Reminiscences of High-Power Electromagnetics

Carl E. Baum, *Life Fellow, IEEE*

(Invited Paper)

***Abstract*—In the beginning of 1960s, serious attention was paid to the nuclear electromagnetic pulse. This was later extended to conventional high-power electromagnetic sources/antennas. This paper reviews the history in which I played a central part, discussing the major programs, events, and players. The IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY (EMC) was one of the major fora for bringing this technology to the more general scientific/engineering EMC community.**

I. INTRODUCTION

WHEN asked by the Editor to prepare a review paper for this Special Issue for the 50th anniversary of the IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY (EMC) I had to think over the history of what we loosely call high-power electromagnetics. This begins in the 1960s and extends to the present. The history is almost, but not quite, as long as that of the Transactions. Of course, this depends on how one defines the beginning, since the early evidence of the nuclear electromagnetic pulse (EMP) goes back to World War II. However, serious attention began to be paid to this in the 1960s, and, coincidentally, this is when I became involved in 1963.

Before I begin the story, I should list for the reader the major references that document much of the history where one can find many more references than I shall include here. Here [1]–[13] are included for their references and historical significance. From [6], I include a table of important events, updated to the present as Tables I–III.

II. EMP

Our story begins with EMP. There was a very important (and expensive) program during the Cold War. Emphasis was placed on strategic systems: missiles, aircraft, and communications. As such, the emphasis was placed on the effects of a high-altitude burst, since the fields could cover the continental U.S. Even a small chance that the strategic forces could be made largely inoperable was unacceptable. However, some attention was paid to the surface-burst EMP in the case of hardened buried facilities.

The leading roles in this program were initially played by Los Alamos Scientific Laboratory (LASL; C. L. Longmire, R. Partridge, J. Malik *et al.*), RAND Corporation (W. J. Karzas, R. Latter *et al.*), and the Air Force Weapons Laboratory (W. D. Henderson, W. R. Graham, C. E. Baum, J. Darrah, D. Dowler *et al.*), working in close cooperation with each other. From the beginning, as an outgrowth of the Manhattan Project, the British (S. Abercrombie, D. Dracott *et al.*) were heavily involved in both nuclear-test measurements and theoretical calculations of the EMP environment. (I participated in numerous meetings with them in both the U.S. and U.K., beginning in the 1960s.) As time went on, the Defense Atomic Support Agency (P. Haas *et al.*) became significantly involved.

A. Beginnings

As Table I indicates, there was some expectation of some kind of electromagnetic pulse from the first nuclear detonation. In the 1950s, it was noticed that there were instrumentation failures, which were attributed to EMP (the British calling this "radioflash"). This instigated an investigation into the phenomenon. The Compton current density was quickly recognized as the source, but detailed and reliable calculations of the fields were unavailable, leading to some measurement problems during the above-ground nuclear tests. It was established, however, that the fields could be quite large.

Recognizing the potential strategic importance of the high-altitude EMP (HEMP), some important papers were produced. Most notable were those of Karzas and Latter [14] and Longmire. I arrived at the Air Force Weapons Laboratory in June 1963 as my first Air Force assignment after my Master's degree at Caltech (sponsored by the Air Force). Conrad Longmire gave a series of classified lectures to us. One of my first jobs was to proofread the written versions. Much of this material was later published [1, pp. 3–13], [2, pp. 3–13], but I wish that the original papers would be declassified for the historical record. Around the same time, models were also developed for air bursts and surface bursts, and large numerical computer codes were constructed. The Soviets were also working on this problem, and negotiations were undertaken in connection with the above-ground nuclear test treaty (last such test was in 1962). (EMP was one mechanism to detect nuclear explosions.) This had to be discussed with the Soviets, and if we were to tell them, we might as well tell everybody.

B. Electromagnetic Sensors

Part of the problem with the measurements was the lack of adequate sensors to measure the electromagnetic fields, particularly in the nuclear source region with gamma rays, neutrons, and nonlinear air conductivity. So, I was asked to investigate this. This led to a series of papers in the Sensor and Simulation Notes [13] and later to the review paper in [1, pp. 22–35], [2, pp. 22-35] (with many photographs). Yet, later this was summarized in a book chapter [15]. It should be noted that Ralph Partridge of LASL started the Sensor and Simulation Notes in

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The author is with the Department of Electrical and Computer Engineering, University of New Mexico, Albuquerque, NM 87131 USA (e-mail: cebaum@ece.unm.edu).

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TABLE I
IMPORTANT EVENTS IN THE HISTORY OF EMP

1945	TRINITY EVENT; electronic equipment shielded reportedly because of Fermi's expectations of EM signals from a nuclear burst.
1951	C. H. Papas of LASL proposes prompt gamma-produced Compton currents as sources of EMP.
1951—1952	First deliverate EMP observations made by Shuster, Cowan, and Reines.
1951—1953	First British atomic tests; instrumentation failures attributed to "radioflash."
1957	Bethe makes estimate of high-altitude EMP signals using electric dipole model (early-time peak incorrect).
1957	Haas makes magnetic field measurements for PLOMBBOB test series (interest in EMP possibly setting off magnetic mines).
1958	Joint British/U.S. meeting begins discussions of system EMP vulnerability and hardness issues.
1958	Kampaneets (USSR) publishes open literature paper on EMP from atomic explosion.
1959	Pomham and Taylor of the U.K. present a theory of "radioflash".
1959	First interest in EMP coupling to underground cables of Minuteman missile.
1962	FISHBOWL high-altitude tests; EMP measurements driven off scale; first-indications of the magnitude of high-altitude EMP signal.
1962	SMALL BOY ground burst EMP test.
1962	Karzas and Latter publish two open literature papers on using EMP signals for detections of nuclear tests; bomb case EMP and hydromagnetic EMP considered.
1963	Open literature calls for EMP hardening of military systems begin to appear.
1963—1964	First EMP system tests carried out by Air Force Weapons Laboratory (AFWL) (now Air Force Research Laboratory, Directed Energy Directorate)
1963—1964	Longmire gives a series of EMP lectures at AFWL; presents detailed theory of ground burst EMP and shows that the peak of the high-altitude EMP signals is explained by magnetic field turning (magnetic dipole signal).
1964	First note in the LASL/AFWL EMP notes series published.
1965	Karzas and Latter publish first open literature paper giving high-frequency approximation for the high-altitude magnetic dipole signal.
1967	Construction of ALECS as the first guided-wave simulator is completed for EMP simulation on missiles.
1967	AJAX underground nuclear test.
1969	Close-in EMP mechanisms recognized and evaluated by Graham and Schaefer.
1970	EMP underground test feasibility recognized and preliminary design presented by Schaefer.
1973	First joint nuclear EMP meeting at AFWL.
1974	MING BLADE underground EMP test for confirmation of near surface burst EMP models.
1975	DINING CAR underground EMP test as the first system hardware EMP test.
1975	MIGHTY EPIC underground EMP test.

1964. Seeing that I was writing most of the Notes, he suggested that I should be the Editor, and the rest (as they say) is history.

This was a very difficult problem in the case of the nuclear source region. This led to the parallel mesh dipole (PMD) for the electric field, cylindrical moebius loop (CML) for magnetic field, and outside mutual inductance (OML) for currents in pipe-like structures. While I did the basic designs, people at EG&G, Inc. (G. Sower *et al.*) were busy building them for use on underground nuclear tests.

This brings us to the underground nuclear test program. I participated in various such tests (Table I). I crawled around in tunnels and suited up in radiation protection gear for reentry. On one notable occasion (ALVA), I was the last man out before the arming team went in. When my DoD pickup truck reached the perimeter guard, the radiator hose failed, enveloping the guard in a steamy mist. While underground tests could not replicate the full geometry of surface or high-altitude EMP, they were very valuable in understanding the physics of the EMP source region.

Besides the source region, sensors were developed for EMP in more benign environments such as in EMP simulators. They were designed for fast and accurate (calibratable by a ruler) measurements. The most important designs were the asymptotic conical dipole (ACD) for electric fields, and multigap loop (MGL) for magnetic fields. These are still manufactured by a local company (ProDyne). They are used both in the U.S. and Europe. Currently, they are used for measuring the response of various high-power electromagnetic radiators (to be discussed later). Not only were sensors developed for the electromagnetic fields, but for the voltages and currents produced in the electronic systems under test.

C. EMP Simulators and EMP Testing

Also back in the 1960s, a program of EMP testing was begun. For this purpose, we needed EMP simulators, things which could produce EMP-like fields over the system under test. For aircraft and missiles (and some ground-based facilities), this turned out to be possible. So, one day Lt. W. R. Graham (later President Reagan's Science Advisor) walked into my office and encouraged me to take up the task (as if I did not have enough to do with the sensors). For a summary, see [1, pp. 35–53], [2, pp. 35–53], and [6, Sec. IV] (with many photographs).

In 1964, we started reconfiguring ALECS (originally intended for instrumentation calibration and checkout (SSN 1) [13] for testing missiles such as Minuteman. I started calculating (SSN 21), and a MegaVolt pulser was designed to drive the simulator with sufficient fields and risetime. It was immediately recognized that a larger facility (ARES) was needed. So at a meeting with J Darrah, W. J. Karzas, and W. R. Graham it was decided

TABLE II
IMPORTANT EVENTS IN THE HISTORY OF HPE (PART 1)

1976	*Transient Electromagnetic Fields* book (L. B. Felsen (Ed.)), and Proceedings of the IEEE review paper on same subject (C. E. Baum) (includes first reviews on singularity expansion method (SEM)).
1978	Special Joint Issue on the Nuclear Electromagnetic Pulse, IEEE Transactions on Antennas and Propagation and IEEE Transactions on Electromagnetic Compatibility [1].
1978	First public Nuclear EMP meeting (NEM) followed by NEMs in even numbered years.
1978	Lightning-channel physics and direct-strike interaction program begins at Langmuir Observatory, NM, involving N.M. Tech, AFWL, AF Flight Dynamics Lab, and French.
1979	Major EMP simulators beginning with SIEM II (in France) are constructed in Europe.
1980	ATLAS I EMP simulator completed (for large aircraft on wooden trestle test stand).
1980	*EMP Interaction* book (K.S.H. Lee (ed.)), first published by AFWL [3].
1980	Lightning strikes to NASA F-106 begun, later joined by CV-580 and French Transall.
1981	Special Issue on the Singularity Expansion Method, Electromagnetics.
1981	Formation of URSI Commission E International Working Group: Scientific Basis for Noise and Interference Control (C.E. Baum, Chairman)
1982	Special Issue on Lightning and Its Interaction with Aircraft, IEEE Transactions on Electromagnetic Compatibility.
1983	First EMP Interaction and Hardening (EMP 201) short courst (Socorro, NM).
1984	URSI statement: Nuclear electromagnetic pulse (EMP) and associated effects (concerned with civil communications and electrical power).
1985	(First) Special Issue on High-Power Microwave Generation, IEEE Transactions on Plasma Science.
1986	Special Issue on Electromagnetic Topology of Large Systems, Electromagnetics.
1987	Public HEMP waveforms (C. L. Longmire *et al.*).
1987	First High-Power Electromagnetic Special Session, National Radio Science Meeting (USNC/URSI).
1987	*High-Power Microwave Sources* book (V. L. Granatstein and I. Alexeff (Eds.)).
1988	EMPRESS II EMP simulator completed (on ocean-going barge for testing ships).
1990	*Lightning Electromagnetics* book (R. L. Gardner (Ed.)).
1990	Formation of URSI Commission E International Working Group: High-Power Electromagnetics (R. L. Gardner, Chairman).

TABLE III
IMPORTANT EVENTS IN THE HISTORY OF HPE (PART 2)

1992	C. E. Baum, Invited review paper in Proc. IEEE updating the EMP Special Issue.
1992	Special Issue on High-Power Microwaves, IEEE Trans. EMC [7].
1993	EMP Workshop given by Americans in Beijing, China.
1993	IEC (International Electrotechnical Commission) issues first in a series of EMP (and HPE) standards: IEC 61,000-2-9 Immunity to High-Altitude Nuclear Electromagnetic Pulse: Description of HEMP Environment.
1994	The NEM conference broadens to include European locations, first in Bordeaux, France, renamed EUROEM (and AMEREM when in America).
1995—1996	Visit of Americans and other Westerners to Russian EMP simulators in St. Petersburg and Moscow (and later to Kharkov, Ukraine).
1996	AMEREM 1996 (and subsequent) incorporates Ultra-Wideband, Short-Pulse Electromagnetics (3rd conference, formerly sponsored by Polytechnic University, Brooklyn, New York), and Unexploded Ordnance Detection and Range Remediation (3rd conference).
1996	Russian participation in AMEREM 1996, visit to Kirtland AFB and facilities, and induction of several Russians into EMP Fellows.
1999	*Detection and Identification of Visually Obscured Targets* book (C. E. Baum, Ed.)
2004	Special Issue on High-Power Electromagnetics (HPEM) and Intentional Electromagnetic Interference (IEMI).
2004	Report commissioned by U. S. Congress concerning EMP in current context (including terrorism).
2007	The present paper.

that I should come up with a design. This has tested many strategic missiles (including Navy and British), but is no longer in existence after the Cold War. Much was learned from these tests, and necessary corrective measures were taken.

Concerning aircraft, the smaller ones could use those designed for missiles in flight. However, larger ones (bombers, communications aircraft) needed special simulators, both for in-flight conditions and when parked on the ground. This resulted in three new simulators on Kirtland AFB. The largest of these (∼400 m long) was the ATLAS I (Fig. 1) with the large wooden trestle test stand [possibly the largest (by volume) wooden structure in the world]. In my original paper (SSN 82, 1969) [13], I conceived of this by analogy to the wooden trestles used by the transcontinental railroad as it passed through the

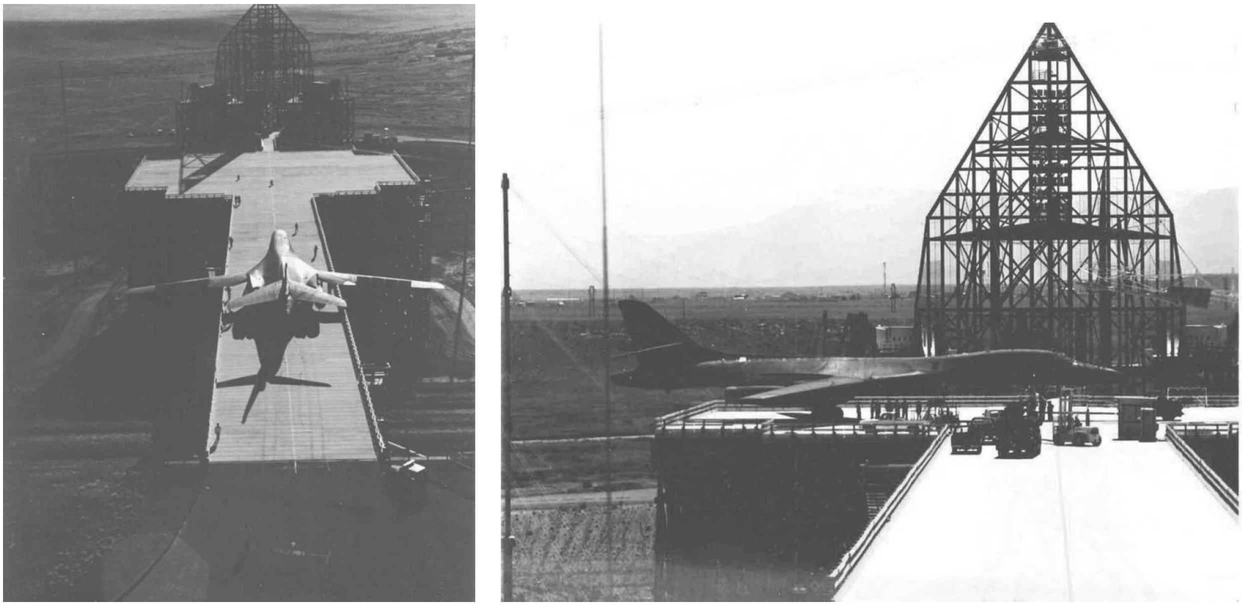

Fig. 1. ATLAS I HEMP simulator for testing large aircraft. Note the enormous wooden trestle test stand.

Rocky Mountains. Instead of lifting the aircraft from the ground (for in-flight, and horizontal polarization) we let the ground fall away from the aircraft by extending the trestle out over Tijeras Arroyo. These simulators tested not only the Air Force planes, but Navy and European planes as well.

Not only were such simulators built on Kirtland AFB, but some were built for the Navy based on these designs. The most interesting one was the EMPRESS II (now decommissioned), which was built on a metal barge and towed out on the ocean for testing ships (to vertical polarization). Many HEMP simulators were also built in Western Europe, with Britain, France, Germany, The Netherlands, Sweden, Switzerland, and Italy being the major ones. Besides my own involvement, great credit is due to D. V. Giri (my alter ego) for many of the detailed calculations, and working with the U.S. pulser manufacturers.

While HEMP was the most important case to be simulated, some attention was paid to the surface-burst case, particularly for missile silos. Even while finishing my Ph.D. study at Caltech in one year (1967–1968), arrangements were made so that I (an Air Force Captain) could travel on military orders to various events around the country. On one occasion, I had been working on a SIEGE I simulator on a missile site in Montana, and traveled from there to a contractor EG&G in Bedford, MA, when a call came in from my boss at AFIT (Air Force Institute of Technology, Wright-Patterson AFB, OH), who asked what I was doing in Massachusetts since he thought I was in California. (Some people never get the word.) And, by the way, he heard that I was finishing up my Ph.D. (about one year early). I said that if and when I passed my thesis defense, he would be the first to know. People at the Air Force Laboratory were already circumventing the bureaucracy to have me reassigned there.

While EMP simulators are essential for EMP testing (in the absence of surface and exoatmospheric nuclear detonations), the story does not end there. In 1992, at the invitation of the IEEE PROCEEDINGS Editorial Board, I published a paper [6], the intent of which was to update the EMP Special Issue. As a part of that (Section VI) I addressed the difficult question of system testing/assessment to which the reader is referred. This was much more difficult and expensive than the simulators. Much was learnt, but unfortunately, I cannot go into detail on real cases. Of course, this led to hardening of various systems.

D. EMP Interaction With Complex Systems

While we were obtaining experimental data on the EMP response of real systems, we wanted to mathematically model the penetration of the electromagnetic fields, whether analytically or numerically. In 1974 [16], I proposed the concept of electromagnetic topology for decomposing the system into smaller parts, which could be separately analyzed. These could be later combined into a large supermatrix scattering equation, the BLT (Baum, Liu, Tesche, or bacon, lettuce, tomato) equation [3], [17], [18]. This has been successfully applied up to approximately 500 MHz on various systems, and has generated a large amount of literature [11, pp. 353–367 (including references)]. Work is continuing on this in both the U.S. and Europe. It is especially important for the more general EMC community.

In the 1970s, with significant EMP funding, we were able to sponsor a large theoretical research program on EMP interaction and simulation. This included a large number of universities and companies. At the time it was one of the major funding source for research in electromagnetic theory. I can remember traveling around the country with Fred Tesche, then of Dikewood (later part of ITT), monitoring all these efforts. We organized a series of conferences, the FULMEN (forum for understanding the latest methods in the EMP Notes) meetings, to better coordinate all these efforts. This eventually resulted in a book [3]. It was quite a busy time.

Perhaps, the largest impact on the electromagnetic-theory community was the singularity expansion method (SEM) that I proposed in 1971 [19]–[22]. This revolutionized our understanding of the transient electromagnetic response of structures and systems. It started an explosion of research papers and resulted in various awards (for me and others). Conveniently, the poles in the complex-frequency(s) plane gave expressions that were equally simple in both frequency and time domains (particularly for late times). While the initial motivation was the understanding of EMP response, its implication for radar target identification based on the aspect-independent pole locations in the s plane [23] was immediately apparent to many people, including myself. It even has application to buried targets [mines, unexploded ordnance (UXO)] identification [24], [25].

E. EMP Goes Public

As the EMP program developed, many of us thought that at least a part of the technology should be made public. This was at least in part due to the view that the technology was primarily defensive in nature (offensive use being unreliable and hard to predict). We were concerned that there be no Achilles heel in the strategic forces, and we thought that it was desirable that the Soviets be aware of our efforts.

So in 1978, two important events occurred. I organized the first nuclear EMP meeting (NEM) in Albuquerque, NM, with support from SUMMA Foundation, of which I am the President. This brought together scientists/engineers from the U.S. and Western Europe. We were allowed to present parts of the technology, except for effects on real military systems, and (of course) nuclear weapons information. This has continued up to this day in the AMEREM/EUROEM conferences.

The second event was the EMP Special Issue. This was the idea of Tetsu Morita of SRI, a member of the AdCom of the IEEE Antennas and Propagation Society. When Dick Schulz, the then Editor of IEEE TRANSACTIONS ON EMC, heard of this he wanted the Special Issue to be published also in the EMC Transactions. Thereby, this Special Issue was published as the first issue of 1978 in both the Transactions with identical pagination. This established the fundamental aspects of EMP technology for the world to see.

Beginning in 1983, we established the week-long short course, EMP interaction and hardening (EMP 201), with myself as Course Director. This was held eight times around the world, including the U.S., Western Europe, Israel, and India. After a hiatus, the short course was revised in 1993 as high-power electromagnetics: environments, interaction, effects, and hardening (HPE 201), now covering a broader range of subjects emphasizing the more modern electromagnetic threats.

At this point, let us recognize the growing West European efforts in the effects area [11]. By analysis and experiment, at least some effects information has been published on various electronic equipment on personal computers, circuit boards, hypothetical small missiles, etc. While the U.S. is reluctant to publish such information, at least we have some real effects information. Combining this with the other aspects of EMP technology published by the U.S., we have a more complete picture of both EMP and HPE. Sponsored by Air Force Office of Scientific Research (AFOSR), a Multi University Research Initiative (MURI) has also resulted in the publication of some canonical effects data.

F. Opening to the Former Soviet Union

With the breakup of the Soviet Union, the *raison d'etre* for the Cold War disappeared. During the visit by a Russian delegation to Kirtland AFB in 1996, we learned more about their EMP simulators. It seemed that they had read many of my papers. They had me autograph my 1978 simulator paper [1, pp. 35–53], [2, pp. 35–53]. I escorted the Russians out to our simulators. The last part consisted of walking out on the trestle into the enormous ATLAS I. Through a translator, General Major Vladimir Loborev commented that this was an excellent facility and I must be very proud of it, but if it were not for them I would not have built this. I responded, "Yes sir. Thank you sir," and shook his hand. When I finally visited the EMP-simulator development group in Kharkov, Ukraine, I found one Lyudmila Alekseeva who had the job of translating my papers into Russian. These latter visits could be considered the end of the EMP Cold War.

With the Russians now more open about their EMP program, we had access to a more real EMP experience. Notably, we learnt of EMP failures in a 1998 paper [26] concerning their 1962 nuclear test series. This complemented our 1962 Starfish data concerning failures caused by EMP [27]. Great credit is due to W. A. Radasky for having this Russian data published. The reader should note that in 1978, the American EMP program effectively went public with the publication of the Special Issue [1], [2]. Now the discussion went both ways.

G. EMP Standards

In the late 1980s, under the leadership of W. A. Radasky and M. W. WIk (of Sweden), the International Electrotechnical Commission (IEC) began work on a series of standards concerning the nuclear EMP, and later, HPE and International Electromagnetic Interference (IEMI) [11, pp. 314–321]. With the opening of EMP information to the world in 1978 [1], [2], this technology now is available not only to governments, but also to the commercial world.

H. EMP Commission

What is the situation now that the Cold War is over? Various EMP test facilities have been demolished or mothballed, although some (primarily in Europe) are still operational. After September 11, 2001, this question is being revisited in the context of terrorism (rogue states and nonstate actors). The U.S. Congress commissioned a study of this question under the chairmanship of my colleague W. R. Graham, now a contractor in the Washington, DC area. A report was issued in 2004 considering both the military and civilian infrastructure [28]. It will be interesting to see how this evolves in the future.

III. CLOSE-IN LIGHTNING

From an EMP perspective, there are reasons to look at natural lightning. For surface-burst EMP, the currents on buried cables rival those of lightning. The physics of the discharge include some of the same air chemistry and electron- and ion-mobility parameters. Thus, understanding the lightning source region might help in our understanding of the EMP source region, in spite of their obvious differences.

In 1980s, my colleagues and I joined the summer lightning experimental program at Langmuir observatory on South Baldy peak near Socorro, NM. Here, we measured rocket-triggered lightning with our EMP sensors (with good high-frequency response), including close-in fields, currents, and optical emission. The data are included in the Lightning Phenomenology Notes and a book [5]. The data began to suggest various approaches to model the lightning. Most notably, a model (the corona model) for the lightning return stroke was developed based on an electromagnetic-shock-wave solution of the approximate nonlinear transmission-line equations. This predicted the observed return-stroke speed of about c/3 from the input physical parameters. This is to be distinguished from the so-called engineering models based on matching the observed distant fields [29].

One of the reasons for studying lightning was to design EMP detectors to alert the strategic forces. These had to be insensitive to lightning to avoid false alarms. Such a system was designed and tested on South Baldy peak. It was based on using a magnetic rather than electric field, time-differentiating the field to emphasize the high frequencies, and the use of multiple locations for redundancy and ensuring adequate distance from the lightning.

A discussion (or rather dispute) developed, concerning the relative importance of lightning and HEMP for affecting electronics on aircraft. Clearly, lightning was more significant for mechanical (structural) damage, as has been demonstrated. Hence, a study was performed concerning fields on the surface of a typical aircraft [5, pp. 491–533]. Roughly speaking, for frequencies below 1 MHz direct-strike lightning is dominant, while for frequencies above 10 MHz HEMP is dominant. Later, measurements were takem (with our help) with an instrumented F-106 to confirm these conclusions. As has been noted [30], [31], lightning testing for interaction with system electronics needs to include the surface electric field (megavolts per meter due to air breakdown) as well as the surface magnetic field.

IV. HIGH-POWER MICROWAVE: HYPOBAND SYSTEMS

With EMP interest waning, the emphasis gradually shifted toward high-power electromagnetic sources/antennas. For attacking electronic systems, one can build conventional but high-power microwave sources. There are good reasons for choosing a hypoband (narrowband) source for this purpose. See [11, pp. 322–328] for a description of the various types and frequency bands of various sources/antennas.) As I discussed in [6, pp. 148–153], one can significantly increase the target response by selecting a frequency corresponding to the peak of a resonance in the transfer function. For this purpose, the width of the microwave pulse (or Q) should be greater than the ring-up time (or Q) of the target resonance. According to “Baum’s Law” [32], an important range of frequencies is around 1 GHz (also experimentally observed), because human beings have built the systems, and many characteristic lengths are of the order of the size of the human hand.

There has been much work done on high-power microwave tubes [33]. For our purposes, the most interesting types are relativistic magnetrons and reltrons, both of which work well in the range of frequencies around 1 GHz. They have powers during the pulse of around 1 GW with pulse lengths of the order of 100 ns (adequate for typical target Qs). Significant work on relativistic magnetrons in both the U.S. and Soviet Union began in the 1970s, with reltrons following later.

Various test facilities have been built in Europe (France, Germany, Britain, and Sweden) with equipment built in the U.S. by a company now called L-3 Communications, Pulse Science Division in San Leandro, CA [11, pp. 329–334].

Much of the technology concerning hypoband systems (also known as PHASERs) has been summarized in [8]. This also includes a discussion of some appropriate antennas, particularly horn-fed reflectors. An interesting variation on this class is a half reflector mounted on a ground plane [34]. This has the advantage of conveniently placing the pulse power and microwave tube near the antenna, but in a noninterfering location (similar to JOLT, discussed later.) The disadvantage of a horn-fed reflector is the required depth of the antenna for a given antenna aperture. The depth can be reduced for applications, which require it (such as aircraft mounting) by a split-waveguide array [35], [36]. In this design, high power is retained in the waveguide by inserting septa perpendicular to the electric field. This subdivides the guide with each subguide gradually expanding its height, turning approximately perpendicular to the original guide direction and radiating out of an appropriately large-horn aperture. Several such split-waveguide antennas can be combined into an array to fill the desired antenna aperture.

V. HYPERBAND SYSTEMS

At the other extreme, we can have band ratios of about two decades for hyperband sources [9]. In this case, we can also make an approximately dispersionless pulse. By driving a conical TEM transmission-line feed (like in some EMP simulators) to a paraboloidal reflector with a step-function-like pulse, we can radiate an approximate impulse with the width given by the risetime of the source. This is one kind (a very practical kind) of antenna called a reflector impulse radiating antenna (IRA). (Other kinds involve a lens or an array.) Of course, there are various details that are not considered, but are in the references. This was a revolutionary approach to antenna design, which resulted in the 1996 John Kraus Antenna Award of the IEEE Antennas and Propagation Society being given to myself along with E. G. Farr and D. V. Giri. Much of this has been summarized in a recent book [10].

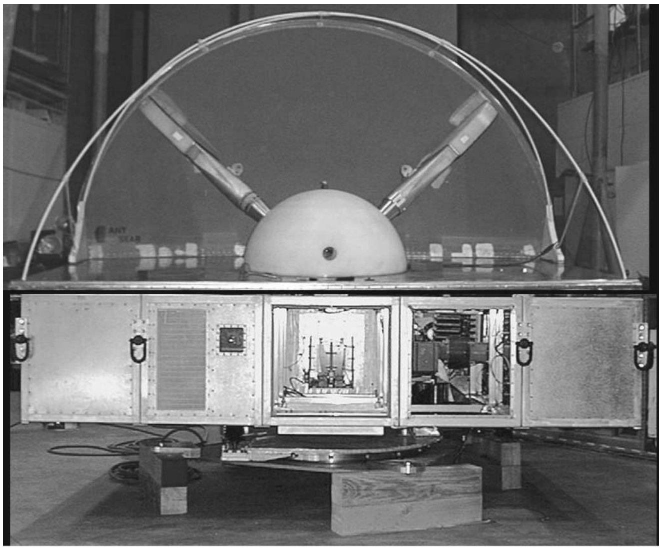

Fig. 2. JOLT high-power impulse radiator.

A. High-Power Versions

One application of such sources/antennas is disruption of electronic systems, whether by transient upset of electronics or by jamming communications. These (also known as DISRUPTERs) are reviewed in [9] and [10] with many references. To summarize, my original paper was in 1989 (SSN 321) [13]. This was followed by the first high-power version in 1995 developed by D. V. Giri and a team from what is now Pulse Sciences Division of L3 Communications. This was a 3.66-m diameter reflector driven by 120 kV, producing a far voltage (field times distance) of about 1.3 MV with a width of the impulsive part of about 100 ps.

Eventually, a 1-MV system known as JOLT (Fig. 2) was built using my half-IRA concept [37] (half reflector with ground plane). This was a large project of the Air Force Research Laboratory in 1997–1999. I can remember sketching diagrams on a white board at ITT (system integrating contractor) in Albuquerque. A team of the best in business was assembled, to which I described the assignments of the subteams. The antenna part was headed by D. V. Giri augmented by E. G. Farr, J. Schonberg, and J. S. Tyo. The pulse power combined personnel from Pulse Sciences and ASR. The roles were divided at the ground plane (antenna *versus* "Siberia") with connection at the final peaking gap at the paraboloidal focus. The far voltage was measured as 5.3 MV with a small increase in the width of the impulse.

B. Lower Power for Transient Radars

With lower voltage sources, one can pay more attention to details concerning waveform speed and mathematical simplicity (for a close-to-ideal interogating waveform). It should also be noted that a reflector IRA also makes a good receiving antenna, being approximately a replicator of the incoming electromagnetic waveform due to the time-domain reciprocity theorem [38]. These have been used in target-identification experiments, including for buried targets such as mines and UXO.

A number of such antennas have been built. Some are commercially available from Farr Research in Albuquerque. They come in various sizes. There is even a collapsible lightweight version.

C. Near-Field Focusing

A new possible application of IRA technology has emerged, namely in the fight against cancer. Fast high-voltage pulses can be driven via electrodes to kill melanoma (a skin cancer) [39]. There is a desire to be able to do this without physical electrical contact to the skin. Here enters the IRA technology.

Since retiring from the Air Force Research Laboratory and joining the Department of Electrical and Computer Engineering of the University of New Mexico, Albuquerque, I have been working on this problem (among others). The basic concept is to replace the paraboloidal reflector by a prolate-spheroidal reflector. This has two foci, one for the source, and the other for the target allowing one to focus in the near field [40]. Besides analytical studies, experiments are being designed with the help of a graduate student and other faculty. Stay tuned!

VI. MESOBAND SYSTEMS

While hypoband sources/antennas are efficient for penetrating into the circuits in a system, they are considerably more complex than hyperband systems. The latter have a high-voltage pulser (Marx or transformer), a fast switch, and an antenna. It would be desirable to use hyperband technology to make a waveform more like the hypoband case. This is achieved by a mesoband (medium band) system (also known as a DISPATCHER).

The basic concept was outlined in 2000 and 2001 [41]. It involves a switched oscillator, which is a quarter-wave resonant length of transmission line (made to withstand hundreds of kilovolts) of very low characteristic impedance. This feeds an antenna at one end and has a closing switch at the other end (such as used in high-power IRAs). The oscillator stores and delivers a lot of energy in a pulse whose width is governed by the ratio of the oscillator characteristic impedance to the antenna impedance (at the resonance frequency). One such system, known as MATRIX, has been built, but this type of system is still in its early development stage.

VII. CONCLUSION

Well, this has been quite a journey. Many people and organizations have been involved. The IEEE EMC Society has been a prominent forum for publishing the accomplishments in this technology. I have been fortunate to have had a central role in the history. Of course, the story is not over. One expects more developments as time goes on.

As a historical footnote, while in high school (Christian Brothers Academy, Syracuse, NY), there was some discussion concerning my future career. My piano teacher wanted me to study music at the Eastman School of Music in Rochester, NY. My father wanted me to study engineering and saw to it that I got into Caltech. However, to this day I have been an amateur musician, directing church choirs and composing music (classical), including for the AMEREM/EUROEM conferences.

REFERENCES

[1] J. H. Darrah *et al.* (Eds.). Special Joint Issue on the Nuclear Electromagnetic Pulse, *IEEE Trans. Antennas Propag.,* pp. 1–193, Jan. 1978.

[2] J. H. Darrah *et al.* (Eds.). Special Joint Issue on the Nuclear Electromagnetic Pulse, *IEEE Trans. Electromagn. Compat.,* pp. 1–193, Feb. 1978.

[3] K. S. H. Lee (Ed.). *EMP Interaction: Principles, Techniques, and Reference Data*. New York: Taylor & Francis, 1986.

[4] C. E. Baum, "A career (to date) in electromagnetics," *IEEE Antennas Propag. Mag.*, vol. 31, no. 6, pp. 12–17, Dec. 1989.

[5] R. L. Gardner (Ed.). *Lightning Electromagnetics*. New York: Taylor & Francis, 1990.

[6] C. E. Baum, "From the electromagnetic pulse to high-power electromagnetics," *Proc. IEEE*, vol. 80, no. 6, pp. 789–817, Jun. 1992.

[7] D. V. Giri (Ed.). Special Issue on High-Power Microwaves. *IEEE Trans. Electromagn. Compat.,* vol. 34, no. 3, pp. 145–274, Aug. 1992.

[8] C. D. Taylor and D. V. Giri, *High-Power Microwave Systems and Effects*. New York: Taylor & Francis, 1994.

[9] C. E. Baum, E. G. Farr, and D. V. Giri, "Review of impulse-radiating antennas," in *Review of Radio Science*, W. R. Stone, Ed. London, U.K.: Oxford Univ. Press, 1999, pp. 402–439.

[10] D. V. Giri, *High-Power Electromagnetic Radiators*. Cambridge, MA: Harvard Univ. Press, 2004.

[11] W. A. Radasky *et al.* (Eds.). "Special Issue on High-Power Electromagnetics (HPEM) and Intentional Electromagnetic Interference (IEMI)," *IEEE Trans. Electromagn. Compat.,* vol. 46, no. 3, pp. 314–496, Aug. 2004.

[12] W. D. Prather, D. V. Giri, and R. L. Gardner, "Dr. Carl Baum: One remarkable career," *Radio Sci. Bull.*, no. 312, pp. 10–20, Mar. 2005.

[13] C. E. Baum (Ed.), CD Collection of Sensor and Simulation Notes (SSN), Interaction Notes (IN), and other miscellaneous Notes, available from the author (note editor) and publicized in *IEEE Antennas Propag. Mag*.

[14] W. J. Karzas and R. Latter, "Electromagnetic radiation from a nuclear explosion in space," *Phys. Rev.*, pp. 1919–1926, 1962.

[15] C. E. Baum, "Electromagnetic sensors and measurement techniques," in *Fast Electrical and Optical Measurements*, J. E. Thompson and L. H. Luessen, Eds. Dordrecht, The Netherlands: Martinus Nijhoff, 1986, pp. 73–109.

[16] C. E. Baum, "How to think about EMP interaction," in *Proc. 1974 Spring FULMEN Meet.*, pp. 12–23.

[17] C. E. Baum, T. K. Liu, and F. M. Tesche, "On the analysis of general multiconductor transmission-line networks," Kirtland AFB, NM, Interaction Note 350, 1978.

[18] C. E. Baum, "Electromagnetic topology for the analysis and design of complex electromagnetic systems," in *Fast Electrical and Optical Measurements,* J. E. Thompson and L. H. Luessen, Eds. Dordrecht, The Netherlands: Martinus Nijhoff, 1986, pp. 467–547.

[19] C. E. Baum, "On the singularity expansion method for the solution of electromagnetic interaction problems," Kirtland AFB, NM, Interaction Note 88, Dec. 1971.

[20] C. E. Baum, "The singularity expansion method," in *Transient Electromagnetic Fields*, L. B. Felsen, Ed. Berlin, Germany: Springer-Verlag, 1976, ch. 3, pp. 129–177

[21] C. E. Baum, "Emerging technology for transient and broad-band analysis and synthesis of antennas and scatterers," *Proc. IEEE*, vol. 64, no. 11, pp. 1598–1616, Nov. 1976.

[22] C. E. Baum "Toward an engineering theory of electromagnetic scattering: The singulaity and eigenmode expansion methods," in *Electromagnetic Scattering*, P. L. E. Uslenghi, Ed. New York: Academic, 1978, ch. 15, pp. 571–651.

[23] C. E. Baum, E. J. Rothwell, K.-M. Chen, and D. P. Nyquist, "The singularity expansion method and its application to target identification," *Proc. IEEE*, vol. 79, no. 10, pp. 1481–1492, Oct. 1991.

[24] C. E. Baum (Ed.), *Detection and Identification of Visually Obscured Targets*. New York: Taylor & Francis, 1999.

[25] C. E. Baum and L. Carin, "Singularity expansion method, symmetry and target identification," in *Scattering*, R. Pike and P. Sabatier, Eds. New York: Academic, 2002, ch. 1.6.3, pp. 431–447.

[26] V. N. Greetsai *et al.*, "Response of long lines to nuclear high-altitude electromagnetic pulse (HEMP)," *IEEE Trans. Electromagn. Compat.*, vol. 40, no. 4, pp. 348–354, Nov. 1998.

[27] C. N. Vittitoe, "Did high-altitude EMP cause the Hawaiian streetlight incident,", Albuquerque, NM, Rep. SAND88-00430, 1988.

[28] W. R. Graham *et al.*, "Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack, vol. 1: Executive report", Report to Congress, 2004.

[29] V. A. Rakov and M. A. Uman, "Review and evaluation of lightning return stroke models including some aspects of their application," *IEEE Trans. Electromagn. Compat.*, vol. 40, no. 4, pp. 403–426, Nov. 1998.

[30] C. E. Baum *et al.*, "The measurement of lightning environmental parameters related to interaction with electronic systems," *IEEE Trans. Electromagn. Compat.*, vol. EMC-24, no. 2, pp. 123–137, May 1982.

[31] C. E. Baum, "Simulation of electromagnetic aspects of lightning," in *Environmental and Space Electromagnetics*, H. Kikuchi, Ed. Berlin, Germany: Springer-Verlag, vol. 1, no. 12, ch. 112, pp. 463–479, 1991.

[32] C. E. Baum, "A time-domain view of choice of transient excitation waveforms for enhanced response of electronic systems," in *Proc. Int. Conf. Electromagn. Adv. Appl.* Torino, Italy, 2001, pp. 181–184.

[33] J. Benford, J. A. Swegle, and E. Shamiloglu, *High-Power Microwaves*, 2nd ed. Boca Raton, FL: CRC, 2007, to be published.

[34] C. E. Baum, "Phaser utilizing a half reflector and ground plane," Microwave Memo 9, Jul. 15, 2000.

[35] C. E. Baum, "High-power scanning waveguide array," Sensor and Simulation Note 459, 2001.

[36] C. E. Baum, "High-power scanning waveguide array," in *Proc. Int. Conf. Electromagn. Adv. Appl.* Torino, Italy, 2005, pp. 3–6.

[37] C. E. Baum, "Variations on the impulse-radiating antenna theme," Sensor and Simulation Note 378, 1995.

[38] C. E. Baum, "General properties of antennas," *IEEE Trans. Electromagn. Compat.*, vol. 44, no. 1, pp. 18–24, Feb. 2002.

[39] K. H. Schoenbach, R. Nuccitelli, and S. J. Beebe, "Zap," *IEEE Spectr.*, vol. 43, no. 8, pp. 20–26, Aug. 2006.

[40] C. E. Baum, "Focal waveform of a prolate-spheroidal IRA," Sensor and Simulation Note 509, Feb. 2006.

[41] C. E. Baum, "Antennas for the switched-oscillator source," Sensor and Simulation Note 455, 2001.

Carl E. Baum (S'62–M'63–SM'78–F'84–LF'06) was born in Binghamton, NY, on February 6, 1940. He received the B.S. (honors), M.S., and Ph.D. degrees in electrical engineering from the California Institute of Technology, Pasadena, in 1962, 1963, and 1969, respectively. He received the degree of Doktoringenieurs Ehren halber (Doctor of Enginering honoris causa) degree from the Otto-van-Guericke University, Magdeburg, Germany, in 2004.

He was stationed at the Air Force Research Laboratory, Directed Energy Directorate (formerly Phillips Laboratory, formerly Air Force Weapons Laboratory), Kirtland AFB, Albuquerque, NM, from 1963 to 1967 and from 1968 to 1971. From 1971 to 2005, he was a Senior Scientist with the Air Force Research Laboratory. Since 2005, he has been a Distinguished Research Professor with the Department of Electrical and Computer Engineering, University of New Mexico, Albuquerque. He is the founder and President of SUMMA Foundation, which sponsors various electromagnetics-related activities including scientific conferences, publications, short courses, fellowships, and awards. He has led short courses on electromagnetic pulses (EMP) and high-power electromagnetics at numerous locations around the globe. He has authored four books: *Transient Lens Synthesis: Differential Geometry in Electromagnetic Theory*, *Electromagnetic Symmetry*, *Ultra-Wideband, Short-Pulse Electromagnetics 3*, and *Detection and Identification of Visually Obscured Targets*.

He received the Air Force Research and Development Award in 1970, the AFSC Harold Brown Award in 1990, and the Air Force Research Laboratory Fellowship in 1996. He is the Editor of several interagency note series on EMP and related subjects, and has received the Richard R. Stoddart award of the IEEE EMC Society in 1984 and the John Kraus Antenna Award of the IEEE Antennas and Propagation Society in 2006. He is the recipient of the 1987 Harry Diamond Memorial Award, one of the IEEE Field Awards with citation "for outstanding contributions to the knowledge of transient phenomena in electromagnetics," and is the recipient of the 2007 IEEE Electromagnetics Field Award with citation "for contributions to fundamental principles and techniques in electromagnetics." He is a member of Commissions A, B, and E of the U.S. National Committee of the International Union of Radio Science (URSI).