A High Temperature Superconducting Anti-Jam GPS Antenna Array

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***Abstract*- The Defense Advanced Research Projects Agency (DARPA) is funding a GPS adaptive antenna array using high temperature superconductor (HTS) technology. This adaptive antenna array is designed to null multiple GPS jammers, while being considerably smaller in size than conventional adaptive arrays. The combination of these two requirements can be satisfied only through the unique properties of thin film HTS antenna elements and circuits. A packaged, ruggedized, multielement HTS based, GPS antenna is due to be delivered by March 2000.**

INTRODUCTION

From luxury car drivers to soldiers, the military's Global Positioning System (GPS) is an ever more important part of the information infrastructure. As more systems become dependent on GPS for accurate location information, it is important that the GPS signal is available at all times. Commercial airlines are being encouraged by the Federal Aviation Administration to incorporate GPS into all flight safety and landing systems. In this scenario loss of GPS due to inadvertent interference could cause a catastrophe. For the military, a jammed GPS signal can have serious repercussions. The current conventional nulling antennas are unacceptably large for many military platforms. Therefore, the Defense Advanced Research Projects Agency (DARPA) undertook to develop a reduced-size GPS adaptive antenna array using high temperature superconductor (HTS) elements. Booz•Allen & Hamilton is coordinating the efforts of the antenna designer, Cryoelectra GmbH and the integrator/mechanical designer, Infrared Components Corporation (ICC), to produce a final technical demonstrator system for service testing in March 2000.

A superconductor has special electromagnetic properties that are valuable for many RF applications. Although the hallmark of superconducting material is a zero DC resistance below the critical temperature, T_c, the RF surface resistance is not zero[1]. It is, however, many orders of magnitude smaller than normal metals (copper, gold) at microwave frequencies, making superconductors attractive for filters, distribution networks, multiplexers, and other RF components.

A superconductor is considered "high temperature" if its T_c is above 77 K, the boiling point of liquid nitrogen. Although liquid cryogens are NOT used in modern RF systems, this designation (HTS) indicates the relative ease of providing cooling with a closed cycle cryocooler, similar to those used in many infrared systems.

In the past few years, superconducting technology has become more commonplace in government and commercial RF systems. The advances in the development of high Q filters and high quality HTS films have allowed the benefits of superconductivity to be used in a variety of applications, from government systems to base stations for commercial cellular communications. DARPA sponsored projects have demonstrated integrated HTS filters and cryogenically cooled low noise amplifiers that have a lower insertion loss, lower noise figure and steeper skirts than conventional filters and amplifiers. These HTS filters/amplifier systems are designed to meet the rigorous environmental test requirements of MIL-STD-810E and will operate in an ambient temperature of 71°C, and will survive common carrier vibration levels.

This paper discusses the HTS adaptive GPS antenna and the implications of its design. Details of the mechanical design are examined and the unique integration issues will be addressed.

INNOVATIVE ANTENNA DESIGN

This adaptive antenna array is designed to null multiple GPS jammers and to be considerably smaller in size than conventional adaptive arrays. The unique qualities of HTS and the other design innovations allow for tighter antenna spacing, smaller antenna elements as well as high jamming rejection.

Miniaturization of antenna arrays is made difficult by interactions between the radiating elements as they are moved closer together. One method to overcome this problem is to design a superdirective multiport antenna. This involves compensating for the radiating element coupling with a network which zeroes the output at the other ports ("matching

[1] M. Tinkham, "Introduction to Superconductivity", McGrawHill, NewYork 1975

and decoupling network, MDN"). It can be shown that, in so doing, the antenna pattern is restored to nearly that of the larger, unreduced array, as illustrated for the example of a 2-element array in Fig. 1. Since operation in the receive and transmit mode are closely related to each other by reciprocity, an explanation is given for the transmit case. In column (a) there are two about $\lambda/2$ spaced elements in an array. A required nulling direction is adjusted by a certain phase difference between the incident waves, e.g., $a_2=\exp(-\Phi_1)a_1$. Here, mutual coupling between the elements is small. As the spacing between antenna elements is reduced (see column b), due to mutual coupling between the elements the power incident at the ports is no longer completely radiated, but a significant portion is transferred back to the generator via the other port ($b_1=S_{21}a_2$ and $b_2=S_{21}a_1$). By a proper choice of the phase difference between a_2 and a_1 the nulling position can be chosen correctly, but the "cross-talk" between the elements reduces the antenna gain (see Fig. 1b). With a matching and decoupling network MDN (see Fig. 1c), the cross-talk between the antenna elements is compensated for by a corresponding path in the MDN, leading to a structure where the entire array possesses a resonant behaviour. Hence, the input ports of the MDN become decoupled. The power of the waves A_1 and A_2 incident at the antenna elements are by a factor of $1/(1-|S_{21}|^2)$ higher than in case b). The corresponding equivalent currents of the antenna elements are also increased and the radiated field is even in the main beam direction characterized by partially destructive interference ("superdirective excitation").

This superdirective principle cannot be implemented without production trade-offs. If the spacing is reduced or more modes are included to reproduce the pattern, the bandwidth will narrow. For the GPS application, the required bandwidth is about 1.5%, allowing a size reduction of 0.75-1.25 times the signal wavelength. This "superdirective antenna" is only useful for these small arrays, where a total size reduction of a half to one wavelength is significant.

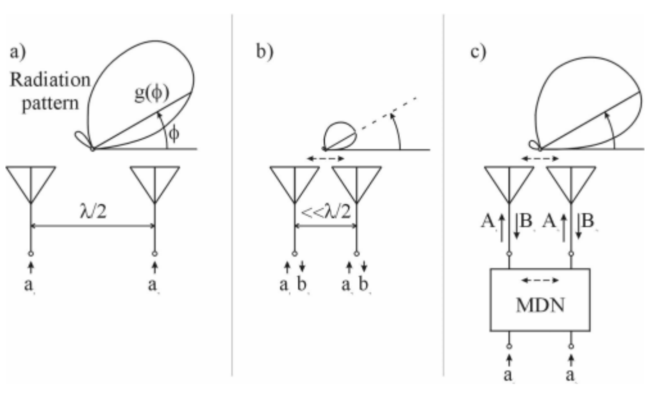

Figure 1. Superdirective principle for a 2-element array

The decoupling, matching and feed network of the DARPA antenna is realized as microstrip circuit and coupled to the antenna elements via apertures in its ground plane. Resonant current enhancement makes this network sensitive to losses. Consequently, HTS material must be used to maintain a sufficiently high efficiency. This explains the use of HTS in the feed network, but such an antenna could still be reasonably efficient with conventional normal metal (copper or gold) radiating elements. In the chosen approach, miniaturized dual frequency radiation elements with multiple-section matching network are used. This produces a sharp bandpass characteristics and therefore excellent out-of-band rejection, but requires the low conductor losses which are offered by HTS. This reduces interference that is near but outside the desired band. Therefore, the elements are designed to resonate at the GPS L1 and L2 frequencies, 1575.42 MHz and 1227.6 MHz respectively, with narrow (about 20 MHz) bandwidths to eliminate jamming energy outside the GPS bands.

The antenna elements are placed on a 6-inch substrate that is located above the coupling network. Each antenna element is identical except rotated 60° with respect to its neighbor as seen in Fig. 2. This provides rotational symmetry and allows for polarization diversity between the elements. It has been predicted that this polarization diversity will improve the jamming rejection of the antenna; however, this effect also depends upon the adaptive electronics used. The effectiveness of this design choice for the DARPA antenna will only be measured and because this is a novel and innovative design the performance cannot be predicted reliably.

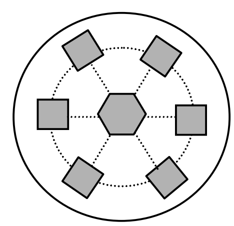

Figure 2. Antenna element alignment

The HTS antenna elements are made of yttrium barium copper oxide (YBCO) that typically has a Tc around 93 K. The YBCO is deposited on a sapphire substrate. Sapphire is a high dielectric material that allows the elements to be made smaller. In equation 1, λ_{eff} is the effective wavelength of the array, λ_0 is the free space wavelength, ε is the permittivity of a material, and ε_0 is the permittivity of a vacuum.

$$\lambda_{eff} = \frac{\lambda_0}{\sqrt{\frac{\varepsilon}{\varepsilon_0}}} \qquad (1)$$

Sapphire was chosen as a substrate because it can be grown in six-inch wafers, and has high, uniform dielectric constant across the substrate. Other HTS substrates, e.g. lanthanum aluminate, vary in dielectric constant across a wafer and are only available in smaller sizes.

Reducing the size of an adaptive antenna introduces a performance compromise. Theoretically, seven antenna elements will allow the antenna to null up to six jammers at once. However, as antenna elements are moved closer together their ability to resolve jammers and maintain adequate signal-to-noise ratio (SNR) may be reduced. A detailed calculation for this antenna geometry, but using isotropic elements,

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suggests that only three jammers can be successfully nulled with adequate SNR for GPS navigation. The same calculation for a 14-inch diameter conventional antenna suggests that four jammers could be nulled.[2] Its overall jamming *rejection* (the combination of nulling and filtering) is expected to be superior to conventional antenna systems due to its excellent out of band rejection and its polarization diversity. The HTS array is 6.3 inches in diameter before packaging in an electrically transparent vacuum dewar. The final system diameter (post packaging) will be approximately 7.5 inches, which offers a significant size reduction from many conventional arrays.

SYSTEM DESIGN ISSUES

In addition to the electromagnetic design of the antenna, it is important to look at the mechanical design of the whole system. This includes identifying cooling, vibration and housing issues and the interaction of the electromagnetic fields with the packaging materials.

One of the challenges is cooling for the HTS antenna elements. Today's Stirling cycle cryocoolers can rapidly cool down to 77 K and require no user attention. The military has used these coolers in Forward-Looking Infrared (FLIR) sensor engines on combat aircraft for many years. The design goal for the GPS HTS antenna is cool down time of 10-15 minutes, a time that is comparable to FLIR systems while requiring at most 200W of power. To achieve this goal, the mechanical system designer must pay special attention to the thermal mass of the antenna inside the cooler. The challenge is to minimize cooled mass while maintaining the dielectric volume required by the antenna design. Since the passive sapphire dielectric elements do not require cooling, thermally separating these from the cooled matching network and antenna elements is a logical thermal optimization approach. This presents several complications, including microphonics and increased surface area for radiation heat loading, as well as increased thermal gradients. Key to the success of the design is to employ structural materials with high strength, high thermal conduction and low volumetric thermal mass. Beryllium meets these goals rather well, and also has a coefficient of thermal expansion over the temperature interval (71°C to 77 K) close to sapphire that minimizes thermally-induced stress. Through aggressive design and careful study, the thermal mass has been greatly reduced to result in a shorter cool down time.

Another issue in cooling is incident radiation heating of the elements. A quartz window is used as an electrically transparent aperture to couple the signal into the cooled elements in the metal dewar. This permits parasitic heating of the HTS elements by outside radiation, particularly solar loading. To combat visible radiation, a traditional composite radome can be employed. To combat thermal emissions from the window surface to the cooled elements, the quartz window will be coated to reduce its thermal emissivity while allowing electromagnetic (RF) radiation to pass into the antenna. Traditional gold sputter-coatings meet the thermal requirements, but attenuate the GPS signal excessively (>85%). Therefore, a dielectric coating stack will be employed as a frequency-selective low emissivity coating optimized for thermal energy in the mid to long-wave infrared region of $\lambda > 4\mu m$. Two potential options exist for this coating: traditional oxide dielectric stacks and omni-directional dielectric mirrors similar to those proposed by MIT[3]. A conservative analysis predicts that total parasitic heat load can be kept to under 1 Watt at operational temperature and high-ambient conditions, potentially permitting the use of efficient and reliable tactical cryocoolers such as used in the military Standard Advanced Dewar Assembly (SADA) program. The GPS HTS antenna will be built to satisfy the military requirements for flight qualification. A selection criterion for the cryocooler is to be reliable to a minimum of 4000 hours mean time between failure (MTBF).

Further design challenges include vacuum integrity and electrical interconnections. Design and processing methods for long-life permanently evacuated dewars have been developed for military and commercial infrared sensor programs. While the processing requirements, material selection and mechanical design issues are quite rigorous, this technology has matured over the past ten years, and the design team has much first-hand experience. The interconnections present unique problems as the noise figure and insertion loss must be quite low, yet the interconnections bridge the gap between cryogenic and high military ambient temperature conditions, and between Ultra-High Vacuum (UHV) levels and the atmosphere. Complicating the problem is the need to minimize the parasitic heat load conducted along the length of any cabling scheme. Since the GPS antenna array includes a minimum of 7 interconnections, the heat load of each interconnection becomes a limitation on the thermal performance of the system. The very weak GPS signals do not permit sufficient performance margin for cabling-induced noise figure or insertion loss, both of which adversely impact system signal to noise ratio. The traditional approach is to use stainless steel jacketed, expanded Teflon® dielectric coaxial cabling. Unfortunately, the parasitic heat load is typically in excess of 0.200 Watts per cable, the space required is incompatible with a compact system (as much as 10 inches of cable length is required to minimize the thermal load to 0.200 Watts), and the materials exhibit high outgassing rates. This problem has been addressed with a new interconnection method designed by ICC and known as the Taylor Feed™. This technology permits a compact, low loss, vacuum compatible solution which exhibits low thermal load of approximately 0.025 Watts per connection. The vacuum feed-through for this system has been fielded over 75,000 times for up to 7 years with an in-field failure rate of 40 ppm.

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[2] R.T. Compton, Jr., "The Jammer Nulling Capability of Small Circular Adaptive Arrays," Compton Research, Inc., Technical Report 12-1, April 1998.

[3] Y. Fink et al, "A Dielectric Omnidirectional Reflector," Science, vol.282, pp.1679-1682, November 27, 1998

INSERTION ISSUES

It is important to look at the issues involved in integrating the GPS HTS antenna into an airborne platform. The GPS HTS antenna is half the area of a conventional adaptive antenna array. This is a large advantage on current space constrained platforms. The antenna will be conformal to the platform and thus will not induce drag by protruding into the air stream as the current antenna does. It is possible that the antenna will have a lower radar cross-section than conventional antennas, although resonances built into the elements and matching network complicate analysis. Integration with current adaptive antenna array electronics is expected to be straightforward. The GPS HTS antenna was designed with the current back-end electronics in mind. The antenna is designed to plug into the current electronics without modification.

The conformal mounting scheme may not be useful for all tactical aircraft. Some platforms may not have enough space between the skin and the frame to achieve installation. A study of the change in stress caused by cutting a hole in the skin must be done to determine accurately the problems involved with installing the antenna underneath the skin.

Another issue is the power consumption requirements. Most antennas are passive and have no need for power. The cryocooler must be powered for the GPS HTS antenna to operate. The specified maximum power consumption of the HTS antenna system is 200W.

The GPS HTS antenna provides the needed anti-jam capabilities using less area than conventional antenna arrays. The benefits of the GPS antenna to size constrained platforms, include smaller size, better performance and conformal installation. The plug and play design is transparent to the user and only requires 200W to function.

CONCLUSION

The GPS HTS antenna is an innovative system that incorporates unique design elements to make a small anti-jam GPS antenna. The HTS elements in the design are expected to maintain the high performance of a larger antenna, but at less than half the size. HTS is a maturing and increasingly common technology that will offer significant enhancements to the GPS reception in a high interference environment. The cryogenic packaging is challenging but well understood, with an experienced team performing analysis, design and testing.

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