SFOL Pulse-Based DME Developments: Challenges and Solutions

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ABSTRACT

The Streched-FrOnt-Leg (SFOL) is an advanced DME pulse designed from utilizing genetic algorithms to achieve superior ranging accuracy compared to conventional Gaussian DME pulses. This innovation aligns with ICAO DME transponder pulse specifications while significantly reducing multipath-induced range errors by a factor of five when compared to a conventional Gaussian pulse. As part of our commitment to commercializing the SFOL pulse-based DME, our research has been dedicated to identifying efficient solutions for seamlessly transitioning from a Gaussian pulse-based DME transponder to one that transmits SFOL pulses with minimal modifications. This paper delves into the challenges encountered during the development of a high/low power SFOL pulse-based DME transponder derived from a commercial Gaussian pulse-based DME. We explore the difficulties faced and present viable solutions that have emerged throughout this transformative process.

INTRODUCTION

The Federal Aviation Administration (FAA) of the United States decided to utilize DME as a short-term Alternative Positioning, Navigation, and Timing (APNT) system in 2016 [1]. Due to the insufficient accuracy of DME ranging, there is a demand for APNT systems with higher precision. However, developing a new APNT system for aircraft navigation over a wide area presents significant challenges in terms of resources and time. A cost-effective solution to enable a more capable APNT system involves upgrading the ground network of DMEs and airborne DME avionics to achieve higher ranging accuracy with minimal software and hardware modifications.

In this context, the SFOL DME pulse was introduced as an advanced DME pulse that offers resistance to multipath effects, resulting in approximately five times better ranging accuracy compared to conventional Gaussian pulse-based DME [2]. The design goal of the SFOL pulse was to ensure compatibility with current ICAO DME specifications, making it usable with existing DMEs. However, achieving compatibility with current DME specifications does not automatically guarantee immediate integration into operational DME systems. Transmitting a specific pulse shape like the SFOL pulse necessitates tuned hardware and software. Attempting to transmit the SFOL pulse in a Gaussian pulse-based DME without modifications would fail due to the mismatch in pulse shapes. Moreover, receiver modules must have wide front-end filters to maintain the SFOL pulse shape and accurately detect its half amplitude point. This paper addresses these challenges and explores methods to transmit the SFOL pulse through a conventional Gaussian pulse-based DME using software modifications or minor hardware adjustments. The focus in this paper is on discussing the encountered challenges and the solutions developed during the recent commercial SFOL-based DME transponder development in 2022. Figure 1 shows the SFOL pulse and the commercial SFOL-based DME manufactured by Mopiens Inc.

The development of the SFOL pulse-based DME commenced with a low-power mode in 2020. Early in the development process, a significant issue encountered was the distortion of the pulse waveform when integrating the SFOL pulse shape into a commercial Gaussian pulse-based DME. The primary cause of this distortion was identified as the nonlinearity of class C power amplifiers typically employed in Gaussian pulse-based DMEs. An effective solution to this problem was to utilize a pre-distorted SFOL pulse as the baseline pulse, generated in real-time through an inverse learning algorithm [3]. With the implementation of pre-distortion techniques, the SFOL pulse was successfully transmitted in a low-power mode, meeting the ICAO DME pulse shape requirements [4]. The multipath mitigation capability of the transmitted SFOL pulse was confirmed through in-house multipath testbeds. However, during high-power mode operations, it was noted that the transmitted SFOL pulses occasionally exceeded DME pulse spectrum requirements, despite the similarity between the original and transmitted pulse shapes being very close. This issue was attributed to a relatively high noise floor in the transmitter electronics or minor anomalies in the transmitted pulse, which would have been acceptable in low-power mode. This paper suggests two advanced signal processing techniques to facilitate the transition from a Gaussian pulse-based DME to an SFOL pulse-based DME through software enhancements only: enhanced digital predistortion techniques employing truncated singular value decomposition (SVD) and variant SFOL pulses with narrower spectrum power. These methods are further elaborated on in the subsequent sections.

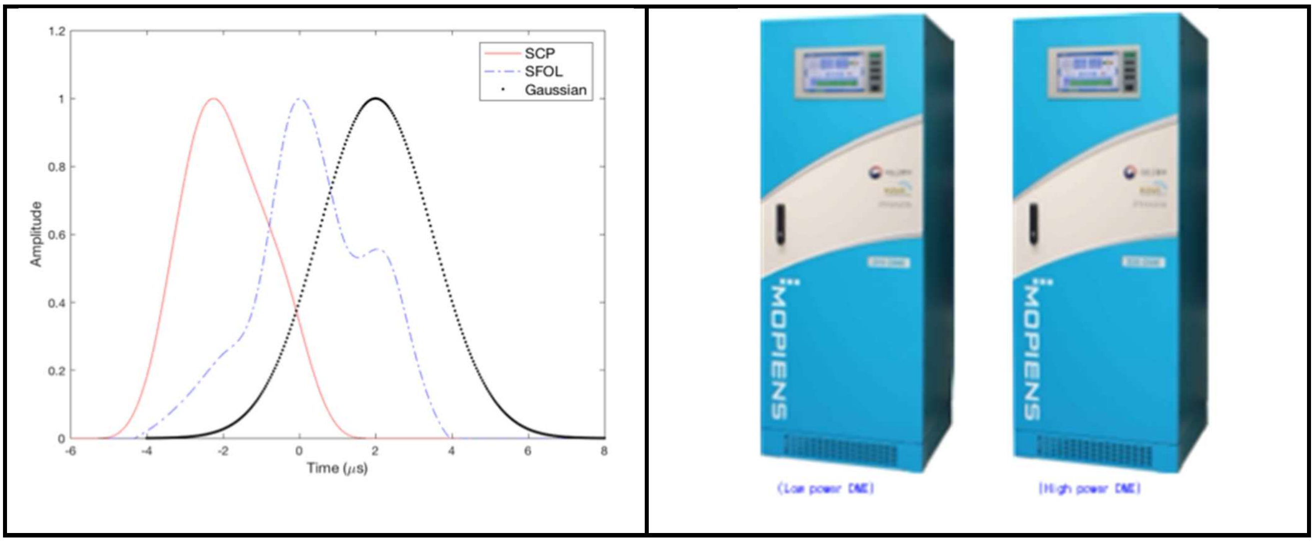

Figure 1. Pulse shapes of Gaussian, SCP, and SFOL pulses

ADVANCED SIGNAL PROCESSING TECHNIQUES

Variant SFOL pulse

As the original SFOL pulse was specifically designed to combat multipath effects with its dynamic pulse shape, it utilized a significant portion of the allowed DME pulse spectrum. However, it is possible to make compromises on the original SFOL pulse shape to reduce Effective Radiated Power (ERP) while accepting a slight decrease in multipath mitigation performance. This modified pulse is referred to as a variant SFOL (V-SFOL) pulse and can be generated using genetic algorithms similar to those used for the original SFOL pulse. The V-SFOL pulse also adheres to ICAO DME pulse shape requirements and exhibits a 7.4 dBm lower ERP at a frequency adjacent to 0.8 MHz. Figure 2 (a) illustrates a comparison between the original SFOL pulse and the V-SFOL pulse, highlighting the smoother nature of the V-SFOL pulse. Despite its smoother shape, the V-SFOL pulse still delivers excellent multipath mitigation performance when compared to the Gaussian pulse, as depicted in Figure 2 (b).

Enhanced DPD through SVD

A challenge with employing DPD techniques for the SFOL pulse lies in the near-singularity of the memory polynomial model matrix. While this ill-conditioned model isn’t an issue in low-power modes, it could pose problems in high-power Distance Measuring Equipment (DME). During the DPD process, the pre-distorted pulse is determined using the damped Newton algorithm as follows

$$\boldsymbol{a}_{p+1} = \boldsymbol{a}_p + \boldsymbol{\mu}(\boldsymbol{Y}^T\boldsymbol{Y})^{-1}\boldsymbol{Y}^T\boldsymbol{e}$$

where $\boldsymbol{e}$ is the difference vector between the pre-distorter and post-distorter [3]. $\boldsymbol{Y}$ is a memory polynomial model of a transmitted pulse. $\boldsymbol{a}$ is a predistortion parameter vector. The low pulse amplitudes near zero naturally makes $(\boldsymbol{Y}^T\boldsymbol{Y})$ to be ill-conditioned. For a better numerical stability, a low rank approximation of $\boldsymbol{Y}$ can be used instead. Through lab tests, the low rank approximation could suppress ERP about 2~4 dBm in the adjacent and alternative channels. While an alternative approach involves reducing the order of $\boldsymbol{Y}$ instead of using truncated Singular Value Decomposition (SVD), this is generally discouraged due to potential negative impacts on Digital Pre-Distortion (DPD) performance

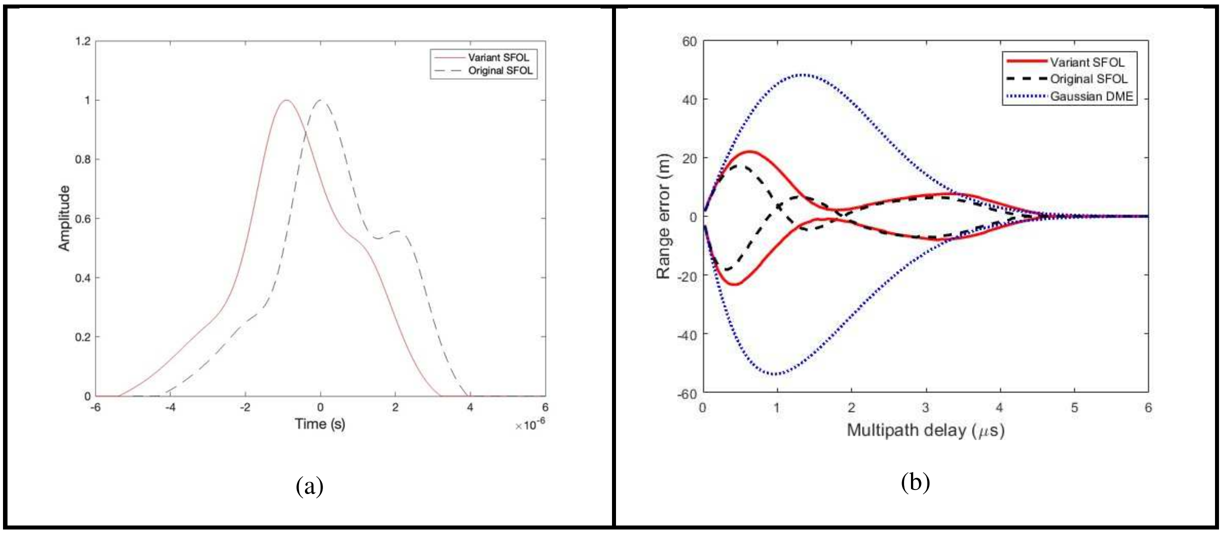

Figure 2. (a) comparison of the original and variant SFOL pulses (b) comparison of the multipath induced range errors of the Gaussian, original SFOL, and variant SFOL pulses.

CONCLUSIONS

The paper introduces two advanced signal processing techniques applicable to Gaussian-based DME systems, enabling the transmission of highly accurate SFOL or variant SFOL DME pulses with minimal software and hardware adjustments. Variant SFOL pulses can be designed based on excess Error Power Ratio (ERP) levels and specifically tailored for high-power DME systems to meet ERP requirements for pulse shaping. However, the variant SFOL pulse does exhibit a minor reduction in multipath mitigation performance compared to the original SFOL pulse. Additionally, employing a low-rank approximation of the Digital Pre-Distortion (DPD) can further reduce the Error Power Ratio (ERP) in transmitted pulses. Although this method introduces slight modifications to pulse waveforms, its impact on multipath mitigation performance remains minimal." In summary, these two proposed methods effectively enhance Gaussian-based DME systems, enabling them to transmit SFOL pulses in high-power scenarios.

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