A Passive SAW Based RFID System for Use on Ordnance

Paul R. Hartmann, *Senior Member, IEEE*
RF SAW, Inc.
Richardson, Texas, USA
Email: phartmann@rfsaw.com

Abstract— **Automatic RFID tracking of ordnance in transport or storage has been difficult or impossible due to the dangers that arise from possible accidental actuation of electro-explosive devices by RF electromagnetic fields. Limits on the maximum RF power densities that meet Hazards of Electromagnetic Radiation to Ordnance (HERO) emission standards preclude many passive RFID systems from operating safely in the vicinity of ordnance due to the high level of RF radiation needed to power the electronics onboard the RFID tag. This paper describes a Surface Acoustic Wave (SAW) based RFID system that allows safe operation of an RFID system with no standoff or separation distance between the reader antenna and the item of ordnance. Surface Acoustic Wave RFID systems are a "chipless" technology that utilize the piezoelectric properties of certain monolithic crystal materials to provide a truly passive RFID technology which can be operated at RF power levels well below those established for safety near ordnance.**

Index Terms— **Electro-explosive, HERO, ordnance, RFID, SAW**

I. INTRODUCTION

RFID technology has grown rapidly in the past few years as the need for rapid, automatic identification and tracking of goods has become increasingly important. In many instances, the data network and information systems have moved far beyond the ability of the tracking systems to quickly and accurately determine the locations of items to be tracked. In many of these applications, RFID systems are the obvious choice.

This paper looks at a more difficult problem which is the question of safety in the vicinity of the items being tracked. The specific application is one in which the items being tracked are ordnance. Many of these devices are electro-explosive meaning that they can be actuated by the presence of electric fields that are of sufficiently high field strength.

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II. RF EMISSION LIMITS FOR ORDNANCE

The safety issues surrounding RF emissions in the vicinity of ordnance and other electro-explosive items during transport and storage have been recognized for some time. In general, the approach used to manage or eliminate these issues has been to limit the RF power levels involved and to provide a separation distance that assured that the RF levels were sufficiently low to allow safe handling and transport of ordnance.

The US Navy and other agencies have studied this subject extensively over the years and have devised methods and measurements to assure safety near ordnance. More recently, the US Navy has extended this work to establish new standards [1] that recognize the potential hazards from small handheld and other devices including RFID readers because of the pervasiveness of these devices and the potential improvement in the speed and accuracy of inventory and tracking information that can be gathered by these systems. This work has included studies across a very large portion of the radio electromagnetic spectrum and has considered the effects of the configuration of spaces such as magazines and the combined effects of several emitters operating simultaneously. The result has been to quantify standards known as Hazards of Electromagnetic Radiation to Ordnance (HERO), Hazards of Electromagnetic Radiation to Personnel (HERP), and Hazards of Electromagnetic Radiation to Fuels (HERF). This paper will address the effects on ordnance since that is generally the most restrictive case and is the subject of the SBIR grant that supported portions of this work.

In the case of ordnance, the two major concerns are that the presence of RF emission will cause 1) unwanted actuation of an Electrically Initiated Device (EID) or 2) the degradation of the EID so that it will not operate properly when called upon to do so. The effect of the RF emission is to cause EM energy to be coupled into the EID thru leads thereby causing unwanted heating in the EID.

When considering the question of hazards from electromagnetic radiation on ordnance, there are two major items to consider. The first is the level of RF field in the vicinity of the ordnance and the second is the sensitivity or susceptibility of the ordnance in question. For many new items of ordnance, the RF susceptibility of the items has been built to known standards and tested to show compliance with those standards. For many older items, the RF susceptibility is not as well defined and so a greater burden must be placed on the RF emissions generated by radiating devices to ensure safe handling and storage can be achieved.

In the HERO standard [1] the US Navy has reflected these two conditions in the charts in Figures 1 and 2 shown below.

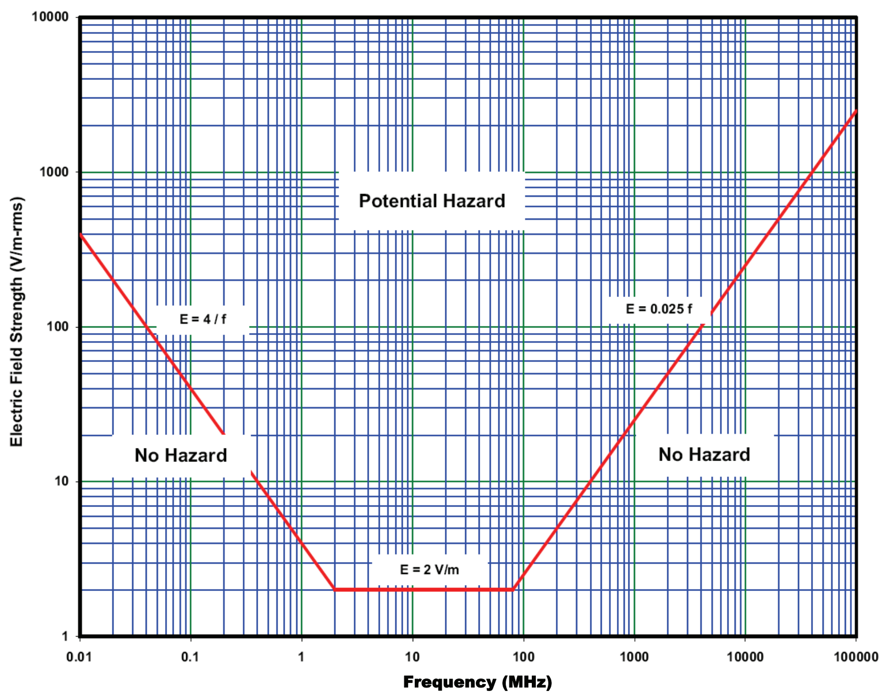


Figure 1
Safe Field Strength Limits for
HERO SUSCEPTIBLE ORDNANCE [1]

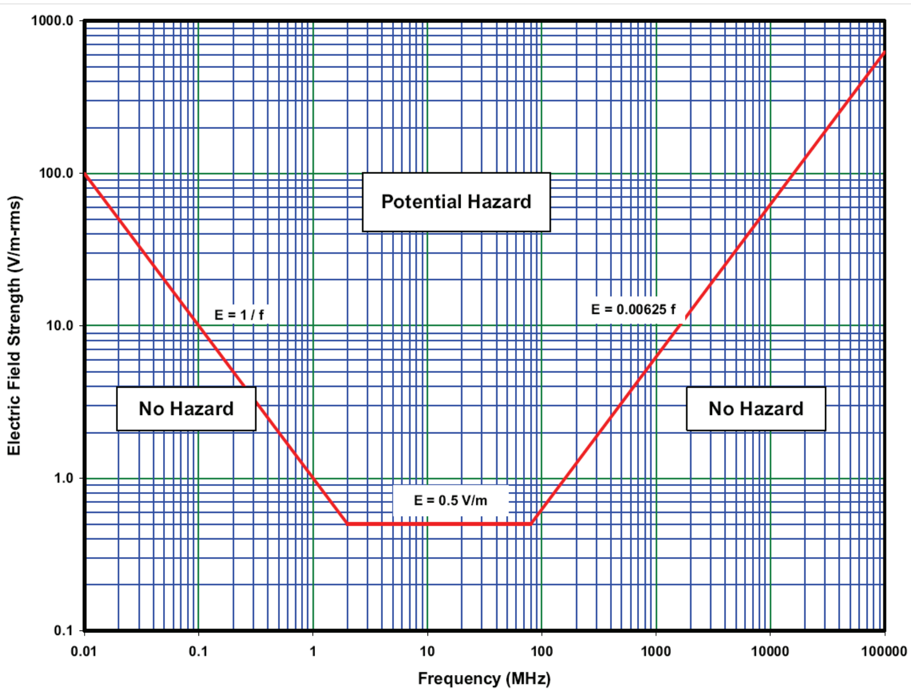


Figure 2
Safe Field Strength Limits for
HERO UNSAFE and HERO UNRELIABLE ORDNANCE [1]

The first shows the limits on the electric field expressed in volts/meter for ordnance meeting the HERO SUSCEPTIBLE standards as defined in [1]. The more restrictive case is shown in Figure 2 and shows the limits for ordnance that are HERO UNSAFE and HERO UNRELIABLE. There are also new items of ordnance that are classified as HERO SAFE.

These charts set the Maximum Allowable Environment (MAE) for emitters in the vicinity of ordnance in the absence of data on that particular item of ordnance. Each of the limits is divided into three frequency ranges. Since we intend to limit our discussion to RFID systems that use SAW based tags, the range we are concerned with is the highest frequency range. The equations for the MAE then becomes

$$E = 0.25 f \qquad (1)$$

and

$$E = 0.00625 f \qquad (2)$$

respectively for the two cases shown in the HERO SUSCEPTIBLE ORDNANCE chart (Figure 1) and the HERO UNSAFE and HERO UNRELIABLE ORDNANCE chart (Figure 2) where E is the maximum strength of the electric field in Volts/ meter and f is the frequency of operation in MHz. Since we intend to deal with the more restrictive case that allows an RFID system to work in the widest possible range of RF emission susceptibilities, we will restrict our discussion to the field strength values in Figure 2 and equation (2) above. In this instance, we can make the field strength and MAE values more useful by expressing the information in terms of transmit power, antenna gains, operating frequency and distance between the antenna and the item of ordnance. At distances that fall in the far field region of the antenna, the minimum standoff distance can be calculated as

$$D = \frac{876}{f}\sqrt{P_t G_t} \qquad (3)$$

where D is the distance from antenna to ordnance in Meters
f is the frequency in MHz
P_t is the transmitter power in Watts
G_t is the far field gain ratio of the antenna.

This equation is derived from the equation for power density as described in [1]. However, for RFID systems there is often a need to operate at distances that are less than the far field region of the transmit antenna and in those cases, the methodology described in [1] uses a correction factor when operating in the antenna near field. When the distance becomes even shorter or approaches zero standoff, a simplified method for setting the maximum power density that can be used is to specify the maximum EIRP that the transmitter and antenna combination can emit. In the most restrictive case, that EIRP level above 100 MHz is:

$$\text{EIRP} \leq 0.025 \text{ watts} \qquad (4)$$

It is recognized that at zero standoff, the power density will generally be higher for a small aperture antenna (low gain) since the transmit energy is spread over a smaller area than it will be for a larger aperture antenna. Nevertheless, this approach provides a simple way to evaluate the acceptability of an RFID reader that may be operated intentionally or accidentally at zero standoff distance from an item of ordnance. It should also be pointed out as mentioned in [1] that the other factors that need to be taken into account in many RF susceptible environments include the effects of reflections from walls and other reflectors and the cumulative effects that result from the operation of several RF emitters simultaneously.

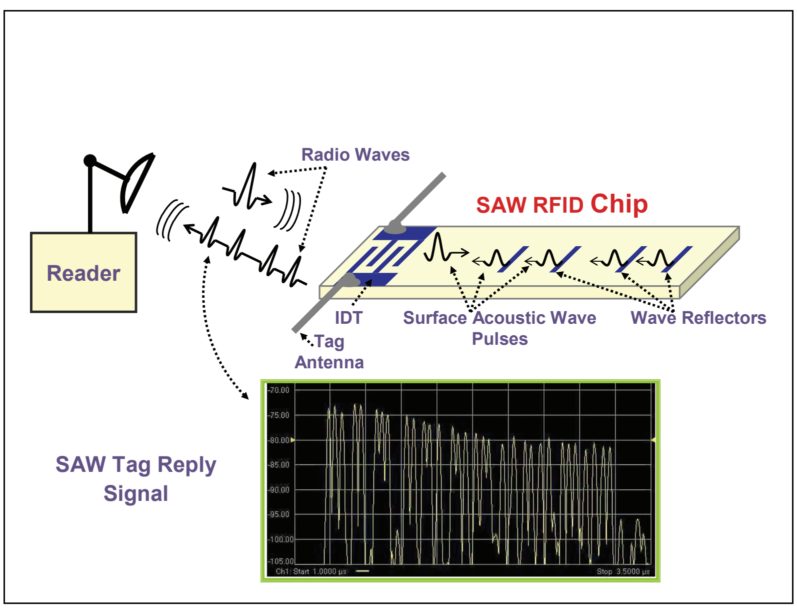


Figure 3
SAW-Based RFID System Operation

III. SAW RFID SYSTEM OPERATION

The basic operation of a SAW-based RFID system is shown in Figure 3. In its simplest form, a single pulse of RF signal is sent from the reader and antenna to the SAW tag. At the tag, the signal is received by the tag antenna which is connected to an Inter-Digital Transducer (IDT) on the SAW device. The SAW device is built on a bar of crystalline material such as lithium niobate which is piezoelectric. The received reader signal that appears on the IDT from the antenna is now converted to a nano-scale Surface Acoustic Wave (SAW) replica of the reader RF Signal. The wave travels down the length of the SAW device and is then partially reflected at wave reflectors that have been placed on the surface of the device. These reflected waves then travel back to the IDT where they are reconverted to an electrical signal by the reverse piezoelectric effect and are radiated by the tag antenna to be sent to the reader antenna. The information that is encoded on the device is contained in the precise location of the wave reflectors for a given tag code. The importance of this conversion is that surface wave velocity is now approximately 5 orders of magnitude slower than the velocity of an electromagnetic wave. This means the physical size of the device needed to produce the delays needed for this type of signal encoding is a practical size for an RFID tag application. The SAW operation shown in the upper portion of Figure 3 shows an example of a four pulse encoding scheme. The SAW tag reply signal shown in the lower portion of Figure 3 shows an example of a 128 bit tag signal as discussed in [2]. An example of a commercial SAW-Based RFID system is shown in Figure 4. The system consists of the 2.4 GHz reader on the left of the photo, a flat panel antenna on the right hand side of the photo and ancillary items such as cables, power supplies, and antenna mounts in the center. The system operates in the 2.4 GHz ISM band. Total RF output power from the reader is less than 1 milliwatt. Examples of typical SAW tags used with this system are shown in Figure 5and 6.

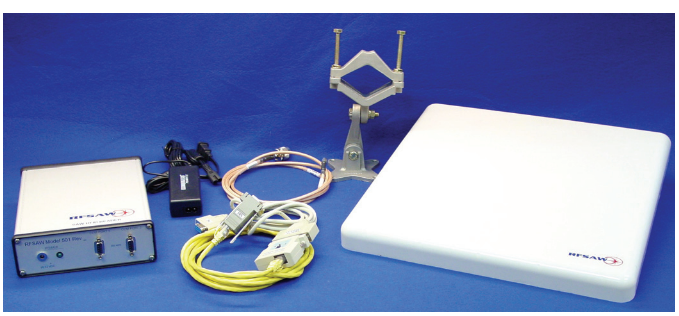


Figure 4
RF SAW Model 501 Reader System

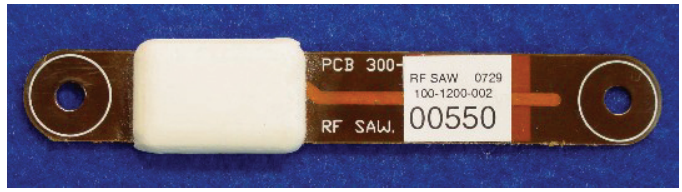


Figure 5
SAW Tag with Flexible Monopole Antenna

The SAW device for the tag shown in Figure 5 is molded into the white housing near the left end of the tag and the monopole antenna is visible as the horizontal line on the right hand side of the tag. Total length of the tag is approximately 7cm (2.75in.) Tags can also be configured with higher antenna gain to extend the reading distance or signal margin for the reading process. A typical example is shown in Figure 6. The tag uses a patch antenna design with a gain of approximately 6 db.

Figure 6.
SAW Tag with Path Antenna

IV. SAW RFID SYSTEM DESIGN

Starting from the emission limits above one can then look at the design of a SAW based RFID system. Among the first considerations for an RFID system for tracking ordnance is the desirability of using a tag design that is passive. This not only eliminates concerns about the life of the battery needed for active systems but also any potential hazards arising from the batteries themselves. Other considerations include the frequency of operation and the design of the reader signal itself. A number of these factors have been discussed previously in [2], [3], and [4]. From an operating frequency perspective, 2.4 GHz provides a good balance of SAW device size for given amount of encoding capacity, lithography tolerance, available bandwidth, and a common frequency band around the world. It is a shared frequency allocation in many regions which means that intrasystem and intersystem interference effects must be taken into account. From a reader signal design perspective, an FMCW radar signal [5], [6] is a good choice since it spreads the reader power over the occupied bandwidth and reduces the peak power very substantially compared to a short interrogating pulse reader signal such as the one shown as the reader signal in Figure 3.

With the operating frequency and reader signal structure established, it is possible to evaluate a SAW Based RFID system from the point of view of its fit in the ordnance environment. Starting with equation (4), we can see that we reach the 0.025 watt limit with a transmit power level of 0.5 milliwatts and antenna gain of 17dbi which is very nearly the parameters for the reader system shown in Figure 4. If we use those values in equation (3) to calculate a standoff distance using the far field assumptions we calculate a distance of 5.7cm. Reference [1] also uses a standard approximation for the determining distance from the antenna to the far field which is:

$$FF \geq \frac{2d^2}{\lambda} \qquad (5)$$

where FF is the far-field region
d is the largest dimension of the antenna
λ is wavelength at the operating frequency

Evaluating this equation for an antenna such as the one used in the calculation above we find that the edge of far-field would occur at 2.6 meters given an antenna dimension of 40cm. Obviously the 5.7cm distance calculated above would be very deep inside the near field of the antenna and at that point, the far-field gain of the antenna overstates the field strength calculated. As pointed out in reference [1] a gain correction factor is used in the equation for determining the standoff distance. This approach leads one to an incorrect conclusion which is that large antennas are more hazardous in the near field than small antennas at a given level of transmit power. To see this we can gain some additional intuitive insight by converting the limits in equation (2) to power density in watts per meter^2 using the relationship:

$$P_d = \frac{E^2}{Z_0} \qquad (6)$$

where Pd is the power density in watts/meter^2
E is the Electric field in volts/ meter
Z_0 is the intrinsic impedance of free space

This is a standard equation in an area where the E field and H field are related by 377 ohms which is the intrinsic impedance of free space. At 2440 MHz which is the center of the 2.4GHz ISM band, we calculate a value of 0.617 watts per meter^2 or 0.0617 milliwatts per cm^2. The region at which the E and H field are not related by the intrinsic impedance of free space becomes smaller as the frequency is increased and as the size of the antenna is reduced.

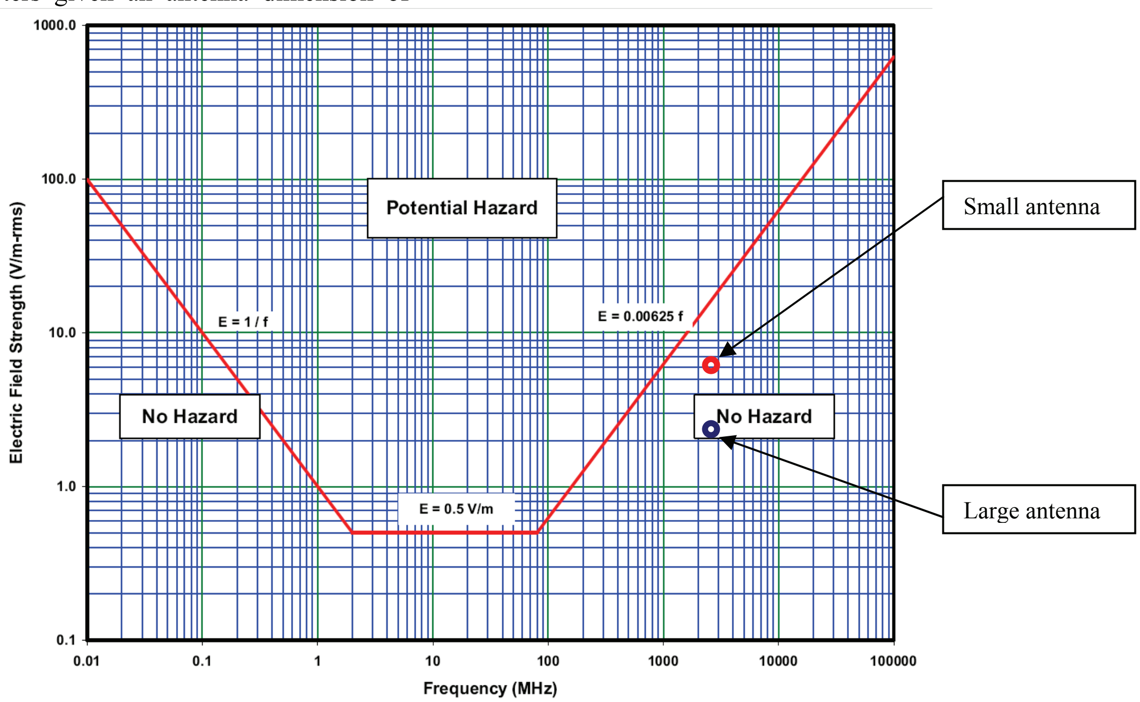


Figure 7
Safe Field Strength Limits for
HERO UNSAFE and HERO UNRELIABLE ORDNANCE
With approximate Field Strength of Small and Large Antennas at Zero Standoff

The smallest practical antenna for use with a reader is an antenna with a maximum dimension of approximately ½ wavelength. At 2.4 GHz the area of a square aperture of that size is approximately 36 cm^2 which means that the total power that would be allowed in that size area would be approximately 2.2 milliwatts. As the antenna size is increased, the power density near the antenna drops since the transmit power from the reader is distributed over an area that is increasing by the product of the height and width of the antenna. This is quite easy to see in the design of flat panel array antennas where the larger aperture is realized by assembling an array of small radiators that are driven from a power divider and phasing network. If the power density is measured in small areas on the face of such an antenna, one finds that the power is lower than a similar measurement on the face of a small antenna of the same general design. This leads to the general conclusion that smaller antennas present more of a limitation to operating at zero standoff than large antennas do for a given amount of transmitter power particularly in the UHF and microwave frequency bands. With minimum standoff distances that allow the system to operate in the far-field of the reader antenna, the opposite is true. Figure 7 repeats the limit curves from Figure 2 but with the addition of two points that show the approximate field strength values for a small aperture antenna and for an antenna with gain of 17 dbi as discussed above when driven with a -3 dbm signal from a Model 501 Reader.

Measurements have been conducted by the US Navy on an RF SAW Model 501 reader system with various antennas. The measurements also included effects from reflections in the space where the measurements were made. Based on these measurements, the US Navy has certified this equipment for operation with zero standoff.

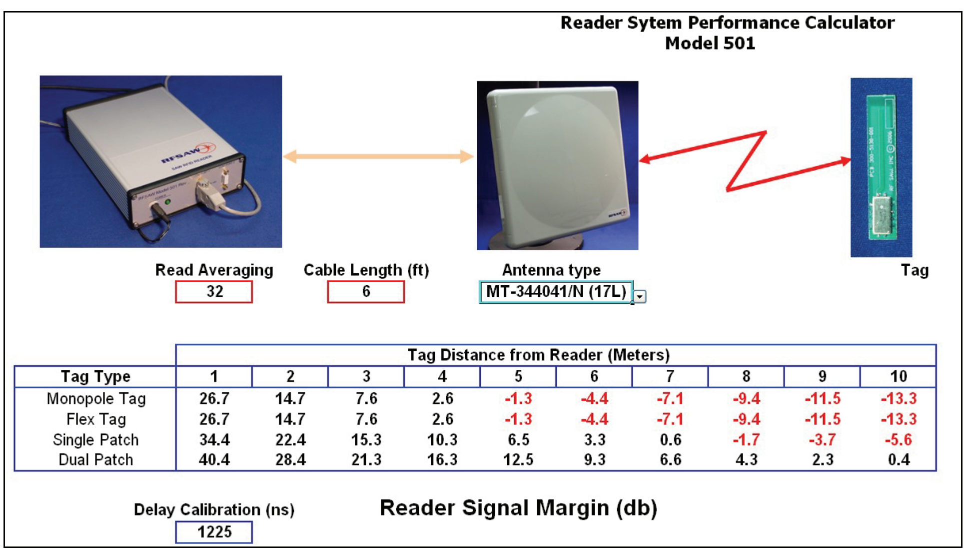
V. RF SAW SYSTEM PERFORMANCE

While this paper has looked primarily at the issues associated with safe operation near ordnance, it is also important to look at the predicted and measured performance of a SAW based RFID system. A typical Model 501 Reader system would have the following parameters.

Model 501 System Parameters

PARAMETER	**VALUE**
OUTPUT POWER	-3 DBM
ANTENNA GAIN	17 DBI
CABLE LOSSES	1DB
TAG TYPE	80 BIT PLATFORM 40 BIT PAYLOAD

The chart below (Figure 8) shows the calculated reading distances for a Model 501 Reader System with several styles of tags. The values shown in each row indicate the signal margin in db at a given distance. The negative values in the upper right hand portion of the chart reflect reading distances where the received signal at the reader will be below that required for successful reading.



Tag Type	Tag Distance from Reader (Meters) 1	2	3	4	5	6	7	8	9	10
Monopole Tag	26.7	14.7	7.6	2.6	-1.3	-4.4	-7.1	-9.4	-11.5	-13.3
Flex Tag	26.7	14.7	7.6	2.6	-1.3	-4.4	-7.1	-9.4	-11.5	-13.3
Single Patch	34.4	22.4	15.3	10.3	6.5	3.3	0.6	-1.7	-3.7	-5.6
Dual Patch	40.4	28.4	21.3	16.3	12.5	9.3	6.6	4.3	2.3	0.4

Figure 8
Calculated System Performance of SAW Based RFID System with Various Tag Antenna Configurations

VI. CONCLUSION

This paper has reviewed the HERO standards and calculation methods to evaluate the performance of a SAW Based RFID system. Further, this paper has shown that it is practical to build SAW Based RFID systems that simultaneously meet the most stringent HERO UNSAFE and HERO UNRELIABLE ORDNANCE requirements and provide excellent reading range performance. It has been demonstrated that, in the near field and zero standoff cases likely to exist with RFID systems, the highest level of power density from the reader system occurs with small antennas rather than large antennas. The Reader System Performance Calculator displays the level of performance one can expect for a commercial SAW Based RFID system.

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