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Test and Evaluation of Revised Concept Walters Probes—High Sensitivity Differential Temperature, CT2, Probes for Atmospheric Optical Turbulence Characterization

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Abstract

As the Department of Defense (DoD) and industry continue to advance the development of high energy laser (HEL)–based directed energy weapon (DEW) systems, the need for modernized test and evaluation (T&E) and experimentation capabilities for DEW has become critical. This will allow airborne, ship-based, and land-based HEL systems to be tested against air and surface targets in a well-understood atmospheric environment. T&E capabilities in maritime test arenas and land environments will be enhanced by instrumenting open-air test ranges with advanced sensor systems, including atmospheric optical turbulence measurement systems, which play a critical role in HEL device beam and fire control. Teknicare, Inc., in conjunction with NAWC WD Pt Mugu, has conducted extensive improvement and testing of reverse engineered differential temperature sensors at various locations including San Nicolas Island and Point Mugu NAWC on the PMSR as well as China Lake NAWC. This effort has included research of related designs, schematics, theses, and reports conducted at Naval Postgraduate School by Dr. Donald L. Walters and his students. The devices, now known as Walters Probes, make use of precision fine wire thermocouples separated at a known distance, including an added variable separation capability, to provide a measurement of temperature difference. The associated electronics provide necessary amplification and sampling rate to ensure a measurable ensemble average is obtained to determine CT2 at the Walters Probe location. These systems are capable of low noise operation and hence measurement of CT2 values that render atmospheric optical turbulence at extreme values indicative of terrestrial neutral vents, therefore they can easily measure values expected in the near maritime environment. Testing and evaluation have been conducted to determine reliability, sustainability, operability, and maintainability revisions to be undertaken to ensure the Walters Probes meet DEW T&E mission OPTEMPO requirements.

Motivation

The Department of Defense (DoD) and industry continue to advance the development of high energy laser (HEL)–based directed energy weapon (DEW) systems. Consequently, there is a need for modernized test and evaluation (T&E) and experimentation capabilities for DEW that has become critical. These capabilities will allow airborne, ship-based, and land-based HEL systems to be tested against air and surface targets in a well-understood atmospheric environment. T&E capabilities in maritime test arenas and land environments will be enhanced by instrumenting open-air test ranges with advanced sensor systems, including atmospheric optical turbulence measurement systems, which play a critical role in HEL device beam and fire control.

Background

Teknicare, Inc. has conducted extensive reverse engineering of an existing differential temperature sensor previously used in data collection at various locations including Starfire Optical Range, Los Alamos National Laboratory, Nevada Test Site, Nellis Air Force Base, San Nicolas Island, and Point Mugu NAWC on the PMSR, as well as China Lake NAWC. This effort has included detailed requirements analysis as well as research of related designs, schematics, theses, and reports conducted at Naval Postgraduate School by Dr. Donald L. Walters and his students. The devices, now known as Walters Probes, make use of precision fine wire thermocouples separated at a known distance to provide a measurement of temperature difference. The associated electronics provide necessary amplification and sampling rate to ensure a measurable ensemble average is obtained to determine C_T^2 at the Walters Probe location. These systems are capable of low noise operation and hence measurement of C_T^2 values that render atmospheric optical turbulence at extreme values indicative of terrestrial neutral events, therefore they can easily measure values expected in the near maritime environment. Revisions to the design to enhance reliability, sustainability, operability and maintainability have been undertaken to ensure the Walters Probes meet T&E mission OPTEMPO requirements. Progress on this design effort is detailed in an associated report (Nelson et al., 2024).

Theory

The index-of-refraction structure parameter is a mean-square statistical average of the difference in the index of refraction between two points in space which are separated by the distance r_{12} (Walters, 1981). It is defined by

$$C_n^2 = \langle (n_1 - n_2)^2 \rangle / r_{12}^{2/3},$$

where angled brackets stand for an ensemble average. The differences in index of refraction stem from density fluctuations induced by the velocity fluctuations in the atmosphere. These differences are caused by the mixing in a turbulent velocity field of passive contaminants such as heat and moisture. C_n^2 is quite difficult to measure directly. It is usually more convenient to measure the temperature structure parameter C_T^2, which is related to C_n^2 (neglecting humidity effects, which may have some contribution in maritime environments) by[1]

$$C_n^2 = (79 \times 10^{-6}\ P/T^2)^2\ C_T^2$$

where P is the atmospheric pressure in millibars and T is the atmospheric temperature in Kelvins (Tatarski, 1961). C_T^2 is defined in a similar manner as C_n^2

$$C_T^2 = \langle (T_1 - T_2)^2 \rangle / r_{12}^{2/3}.$$

This temperature structure parameter is commonly measured using a pair of fast response temperature probes as was done by Walters with his original devices.

Note that as long as the distance r_{12} falls within the inertial subrange, between the outer scale, L_0, and the inner scale, l_0, the definition above of C_T^2 should remain valid if Kolmogorov theory applies. The inner scale is nominally a few mm. The outer scale is theoretically ~1/2 the probe height (~2 m), in this case ~1 meter. This concept will be put to the test with the Interim Variable Separation Test Prototype.

T&E of Initial Selected Revisions

Over several support test series in coordination with NAVAIR Pt Mugu Geophysics Branch, the original probes were deployed with improved seals with a qualitative improvement in performance. However, there were insufficient hours to fully quantify the effect of these improvements to the probes.

The operational revision of gently rinsing the thermocouples with distilled water upon cycling the probes off duty also appeared to provide a lower failure rate and increased quality of data. However, insufficient hours to fully quantify the effect were logged after these improved procedures were undertaken.

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[1] Per Robi Garcia, the fixed value of 79 which appeared in the original development Kolmogorov formula has been compared to empirical results and may be adjusted to as high as 80 in maritime environments.

T&E of Interim Variable Separation Test Prototype

A test of the Interim Variable Separation Test Prototype was undertaken in June 2023 with an original probe used as a control device. The original probe had thermocouples at a separation of 50 cm. The test location and predominant wind direction are shown in Figure 1.

Figure 1. Test Location in June 2023 for the Interim Variable Separation Test Prototype

Note: Conducted on San Nicolas Island (left) on a test pad in the vicinity of Thousand Springs (center) with winds predominately from the NW so some terrestrial influence prior to reaching the test setup location for the Interim Variable Separation Test Prototype and the original control probe (right).

Results

The Interim Variable Separation Test Prototype was set to several separations as shown in Figure 2.

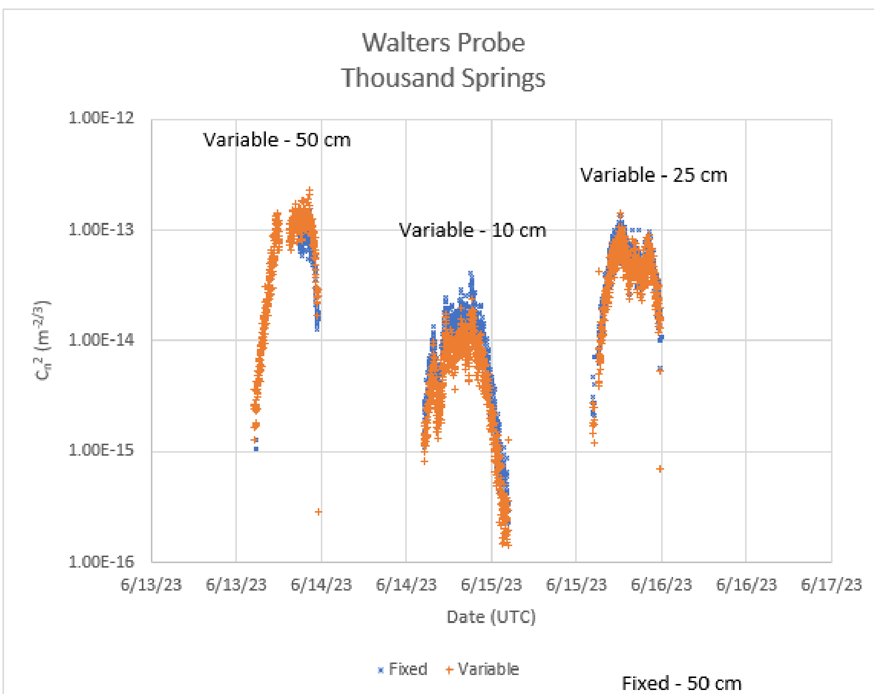

Figure 2. Results for Comparison of Interim Variable Separation Test Prototype with Original Probe.

Note: Original probe thermocouple separation was 50 cm**.** Interim Variable Separation Test Prototype was varied to match the original on the first day, then set at 10 cm separation on the second day, and then set at 25 cm separation on the third day. In all cases, the thermocouple separations of all probes fall within the expected inertial subrange. There was a high standard applied to this data. If there were any dropouts due to moisture in electronics, etc. over an ensemble averaging time period, then that data was not counted. However, for the data logged there is a strong visual correlation, as expected, regardless of separation.

The original probe thermocouple fixed separation was 50 cm. The Interim Variable Separation Test Prototype was varied to match the original on the first day, then set at 10 cm separation on the second day, and then set at 25 cm separation on the third day. In all cases, the thermocouple separations of all probes fall within the expected inertial subrange. There was a high standard applied to this data. If there were any dropouts due to moisture in electronics, etc. over an ensemble averaging time period, then that data was not counted. However, for the data logged there is a strong visual correlation, as expected, regardless of separation. This provides evidence that the Interim Variable Separation Test Prototype operates on sound principles and can be used to conduct optimal separation or theoretical turbulence studies.

In Figure 2 it is seen that atmospheric optical turbulence levels varied from day to day despite the agreement between the two style probes. Figure 3 shows the ambient temperature at the site during the test series that, in part, drove the terrestrial influenced turbulence levels.

Note that the level of temperature follows the general trend of atmospheric optical turbulence level for each day. The predominant wind direction during the test series resulted in a significant terrestrial influence on turbulence level. The atmospheric flow took a path that allowed surface heating and at least some convective flow of the air prior to measurement by the co-located sensors. For a rise in ambient temperature, the surface heating was likely more prevalent resulting in higher levels of atmospheric optical turbulence measured on days with higher temperature.

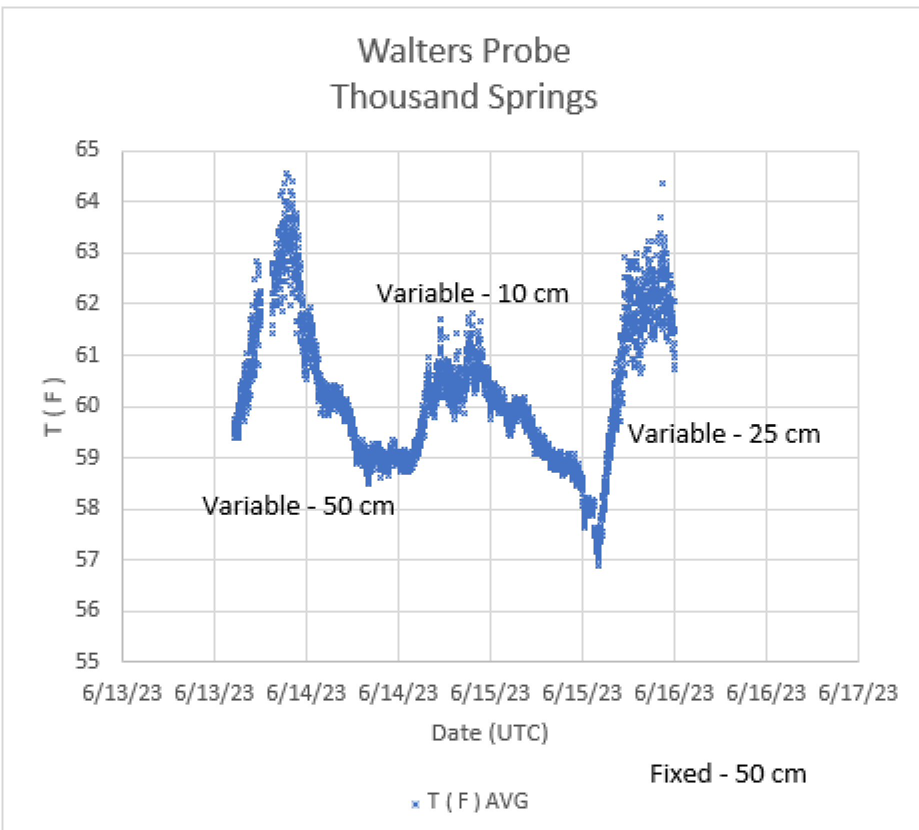

Figure 3. Ambient temperature at the Test Pad Where the Two Probes Were Taking Measurements

Note: That the level of temperature follows the general trend of atmospheric optical turbulence level for each day. The predominant wind direction during the test series resulted in a significant terrestrial influence on turbulence level and hence the importance of the ambient temperature given likely surface heating.

Summary and Conclusions

The ability to verify requirements for improvements to the original Walters probes in a challenging (maritime) test environment has been invaluable. The addition of seals and the rinsing of thermocouples during operations provided longer life and greater sensitivity to the deployed systems. In addition, the variable separation feature provides the ability to explore optimal probe separation distances for test operations as well as investigate theoretical premises in extended environments. These tests were a mere step along the way but provide confidence that a low noise atmospheric optical turbulence measurement solution is feasible for longer durations and extended environments.

Acknowledgments

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