

Antenna Characterization Supported by Optical Wireless Phase Reference

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ABSTRACT

Coherent Near-Field (NF) antenna measurements require the measurement receiver to access a phase reference synchronized with the excitation of the Antenna Under Test (AUT). Frequently, the probe is mounted on a mobile or mechanically unconstrained platform—such as cable-suspended gondola scanners used for space-antenna testing or systems integrated into Optical Ground Support Equipment (OGSE) for pre-launch qualification—conventional; in that case, distributing the reference via physical cables introduces severe mechanical drag, phase distortion from cable flexing, and operational constraints. In this work, we present and experimentally assess a proof-of-concept Light Emitting Diode (LED)-based Optical Wireless Communication (OWC) architecture for the cable-free distribution of a coherent phase reference. Since the adopted LEDs cannot be directly modulated at the 10 GHz antenna-measurement frequency, the reference is optically conveyed at an Intermediate Frequency (IF) of 40 MHz. A dual-Phase-Locked Loop (PLL) architecture is then employed to generate both the AUT excitation and the coherent reference required by the measurement receiver at 10 GHz.

Relative motion between the optical transmitter and receiver produces a position-dependent phase contribution that is not related to the field radiated by the AUT. To estimate and compensate for this contribution, we introduce a bidirectional round-trip optical configuration. Preliminary experimental results are obtained from planar NF measurements, performed at different optical path lengths and combined to emulate a scan affected by probe-position-dependent path variations. After applying the proposed optical-path compensation and the necessary calibration procedures, the recovered NF phase matches that obtained using a conventional wired reference along representative cuts of the scanning plane. The residual discrepancies are compatible with Near-Field/Far-Field processing. These results demonstrate the feasibility of a coherent reference distribution based on OWC: this offers a reliable, contactless phase synchronization strategy for spaceborne payload verification and large-scale antenna characterization.

Keywords: Optical wireless communication, antenna measurements, near-field, phase reference distribution, coherent sensing.

1. INTRODUCTION

Near-Field (NF) measurements are pivotal tools for the experimental characterization of radiating and scattering systems.^{1–3} The acquired NF data consist of samples of the radiated or scattered field and can be processed to retrieve a variety of information. These include the electromagnetic properties of the system under test,^{2,3} its Far-Field (FF) radiation or scattering characteristics through Near-Field/Far-Field (NF/FF) transformations,^{2,4,5} and signatures of possible faults or defects obtained by appropriate processing techniques. Although the foregoing considerations apply to both radiating and scattering systems, the present work specifically addresses antenna characterization for space applications. Accordingly, the discussion that follows is focused on radiating systems, and the system under test is henceforth referred to as the Antenna Under Test (AUT). Nevertheless, the concepts, measurement architectures, and phase-compensation procedures presented herein can be directly extended to the NF characterization of scattering systems, with the AUT replaced by the corresponding scatterer under test.

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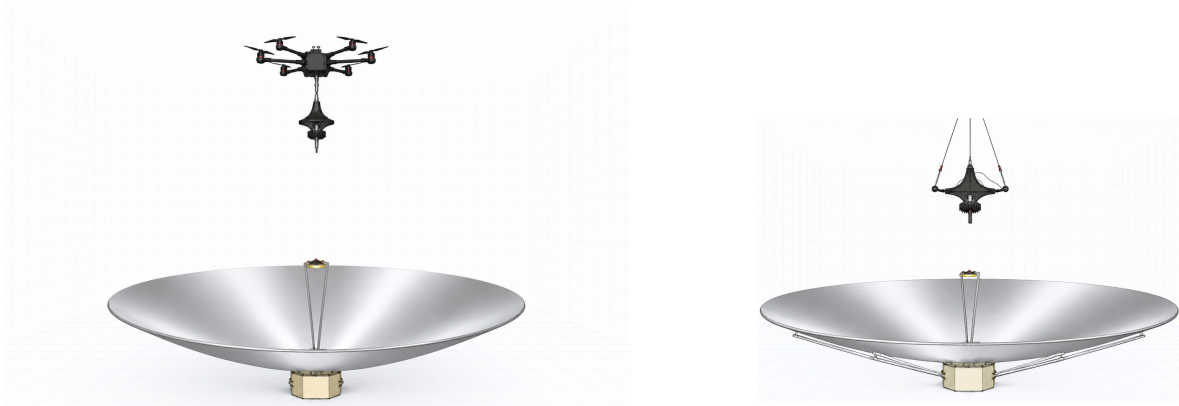


Figure 1. Conceptual illustrations of the in-situ NF characterization of an electrically large reflector antenna using a UAV-mounted probe (left) and a gondola-suspended probe (right).

Traditionally, NF measurement facilities rely on controlled environments and prescribed scanning geometries, typically planar, cylindrical, or spherical. Depending on the acquisition architecture, the probe measures either the complex field, namely, amplitude and phase,⁶ or amplitude-only data.^{7,8} The latter option enables phaseless characterization and removes the need to distribute a phase-coherent reference to the receiver. This simplification, however, transfers much of the complexity to the reconstruction stage: the missing phase must be recovered by solving a nonlinear, and generally non-convex, inverse problem. Its uniqueness and robustness often rely on additional measurement diversity, such as acquisitions over multiple surfaces⁹ or with different probe configurations.¹⁰ Phaseless techniques may therefore require more redundant data and a greater computational effort, while also being more sensitive to algorithm initialization. Therefore, coherent measurement approaches are generally preferred whenever a sufficiently stable phase reference is available, since they provide direct access to the complex field and enable the application of well-established NF processing techniques.

Today, many antenna-characterization scenarios fall outside the controlled conditions of conventional NF facilities. The in-situ characterization of electrically large or immovable AUTs, such as large reflector antennas and satellite ground-station antennas, often requires the probe to be carried by mobile or mechanically unconstrained platforms. Representative solutions include robotic arms,¹¹ Unmanned Aerial Vehicles (UAVs) operating either outdoors^{12,13} or indoors in constrained environments,^{14,15} and gondola-based scanners employed for testing large space antennas.¹⁶ In Fig. 1, the left and right panels conceptually illustrate UAV- and gondola-based implementations, respectively.

For all these mobile-platform configurations, maintaining phase coherence is significantly more challenging than in conventional controlled facilities. In coherent systems, the AUT is fed with a test signal, while a phase-locked reference is delivered to the measurement equipment, typically through coaxial or fiber-optic links, as exemplified in Fig. 2a. However, on UAVs, such wired links degrade maneuverability and impose severe operational constraints. Long coaxial cables introduce a significant mechanical load,^{17,18} whereas fiber-optic links, despite their lower mechanical impact, may exhibit response variations due to temperature fluctuations.¹⁹

In this context, we investigate, for the first time, the use of Optical Wireless Communication (OWC) technology for the wireless distribution of a coherent phase reference in NF antenna measurements. The underlying concept is the subject of a joint Provisional European patent.²⁰ Building on the established capabilities of OWC systems,^{21–24} the proposed approach removes the need for a wired reference connection, thereby providing a lightweight and motion-tolerant solution. Moreover, because the reference is conveyed optically, the link introduces no additional Radio Frequency (RF) emissions into the measurement environment and therefore does not electromagnetically perturb the field under test or couple to the AUT.

A particularly relevant application is the ground-based testing of spaceborne antennas during qualification, integration, and verification activities prior to launch. In this setting, an OWC link, as exemplified in Fig. 2b, can be incorporated into the Optical Ground Support Equipment (OGSE) used for pre-launch antenna testing,



Figure 2. Conceptual illustration of phase-reference distribution in antenna measurement configurations: wired link in a gondola-based setup (left) and optical wireless link in a UAV-based setup (right).

providing the measurement receiver with a coherent reference while avoiding cable routing around the flight hardware.

The main challenge associated with integrating OWC links into coherent RF measurements is the position-dependent phase shift caused by variations in the optical path length as the Transmitter (TX) and Receiver (RX) move relative to each other. This phase contribution is unrelated to the field radiated by the AUT and must therefore be estimated and compensated for. This work presents and experimentally characterizes a novel OWC architecture that simultaneously distributes the phase reference and tracks variations in the free-space optical path, thereby enabling coherent NF measurements on a moving platform.

The proposed implementation employs an intensity-modulated Light Emitting Diode (LED)-based TX. Its wide emission angle reduces sensitivity to pointing errors and relaxes the alignment requirements while providing a robust and low-cost solution. Preliminary experimental results are presented to provide an initial assessment of the feasibility of the proposed concept and its implementation. In particular, we show that the phase of the antenna NF can be recovered, despite the phase term introduced by the relative motion of the measurement probe, once the optical-path contribution is properly estimated and compensated for.

The paper is organized as follows. Section 2 introduces the OWC-based phase-reference distribution architecture and sketches the round-trip feedback technique used to estimate and compensate for the position-dependent phase contributions due to variations in the optical path. Section 3 describes the experimental implementation of the proposed approach, including the optical and RF subsystems and the dual-Phase-Locked Loop (PLL) measurement architecture. Section 4 presents preliminary results under realistic NF measurement conditions. In particular, it describes the reference NF acquisition, the feedback-phase measurements performed at different optical TX–RX distances, the calibration of the power-dependent PLL phase contribution, and the comparison between the reference and feedback-compensated NF phases. Finally, Section 5 summarizes the main findings and outlines directions for future developments.

2. THE PROPOSED APPROACH

2.1 OWC-based phase-reference distribution

The aim of the proposed approach is to replace the wired phase-reference distribution links with OWC connections and still preserve the coherence required for complex NF measurements. The general architecture is illustrated in Fig. 3. An optical carrier is intensity-modulated by an electrical reference signal and transmitted over free space

toward the moving measurement assembly. The reference is then recovered at the receiver side and supplied to Measurement Equipment (ME) #1 for coherent processing of the signal acquired by the probe.

If the operating frequency lies within the modulation bandwidth of the optical source, the reference can be directly distributed at the measurement frequency. Otherwise, it is transmitted at a lower Intermediate Frequency (IF) and subsequently converted to the target RF by means of phase-locked frequency synthesizers. In the latter case, a dual-PLL architecture is employed: one PLL generates the signal used to excite the AUT, whereas the other regenerates the receiver reference from the optically distributed signal. Since both branches are derived from the same master reference, a coherent relationship is maintained between the AUT excitation and the reference used by the measurement receiver.

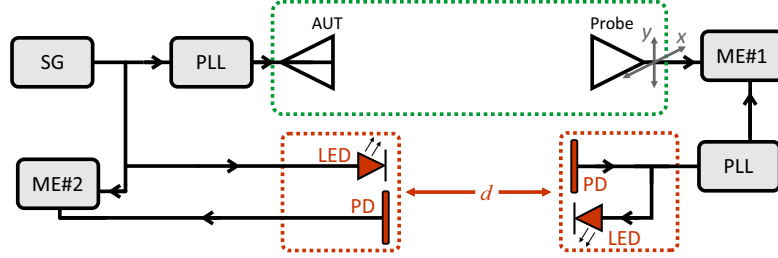


Figure 3. Blocks of the experimental setup of the proposed coherent NF measurement architecture. SG: Signal Generator; PLL: Phase-Locked Loop; ME: Measurement Equipment; LED: Light Emitting Diode; PD: Photo-Diode.

2.2 Round-trip feedback compensation

A fundamental issue associated with the use of an OWC link is the position-dependent phase shift introduced by the variations in the free-space optical path length. As the probe assembly moves across the scanning surface, the relative positions of the optical TX and RX change. The resulting phase contribution is not related to the field radiated by the AUT and, if left uncompensated, would corrupt the measured NF phase. The proposed architecture thus estimates this contribution without requiring external information about the probe position. As illustrated in Fig. 3, the optically distributed reference follows a forward path toward the moving measurement assembly, where it is recovered and supplied to ME #1. The recovered reference is also retransmitted toward the stationary side through a feedback optical link. There, ME #2 compares the returned signal with the locally available reference.

Let d_0 denotes the one-way optical path length at a reference probe position and let $d = d_0 + \Delta d$ be its value at a generic sampling point. The incremental phase accumulated by the electrical modulation signal over the one-way OWC link is

$$\Delta\phi_{OW}(d) = \phi_{OW}(d) - \phi_{OW}(d_0) = \beta_m \Delta d, \quad (1)$$

where $\beta_m = 2\pi/\lambda_m = 2\pi f_m/c$ is the free-space propagation constant associated with the electrical modulation frequency f_m .

The direct phase measured by ME #1 is given by

$$\phi_{dir}(d) = \Delta\phi(d) + \Delta\phi_{OW}(d) + \phi_c, \quad (2)$$

where $\Delta\phi(d)$ represents the target phase contribution introduced by the AUT, and ϕ_c accounts for position-independent instrumental phase terms.

The feedback signal accumulates the phase contributions associated with both the forward (Δd_f) and return (Δd_{fb}) optical paths, yielding a total feedback-phase increment relative to the reference value $\phi_{fb}^{(0)}$ of

$$\phi_{fb}(d) - \phi_{fb}^{(0)} = \beta_m (\Delta d_f + \Delta d_{fb}), \quad (3)$$

Because the forward and return paths experience identical length changes during probe movement, we can write $\Delta d_f \simeq \Delta d_{fb} \simeq \Delta d$. Consequently,

$$\phi_{fb}(d) - \phi_{fb}^{(0)} = 2\Delta\phi_{OW}(d), \quad (4)$$

Thus, the one-way optical-path contribution can be estimated as

$$\widehat{\Delta\phi}_{\text{OW}}(d) = \frac{1}{2} \left[\phi_{\text{fb}}(d) - \phi_{\text{fb}}^{(0)} \right]. \quad (5)$$

Subtracting this estimate from $\phi_{\text{dir}}(d)$ and eliminating the remaining constant offset ϕ_c via a reference calibration, isolates the target phase $\Delta\phi(d)$ at each sampling location.

Several theoretical and technological aspects may still be investigated and optimized to further improve the robustness, accuracy, and overall reliability of the proposed measurement approach.

3. EXPERIMENTAL SETUP

The proposed architecture is experimentally implemented through the LED-based dual-PLL configuration, which is schematically represented in Fig. 3. LEDs are chosen because their high optical power and wide beam divergence relax the alignment requirements and reduce sensitivity to pointing errors, this is particularly advantageous when the optical receiver is mounted on a moving platform.

We note that the LEDs have limited electrical modulation bandwidth and this prevents the direct distribution of the phase reference at the RF frequency required for antenna characterization. Hence, the reference is transmitted over the OWC links at an IF of 40 MHz, while AUT measurements are conducted at 10 GHz. A dual-PLL architecture establishes the required coherent relationship between the AUT excitation and the reference supplied to the measurement receiver.

The signal generator provides the primary 40 MHz reference. On the stationary side, one branch drives a source-side PLL that generates the 10 GHz signal used to excite the AUT. The other branch intensity-modulates the light from the first LED, which is then transmitted through the forward OWC link to the moving probe assembly; here, an Avalanche Photo-Diode (APD) recovers the electrical IF reference to drive the receiver-side PLL. The latter generates the coherent 10 GHz reference supplied to ME #1 to be compared with the signal acquired by the probe. In parallel, the recovered IF reference is retransmitted toward the stationary side using the feedback OWC link. The return signal is detected by the second APD and supplied to ME #2, which compares it with the locally available reference. The resulting feedback-phase measurement is recorded and subsequently used to estimate and compensate, through offline post-processing, for the phase contribution introduced by variations in the optical path length, according to the procedure described in Section 2.2.

As shown in Fig. 4, the forward and feedback optical links employ two LEDs operating at wavelengths of 450 nm (blue) and 650 nm (red), respectively. Each source has a beam divergence of approximately 120°, which significantly relaxes the alignment requirements, while their spectral separation minimizes crosstalk between the two channels. The optical components and their arrangement within the experimental setup are shown in Fig. 4. The TX and RX units are mounted on opposite sides of the scanning region and aligned along the corresponding free-space optical paths.

On the RF side (Fig. 5), the subsystem comprises a signal generator providing the common 40 MHz IF reference, two Vector Network Analyzers (VNAs) operating in receive-only mode, and the supporting RF electronics required to generate and distribute the coherent signals used by the measurement setup.

4. RESULTS

The measurement setup, shown in Fig. 6, consists of a planar NF scanner and the optical and RF instrumentation described in Section 3. To accommodate all subsystems within a compact laboratory space, a bench-top configuration was adopted, resulting in semi-anechoic measurement conditions where environmental reflections were only partially suppressed. Before the final data acquisitions, the dominant scattering contributions were identified and mitigated by placing additional absorbing material at the most critical locations.

The experimental results presented in this section demonstrate that phase contributions introduced by optical path length changes can be recovered and compensated in a realistic NF antenna measurements.

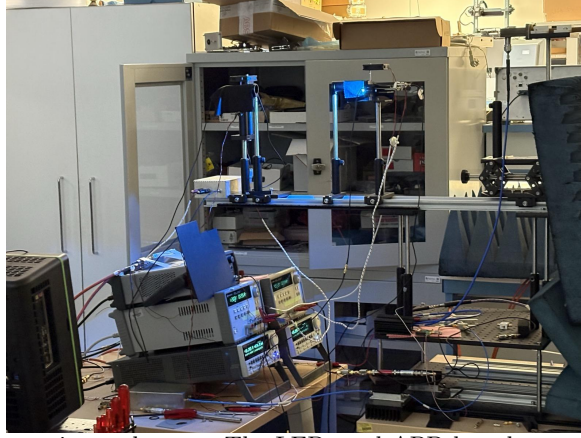
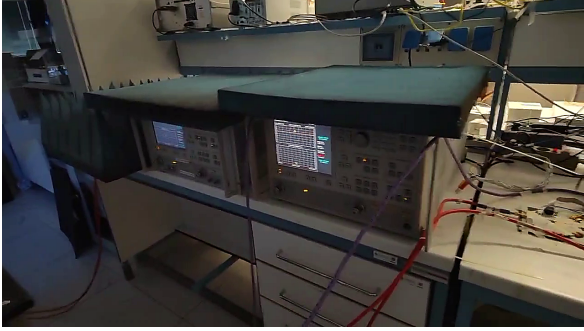
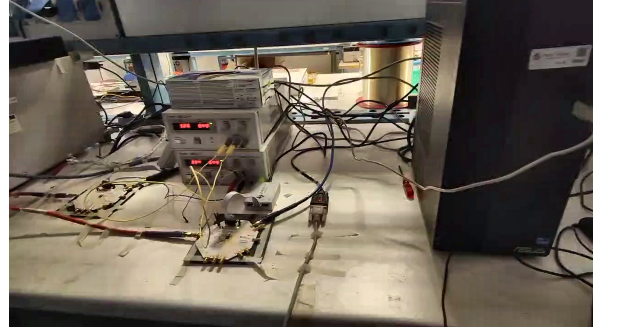


Figure 4. Optical section of the experimental setup. The LED- and APD-based transmitting and receiving units implementing the forward and feedback OWC links are mounted on opposite sides of the scanning region and aligned along the corresponding free-space optical paths.



(a) The two VNAs.



(b) The two PLLs.

Figure 5. RF instrumentation employed in the experimental implementation: the two VNAs operating as measurement receivers are shown in the left panel, whereas the two PLLs used to establish the coherent 10 GHz measurement chain are shown in the right panel.

4.1 Experimental Validation and Feedback Phase Compensation

To assess the proposed architecture, a reference NF acquisition was first conducted using a conventional coherent RF setup, with the optical subsystem excluded from the measurement chain. This establishes a baseline for comparison with those recovered using the proposed OWC-based phase-reference distribution and compensation approach.

In order to characterize the phase variations induced by optical path-length changes during realistic scanning, the feedback phase was measured across the scanning plane for three different optical TX–RX distances, (d_1 , d_2 , and d_3). Three complete NF acquisitions were carried out at different distances, while keeping the separation between the AUT aperture and the scanning plane fixed.

A composite dataset was then constructed to emulate a scan during which the optical path changes with the probe position. In particular, the first third of the scanning plane was taken from the acquisition performed at d_1 , the second third from that performed at d_2 , and the remaining third from that performed at d_3 . The resulting phase distribution contains the position-dependent contributions introduced by the different optical path lengths. The recorded feedback phase was used to compensate for these optical contributions at each sampling location according to the procedure described in Section 2.2, and the recovered phase was validated against the baseline RF reference.

Representative cuts along the x - and y -directions are shown in Fig. 7. In both cases, the feedback-compensated phase matches the reference phase over the entire scanning interval, despite the optical-path variations introduced

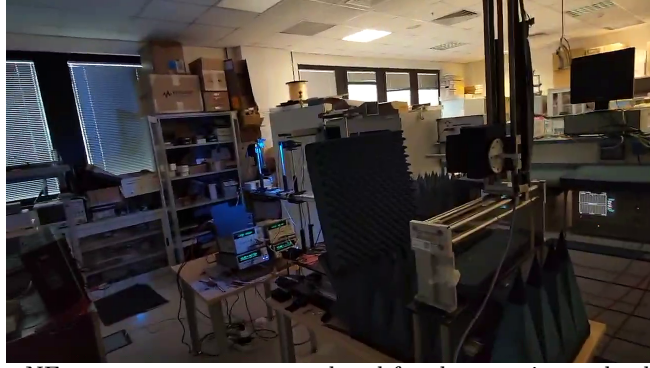
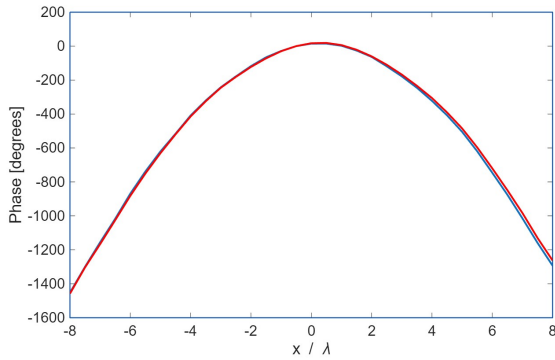
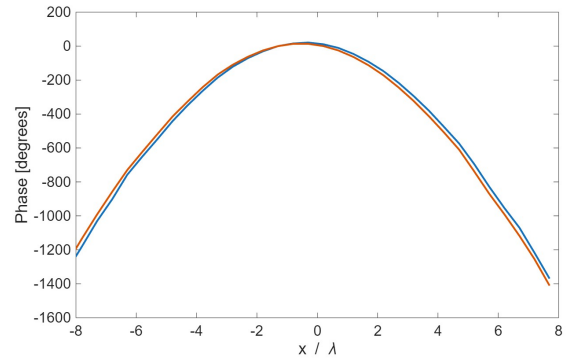


Figure 6. Semi-anechoic planar NF measurement setup employed for the experimental validation of the proposed OWC-based phase-reference distribution architecture.



(a) x -directed cut.



(b) y -directed cut.

Figure 7. Comparison between the reference NF phase and the phase recovered using the proposed feedback compensation along representative cuts in the x -direction (a) and in the y -direction (b).

in the composite acquisition. The residual discrepancies remain compatible with the phase accuracy required for the intended NF/FF processing. These results demonstrate that the proposed feedback mechanism is capable to remove the motion-induced optical-path phase contribution and preserves the phase information required for coherent NF measurements.

5. CONCLUSION AND FUTURE DEVELOPMENTS

This work has presented a proof-of-concept OWC-based architecture for the cable-free distribution of the coherent phase reference required in NF space-antenna testing or systems integrated into Optical Ground Support Equipment (OGSE). Preliminary experimental results support the feasibility of the proposed approach, which avoids the wired connection between the stationary instrumentation and the moving probe assembly while preserving coherent operation.

Our preliminary results demonstrate the feasibility of compensating for the phase contribution introduced by variations in the optical path. This was achieved by a combination of theoretical considerations, calibration procedures, and implementation-specific technical measures, whose detailed discussion is omitted here for brevity.

The proposed approach is particularly promising for the measurement configurations where a wired connection to the moving receiver would require significant mechanical or operational constraints. Although the experimental validation presented here focuses on antenna measurements, the same principle can be also directly extended to coherent scattering measurements involving mobile receivers.

Future work will first address the application of an NF/FF transformation to the feedback-compensated data. This will allow the effects of the residual phase errors to be quantified directly in terms of the reconstructed FF

pattern and compared to the pattern obtained using a conventional wired reference. Furthermore, additional experiments will consider a continuously varying optical path during a single acquisition, rather than the composite three-distance scenario adopted in the current validation.

ACKNOWLEDGMENTS

This work was partially supported by the MIUR Progetti di Ricerca di Rilevante Interesse Nazionale (PRIN) Bando 2022 - grant 2022T3FHLH.

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