Synchronization of Phased Array Pulsed Ring-down Sources using a GPS based timing system

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***Abstract* — A collaborative effort at Texas Tech University on high power RF transmitters has directly translated to the development of phased array pulsed ring down sources (PRDS). By operating an array of PRDS, peak radiating power on target can theoretically be multiplied by the number of sources. The primary limitation on the application of the array concept is the jitter with which the individual sources can be fired. An ideal jitter of a small fraction of the risetime is required to accurately synchronize the array to steer and preserve the risetime of the radiated pulse. This paper describes in detail the implementation of a GPS based timing system that will synchronize the individual antennas to operate at different geo-locations to function in a coordinated fashion to deliver the peak power of each element to a single position. Theoretical array performance is shown through Monte Carlo simulations, accounting for switch jitter and a range of GPS timing jitter. Each module will include a control unit, low jitter pulser [1], low jitter spark gap, antenna element, as well as a GPS receiver. The location of each module is transmitted to a central controller, which calculates and dictates when each element is fired. Low jitter in the timing of the GPS reference signal is essential in synchronizing each element to deliver the maxim power. Testing using a preliminary setup using GPS technology is conducted with both 1 pps and 100 pps outputs. Jitter results between modules are recorded to ~10 ns without any correction factors. With the timing and geospatial [2] errors taken into account, the proposed concept will show usable gains of up to several hundred MHz.**

I. INTRODUCTION

The current need for far field energy deposition has necessitated further research into pulsed ring down antennas, specifically as a mesoband source. Mesoband sources generate high power microwaves (HPM) in the 100 – 700 MHz range, and offer a tradeoff between the high output power levels of hypoband sources and the high bandwidth of hyperband sources. These sources can usually be classified by the bandwidth ratio, which is directly related to the fractional bandwidth. Mesoband sources require a fast rising voltage step that is connected to a differentiating antenna. This antenna then produces a time derivative of the incoming pulse, which converts the fast voltage step into an electric spike in the radiation field. The peak-radiated E-field at a distance is highly dependent on the rate of rise of the voltage. A widely used figure of merit for UWB devices is the range normalized peak radiated E-field, or also known as the far field voltage. By implementing the pulsed ring-down antennas into a phased array, theoretically, the peak power is multiplied by the number of elements and the system can become highly directive with beam steering capabilities.

The proposed application allows for elements to be placed at different geo-locations, where line of sight may not be possible. A method of using Global Positioning System (GPS) technology to provide accurate positioning and specifically accurate timing is discussed in this paper. A block diagram of a functioning PRDS array system is seen in Fig.1. Each unit will be a standalone system that can be placed in separate geo-locations which can communicate with a master controller. A control unit is used in each module to relay the geographical location measured by the GPS receiver to the mater controller. The master controller calculates a firing time to maximize the field on target, sends it to the control unit and synchronized with the GPS time reference, which fires the low jitter trigger into a low jitter switch that energizes the antenna element.

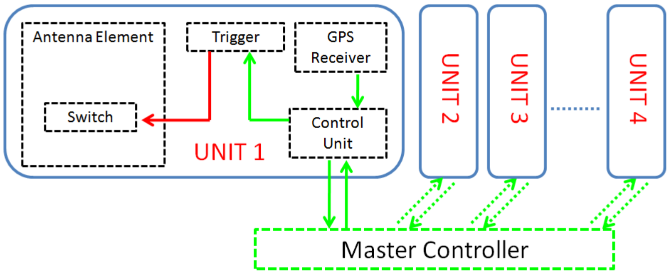

Figure 1. PRDS array concept.

In the proposed operating functions of the project, four sources of inaccuracies compromise the effectiveness of the PRDS array. The switch jitter [3], trigger jitter [1], GPS position errors [2], and GPS timing error. This paper will discuss in detail GPS timing jitter and its effect on a projected PRDS array. Simulations are conducted to predict the efficiency of the array while introducing timing errors such as switch and GPS jitter. Testing is also conducted with current GPS technologies in trying to achieve ns second jitter between modules.

II. SIMULATION

Simulation using Monte Carlo type analysis was conducted to predict how GPS timing jitter will affect the efficiency, or power on target, of a proposed 16 element PRDS array. All simulation results presented in this paper use 175 MHz with a sample size of 1000 shots. The first shot of the sample represents ideal conditions from which the delays are

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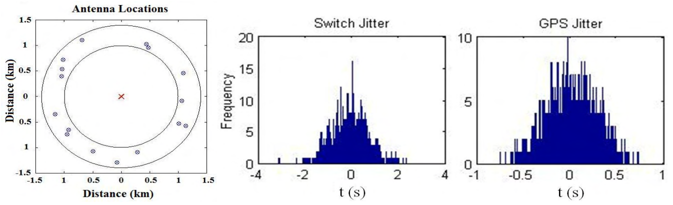
calculated. Each successive shot then introduces a timing error, which is pre-specified in the code, into the simulation. The positioning error is set to 0 as it is discussed in detail in [2]. A timing error of 0.7 ns was included in the base simulation to account for the switch jitter, as a triggered, 50 kV, 100 Hz, gas spark gap, for similar applications, is shown to have sub-ns jitter results for various parameters in [5]. The GPS jitter is the deviations in the time stamps that the GPS receivers will provide to each element.

Each PRDS array element is located at a random position, while ideally outputting an exponentially decaying sinusoid waveform. The random element locations are set to have a random circular distribution between 1 – 1.5 km away from the proposed target. A sample test run shows the random element locations, Fig. 2(a), and a normal distribution of the switch jitter and GPS jitter over 1000 shots, Fig. 2(b). An ideal delay is calculated based on the distance from the antenna to the target, allowing the first peaks of each element to center on the target. With an ideal case, the peak field intensity on the target will be the multiplied by the number of elements.



(a) (b)

Figure 2. Test simulation runs of (a) Antenna locations (b) Switch and GPS jitter.

Due to the primary objective of the PRDS array of maximizing the amount of energy it can focus on a specified target, the simulations will show the magnitude of the normalized electric field intensity as a percentage of the ideal case over increasing GPS jitter times. Simulations dealing with GPS positioning error and operation frequency are seen in [2]. A 2D and 3D color map of the simulation results from ideal conditions to a GPS jitter of 10 ns is seen in Fig. 3. It is noted that the ideal condition test did not include the switch jitter of 0.7 ns. The color maps cover a 5 m x 5 m square centered on the proposed target. It is seen that the power on target is greatly reduced after 4 ns GPS jitter times, with little to no power on target at 10 ns GPS jitter.

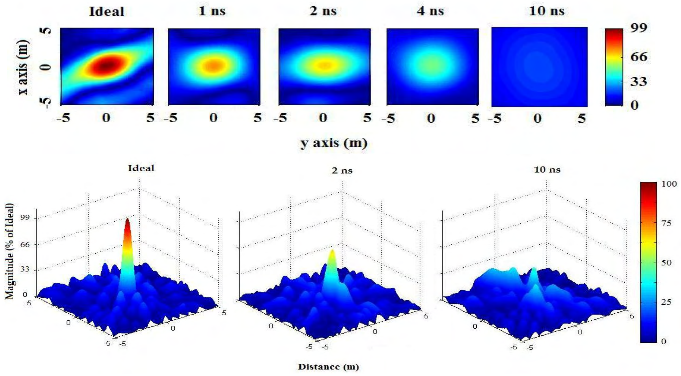


Figure 3. 2D and 3D color maps of simulated power on target from ideal to 10 ns GPS jitter.

The GPS jitter that was introduced in the simulation ranged from 0 – 20 ns. Table1 shows simulation results ranging from 0.1 to 20 ns with magnitude as the percent of ideal and error percent ratio (EPR - sum of the error sources divided by the period of the propagating wave) for each simulation recorded. The magnitude vs. GPS jitter over this range is plotted in Fig. 4. It is seen that even at a 5 ns GPS jitter with switch jitter included, over 50 percent of the ideal power is delivered to the target. This result is seen to be similar to previous assessments seen in [6]. It is important to note that as the as the frequency is increased from the 175 MHz baseline, the overall jitter will have to be lowered to achieve the same performance.

TABLE 1
SIMULATION DATA OF MAGNITUDE AND EPR VS. GPS JITTER TIMES

GPS Jitter (ns)	Magnitude (% of Ideal)	EPR	GPS Jitter (ns)	Magnitude (% of Ideal)	EPR
0.01	77.98	0.095	5	50.93	0.186
0.5	77.56	0.091	7.5	43.76	0.283
1	75.96	0.106	10	40.15	0.318
2	70.35	0.121	15	36.36	0.613
3	63.61	0.118	20	33.19	0.733
4	56.29	0.184			

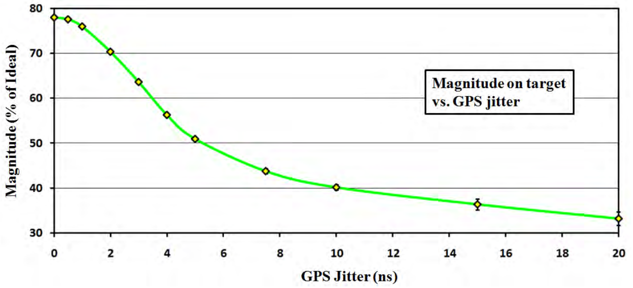


Figure 4. Magnitude on target (% of Ideal) vs. GPS jitter times.

III. EXPERIMENTAL SETUP

Initial evaluation of GPS timing jitter was conducted with a low cost GPS evaluation kit from Synergy. The kit includes the M12M GPS receiver and timing board from I-lotus and an AR-10 GPS Antenna. Each module will consist of a GPS evaluation kit that communicates with a dedicated processor and sends an output signal to an oscilloscope. A block diagram of the test setup is seen in Fig. 5.

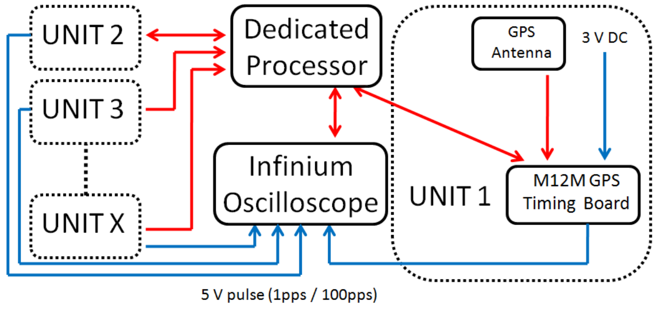


Figure 5. Magnitude on target (% of Ideal) vs. GPS jitter times.

The M12M timing receiver features precise, programmable, one-pulse-per-second (1PPS) or 100 pulse-per-second

(100PPS) operations. It incorporates a 12 channel parallel receiver design and operates using L1 at 1575.42 MHz. The receiver also features Time Receiver Autonomous Integrity Monitoring (T-RAIM), an algorithm that uses redundant satellite measurements to confirm the integrity of the timing solution. The receiver states a < 10 ns jitter without clock granularity message corrections, and is powered with 3 V DC.

The actual test setup with a dedicated processor running the WinOncore 12 tracking software provided by synergy is depicted in Fig. 6. It also shows the four GPS timing boards that are connected to the dedicated processor via serial cable. This allows the GPS boards to provide information to the WinOncore software while being able to receive commands from the software. A 4 GS/s Infiniium oscilloscope used to capture the output pulses from the GPS timing boards is also seen in Fig 6. The timing boards are connected to their respective GPS antennas that are located outside of the building via an MMCX connector. The AR-10 from Synergy Systems is a compact, magnetic mount external antenna, which runs off 3V DC from the timing GPS receiver and is attached via an MMCX connector.

The WinOncore 12 tracking software allows for satellite tracking (up to 12), and shows the signal strength of each tracked satellite. A survey window tracks the GPS unit over time and provides information on the longitude, latitude, and height, as well as their standard deviations. The timing window shows the timing information for each unit as well as allow for T-RAIM. Operation modes (1PPS or 100PPS) can also be selected in the setup. A spate window shows a negative saw-tooth correction time (clock granularity)

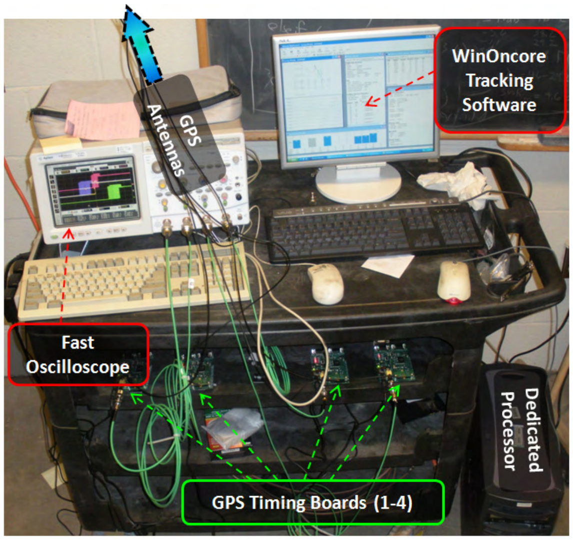


Figure 6. Actual testing setup with GPS timing units, dedicated processor, and 4 GS/s oscilloscope.

IV. TESTING AND RESULTS

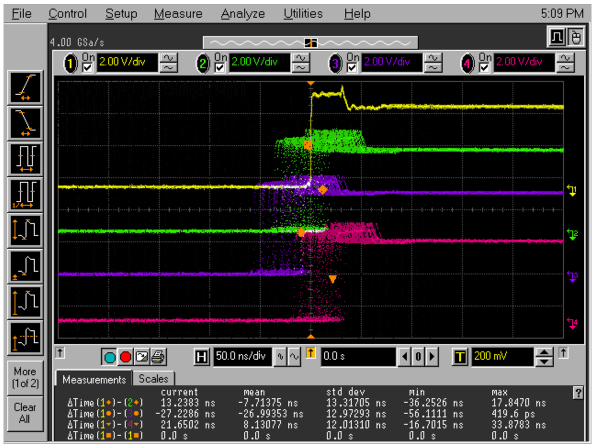
Using the previously mentioned setup, 4 GPS units were tested. The focus on the testing was to evaluate the timing error, or difference of GPS timing signals with respect to each other.

A. *1 PPS preliminary testing*

Preliminary testing of the GPS units involved operations with 1 PPS output. The GPS unit outputs a 5 V, 200 ms, square pulse, with a ~1 ns rise time. 3 GPS units were used in the initial testing to investigate the timing errors of the GPS units with respect to each other. The midpoint of the rising edge of the 1st unit output pulse was used as the reference, with the difference in times to the midpoint of the other units specified as the timing error. The timing jitter is determined as the standard deviation of a set randomly collected timing errors between each GPS unit. For 1 PPS operations, 30 random shots were evaluated with a 12.80 ns jitter between GPS unit 1 and GPS unit 2. GPS unit 1 and GPS unit 3 resulted in an 11.78 ns jitter.

B. *100 PPS*

Since the short term jitter of GPS signals were expected to be unsatisfactory, the 100 PPS operations were considered with with an averaging method to possibly lower the jitter. The 100 PPS output pulses are 2 ms wide square pulses with a similar ~1 ns rise time. With 100 PPS pulses, the scope was able to average more shots in a shorter time. A screen capture tracing output signals from 4 different GPS units over 10 seconds is seen in Fig 8. The scope also measures the time deviation of a current shot, as well as the mean, standard deviation, minimum, and maximum over this certain time period. This is done for comparisons between GPS units 2 – 4 against GPS unit 1, see Fig. 8.



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                 current       mean           std dev        min           max
ΔTime(1)-(2)   13.2383 ns    -7.71375 ns    13.31705 ns    -36.2526 ns    17.8470 ns
ΔTime(1)-(3)  -27.2286 ns   -26.99353 ns    12.97293 ns    -56.1111 ns    419.6 ps
ΔTime(1)-(4)   21.6502 ns     8.13077 ns    12.01310 ns    -16.7015 ns    33.8783 ns
ΔTime(1)-(1)   0.0 s          0.0 s          0.0 s           0.0 s         0.0 s
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Figure 8. Screen capture of GPS timing errors at 100 PPS over 10 seconds

Using the same 10 second intervals, 100 data sets were collected for each GPS unit comparison. The recorded current shot, as well as the mean, minimum, and maximum over the 100, 10 seconded intervals of the time differences between GPS unit 1 and GPS unit 2 is recorded in Fig 9. It is seen that while the measured current shot fluctuates greatly and results in jitter of ~14 ns, the average data does not fluctuate as much, with a resulting jitter of ~ 5 ns, see Table 2. Similar comparisons using GPS unit 3 and 4 were conducted with results recorded in Table 2. The results showed increased jitter for both the raw and averaged data due to a drift in the measurements, see Fig. 10. The short term drifts is seen to compromise the effects of lowering jitter through averaging.

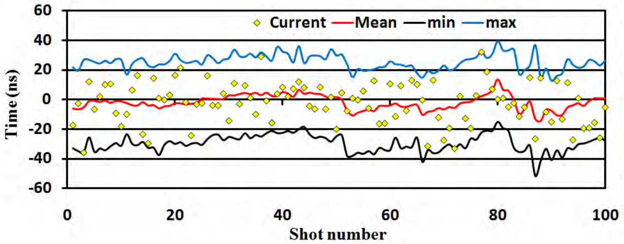

Figure 9. Data for GPS 1 vs. GPS 2 (10 sec. intervals)

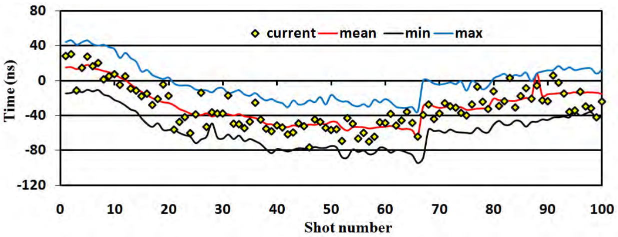

Figure 10. Data for GPS 1 vs. GPS 3 (10 sec intervals)

The standard deviation for shots recorded by the scope over the 10 second span is also recorded for the 100 shot duration, see Fig. 11. The standard deviation is seen to average around ~13 ns for all GPS unit comparisons with small increase spikes over the testing period.

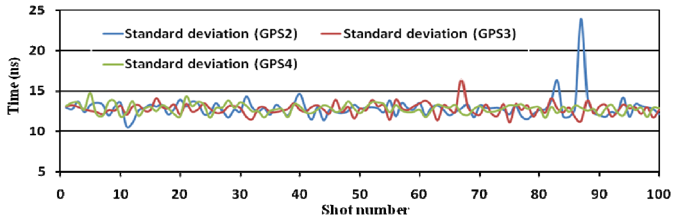

Figure 11. Standard deviation for GPS unit comparisons with 10 second intervals.

Using a 1 minute test interval, the same tests were conducted with the results recorded in table 2. It is seen that the standard deviation for each interval still averages out to be ~13 ns, while showing less deviation between the different GPS unit comparisons. The jitter for the raw data improves (on average) as well as the jitter of the averages. This is evident in the fact the variation between the GPS unit comparisons are seen to be smaller. The GPS 1 vs. GPS 3 comparisons is still seen to be worse than the other 2. A distribution for the raw and average data over the 100 shot testing period (1 min intervals) between GPS unit 1 and 2 is seen in Fig. 12.

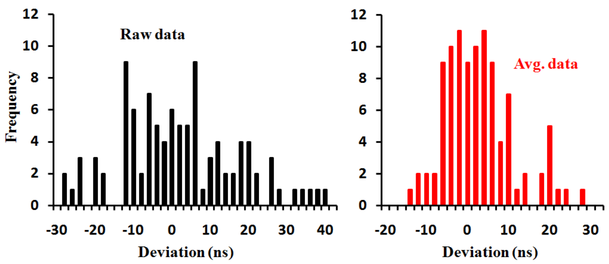

Figure 12. Histogram of GPS 1 vs. GPS 2 raw and average data for 1 minute intervals.

The results for the 1 minute interval testing was also seen to be affected by the shifting of the all the measurements that affected the previous testing (10 second intervals). Current investigation involving an antenna splitter suggests that the drift in the average/mean data is due to antenna errors. Testing results are currently assessed with better performing antennas sure to improve the jitter for the averaged data.

TABLE 2
TESTING RESULTS WITH 10 SEC SAMPLES AND 1 MIN SAMPLES

GPS Jitter comparisons (10 sec samples)				
	Jitter (Raw data)	Jitter (Avg. Data)	Std Avg. (Raw Data)	Jitter (Std.)
GPS1 vs. GPS2	13.98	4.83	12.89	1.36
GPS1 vs. GPS3	23.93	21.14	12.79	0.72
GPS1 vs. GPS4	21.28	12.57	12.80	0.62
GPS Jitter comparisons (1 min samples)				
	Jitter (Raw data)	Jitter (Avg. Data)	Std Avg. (Raw Data)	Jitter (Std.)
GPS 1 vs. GPS 2	15.22	8.32	13.00	0.89
GPS 1 vs. GPS 3	18.79	14.41	12.99	0.67
GPS 1 vs. GPS 4	16.33	8.58	13.01	0.70

V. CONCLUSION

Simulation results show that a proposed PRDs system can have usable gain with total system jitter of < 5 ns for operations at 175 MHz. Current preliminary testing shows raw GPS signal jitter results of ~13 ns between four separate modules, each with their own antenna and GPS timing unit. Through averaging techniques with different sampling sizes, these numbers are seen to be lowered considerably. A short term drift is seen by each module, occurring at random times, which affects the credibility of jitter and average results between the different modules. Testing involving one antenna with the signal split to the four receivers is seen to improve average time fluctuations between the GPS boards, which in turn will improve average jitter numbers. Better GPS antennas will be implemented in the future to solve the issue of short term drift. GPS jitter times can also be improved by including the clock granularity message (saw tooth error) provided by the WinOncore software. A better algorithm for averaging the GPS receiver data is also needed in the future.

REFERENCES

[1] A. Myers, J. Walter, J. Dickens, M. Kristiansen, “Pulsed Ring-down Source Array,” 2010 IEEE International Power Modulator and High Voltage Conference, May 2010 .

[2] D. Reale, J. Mankowski, S. Holt, Y. Chen, J. Walter, and J. Dickens, “Theoretical Performance of a GPS Linked Pulsed Ring Down Array,” 2010 IEEE International Power Modulator and High Voltage Conference, May 2010.

[3] Y. Chen, J. Dickens, J. Mankowsi, and M. Kristiansen, “Optimization of a Low Jitter, 50 kV, 100 Hz Triggered Spark Gap with High Pressure Gas Mixtures,” Dielectrics and Electrical Insulation, IEEE Transactions on, vol. 16, issue 4, pp. 971-978, Aug. 2009

[4] J. Walter, J. Dickens, J. Mankowski, and M. Kristiansen, “Theoretical Pulsed Ring Down Antenna Array Performance,” Pulsed Power Conference, 16th IEEE International, vol. 1, pp. 682-685, Jun. 2007.