Multistatic Pulse-Wave Angle-of-Arrival-Assisted Relative Interferometric RADAR

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Abstract—**In this work we propose a Pulse-Wave (PW) extension to the Angle-of-arrival-assisted Radio Interferometry (ARI) technique to dramatically reduce the scan-time and the number of vantage points necessary to obtain high-fidelity target position estimation. Accordingly, we call this enhanced process PW-ARI. PW-ARI is the fusion of data from three domains: time (time-of-flight), phase (relative phase-of-arrival), and angle (direction-of-arrival). It has a number of desirable attributes. Foremost among these are its ability to rapidly image extremely large volumes with high accuracy and dense target clusters, support an infinite number of friendly aircraft while providing stealth operational support, and present a spectrally small footprint to both hostile (evade detection and counter-measures) and friendly (maximize electromagnetic compatibility) systems.**

I. INTRODUCTION

Target presence and position discovery is fundamental to military operations. The ability of Radio-based Detection and Ranging (RADAR) systems to provide early warning of enemy aircraft or warships has, indeed, changed the course of history [1]. In our prior work [2], we proposed the use of Angle-of-Arrival (AoA) information in conjunction with local interferometry to improve target location estimation in the spatial domain. In this work we propose a Pulse-Wave extension to our prior technique that dramatically improves the scan-time required and reduces the vantage points necessary to obtain high-fidelity target position estimation. Accordingly, we call this enhanced process Pulse-Wave Angle-of-arrival-assisted Radio Interferometry (PW-ARI, pronounced “P-W-are-eee”). As we will show, it has a number of desirable attributes. Foremost among these are its ability to rapidly image extremely large volumes with high accuracy and dense target clusters, support an infinite number of friendly aircraft while providing stealth operational support, and reducing the synchronization and hardware requirements when operating as the sole RADAR modality.

A Pulse-Wave Angle-of-arrival assisted Radio Interferometry (PW-ARI) system consists of two closely-located transmitting beacons (they might be almost co-located and appear to an operator as a single piece of equipment – as shown in figure 2) and any number of passive receive-only aircraft or ground-stations (assets) each of which is equipped with a sector (or steerable) directional antenna. The beacons are tightly time-synchronized. Each beacon transmits a unique pair of frequencies, creating a beat envelope in the transmitted signal which is not unique to any beacon (the ARI payload). The receiver can then identify scattering targets in the intermediate environment through the fusion of the Time-of-Arrival (ToA) of the pulses and the Phase-Difference-of-Arrival (PDoA) of their ARI payload. Target positions are further disambiguated by the known look-directions of the antennas.

ARI encoding [2] offers the unique property that the electromagnetic wavelength and the wavelength used for localization may be chosen independently. Airborne target detection might best be performed using frequencies in a particular portion of the S-Band, thereby maximizing the effective Radar Cross Section (RCS) of the expected targets. Target localization, however, is best performed at substantially lower frequencies to maximize phase disambiguity and, therefore, target bearing. ARI encoding allows both of these conditions to be met.

This independent frequency selection may be exploited to achieve the same volumetric coverage as other RADAR modalities with substantially fewer transmitters. Or this selection can allow a PW-ARI system to image the airspace in a single transmitted pulse, since PW-ARI stations do not need to mechanically scan, nor transmit one pulse per bearing (as in electronic steering). For a given number of ground stations this coverage expansion manifests as greater system redundancy, which in turn makes the network harder to attack. In an eight-node network, the system would need to experience >85% loss to enemy action before it is no longer combat effective. Conversely, repairing just one of those stations restores the network to operation. As PW-ARI transmitters cover a large volume, they may be distributed spatially to further harden the network.

The actual target detections and determinations are made by the assets which operate continuously in a passive mode. The assets must maintain time synchronization with the beacons in order to disinter ToA data, but this does not require any transmission on their part. Target detections from various assets may be fused to improve resolution, accuracy, and

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coverage.

RADAR is the primary mode of aircraft detection in the battlespace as well as the principal safety and control mechanism for commercial aviation in the private sector. PW-ARI offers an inexpensive supplement or alternative to the commercial Traffic Collision Avoidance System (TCAS) because it requires few transmitters for a wide coverage area and, as the high-power transmitters are on the ground, does not stress the electrical system of the passenger aircraft (which results in greater fuel costs). PW-ARI can detect aircraft beyond those equipped with a compliant TCAS transponder (used in general aviation) and those for which the transponder is malfunctioning or otherwise disabled.

II. PULSE-WAVE ARI

The fundamental contribution of this work is the addition of time-of-flight information to the ARI regime. PW-ARI is the fusion of data from three domains: time (time-of-flight), phase (relative phase-of-arrival), and angle (direction-of-arrival) – while conventional ARI includes only the latter two. Further, the relatively narrow beamwidth constraints of ARI are substantially relaxed under PW-ARI as the requisite close spacing of the transmitting beacons allows broader beamwidths to be accommodated. PW-ARI is also substantially faster at imaging large volumes replete with multiple targets as it does not need to rely on differential target illumination (sweeping) to separate targets at multiple distances (this may now be done in the time domain).

The PW-ARI performance improvements stem from the observation that the isolines created in the phase domain are independent of the isolines in the time domain. By combining the two, a coordinate grid is created which is easily mapped onto Cartesian space.

In the top frame of figure 1, the isophasic contours are drawn in space for a pair of PW-ARI beacons centered at $(0, 3)$. The points of each contour represent the set of locations from which the difference in the path length from the point to each of the two transmitters is the same constant. By definition, the isolines take on a hyperbolic fan-like appearance concentrating near the beacons and separating in an angular fashion.

In the middle frame of figure 1, the contours represent the locations from which a particular time-of-flight will be observed should a signal leaving the beacons strike a target at that location and return to an asset receiver located, in this case, at $(0, 3)$. The isolines are roughly circular in shape (with the irregularity being caused by the beacons' non-collocation with the asset) since the time-of-flight corresponds to distance travelled and the distance from a circle's perimeter to its center is constant.

Combining these two observations results in the bottom frame of figure 1. In this scenario the beacons are located at $(0, 6 \pm 1)$ and the asset is at $(0, 3)$. The isolines based on phase and those based on time are overlaid and the resulting grid system becomes apparent. PW-ARI recovers the phase-difference of arrival and the time-of-arrival simultaneously, which makes accurate fusion possible. The following sections explore how this unique capability is achieved.

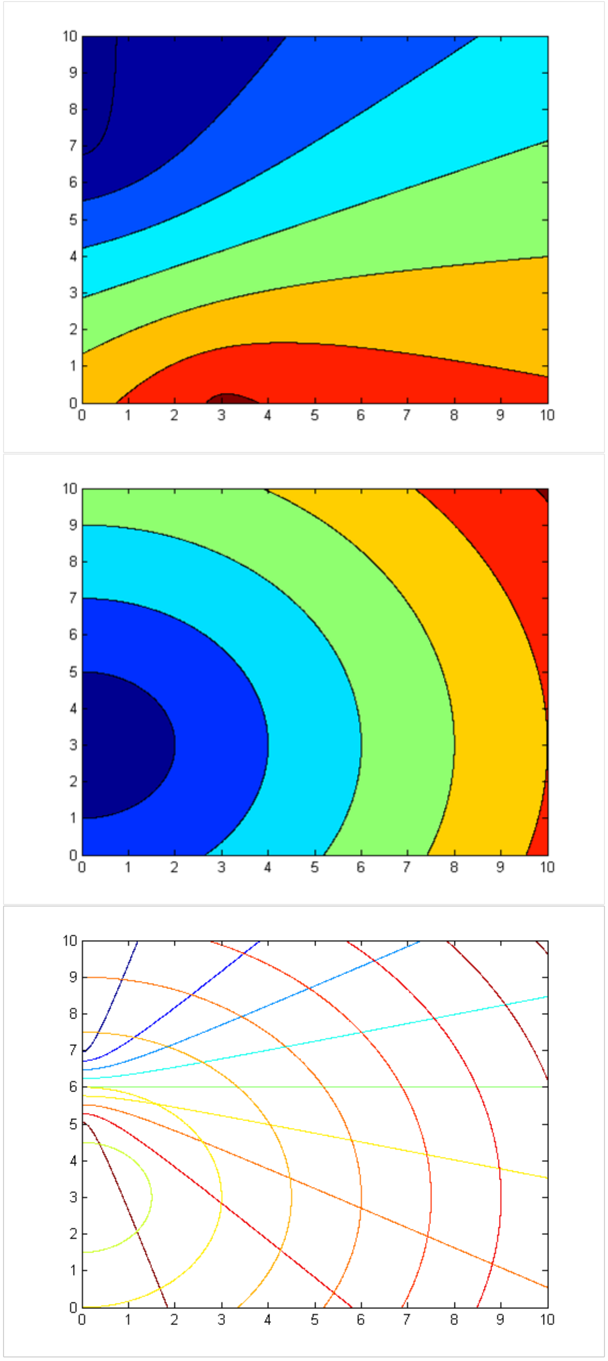

Fig. 1. PW-ARI phase contours *(top)*, time-of-flight contours *(middle)*, and these two contour sets overlaid *(bottom)* as observed at the receiver. Note the grid-like coordinate system created from the fusion of these two contour sets. PW-ARI recovers the phase-difference of arrival *(top)* and the time-of-arrival *(middle)* simultaneously making fusion possible.

II.A. Nomenclature

For clarity, we will use f_{x_n} to refer to individual frequencies, where x is a generic transmitting beacon, a specific transmitting beacon ($x = a, b, c...$), or a receiving asset

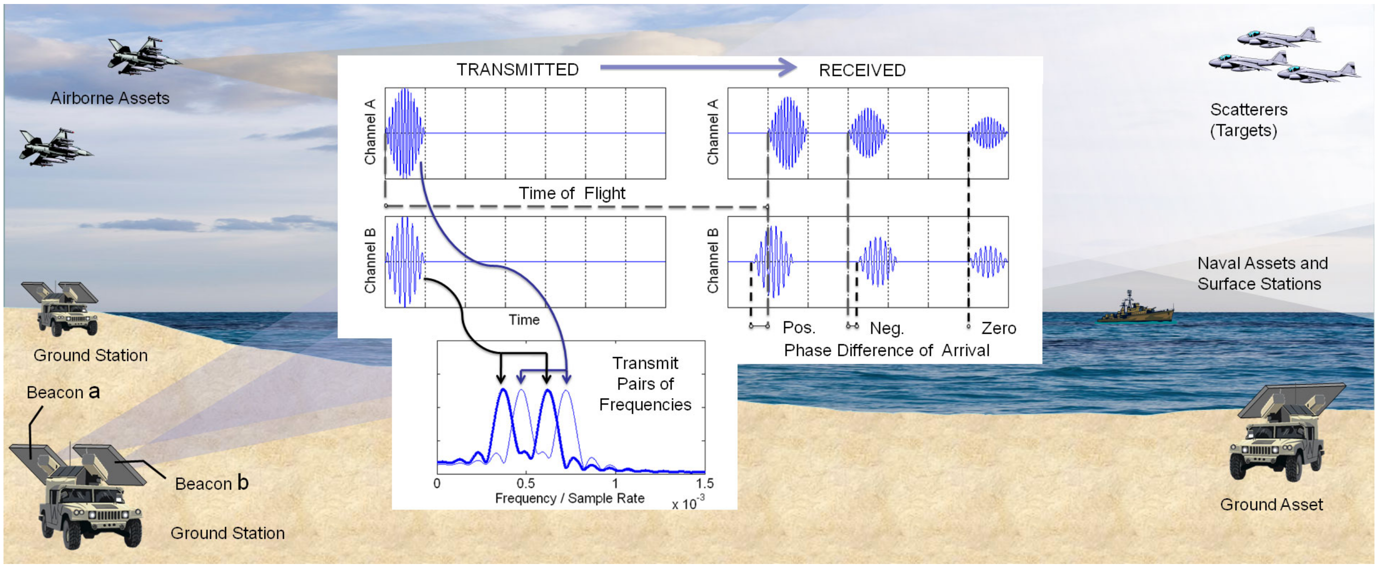

Fig. 2. A Pulse-Wave Angle-of-arrival-assisted Radio Interferometry (PW-ARI) based system consists of pairs of transmitting beacons, grouped into stations, and passive receive-only assets which make use of the transmitter timing and RADAR echo information to locate targets. The beacons transmit unique pairs of frequencies creating a beat envelope which is not unique to any beacon allowing phase comparison.

$(x = r)$. n is the frequency designator $(1, 2,$ or c for carrier) for the ARI component indicated by x. We do not designate assets individually since the friendly assets (receivers) are passive and may be considered independently. Further, we do not designate ground stations explicitly since a ground station is any two beacons appropriately located and synchronized.

II.B. *Transmission*

The transmitted signal from each beacon consists of two frequencies – one that is unique to the beacon, f_{x_1}, and one that is shared across all beacons, f_{com}. A Hartley modulator architecture [3] is used to produce the following signal over the air:

$$\begin{aligned}
&\sin(2\pi f_{x_c} t)\left(\sin\left(2\pi f_{a_1} t\right) + \sin\left(2\pi \ \left(f_{a_1} + f_{com}\right) t\right)\right) + \\
&\cos(2\pi f_{x_c} t)\left(\cos(2\pi f_{a_1} t) + \cos\left(2\pi \ \left(f_{a_1} + f_{com}\right) t\right)\right) + \\
&\sin(2\pi f_{x_c} t)\left(\sin\left(2\pi f_{b_1} t\right) + \sin\left(2\pi \ \left(f_{b_1} + f_{com}\right) t\right)\right) + \\
&\cos(2\pi f_{x_c} t)\left(\cos(2\pi f_{b_1} t) + \cos\left(2\pi \ \left(f_{b_1} + f_{com}\right) t\right)\right) \\
&\text{...for } t = [0..\tfrac{1}{f_{com}}]
\end{aligned} \tag{1}$$

Algebraically we see that (1) resolves to one period of a signal with frequency f_{com} that consists of signal at just four frequencies: $f_c + f_{a_1}$, $f_c + f_{b_1}$, $f_c + f_{a_1} + f_{com}$, and $f_c + f_{b_1} + f_{com}$ [3]. This is a Single Side Band-Suppressed Carrier (SSB-SC) transmission. Since this is the absolute minimum amount of spectrum required to convey all of the information required for PW-ARI, we are as spectrally efficient as possible.

II.C. *Reception*

PW-ARI signals are received as an ARI-encoded pulse train on two channels – each corresponding to a particular beacon's unique frequency pair. The ToA on either channel implies the target range while the PDoA between the payloads of each pulse in the two channels, at f_{com}, implies the bearing. Unfortunately, two transmitters on the same frequency will interfere and obscure the identity and phase of each. ARI supports multiple simultaneous transmissions without interference because the common frequency information is actually present on multiple unique frequencies ($f_{x_2} = f_{x_1} + f_{com}$, for $x = a, b, c...$). Accordingly, we designate f_{com} as the baseband signal and task the PW-ARI receiver with recovering it from each beacon.

Although the transmitted signal is up-converted in quadrature pursuant to [3], the received signal does not require down-conversion in quadrature – a single conversion superheterodyne receiver is sufficient. The spectrum of the resulting intermediate signal contains the identities of any beacons transmitting towards any in-range assets. Beacons may be identified by the presence of a signal at f_{a_1}, f_{b_1}, etc and at each of these frequencies offset by f_{com} (a Doppler correction is required).

Multiple beacons are detected through the use of multiple beacon-specific blocks. Each contains the appropriate channel selecting filters and a pair of Variable Gain Amplifiers (VGA) that are used to equalize the amplitudes of the two frequency components (f_{x_1}, f_{x_2}) and to perform time-range compensation. This maximizes the amplitude of the recovered f_{com}. If multiple beacons exist, the equalized output from each beacon at f_{com} is compared in a phase detection unit.

The phase detection unit is constructed from a network of delay lines tapped and connected to a correlator (a summing circuit followed by a peak-detector). The tap point returning the strongest signal represents the most-likely phase of arrival value. As reported in [4], such an architecture can resolve a time difference of 8 picoseconds for signals at a common frequency. Applying the error model in [2] and using commercially available component performance values, this resolution degrades to ≈ 14 picoseconds – or about 0.1^o at 20MHz.

In the simplest two-beacon case, the phase detector would return the signal $\Delta\phi = \phi_a - \phi_b$, the phase difference between the signals from beacons a and b at their recovered common frequency.

$$\Delta\phi = \frac{(d \bmod \lambda) f_{com}}{c} \tag{2}$$

This phase difference corresponds to the relative physical distance between the paths from each beacon, through the environment (which may be reflected or otherwise indirect), to the asset. This relationship is presented in (2). As the beacons are closely spaced, the isophasic lines are more useful in determining target bearing with respect to the beacon pair than target range.

II.D. EW Considerations

PW-ARI offers a number of benefits relevant to Electronic Warfare (EW) concerns. Passive assets are intrinsically stealthy since synchronization and target detection do not require active transmission. The powerful long-range transmitters may therefore be well defended by hidden forward-positioned assets. PW-ARI transmissions may be made extremely narrow-band whereas enemy Radar Warning Receivers (RWR) must incorporate a wide-band receiver with its associated higher noise floor [5]. Time synchronization allows a frequency hopping scheme to further hide the transmitter's spectral location.

II.E. RADAR Classification

The most common modern day RADAR is monostatic. In a monostatic RADAR, the transmitting and receiving antennae are collocated (as in the nose of an aircraft). In a bistatic RADAR, the transmitting and receiving antennae are spatially separated [5]. PW-ARI is essentially two bistatic RADAR systems which share a receiver (the asset) and in which the transmitters are tightly time synchronized. Further, multiple independent receivers can pair with the same transmitters to form independent PW-ARI RADAR systems. Or, this data can be shared among assets to improve target location accuracy, precision, and detection range. This arrangement contains attributes common to passive RADAR as well as bistatic systems, and although PW-ARI does not fit the most typical definition of multistatic RADAR [6], we categorize it as such, nonetheless.

III. PERFORMANCE EXPECTATIONS

III.A. Timing Requirements

Current time synchronization technology allows us to synchronize two systems to an accuracy well below 50ns. The Global Positioning System (GPS) is one technology which allows clocks to synchronize to Universal Time, Coordinated (UTC) to within 10ns [7]. However, time synchronization is not the only thing necessary to make PW-ARI work. We also need to be able to keep the accuracy of time below 50ns over the long term, because the receivers and transmitters could be jammed or, as was recently shown in [8], spoofed. Therefore, the receivers need very accurate clocks in order to keep accurate timing for the extent of the mission. The stability of the clock has to be

$$\delta f \cdot T \leq 50ns,$$

where δf is the clock stability measured in parts per million (ppm), and T is the length of time for which the clock has to perform without a resynchronization event. For example, for a mission length of 5 hours, the clock stability has to be less than 10^{-12}. Available Rubidium oscillators are near this level of frequency stability and the advent of chip scale atomic clocks [9] supports our belief that, in future systems, this level of clock stability will be readily available.

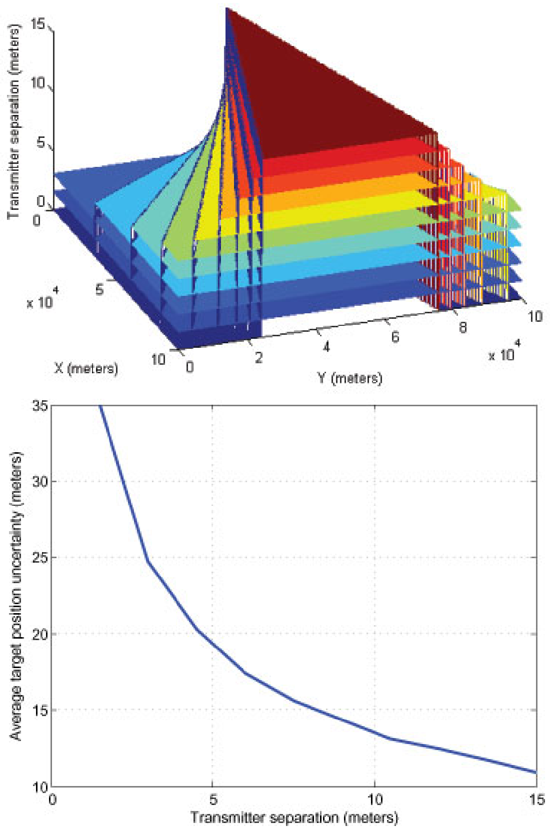

Fig. 3. PW-ARI coverage area vs. inter-beacon distance *(top)*. Average accuracy for a target 50km in range using 20*MHz (bottom)*.

III.B. Common Design Parameters

PW-ARI shares a number of design parameters with pulsed RADAR systems in general. As previously discussed, ARI encoding allows the independent choice of carrier frequency, which should be chosen to accommodate EW concerns (target reflection, frequency hopping hardware limitations, etc). With any pulsed system, the Pulse Repetition Frequency (PRF) is of concern although it is well understood from PW RADAR, medical ultrasound, and other domains.

III.C. The Resolution-Coverage Trade-off

Of principal and unique interest in PW-ARI system design is the ARI frequency and beacon separation distance. For constant frequency, increasing the inter-beacon distance improves localization accuracy at the expense of reduced coverage volume. For constant separation, increasing the frequency reduces coverage and improves bearing resolution. Thus, the effects are largely reciprocal, suggesting an optimal configuration for each $\langle volume, accuracy \rangle$ tuple.

Given an ARI frequency, f_{com}, of 20*MHz*, figure 3 (top) shows the effect of inter-beacon distance on the PW-ARI coverage area over a $100km \times 100km$ surface. The area-to-separation function is non-linear. In the lower plot of figure 3, the target location accuracy at $50km$ is shown versus the inter-beacon separation distance. Increasing the distance narrows the isophasic lines and therefore improves target bearing resolution, in turn, improving accuracy. In this example, the target bearing was directly along the boresight where ARI angular resolution is at its worst-case performance since the signal phase difference is near-zero.

To illustrate this further, consider figure 4. Here a central target (yellow circle) is illuminated by a ground station $50km$ due West. The receiving asset, a friendly aircraft flying patrol, is located to the South-West of the figure. The horizontal band in the figure represents the region of likely target detection based on the PDoA from the PW-ARI payload in the return signal. The diagonal band lies orthogonal to the asset's flight-path and represents the region of likelihood based on the ToA data derived from the worst case $50nS$ time synchronization between asset and beacon. The intersecting region is the target detection estimated position. Were other assets available to corroborate the detection, the data could be fused. Observed from different asset-to-target angles, the target estimation volume would reduce substantially.

Finally, PW-ARI requires hard-sector transmission – the simultaneous illumination of an entire RADAR sector, as opposed to sweeping through a sector with a narrow beam. Antennas of this type are inherently more power efficient than electronic steering and faster than mechanical scanning. However, the antenna pattern of the beacon must be limited to the sector size or returns from outside the sector will alias in the phase domain.

IV. CONCLUSION

In this work, we have introduced a pulsed variant to the ARI architecture and discussed its possible limitations and implementations. The speed, simplicity, redundancy, and stealth offered by PW-ARI RADAR systems is extremely attractive and the technology necessary to achieve such systems is within the range of possibility at the time of authorship. Furthermore, the lack of sophisticated antenna systems and mechanical components suggests that a PW-ARI RADAR system might be sufficiently cost-effective and reliable to suffice for civilian aviation, border patrol, and other high-quantity applications.

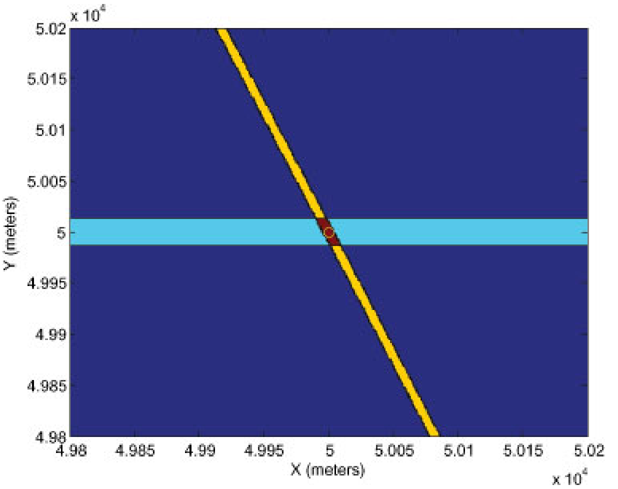

Fig. 4. A PW-ARI RADAR system imaging a target at 20MHz, from 50km.

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