POLLEX trial report
A study of turbulence in the littoral zone

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Abstract

The POLLEX trial was carried out to study the effects of refraction and turbulence on atmospheric propagation and their impact on optical imaging systems, in particular Infrared Search and Track systems (IRSTs). During earlier NATO trials (MAPTIP and LAPTEX) the data collected on point target signatures showed quantitative scintillation effects when the optical paths propagated through the lowest regions of the marine boundary layer. Similar effects have also been observed during other measurement campaigns; however, a consistent problem has always been the determination or measurement of the refractive index structure function coefficient, $C_n^2$, upon which all turbulence calculations depend. The group’s need for additional data sets obtained under stable atmospheric conditions, when the air-sea temperature difference (ASTD) is positive and over-the-horizon detection is possible, was also a driving force for this trial.

TG16 chose to perform the trials in Livorno during the month of May because of the high probability of the occurrence of stable atmospheric conditions in the spring. With a water temperature of 17 °C and an offshore wind, air temperatures of up to 22 °C and higher were expected. In addition, Mariteledarad (MTR), the Italian Defence Research Institute, agreed to host the trial, offered secure locations for the group’s measurement equipment, the use of the ship, Porpora, to install an instrumented buoy and perform runs with calibrated IR sources and a RF reflector, access to the island of Gorgona at a range of 34 km for the installation of a set of fixed IR sources and RF reflectors, and access to a breakwater at 2 km from the site for the study of turbulence.

DRDC Valcartier’s primary interest was to obtain quality turbulence data using access to the breakwater, as it provided an excellent opportunity to study the effects of turbulence while simultaneously measuring the index of refraction structure coefficient using several independent techniques. As such, while the report provides general information about the efforts of the other nations and Canada’s complete effort, the principal emphasis of the report is restricted to the turbulence work.

Résumé

La campagne de mesure POLLEX a été effectuée pour étudier les effets de la réfraction et de la turbulence sur la propagation atmosphérique et leur impact sur les systèmes d’imagerie, en particulier les systèmes infrarouges de recherche et de poursuite (IRSTs). Lors de campagnes de mesures précédentes de l’OTAN (MAPTIP et LAPTEX), les données recueillies sur les signatures de cibles non résolues ont montré des effets de scintillation lorsque les chemins optiques passent par les régions inférieures de la couche atmosphérique marine. On a également observé des effets semblables lors d’autres campagnes de mesure. Cependant, le problème de la détermination ou la mesure du coefficient de fonction de structure d’indice de réfraction, $C_n^2$, dont tous les calculs de turbulence dépendent, était toujours présent. Les besoins du groupe pour obtenir des données additionnelles dans des conditions atmosphériques stables, quand la différence de température air-mer (DTAM) est positive et la
détectection au-delà de l'horizon est possible, constituaient également un puissant incitatif à la participation à cette campagne de mesures.

TG16 a choisi d'exécuter ces essais à Livourne pendant le mois de mai en raison de la probabilité élevée de conditions atmosphériques stables. Avec la température de l'eau à 17°C et le vent en provenance de la mer, on pouvait s'attendre à ce que la température de l'air atteigne jusqu'à 22°C. Un autre avantage de nature plus pratique était la présence de Mariteleradar (MTR), l'institut de recherche Italien pour la défense, qui avait offert son site, des endroits sécuritaires pour les équipements et plusieurs autres services. La présence d'un port naval et l'utilisation du navire Porpora pour installer une bouée instrumentée et effectuer des trajets avec des sources IR étalonnées, de l'équipement météorologique et des sources optiques, représentaient également de grands avantages. La présence de l'île de Gorgona, distante de 34 kilomètres, permettait également l'installation d'un ensemble de sources fixes pour une étude continue. Finalement, la présence d'un brise-lames à 2 kilomètres de l'emplacement de MTR fournissait une excellente occasion d'étudier les effets de la turbulence sur une cible, une image construite expressément pour ces essais, tout en mesurant simultanément le coefficient de l'indice de réfraction à l'aide de plusieurs techniques.

L'intérêt de RDDC Valcartier pour ces essais a été en grande partie motivé par le désir d'obtenir des données de turbulence de bonne qualité au-dessus du corridor optique de 2 kilomètres en direction du brise-lames. Ce rapport présente des informations générales au sujet des travaux effectués par les autres nations, ainsi que l'ensemble des travaux effectués par le Canada. La plus grande partie du rapport porte plus précisément sur les études de turbulence dans le corridor optique de 2 km.
Executive summary

DRDC Valcartier has a long-standing interest in studying the effects of the marine boundary layer on the propagation of optical radiation through the atmosphere and its effects on imaging systems. As such, the Sensor Performance Prediction group within the Sensing (Air and Surface) Optronic Section has been highly implicated in the work of NATO task group RTO\SET\TG16. TG16 is a Task Group under the Sensors and Electronics Technology Panel of NATO’s Research and Technology Organization, and its work program is called Infrared Measurements and Modelling for Ship Self Defence.

TG16 organized the POint targets at Low eLevation EXperiment (POLLEX) trial to investigate the effects of refraction and turbulence on atmospheric propagation and their impact on optical imaging systems like Infrared Search and Track systems (IRSTs) and to improve the post-processing techniques used for target detection and identification. In earlier trials, data on point target signatures showed quantitative scintillation effects when the beam propagated through the lowest part of the marine boundary layer. However, a consistent problem has always been the determination or measurement of the refractive index structure function coefficient, $C_n^2$, upon which all turbulence-based calculations (scintillation, temporal correlation, spatial correlation, etc.) depend.

To answer these questions, TG16 chose to perform the trials in Livorno during the month of May because of the high probability of stable atmospheric conditions in the spring. With a water temperature of 17 °C and an offshore wind, air temperatures of up to 22 °C and higher were likely to occur. In addition, Mariteleradar (MTR), the Italian Defence Research Institute, agreed to host the trial, offered secure locations for the group’s measurement equipment, the use of the ship Porpora to install an instrumented buoy and perform runs with calibrated IR sources and an RF reflector, access to the island of Gorgona at a range of 34 km for the installation of a set of fixed IR sources and RF reflectors, and access to a breakwater 2 km from the site for the study of turbulence. This breakwater provided an excellent opportunity to study the effects of turbulence on a specially constructed image target while simultaneously measuring the index of refraction structure coefficient using several independent techniques.

Sommaire

RDDC Valcartier s'intéresse depuis longtemps à la propagation optique dans la couche atmosphérique située à la frontière maritime et à ses répercussions sur les systèmes d'imagerie. En tant que tel, le groupe de la Prédiction de la Performance des Capteurs de la section de la Détection (Aérienne et en Surface) /Optronique a été fortement impliqué dans le groupe de travail de l'OTAN, RTO/SET32/TG16. TG16 réalise ses travaux sous le panel Technologie Electronique de l'Organisation de la Recherche et de la Technologie de l'OTAN et son programme de travail est consacré aux mesures et à la modélisation de l’infrarouge pour la défense des navires.

TG165 a organisé l'épreuve de POLLEX (POint targets at Low eLevation EXperiment) pour étudier les effets de la réfraction et de la turbulence sur la propagation atmosphérique et leur impact sur les systèmes d’imagerie comme les systèmes infrarouges de recherche et de poursuite (IRSTs), et pour améliorer les techniques de processus antérieur utilise pour la détection et l’identification du cible. Lors d'épreuves précédentes, les données rassemblées sur les signatures de cibles points ont montré des effets quantitatifs de scintillation lorsque le faisceau s’était propagé à travers la partie la plus inférieure de la couche marine. Cependant, il y avait toujours le problème de la détermination ou de la mesure du coefficient de fonction de structure d'indice de réfraction, $C_n^2$, dont tous les calculs de turbulence (scintillation, corrélation temporal, corrélation spatiale, etc.) dépendent.

Pour répondre à ces questions, TG16 a choisi d'exécuter les épreuves à Livourne pendant le mois de mai en raison de la probabilité élevée de l'occurrence de conditions atmosphériques stables au printemps. Avec la température de l’eau à 17 °C et le vent de mer, on se serait attendu à ce que les températures de l’air atteignent jusqu’à 22 °C. Un autre avantage plus pratique était la présence de Mariteleradar (MTR), l’institut de recherche italien pour la défense, qui avait offert son site, des endroits sécuritaires pour l’équipement et plusieurs autres services. La présence d'un port et l'utilisation du navire Porpora pour installer une bouée instrumentée et effectuer des trajets avec des sources IR étalonnées, de l'équipement météorologique et des sources optiques étaient également d’un grand avantage. La présence de l'île de Gorgona, distante de 34 kilomètres, a également permis l'installation d'un ensemble de sources fixes pour une étude continue. En conclusion, la présence d'un brise-lames à 2 kilomètres de l'emplacement de MTR a fourni une excellente occasion d'étudier les effets de la turbulence sur une cible, une image construit spécifiquement pour ces épreuves, tout en mesurant simultanément le coefficient de l'indice de réfraction en utilisant plusieurs techniques.

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Finally, the authors would like to acknowledge the considerable assistance of Luc Gauthier in providing all the necessary technical support to ship the equipment to Italy, install it on site and return it safely to Canada. Without his support none of this work would be possible.
1. Introduction

DRDC Valcartier has a long-standing interest in studying the effects of the marine boundary layer on the propagation of optical radiation through the atmosphere and its effects on imaging systems. As such, the Sensor Performance Prediction group within the Sensing (Air and Surface) Optronic Section has been closely involved in the work of NATO task group RTO\SET32\TG16. TG16 is a Task Group under the Sensors and Electronics Technology Panel of NATO’s Research and Technology Organization, and its work program is called Infrared Measurements and Modelling for Ship Self Defence. Thirteen nations are cooperating in this group on two major topics, one on the modelling of the IR signature of ships, for example, the SHIPIR model (Ref. 1), and one on the modelling of sensors for detection and tracking of low-flying targets at sea, for example, the IRBLEM (Ref. 2) and LWKD (Ref. 3) models. Cooperation among the nations includes common experimental trials that are of benefit to all its members. This report deals with the POint targets at Low eLevation EXperiment (POLLEX) trial that was carried out during the month of May in the Mediterranean Sea near Livorno, Italy by Italy, Germany, The Netherlands, the USA, Denmark, Norway, and Canada.

The POLLEX trial was designed to investigate the effect of atmospheric refraction and turbulence and their impact on optical imaging systems, like Infrared Search and Track systems (IRSTs), and on the development of post-processing algorithms used for target detection and identification. During the 1992 MAPTIP trial (Ref. 4,5) and the 1996 LAPTEX experiment (Ref. 6,7,8), earlier NATO groups collected data on point target signatures showing quantitative scintillation effects when the beam propagates through the lowest part of the marine boundary layer. Similar effects were also observed during other measurement campaigns; however, a consistent problem has always been the determination or measurement of the refractive index structure function coefficient, $C_n^2$, upon which all turbulence calculations depend. The group’s need for additional data sets obtained under stable atmospheric conditions, when the air-sea temperature difference (ASTD) is positive and over-the-horizon detection is possible, was also meant to be addressed during this trial.

TG16 chose to perform the trials in Livorno during the month of May because of the high probability of stable atmospheric conditions in the spring. With a water temperature of 17 °C and an offshore wind, air temperatures of up to 22 °C and higher were likely to occur. Another more practical advantage was the presence of Mariteleradar (MTR), the Italian Defence Research Institute that agreed to host the trial and offered secure locations for the group’s measurement equipment and many other services. The presence of a naval harbour and the use of the ship Porpora to install an instrumented buoy and perform runs with calibrated IR sources, meteorological equipment, and visible sources were also of great benefit. The presence of the island of Gorgona at a range of 34 km also allowed installation of a set of fixed sources for continuous study. Finally, the location of the Pilastro breakwater at 2 km from the MTR site provided an excellent opportunity to study the effects of turbulence on a specially constructed image target while simultaneously measuring the index of refraction structure coefficient using several independent techniques.
DRDC Valcartier’s interest in this trial was largely motivated by a desire to obtain good quality turbulence data over the 2 km path to the breakwater. As such, while this report provides general information about the contributions of the other nations and Canada’s complete effort, the principal emphasis of the report will be the turbulence work carried out over the 2 km path. As such, section 2 provides a description of all the experimental set-ups, section 3 gives an overview of the general meteorological conditions observed during the trial, section 4 provides a discussion on the effects of turbulence on imaging systems, and section 5 presents the results of our estimated structure coefficients, in particular the index of refraction structure coefficient. Finally, section 6 provides some discussion and comparison of our results and section 7 wraps up with some conclusions.

This work was carried out between May 2001 and May 2002 under work unit 1AB11, Propagation Effects in the Marine Boundary Layer.

2. Experimental setup

The physical situation of the Livorno site is shown in Figure 1, with a long experimental path out to the island of Gorgona and a short experimental path out to the Pilastro breakwater. The circle where the two green lines, representing the two experimental paths, meet shows the location of the Italian defence institute, MTR. A second vantage point (lower black line), with a viewing direction of 250° towards Gorgona Island, was situated 2.3 km south of MTR at the Universal Hotel. These two viewing lines were used to observe the set of fixed lights installed on the island. Tracking of the lights on the Italian naval vessel Porpora and of a military helicopter out to the horizon was measured along a viewing direction of 270° as seen from MTR (upper black line). Finally, two buoys were moored about 7.4 km from the shore southwest from MTR. The first buoy was provided by The Netherlands and is capable of measuring the air temperature at multiple heights above the water level and the sea temperature, and the second buoy was a wave-rider buoy provided by NATO’s SACLANT Centre in La Spezia, Italy that could give statistics about the waves. Other meteorological stations were located at MTR, on the Porpora, on the breakwater, and on Gorgona Island. The details of the long and short experimental paths are given below.

2.1 Long experimental path

The main purposes of the long experimental path were to observe the lights on Gorgona Island, track the lights on the Porpora and a military helicopter out to the horizon, and measure the effects of refraction and scintillation on the observation and detection range for various camera systems. All nations used at least one camera system on this path.

The Netherlands installed eighteen 50 Watt quartz halogen lamps on Gorgona Island, that were each mounted in the focal plane of a standard 150 mm diameter parabolic reflector with a divergence of 2° (see Fig. 2). This allowed nine of them to be aimed towards MTR and the other nine towards the Universal Hotel. Their heights above the water are given in Table 1. Each source was protected from the weather by an IR transmitting plastic foil such that the output radiant intensities were about 1.5 kW/sr in the 0.7-1.0 µm spectral band and 60 W/sr in the 3.6-4.0 µm band. For a nominal height of 15 m above water level (the height of most
sensors at MTR) and for a range of 34 km out to the island, the 4 lowest sources of each pair are expected to be below the geometrical horizon. In addition to these optical measurements, a group from Germany also installed a radar corner reflector just to the left of the uppermost lights about 50 m above the water. This was used to compare the observing ability of a millimeter wave system with the group’s various camera systems. Finally, Germany also installed a basic meteorological station near the base of the lights.

**Table 1**: Heights of the 18 lamps installed on Gorgona Island during POLLEX.

<table>
<thead>
<tr>
<th>Lamp #</th>
<th>Lamps towards Hotel</th>
<th>Lamps towards MTR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13.1</td>
<td>12.4</td>
</tr>
<tr>
<td>2</td>
<td>19.0</td>
<td>18.8</td>
</tr>
<tr>
<td>3</td>
<td>24.3</td>
<td>24.2</td>
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<td>30.1</td>
<td>30.3</td>
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<td>5</td>
<td>33.2</td>
<td>33.0</td>
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<td>6</td>
<td>36.3</td>
<td>35.9</td>
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<tr>
<td>7</td>
<td>42.4</td>
<td>42.6</td>
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<tr>
<td>8</td>
<td>46.9</td>
<td>46.6</td>
</tr>
<tr>
<td>9</td>
<td>51.1</td>
<td>51.0</td>
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</table>

**Figure 1.** Chart of the Livorno site showing the location of the breakwater, Gorgona Island and the TNO-FEL buoy with respect to the observing site at Mariteledarad
Figure 3 shows the Porpora and the position of many of the lights that were installed on her. These included two calibrated IR sources mounted on a special 10 m mast by The Netherlands. One of these sources was at a height of 11.4 m above the water level and emitted forward, while the second source, at a height of 11.7 m above the water level, emitted towards the stern. These sources have a large beam divergence of 60° in the horizontal plane to allow for the yaw of the boat, and a beam divergence of 9° in the vertical. The radiant intensity of the sources is 12.8 W/sr in the 3.6-4.0 µm spectral band and 50.6 W/sr in the 8.7-11.6 µm band. The Netherlands also mounted two visible light sources, one pointing aft and the other astern, at the top of this mast. During the trial period, it was noticed that other visible sources could also be observed on the Porpora. These were later determined to be deck lights or navigation lights. In addition, as the Porpora’s exhaust outlet is at the waterline, none of the sources, particularly the IR sources, were perturbed. Finally, as the cruising speed of the boat is 10 kts (~30 km/hr), the time to do both an outbound and inbound run to 30 km took approximately 3 hours. This is important, as weather conditions can easily change during this period and must be properly taken into account when performing any analysis of the sources. The millimeter wave radar group from Germany also installed two radar corner reflectors, one facing aft and the other astern, at about 6 m above the water level. These were used to compare the observing ability of their system with the group’s various
camera systems. Lastly, The Netherlands installed a meteorological station on the Porpora that included a visibility meter, a solarimeter and a pyrgeometer.

![Image of the Porpora showing the stern-facing visible source and the calibrated IR source at the top of the mast, and the radar corner reflector (the triangular object in the middle of the image). Many of the other visible sources (navigational aids) can also be observed.](image)

**Figure 3.** Image of the Porpora showing the stern-facing visible source and the calibrated IR source at the top of the mast, and the radar corner reflector (the triangular object in the middle of the image). Many of the other visible sources (navigational aids) can also be observed.

**Table 2: Characteristics of the sensors used during POLLEX over the long path.**

<table>
<thead>
<tr>
<th>Camera</th>
<th>Country</th>
<th>Height AWL (m)</th>
<th>Spectral Band (µm)</th>
<th>Material</th>
<th>Array Size</th>
<th>Focal Length (mm)</th>
<th>IFOV (mrad)</th>
<th>NEI (W/m²)</th>
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<tbody>
<tr>
<td>Rad. HS</td>
<td>NL</td>
<td>18.79</td>
<td>3-5</td>
<td>InSb</td>
<td>256x256</td>
<td>250</td>
<td>0.12</td>
<td>2.5x10⁻¹¹</td>
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<td>QWIP</td>
<td>NL</td>
<td>18.88</td>
<td>8-9</td>
<td>Ga:Al:As</td>
<td>640x480</td>
<td>100</td>
<td>0.24</td>
<td>1.2x10⁻¹⁰</td>
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<td>NL</td>
<td>18.84</td>
<td>3.3-4.2</td>
<td>PtSi</td>
<td>256x256</td>
<td>90</td>
<td>0.55</td>
<td>1.0x10⁻⁹</td>
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<td>Inframetrics</td>
<td>NL</td>
<td>18.74</td>
<td>8-12</td>
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<td></td>
<td></td>
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<tr>
<td>Near IR (U)</td>
<td>NL</td>
<td>14.50</td>
<td>0.7-1.0</td>
<td>Si</td>
<td>1250</td>
<td></td>
<td>0.0067</td>
<td></td>
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<tr>
<td>Near IR</td>
<td>NL</td>
<td>18.74</td>
<td>0.7-1.0</td>
<td>Si</td>
<td>400</td>
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<td></td>
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<tr>
<td>SBFP</td>
<td>DK</td>
<td>12.92</td>
<td>3.56-4.14</td>
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<tr>
<td>AIM-10µm</td>
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<td>8-12</td>
<td>HgCdTe</td>
<td>256x256</td>
<td>400</td>
<td>0.10</td>
<td>1.0x10⁻¹¹</td>
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<tr>
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<td>Sensor</td>
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<td>Model</td>
<td>Frequency</td>
<td>Resolution</td>
<td>Sensor Design</td>
<td>Emissivity</td>
<td>Sensitivity</td>
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<tr>
<td>CEDIP-MB GE</td>
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<td>13.16</td>
<td>3-5 sub-bands</td>
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<td>3.5-5.2</td>
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<td>256x256</td>
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<tr>
<td>High Frame Rate GE</td>
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<td>Si</td>
<td>1124</td>
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<tr>
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<td>2000</td>
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<td>USA</td>
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<td>3-5</td>
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</tr>
</tbody>
</table>

Figure 4 shows the site at MTR where most of the sensors were installed on the second floor. Germany’s white van containing its millimeter wave radars (35 & 94 GHz) is also visible, along with a tent that was used by The Netherlands on the roof. Table 2 gives some of the characteristics of most of the sensors used to make observations over the long experimental path. The sensors installed in rooms on the second floor of the MTR building were at a nominal height of 13.0 m above the water level, except for those installed by The Netherlands on the roof of MTR, at 18.8 m above the water level. The Netherlands also had two sensors at the Universal Hotel at an elevation of 14.5 m above water level. Of the sensors used by The Netherlands, the first three were directed at the point sources on the Porpora, the helicopter, and other targets of opportunity. Their fourth sensor was used to characterize sea and sky backgrounds, and their last two sensors were used to observe the visible lights on Gorgona Island and on the Porpora. Both of Denmark’s sensors and the first of the Italian sensors were directed at the point sources on the Porpora and the helicopter and other targets of opportunity. The last two Italian AGEMA sensors were used to characterize the sea and sky backgrounds. The sensors provided by the USA were directed at the point sources on the Porpora and the helicopter and other targets of opportunity. The first two German sensors were also directed at the point sources on the Porpora and the helicopter and other targets of opportunity. Their last two sensors and the sole Canadian sensor (Fig. 5) were directed at the lights on Gorgona Island and on the Porpora. Our sensor system consisted of a 2 m focal length f/10 Celestron telescope coupled to a Sony CCD camera operating at a frame rate of 30 Hz with the images being recorded to a computer-controlled Super VHS recorder. The computer control of the recorder allowed for sequences of images to be automatically recorded at regular intervals without the need for any human in the loop. Finally, Italy also supported a meteorological station on the roof of MTR.
Figure 4. Image of the MTR site showing the white German radar van to the right, and the Dutch tent on the roof above it. The other nations were located at many of the windows on the second floor.

Figure 5. Visible camera imaging system used to observe the lights on Gorgona and on the Porpora.
2.2 Short experimental path

The short experimental path was used to measure the index of refraction structure parameter, $C_n^2$, using two different scintillometers; to measure the effect of turbulence on imaging; and to measure other structure parameters and micrometeorological and meteorological parameters using a fast sonic anemometer and infrared differential hygrometer. Only two nations, Canada and Germany, were involved in these measurements. The arrangement of the path, seen in Fig. 1, consisted of a base site at MTR (see Fig. 6), and at the other end, over 2 km of water, a breakwater called Pilastro (see Fig. 7). To protect the equipment at the base site, MTR kindly provided their newly acquired motor home, which can be seen in the middle of Fig. 6, for our use. Originally, both scintillometer receivers were stationed at the base site along with their computer acquisition systems; however, this setup was found to cause interference among the receivers and to destroy the integrity of their data. As a result, the Scintec receiver was moved to the breakwater and its transmitter to the base camp. For this side-by-side comparison of $C_n^2$, Germany provided a scintillometer manufactured by Scintec (LAS900) and Canada provided one manufactured by Scientific Technology (LOA-004). Canada also positioned a camera system consisting of a CCD camera, a 2 m focal length f/10 Celestron telescope, and a computer-controlled Super VHS video recorder. Figure 8 shows the final arrangement of this equipment at the base site.

Apart from the receiver or transmitter of the two scintillometers being installed on the breakwater, Canada installed a METEK sonic anemometer and an M100 infrared differential hygrometer from Applied Technologies Inc. The hygrometer system also supported the measurement of air temperature and atmospheric pressure. Canada also installed a specially constructed 1 m x 2 m panel on the breakwater so as to measure the effects of turbulence on image formation over the 2 km path. The computer acquisition system for the sonic anemometer and hygrometer and the batteries to provide power to all the electronics were housed within a 1 m x 2 m x 1 m (H x W x D) wooden container, to which the specially constructed panel was attached. From Fig. 7, the placement of the container can be observed just to the left of the tree-like tower structure at the left side of the breakwater, and the actual setup of the equipment can be seen in Fig. 9.
**Figure 6.** View of the trailer’s location at Mariteleradar as seen from the breakwater

**Figure 7.** View of the breakwater as seen from the trailer
Figure 8. View of the equipment at the base site of the short experimental path. At the left is the German scintillometer (transmitter), in the middle is the CCD camera with its 2 m focal length telescope, and at the far right is the Canadian scintillometer (receiver).

Figure 9. View of the equipment on the breakwater for the short experimental path. At the left is the Canadian scintillometer (transmitter), close by is the German scintillometer (receiver), the mast supporting the sonic anemometer and hygrometer are just behind, and the wooden container with our special panel is to the right.
3. Environmental conditions during the trial

Figures 10 to 19 show the meteorological conditions that were measured by sensors on the breakwater, on the TNO-FEL buoy, at MTR, and on the SACLANT buoy during the two weeks of the trial.

Figure 10 shows the wind speed and direction measured by the sonic anemometer on the breakwater. From this graph, it can be seen that the wind speeds were usually greater than 2 m/s and were generally stronger in the afternoon and on certain days reached speeds up to 10 m/s. The blue and green horizontal bands indicate the range of wind directions for which the wind is generally coming from the sea or the land, respectively. Thus, wind directions between 160 and 350 degrees are taken to come from the sea, wind directions between 0 and 150 degrees are taken to come from the land, and all other wind directions are assumed to flow along the coast. In this respect, Fig. 10 indicates that the wind generally came from the land in the morning, swings around to come from the sea in the afternoon, and then swings around to come from the land through the night.

Figure 11 also shows the wind speed measured by the sonic anemometer on the breakwater. However, in this case the vertical blue and green horizontal bands are included to indicate that, during the time period covered by the band, the wind came from the sea or the land, respectively. All other time periods indicate coastal winds whose origins are more difficult to determine. Similar vertical blue and green bands are included in most of the subsequent meteorological graphs and allow for a preliminary analysis of the conditions that are dependent upon the direction of the wind. In particular, it can be seen that sudden changes in wind speed are often associated with changes in wind direction. This is particularly evident on the 15th when the wind speed increases quickly as the wind changes to a sea wind and then decreases quickly as it changes to a land wind early on the 16th.

Figure 12 shows the atmospheric pressure measured on the breakwater and the solar irradiance as measured by the Italian group from their site on the roof of the MTR building. We note that the pressure was high (~1020 mb) at the beginning of the trial on the 9th, dropped steadily after lunch and during the 10th, and finally reached a minimum (~1010 mb) at midnight. It then remained close to this level until the 15th, when it began to rise steadily and reached ~1017 mb near noon on the 16th. This indicates that the area was under the influence of high-pressure systems at the beginning and at the end of the trial and under lower-pressure systems the rest of the time. As there are generally more clouds during low-pressure periods, this would also indicate that the solar irradiance would have been greater at the beginning and at the end of the trial, and less at other times. Unfortunately, as seen in Fig. 12, only sporadic measurements of solar irradiance were made during the trial. Nevertheless, we can make a number of observations. First, the sun rose at about 0600 hours local time each morning and set at about 1700 hours each evening, and the maximum irradiance each day was about 1000 W/m².

Figure 13 shows the vapour density measured by the hygrometer on the breakwater (black line) and by the TNO-FEL buoy’s 5 m sensor (red line). While the two data sets do have similar structures, the peaks and valleys occur at much the same times and the values measured on the breakwater have both higher peaks and lower valleys. Two factors that may
partly explain this difference are their different placement, and the difference in the relative
effects of a change in the wind direction from the sea to the land and vice versa. In both
cases, it is quite obvious that the vapour density rises when the wind is from the sea and falls
when it is from the land, except that the scale of these changes is greater closer to shore on the
breakwater than it is farther away from the coast.

Figure 14 shows the air temperature measured by the sonic anemometer (black line) and the
thermometer attached to the hygrometer (red line) on the breakwater. While the two data sets
do follow each other and have similar structures, the temperatures measured by the
thermometer (red line) can be almost 2 degrees greater. This is particularly true during the
day and leads us to believe that one of the reasons for this difference is due to the fact that a
non-aspirated shield was used with the sensor and that the measurements are contaminated by
the effect of local solar heating. If we now consider Fig. 15, which shows the air temperatures
measured by the sonic anemometer (black line) on the breakwater and the 5 m thermometer
on TNO-FEL’s buoy (red line), we see that these two data sets are amazingly similar. Not
only are their structures very similar, but their absolute values are as well. Consequently, for
the rest of the report, the air temperature at the breakwater will always be that given by the
sonic anemometer and is the air temperature that is used in all the analysis, unless otherwise
indicated. The effect of changes in the wind speed direction can also be seen in Figs. 14 and
15. Specifically, the air temperature can change very suddenly when the wind swings from
the sea to the land or vice versa. This is very well illustrated on the 10th, 11th and 12th, when
the temperature changes by almost 3 degrees.

Figure 16 shows the sea temperature measured by TNO-FEL’s buoy (black line), several
measurements taken using a bucket thermometer (solid blue circles) along the short
transmission path, and a curve (red line) that corresponds to the same buoy data, but which
has been lowered by 1 degree to fit the “average” values measured by the bucket
thermometer. While this procedure is less than ideal, it does give us an idea as to the possible
variance in the sea temperatures between the two sites and the potential range of the sea
temperatures. Nevertheless, for the rest of the report, the sea temperatures provided by the
corrected data (red line) will be used and referred to as the sea temperature, unless otherwise
stated, although many later calculations have also been performed using both sea temperatures
so as to include a measure of the sea temperature’s uncertainty.

Figure 17 shows the virtual potential air-sea temperature differences (VPASTD) that result
from using either of the sea temperature curves given in Fig. 16, where the blue line
corresponds to our use of the sea temperature from the TNO-FEL buoy and the red line
corresponds to our use of the corrected sea temperature. It shows that during the first week,
when there was a predominant land wind, the conditions, while being predominantly unstable
(VPASTD <= 0) or sub-refractive, often became stable (VPASTD > 0) or super-refractive as
the air warmed up during the day. On the other hand, during the second week, when there
was a predominant sea breeze, it was frequently unstable (sub-refractive) or neutral (VPASTD
<= 0).

Finally, Fig. 18 shows the significant wave heights (H1/3) as a function of time (t) obtained
from our analysis of the sampled wave structure provided by the SACLANT buoy (solid
circles). As data was only provided during periods corresponding to the trial’s helicopter or
ship runs, a simple model that relates the measured significant wave heights to the measured
wind speed (WS) and direction was developed to provide values during other time periods. The solid line in Fig. 18 gives the results of this model fit (solid line in Fig. 19), which is only expected to have any validity for this specific location and our trial period. It is given by

\[ H_{1/3}(t) = 0.1115 \left[ \frac{1}{n_i} \sum_{j=0}^{3} \left[ \delta(t_{k-j}) WS(t_{k-j}) \right] + \left[ 1 - \delta(t_i) \right] WS(t_i) / 6 \right] = 0.1115 \times WW(t) \],

(3.1)

where for all \( p \)

\[ \delta(t_p) = \begin{cases} 1 & \text{if wind is from the sea at time } t_p \\ 0 & \text{if wind is not from the sea at time } t_p \end{cases} \]

(3.2)

\[ n_i = \sum_{j=0}^{3} \delta(t_{k-j}) \]; where \( k \) is chosen such that: \( k \leq i \), \( \delta(t_k) = 1 \), & \( i - k \) is a minimum,

(3.3)

and

\[ WW(t) = \left[ \frac{1}{n_i} \sum_{j=0}^{3} \left[ \delta(t_{k-j}) WS(t_{k-j}) \right] + \left[ 1 - \delta(t_i) \right] WS(t_i) / 6 \right] \]

(3.4)

is defined to be the “wave” wind (black circles in Fig. 19). While the model looks complicated, it is actually quite simple as the first term of Eq. 3.4 takes into account the contribution due to the most recent wind that came from the sea, and the second term takes into account any contribution due to a wind from the land. If we consider the second term first, it is obvious that it is only non-zero when the wind is presently coming from the land. On the other hand, the first term is an average of up to four wind speeds (about 2 hours) starting with the most recent that was measured to be coming from the sea. For example, if the wind is presently coming from the sea, then \( k = i \); the second term is zero and only the first term is used to determine the significant wave height; but if the wind is presently from the land, then the second term is used and the first term is obtained using the most recently measured wind speed that came from the sea. Thus, while the model does take into account the effects of a land breeze in the creation of waves, the most dominant effect is always the most recent wind that came from the sea, which, due to the longer fetch, creates the highest waves and take longer to dissipate after the wind changes. These effects are evident in Fig. 19 when one considers the lack of any obvious relationship of wave height to measured wind speed when the wind is coming from the land (green circles), and the fairly linear relation that exists when the wind is coming from the sea (blue circles).
Figure 10. These two graphs show the wind speed and direction for the two weeks of the trial. The green and blue shaded areas correspond to wind directions that are considered to come from the land and sea directions, respectively.
Figure 11. These two graphs show the wind speed for the two weeks of the trial. The green and blue shaded areas correspond to wind directions that are considered to the time-periods when the wind came from the land or sea direction, respectively.
Figure 12. These two graphs show the atmospheric pressure and the solar irradiance for the two weeks of the trial. The green and blue shaded areas correspond to time-periods when the wind came from the land or sea direction, respectively.
Figure 13. These two graphs show the vapour density measured at the breakwater and at the buoy for the two weeks of the trial. The green and blue shaded areas correspond to time-periods when the wind came from the land or sea direction, respectively.
Figure 14. These two graphs show the air temperatures measured by the sonic anemometer and a standard thermometer at the breakwater for the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 15. These two graphs show the air temperature measured by the sonic anemometer on the breakwater and by the highest sensor on the buoy for the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 16. These two graphs show the sea temperature for the two weeks of the trial. The blue curve is that measured by the buoy and the red curve is obtained from the blue curve by normalizing it to a couple of measurements made by a bucket thermometer along the short transmission path. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 17. These two graphs show the virtual potential air-sea temperature differences for the two weeks of the trial that are used for the analysis performed in the later sections of this report. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 18. These two graphs show the significant wave height ($H_{1/3}$) for the two weeks of the trial, where the solid circles are the measured data from the buoy and the solid line comes from a wind model fit. The green and blue shaded areas correspond to time-periods when the wind came from the land or sea direction, respectively.
4. Turbulence effects on imaging

In this section, we give a brief theoretical overview of the effect of atmospheric turbulence on imaging. Here we shall model the imaging system (telescope + CCD camera) as a thin lens with a focal length of 2 m. This simple model will nonetheless describe all the essential features of the real imaging system (see Ref. 9 for more details).

As we see in Fig. 20, the imaging system is looking at an object a distance $L$ away. With a focal length $f_0$, the image forms at a distance $f$ behind the lens such that $f^{-1} = f_0^{-1} - L^{-1}$. If the object has a height $h_o$, then the image has a height $h_i = -f h_o / L$. It will be convenient to use normalized image plane coordinates $\alpha_i = h_i / f$ and normalized object plane coordinates $\alpha_o = h_o / L$. We begin by considering what happens to the electromagnetic fields, which we represent without loss of generality by the complex scalar field $E = A \exp(i\phi)$, as they propagate from the object to the surface of the lens. This is best described by the Huygens-Fresnel principle,
\[ E_i(\tilde{\rho}_i) = \int d^2 \alpha_o h(\tilde{\alpha}_o, \tilde{\rho}_i) e^{i\psi(\tilde{\alpha}_o, \tilde{\rho}_i)} E_o(\tilde{\alpha}_o) \]  
\hspace{1cm} \text{(4.1)}

where \( E_i(\tilde{\rho}_i) \) is the electromagnetic field at the surface of the lens, \( E_o(\tilde{\alpha}_o) \) is the electromagnetic field at the object plane, and we have assumed that the object can be approximated as a two-dimensional surface parallel to the lens. The function \( h \) represents a spherical wave originating from the point \( \tilde{\alpha}_o \) at the object plane and propagating over a distance \( L \) to the point \( \tilde{\rho}_i \) on the lens. For small angles this function is approximated by,

\[ h(\tilde{\alpha}_o, \tilde{\rho}_i) = \frac{kL}{2\pi i} \exp\left[ i kL + i \frac{1}{2} kL (\tilde{\alpha}_o - \tilde{\rho}_i / L)^2 \right], \hspace{1cm} \text{(4.2)} \]

where \( k = 2\pi / \lambda \) is the wavenumber and \( \lambda \) is the wavelength of the radiation. The function \( \psi \) represents the effect of atmospheric turbulence on the propagated electromagnetic wave and is approximated by

\[ \psi(\tilde{\alpha}_o, \tilde{\rho}_i) = -\frac{k^2}{2\pi} \int d^2 \rho \frac{1}{\rho} m(\tilde{\rho}_i, L\delta) \exp\left[ \frac{i kL}{\delta (1-\delta)} \left( \frac{\delta \tilde{\rho}_i}{L} + \frac{(1-\delta)\tilde{\alpha}_o - \tilde{\rho}_i}{L} \right)^2 \right], \hspace{1cm} \text{(4.3)} \]

where \( \delta = z/L \) is the normalized range between the object and the lens (the object is at \( \delta = 0 \) and the lens at \( \delta = 1 \)), and \( n \) is the field of turbulent fluctuations of the refractive index of the air. Equation 4.3 is a complex function, \( \psi = \chi + iS \), where \( \chi \) is the log-amplitude variation of the electromagnetic wave due to turbulence, and \( S \) is the turbulent phase variation.

The next step is to describe how the image is formed at the image plane. Incorporating a ‘reversed’ spherical wave that propagates from the entire surface of the lens and concentrates at a specific point on the image plane does this. The electromagnetic field at the image plane is given by,

\[ E_i(\tilde{\alpha}_i) = \int d^2 \alpha_o m(\tilde{\alpha}_o, \tilde{\alpha}_i) E_o(\tilde{\alpha}_o), \hspace{1cm} \text{(4.4)} \]

where \( m \) is called the transfer function and is given by,

\[ m(\tilde{\alpha}_o, \tilde{\alpha}_i) = \int d^2 \rho g(\tilde{\rho}_i, \tilde{\alpha}_i) h(\tilde{\alpha}_o, \tilde{\rho}_i) e^{i\psi(\tilde{\alpha}_o, \tilde{\rho}_i)}, \hspace{1cm} \text{(4.5)} \]

where

\[ g(\tilde{\rho}_i, \tilde{\alpha}_i) = \frac{k e^{ikf}}{2\pi i f} W(\tilde{\rho}_i) \exp\left[ \frac{i k f}{2} \frac{\alpha_i^2 + f k\tilde{\alpha}_i \cdot \tilde{\rho}_i - i k}{2L} \rho_i^2 \right], \hspace{1cm} \text{(4.6)} \]

is the reverse spherical wave and \( W \) is the characteristic function of the lens; such that \( W = 1 \) for \( |\tilde{\rho}_i| \leq D/2 \) and \( W = 0 \) elsewhere, and \( D \) is the diameter of the lens. Upon evaluating Eq. 4.5, we obtain

\[ m(\tilde{\alpha}_o, \tilde{\alpha}_i) = -\frac{k^2 L e^{ikf}}{4\pi^2 f} \int d^2 \rho_i W(\tilde{\rho}_i) e^{i \frac{L + f + f L^2 / 4 + f L^2 / 4}{2L} \rho_i^2} \left[ i \tilde{\rho}_i \cdot (\tilde{\alpha}_i - \tilde{\alpha}_o) + \psi(\tilde{\alpha}_o, \tilde{\rho}_i) \right]. \hspace{1cm} \text{(4.7)} \]

However, it is not the electromagnetic fields at the image plane that are required, but the intensity of the light, \( I \propto E^* E \). Assuming that the object is incoherently lit, which means that the phase of the electromagnetic field at the object’s surface is random and is virtually uncorrelated, then the intensity is given by
\( E_o^* (\tilde{\alpha}'_o) E_o (\tilde{\alpha}_o) \propto \left( \frac{\lambda^2}{\pi L^2} \right) \delta (\tilde{\alpha}_o - \tilde{\alpha}'_o) I_o (\tilde{\alpha}_o) , \) \hspace{1cm} (4.8)

where the over-bar denotes a time average. Using Eq. 4.8 in Eq. 4.4, we finally obtain the following expression for the intensity at the image plane;

\[ I_i (\tilde{\alpha}_i) = \int d^2 \alpha_o \ P(\tilde{\alpha}_o, \tilde{\alpha}_i) I_o (\tilde{\alpha}_o) , \] \hspace{1cm} (4.9)

where \( P \) is the point-spread function (PSF) and is given by,

\[
P(\tilde{\alpha}_o, \tilde{\alpha}_i) = \frac{\lambda^2}{\pi L^2} \left| m(\tilde{\alpha}_o, \tilde{\alpha}_i) \right|^2 \\
= \frac{k^2}{4\pi^3 f^2} \int d^2 \rho \ d^2 \rho'_l \ W(\tilde{\rho}_l) W (\tilde{\rho}'_l) e^{i(\tilde{\alpha}_o - \tilde{\alpha}_i) \cdot (\tilde{\rho}_l - \tilde{\rho}'_l)} . \hspace{1cm} (4.10)
\]

\textbf{Figure 20.} A highly idealized depiction of an imaging system operating in turbulence. The imaging system is modelled as a thin lens with focal length \( f_0 \), observing an object through atmospheric turbulence a distance \( L \) away. The turbulent image is formed a distance \( f \) behind the lens.

As can be seen in Eq. 4.10, the PSF depends on the turbulent function \( \psi \), and so fluctuates due to atmospheric turbulence. It is also linear, as it does not depend on the object’s initial intensity. It is therefore useful to determine the average PSF. To that end, we point out the well-known result for turbulent propagation,

\[
\left\langle \exp \left[ \psi (\tilde{\alpha}_o, \tilde{\rho}_l) + \psi^* (\tilde{\alpha}_o, \tilde{\rho}'_l) \right] \right\rangle = \exp \left[ - \left( |\tilde{\rho}_l - \tilde{\rho}'_l| / \rho_0 \right)^{\frac{3}{2}} \right] , \hspace{1cm} (4.11)
\]

where \( \rho_0 \) is the transverse coherence length and is given by,
\[ \rho_0 = \left[ 1.46k^2L \int_0^1 C_n^2(\delta) \delta^{5/3} d\delta \right]^{3/2}. \quad (4.12) \]

Placing Eq. 4.11 into Eq. 4.10, using the variables \( \bar{r} = (\bar{\rho}_i + \bar{\rho}_i')/2 \) and \( \bar{\eta} = \bar{\rho}_i - \bar{\rho}_i' \), and integrating with respect to \( \bar{r} \), we obtain,

\[
\langle P(\bar{\alpha}_o, \bar{\alpha}_i) \rangle = \frac{k^2}{4\pi^2} \int d^2\eta \Theta(\eta, D) \exp \left[ ik\bar{\eta}^* (\bar{\alpha}_i - \bar{\alpha}_o) - (\eta/\rho_0)^{3/2} \right], \quad (4.13)
\]

where \( \eta = |\bar{\eta}| \) and \( \Theta \) is the circular overlap function. The function \( \Theta \) represents the number of pairs of points a distance \( \eta \) apart where both points are on the lens. It is also the area of overlap between two circles of diameter \( D \) whose centres are displaced a distance \( \eta \) apart, and it is given by,

\[
\Theta(\eta, D) = \frac{D^2}{2} \left\{ \cos^{-1} \left( \frac{\eta}{D} - \frac{\eta}{D} \left[ 1 - \left( \frac{\eta}{D} \right)^2 \right]^{1/2} \right) \right\}, \quad \text{if } \eta \leq D.
\]

\[
= 0, \quad \text{if } \eta > D. \quad (4.14)
\]

**Figure 21.** The circular overlap function normalized with respect to the area of the lens \( A \) and plotted with respect to its normalized argument.

The form of this function is shown in Fig. 21. It is notable that the average PSF in Eq. 4.13 only depends on the difference of the object and image coordinates, \( \langle P(\bar{\alpha}_o, \bar{\alpha}_i) \rangle = \langle P(\bar{\alpha}_i - \bar{\alpha}_o) \rangle \). The average PSF is therefore said to be isoplanatic. In fact,
no optical system is strictly isoplanatic, but this is nonetheless a good and useful approximation. Isoplanatism means that, when using Eq. 4.9, the average image is the convolution of the object with the average PSF, \( \langle I_\gamma \rangle = I_0 * \langle P \rangle \). This, in turn, leads to the following simple relationship between the Fourier transform of the average image

\[
\langle F_i (\bar{n}) \rangle = F_o (\bar{n}) \langle M (\bar{n}) \rangle,
\]

(4.15)

where \( \bar{n} \) is the wavenumber vector, \( F_o (\bar{n}) \) is the Fourier transform of the object, and \( \langle M (\bar{n}) \rangle \), the modulation transfer function (MTF), is the Fourier transform of the average PSF. Taking the Fourier Transform of the PSF given in Eq. 4.13 results in the following MTF,

\[
\langle M (\bar{n}) \rangle = \frac{2}{f^2} \Theta (n/k, D) \exp \left[ -\left( \frac{n/k \rho_0}{\sigma} \right)^{5/3} \right].
\]

(4.16)

This average MTF can be seen as the product of an optical system MTF (the circular overlap function) and an atmospheric MTF (the exponential term). However, this is only true for long-exposure images, in other words, for images that have averaged out the turbulence induced image displacement along with all the other turbulent distortions. Short-exposure MTFs, which are averages over the turbulent distortions for a fixed image displacement, cannot be so easily separated into system and atmospheric components, as they have different time scales.

5. Measurements of \( C_n^2 \)

This section presents the values of index of refractivity structure parameter, \( C_n^2 \), as determined by a number of different techniques. The first section shows the results obtained from the Canadian LOA-004 scintillometer and the German LAS900 scintillometer, the second section uses bulk meteorological measurements with our LWKD model (based on Monin-Obukhov theory), the third section shows a way of calculating it using a fast sonic anemometer, and the last section shows a technique that uses visible imagery.

5.1 From an optical anemometer/scintillometer

As described in section 2.2, two scintillometers were used over the short propagation path. The results of these measurements over the two-week time period are shown in Figs. 22 and 23. As both instruments are capable of calculating both \( C_n^2 \) and the cross-wind velocity (wind velocity component perpendicular to their transmission axis), Figure 22 shows a comparison of the cross-wind measurements made by the two scintillometers and those calculated using the sonic anemometer, and Fig. 23 shows a comparison of the \( C_n^2 \) measurements obtained from the two scintillometers. As can be seen from Fig. 22, the cross-wind speeds compare quite well with those obtained from the sonic anemometer for both scintillometers. One problem that was noticed was the inability of the output from the German scintillometers to cross the zero wind speed when operated in a certain way (around noon on May 12). This is not a problem with the instrument; it occurs as a result of its operational mode. From Fig. 23, we notice that there is quite good agreement between the refractive index structure parameters
calculated by the two instruments. A problem with the Canadian scintillometer (LOA) was noted in that its outputs were discovered to be about 1000 times greater than those produced by the German scintillometer, which were much more reasonable. Consequently, it was discovered that this was due to the use of the wrong transmission range in its acquisition software. To correct this problem, the original results from the LOA have been scaled by a factor of 1260 or (2000 m/185 m)\(^{1/3}\) and are now in close agreement with those from the German scintillometer.

5.2 From bulk meteorology and MO theory (LWKD model)

This technique uses the bulk meteorological measurements shown in section 3 along with the LWKD model, which is based on Monin-Obukhov theory (Ref. 3), to produce various micrometeorological parameters and various structure parameters, including the index of refractivity structure parameter. Furthermore, for each case studied, the model is applied using the two different sea temperatures discussed in section 3, namely the sea temperature measured by the TNO-FEL buoy and a sea temperature obtained by applying a correction to that obtained from the TNO-FEL buoy. Using these two sea temperatures allows us to consider the possible variation that could exist in the parameters derived from the LWKD model. The following subsection shows the values of the micrometeorological parameters, and the subsequent subsection, the various structure parameters.

5.2.1 Micrometeorological parameters

The LWKD bulk model produces outputs for three scaling parameters, three roughness heights, and the Monin-Obukhov length. As they are not all independent, only the three scaling parameters and the wind speed roughness height are shown in the following figures.

Figure 24 shows the friction velocities (or wind speed scaling parameters) that are obtained from the LWKD model. As can be seen, the results are quite independent of the exact sea temperature that is used, and are also independent of the direction of the wind. Consequently, in later discussions we will always use the values given when the corrected sea temperature is used in the model. We also notice that its value ranged from about 0 m/s to 0.4 m/s during the two-week period.

Figure 25 shows the virtual potential temperature (VPT) scaling parameters that are obtained from the LWKD model. As can be seen, the results are quite independent of the exact sea temperature that is used. Also, they seem to be generally closer to a value of zero when the wind is from the sea than when it is from the land. This is as expected, since this scaling parameter is proportional to the difference between the air and sea temperatures (air-sea temperature difference or ASTD) and the surface layer is more uniform when the wind is from the sea. Furthermore, the values obtained when the corrected sea temperature is used are about 0.05 K greater than for the uncorrected sea temperatures, and its range of values is from about –0.12 to 0.11 K.
Figure 22. These two graphs show the cross-wind speeds as measured by the German scintillometer, Canada’s scintillometer (LOA), and Canada’s sonic anemometer (METEK) during the first week of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 23. These two graphs show the refractive index structure parameters measured by the two scintillometers over the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 26 shows the specific humidity (SH) scaling parameters that are obtained from the LWKD model. As in Fig. 25, the results are dependent on the exact sea temperature that is used and in general seem to be closer to zero when the wind is from the sea than when it is from the land. In other words, as for the temperature, the specific humidity is more uniform when the wind is from the sea. Furthermore, the values obtained when the corrected sea temperature is used are often about 0.05 g/kg greater than for the uncorrected sea temperatures, and its range of values is from about –0.4 to 0 g/kg.

Figure 27 shows the wind speed roughness heights that have been determined from the LWKD model. The first thing that one notices is that it has a minimum value of about 3x10^{-5} m. Looking at the graph of wind speed, one also notices that while the two curves seem to follow one another for values above the minimum value, this breaks down when the wind speed is less than 1 m/s. In fact, at this point the roughness heights can increase quite quickly to values up to 10 times greater. The virtual potential temperature roughness heights, z_{0\theta}, and the specific humidity roughness heights, z_{0q}, are not shown, since in the LWKD model they are directly related to the wind speed roughness heights through the following two equations:

\[
\ln\left(\frac{z_{0\theta}}{10}\right) = -\kappa^2 \left[ C_{TN} \ln(z_{0u}/10) \right] \quad (5.1)
\]

and

\[
\ln\left(\frac{z_{0q}}{10}\right) = -\kappa^2 \left[ C_{EN} \ln(z_{0u}/10) \right], \quad (5.2)
\]

where \(\kappa\) is von Karman’s constant, \(C_{TN}\) is the 10 m neutral heat flux coefficient, and \(C_{EN}\) is the 10 m neutral moisture flux coefficient. As a result, the virtual potential temperature roughness heights have a maximum value of about 2x10^{-5} m, the specific humidity roughness heights have a maximum value of about 1.8x10^{-4} m and both can be as much as a factor of 10 less.

5.2.2 Structure parameters and \(C_n^2\)

In the LWKD model, the index of refraction structure parameter, \(C_n^2\), is calculated using an equation of the form

\[
C_n^2 = \alpha^2 C_T^2 + 2\alpha\beta C_{TQ} + \beta^2 C_Q^2, \quad (5.3)
\]

where \(C_T^2\) is the temperature structure parameter, \(C_Q^2\) is the water vapour density structure parameter, \(C_{TQ}\) is the temperature-water vapour density structure parameter, and \(\alpha\) and \(\beta\) are coefficients. Figures 28, 29, 30 and 31 show the results of our LWKD calculations for the index of refraction structure parameter and the three terms; in other words, \(\alpha^2 C_T^2\), \(\beta^2 C_Q^2\), and \(2\alpha\beta C_{TQ}\), respectively for a height of 6.45 m.

A number of observations can be made from these graphs. First, one should note that the \(C_T^2\) term (Fig. 29) varies by a factor of 3 billion from a minimum value of about 2x10^{-23} m^{-2/3} to a maximum value of about 6x10^{-14} m^{-2/3}, whereas \(C_n^2\) (Fig. 28) only varies by about 600 from a minimum value of about 1x10^{-17} m^{-2/3} to a maximum value of about 6x10^{-14} m^{-2/3}. While the maximum values for the \(C_T^2\) term and \(C_n^2\) term are almost identical, the minimum values are not. This is largely due to the effect of the \(C_Q^2\) term (Fig. 30), which varies by a factor of 100,000 from a minimum value of about 2x10^{-19} to a maximum value of about 2x10^{-14}. In addition, its minima do not
coincide with those for the $C_T^2$ term. As a result, if we were to neglect the $C_{TQ}$ term when calculating $C_n^2$, we would not expect it, as is observed, to drop below about $1 \times 10^{-16}$ m$^{-2/3}$ very often. The effect of the $C_{TQ}$ term, which is almost always negative because the boundary layer is mostly unstable (VPASTD < 0), is to reduce the value of $C_n^2$. From its graph, Fig. 31, we see that it ranges from a minimum value of about $1.7 \times 10^{-14}$ m$^{-2/3}$ to a maximum value of about $1 \times 10^{-15}$ m$^{-2/3}$. Next, one should note that the values of $C_n^2$ that are calculated from the two data sets can vary significantly, from $1 \times 10^{-18}$ m$^{-2/3}$ to $3 \times 10^{-14}$ m$^{-2/3}$, and that the differences between the two sets are not always either positive or negative.
Figure 24. These two graphs show the friction velocities obtained using the bulk meteorological data with the LWKD model over the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 25. These two graphs show the virtual potential temperature scaling parameter obtained using the bulk meteorological data with the LWKD model over the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 26. These two graphs show the specific humidity scaling parameter obtained using the bulk meteorological data with the LWKD model over the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 27. These two graphs show the wind speed roughness heights obtained using the bulk meteorological data with the LWKD model over the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 28. These two graphs show the index of refraction structure parameter obtained using the bulk meteorological data with the LWKD model over the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 29. These two graphs show the first term of $C_n^2, a^2 C_r^2$, obtained using the bulk meteorological data with the LWKD model over the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 30. These two graphs show the third term of $C_n^2 \beta^2 C_0^2$, obtained using the bulk meteorological data with the LWKD model over the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 31. These two graphs show the second term of $C_n^2 \cdot z \alpha \beta C_T$, obtained using the bulk meteorological data with the LWKD model over the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
5.3 From a fast sonic anemometer and hygrometer

In this section we show the results obtained using the measurements from the sonic anemometer (METEK) and the differential absorption hygrometer when synchronously operated. A description of the technique employed and a description of the calculations performed using the DRDC Valcartier developed program METCALC can be found in an earlier publication (Ref. 10).

In the following section, we will show various micrometeorological parameters and, when relevant, their comparison with the results from the LWKD bulk model. In the subsequent section, we will show various structure parameters for later comparison with those obtained using the scintillometers, the LWKD model, and the video images.

5.3.1 Micrometeorological parameters

Using data from the sonic anemometer and hygrometer, the METCALC program can calculate three scaling parameters, the Monin-Obukhov length, and many other parameters. It does not presently calculate any roughness heights, but these can be determined using Eqs. 5.1, 5.2 and the following equation (Ref. 3):

\[ z_{0u} = (\alpha_c / g) u^2 + \frac{a_d \theta_v + b_d}{u^*} e^{-C_x} \]  

where \( z_{0u} \) is the wind speed roughness height, \( \kappa \) is von Karmen’s constant, \( g \) is the acceleration due to gravity, \( \alpha_c (=0.011) \) is Charnock’s constant, \( u^* \) is the friction velocity, \( \theta_v \) is the virtual air temperature (K), and \( C (=5.5) \), \( a_d (=9.267 \times 10^{-8}) \) and \( b_d (=1.346 \times 10^{-5}) \) are constants.

Figure 32 shows the friction velocities (or wind speed scaling parameters) that are obtained from the covariance measurements and a comparison with those obtained from the LWKD model (using the corrected sea temperatures). As can be seen, while the two results do in general follow each other, the results from the measurements are about double those from the LWKD model (see Fig. 33). Thus, it appears that either the friction velocity over the breakwater is double that over the sea or we have a significant disagreement between the two methods. This has greater consequences, as many other parameters, in particular the Monin-Obukhov length and the roughness heights, are directly dependent on the friction velocity.

Figure 34 shows the virtual potential temperature (VPT) scaling parameters that are obtained from the covariance measurements compared with those obtained from the LWKD model. What is evident from these graphs is that the results can differ quite significantly. This is particularly true during the day, and is probably due to solar heating of the breakwater’s rock and concrete structure. This would cause the breakwater’s surface temperature to increase well above that of the water surface and the VPT scaling parameter to decrease in agreement with our observations. However, during the late evening and early morning, when the sun is below the horizon, there is much better temporal and quantitative agreement between the results. In this case, we find that the covariance measured VPT scaling parameters are generally greater than those obtained from the LWKD model. Furthermore, as they are generally greater than those obtained when using the corrected sea temperatures, it would appear that,
since the measured air temperatures are quite similar in both locations, either the sea’s surface temperature is, say, 0.5 degrees warmer than the breakwater’s surface, or the breakwater’s surface is 0.5 degrees cooler than the sea surface. While this kind of difference does not seem to be significant, it can significantly affect the calculation of structure parameters when the VPASTD is around zero.

Figure 35 shows the specific humidity (SH) scaling parameters that are obtained from the covariance measurements and a comparison with those obtained from the LWKD model. What is evident from these graphs is that the two results are strikingly different. Not only do they differ significantly in magnitude, but they also appear to mirror one another. That is, when one decreases in value the other increases, and when one increases in value the other decreases. As for the VPT scaling parameters, this is most likely due to the fact that while the covariance measurements were taken over the rock and concrete surface of the breakwater, the LWKD model uses measurements that were taken over the sea surface; consequently, the measurements taken over the breakwater have no natural source of water vapour and the surface relative humidity can not be close to 100%, an assumption that is made for the LWKD model calculations. Consequently, while more water vapour can be added to the air over the sea surface as the sun warms it up, thus increasing the specific humidity, the same is not true as the sun warms up a concrete surface. Furthermore, as significant amounts of water vapour can be added and removed from the air over a sea surface, the SH scaling parameter will be much more variable than that measured over a dry concrete surface.

Figure 36 shows the wind speed roughness heights that have been determined using the friction velocity determined from the sonic anemometer with Eq. 5.4 and those determined from the LWKD model. The first things one notices are that they both have a minimum value of about 3x10^{-5} m, and those obtained from the sonic anemometer are generally (about 4 times) greater. This is directly due to the factor of 2 that has been observed between the friction velocities (u*) and the factor of u*^2 in Eq. 5.4. The virtual potential temperature roughness heights, z_{0θ}, and the specific humidity roughness heights, z_0q, are not shown as they are directly related to the wind speed roughness heights through Eq. 5.1 and 5.2. As a result, the virtual potential temperature roughness heights still have a maximum value of about 2x10^{-5} m, the specific humidity roughness heights still have a maximum value of about 1.8x10^{-4} m, and both can be a factor of 50 to 100 less.

Before proceeding to the structure parameters, we present the results from our calculations of various variances or covariances and their respective correlation lengths. Due to the importance of the parameters u, T and Q, these graphs are limited to their six combinations.

Figure 37 shows the UU variances (\(\sigma_{UU}\)), where U is the wind speed along the axis defined by the wind’s direction, and their associated correlation lengths as obtained from the sonic anemometer. From the graphs one notices that over the two week period the variance varied between zero and 4 m^2/s^2, with most values being below 0.5 m^2/s^2. Comparing this to the wind speed shown in Figs. 10 and 11, it is also clear that the maximum variances occurred during the periods of greatest wind speed on the
11th and 15th. Similarly, the correlation length varied between 0.5 and 10 m, with most being less than 3 m. Likewise, the maximum correlation lengths also coincide with the greatest wind speed.

Figure 38 shows the $T_s T_s$ variances ($\sigma_{T_s T_s}$), where $T_s$ is the sonic temperature, and their associated correlation lengths as obtained from the sonic anemometer. From the graphs one notices that over the two week period the variance varied between zero and 0.5 °C², with most values being below 0.05 °C² when the wind comes from the land and over 0.1 °C² when it comes from the sea. Comparing with Figs. 15 to 17, we also note that there is no noticeable correlation between the air temperature, sea temperature and VPASTD. However, we also notice that the larger variances also occurred only during the day, when solar heating is the greatest. Thus, one expects there to be a close correlation between the variance and the solar irradiance, and upon examining Fig. 12, this appears to be the case. Similarly, the correlation length varied between less than 0.5 m and, say, 8 m, with most being less than 2 m. As with the $UU$ correlation length, the maximum correlation lengths also coincide with the greatest wind speed.

Figure 39 shows the $QQ$ variances ($\sigma_{QQ}$), where $Q$ is the vapour density, and their associated correlation lengths as obtained from the differential hygrometer. From the graphs one notices that over the two week period the variance varied between zero and 0.2 g²/m⁶, with most values being below 0.1 g²/m⁶. Comparing this with the wind speed shown in Figs. 10 and 11, it is also clear that the maximum variances occurred during the periods of greatest wind speed on the 11th and 15th. Similarly, the correlation length varied between 0.5 and 12 m, with most being less than 4 m. Similarly, the maximum correlation lengths also coincide with the greatest wind speed, although there also appears to be a diurnal component.

Finally, Fig. 40 shows the $QT_s$ covariances ($\sigma_{QT_s}$), where $Q$ is the vapour density and $T_s$ is the sonic temperature, and their associated correlation lengths as obtained from the combined data from the sonic anemometer and differential hygrometer. From the graphs one notices that over the two week period the covariance varied between 0.08 and 0.06 °C·g/m³, with most values being between ± 0.02 °C·g/m³. Similarly, the correlation length varied between 0.5 and 10 m, with most being less than 4 m. Similarly, the maximum correlation lengths also coincide with the greatest wind speed, although again there appears to be a diurnal component.

5.3.2 $C_n^2$ structure parameter

Figures 41 to 44 show the structure parameter, $C_n^2$, and the three terms used to calculate it (see Eq. 5.3). The calculation is performed in exactly the same manner as in the LWKD model (Ref. 3). These three terms depend directly on the $C_T^2$ structure parameter, the $C_Q^2$ structure parameter and the $C_{TQ}$ structure parameters that were determined from the sonic anemometer and differential hygrometer. Other structure parameters that depend on the wind speed components are not shown in this report, but are available to those having a particular interest. In addition, for comparison, the figures also show the same calculations given by the LWKD model using the bulk meteorological data with the corrected sea temperatures.
Figure 41 shows the respective data for the $C_T^2$ terms. From the graph it is immediately clear that the results are significantly different. First, the LWKD model results are almost always at least an order of magnitude less than those obtained from the anemometer-hygrometer data. In addition, the two results do not have similar trends in the data, except perhaps occasionally. This is not surprising, as similar discrepancies were noticed in Fig. 34 when comparing their respective air temperature scaling parameters. Finally, we also note the dynamic range of the two data sets. While the LWKD model results can vary over at least 4 decades, the anemometer-hygrometer data only varies over 3 decades. The reasons for this are not completely clear, but it may be related to the measurement limitations of the sonic anemometer.

Figure 42 shows the respective data for the $C_Q^2$ terms. From this graph we notice that these results are much more similar. First, the two results are more often of the same order of magnitude, and there seem to be periods when the two results have similar trends in their data. In particular, upon closer examination, the two results appear to be very similar at night and in the early morning. This is somewhat surprising, as their respective specific humidity scaling parameters (see Fig. 35) are quite different. Finally, one should note that their dynamic ranges are very similar to those seen for the $C_T^2$ term.

Figure 43 shows the respective data for the $C_{TQ}$ terms. From this graph we notice that these results are significantly different and that they are shown using a linear scale, not a logarithmic scale. The linear scale is used because this term can be both positive and negative. Looking at the graphs, a number of differences can be remarked. First, the results from the anemometer-hygrometer are seen to be both positive and negative, whereas the results from the LWKD are always very small. Second, the results from the anemometer-hygrometer can be just as negative as they can be positive. Last, we notice that when the two results are negative, the trends in the data have some similarity, even though there is something like a factor of 2 between them.

Finally, Fig. 44 shows the respective data for the index of refractivity structure parameter, $C_n^2$. From our comments with respect to Figs. 41 to 43, it is not surprising to see that the results from the anemometer-hygrometer and the LWKD model are also quite different. Looking at the graphs, a number of observations can be made. First, the two results are seen to be in closer agreement when the wind is from the land than when it is from the sea. This is not so surprising, as the same is also true for the $C_{TQ}$ and $C_Q^2$ terms, and partially for the $C_T^2$ term. Second, when the wind is from the land, the results from the anemometer-hygrometer are seen to be only about 1 decade greater than the LWKD model results, whereas when it is from the sea, it can be 2 to 3 decades greater. Why this should be so is not obvious, but it may be that the placement of the anemometer-hygrometer combination on the Pilastro breakwater results in measurements that are more representative of air masses flowing off the land than those coming from the sea.
Figure 32. Plot of the friction velocities obtained from the LWKD model versus those obtained from the covariance measurements over the two weeks of the trial. The solid line is the best straight-line fit. The corresponding equation and its $R^2$ parameter are also shown on the graph.
Figure 33. These two graphs show the friction velocities obtained from the covariance measurements and from the LWKD model over the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 34. These two graphs show the virtual potential temperature scaling parameter obtained using the bulk meteorological data with the LWKD model over the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 35. These two graphs show the specific humidity scaling parameter obtained using the bulk meteorological data with the LWKD model over the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
**Figure 36.** These two graphs show the wind speed roughness heights obtained using the friction velocity determined from the sonic anemometer with Eq. 5.4, and from the LWKD model over the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 37. These two graphs show the UU variances ($\sigma_{UU}$) and their associated correlation lengths as obtained from the sonic anemometer over the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 38. These two graphs show the $T_s T_a$ variances ($\sigma_{T_s T_a}$) and their associated correlation lengths as obtained from the sonic anemometer over the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 39. These two graphs show the QQ variances ($\sigma_{QQ}$) and their associated correlation lengths as obtained from the differential hygrometer over the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 40. These two graphs show the $QT_s$ variances ($\sigma_{QT_s}$) and their associated correlation lengths as obtained from the combined data from the sonic anemometer and differential hygrometer over the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 41. These two graphs show the $C_{T2}$ term of $C_{n2}$ as obtained from the combined data from the sonic anemometer and differential hygrometer and from the LWKD model using the corrected sea temperature data over the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 42. These two graphs show \( C_{\theta}^2 \) term of \( C_n^2 \) as obtained from the combined data from the sonic anemometer and differential hygrometer and from the LWKD model using the corrected sea temperature data over the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 43. These two graphs show the $C_{\text{TO}}$ term of $C_n^2$ as obtained from the combined data from the sonic anemometer and differential hygrometer and from the LWKD model using the corrected sea temperature data over the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
Figure 44. These two graphs show the structure parameter, $C_n^2$, as obtained from the combined data from the sonic anemometer and differential hygrometer and from the LWKD model using the corrected sea temperature data over the two weeks of the trial. The green and blue shaded areas correspond to when the wind came from the land or sea direction, respectively.
5.4 From long-exposure video images

Here we present a method for estimating the value of $C_n^2$ from the turbulent blurring of a long-exposure image. In this case, the image without blurring is known. However, much of the blurring in the long-exposure video images is due to the measuring and recording equipment itself. Therefore, no estimation of $C_n^2$ can be attempted without first taking into account the blurring caused by our equipment. It is for this reason that a “hallway” experiment was performed and is described in the next subsection. Note that the method used assumes that the effect of the equipment is linear and isoplanatic, something which is not necessarily the case (Ref. 11). Of the two, non-linearity is potentially more serious, since it implies that a non-turbulent image that is blurred by the equipment, and to which turbulent blurring is added, is not necessarily equal to a turbulent image blurred by the equipment. Furthermore, the method is sensitive to any misalignments, which can cause an overestimation of the estimated $C_n^2$ value.

5.4.1 Measuring instrumental blurring

The “hallway” experiment consisted in taking long-exposure video images of the target shown in the upper part of Fig. 45 in a 40 m long hallway using the same equipment employed over the short experimental path in Livorno (Celestron telescope + CCD camera + Super VHS recorder). The indoor hallway was used to ensure that the images were not affected by significant turbulent blurring. The target used was identical to the one shown in Fig. 45 but was scaled down to 4 cm in width, such that from 40 m it would seem identical to the 2 m wide target 2 km away at Livorno. The result of this experiment can be seen in the lower part of Fig. 45, and it is that image that defines the zero turbulence case.

5.4.2 Obtaining $C_n^2$ estimates

The first step towards estimating the $C_n^2$ value is to find the Fourier transform of the zero-turbulence image taken in the “hallway” experiment. We then make an estimate of the $C_n^2$ value and find its corresponding MTF using Eqs. 4.12 and 4.15. Multiplying this MTF by the zero-turbulence Fourier transform and taking the inverse Fourier transform gives us an estimate for the long-exposure turbulent image. The real long-exposure turbulent image is then obtained by averaging the video images over a sufficiently long time, and the correlation is calculated between the real and estimated images (see Fig. 46). The best value of $C_n^2$ is found by varying it until the correlation becomes a maximum. It is also important to ensure that the images obtained from the camera system are properly aligned before obtaining the average video image; otherwise, additional turbulence effects can be included. Given the normal blurring of the images, this is not always easy to do and any misalignment can cause an overestimation of the estimated $C_n^2$ value. This overestimation is shown in Fig. 47, and can sometimes be quite severe. For example, consider the case of May 10 at 1600 hours local time, where the estimate is a little over 1000 times greater than the scintillometer measurement. On the other hand, the other three estimates are two to five times greater than the scintillometer measurements.
Figure 45. Above is an idealized representation of the target for the turbulent blurring measurements. Below is the image taken in the “hallway” experiment.
5.4.3 Case studies

Here we examine two cases of turbulent imaging on two different days with similar meteorological conditions but markedly different turbulent image effects. The first case occurred on May 10 at 1600 hours local time (LT), and the second on May 12 at 1130 LT.

5.4.3.1 May 10, 1600 LT

The virtual potential air-sea temperature difference (VPASTD) is the principal quantity for characterizing the surface layer because it determines
its stability. Figure 17 shows two VPASTD curves due to the uncertainty of the sea surface temperature above the short path. The corrected VPASTD indicates that prior to 1600 LT on May 10, the surface layer was stable, and occasionally very stable, from about 0200 LT to about 1400 LT. The uncorrected VPASTD has only brief periods of stability prior to and at noon. The colour coding in Fig. 17 and Fig. 11 shows that the winds were predominantly from the land. Presumably, the wind transported warm air from the land over the cool water, thereby creating a stable layer. It was only at about 1200 LT that the wind changed direction and came from the sea. This caused the surface layer to become approximately neutral. The end result is that prior to 1600 LT, the surface layer likely spent most of its time in a stable regime. It is therefore reasonable to assume that the surface layer had a more or less well-defined stable characteristic at the time of this video sequence.

5.4.3.2 May 12, 1130 LT

The most striking feature of this case is the non-stationarity of the surface layer prior to the video sequence. Both the corrected and uncorrected VPASTD curves in Fig. 17 show that the surface layer was largely unstable for most of the morning, then became highly stable just prior to the video sequence. The instability is confirmed by the winds coming from the cooler land and travelling over a warmer sea during the night, and also suggests a highly non-stationary surface layer.

5.4.3.3 Comparison and analysis

Table 3 compares various meteorological and turbulence parameters that were determined for these two cases. Some parameters are quite similar, such as relative humidity, while others are reasonably similar, such as wind and cross-wind. The uncertainty in the VPASTD also gives us intervals with considerable overlap. Since the meteorological parameters are quite similar, the LWKD software, which assumes homogeneity and stationarity, yields comparable estimates of $C_n^2$. From Table 3, these are seen to have values of about $2 \times 10^{-16}$ m$^{-2/3}$ at each indicated time; however, when one considers the variation in the values between half an hour before the indicated time and half an hour after the indicated time, we see that on May 10 it ranged from $4.8 \times 10^{-17}$ m$^{-2/3}$ to $3.4 \times 10^{-16}$ m$^{-2/3}$, or about one decade. On the other hand, on May 12 it ranged over two decades from $1.7 \times 10^{-16}$ m$^{-2/3}$ to $1.7 \times 10^{-14}$ m$^{-2/3}$. Now, comparing this with the values from the scintillometer, we see that there is a factor of 60 between the values measured at their respective times. However, if we also look at their variation in time, we see that on May 10 it ranged from $4.0 \times 10^{-16}$ m$^{-2/3}$ to $1.7 \times 10^{-15}$ m$^{-2/3}$, or a factor of about 3, and on May 12 it varied by a factor of 20 from $3.6 \times 10^{-15}$ m$^{-2/3}$ to $6.9 \times 10^{-14}$ m$^{-2/3}$. Thus, it would appear that the difference in the level of turbulence measured by the scintillometer at these two times was close to 1 decade, say, from $1 \times 10^{-15}$ m$^{-2/3}$ to $1 \times 10^{-14}$ m$^{-2/3}$. Finally, if we compare these values with those
obtained using the LWKD model, we note that the LWKD value is about 1
decade less on May 10, but perhaps less than a decade different on the 12th. It
should be pointed out again that both observations occurred quite close to a
change in wind direction from the land to the sea, and the VPASTD changed
by close to 3 degrees.

The video sequences on the two days are also very different. The sequence
on May 10 exhibits low frequency image displacements and overall blurring
(it looks defocused), while on the 12th the sequence shows no significant
displacements or defocusing. Rather, there are small-scale image distortions
that appear to travel from left to right across the camera’s line of sight. We
have attempted to depict these effects in Figs. 48 and 49.

In order to explain these differences, we must point out that turbulent image
effects depend primarily on the turbulent phase fluctuations of the
wavefronts. These phase fluctuations depend mainly on the large-scale
characteristics of the turbulence, in other words, on the outer scale of the
turbulence, whereas the $C_n^2$ measurements depend mostly on eddies the size
of a Fresnel zone, about 3.2 cm in this case (Ref. 9). Since the only real
difference between these cases is their prior history, we can only conclude
that the $C_n^2$ value is not sufficient to fully characterize the effect of turbulence
on imaging. The large-scale features of the turbulence are also important.
These features may depend on the history of the surface layer, which in turn
may determine whether or not an internal boundary layer is present or if the
turbulence spectrum possesses Kolmogorov scaling, for instance. This
suggests that instantaneous meteorological parameters may not be sufficient
to fully characterize turbulence effects on imaging.
Figure 47. Comparison of the values of $C_n^2$ measured by the scintillometer and by the LWKD model, and those obtained from the long-exposure images.
Table 3. Case study comparison

<table>
<thead>
<tr>
<th>ATMOSPHERIC QUANTITY</th>
<th>MAY 10, 1600</th>
<th>MAY 12, 1130</th>
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<tbody>
<tr>
<td>VPASTD (ºC)</td>
<td>-0.99 to 0.16</td>
<td>-0.37 to 0.77</td>
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<tr>
<td>Relative humidity (%)</td>
<td>91.6</td>
<td>89.0</td>
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<tr>
<td>Wind velocity (m/s)</td>
<td>1.34</td>
<td>2.08</td>
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<tr>
<td>Cross-wind component (m/s)*</td>
<td>-0.27 ± 0.28</td>
<td>0.01 ± 0.61</td>
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<tr>
<td>$C_n^2$ (Scintec) (m$^{-2/3}$)</td>
<td>$6.90 \times 10^{-16}$</td>
<td>$3.96 \times 10^{-14}$</td>
</tr>
<tr>
<td>$C_n^2$ (Scintec) (m$^{-2/3}$)**</td>
<td>$4 \times 10^{-16}$ to $16.7 \times 10^{-16}$</td>
<td>$35.7 \times 10^{-16}$ to $694 \times 10^{-16}$</td>
</tr>
<tr>
<td>$C_n^2$ (LWKD) (m$^{-2/3}$)***</td>
<td>$2.01 \times 10^{-16}$ to $2.07 \times 10^{-16}$</td>
<td>$1.67 \times 10^{-16}$ to $1.88 \times 10^{-16}$</td>
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<tr>
<td>$C_n^2$ (LWKD) (m$^{-2/3}$)****</td>
<td>$0.475 \times 10^{-16}$ to $3.38 \times 10^{-15}$</td>
<td>$1.67 \times 10^{-16}$ to $168 \times 10^{-16}$</td>
</tr>
</tbody>
</table>

* A positive cross-wind velocity indicates advection from the left towards the right of the video images.

** The value obtained at the indicated time.

*** The range obtained is for both VPASTDs at the indicated time.

**** The range obtained also includes values obtained ½ hour before and after the indicated time.
Figure 48. Above, a relatively sharp image taken from the video sequence at 1400 on May 10. Below, a significantly blurry image taken from the same sequence.
6. Discussion

We have seen four different ways of evaluating $C_n^2$ (three are shown in Fig. 47). The first method is measurement using a large aperture scintillometer. Nothing can really be said about this method, as it is taken to be our ground truth. It is the only direct measurement of $C_n^2$ at our disposal and serves to evaluate any other method. The second method consists in employing a bulk surface layer meteorological model that uses the locally measured temperature, humidity and wind measurements. The main difficulty with this method resides in the scattered nature of these measurements and the local nature of the measuring instruments. For example, the buoy providing important meteorological data was located a significant distance from the propagation path, which resulted in, among other things, considerable uncertainty regarding the sea surface temperature. There is also the highly changeable nature of a coastal surface layer that is not modelled by a bulk model that uses using M-O similarity theory.

The third method used is essentially an eddy-correlation technique from fast sonic anemometer and hygrometer data. This method suffers primarily from the location of the instruments, atop the Pilastro breakwater. The breakwater most likely imparted its own turbulent disturbance to the flow owing to its shape within the air flow and the local heating that occurred during the day, both of which probably falsified the results obtainable from this method for the propagation path.
The fourth and final method used the turbulent blurring measured from long-exposure video images. This method has the advantage of being optical in nature, much like the scintillometer. However, it is quite sensitive to misalignments between the real and simulated images, leading more often than not to an overestimation of $C_n^2$. The video sequences themselves display a complexity not describable by the meteorological measurements alone. This is evident from the two case studies with similar meteorological parameters but very different temporal imaging characteristics. This leads us to conclude that the full description of an image sequence through turbulence depends very much on the large-scale characteristics of the turbulence, which is also a product of the geography and history of the local surface layer.

7. Conclusions

The POLLEX trials in Livorno, Italy were in most respects very successful. For our part, the trial provided Canada with its own large body of data and access to an even larger body of data from our TG16 colleagues. To date, limited analysis has been performed on all these data; however, many countries have ongoing programs in the areas of interest studied during the POLLEX trial, and results should continue to come forward in the years ahead.

Section 5 presented four methods for determining the index of refraction structure parameter, and section 6 contained a discussion of the merits of each method. The first method was based on the use of optical scintillometers; the second, bulk meteorology and our LWKD similarity model; the third used the combined measurements of a fast sonic anemometer and hygrometer; and the last used the modulation transfer function determined from the visible imagery of a specially created chart. The second and third methods also allow for the estimation of many other micrometeorological parameters, such as the friction velocity and the temperature structure parameter. Comparison of the micrometeorological parameters determined from these two methods also provides much insight into the problems encountered when trying to extend measurements obtained from a platform like the Pilastro breakwater to those obtained directly over the water. In particular, we found that the friction velocities were, apart from a factor of about 2, quite similar in both cases, but the temperature scale parameters were only close to one another during the night when there is essentially no local heating of the Pilastro breakwater’s concrete surface. Consequently, the structure parameters from these two methods also tended to agree only during the night.

From our results it appears that the best method for determining the index of refraction structure parameter is by using optical scintillometers. The difficulty with this method is that it requires an optical path between source and receiver that does not exceed a few kilometers. Consequently, although this technique is highly accurate, it is not likely to be used on our naval ships, but its invaluable for ground-truthing the results from any other technique.

The parameter can also be determined by optical imaging. This technique can be used over longer ranges but is still limited by the requirement that there be two end-points for a target and a receiver. Thus, it also is not an obvious candidate for use on our naval ships. Moreover, any imaging data must be taken with as few additional modulation effects as
possible being added to the image. Consequently, future measurements of this nature should only be performed using complete digital systems. Tests of such a digital system were recently performed by DRDC Valcartier in a recent NATO trial over a range of almost 10 km.

The bulk method technique was also shown to be relatively good; however, it does require an excellent determination of the air and sea temperature somewhere midway along the transmission path, as extrapolations from one area to another can be problematic. This technique is also very easily adapted to current meteorological configurations on our naval ships. Their position is critical, however, as the air and sea temperature measurements are de facto determinations of local heat flux, which is the dominant parameter controlling local turbulence.

Finally, while the fast sonic anemometer and hygrometer technique showed promise, it is particularly useful for determining a large number of micrometeorological parameters, and their placement is extremely critical. As shown for their placement on the breakwater, this is because the effects of local heating cause the estimates of heat flux to be totally unrepresentative of the transmission path over the sea. As a result, in this trial it only gave representative values during the night, when solar heating is at a minimum. Thus, any future use of this technique for determining the index of refraction structure parameter over the sea must be placed in a location such that the measured heat and moisture fluxes are representative of those over the path.
8. References


<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>DRDC</td>
<td>Defence Research and Development Canada</td>
</tr>
<tr>
<td>NATO</td>
<td>North Atlantic Treaty Organization</td>
</tr>
<tr>
<td>RTO</td>
<td>Research and Technology Organization</td>
</tr>
<tr>
<td>SET</td>
<td>Sensors and Electronics Technology</td>
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<tr>
<td>TG</td>
<td>Task Group</td>
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<tr>
<td>IR</td>
<td>Infrared</td>
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<tr>
<td>POLLEX</td>
<td>POint targets at Low eLevation EXperiment</td>
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<td>IRST</td>
<td>Infrared Search and Track</td>
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<td>MAPTIP</td>
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<td>Low Altitude Point Target Experiment</td>
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<td>Air-Sea Temperature Difference</td>
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<td>Mariteleradar</td>
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<td>RDDC</td>
<td>Recherche et Développement pour la Défense Canada</td>
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<td>OTAN</td>
<td>Organisation du Traité de l’Atlantique Nord</td>
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<td>DTAM</td>
<td>Différence de Température Air-Mer</td>
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<td>Ship Infrared</td>
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<td>IRBLEM</td>
<td>Infrared Boundary Layer Model</td>
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<td>LWKD</td>
<td>Luc-Walmsley-Kel-DREV</td>
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<td>TNO-FEL</td>
<td>TNO-Fysisch en Elektronisch Laboratorium</td>
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<td>CCD</td>
<td>Charge Coupled Device</td>
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<td>LOA</td>
<td>Long Optical Anemometer</td>
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<td>SACLANLNT</td>
<td>Supreme Allied Commander, Atlantic</td>
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<td>AWL</td>
<td>Above Water Level</td>
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<td>IFOV</td>
<td>Instantaneous Field of View</td>
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<td>NEI</td>
<td>Noise Equivalent Irradiance</td>
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<td>Large Aperture Scintillometer</td>
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<td>Video Home System</td>
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<td>MTF</td>
<td>Modulation Transfer Function</td>
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<td>METEK</td>
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<td>METCALC</td>
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## List of symbols

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<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Value</th>
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<tr>
<td>H/3</td>
<td>Significant wave height</td>
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<td>Eᵣ()</td>
<td>Electromagnetic field at the surface of the lens</td>
<td></td>
</tr>
<tr>
<td>Eₒ()</td>
<td>Electromagnetic field at the object plane</td>
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<tr>
<td>π</td>
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<td>Reverse spherical wave</td>
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<td>Diameter of a circle</td>
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<td>Fourier transform of the image</td>
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<td>Virtual potential temperature roughness height</td>
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<td>z₀u</td>
<td>Wind speed roughness height</td>
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<td>z₀q</td>
<td>Specific humidity roughness height</td>
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<td>k</td>
<td>Von Karman’s constant</td>
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<td>10 meter neutral heat flux coefficient</td>
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<td>CEN</td>
<td>10 meter neutral moisture flux coefficient</td>
<td>1.2 x 10⁻³</td>
</tr>
<tr>
<td>Cn²</td>
<td>Index of refraction structure parameter</td>
<td></td>
</tr>
<tr>
<td>Ct²</td>
<td>Temperature structure parameter</td>
<td></td>
</tr>
<tr>
<td>Cₒ²</td>
<td>Specific humidity structure parameter</td>
<td></td>
</tr>
<tr>
<td>g</td>
<td>Acceleration due to gravity</td>
<td>9.8 m/s²</td>
</tr>
<tr>
<td>αc</td>
<td>Charnock’s constant</td>
<td>0.011</td>
</tr>
<tr>
<td>u*</td>
<td>Friction velocity</td>
<td></td>
</tr>
<tr>
<td>θv</td>
<td>Virtual potential temperature</td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>Wind speed</td>
<td></td>
</tr>
<tr>
<td>σUU</td>
<td>UU variance</td>
<td></td>
</tr>
<tr>
<td>Tₛ</td>
<td>Sonic temperature</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{T_s T_s}$</td>
<td>$T_s T_s$ variance</td>
<td></td>
</tr>
<tr>
<td>------------------</td>
<td>-------------------</td>
<td></td>
</tr>
<tr>
<td>$Q$</td>
<td>Specific humidity</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{Q Q}$</td>
<td>QQ variance</td>
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</tr>
<tr>
<td>$\sigma_{Q T_s}$</td>
<td>QT$_s$ covariance</td>
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The POLLEX trial was carried out to study the effects of refraction and turbulence on atmospheric propagation and their impact on optical imaging systems, in particular Infrared Search and Track systems (IRSTs). During earlier NATO trials (MAPTIP and LAPTEX) the data collected on point target signatures showed quantitative scintillation effects when the optical paths propagated through the lowest regions of the marine boundary layer. Similar effects have also been observed during other measurement campaigns; however, a consistent problem has always been the determination or measurement of the refractive index structure function coefficient, $C_n^2$, upon which all turbulence calculations depend. The group’s need for additional data sets obtained under stable atmospheric conditions, when the air-sea temperature difference (ASTD) is positive and over-the-horizon detection is possible, was also a driving force for this trial.

TG16 chose to perform the trials in Livorno during the month of May because of the high probability of the occurrence of stable atmospheric conditions in the spring. With a water temperature of 17 °C and an offshore wind, air temperatures of up to 22 °C and higher were expected. In addition, Mariteleradar (MTR), the Italian Defence Research Institute, agreed to host the trial, offered secure locations for the group’s measurement equipment, the use of the ship, Porpora, to install an instrumented buoy and perform runs with calibrated IR sources and a RF reflector, access to the island of Gorgona at a range of 34 km for the installation of a set of fixed IR sources and RF reflectors, and access to a breakwater at 2 km from the site for the study of turbulence.

DRDC Valcartier’s primary interest was to obtain quality turbulence data using access to the breakwater, as it provided an excellent opportunity to study the effects of turbulence while simultaneously measuring the index of refraction structure coefficient using several independent techniques. As such, while the report provides general information about the efforts of the other nations and Canada’s complete effort, the principal emphasis of the report is restricted to the turbulence work.

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Surface layer turbulence, maritime surface layer, imaging, scintillation
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