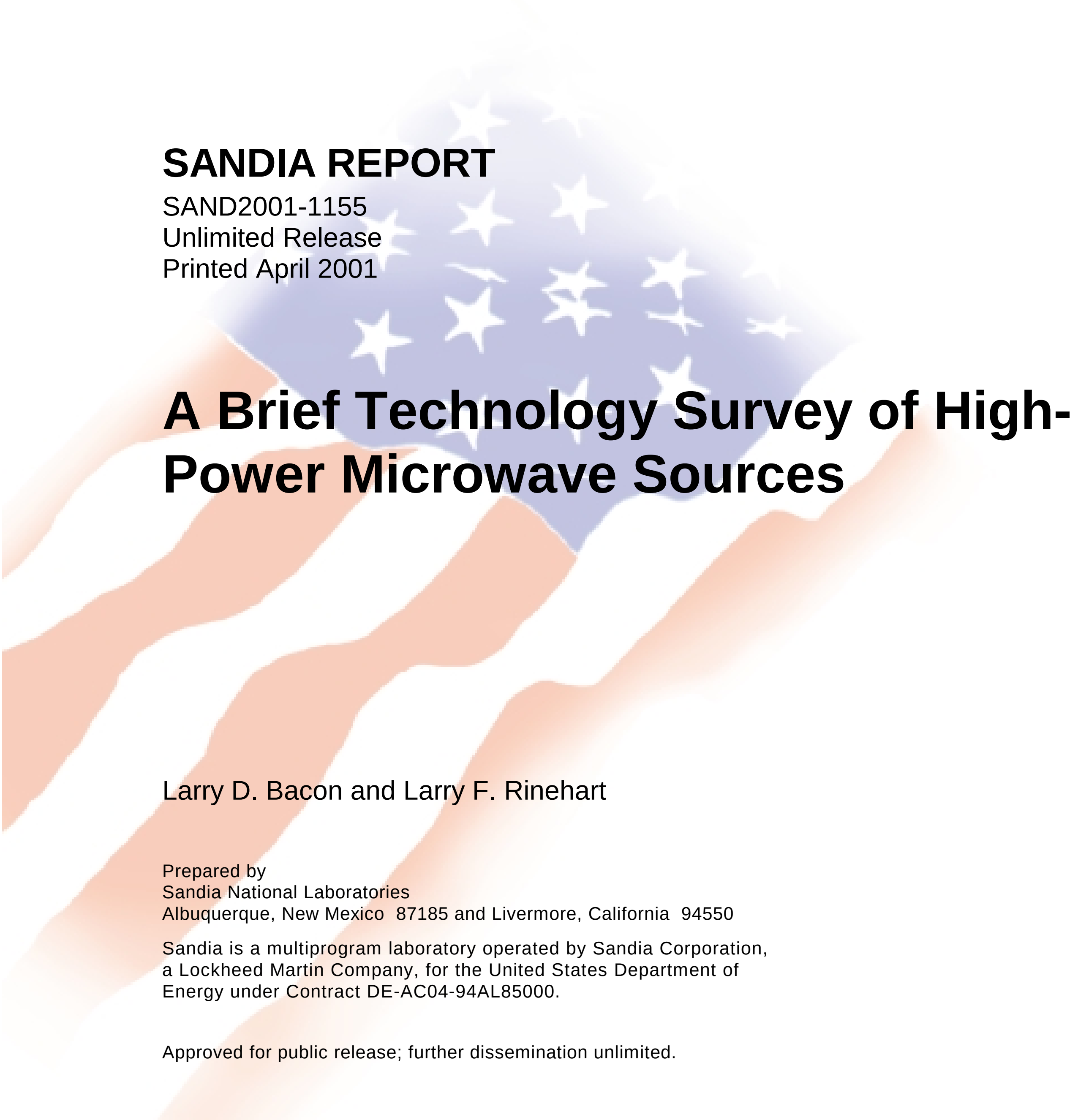

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A Brief Technology Survey of High-Power Microwave Sources

Larry D. Bacon and Larry F. Rinehart

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A BRIEF TECHNOLOGY SURVEY OF HIGH-POWER MICROWAVE SOURCES

Larry D. Bacon and Larry F. Rinehart

Prepared by
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A Brief Technology Survey of High-Power Microwave Sources

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Abstract

This report provides a brief summary of the characteristics of contemporary high-power microwave sources. The focus is on their physical and operational characteristics and regions of application rather than their theory of operation. Magnetrons, linear beam tubes, split-cavity oscillators, virtual cathode oscillators, gyrotrons, free-electron lasers, and orbitron microwave masers are described. Power supply requirements and engineering issues of the application of HPM devices are addressed.

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1.0 INTRODUCTION

The purpose of this report is to review briefly the major types of HPM sources. The focus will be on their physical and operational characteristics and regions of application rather than their theory of operation. Several books and journal review articles discuss the theory of operation of these sources in detail (for examples, see Granatstein and Alexeff 1987; Benford and Swegle 1992; and Taylor and Giri 1994).

Section 2 discusses general characteristics of the major types of HPM sources. Section 3 describes the power supplies needed for these sources, and Section 4 addresses some of the issues that must be dealt with in engineering these sources into militarily useful weapons. Section 5 lists references used in compiling this report.

2.0 GENERAL CHARACTERISTICS OF HPM SOURCES

All HPM sources have three basic components (Schlerer 1999, 475):

- Electrical or explosive prime power
- RF generator
- Antenna

In impulsive sources, the RF generator is implemented by charging the antenna, a transmission line, or a tuned circuit directly and causing them to ring for one or several cycles by closing a switch. Examples of this source type are the various ultrawideband (UWB) sources and the LC Oscillator (LCO).

In linear beam sources, the RF generator includes an electron beam generator, beam transport, and a wave structure. These sources work by converting the kinetic energy of an electron beam into the electromagnetic energy of the microwave beam. Examples of these sources include:

- Magnetrons
- Linear Beam Tubes (Klystrons, Backward Wave Oscillators, Travelling Wave Tubes)
- Split-Cavity Oscillators
- Virtual Cathode Oscillators
- Gyrotrons
- Free-Electron Lasers
- Orbitron Microwave Masers

The following sections will discuss these sources and their characteristics.

2.1 IMPULSIVE SOURCES

Impulsive sources convert energy from a power supply into a short pulse of electromagnetic radiation by storing electrical energy slowly (typically in a capacitance) and discharging it rapidly. Unlike the other sources discussed in this report, they do not utilize electron beams to generate their electromagnetic energy. These sources are sometimes known as Wideband or UltraWideband (UWB) sources, since their bandwidth is typically a large fraction of their center frequency. The specifications for three impulsive sources built at Sandia follow. A more complete description of their characteristics and performance may be found in Rinehart et al. (1994).

SNIPER (Sub-Nanosecond ImPulsE Radiator) runs at 290 kV at greater than 1 kHz pulse repetition rate. The peak power in the 3.5 ns wide pulse is 1.25 GW. The risetime is approximately 140 ps, which leads to good spectral content from 100 MHz to 1.2 GHz. The radiated field strength normalized to a distance of 1 meter is 120 kV/m,using a TEM horn.

EMBL (EnantioMorphic BLumlein, ie., mirror-image Blumlein) runs at 750 kV at a power supply limited 700 Hz pulse repetition rate. The peak power in the 3.5 ns wide pulse is 11 GW. The risetime is less than 200 ps. EMBL radiates a 285 ps impulse with an abrupt aperture (differentiating) TEM horn antenna. Its spectral content extends from .2 - 1.2 GHz, with the peak at 800 MHz. The radiated field strength normalized to a distance of 1 meter is 350 kV/m.

Several L-C Oscillators (LCOs) have been built at Sandia in frequency bands from HF to UHF. One example had a 700 MHz center frequency and a 50 MHz 3 dB bandwidth. It was capable of 10’s of minutes of run time at greater than a 1 kHz repetition rate. The radiated field strength from a 26 dBi dish antenna normalized to a distance of 1 meter is more than 400 kV/m.

The highest peak power device built at Sandia is a bipolar TLO (transmission line oscillator) operating at 1.4 MV. The center frequency is approximately 50 MHz. The peak power is 20 GW peak, single-shot. The radiated field strength of all these sources is corona-loss limited. No attempt was made to miniaturize or ruggedize these sources, although they were rugged and transportable enough for field testing. Switch recovery and efficiency are a limiting factor to repetition rate.

2.2 MAGNETRONS

HPM magnetrons are basically relativistic, cold cathode versions of their conventional counterparts. They are characterized by relatively high efficiency, low power densities internal to the tube, robust operation, and compact size. Their modulators and power supplies are simple and inexpensive compared to linear beam tubes (English 1991, 72; Granatstein and Alexeff 1987, 351). Relativistic magnetrons have achieved efficiencies of 10-30% in the bands from 0.5 to 10 GHz at power levels of about 5 gigawatts (Florig

1988, 52). Pulse widths are typically on the order of 100 ns or less, limited by plasma closure of the anode-cathode gap.

Magnetrons may be phase locked for higher output power. Varian, Ratheon, and English Electric Valve have reported on the injection-locking of conventional magnetrons (Hoeberling and Fazio 1992, 256). In conventional magnetron phase-locking, fractional bandwidths of up to 2% at gains of 10 to 13 dB per locked stage have been achieved. Gain, bandwidth, and system complexity are the tradeoffs involved. They do not, however, achieve the gain of klystrons nor the gain-bandwidth product of TWTs (English 1991, 67). Sze, et al. (1992) describe successful phase-locking experiments on strongly coupled relativistic magnetrons.

A magnetron that uses the magnetic field of the beam current itself to provide the required magnetic insulation between the cathode and anode has been developed (Clark, Marder, and Bacon 1988; Benford and Swegle 1992). The Magnetically Insulated Line Oscillator (MILO) eliminates the need for pulsed magnets and their power supplies in this way–a significant advantage. The efficiency tends to be fairly low.

2.3 LINEAR BEAM TUBES

HPM linear beam tubes, such as backward wave oscillators (BWOs), travelling wave tubes (TWTs), and relativistic klystron amplifiers (RKAs), are also very similar in concept to their conventional counterparts. The main differences lie in the techniques of beam formation, the use of pulsed, large magnitude axial magnetic fields for beam transport, and the application of relativistic voltages and very high beam currents.

BWO efficiencies as high as 35% have been reported at moderate power levels, but as power levels were increased, the outputs saturated and spectra broadened. These effects were probably due to beam breakup and turbulence. To maintain high beam quality, large magnetic fields are required for high-power operation. An approximately 25 to 50 kG applied axial field implies that mechanically strong solenoidal magnets–with pulsed capacitor banks to drive them–are required (Granatstein and Alexeff 1987, 41, 43).

TWTs can be made with many of the same techniques as BWOs. The difference is that the beam-wave interaction is with a forward wave. Consequently, they have many of the same issues and limitations (Granatstein and Alexeff 1987, 44). RKAs use cavities for beam bunching and power extraction rather than the continuous slow wave structures of BWOs and TWTs. Some use extended structures for power extraction to reduce the power densities and to increase efficiency.

Two different approaches have been taken to extending the performance of klystrons into the HPM regime (Benford and Swegle 1992, 340). The first concentrates on developing high average power, low beam current devices for continuous, repetitively pulsed applications such as the Stanford Linear Accelerator (SLAC). SLAC has developed the technology in their 2.856 GHz klystrons to the 67 MW, 3.5 μs, 180 Hz repetition rate level. These tubes operate at 350 kV. The tube can be operated at 100 MW for 1 μs, at 48% efficiency and 415 kV. The beam currents in these tubes are at the several hundred ampere level.

The second approach uses high beam currents where space charge forces become dominant in the bunching process. Tubes have been developed at the 10 GW power level (Benford and Swegle 1992, 398). They used 0.5 to 1 MeV beams guided by axial magnetic fields of about 10 kG. The reported efficiencies were on the order of 50%.

Both types of RKAs are narrowband devices. The low-current devices appear to be approaching technological limits to increasing their performance. The high-current tubes are encountering issues of beam transport, beam loading of the cavities, base pressure of the vacuum system, xray production, and beam breakup. The combination of xrays and the high base pressures of pulsed power sources has led to breakdowns in the cavities and unstable beam propagation. So far, these issues have made repetitive operation impractical (Benford and Swegle 1992).

2.4 SPLIT-CAVITY OSCILLATORS

The Split-Cavity Oscillator (SCO), which utilizes transit-time bunching of the beam to generate microwave energy, has been investigated by Marder, Clark and coworkers (Marder et al. 1992). Power output is moderate; Pulses in the range of 100 MW for durations on the order of 100 ns have been achieved. Because no magnetic field is required and low beam quality consistent with simple pulse power sources is adequate, the SCO can be very compact. An entire system including power supply and mode converting antenna has been built on a roll-around laboratory cart. Multiple SCOs have been injection locked (Bacon et al. 1991).

2.5 VIRTUAL CATHODE OSCILLATORS

Unlike the tubes discussed earlier, Virtual Cathode Oscillators (VCOs or vircators) operate because of a phenomenon of intense beam physics. They have no conventional counterpart. Their general characteristics are operating frequencies in the range from 300 MHz to 40 GHz, simple construction, no magnetic field required (although they are sometimes used), broadband/tunable frequency, and very low efficiency (Schleher 1999, 484; Hoeberling and Fazio 1992, 252). Examples of reported performance are 200 MW at 450 MHz and 0.4% efficiency; 3.3 GW at 2.15 GHz and 10% efficiency; and 8.5 GW in the band 0.5–2 GHz. 850 J in a single pulse has been reported. Efficiencies are typically 1 to 3%. Best cases reported are in the 8 to 10% range. Operation is typically in a TM mode in a cylindrical geometry, making mode conversion necessary for efficient radiation.

The frequency of oscillation of a free-running vircator is related to the relativistic beam plasma frequency and typically chirps upward significantly during the pulse. Its frequency can be stabilized by employing a resonant cavity to contain the oscillating beam. If the resonant cavity is driven by an external source, the vircator can be made to lock to the external signal. Phase locking and amplification at high powers with approximately 4.5 dB (2.8 X) gain have been observed (Hoeberling and Fazio 1992, 256).

Although its simplicity is a major advantage, its very low efficiency is a real problem for reasonable weaponization. They have been used as a suite of sources for testing, where efficiency is not such an issue (Miner et al. 1992, 231, Tables I and II). Plasma closure effects limit pulse length and the ability to repetitively pulse–as is the case for most if not all HPM sources.

The tubes that have been discussed so far, with minor exceptions, have operated in the cm wavelength range, with the major focus in the 1 to 10 GHz (30 to 3 cm) regime. The following tubes, gyrotrons, free-electron lasers, and orbitron microwave masers, continue upward in frequency into the millimeter and sub-millimeter bands.

2.6 GYROTRONS

The basic idea of gyrotrons and free-electron lasers is to amplify or generate coherent electromagnetic radiation by radiative emission from a relativistic electron beam. Electrons are accelerated and oscillate transverse to the direction of beam propagation due to interaction with an externally applied force (Granatstein and Alexeff 1987, 11). The externally applied force for a gyrotron is the rotational velocity component of the beam interacting with an applied axial magnetic field. In the basic gyrotron, this interaction takes place in a cylindrical cavity. There are other forms that are related structurally to other tube types and that are known as the gyro-TWT, the gyro-BWO, the cyclotron autoresonance maser (CARM), which is analogous to the free-electron maser, and the gyroklystron (Benford and Swegle 1992, 261).

Gyrotrons operate in the mm-wave band, nominally 30 to 300 GHz. They are narrow in bandwidth, and capable of CW operation at high power. Pulsed peak powers of greater than 7 GW have been reported. Like the linear beam tubes, they are driven by a high energy electron beam–which implies a bulky accelerator. A high quality, monoenergetic beam is required. Frequency is determined in part by the amplitude of the axial magnetic field. High frequencies require large fields. Theoretical efficiencies are very high–on the order of 70 to 90%. Experimentally achieved efficiencies of 30% are typical (Granatstein and Alexeff 1987, 13; Schleher 1999, 484; Florig 1988, 52; Benford and Swegle 1992).

2.7 FREE-ELECTRON LASERS

The original free-electron lasers (FELs) were developed in the 1950’s and were referred to as ubitrons. Like gyrotrons, free-electron lasers operate in the mm-wave regime. The external force that causes transverse acceleration of the beam is typically alternating, transverse magnetic field lines known as the wiggler field. FEL beam quality requirements are similar to those of the gyrotron. Thus, they use high-quality relativistic beams as produced by accelerators. Linear accelerators, microtrons, and electrostatic accelerators have all been used in the low beam density, high beam voltage (Compton) operating regime. Induction accelerators are used in the high-beam density, lower voltage (Raman) regime (Granatstein and Alexeff 1987, 19).

The FEL may be continuously tuned by changing the beam energy. Radiation in the far IR is produced by 1-2 MV beams. Beams of 10 to 1000 MeV produce radiation in the IR to UV range. Peak powers of greater than 1 GW have been reported. The intrinsic efficiency of a free-electron laser is very low. In the Compton regime it is a fraction of a percent; in the Raman regime it is a few percent. Tapered undulators (wigglers) produce reasonably high efficiency. Forty percent has been reported.

2.8 ORBITRON MICROWAVE MASERS

The final tube type to be discussed is the orbitron microwave maser. This device produces power in the millimeter to sub-millimeter regions–TeraHertz (1000 GHz) radiation has been reported at the 1 W power level. They may serve to bridge the gap between microwave tubes and lasers. Their advantages are that they require neither high magnetic fields nor relativistic electrons. More recent literature needs to be checked to determine whether high-power, as well as high frequency, operation has been achieved (Granatstein and Alexeff 1987).

3.0 POWER SUPPLIES FOR HPM SOURCES

Power supplies have been mentioned only briefly in the discussion of source types above. Yet the HPM tube is typically a small fraction of the size and weight of an HPM weapon system design. The bulk of the device lies in its power-generating and conditioning equipment (Florig 1988, 53). In 1988, Florig gave a rough power supply size scaling for two classes of sources. For the 0.5 to 2 MJ/pulse class, he estimated the volume at 3 to 10 cubic meters. For the 5 to 20 MJ/pulse class, he estimated the volume at 30 to 100 cubic meters. Although he was discussing Star Wars class sources which have never been built, and although the largest reported single pulse energy of the sources discussed above is on the order of 1 kJ, or 0.001 MJ/pulse, it would not be reasonable to reduce his 3 cu. m by a factor of 500 to get 0.006 cu m (0.22 cu ft.). The actual power supply that drove the 1 kJ RKA was much larger. Much higher energy densities can be achieved in explosive sources, but they are limited, of course, to single shot operation, and the beam quality achievable by such a source would not drive a linear beam tube like the RKA without additional bulky power conditioning equipment.

4.0 HPM SOURCE ISSUES

Several issues must be dealt with before HPM sources can be taken out of the laboratories and weaponized. They include compactness, efficiency, antenna size, and peak versus average powers. In addition, the supporting technologies of tracking, aiming, and damage assessment must be developed.

4.1 COMPACTNESS

Compactness is a general problem of military applications of HPM sources. (Benford and Swegle 1992, 19) The *size* of a particular HPM technology is often not apparent from a book or technical article describing only the tube. It is an HPM weapon *system* that must be fielded, not just a tube. The system includes the prime power source, power conditioning, microwave energy transport to the antenna, and the antenna. High powers, whether peak or average, drive up the size and weight of the system.

4.2 EFFICIENCY

Efficiency has a major impact on compactness as well. The prime power requirements of an inefficient source rapidly outpace the capabilities of even large platforms. The efficiency of most HPM sources depends strongly on beam quality (Granatstein and Alexeff 1987, 6). This places constraints on beam transport, acceleration, current levels achievable for a given turbulence, etc. A balancing factor is that high beam quality itself requires fairly complex systems, which drives up the size and weight.

4.3 ANTENNA SIZE

High power density on target at significant ranges requires both high powers and high directivity in the antenna. High directivity requires an antenna many wavelengths in size. Maneuverability requirements, survivability under fire, drag, visual signature, etc. make room for large antennas very difficult to find on any platform. In addition, increasing the power passing through a fixed antenna aperture increases the probability of electrical breakdown, especially at high altitudes or in a dusty environment.

4.4 PEAK VERSUS AVERAGE POWER

HPM sources have typically been designed to provide high peak powers, but not high average power. (An exception to this is the SLAC klystron.) They are limited in their average power output by power conditioning performance (mainly switching performance at high energy per shot), vacuum under repetitively pulsed conditions, cooling, and materials. In many of the sources, wave circuits–ie slow-wave structures or cavities–are used to achieve wave-particle resonance, to control modes, and to match the wave to the beam parameters. They are often a limiting factor in power handling due to breakdown, heat dissipation, and spurious mode generation (Granatstein and Alexeff 1987, 5). Cooling is directly related to this issue. The active heat load for these devices is limited to several kW/cm^2 (Granatstein and Alexeff 1987, 27). This creates, of course, an average power/volume constraint. Magnetrons, linear beam tubes, and vircators operate at high peak powers below about 10 GHz. Cavity dimensions and frequency are inversely related. High frequencies, then, mean smaller cavity dimensions, higher power densities, and lower breakdown levels, even for single shot operation. To an extent, gyrotrons and free electron lasers, like optical lasers, avoid this issue because the dimensions of their interaction regions are much larger than the wavelength being produced (Benford and Swegle 1992, 394).

The high peak powers of many of these sources require field gradients on the order of megavolts per centimeter. High field gradients cause surface emission and the formation of surface plasmas. Closure of gaps by these plasmas detune the tubes and truncate individual pulses. High current densities lead to bipolar space-charge limited flow, where the anode emits positive ions. At still higher current densities, they create anode spots that produce microparticles–neutral droplets of metal–that coat the diode and lead to gap closure and breakdown (Gray and Rinehart 1985). Sonic velocities limit the ability of the vacuum systems to re-establish the base vacuum levels for the next shot, limiting the achievable repetition rate and average power. At high repetition rates, cathode materials and diode foils, if used, burn out (Granatstein and Alexeff 1987, 39, 26; Agee 1998).

4.5 SUPPORTING TECHNOLOGIES

A key supporting technology for HPM source development has been modeling and simulation. The goal of modeling and simulation is to produce a correct design that meets the design specifications by iterating the design in software, not in expensive and time consuming hardware iterations. Antonsen et al. (1999) discusses the current state of the art and future directions of modeling and simulation in vacuum power tube development.

Some other important supporting technologies for an HPM weapon system are target tracking and aiming equipment and methods of damage assessment. Target tracking and aiming for HPM weapons is, in one sense, easier than for lasers because the beam width and spot size are so much larger. On the other hand, since one advantage of the microwave region is its ability to penetrate smoke, clouds, and fog, target tracking may have to depend on radar imaging techniques. Aiming can be difficult mechanically due to the size of high gain antennas. Electronic beam steering would depend on accurate phase control of multiple HPM sources. Damage assessment is perhaps the most difficult supporting technology of all to develop. Since HPM weapons usually depend on electronic kill or upset, there is no “smoking hole” as an observable.

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