An Integrated Radio-Frequency Wireless Head Coil Array with Global Navigation Satellite System (GNSS) Timekeeping for Clock Synchronization in Wireless MRI

Olivia Jo Dickinson[1,2], Fraser Robb[3], Allen Song[1], and Dean Darnell[1,2]
[1]Duke-UNC Brain Imaging and Analysis Center, [2]Duke University Medical Physics Graduate Program, [3]GE Healthcare (Aurora, OH)

Introduction

The integrated RF/wireless (iRFW) coil design can perform simultaneous near-field MR signal reception and far-field wireless data transfer (e.g., MRI and timing data) by allowing MRI and wireless RF currents to flow with electrically large (i.e., poor far-field radiator) and similar (i.e., good far-field radiator) wavelengths relative to its circumference, respectively[1,2]. For example, the small diameter coil elements in a MRI soccer ball coil array[3] can provide both a uniform SNR and generate a far-field wireless signal gain pattern at intermediate (e.g., 1.575 GHz GNSS) or high (e.g., 5.5 GHz WiFi 6E) frequencies to receive (GNSS) or transmit (WiFi) data from within the bore. In this work, simulations of a 16-channel iRFW soccer ball coil array are performed to determine the optimal iRFW coil element positions/diameters that provide a uniform MRI SNR and high WiFi/GNSS gain patterns for wireless data transfer and a new GNSS-assisted grandmaster clock (GMC) precision time protocol (PTP) wireless MRI clock-synchronization method to replace a standard scanner system clock **(Fig. 1, 2)**. Specifically, PTP uses message passing between networked connections (e.g., scanner and RF coil array) instead of the standard wired MRI system clock to determine time offsets relative to a reference time (i.e., satellite atomic clock signal received by a GMC), which is used to synchronize all independent hardware clocks (e.g,. scanner and array). Preliminary bench-top measurements will be performed to demonstrate the feasibility of using PTP for MRI **(Fig. 3)**.

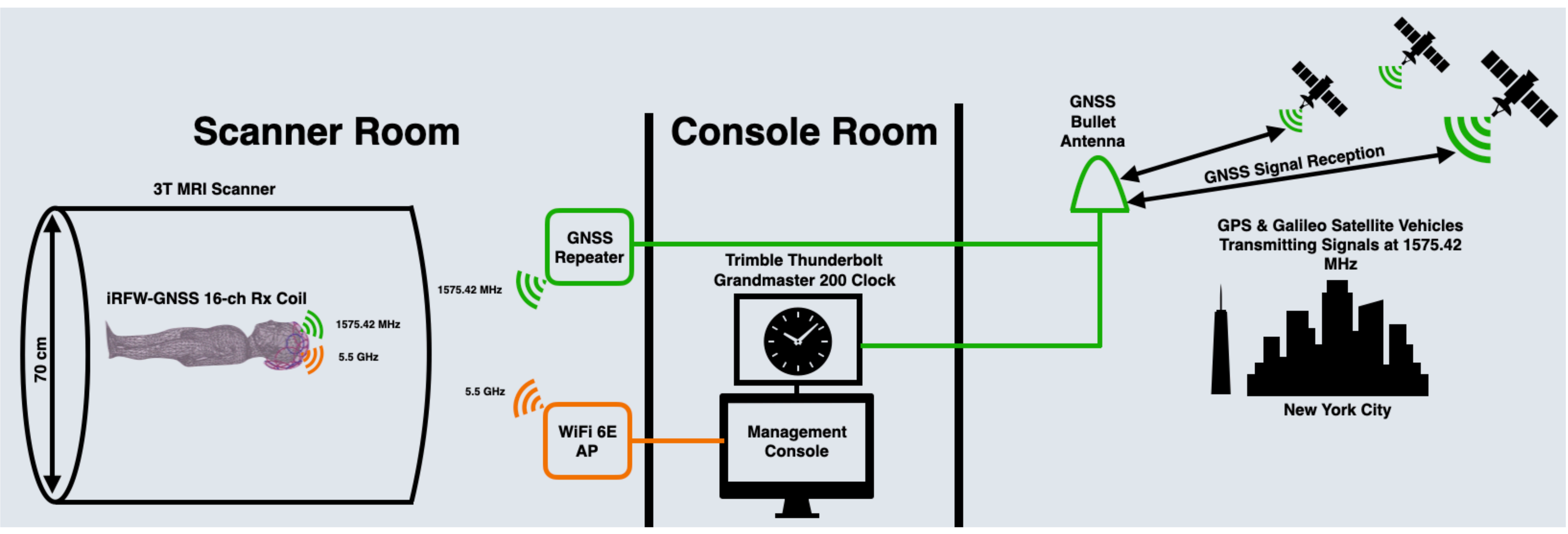
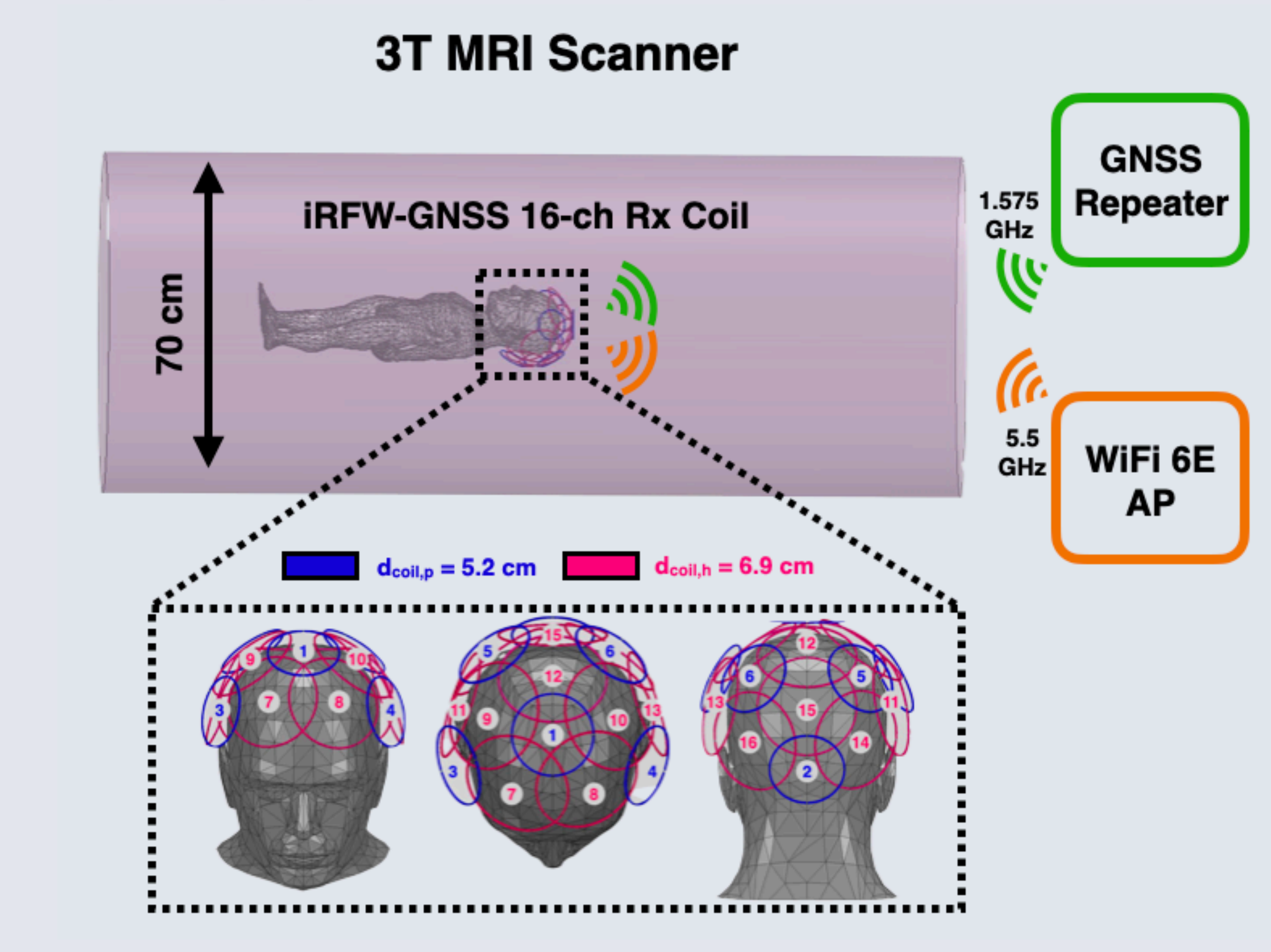


FIGURE 1. Wireless Data and Clock Synchronization. A GNSS bullet antenna placed outside of the scanning and console room will be set to receive timing signals from selectable satellite constellations (i.e., GPS, Galileo or GLONASS). The satellite timing signals are then passed to a GMC and to the iRFW-GNSS coil array via a GNSS repeater. The GMC attached to the scanner and the iRFW-GNSS coil array are then time-synchronized using PTP to align the scanner protocol events (e.g., RF Tx pulse, gradients) and the received MRI signal for image reconstruction.

Methods



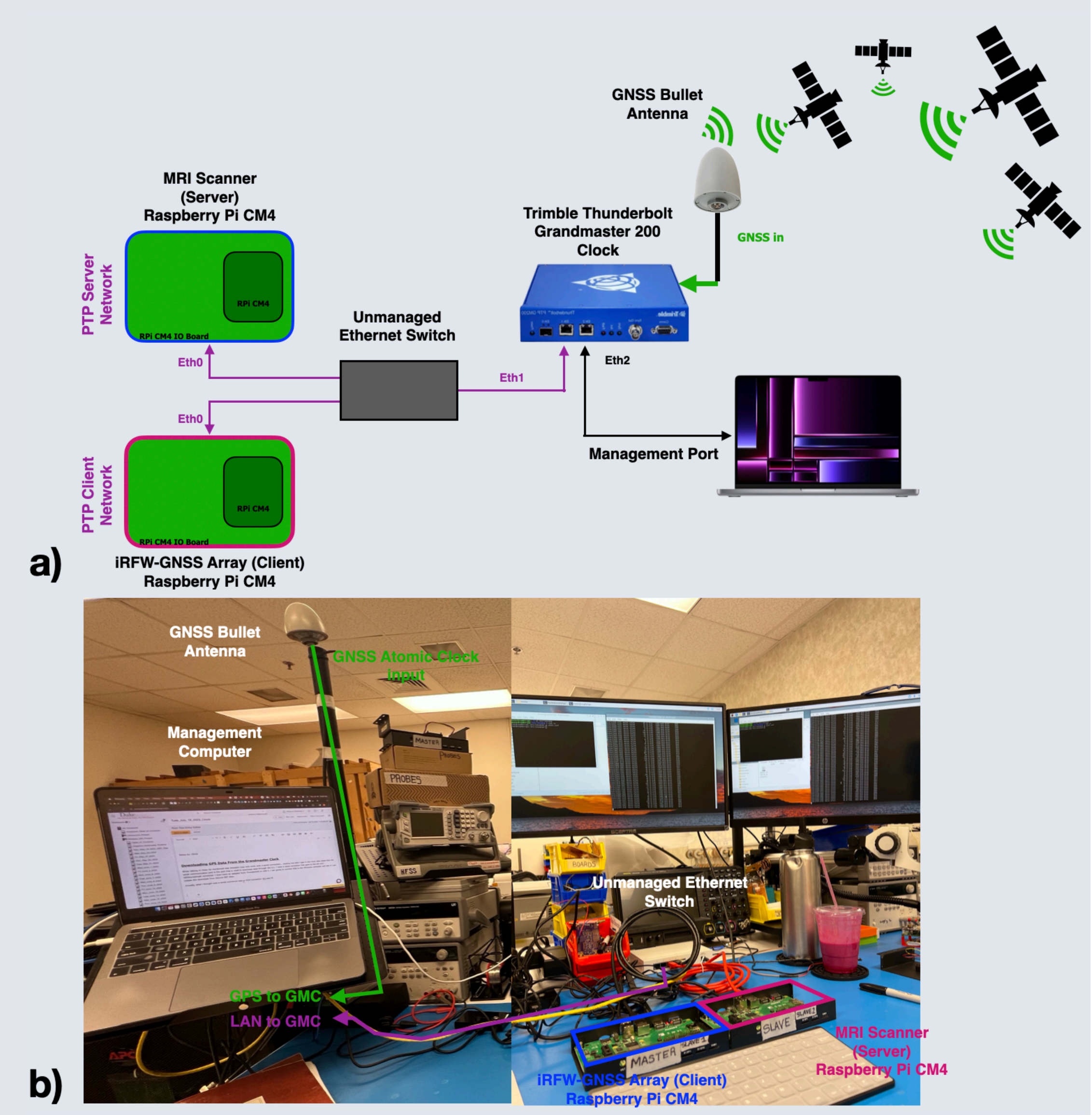
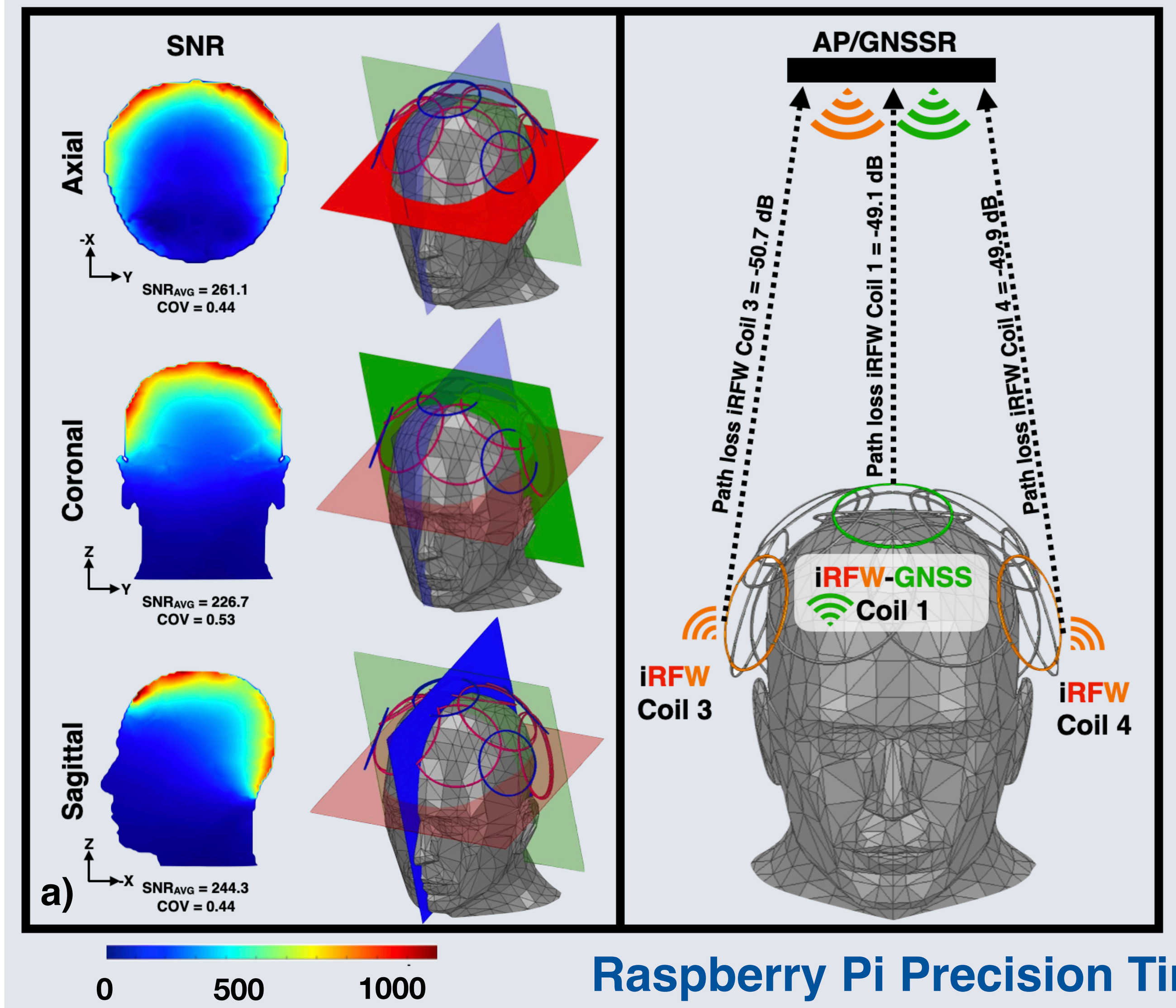


FIGURE 2. Simulation Model 16-channel coil soccer-ball array with six 5.2 cm diameter (blue) and ten 6.9 cm diameter (pink) coil elements simulations were performed inside a 70 cm scanner bore at the 3T Larmor (127.7 MHz), WiFi 6E (5.5 GHz), and GNSS (1.575 GHz) frequencies to determine its MRI SNR and WiFi 6E/GNSS far-field gain patterns producing the most radiated signal outside the scanner bore to an access point (AP) or GNSS repeater on scanner room wall.

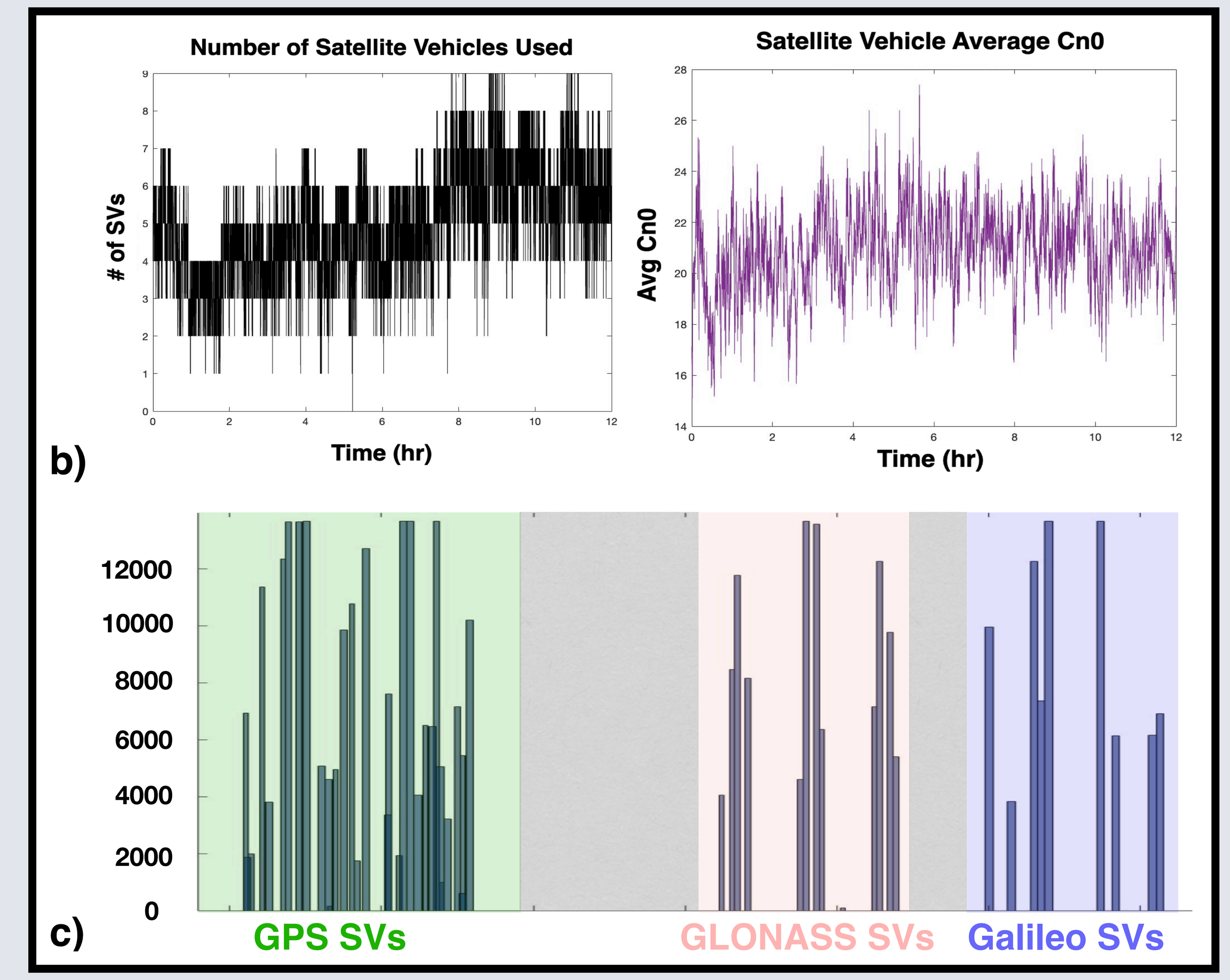
FIGURE 3. Bench top PTP Measurement A PTP network was designed with a single GMC, ethernet switch, and two separate Raspberry Pi CM4 to represent the iRFW coil array and scanner **(a)**. The network was implemented on a lab bench located on first floor of our hospital and the offset between each RPi clock and the GMC was measured to demonstrate the networks time keeping precision **(b)**.

Results

iRFW-GNSS Coil Array Simulations



GNSS Satellite Vehicle Measurements



Raspberry Pi Precision Time Protocol Measurements

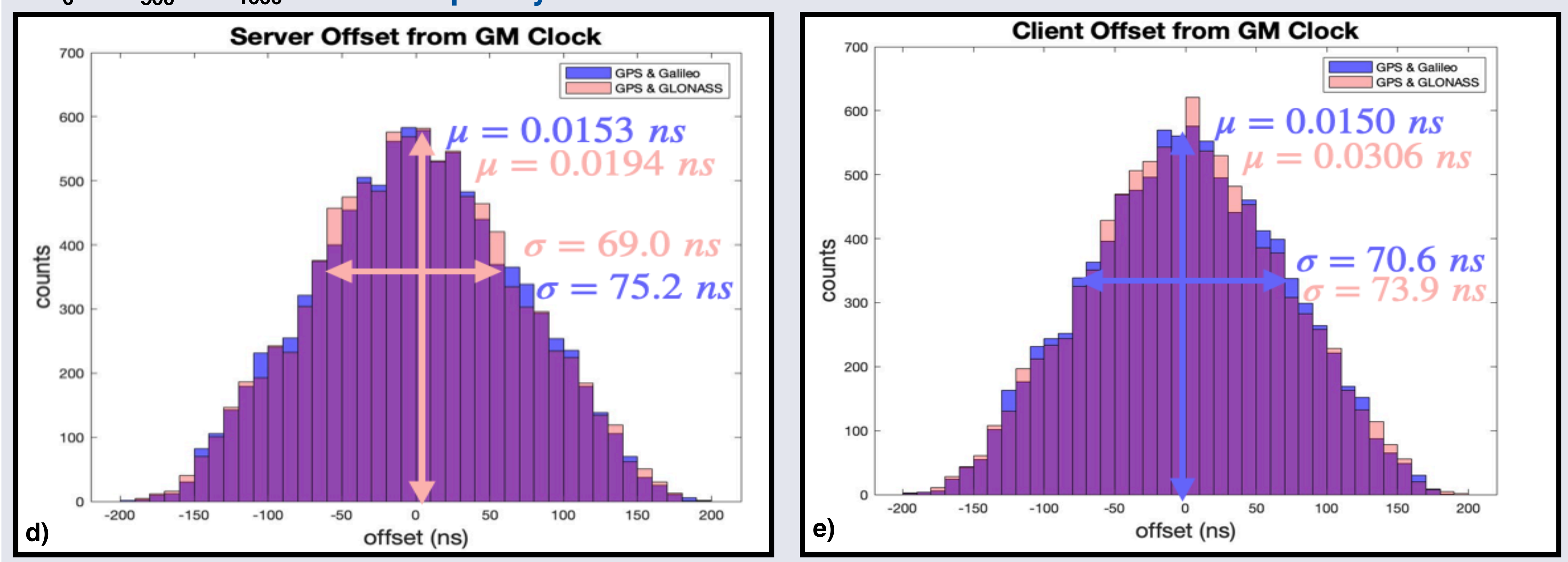


FIGURE 5. Bench top PTP Measurement Offset Simulations of the 16-channel iRFW-GNSS coil array had a uniform SNR in the head with average and COV SNR values in the axial, coronal, and sagittal planes of 261.1,226.7, 244.3 and 0.44, 0.53, 0.44, respectively **(a)**. Satellite CN0 and time offset between the GMC and RPi CM4 were recorded every second for a 12-hour period to determine the number of satellites used **(a)** , the quality of the satellite signal **(b)**, and the frequency of satellites used per **constellation (c)**. Time signals for clock synchronization were acquired from three different satellite constellations. The offset corrections represent the time precision PTP can correct for when acquiring signal from GPS & Galileo versus GPS & GLONASS. The timing corrections for both pairs of satellite constellations are within nanosecond precision with a STDEV of 75.2 ns and 70.6 ns when using GPS & Galileo on the server **(d)** and client **(e)** clock respectively, and a STDEV of 69 ns and 73.9 when using GPS & GLONASS on the server **(d)** and client **(e)** clocks respectively.

Discussion

The simulation of iRFW-GNSS coil path loss of -49.9 dB is sufficient to receive an amplified time signal from a GNSS repeater or to receive GNSS signals independently if followed by amplification. This justifies the use of the iRFW-GNSS coil to add redundancy of grandmaster clock acquired time signal or to acquire its own time signal to maintain accurate and precise time synchronization with the scanner and other network devices present in a wireless MRI architecture. The bench-top testing of PTP using a Grandmaster clock and RPi CM4 validates the possibility to use recorded nanosecond clock offset to correct timestamps across various nodes of a PTP network. In this work we showed the process of using GNSS atomic time signals to synchronize clocks over the LAN. In order to develop this into a wireless architecture, leveraging fine timing measurement (FTM) instead of PTP will be necessary. FTM can generate timestamps closer to the physical layer achieving picosecond resolution which is below the accepted threshold of acceptable clock-jitter that exists in the current MR scanner architecture thus not contributing to image artifacts during the wireless synchronization and transmission.

ACKNOWLEDGEMENTS: This work was in part supported by NIH S10 OD021480, Ansys Partnership Donation, and GE Healthcare.

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