Interaction Notes

Note 634

28 January 2020

(Revised 24 June 2020)

A Preliminary Assessment of Radio Frequency Threats to Airports

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Abstract

This note deals with the subject of a site survey of a generic airport and evaluation of potential RF vulnerabilities and identifies further steps in this evaluation. It is noted that this work was performed in 2007. This note is written ~~more~~ from the perspective of High-Power Electromagnetic (HPEM) engineers surveying a chosen facility.

Acknowledgement

The authors are thankful to Mr. Heinz Wipf of AIRNAV CONSULTING GmbH for his valuable inputs and guidance, during the preparation of this note.

1. Introduction

Civil aviation has become an integral component of present-day societies. It promotes an economic base for a community, assists and encourages trade, and is vital for the health, safety and welfare of the general public. Yet, we all know some of its vulnerabilities even from very low-level electromagnetic emitters. For example, cell phone use is prohibited in at least the takeoff and landing phases of a flight, due to its potential adverse effects on navigational electronics on-board the aircraft. Other passenger electronic devices (PED) such as lap-top computers, DVD players etc., have been known to cause interference and are prohibited during the take-off and landing phase of a commercial flight. In addition to these low-level emitters, both military and civilian aircrafts are routinely required to operate under adverse electromagnetic environments (EME), such as

- Natural- lightning electromagnetic pulse (N-LEMP)
- Electrostatic discharge (ESD)
- Electromagnetic environment in and around airports
- Intra-system electromagnetic interference (EMI)
- Inter-system EMI.

Over the period of 1959-1988, there have been at least seven cases of aircraft falling out of the sky due to natural lightning, which have been documented by the U. S. National Lightning Safety Institute (NLSI) included in this report in Appendix A. Lightning is a nature's way of maintaining electrical neutrality in a global electrical circuit. Typical photographs of natural lightning are shown in Figure 1.

Figure 1. Typical lightning: cloud to ground (left) and cloud to cloud (right). Photograph is from NOAA.

Two authors of this note (DVG and FMT) had a role to play [1] in analyzing the data collected from an instrumented research F-106B aircraft, owned, and operated by NASA Langley Research Center. This aircraft is pictured in Figure 2.

Figure 2. F-106B (NASA 816) research aircraft during Storm Hazards Program in 1982. (Note paint spots applied to aircraft that denote lightning attachment points.)

The experimental data gathered by NASA Langley has been very valuable in understanding the phenomenology of natural lightning and its interaction with aircraft. As a result, rigorous lightning certification tests are now applied to civilian aircraft to verify the safety of design, so that accidents such as those listed and described in Appendix A are indeed very rare today.

There are also documented losses of aircraft due to excessive EM fields from external interfering sources other than natural lightning. The following is a quotation from [2] relating to an F-16 Crash near a Voice of America (VoA) Transmitter.

> *"An F-16 fighter jet crashed in the vicinity of a Voice of America (VoA) radio transmitter because its fly-by-wire flight control system was susceptible to the HIRF transmitted. Since the F-16 is inherently unstable, the pilot must rely on the flight computer to fly the aircraft. Subsequently, many of the F-l6's were modified to prevent this type EMI, caused by inadequate military specifications on that particular electronics system. This F-16 case history was one of the drivers for institution by the Federal Aviation Administration (FAA) of the HIRF certification program."*

There are also other EMI incidents that have brought aircraft down such as the German Tornado fighter aircraft near the VoA station in Munich, Blackhawk helicopters and an F-111 crash during the U. S. air strike of Libya in 1986.

Aircraft certification has a technical basis for protecting electrical and electronic systems on civilian aircraft from the effects of high intensity radiated fields (HIRF) generated by sources external to the aircraft. The U.S. Federal Aviation Administration (FAA) and the European Joint Airworthiness Authorities (JAA) have jointly worked with the assistance of the U.S. Society of Automotive Engineers (SAE) and the European Organization for Civil Aviation Electronics (EUROCAE). This has resulted in a set of

HIRF environments and associated testing methods [3]. These requirements are provided in the present report in Appendix A[1].

In Appendix A, the HIRF environment I set forth test and analysis levels that are used to demonstrate that an aircraft and its systems meet basic HIRF certification requirements. HIRF environment I represent the range of electromagnetic field strengths that an aircraft could encounter during its operational life. HIRF environment II is an estimate of the electromagnetic field strengths more likely to be encountered in the airspace above an airport or heliport at which routine departure and arrival operations take place.

These HIRF certification levels are plotted in Figures 3 and 4 are important because if an intentional RF weapon system produces a HIRF level that exceeds the above levels by an order of magnitude, serious consequences may become possible.

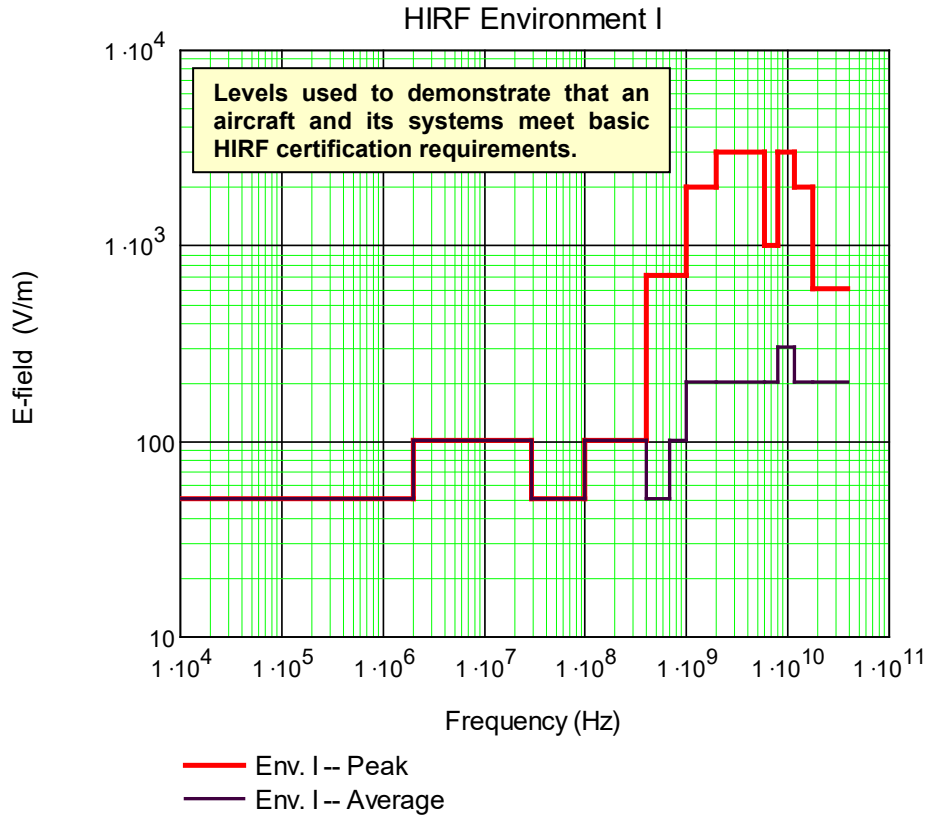

Figure 3. HIRF Type I Environments (effective September 2007).

[1] Note that these requirements are from September 2007.

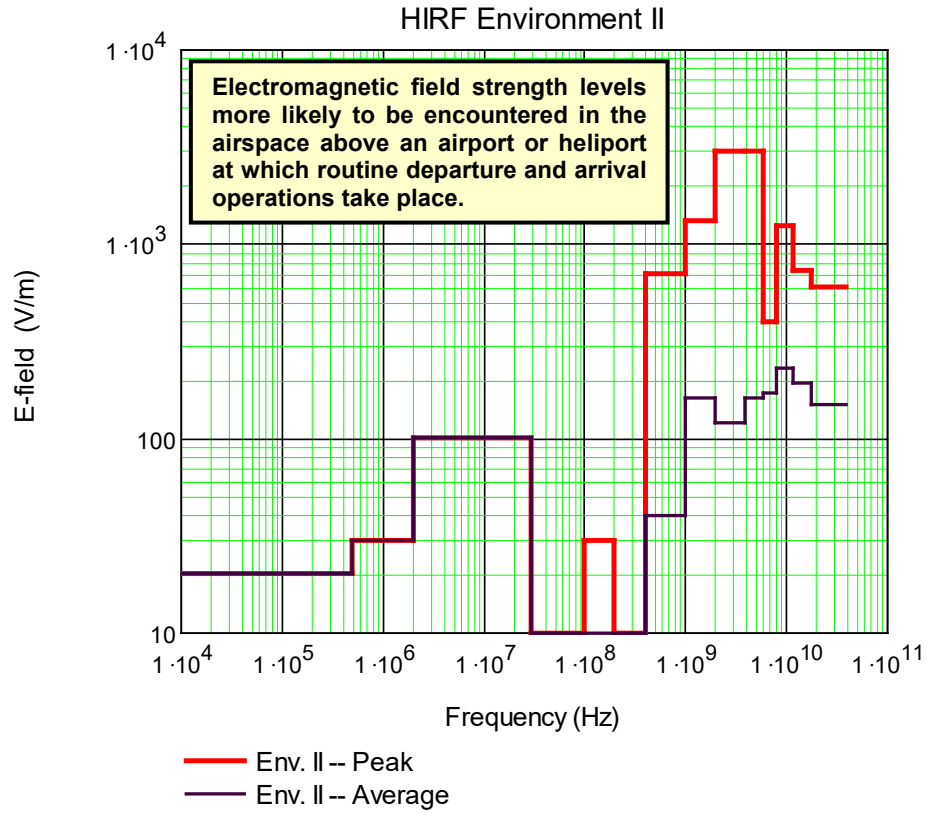

Figure 4. HIRF Type II Environments (effective September 2007).

From FAA / JAA standards it is safe to conclude that unintentional electromagnetic signals can pose a threat to aviation. It is entirely possible that RF terrorism [4, 5 and 6] can bring such threats with intentional electromagnetic signals.

Furthermore, airports cannot run without networked computers operating in unison. Ground components such as, passenger terminals, air-traffic management (ATM) and airport vehicles are also subject to potential RF threats. There may not be a loss of life as in the case of loss of aircraft, but severe disruption of aviation services can be the price to pay. A coordinated RF attack on several passenger terminals aimed at disrupting networked computers [7, 8 and 9] can have serious psychological and economic consequences.

There is one more plausible argument that motivates this study. Prior to Nine-Eleven, the access to the cockpit was discussed extensively between airline operators and authorities. It was decided before Nine Eleven to not lock the doors and to not strengthen the doors. The consequences of this was clearly shown in the Germanwings accident, in which the crew was unable to enter the cockpit when the pilot decided to crash the aircraft...Aircraft were used as missiles on Nine Eleven. Since Nine Eleven, access to the cockpit is more restricted and cockpit doors have been strengthened by some airline operators. This still does not prevent a pilot from crashing the aircraft. In retrospect, it would have been prudent to restrict access and strengthen cockpit doors prior to Nine Eleven. We live in a world where the actions of a few individuals can affect the lifestyles

of many. In our opinion, it is prudent to be pro-active and preempt such RF threats to civil aviation rather than react to it after the fact.

2. A Topological View of an Airport

A civilian airport is a facility where three components of air transportation system come together [10], as illustrated in Figure 5.

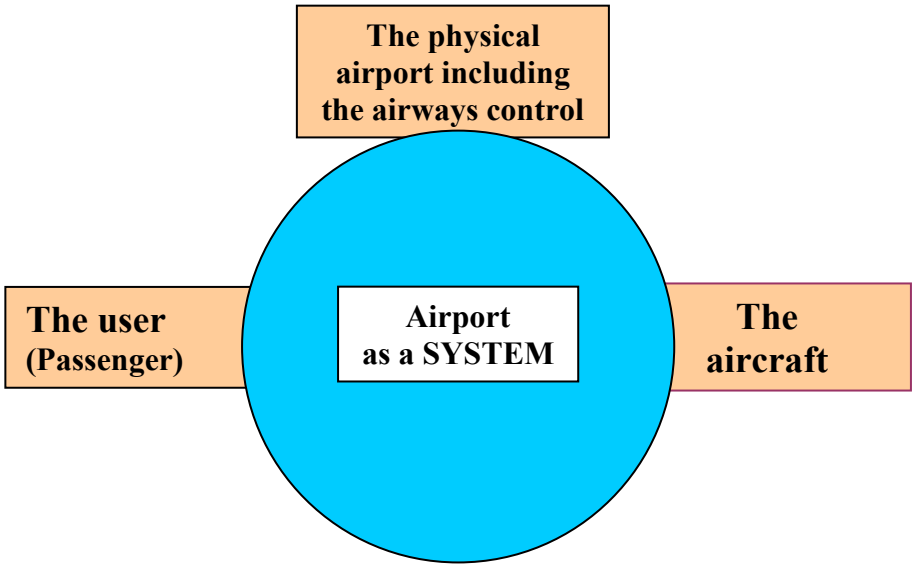

Figure 5 A system theoretic view of an airport

A typical airport operation includes, but not limited to, the following:

• Air Traffic Control • Telecommunications • Meteorology • Approach and Landing Aids • Runway Lighting • Airfield Inspections • Air Operations in Bad Weather Conditions • Power System Management • Passenger Service • Baggage Operations • Ground Handling • Airport Security	• Baggage Operations • Emergency Management • Personnel Requirements • Fire-Fighting Equipment and Readiness • Access Control • Authorized Ground Vehicles • Foaming the Runway when Needed • De-icing the aircraft when Needed • Airport Terminal Operations • Noise Control Strategies, etc • Licensing and Certification issues • Noise Control Systems

Out of all the elements of airport operations listed above, from an electromagnetic viewpoint, the following systems are of present interest to us.

- RF interfaces
- Power

- Telecommunication including navigational aids
- Air Traffic Management / Equipment (ATM / Equipment)

We describe all of the above systems and their vulnerabilities in later sections of this note.

3. Comparative Study of Typical Military and Civilian Airports

The most significant difference between civilian and military airports is the fact that there are a lot of training missions and flights in a military airfield. Military airports are typically located on military bases, where military personnel are housed as well. The military pilots undergo intensive training in the confined airspaces. Jet fighters and sophisticated helicopters are flown in and out of military airfields.

A generic airport which we surveyed in May 2007, is a military airport wherein with an outside entity providing the air traffic control services. The runway is 2.5 km long and the airport handles about 1000 landings/year, other than the military use.

There are significant differences in the operational structure of military and civilian airports. These are typically in the areas of:

- Passenger Service,
- Baggage Operations,
- Ground Handling,
- Airport Security,
- Baggage Operations,
- Emergency Management,
- Personnel Requirements,
- Fire-Fighting Equipment and Readiness, and
- Access Control.

However, in four primary areas of concern to us in the present study, there are no major differences. These areas are:

- RF interfaces,
- Power,
- Telecommunication including navigational aids, and
- Air Traffic Management / Equipment (ATM / Equipment).

It is noted however, that the military airports may have ordnances and likely have expanded RF interfaces compared to their civilian counterparts.

4. RF Interfaces at a Typical Airport

A topological view of the RF interfaces is illustrated in Figure 6.

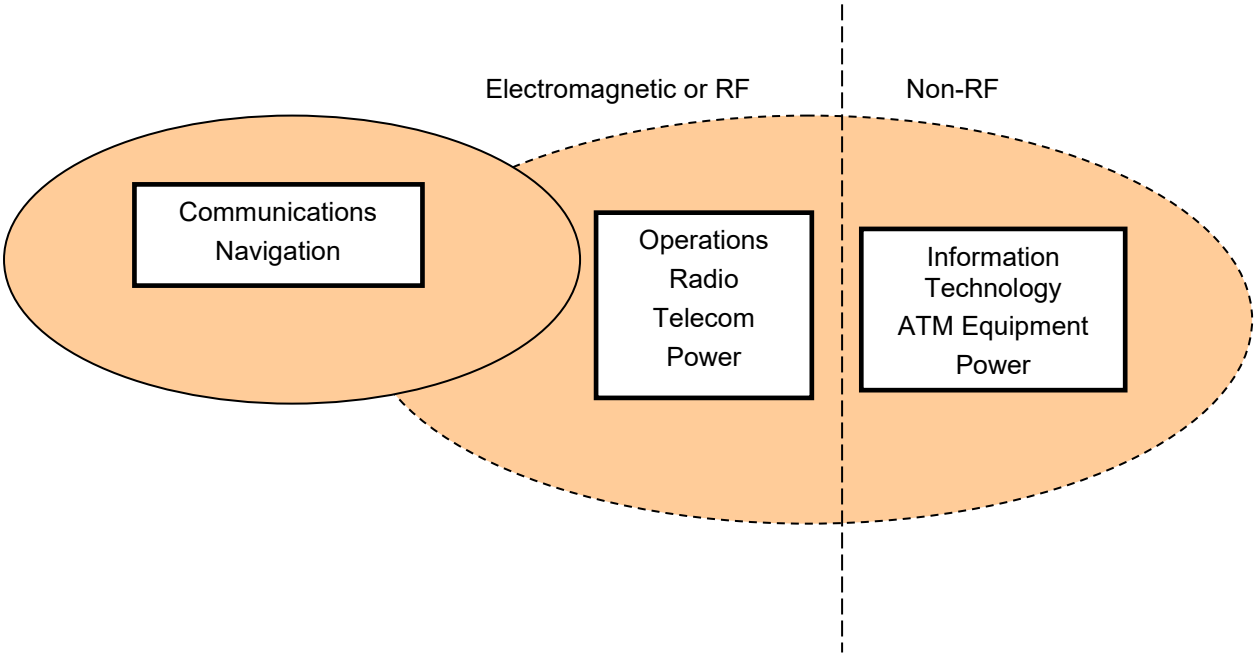

Figure 5. Topology of Air Navigation Services

Common RF interfaces identified in the above figure are listed and described in the following sections.

4.1 Navigational Aids:

There is a variety of navigational aids in terms of accuracy, coverage and capabilities. Most often, the navigational aids in use are designed around the geographical location and are ground based. Newer technology that is finding increasing use is a satellite based (GPS) system that is augmented by ground-based systems.(See ICAO Annex 10 Vol 1 Radio Naviagtion Aids)

4.1.1 VHF Omni Directional Range (VOR)

The VOR is the primary ground-based en-route navigational aid and is made up of a series of ground stations that broadcast directional signals used by aircraft in determining its vector or bearing relative to or from the VOR station.

4.1.2 Non-Directional Beacons (NDB)

The NDB is another ground based transmitted used in navigation. It sends low to medium frequency signals to a direction finder located on the airplane. Pilots can use the NDB to navigate to and from the ground stations.

4.1.3 Instrument Landing System (ILS)

The ILS guides the aircraft precisely to a runway. This is done by providing very accurate course, glide slope, and distance information (see DME) to a given runway. Some airports are equipped with ILS and many are not. The ILS is valuable in adverse weather conditions with poor visibility.

4.1.4 Distance Measuring Equipment (DME)

The DME ground installation provides for continuous cockpit indication of the slant range distance from a ground reference point. The whole subsystem comprises two components, one in the aircraft the other installed on ground. The aircraft component is the interrogator and the ground component responds. The ground station works as a transponder. In operation, interrogation leads to a synchronized transmission to the aircraft. This provides a means for accurate slant distance measurements.

4.1.5 Global Position System (GPS)

The GPS is a satellite-based radio positioning, navigation and time-transfer station developed and maintained by the United States Department of Defense. At any given time, GPS utilizes minimum of four of the nominally 24 satellites to calculate the aircraft's position. From this knowledge, it can determine the distance, bearing (vector) and estimated time of travel to the next waypoint.

4.1.6 Radar

Pilots prefer a pilot-interpreted approach and landing aid such as ILS in contrast with a PAR where the controller interprets the signals. However, the commonly used air-traffic management (ATM) methodology is to use ground-based, air-traffic controller-interpreted surveillance and to guide the pilot onto the final approach and landing aid. This is done using radars. The use of radars makes it possible to facilitate landings and takeoffs in busy airports and thus increase airspace capacity.

The primary radar is an interrogator used in detecting the presence of a flying object and it is displayed on the controller's radar screen. A narrow beam sweeps through 360 degrees of azimuth and typically the beam width of the antenna can cover altitudes of up to 3,000 m to 3,600 m and out to a range of 30 to 50 km. Any flying object having a certain size within that coverage volume is detected and displayed, but without altitude.

The secondary radar works with an interrogator and a cooperative transponder fitted on the aircraft. In this sense it is strictly not radar at all. However, the term secondary radar has been loosely applied. The transponder receives the transmitted pulse and sends back a distinctive signal with its identity. The controller then uses the displays of this received signal from the transponder on his/her screen and thus the flow of the aircraft is kept track on the radar screen. The displayed signal identifies the aircraft, its position and height.

5. RF Interfaces at a Generic Airport

Some of the RF interfaces at a generic airport are listed and described below.

- Primary Radar
- Secondary Radar
- Quad Approach Radar
- Instrument Landing System (ILS) and its components
  – ILS Localizer Transmit Antenna Array with its integral monitor
  – ILS Localizer field monitor antenna
  – ILS Glide Slope Antenna Array with its integral monitor system
  – VHF Communication Antenna for communication with a flight inspection crew
  – Access hatches on the ground at the ILS Localizer
- Radio Towers for Transmit and Receive (Control Tower Communication)
- Direction Finding Antenna

The primary and secondary radar operate respectively at 2.4 GHz and 1 GHz. The primary radar is 2.4 GHz horn-fed parabolic reflector with elliptical aperture and secondary radar is a 1 GHz array (on the top). Both rotate at the same speed.

The quad approach radar typically has two parabolic dishes with elliptical shapes, one horizontal and the other vertical (to scan in the horizontal and vertical direction).

The next major RF interface is the ILS and associated interfaces. They are the Localizer transmitting antenna, array with its integral monitor, the localizer field monitor antenna, , the glide slope antenna array with its integral monitor systems, and the VHF communication antenna for communication with a flight inspection crew,

The radio towers for transmitting and receiving the tower communications (220 MHz) and the direction-finding antenna are also important RF interfaces at the airfield.

Table 1 summarizes the preceding RF interfaces at a typical Airport.

Table 1. RF Interfaces at a typical airport

#	RF Interface	Remarks
1	Primary Radar	2.4 GHz horn-fed reflector with elliptical aperture
2	Secondary Radar	1 GHz array
3	Quad Approach Radar	Each of the two antenna systems has two parabolic dishes with elliptical shapes, one for horizontal and the other vertical scan.in order to determine the position of the approaching aircraft.
4	ILS: Localizer Transmit Antenna array and integral monitor Localizer field monitor	ILS guides the aircraft precisely to a runway. This is done by providing very accurate course, glide slope, and distance information to a given runway

	Glide Slope Array and integral monito Glide scope near field monitor DME antenna Communication Antenna Access Hatches	
5	Tower Communications Radio	Receive and Transmit
6	Direction Finding Antenna	It receives VHF/UHF transmissions and detects the direction from which these transmissions are coming. It has receivers for all the communication channels in use at the airport.
7	Visual Aids	Approach, runway, lighting

5.1 Power System Management and Telecommunication at generic airport

The power management and communications equipment may be located in a facility that is either above or below ground.

The power management equipment can be underground for protection against physical attacks. The higher level of protection of power equipment makes this equipment invulnerable to radiated electromagnetic fields. The only exposure here may be conducted transients on the power line that can overwhelm the built-in transient protection components. Electromagnetic field protection can also be achieved if the power management equipment is above ground as well.

However, the power system enclosure was alongside a public road with a very clear access, to anyone and this appeared to be a very weak link in the power

We did not gather much information at our site survey regarding specific telecommunication equipment, other than in and around the control tower. There is a hangar and an office building next to the tower building.

The office building is expected to have telecommunication equipment. Some of the antennas used for communication purposes have already been included in the RF interfaces.

5.2 Air Traffic Management (ATM) Equipment

During the site survey, the airport personnel were very cooperative and provided all the information dealing with the air traffic management from the control tower, which is an essential part of the airport operations. We observed an air vent on the control tower (Figure 7) which is a potential PoE. It is possible that there is RF protection behind the vent by means of waveguides beyond cut off.

Figure 6. Close-up of air vent on tower, which could be a point of entry in the GHz frequency regime.

The control tower can be seen in Figure 8. The large windows in the control tower will contribute to aperture coupling electromagnetic fields into the interior of the tower that can couple to cables inside.

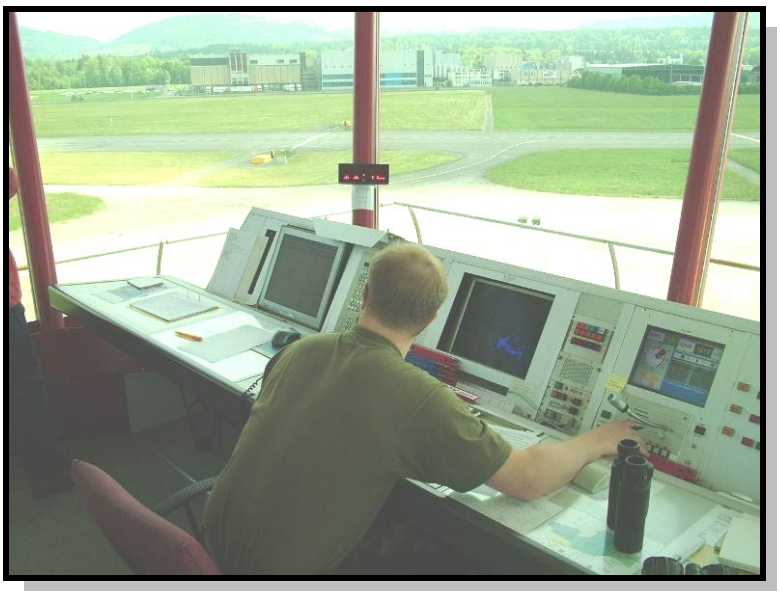

Figure 8. Air traffic controller's console.

5.3 Runway, Taxiway and Access Roads

The closest distance from the runway / taxiway to a vehicle with a hostile intention is an important element in the evaluation of the RF vulnerability of aircraft when they are moving on the ground, parked, taxiing, take-off and landing phases. The data gathered during the sire survey is presented in Figure 9.

Figure 9. Northwest side of airfield near the south end, taken from the public road parallel to the runway. Metallic /mesh Fence here is high with barbed wire on top.

6. Current and Near-term HPEM Systems (Evolving Technology)

6.1 Source Considerations

In conducting an assessment of the possible EM effects on the airport, it is important to note that there are many different types of sources and radiating antennas that could be used for such an attack on either ground equipment or aircraft. There are several important factors that enter into the description of the EM environment produced by a HPEM source, and which serve to determine whether there is an upset or permanent damage induced in a targeted system. These factors include the amplitude of the EM field at the position of the target and the classification of the excitation waveform, which is one of the four categories below:

- Narrowband High-Power Microwave (with fractional bandwidth ~ 1 %),
- Moderate band (with fractional bandwidth ~ 1 to -100%),
- Ultra-moderate band (with fractional bandwidth ~ 100% to 163.64 %), and
- Hyperband (with fractional bandwidth ~ 163 -200%

One example of a hyperband source and antenna is the Swiss Impulse Radiating Antenna (SWIRA), which has been described in [11]. This antenna has been shown to be a useful tool for testing electrical systems in electromagnetic (EM) environments. Early versions of this antenna have been used in Civil Defense test programs in 2000 [12] and 2003 [13]. This antenna is shown in Figure 10.

Figure 10. Illustration of the Swiss Impulse Radiating Antenna (SWIRA).

A computational model for determining the radiated EM fields from the SWIRA has been described in [14], and these results can be used to illustrate the nature of the radiated E-field at various locations in front of the antenna where a target could be located. Using the FID FPG 10-50MK pulser, which provides a 10 kV fast-rise pulse into the antenna, the radiated transient E-field in the boresight direction has been calculated and is displayed in Figure 11 for different distances from the antenna.

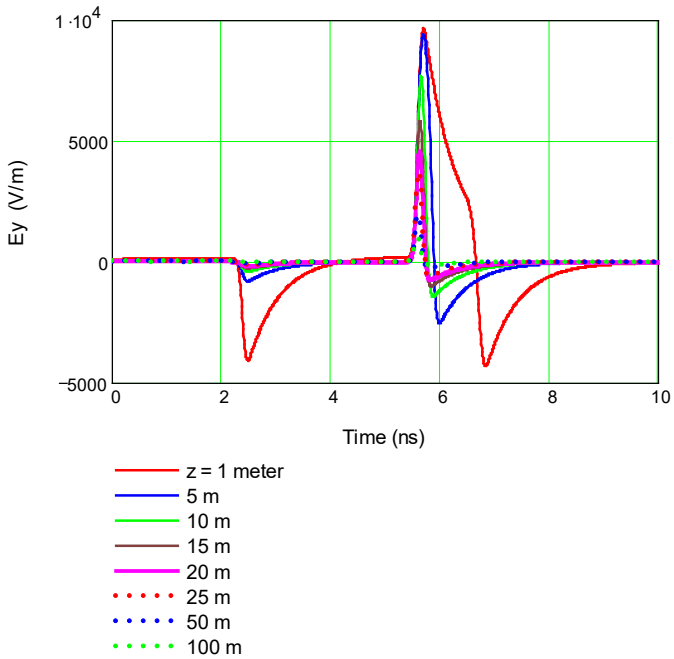

Figure 11. Plots of the principal component of the transient SWIRA E-field at different observation ranges (z) from the antenna.

From Figure 11 it is noted that the peak value of the radiated field decreases as the distance of the antenna is increased. Figure 12 summarizes the behavior of the peak value of the main pulse of the SWIRA E-field as a function of range. A close examination of this plot shows that for distances greater than about 20 meters the field amplitude is falling off as 1/range, which is typical of the radiation from a point source.

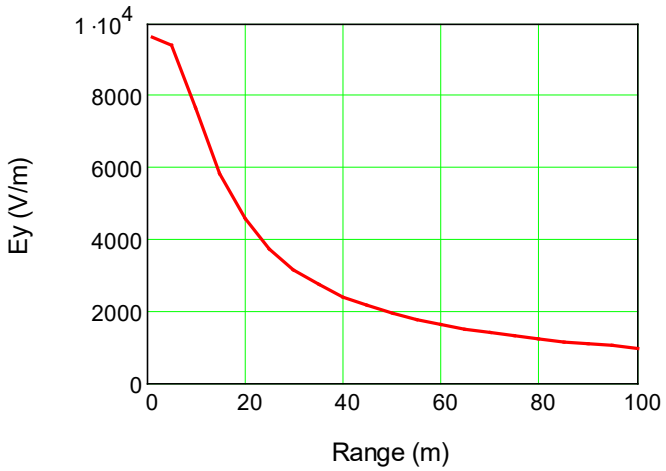

Figure 12. Variation of the peak E-field from the SWIRA as a function of range.

The radiated field waveforms serve to illustrate several important features of the EM threat environment. First and foremost is the fact that the on-target E-field is a strong function of the distance from the source. While a damaging effect might be noted for an illuminated system very close to the antenna, at farther distances such damage may be less likely due to the field fall-off.

Furthermore, the amplitude of the radiated waveform from the antenna is directly proportional to the strength of the excitation source. If the source's voltage is doubled, then the field strength at any distance will also be doubled. In this manner, the field reduction effects of an increasing range can be offset by increasing the excitation voltage. Of course, a larger excitation voltage requires a more costly source and ultimately is limited by air breakdown in the vicinity of the antenna.

Finally, other waveforms could be considered, as suggested in the list above, and it is possible by adjusting the spectral content of the incident EM field appropriately to match the vulnerable frequencies of a target, the likelihood of damage could be increased. It is important to keep in mind that even with these different waveforms, the fundamental 1/r fall-off of the field with distance from the source will be observed.

6.2 Source Placement

In examining the possibility of an EM attack on the airport, it is difficult to predict exactly where a potential attacker would choose to locate a radiation source. It is likely, however, that the attacker would try to use an area that was easily accessible, and which did not draw unwanted attention to his activities. At the same time, he would want a location that is as close as possible to the targeted component on the airfield so as to cause

maximum damage. It is logical, therefore, that the attacker would not locate his antenna inside the security fence of the airfield. Figure 13 presents a map of the airport, with this security perimeter indicated by the red boundary.

Figure 13 also shows the locations of the major antennas installed at the airport. Some of these antennas are positioned inside of the access-controlled section, while others like one of the ILS localizer arrays, the UHF communications antennas and the search radar antennas are located outside. For those inside the perimeter, the EM field strength exciting them from a source located outside the airport is expected to be significantly less than that acting on the outside antennas. In addition, the control tower is located right on the edge of the access control boundary, and it can be expected to have a potentially large excitation, depending of course, on the nature of the source.

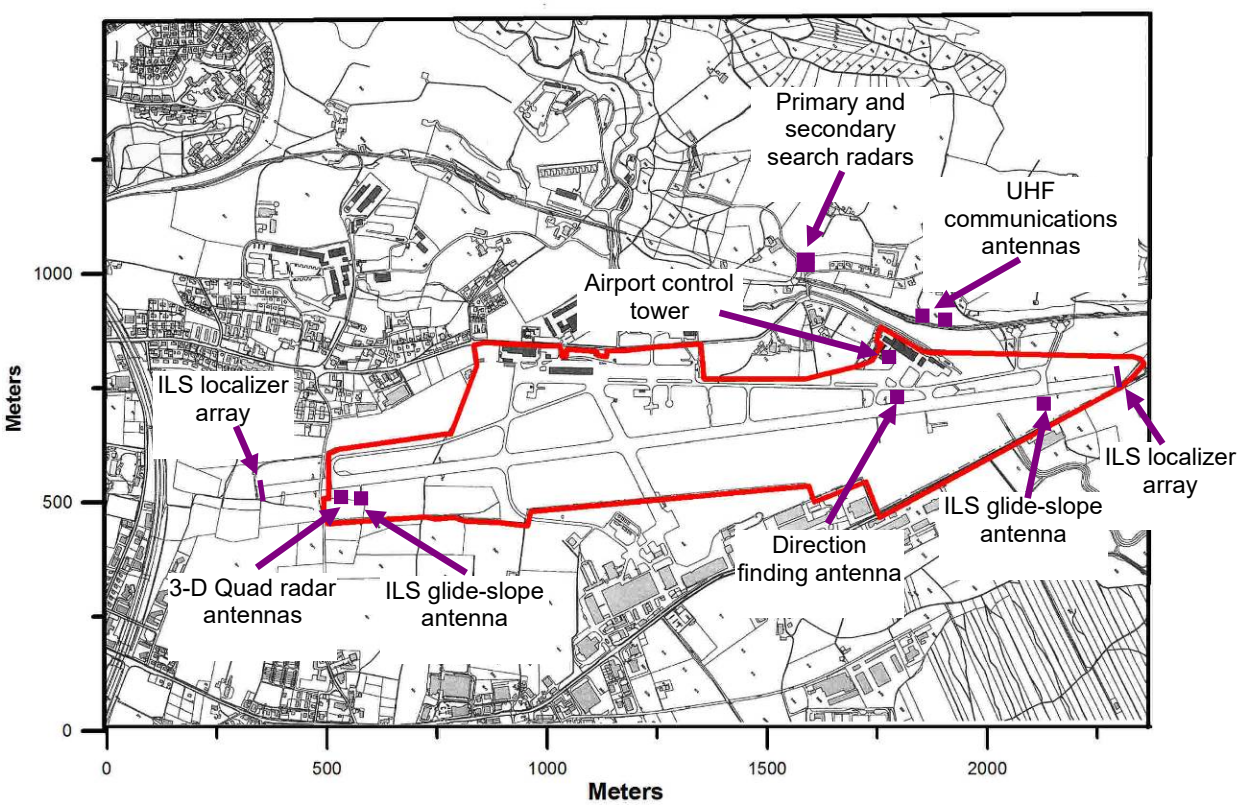

Figure 13. Map of the airport and surroundings, with the access control perimeter and major antennas indicated.

To quantify the amount of EM field reduction that is provided by limiting access of potential antenna threats at the airport, it is possible to provide a contour plot of the field attenuation due to antenna/target separation, as shown in Figure 14. This plot was constructed by assuming that the radiating HPEM antenna is located as close as possible to the airfield, but not inside the protected area. Thus, the antenna is located just on the access control perimeter.

By moving the antenna along the perimeter boundary, and assuming that it can be rotated in all directions to produce the maximum field in any direction, the largest E-field at any point inside the controlled region is calculated. The ratio of this E-field relative to that produced by the antenna at a distance of 1 meter is calculated, and when expressed in

dB, this quantity provides an effective attenuation of the E-field as a function of position in the airport.

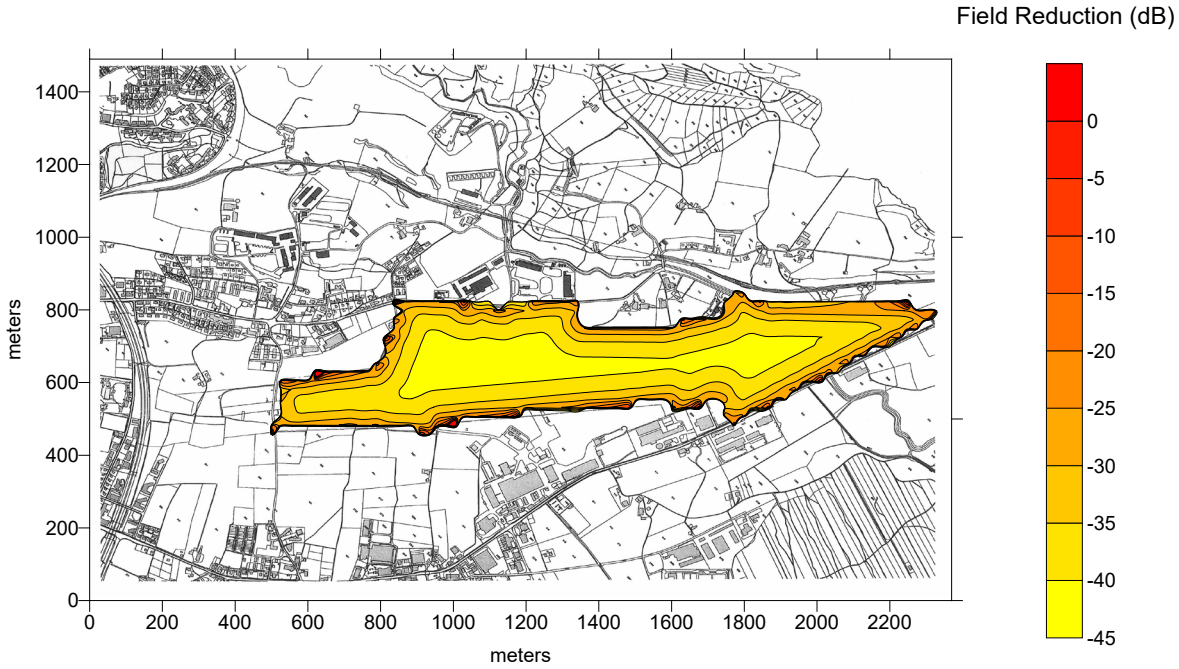

Figure 14. Contour plot of the E-field reduction factor (in dB) for points inside the access-controlled region of the airport, for radiating antennas located at the boundary.

In examining the data of Figure 15, we note that on the boundary, the effective attenuation factor is 0 dB, which indicates the fact that the external antenna is located very close to the system being illuminated and there is no field reduction due to the distance. Deep inside the airfield, however, we note that there is a 45 dB attenuation of the E-field.

7. MIL STD 464 A and HIRF Standards on Aircraft

In this section we list 2 standards that are presently applicable to civilian aircraft. They are MIL STD 464 A and the recently (September 2007) published HIRF standard. One way to assess the vulnerability of aircraft is to use the standards and state that if the RF threat is significantly higher than the standard, there is some potential for vulnerability.

MIL-STD -464 [15] has different EME standards for aircraft operated from top side of a ship (Table 1 A, page 7 of the Standard) and a slightly lower values for all other aircraft. The baseline EME is expected to be higher on shipboard and hence the difference in the standard.

Table 2 below lists the base line EME applicable to aircraft, from the current MIL-STD-464. We also recall the most recent HIRF Standards provided in Appendix A and plotted here in Figure 3 and Figure 4.

Table 2. Baseline external EME for systems that include aircraft.

Frequency Hz	Environment (V/m – rms)	
	Peak	Average
10k-100k	50	50
100k-500k	60	60
500k-2M	70	70
2M-30M	200	200
30M-100M	30	30
100M-200M	150	150
200M-400M	70	70
400M-700M	4020	935
700M-1000M	1700	170
1G-2G	5000	990
2G-4G	6680	840
4G-6G	6850	310
6G-8G	3600	670
8G-12 G	3500	1270
12G-18G	3500	360
18G-40G	2100	750

In examining these standards, it is somewhat evident that the RF threat most likely to disrupt or cause serious problems in aircraft operation is either a tunable narrow band source or a moderate band (bandwidths of ~ 10 to 20 %) source. A hyperband source like the SWIRA [14] is not likely to have a lot of spectral content at any given frequency, unless it is integrated with MV sources as in JOLT [15,16].

Thus, RF threats are likely to come from:

- High-Power Microwave Sources (500 MHz to 12 GHz) [17, 18]
  -- Narrowband sources such as Magnetrons, Reltrons integrated with antennas such as pyramidal horns and horn-fed reflectors
- Damped Sinusoidal Source (100 MHz to 500 MHz) [19, 20]
- Switched Oscillators integrated with IRA or SWIRA-like antennas and also helical antennas, because of their lower profile.
- Marx pulsers integrated with dipole antennas such as DIEHL systems [21]
- IRA or SWIRA like antennas excited by high-power CW sources

The above listed systems some of which are mature technology, and some are evolving operate in the frequency ranges, where RF interfaces are present in nearly all civilian airports. For example, a damped sinusoidal oscillator system called MATRIX [22]

is capable of producing 2 kV/m electric field at a frequency of about 180 MHz, at a distance of 80m yielding an rE product of 160 kV. Consider a realistic distance of a distance of 400 m; the field will be 400 V/m at 180 MHz. This value far exceeds the MIL-STD-464 baseline EME for aircraft 150 V/m) as well as both Environment I (100 V/m) and Environment II (30 V/m) of HIRF.

8. Emerging Technologies and Potential RF Threats

It is observed that although the airport is gated and fenced, a potentially lethal and camouflaged vehicle can easily park within a few hundred meters of slant range to aircraft in landing and take-off phases of flight.

Vulnerable infrastructure elements in a typical airport (in decreasing order of significance)

1. Aircrafts (Landing and Take-off)

   Front and back door coupling to aircraft; *sensitive receivers and computers*

An example of front door coupling is via the antennas on the aircraft. Back door coupling is via apertures, slots, and slits on the aircraft skin.

Computer kill → passenger kill

2. Control Tower *(Operational disruption to aircraft traffic, radars, monitors etc*)

3. Airport Safety (Operational disruption to fire, security, and surveillance systems)

4. Terminal Area (*Operational disruption to* n*etworked computers)*

5. Ground Vehicles *(Operational disruption to ground operations)*

Looking at the RF vulnerability of an airport from an Electromagnetic spectrum point of view, it is noted that aircraft and airport operations cover a very broad range. The electronic equipment at the airport and others that support the airport system can be broadly classified into two groups as illustrated in Figure 15.

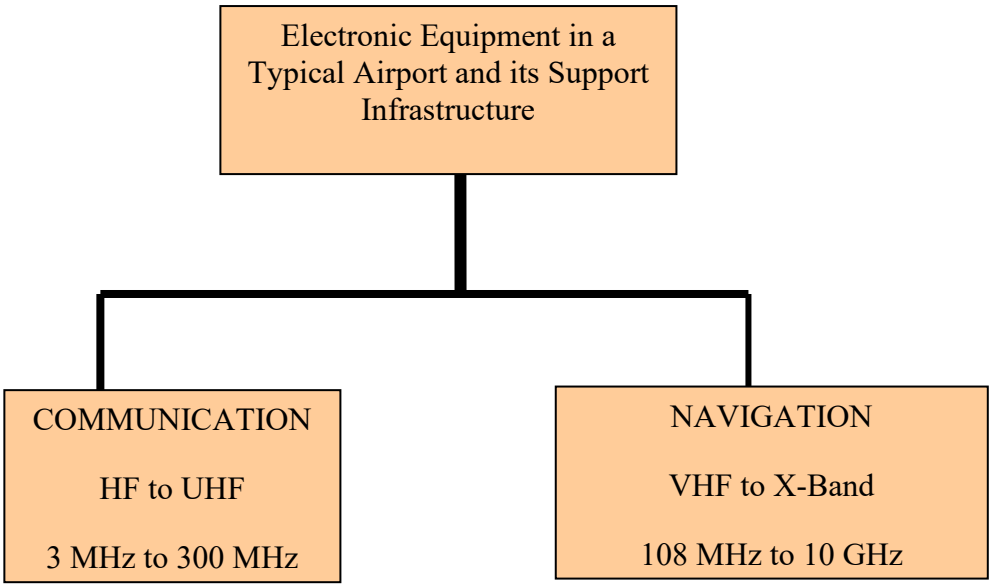

Figure 15. Electromagnetic Spectral View of RF Equipment in an Airport as a System

The breakdown of communication and navigational systems and their operating range of frequencies are indicated in Table 3. [23, 24].

It is noted that not all of the following equipment may be present at any given airport, but these are the ranges of equipment at typical airports.

Table 3. Electromagnetic Spectrum Covered by Equipment in an Airport System

#	Function	Frequency Range
	Communication Systems	**VHF to UHF** **[100 MHz to 500 MHz]**
1	Tower Communication Radio in generic location (an example of communication system)	118 – 137 MHz 220-380 MHz
	Typical Navigational Systems	**VHF to X-Band** **[108 MHz to 10 GHz]**
2	Distance Measuring Equipment DME	960 MHz to 1.215 GHz
3	Airborne Collision Avoidance System	950 MHz to 1.2 GHz
4	Global positioning System (GPS)	1.22 GHz to 1.57 GHz

5	Secondary Radar at generic location	1030 and 1090 MHz L-Band
6	Primary Radar at generic location	~ 2.4 GHz S-Band
7	Quad Radar at generic location	X-Band
5	Radio Altimeter	4.2 GHz to 4.4 GHz
8	Meteorological Radar	9.4 GHz

We can now consider a couple of examples of potential RF weapon system and its characteristics.

8.1 L-band (~ 1 GHz, 1 GW Source)

High-power microwaves (HPM) (≥ 100 MW) [18, 19] operating in a single-shot or with tens or hundreds of Hz repetition rates are being developed in various countries and they are reaching power levels in the GW range, and are also frequency agile. They can be used to create intense electromagnetic signals in the range of ~ 500 MHz to 3 GHz, that can couple to and cause electronic damage in many systems. Within this range, there exist accepted frequency-band designations in accordance with International treaty. The HPM systems under development occupy a frequency range of about 0.5 to 3 GHz, due primarily to the coupling effects and generic electronic system vulnerabilities. With the advent of sources capable of producing output powers in the GW range, there has been an interest in using high-power microwave devices in military defense applications to disrupt or destroy offensive electronic systems. Many nations are studying the feasibility of HPM systems. Some of these studies deal strictly with an understanding of coupling effects with the aim of being able to protect critical electronic (military and civilian) systems.

Such devices are proliferating and could come into the hands of hostile groups and pose potential threats to modern-day societies.

For illustrative purposes, consider a HPM system with the following characteristics [18]:

Frequency = 1.1 GHz Wavelength = 0.2727 m Period = 0.909 ns

Peak power = 2 GW Average power = 1 GW; single shot operation

Waveguide = WR-975 Pulse width = 100 ns; contains 110 cycles

One can show that with such a source and a horn-fed paraboloidal reflector antenna, it is possible to produce the following levels of fields and power densities at various ranges , as shown in Table 4.

Table 4. Far field Parameters of an L-band source / reflector antenna system

R (km)	E_{peak} (far field) kV/m	P_{avg} (far) kW/m^2	Fluence U J/m^2
1	12.8	220	2.2×10^{-2}
3	4.3	24	2.4×10^{-3}
10	1.3	2	2.2×10^{-4}
20	1.64	0.54	0.5×10^{-4}

The L-band HPM source considered in the above example is a commercial hardware. In addition, surplus radars in L-band (~ 1 GHz) and S- band (2.4 GHz) are easily procured and these are complete systems, which can be converted to weapon systems. Note that the far field parameters of Table 4, far exceeds both the MIL-STD 464 (1700 V/m) and the HIRF standards (700 V/m) even at a distance of 1 km.

There is the question of compactness and camouflaging such systems in trucks and hidden behind dielectric walls. The emerging technology of compact Marx pulsers, arrayed solid-state devices will make this happen sooner or later, since there do not seem to be any physics- based obstacles.

There is a certain essential similarity in all airports in terms of RF vulnerability. That is they all use electronic equipment for communication and navigation. The equipment may vary, but the frequency range of operation are the same. The discriminator between the airports is one of "range". In other words, how close can a camouflaged truck-mounted weapon system get to the airport? In earlier times, the civilian airports were built at large distances from residential areas , but the trend now-a-days is to have housing developments very close to the airports and thus increase the accessibility of airports to unauthorized individuals with hostile intentions. If such systems get closer to airports, they can have slant range accessibility to aircraft at 300-500m. Such ranges make it easier on the hostile systems.

If we consider the 1 GHz system of Table 4 above [18], and put its far field parameters on a curve of Fluence vulnerability [25], we see that the 1 GW source and a horn-fed reflector has a significant potential in upsetting/ causing damage to electronics , but is not powerful enough to cause biological damage. This can be seen in Curve A of Figure 16.

8.2 HPM Sources in the kW to MW Power Levels

In the context of civilian airport electronics systems and facilities, various elements of electromagnetic threat environments include:

a) Source characterization

b) Feed and antenna system

c) Propagation distances and losses

d) Coupling to the facility exterior

e) Transfer function to the system interior.

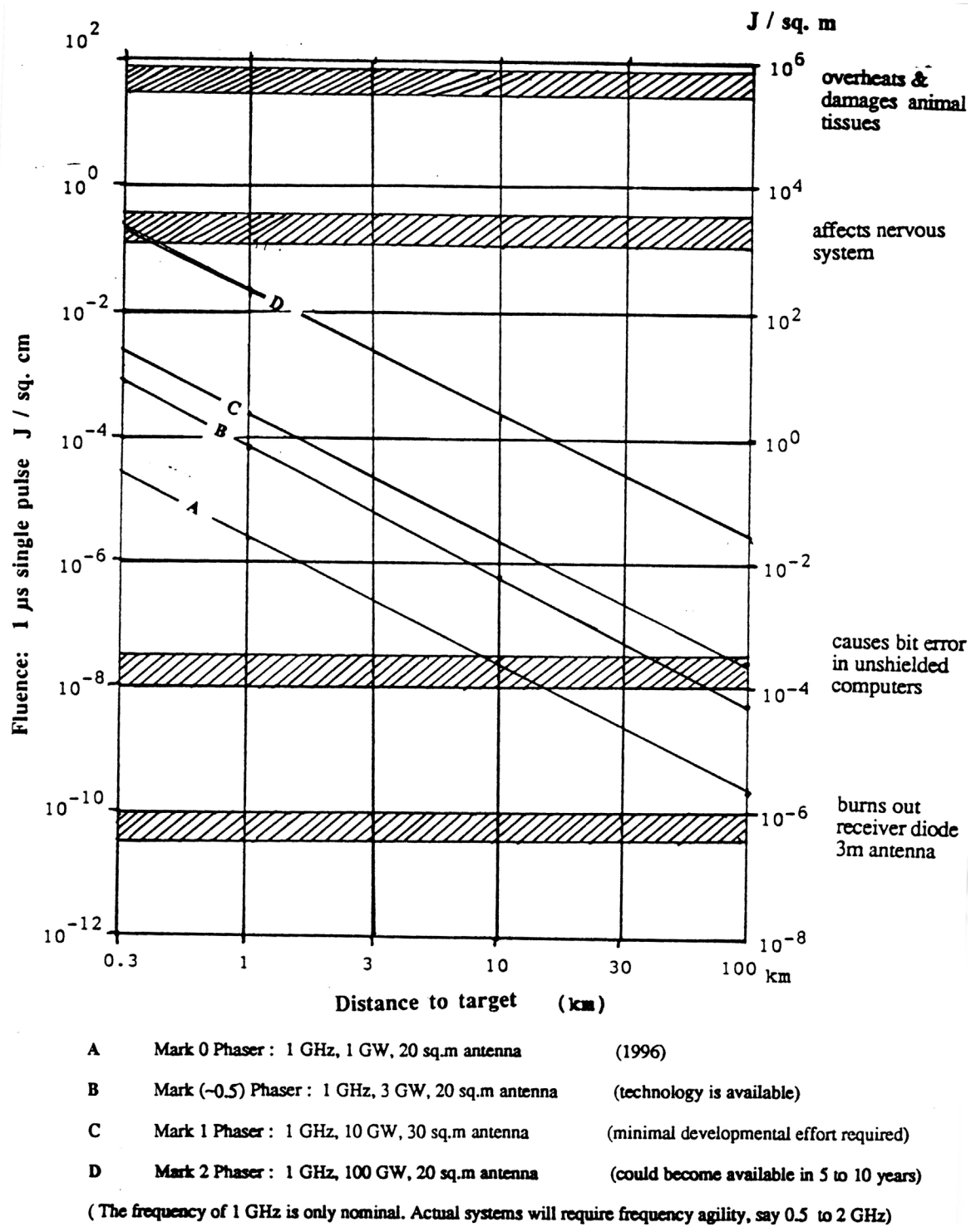

Figure 16. Fluence thresholds and performance of HPM weapon systems [18, 25]

The source is characterized by its output power, frequency, frequency agility, duration and repetition rates for pulsed sources and burst lengths. Feed and antenna systems in this frequency range of (200 MHz to 5 GHz) consist of electromagnetic horns and reflectors. This frequency regime covers a host of equipment in the airport system.

Frequency range	200 MHz to 5 GHz
Wavelength range	6 cm to 150 cm
CW source power (rms)	1 kW (microwave oven) to 10 MW (radar tubes)
CW source power (peak)	P = 2 kW to 20 MW (Twice the rms power for sinusoids)
Antenna aperture area	A = up to 10 m^2 (a practical sized antenna that can be truck mounted and be driven under overpasses and on bridges)
Peak e-field on radiating aperture	$E_0 = \sqrt{PZ/A}$
Peak radiated e-field	$E_f = E_0 A / (r \lambda)$

We assume an antenna aperture area A of 10 m^2 (which is easier to camouflage in a truck mounted system). The peak power P varies from 2 kW to 20 MW. Knowing P, Z = 377 Ohms and A =10 m^2 , we can easily calculate the aperture field E_o . The product of range and far field ($r E_f$) is then calculated using the formula above.

2 kW < P < 20 MW

274 V/m < E_0 < 27.4 kV/m (no antenna losses)

4.57 kV < $r E_f$ (at f = 0.5 GHz) < 457 kV

9.13 kV < $r E_f$ (at f = 1 GHz) < 913 kV

18.27 kV < $r E_f$ (at f = 2 GHz) < 1.83 MV

27.40 kV < $r E_f$ (at f = 3 GHz) <2.74 MV

CW sources that can produce average power levels in the range of 1 kW (continuous) to 10 MW (pulsed) are readily available today, and the estimates above appear to be environments that can be easily produced. We can now estimate the electric field levels as a function of frequency and range with the above commercial sources. This leads to the results in Table 5.

Table 5. Range of radiated electric field at various frequencies and power levels.

Frequency	Range	Range of e-field with an antenna aperture and output powers of 2 kW to 20 MW
500 MHz	**300m**	**15.23 V/m to 1.52 kV/m**
	1 km	**4.57 V/m to 457 V/m**
1 GHz	**300m**	**30.43 V/m to 3.04 kV/m**
	1 km	**9.13 V/m to 913 V/m**
2 GHz	**300m**	**60.90 V/m to 6.09 kV/m**
	1 km	**18.27 V/m to 1.83 kV/m**
3 GHz	**300m**	**91.33 V/ m to 9.13 kV/m**
	1 km	**27.40 V/ m to 2.74 kV/m**

The CW results indicate that with the commercially available sources that have rms outputs ranging from 1 kW to 10 MW, it is indeed possible to produce greater than 100 V/m signals at kilometer distances, with modest sized antennas. The frequency range of sources in the L-band is likely to cause more electronic damage than higher bands (10 GHz radar for example). While the 1 GW system considered in Section 8.1 may not yet be truck-mountable, the lower –power CW or pulsed HPM system that we have considered in Section 8.2 certainly is mountable in a camouflaged truck, in a way similar to what Dupouy [24] has illustrated. We show the Dupouy-scenario in Figure 17.

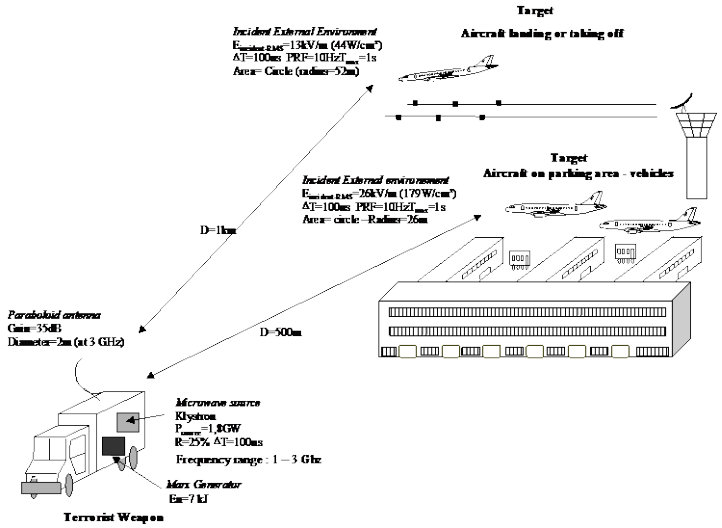

Figure 17. RF Threat scenario, as illustrated by Dupouy [24].

Dupouy [24] also presents a scenario of suitcase weapon aimed at computer networks inside a passenger terminal, as illustrated in Figure 18.

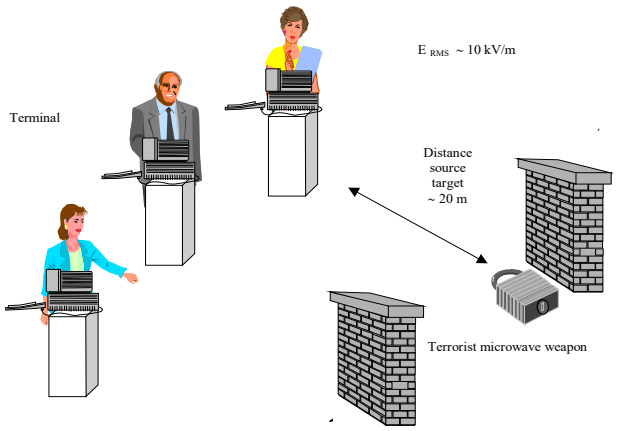

Figure 18. RF Threat Scenarios inside a Passenger Terminal aimed at Networked Computers.

Recently, two networked computers were illuminated at the HPE Laboratory with a switched oscillator source and a helical antenna. The source /antenna system produced a few kV/m of damped sinusoidal waveforms at 500 MHz, with a Q of about 6. The effect on the computer network was merely harmless noise and some temporary disruption on the screen with an immediate recovery. This suggests that the frequency of illumination was not the right one, since many other researchers have found more drastic effects on computers at much lower levels at other frequencies [7, 8 and 9]. In fact, some data loss, and upset type of effects have been observed at filed levels as low as 30 V/m, in the L and S bands of frequencies. It has been well known and established that the coupling of electromagnetic waves to electronic systems is strongly dependent on frequency Such suitcase systems are becoming commercially available, thus increasing the potential of RF threats.

9. Recommendations

The site survey is now complete at this generic Airport. The next steps can consist of two more phases:

9.1 Phase 1.

9.1.1. Determination of Operating RF Environments

The site survey that has been performed has resulted in a set of key places of the airport, where it would be desirable to measure the operating RF environment. This task would involve going to these parts of the airport and measure the EM environments that typically exist at different times of a typical day at the airport. It is noted that this task does not involve using any kind of transmitters, but consists of only passive sensors, network analyzers / oscilloscopes. The passive sensor acts like a broad band receiving antenna over a frequency range of (1MHz to 4 GHz) and measures the RF environment.

9.1.2. Determination of RF Threat Scenarios Including Electromagnetic Coupling to selected systems such as aircraft on the glide slope, control tower etc.

The results of the measured data will feed into a determination of what it takes to disrupt the airport operation. Given the public access and proximity to the glide path of the aircraft, control tower, etc., we can then go on to determine what type (frequency, power levels, antenna aperture, directivity etc.,) of an RF weapon that can be potentially disrupt airport operations. Are such mobile RF weapons feasible, given the state-of-the-art in source technology? What are the consequences for aircraft and airport operations?
Activities: Analyze several attack methods; several scenarios will be quantified. (Weapon type and characteristics, propagation losses, field on target)

9.1.3. Ranking of these Scenarios

It may become apparent that certain threats are less likely than others, and development of a set of criteria to rank these threat scenarios need to be developed, depending on the anticipated consequences of the threat.

9.1.4 Security Responses to the Attack Scenarios

Activities: Define measures which can be taken to counter the threat scenarios either before they occur or afterwards. Categories of response include

1) warning devices
2) shielding installation or upgrades, and
3) target hardening.

The purpose of sensors and monitors is to gather measured data like voltages and currents at critical nodes on a routine basis. If some abnormal readings are seen, certain security response actions would be triggered. This is an efficient way of determining there has been an RF attack (since such an attack leaves no trace) and take immediate preventive measures.

9.2 Phase 2

Implementation of sensors monitors, shielding installation and upgrades etc.

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Appendix A

HIRF Environments and Associated Testing Methods

(Federal Register, August 6, 2007 (Volume 72, Number 150), Rules and Regulations, Page 44015-44028. Taken from the Federal Register Online, via GPO Access wais.access.gpo.gov, DOCID: fr06au07-17.)

Appendix J to Part 23--HIRF Environments and Equipment HIRF Test Levels

This appendix specifies the HIRF environments and equipment HIRF test levels for electrical and electronic systems under Sec. 23.1308. The field strength values for the HIRF environments and equipment HIRF test levels are expressed in root-mean-square units measured during the peak of the modulation cycle. These requirements are summarized in Table A- 1 and Table A-2.

Table A-1. HIRF Environment I

	E-Field strength (Volts/meter)	
Frequency	**Peak**	**Average**
10 kHz-2 MHz	50	50
2MHz-30 MHz	100	100
30 MHz-100 MHz	50	50
100 MHz-400 MHz	100	100
400 MHz-700 MHz	700	50
700 MHz-1 GHz	700	100
1 GHz-2 GHz	2,000	200
2 GHz-6 GHz	3,000	200
6 GHz-8 GHz	1,000	200
8 GHz-12 GHz	3,000	300
12 GHz-18 GHz	2,000	200
18 GHz-40 GHz	600	200

In this table, the higher field strength applies at the frequency band edges.

Table A-2 HIRF Environment II

	E-Field strength (Volts/meter)	
Frequency	**Peak**	**Average**
10 kHz-500 kHz	20	20
500 kHz-2 MHz	30	30
2 MHz-30 MHz	100	100
30 MHz-100 MHz	10	10
100 MHz-200 MHz	30	10
200 MHz-400 MHz	10	10
400 MHz-1 GHz	700	40
1 GHz-2 GHz	1,300	160
2 GHz-4 GHz	3,000	120
4 GHz-6 GHz	3,000	160
6 GHz-8 GHz	400	170
8 GHz-12 GHz	1,230	230
12 GHz-18 GHz	730	190
18 GHz-40 GHz	600	150

In this table, the higher field strength applies at the frequency band edges.

Equipment HIRF Test Level 1.

1. From 10 kHz to 400 MHz, use conducted susceptibility tests with continuous wave (CW) and 1 kHz square wave modulation with 90 percent depth or greater. The conducted susceptibility current must start at a minimum of 0.6 mA at 10 kHz, increasing 20 decibels (dB) per frequency decade to a minimum of 30 mA at 500 kHz.
2. From 500 kHz to 40 MHz, the conducted susceptibility current must be at least 30 mA.
3. From 40 MHz to 400 MHz, use conducted susceptibility tests, starting at a minimum of 30 mA at 40 MHz, decreasing 20 dB per frequency decade to a minimum of 3 mA at 400 MHz.
4. From 100 MHz to 400 MHz, use radiated susceptibility tests at a minimum of 20 volts per meter (V/m) peak with CW and 1 kHz square wave modulation with 90 percent depth or greater.
5. From 400 MHz to 8 gigahertz (GHz), use radiated susceptibility tests at a minimum of 150 V/m peak with pulse modulation of 4 percent duty cycle with a 1 kHz pulse repetition frequency. This signal must be switched on and off at a rate of 1 Hz with a duty cycle of 50 percent.

Equipment HIRF Test Level 2.

Equipment HIRF test level 2 is HIRF environment II in table II of this appendix reduced by acceptable aircraft transfer function and attenuation curves.

Testing must cover the frequency band of 10 kHz to 8 GHz.

Equipment HIRF Test Level 3.

1. From 10 kHz to 400 MHz, use conducted susceptibility tests, starting at a minimum of 0.15 mA at 10 kHz, increasing 20 dB per frequency decade to a minimum of 7.5 mA at 500 kHz.
2. From 500 kHz to 40 MHz, use conducted susceptibility tests at a minimum of 7.5 mA.
3. From 40 MHz to 400 MHz, use conducted susceptibility tests, starting at a minimum of 7.5 mA at 40 MHz, decreasing 20 dB per frequency decade to a minimum of 0.75 mA at 400 MHz.
4. From 100 MHz to 8 GHz, use radiated susceptibility tests at a minimum of 5 V/m.

Appendix B.

Aviation Losses from Lightning Strikes

(National Lightning Safety Institute)

26.06.59 (ca. 17.35) Lockheed L-1649A Star liner
N7313C (1015) Trans World Airlines - TWA
Occupants: 9 crew + 59 passengers = 68
Fatalities: 9 crew + 59 passengers = 68.
Accident Occurred: During Climb
Location: Milano; 20 mi NW (Italy)
Flight: Milano-Malpensa APT - Paris-Orly Flight Number: 891
Source: ICAO Accident Digest Circular 62-AN/57 (132-152)

12.08.63 (13.19 GMT) Vickers 708 Viscount
F-BGNV (39) Air Inter [year built: 1954]
Occupants: 4 crew + 16 passengers
Fatalities: 4 crew + 16 passengers
3rd party fatalities: 1
Accident Occurred: Initial Approach
Location: Lyon; 24 km N (France)
Flight: Lille - Lyon-Satolas APT Flight nr.: 2611
Source: ICAO Accident Digest No.15 - Volume II, Circular 78- AN/66 (179-185)

08.12.63 Boeing 707-121
N709PA (17588/3) Pan American World Airways [year built:1958]
Occupants: 8 crew + 73 passengers
Fatalities: 8 crew + 73 passengers
Accident Occurred: Initial Approach
Location: Elkton, MD (USA)
Flight: Washington-Baltimore IAP, DC - Philadelphia IAP Flight Number.: 214
Total airframe flying hours: 14609; cycles
Comments: In-flight explosion of fuel tank due to lightning strike.
Source: ICAO Accident Digest No.15 - Volume II, Circular 78- AN/66 (121-133)

24.12.71 (12.36) Lockheed L-188A Electra
OB-R- 941 (1086) LANSA [year built: 1959]
Occupants: 6 crew + 86 passengers
Fatalities: 6 crew + 85 passengers
Accident Occurred: Cruise
Location: Puerto Inca (Peru)
Flight Lima-Jorge Chavez IAP – Flight Number.: 508
Comments: About forty minutes after take-off, the aircraft entered a zone of strong turbulence and lightning. After flying for twenty minutes in this weather at FL210 lightning struck the aircraft, causing fire on the right wing which separated, along with part of the left wing. The aircraft crashed in flames into mountainous terrain. Structural failure occurred because of the loads imposed on the aircraft flying through a severe thunderstorm, but also because of stresses resulting from the maneuvers to level out the aircraft.
Source:

09.05.76 (14.35 GMT) Boeing 747-131F
5-8104 (19677/73) Islamic Republic of Iran Air Force [year built: 1970]
Occupants: 10 crew + 7 passengers
Fatalities: 10 crew + 7 passengers
Freight loss
Accident Occurred: Descent
Location: Madrid; nr (Spain)
Flight Tehran-Mehrabad IAP - Madrid-Torrejon AFB Flight Number: 48
Comments: The Boeing was operated on a military logistic flight from Tehran to McGuire AFB via Madrid. The flight took off from Tehran at 08.20h GMT and climbed to a cruising altitude of FL330. After establishing contact with Madrid control, clearance was received to CPL VOR via Castejon. At 14.25h the flight was cleared to FL100. At 14.30 the crew advised Madrid that they were diverting to the left because of thunderstorm activity, and at 14.32 Madrid cleared ULF48 to 5000ft and directed him to contact Madrid approach control. At 14.33 the crew contacted approach control and advised them that there was too much weather activity ahead and requested to be vectored around it. Last radio contact was when ULF48 acknowledged the 260deg heading instructions and informed Madrid that they were descending to 5000ft. The aircraft was later found to have crashed in farmland at 3000ft msl following left wing separation. It appeared that the aircraft had been struck by lightning, entering a forward part of the aircraft and exiting from a static discharger on the left wingtip. The lightning current's conductive path to the static discharger at the tip was through a bond strap along the trailing edge. Concentration of current at the riveted joint between this bond strap and a wing rib were sufficient conductive to cause the flash to reattach to this rivet and to leave the discharger. Fuel vapors in the no.1 fuel tank then ignited. The explosion caused the upper wing skin panel to separate, causing a drastic altering of the aero-elastic properties of the wing, and especially the outboard section of wing. The outer wing began to oscillate, developing loads which caused the high-frequency antenna and outer tip to separate. The whole wing failed a little later.
Source: FI 15.5.76(1283); NTSB-AAR-78-12

05.09.80 Lockheed L-100-20 Hercules
KAF317 (4350) Kuwait Air Force
Occupants: crew + passengers
Fatalities: crew + passengers
Location: Montelimar; nr (France)
Comments: Crashed after lightning strike.
Source: FI 03.01.1981 (29)

08.02.88 (07.58) Swearingen SA.227AC Metro
D-CABB (AC-500) Nrnberger Flugdienst - NFD
Occupants: 2 crew + 19 passengers
Fatalities: 2 crew + 19 passengers
Accident Occurred: Initial Approach
Location: Mulheim; nr (Germany)
Flight Hannover-Langenhagen APT - Düsseldorf Flight Number.: 108
Comments: The Metro aircraft suffered a lightning strike, following which the electrical system failed. The right wing broke off in an uncontrolled descent and the aircraft disintegrated.