Summary

GPS (Global Positioning System) has enabled accurate, affordable, and almost ubiquitous positioning and timing. This has not only resulted in its wide spread usage, increased popularity, and numerous new applications, but it has also resulted in an increased dependency of the Global Navigation Satellite Systems. The ever-improving performance of GPS has long fueled the thought that GPS — and GPS alone — was to be the designated future of radio positioning and timing. The 2001 Volpe study, and later the 2004 proposed ERNP (European Radio Navigation Plan), stated otherwise: although very accurate, GPS and other satellite navigation systems are not considered reliable enough to be used as the sole-means for safety, environmental, and/or economically critical applications. Those critical applications need a backup system with dissimilar failure modes. The solution suggested by the Volpe-report and by the ERNP-proposal is — perhaps rather surprisingly — an old and almost forgotten radionavigation system: Loran-C. This system with its high-energy, low-frequency pulses is largely dissimilar to GPS. The combination of Loran-C and GPS, therefore, has the potential to be far more robust than either system individually. However, the "official" performance of the 1958 Loran-C system is no match for the stringent requirements of most modern applications. Fortunately, this Loran performance reflects the capabilities of outdated technology rather than the foundations of low-frequency radionavigation. The following question now arises:

What are the fundamental limits of low-frequency radionavigation and how do they affect potential applications?

Loran-C is currently the only operational and publicly available low-frequency radionavigation system with regional coverage. This dissertation, therefore, primarily focuses on Loran-C although most results will also be applicable to other low-frequency radionavigation systems. Chapter 2 introduces the system details of Loran-C.

The search for the fundamental limits begins by identifying the potential error sources. Chapter 3 contains a thorough system analysis, starting with the transmitter, and covering propagation, antenna, receiver algorithms, and concluding with calculated position and time.

Low-frequency ground waves experience delays as a function of ground conductivity, topography, seasons, and weather. These propagation delays can cause significant position errors if left uncompensated. Chapter 4 discusses the use of a differential reference station to compensate for the temporal fluctuations in propagation. A spatial correction map further reduces the propagation related positioning errors. The resulting positing accuracy is potentially sufficient for such situations as the stringent 20 meter, 95% accuracy requirement of the maritime Harbor Entrance and Approach procedure.

Chapter 5 pays special attention to the H-field antenna; the chapter discusses error sources such as noise, E-field susceptibility, tuning, and cross talk thoroughly, as well as novel mitigation techniques and their successful implementation.

Chapter 6 discusses various measurement campaigns that bring the presented theory into practice. Throughout the Ph.D. research, the author of this work developed a highly accurate measurement system. The Reeuwijk measurements show the first step with precise dual-difference measurements; both the temporal domain and the spatial domain reveal local propagation effects. The land-mobile measurement campaign in Boston expands the measurement setup further. Simultaneous measurement of both E-field and H-field took place there allowing unprecedented analysis of re-radiation and an assessment of the applicability of low-frequency radionavigation in a land-mobile environment. The introduction of differential corrections and H-field antenna calibration for the Tampa Bay campaign resulted in an unprecedented measurement performance. Chapter 6 also shows the effect of bridges on positioning performance quantitatively, and presents the successful results of a unique re-radiation detection algorithm. This algorithm enables detection of local disturbances allowing a timely warning of potential erroneous position information. Finally, Chapter 6 shows the achievement of a positioning performance of better than 10 meters with 95% confidence during a realistic "Harbor Entrance and Approach" (HEA) scenario.

This dissertation concludes with an assessment of the potential of low-frequency radionavigation, based on the results of the author's Ph.D. research combined with his personal views.

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Delft, November 2006