints to form a statistically significant sample for carefully monitored and repeatable wave states ranging from capillary to moderate-amplitude gravity waves. As the reflected beam grazes through the field of view of the detector, the good signal-to-noise ratio generates clean profiles revealing the inherent link between surface dynamics and projected trajectories. The system will also allow us to study any deviations from standard theories due, for example, to curved water surfaces.

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