9.8 INFRARED PROPAGATION IN THE MARINE ATMOSPHERIC SURFACE LAYER: EXTINCTION AND REFRACTION

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1. INTRODUCTION

The near-surface portion of the marine atmospheric surface layer is a dynamic propagation environment for optical and infrared (IR) signals. Particularly eminent are the effects of strong vertical refractivity gradients and localized aerosol gradients. The type and concentration of aerosols and gases in the intervening atmosphere result in a degradation of the IR and visible (VIS) signals. For a number of different viewing angles close to the horizon the atmospheric transmittance is determined by the absorption by atmospheric gases and by the absorption and scattering by aerosols. A long-range goal of the studies of the performance of IR/VIS systems is to obtain an understanding of the effects generated by the mixture of different meteorological conditions, locations (over ocean or over land), and solar position. Typically the atmospheric effects result in three primary distortions: a) extinction, which results from absorption and scattering by aerosols and molecules, b) refraction, which results from the collective bending of the beam, and c) scintillation, which results from incoherent scattering. The above distortions affect various types of systems, i.e., IRST (IR Search & Track), and wavelengths, such as laser at IR and visible frequencies, and radar in radio frequencies.

A number of field studies both over land and over ocean has been conducted to better understand the above distortions (Doss-Hammel et al., 2002a, Jensen et al., 2001, and Tsintikidis and Doss-Hammel, 2002). The Rough Evaporation Duct (RED) campaign assessed the effects of the air-sea boundary layer on microwave (MW) and IR signal propagation near the sea surface during the summer of 2001. The RED experiment was designed around the Floating Instrument Platform (FLIP), which was moored 10.5 kilometers off the northeast shore of Oahu, Hawaii.

In this report we present measurements collected by the EO group of the Atmospheric Propagation Branch from the Space and Naval Warfare (SPAWAR) Systems Center (SSC), San Diego during the period of 15 August – 15 September 2001. The primary objective of the SSC EO group was to characterize the atmospheric propagation path, and the experiment was designed to measure both the transmission and scintillation signals. Preliminary results are presented on the analysis of the transmission signal detected during the RED field campaign.

2. EXPERIMENTAL CONFIGURATION AND POINTING ISSUES

The field test was based upon measurements collected by a transmissometer system. The transmissometer system comprises a transmitter and a receiver. The primary reference transmissometer consists of a broadbeam transmitting source and a receiving telescope. The broadbeam source comprised 18 halogen lamps modulated by a 690-Hz chopper wheel. The source also has a usable beam width of approximately 25° (full angle). The chopped signal is relayed to the receiver via a radio link at 162.1 MHz. The receiver telescope has a primary mirror that is a gold-plated paraboloid 20 cm in diameter and a focal length of 1.22 m (F/6) (see Zeisse et al., 2000, for details of a similar to SSC's transmissometer system).

The original receiver system consisted of the telescope and a mid-wave IR detector. The detector is a non-imaging device cooled to 77 °K. For a given source radiance (in our case defined by the combined strength of the 18 halogen lamps) the detector responsivity, noise density, and bandwidth determine the signal-to-noise ratio in the field. The mid-wave detector is a 2-mm circular diameter InSb photodiode mounted below a cold optical filter with an almost square bandpass between 3.5 μm and 4.1 μm. The signal from the detectors is separated from the chopped carrier waveform by means of a lock-in amplifier system.

The platform for the transmissometer source was FLIP, which is operated by the Marine Physical Laboratory of the Scripps Institution of Oceanography for the Office of Naval Research. FLIP is a stable oceanographic research platform 110 m in length that consists of a long slender tubular hull terminating in a normal ship's bow section, which is 17 m in length. In its operational mode portions of the hull are flooded with water and the vessel is flipped so that the long axis of the hull is vertical and largely submerged. Long booms extend horizontally from the bow section for instrument placement.

The port side boom, about 17 m in length, has a vertical mast at its end that extends downwards into and below the ocean surface. Mean and turbulent profiles of the basic meteorological quantities as well as ocean surface elevation statistics were made from this mast.

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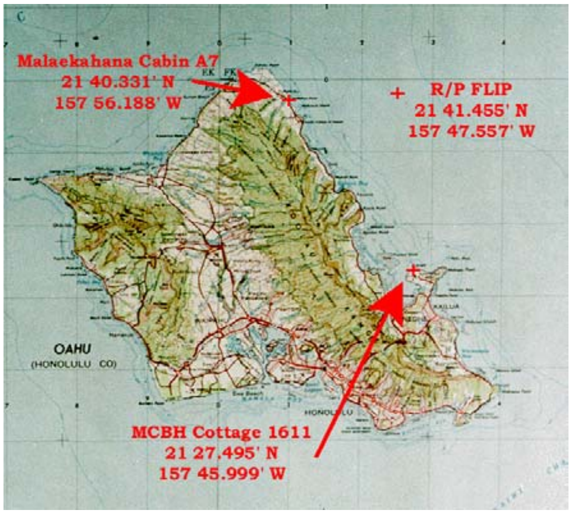

Figure 1: Various locations of interest: FLIP's anchor point, Malaekahana State Park, and MCBH Cottage (used by the RF component of the RED experiment).

At the same time various instruments located on the bow section measured aerosols and solar radiance.

The transmitting broadbeam source was mounted on one of FLIP's horizontal booms. The overall height above sea level (ASL) was 12 m. The receiver was installed approximately 10.5 kms from FLIP in the Malaekahana State Park in the northeast coast of Oahu, HI (see Fig. 1), and at a height of 3 m ASL. The data generated for this path spanned days-of-year (DOY) 241 through 257.

According to the data collection protocol one-minute averaged transmission data were recorded every minute, with interruptions for high-speed scintillation measurements. These interruptions occurred every 15 minutes. The scintillation measurement procedure sampled the signal at a 300-Hz rate and for a continuous 109-second period.

During the past, the SSC EO group participated in field campaigns conducted mostly over land where the narrowbeam transmitter was used since there is no motion associated with the transmitter location (see, for example, Tsintikidis and Doss-Hammel 2002). During the RED Experiment the overwhelming majority of instruments was mounted onboard FLIP. FLIP is a stable platform but at the same time it is susceptible to sea current motions especially if its mooring lines are not tight enough. In addition, FLIP also rotates around its vertical axis (in its vertical configuration) due to wind loading on the booms. The above considerations led to the inclusion of the broadbeam source instead of the narrowbeam one that has been used in the majority of past field campaigns.

FLIP's range from the Malaekahana cabin changed by only about ±100 m around its intended position (at approximately 10500 m). However, as Figure 2 suggests large beam-pointing excursions occurred, i.e., up to 54 degrees (for the heading of 266° the broadbeam source points exactly at the receiver in the Malaekahana cabin). The variations in both range and pointing were attributed to long mooring lines that had not been adequately tightened. Due to FLIP's large pointing excursions and the narrowbeam nature of the receiver at Malaekahana it was required to realign the receiving telescope frequently hence a realignment was performed every hour, on the hour. With the exception of a few hours during the night realignments were done for the majority of hours in a 24-hour period (resulting in 20 – 24 realignments per day).

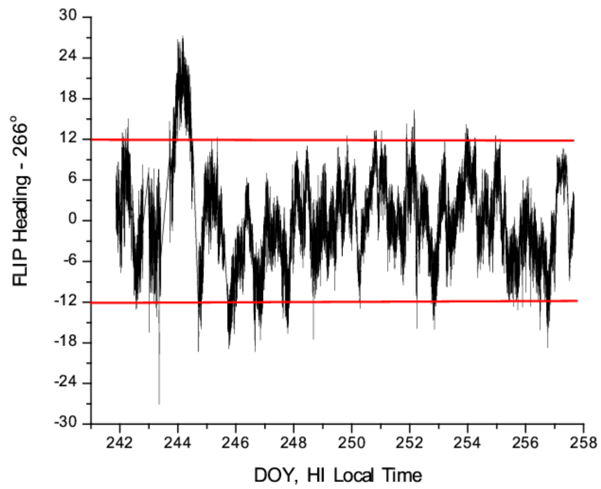

Figure 2: Beam-pointing excursions from the bearing of 266°, the bearing that corresponds to pointing exactly at the receiver site at the Malaekahana State Park. Note the wide variation in pointing values and the fact that the majority of headings are within 24 degrees.

In addition, meteorological data were collected via the Naval Postgraduate School (NPS) 'flux' buoy that was anchored approximately in the middle of the transmissometer path. The suite of meteorological instruments onboard the NPS buoy provided data on air temperature, pressure, humidity (at various heights ASL), wind speed and direction, sea surface temperature. The NPS 'flux' buoy meteorological data set is crucial in the analysis of the transmission and scintillation time-series. Finally, it should be noted that additional meteorological data was collected at the receiver site via a Davis meteorological station (air temperature, pressure, humidity, wind speed and direction) that was positioned approximately 30 ft above the ground. However, the Davis meteorological station data set is of more limited scope when compared to its NPS 'flux' buoy counterpart.

3. DATA ANALYSIS

The data analysis and quality assurance procedure began with a correction for signal intensity to compensate for intensity changes due to beam axis pointing excursions (see Fig. 3). As noted above, FLIP did experience a yaw motion about the vertical axis over a maximum range of 54° (see Fig. 2), and our calibrated angular beam extent was 20°. The source beam axis bearing was recorded from GPS and inertial navigation equipment onboard FLIP. We eliminated all transmission data points for which the beam axis was outside this range.

As a next step, all transmission data points for which there were no FLIP position and bearing data available were eliminated. The signal levels were then normalized to the computed free-space value for our source at the range of 10470 m (the mean range of FLIP from the Malaekahana cabin).

The primary factors in received signal intensity are refraction, extinction, and scintillation. The scintillation measurements will be described in a companion paper

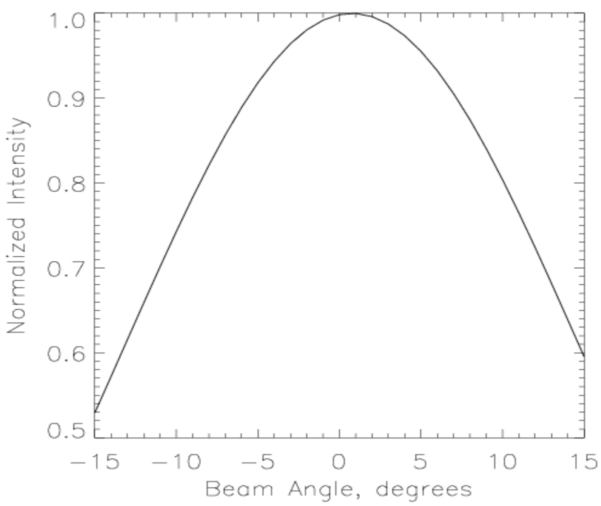

Figure 3: The correction function for the broadbeam source. The source beam intensity was measured for angles to ±10°. The curve is not symmetric about 0°: the measured maximum beam intensity occurs at 1°.

(Doss-Hammel et al. 2003), and scintillation phenomena do not appear in the transmission data because of the long averaging times (one-minute) for each transmission measurement. The two remaining factors are therefore the primary determinants of the received signal intensity.

The meteorological conditions for the RED test produced a `typical' maritime sub-refractive environment: T_{air} - $T_{surface}$ < *0*. This environment can produce inferior mirages, which will augment the signal intensity at the receiver. In previous tests, refractive effects have been an important constituent of the full infrared signal analysis (see Doss-Hammel et al. 2002a, and Doss-Hammel and Zeisse, 2002). However, during the RED experiment, refractive changes in the signal intensity did not appear to be a significant factor. The test configuration geometry included a receiver near the sea surface, a source relatively high above the sea-surface, and a moderate range between the two. In addition, there were almost always significant wave heights during the test. Initial application of ray-trace models, using the EOSTAR propagation assessment tool, predicts that mirage images do not occur for the geometric and environmental conditions during the test. Our normal operational procedure includes an IR imaging system to provide direct imagery of the propagation environment. Unfortunately we were unable to use this equipment for this test, and we are therefore unable to corroborate the above claims.

On the other hand, the signal extinction due to aerosols and gases was a critical effect. The model for extinction was generated in a two-step process. First, MODTRAN (Berk et al., 1999) was used to predict gaseous extinction for each meteorological data point we had. The second step of the process utilized the Advanced Navy Aerosol Model (ANAM) to predict the

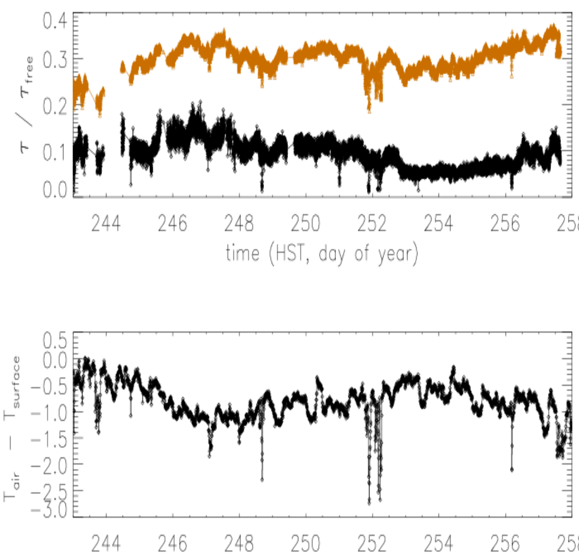

Figure 4: The record of the corrected values for the normalized transmission τ over the 15 days of the validated data collection is shown in the upper panel. The upper curve shows the predicted signal intensity using the combined extinction models. The lower curve shows the measured normalized signal intensity. The lower panel shows the record of T_{air} – $T_{surface}$ measured at the mid-path by the NPS met buoy.

effects of aerosols on propagated signals (van Eijk et al., 2002). The ANAM model extends and elaborates the single-height Navy Aerosol Model (NAM) model by providing a height-dependent extinction profile.

To provide a sense of the signal propagation environment, Figure 4 displays almost the entire useful infrared transmission data set from RED. It consists of a 15-day record of transmission τ as recorded by the transmissometer and a comparison with the predictions from the extinction model. For the first 10 days (DOY 243 to 252) the recorded field data is a factor of ~3 smaller than the predicted signal after extinction effects alone. For the last 5 days of the data set, the ratio between model and observation is between 4 and 5. The sharp downward spikes that correlate through both time series correspond to rain shafts moving through the propagation path. The signatures of the various rainfall events can be seen additionally at relative humidity, air, and sea temperature time series from the NPS 'flux' buoy data.

A single day (DOY 245) comparison of the modeled transmission and the observed normalized signal is shown in Figure 5. The lower panel displays the measured quantity T_{air} - $T_{surface}$ from the NPS flux buoy. This quantity is the primary indicator of the refractivity state and optical turbulence conditions. The upper panel displays the normalized transmission τ/τ_{free} where τ_{free} is the calculated free-space value for the signal

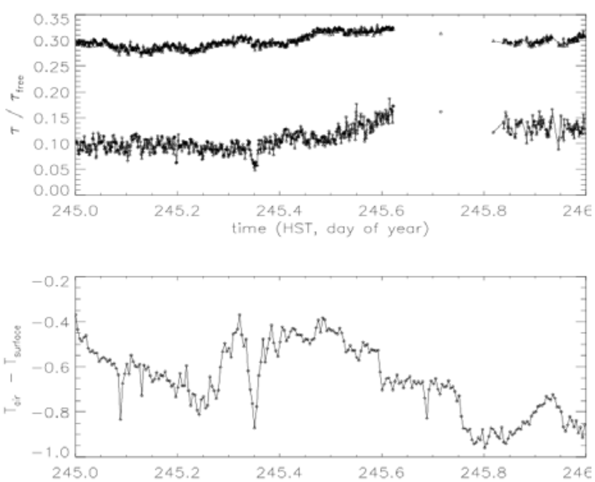

Figure 5: Single 24-hour day view of the comparison between modeled transmission (upper curve) and observed infrared intensity (lower curve) is shown in the upper panel. The lower panel shows the corresponding values of T_{air} – $T_{surface}$.

over the propagation range. If there are no other factors that modify intensity, and if the model is perfect, the two curves in the upper panel should coincide. It can be seen that the trends in the two curves match fairly well. The correlation between the extinction model prediction and the observed infrared signal intensity is χ~0.61.

Finally, one more view of the 24-hour signal for DOY 252 is shown in Figure 6 to elucidate the components of the modeled signal. The green line shows the ANAM-based aerosol transmission prediction τ_{aero}, the blue line shows the MODTRAN-based molecular transmission prediction, τ_{molec}, of the signal, and the brown line shows the product of the two. The black line shows the transmission observations and the red line superimposed on the black one shows the best fit of the brown line to the observations $0.27\,\tau_{aero}\,\tau_{molec}$. The downward pointing spikes in both the predicted and observed signals correspond to early morning rain showers. Such spikes would also be visible in the T_{air} - $T_{surface}$ time-series. The model captures the trend nicely, even though it does not invoke any precipitation extinction.

The discrepancy between modeled signal and observed signal is apparent in figures 4 – 6. Currently an effort is underway concentrating on the possible

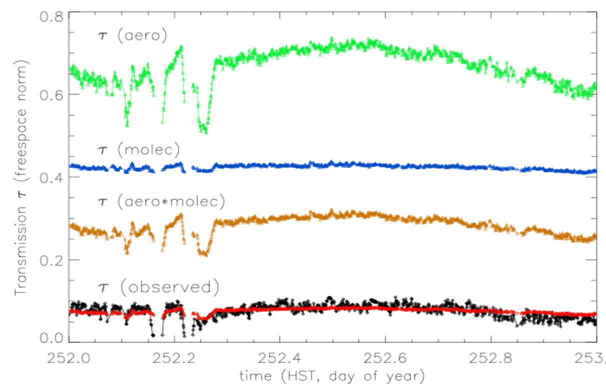

Figure 6: The green line corresponds to the ANAM-based predicted signal, the blue line to the MODTRAN-based predicted signal, the brown line is the product of the two, the red line is the best fit of the brown line to the observations (black line).

reasons that could explain the discrepancy. The contribution of coastal aerosol may play a significant role in the signal extinction. The IR propagation path passed over a near-shore surf zone containing breaking waves. The first kilometer of the propagation path from the receiver was within ~3 m of the surface. Clarke et al., 2003, made coastal aerosol measurements at various times at a point roughly 400 m from the receiver site. Their analysis for a wavelength of 4 μm, and assuming a zone of 1000-m surf exposure, yields an additional transmission factor τ_{surf}. If we represent the signal $\sigma=\tau_{surf}\tau_{aero}\tau_{molec}$, the analysis by Clarke et al. indicates $\tau\approx0.5$ is a possibility for a full 1000-m surf zone exposure. Note that the τ_{surf} of this magnitude still fails to close the gap between predicted transmission and observed signal. We expect that the variability in this factor is larger than the gap.

Our receiver, when the tidal motion is considered, was between 2 and 3 m ASL, a fact that can increase extinction by an additional 20%. Increased humidity close to the Malaekahana cabin, and the presence of whitecapping along the propagation path, could further increase the extinction estimates (Tony Clarke, private communication).

4. CONCLUSIONS

The RED experiment provided a unique opportunity to study a propagation environment with warm water, sustained winds, and correspondingly rough sea surfaces in a nearly open ocean environment. For the transmission test geometry that we used, the rough sea surface acted primarily as a barrier to the appearance of an inferior mirage image of the source. This removes the possibility for a signal augmentation by refractive propagation factors (Doss-Hammel et al. 2002a, and Doss-Hammel and Zeisse 2002).

Over the duration of the field test the received infrared signal was smaller than model predictions by a factor that ranged from 2.5 to 5. The small signal induced a further problem in signal-noise ratio, which in particular made calculations of the refractive index structure function C_n^2 problematic (Doss-Hammel et al. 2002b, 2003).

The fundamental puzzle generated by the infrared measurement campaign during RED is to reconcile a model that over-estimates the measured signal by factors that vary from 2.5 to 5. The resolution of this question may necessitate a follow-up experiment in another environment with similar meteorological conditions. The discrepancy may also provide the impetus for further work on the scaling parameters for the aerosol extinction models NAM and ANAM. Finally, the impact of coastal aerosols on the transmission signal should be examined in great detail.

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