Development of Highly Accurate Stretched-Front-Leg Distance-Measuring Equipment and the Testbed Results

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ABSTRACT

Distance measuring equipment (DME) has been used as a terrain-based navigation system for several decades. Although global navigation satellite systems have emerged as primary positioning systems, DME is expected to serve as an indispensable backup system for aircraft navigation. One of the primary drawbacks of DME is its poor ranging accuracy, which could be greater than 100 m in a multipath environment. Improving the ranging accuracy of DME would provide several benefits to aircraft navigation, such as area navigation or required navigation performance with higher DME/DME positioning accuracy in terminal areas. Previous studies have investigated various methods for improving the ranging accuracy of DME, such as methods involving the use of advanced DME pulse shapes. Among these pulses, the stretched-front-leg (SFOL) pulse provides approximately 4–5 times better ranging accuracy than conventional Gaussian DME pulses while meeting the International Civil Aviation Organization’s DME pulse shape specifications. For currently deployed DME, an ability to transmit the SFOL pulse without any changes would be desirable. However, the currently deployed DME is not capable of transmitting the SFOL pulse because its software and hardware are designed to transmit conventional Gaussian pulses. Our tests revealed that a significantly distorted SFOL pulse was transmitted if the Gaussian pulse was simply replaced with the SFOL pulse in the transmitter unit of commercial Gaussian pulse-based DME. This distortion of the transmitted SFOL pulse was primarily caused by a series of power amplifiers. This paper introduces digital pre-distortion techniques for power amplifiers that allow Gaussian pulse-based DME to transmit the SFOL pulse. Additionally, this paper introduces a design method for the SFOL DME pulse and testbed results using a commercial DME transponder with the proposed pre-distortion methods.

INTRODUCTION

Distance measuring equipment (DME) has been employed for aircraft navigation since the 1950s. While a global navigation satellite system (GNSS) serves as the primary means of aircraft navigation, DME is expected to serve as a back-up system for GNSSs. Over the past few decades, GNSSs have evolved from the standalone global positioning system (GPS) to a multi-constellation and multi-frequency GNSS. In addition, several augmentation systems for GNSSs have been proposed, including ground-based and space-based augmentation systems, and these systems have improved the accuracy, integrity, continuity, and availability of a standalone GNSS [1]. Commercial DME has also improved over the past few decades. However, its advancement is primarily in terms of the electronics, signal processing algorithms, and user interfaces. Unfortunately, no significant changes have been observed in the operating principles and ranging performance of DME. Around 2010, the Federal Aviation Administration (FAA) of the United States began to search for promising alternative position, navigation, and timing (APNT) methods for possible GNSS outages in a local or wide area [2–4]. In 2016, the FAA announced that DME would serve as a back-up for the GPS until around 2030 while the search for a better APNT candidate continued [5]. The primary reason for the consideration of DME as only a temporary back-up system was presumed to be its poor ranging accuracy compared with that of a GNSS.

The largest ranging error source for DME is the multipath error, which is primarily dependent on the pulse shape. While the Gaussian DME pulse adopted by most DME manufacturers demonstrates a low effective radiated power (ERP) around a center frequency, it may also exhibit a large multipath-induced range error over 100 m. To improve the DME ranging accuracy, alternative DME pulses have been proposed [6–8], and the stretched-front-Leg (SFOL) pulse is known to demonstrate the best multipath resistance. The SFOL pulse was designed using genetic algorithms to meet the International Civil Aviation Organization's (ICAO) DME transponder specifications for the pulse shape and ERP. Benefits of using the SFOL pulse for a ground DME transponder network and the DME/DME positioning accuracy have been reported in [9,10]. An SFOL DME testbed was recently developed to validate the performance of the SFOL pulse and to investigate the efforts required to transform modern Gaussian pulse-based DME into SFOL pulse-based DME. This paper presents promising algorithms and hardware changes applied to the aforementioned testbed. A few of the remaining challenges will also be discussed.

OVERVIEW OF SFOL PULSES

Figure 1 presents a comparison of a conventional Gaussian pulse, a smoothed concave polygon (SCP) pulse, and an SFOL pulse [6,8]. The SFOL pulse has a rise time of 2.8 µs, width of 3.4 µs, and falling time of 3.0 µs, and its ERP is illustrated in Figure 2. The SCP pulse is another type of an alternative DME pulse; however, its multipath resistance performance is inferior to that of an SFOL pulse. Figures 1 and 2 confirm that the SFOL pulse meets the ICAO DME transponder pulse-shape requirements. Figure 3 illustrates the multipath-induced range errors of the three pulses obtained through simulations, wherein the amplitude ratio of the multipath and direct pulses was 0.3, and their phase differences were 0° and 180°. Overall, the SFOL pulse eliminated 77% and 60% of the multipath-induced range errors of the Gaussian and SCP pulses, respectively. The strong multipath resistance of the SFOL pulse can be attributed to its unique shape with a rising edge. Details regarding SFOL pulse generation techniques and the characteristics of the pulse can be found elsewhere [8].

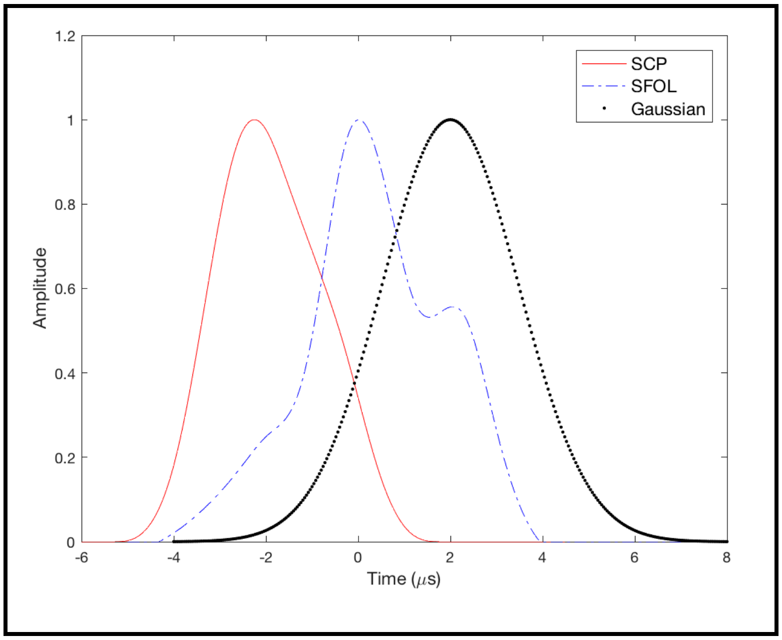


Figure 1. Pulse shapes of Gaussian, SCP, and SFOL pulses [8]

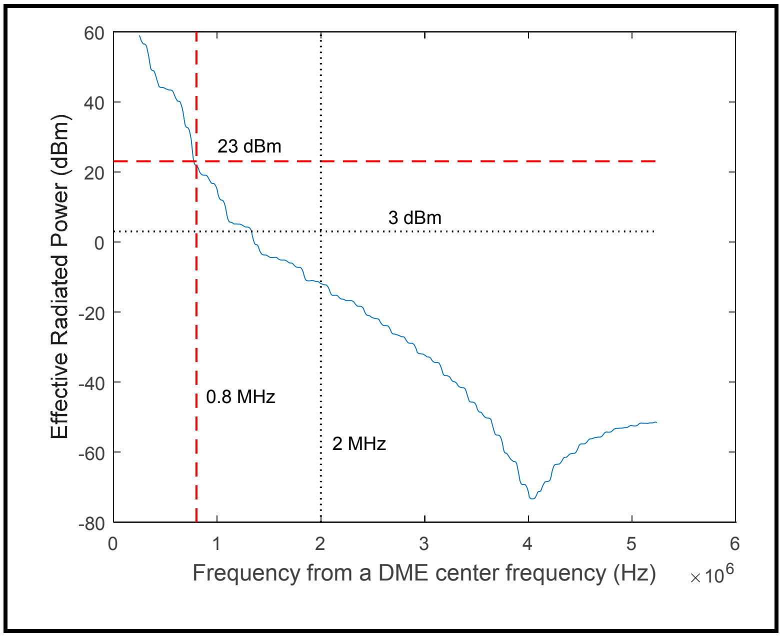


Figure 2. Effective radiated power of an SFOL pulse [8]

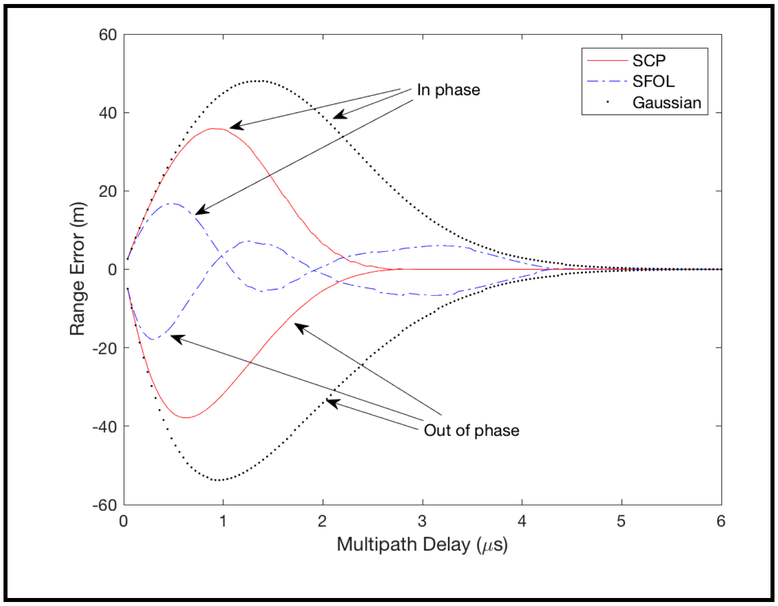


Figure 3. Envelopes of multipath-induced errors for Gaussian, SCP, and SFOL pulses, where the multipath to direct pulse amplitude ratio was set to 0.3 [8]

SFOL PULSE TESTBED DEVELOPMENT

Instead of designing an entirely new SFOL DME transponder, the testbed was developed from modern commercial Gaussian pulse-based DME manufactured by Mopiens Inc. This approach was followed to determine the modifications required to transform Gaussian pulse-based DME into SFOL pulse-based DME. To identify the required modifications, Mopiens' DME was first programmed to transmit the SFOL pulse without any software and hardware changes. As expected, the transmitted SFOL pulse was significantly distorted and failed to meet the ICAO DME pulse-shape requirements. The primary sources of distortion were identified to be power amplifiers (PAs) in the pulse-shaping circuits. The following section will discuss the algorithms and hardware changes applied to the testbed development for proper transmission of the SFOL pulse.

Digital Power Amplifier Pre-distortion as a Key Enabling Technique

Distortion of the SFOL pulse was primarily due to the nonlinearity introduced during the amplification of modulated pulses. In fact, signal distortions introduced by PAs have been reported to be troublesome in several areas including mobile communications. These problems have been resolved by using a digital power amplifier pre-distortion (DPD) technique [11]. The overall procedure of DPD with inverse learning is depicted in Figure 4. Here, an SFOL pulse, x(n), is pre-distorted before passing through a PA. When the pre-distorted SFOL pulse, u(n), passes through the PA, it experiences distortion due to the PA modules. Then, the distorted waveform emerging out of the PA, y(n), is normalized with gain G, and y(n) is fed into the post-distorter and parameter estimator to determine the pre-distorter. This process is iterative, and the converged pre-distorter drives y(n) to closely follow x(n).

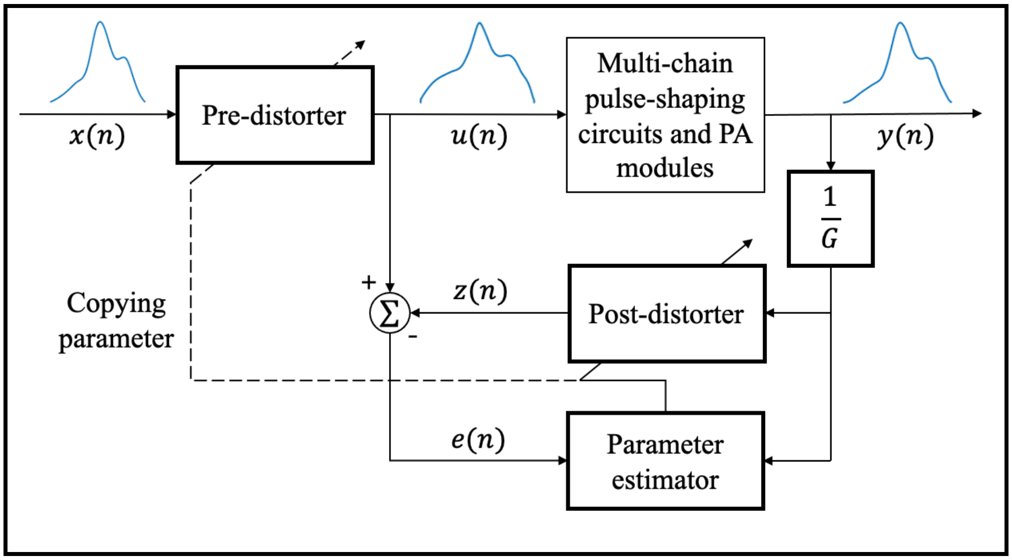


Figure 4. Overall procedure for digital pre-distortion of power amplifiers based on inverse learning

The DPD technique itself only requires software changes, and most commercial DME transponders are capable of capturing the transmitted signals for monitoring purposes. However, because the SFOL pulse spectral density power is higher than that of the Gaussian pulse, internal receiver modules may need to be changed to be able to completely capture the shape of the transmitted SFOL pulse.

During our tests, we observed that the ERP values of the transmitted SFOL pulse were often larger than the requirements in a high-power DME mode. This issue could be attributed to the noise generated in the carrier phase and other electronics, which did not cause trouble when transmitting a Gaussian pulse because the ERP of the Gaussian pulse was much lower than that of the SFOL pulse. Therefore, more refined signal processing algorithms and better electronics with lower noise must be used. Figure 5 illustrates the testbed used during development.

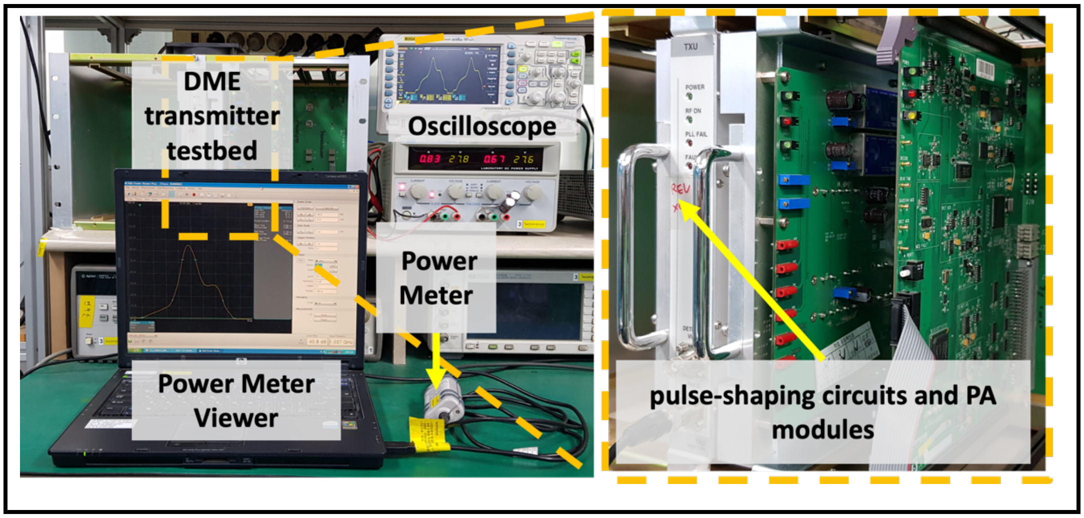


Figure 5. Testbed setup using a DME transmitter unit, oscilloscope, and power sensor

TESTBED RESULTS

Figure 6 presents a comparison of the original SFOL pulse, transmitted SFOL pulse without DPD, and transmitted SFOL pulse with DPD obtained from our testbed in a low-power mode. The transmitted SFOL pulse with DPD closely follows the original SFOL pulse, whereas that without DPD appears significantly distorted. Figure 7 illustrates results of the spectral power density measurements of the original SFOL pulse and transmitted SFOL pulse with DPD. The spectral density of the transmitted SFOL pulse with DPD is higher than that generated by a signal generator owing to noise resulting from various factors in the testbed. The low-power SFOL DME testbed still meets the ICAO DME pulse-shape requirements with a sufficient margin. However, spectral growth should be mitigated for high-power SFOL DME, which will be a part of future research.

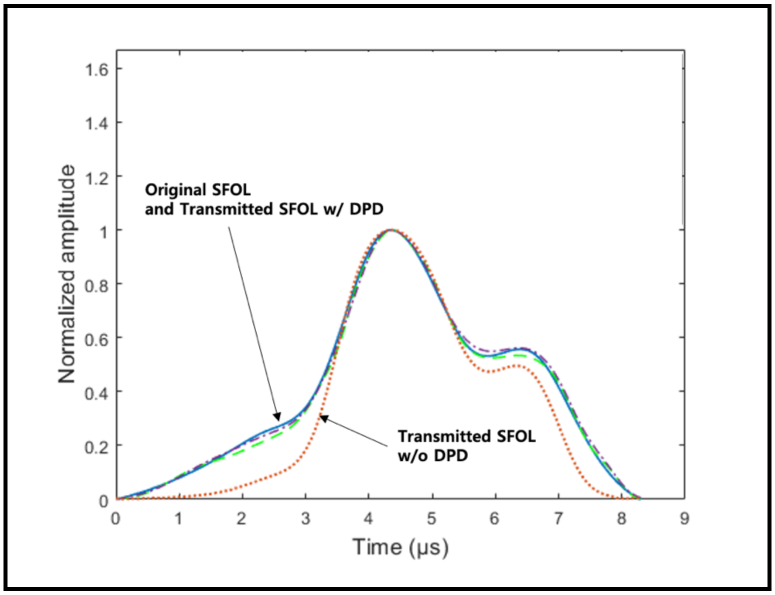
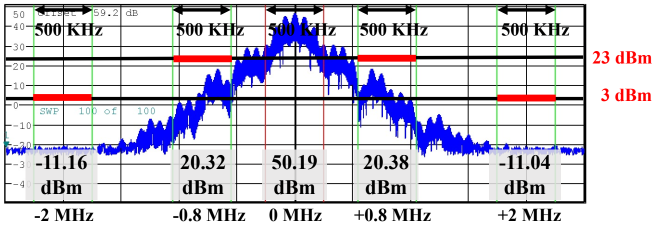


Figure 6. Comparison of the original SFOL pulse, transmitted SFOL pulse with DPD, and transmitted SFOL pulse without DPD

(a) Original SFOL



(b) Transmitted SFOL with DPD

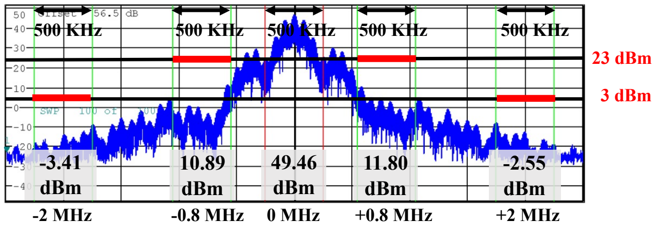


Figure 7. Spectral density measurements of the original SFOL pulse and transmitted SFOL pulse with DPD

CONCLUSIONS

This paper presents the testbed development of SFOL pulse-based DME. The SFOL pulse is a highly accurate DME pulse and is capable of reducing multipath-induced range errors by 77% compared with conventional Gaussian pulse DME while meeting the ICAO DME pulse-shape requirements. Our SFOL pulse DME testbed was developed from commercial Gaussian pulse DME. To successfully transmit the SFOL pulse in our testbed, we applied a digital pre-distortion technique based on an inverse learning method to eliminate nonlinear effects introduced by the PAs. The transmitted SFOL pulse also met the ICAO DME pulse-shape requirements in a low-power mode. However, efforts towards the transmission of SFOL pulses in a high-power mode are currently underway.

ACKNOWLEDGMENTS

The author appreciates the assistance provided by Jiwon Seo, Sunghwa Lee at Yonsei University, Seowoo Park at Hongik University, Kwangwon Lee, and Kyungsoo Lee at Mopiens in the development of the SFOL DME testbed.

FUNDING

This work was supported by the Korea Agency for Infrastructure Technology Advancement (KAIA) through a grant funded by the Ministry of Land, Infrastructure and Transport under Grant 22TBIP-C155921-03.

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