Defense Systems Information Analysis Center

Shielding Against Unwanted Electromagnetic (EM) Waves

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What Will We Cover?

- Unwanted EM Waves – Why Should I Care?
- EM Radiation Basics
- Unwanted EM/Electromagnetic Interference (EMI) and Its Sources
- Protection
- Current, Common EM Shielding Materials
- State-of-the-Art EM Shielding Materials
- Upcoming EM Shielding Materials
  - Legislation
  - Standards
  - Implementation
- Access to Materials

Unwanted EM Waves – Why Should I Care?

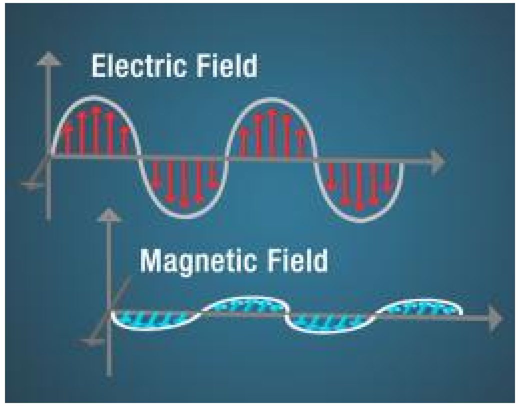
- Future wars with near-peer adversaries will revolve greatly around our ability to deploy weapons with embedded electronics.
- For these to work properly and consistently, proper EMI protection needs to be applied.
- This relates BOTH to direct defense infrastructure and civilian infrastructure that is directly and indirectly critical to defense.

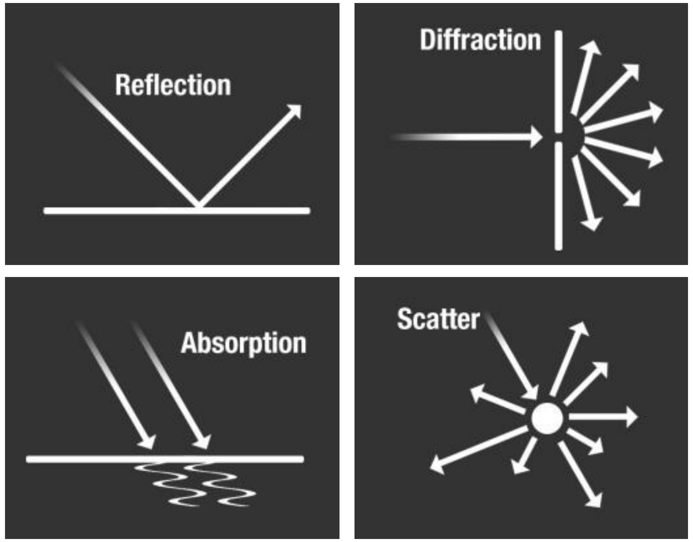
Ohio National Guardsmen (taken from defense.gov)

Active Electronics on Military Systems (taken from HPC.mil)

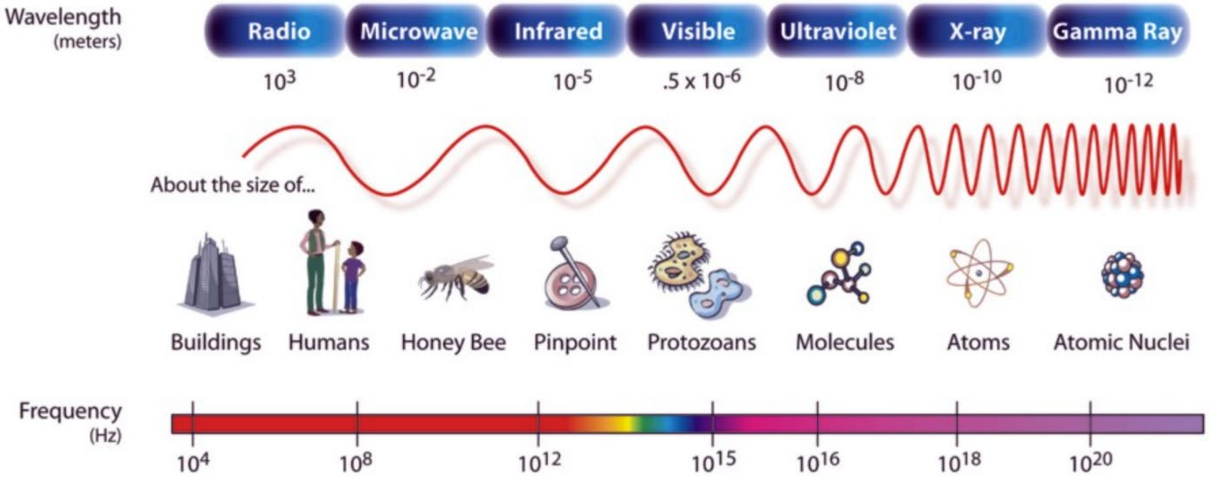
Electromagnetic (EM) Radiation Basics

- EM radiation is a traveling wave of oscillating electric and magnetic fields.
- EM waves are ubiquitous in today's world.
- The wavelength and frequency of these fields decide how the waves interact with normal matter.
- Many different electronics operating in close proximity can cause problems for many different devices (EMI).
- EMI is the result of the effect of an "unwanted" wave picked up at a receiver.





(Taken from NASA.gov)



(Modified from NASA.gov)

So… Where Does EM Radiation Come From?

Everything! Humans, cell phones, incandescent light bulbs, etc.

One can classify EMI in several ways – here, we choose to distinguish them as natural and man-made.

Natural

- Lightning
- Auroras
- Solar flares

Man-made

- Radios
- Cell phones
- Appliances
- The list goes on!

Terrestrial Source - Lightning (taken from Army.mil)

Man-Made Source – Comm Device (taken from Army.mil)

Electromagnetic Interference (EMI)

- For an electronic device to “interfere” with another one, it must produce an electric field (signal) at a frequency close to that of the “victim” device.
- Results in modulation (amplification or reduction).
- Examples…
  - Radio crackling
  - Electric motors causing spikes in power lines
  - Noise in laboratory data
- Extraterrestrial (almost exclusively natural, minus launched spacecraft still transmitting).
- Terrestrial (combination of natural and man-made).

Sources of EMI - Extraterrestrial

- Sources are solar or cosmic.
- Primary source of solar EM is the Sun.
  - Multiple forms, board spectrum (radio to gamma rays)
  - Solar winds radiate EM via stream of charged particles
  - Solar winds interact with Earth's magnetic fields
  - Solar storms (flares)
- Cosmic sources are usually weaker.
  - Cosmic radiation (includes all EM waves)
  - Cosmic rays (charged particles) – these are the greater challenge in space; they are filtered out or deflected by the Earth's atmosphere

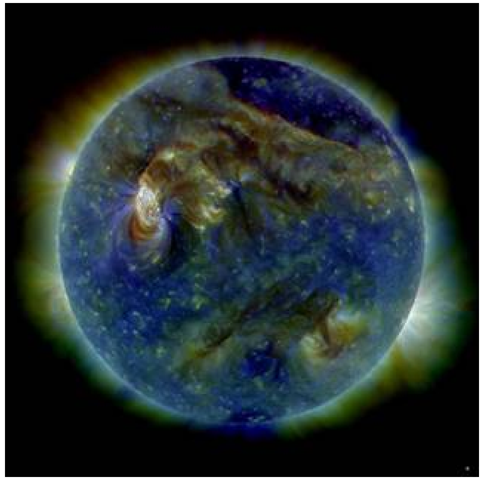
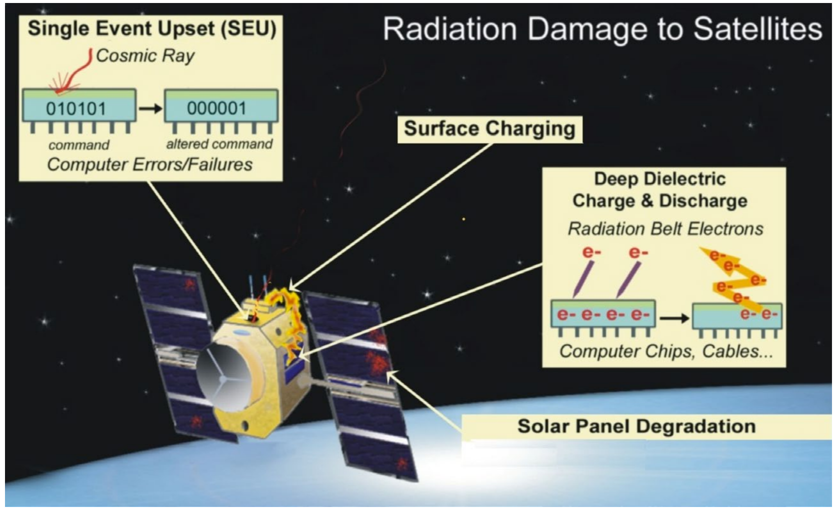


Image of Sun, Extreme UV (NASA/SDO)



Possible Radiation Effects on Military Satellites (NASA)

Sources of EMI - Terrestrial

- Almost countless sources of terrestrial EM.
- These can act to interfere with other transmitters/ receivers (EM interference – EMI).
  - Natural
  - Man-made (most common)
    - Intentional (HEMP weaponry, X-ray machine, transmitters)
    - Unintentional (noise from a computer chip, electric motors, etc.)

Application	Frequency or Range
AM Radio Broadcasts	~530 kHz - 1.7 MHz
Broadcast TV	54-88, 174-261, 470-698 MHz
FM Radio Broadcasts	88-108 MHz
Cell Phone Signals	~850, ~900, ~1800, ~1900 MHz
Global Positioning Systems (GPS)	~1.5 GHz
Satellite Radio	~2.3 GHz
Wireless Computer Networking	2.4 and 5.8 GHz
Satellite TV	12 GHz
5G Bands	Hi-band: 24, 28, 37, 39, 47 GHz Mid-band: 2.5, 3.5, 3.7-4.2 GHz Low-band: 600, 800, 900 MHz Unlicensed: 5.9, 6, >95 GHz
6G Bands (Future)	FCC has granted the 95-GHz to 3-THz band for 6G research (will require clear line-of-sight for transmit/receive)

Protection

Shielding

- Physical materials to reflect, absorb, or both against EM radiation
- Built into components/ assemblies of devices that need to be shielded

Regulation

- Takes the form of standards (IEEE, mil-spec, ASTM), etc.
- Takes the form of legislation in some cases or executive orders

Implementation

- There are many ways to marry physical protections and regulations to protect both civilian and military assets from EMI

Regulation - Legislation

First line of defense – affects 10 defense critical industries:

1. Financial Services
2. Transportation
3. Public Works
4. Global Information Grid Command and Control
5. Intelligence, Surveillance, and Reconnaissance
6. Health Affairs
7. Defense Personnel
8. Defense Space Infrastructure
9. Logistics
10. Defense Industrial Base

Legislation

- Due to complexity – no overarching piece of legislation
- Presidential directives have been used (PDD-63)
- Congress has passed limited scope laws (Cybersecurity and Infrastructure Security Agency Act of 2018)
- FY20 National Defense Authorization Act, Section 1740 "Electromagnetic Pulses and Geomagnetic Disturbances" – Public Law 116-92

Regulation - Standards

- Designing for EM shielding is not easy.
- Measuring shielding effectiveness is not always straightforward.
- Standards have been by adopted a number of different entities:
    - Military (MIL-STD/MIL-HDBK)
    - IEEE (Institute of Electrical and Electronics Engineers)
    - ASTM International (American Standard Test Method)
    - NSA (National Security Agency)
    - FCC (Federal Communications Commission)
    - ANSI (American National Standards Institute)
    - Many other international standards

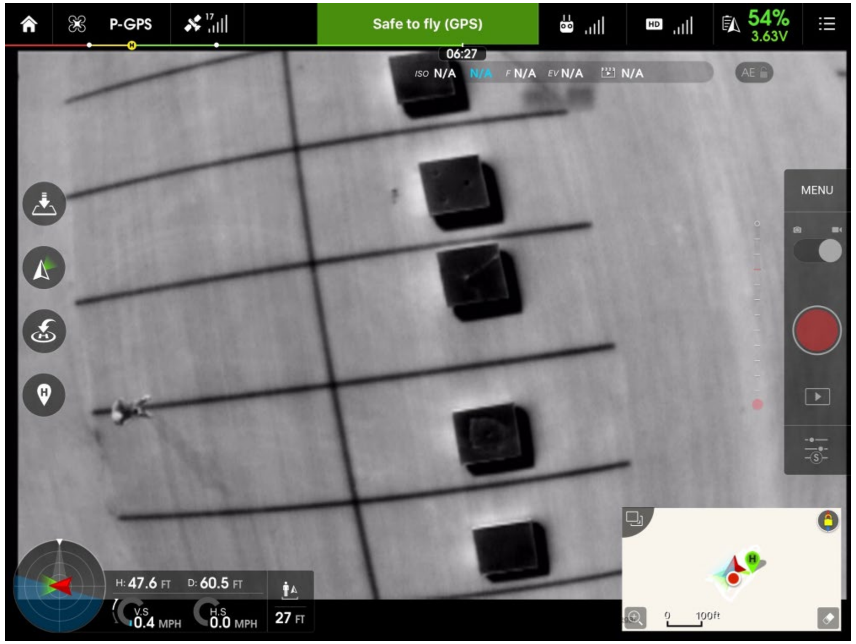
Implementation - Civilian Examples of EMI Protection

Building Materials and Construction Philosophies

- Guided by regulations and standards
- Building materials can act as EMI shields
- Filler materials added to plaster or drywall
- Current efforts focusing on adding small amounts of low-cost additives to keep materials affordable

Telecommunications

- Guided by regulations and standards
- Wired and wireless devices
- Civilian aerospace
- Civilian GPS

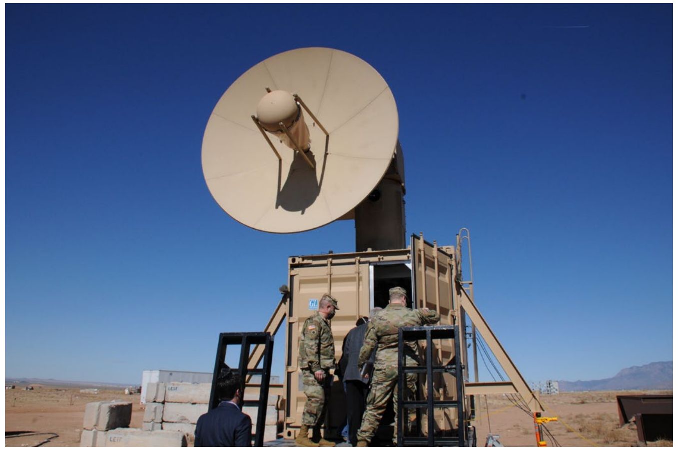


(Taken from AFRL report – Motes, 2016)

Implementation - Military Examples of EM Protection

- Guided by MIL-SPEC/MIL-HDBK
- GPS
- Heat-Seeking Missile Countermeasures
- Future Implementation of Weaponized EM/EMI
  - Intentional jamming
  - Spoofing (potential cause of RQ-170)
  - Non-nuclear EMPs
  - Non-explosive, high-power microwave warhead
  - Microwave attack on personnel

Ensuring UAV Safety During Missions (taken from AF.mil)

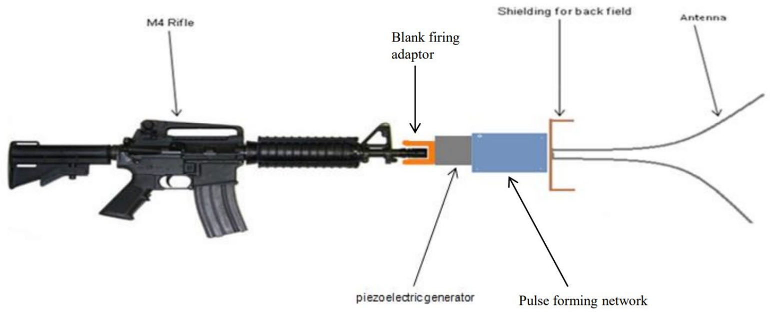


THOR High-Power Microwave System (taken from AF.mil)

Implementation - Military EM Shielding

Electromagnetic Pulses

- Surge of current produces a high voltage pulse
- Can be induced purposefully as a weapon
- High-Altitude EMPs (HEMPs)
- Considered a threat to critical infrastructure



Burke Pulser (U.S. Army RDECOM)

Stealth

- Works via combination of reflecting/absorbing EM waves with different materials
- Many ongoing efforts in the materials science regime to improve this technology

B-2 Bomber (AF.mil)

Implementation - Military EM Shielding

Sensitive Compartmentalized Information Facilities (SCIFs)

- Electronic connections/cables
- Any openings in/out

President Obama and National Security Team in White House Situation Room During Operation Neptune Spear (obamawhitehouse.archives.gov)

Undersea Cables

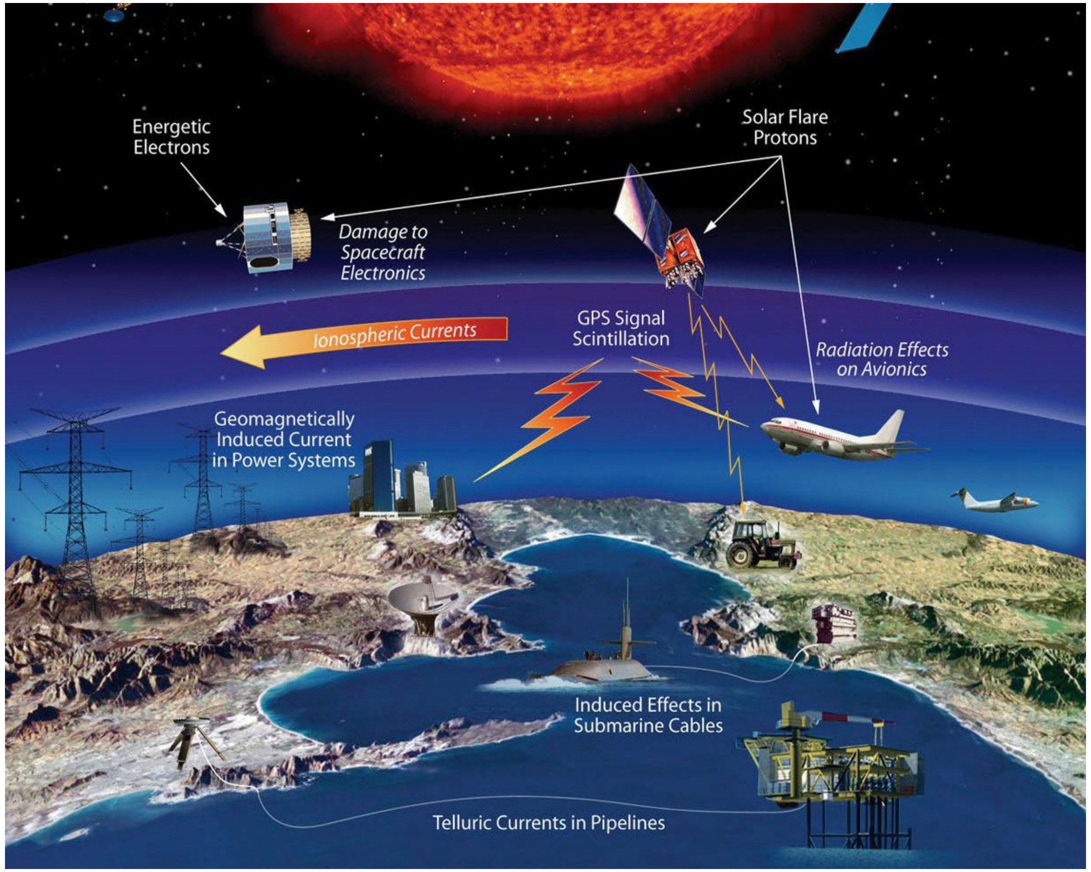
- Upgrades are making tapping into these harder
- Potential for undersea eavesdropping still exists

(Taken from FCC.gov)

Military EM Shielding

Satellite Protection

- There are several unique problems associated with EM shielding in satellites
- Cosmic rays/radiation (high-energy particles – "ionizing radiation")
- Magnetic storms
- Van Allen radiation belts
- HEMPs



Artist's Rendition of Effects of Solar Radiation on Space and Ground Systems (NASA, 2020)

Beyond Regulations, Standards, and Legislation

- Ultimately, defeat of EMI is a materials problem and solution.
- Materials challenge – an EM wave has two components:
  - Magnetic Field
  - Electric Field
- The challenge arises when field frequency comes into play.
  - "Low" frequency (DC to ~10 kHz)
  - "High" frequency (> ~10 kHz)

Materials Science Research for EM Shielding

- Research and development (R&D) for shielding materials is focusing on the study and creation of new and more effective materials for EM shielding.
- This is particularly true for the “high” frequency range.
- Current, commonly deployed commercially available materials are often:
  - Heavy (high density)
  - Expensive
  - Inflexible
  - Opaque
  - Have supply chain issues
  - Susceptible to corrosion (metals)
  - Have low-impact resistance

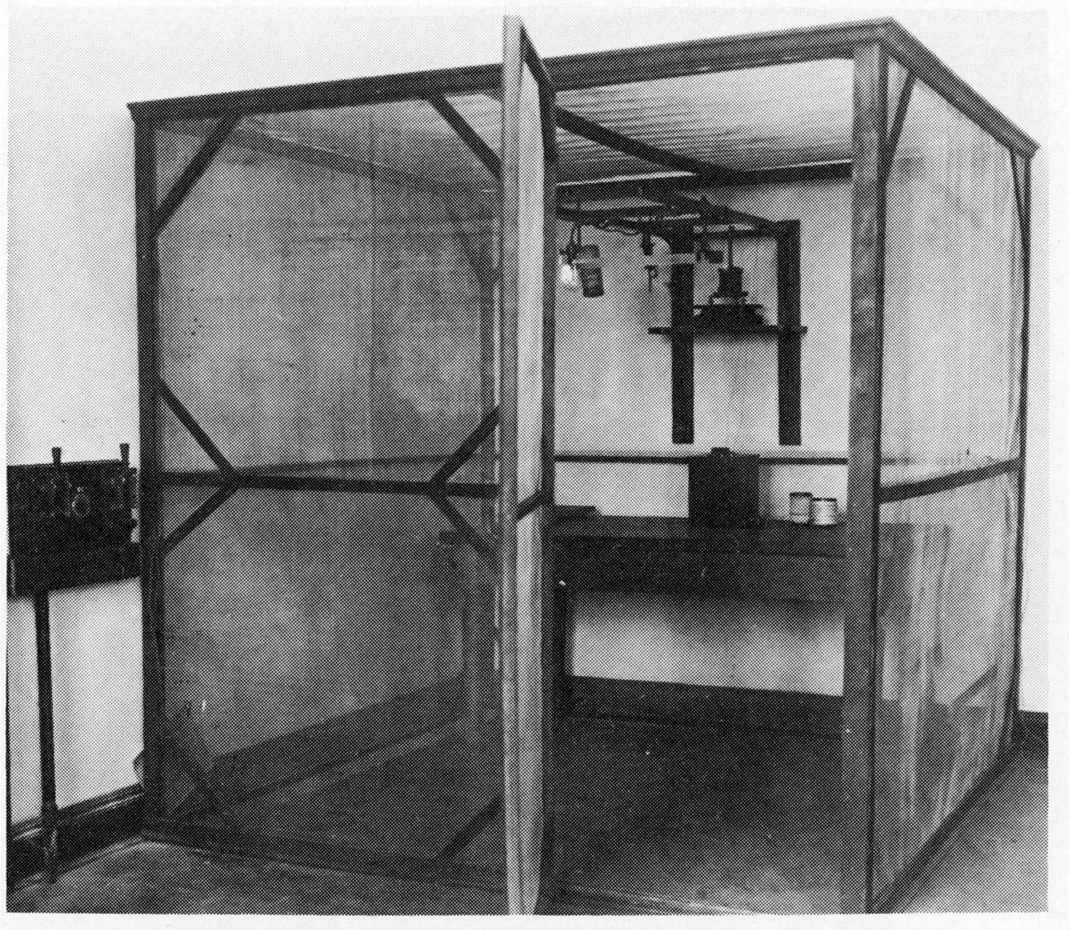
Common EM Shielding

Low Frequency

- Most electrically conductive materials will provide good EMI screening (Fe, Ni, or Co).
- Faraday cages are common.
- Cost effective, but heavy.

High Frequency

- Material electrical conductivity becomes the predominate factor governing shielding.
- In general, the more conductive the material, the better it acts as an "EM mirror" to reflect a wave.



Faraday Cage (taken from NIST.gov)

Current Materials – State of the Art

Ferrite-Based Materials

- Mn-Zn, Ni-Zn, Sr, Ba, Co
- Used to make magnetic cores in devices requiring highly conducting materials (transformers, antennas, and electric motors)

Mu-Metals

- Blend of Fe and Ni
- Soft ferromagnetic
- High relative permeability

Metglas

- Thin amorphous metal alloy ribbon
- Non-crystalline
- Rapid solidification process creates unique ferromagnetic properties, allowing it to be magnetized and de-magnetized
- Very low core losses

Mu Metal Enclosure (taken from osti.gov [Sandia National Labs])

Current Materials – State of the Art

Carbon Allotropes

Graphene

- Single atomic sheet of graphite
- Available commercially as exfoliated graphene, but research continues
- Limited in terms of SE by number of layers used

Carbon Fiber

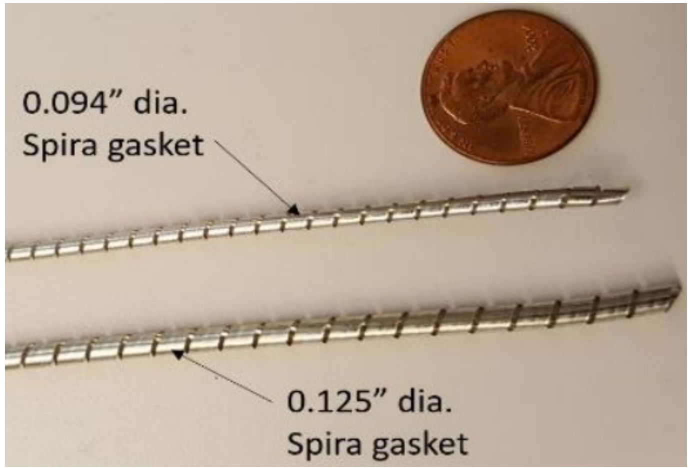
- Composites
- Infused into thermoplastics

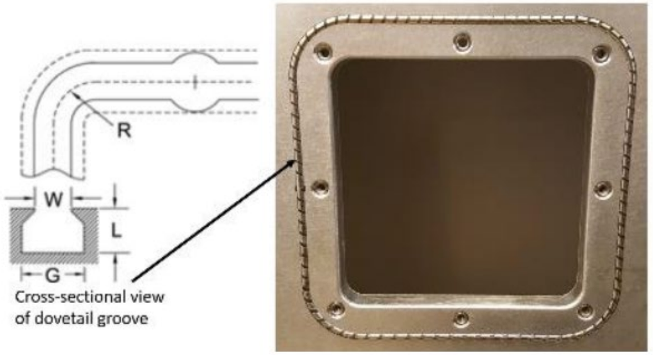
Reduced Graphene Oxide

- Easier to produce than graphene

Flexible Graphite

- Used when a typical metallic is ineffective
- Primarily used for sealing industry





EMI Shielding Gasket Material for NASA Europa Clipper Shielding (NASA)

Current Materials – State of the Art

Polymers With Additives

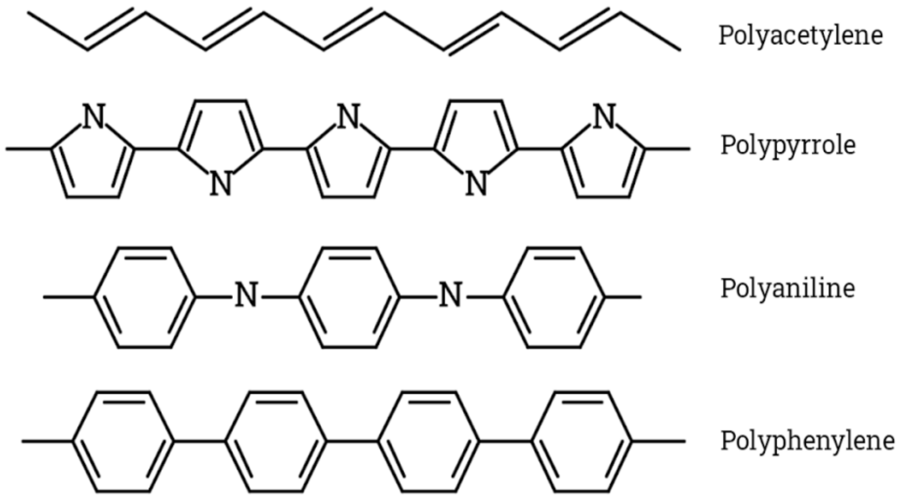
- Thermoplastics with metallic or other particles
- Capable of being 3D printed
- Absorb EM rather than reflect

Coated Polymers

- Absorb EM rather than reflect
- Lightweight and improved processibility

Intrinsically Conducting Polymers (ICPs)

- Conductivity from alternating double and single bonds
- Not widely deployed due to issues with mechanical and chemical stability



Examples of Conductive Polymer Chains

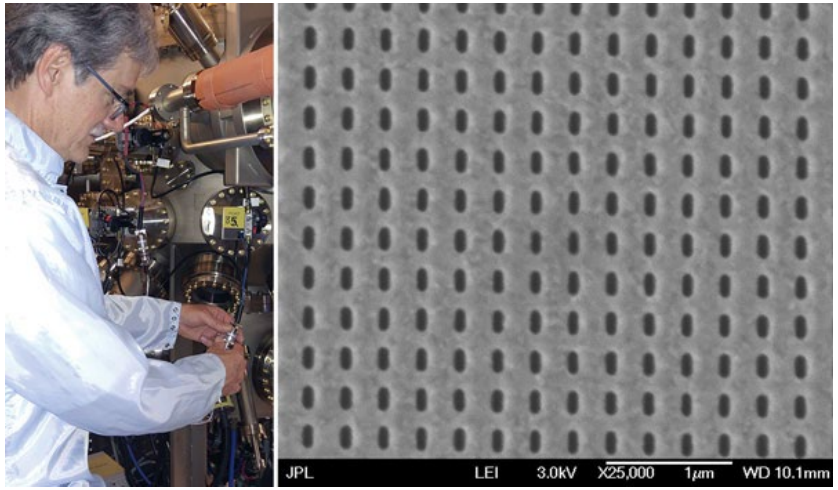
New Materials and Applications

Research is ongoing into the following areas for EM shielding:

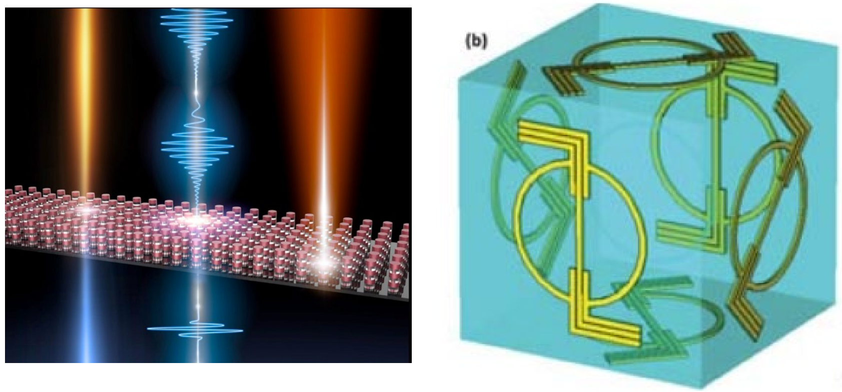
- Naturally derived materials for EM shields
- Thermoset polymers
- Elastomer-based materials
- Polymeric blends
- Biodegradable polymeric materials
- Nanomaterials (carbon and hybrid polymeric)
- Carbon-based reinforced composites
- Ceramics
- Cement based
- Textiles
- High-temperature EM shields
- Further information on this is available in **"Materials for Potential EMI Shielding Applications, Processing, Properties, and Current Trends," J. Kuruvilla, 2020.**

Upcoming Area - Metamaterials

- Metamaterials are a VERY broad category.
- Geometric arrangement of material resulting in EM properties is much different than bulk materials.
- Example – PCBs shown here provide a negative refractive index (a negative refractive index in water is shown).
- At certain frequencies, a metamaterial can be engineered to have a negative refractive index.



2D Metasurface (JPL – NASA)



Metamaterials to Modify EM Waves (Sandia.gov)

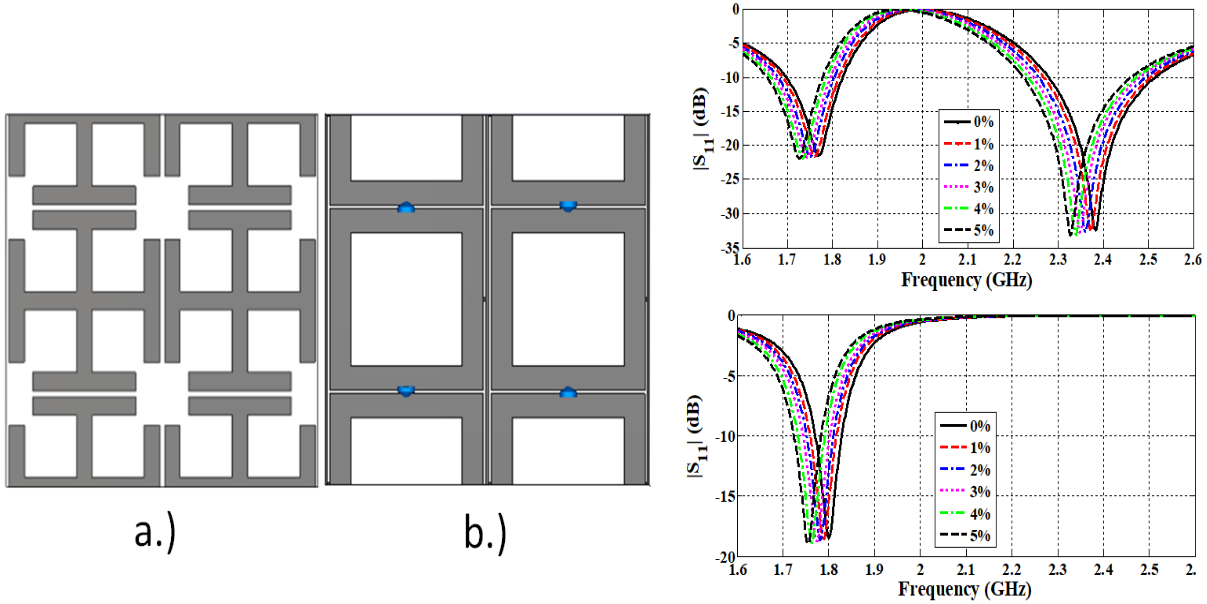
Upcoming Area - Metamaterials

- How do we visualize this?
- A metamaterial takes divergent EMI and focuses it to a point in space (acts as a lens)
- In other configurations, incoming waves are bent around an item to emerge on the other side (analogous to a Star Trek cloaking device) – this was demonstrated in 2003.
- Also possible to have a metamaterial where an incoming wave is completely blocked; a perfect EM shield (invisibility cloak)

  -For electronic devices, they would operate as close to a theoretical perspective as possible.

Upcoming Area - Metamaterials

- Metamaterials are frequency dependent (used for specific antenna or frequency filters).
- Shielding is possible within certain frequency bands (tailoring shielding).
- Research is in progress on this topic over all the different branches of the DoD and NASA.



Developmental Work by Dr. Kristen Donnell of Missouri University of Science and Technology on Frequency Selective Surfaces (2020)

Upcoming Area - Metamaterials

Types:

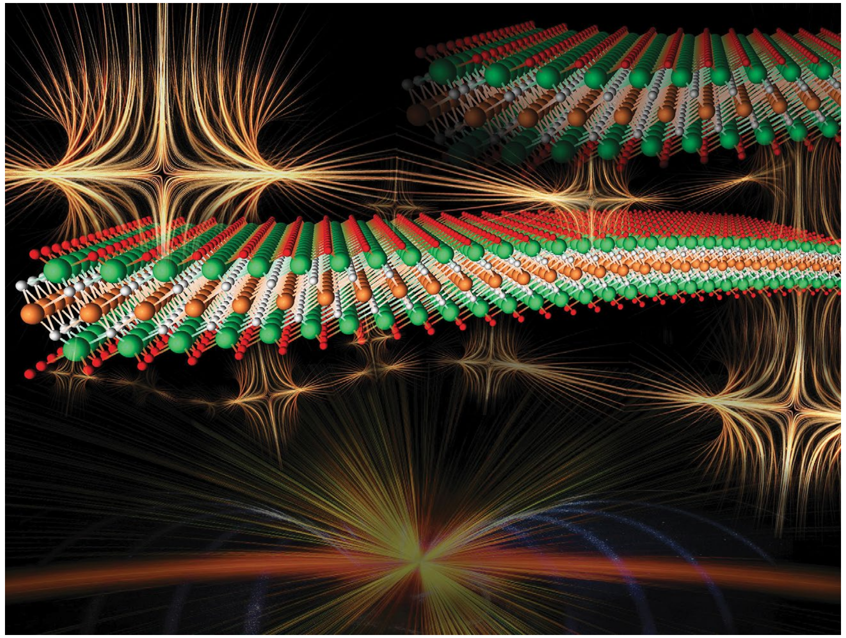
- Negative refractive index
- Single negative
- Hyperbolic
- Bandgap
- Double positive medium
- Bi-isotropic and bi-anisotropic
- Frequency selective surface

EM Applications:

- Antennas
- Absorbers
- Super lens
- Cloaking device
- Radar X-section reduction

Upcoming Area - MXenes

- 2D organic compound – synthesized in 2011
- Materials made by chemical modifications of bulk material (to produce layered materials) via a top-down selective etching process
- Shown to be scalable
- Applied to substrates via spray coatings for use as:
  - Antennas
  - Optoelectronic devices
  - Surface-group-dependent superconductivity
  - Conductive coatings



Artistic Rendering of Mxene Films Surrounded by Magnetic Field Lines (taken from als.lbl.gov)

Upcoming Area – 3D Printing Shielding

- Thermoplastics can be made to act as a delivery mechanism for any number of potential EM shielding particles.
- Far cheaper and faster than molding plastics.
- Recent work (2018) showed that 3D printed material as an EM shield prototype worked, although not as effectively as pressed plastic material.
- 3D printing could be used to apply a thermoplastic EM shield to any number of surfaces.
- This is a rapidly evolving technology - much research continues to focus on this area.

Upcoming Area – 3D Printing Shielding

- Printing can be used to apply EM shielding coatings to substrates.
- In this way, there are many potential paths forward for EM shielding to exist:
  - Shielding over specific frequency ranges
  - Lightweight, optimized shields
  - Geometric optimization

3D Printing (taken from Army.mil)

Manufacturing and Markets for EM Shielding Materials

- Thomasnet.com has 377 companies listed under "EMI/RFI Shielding Suppliers"
- The robustness of the domestic and global markets provides manufacturers with many different options for shielding designs.
- Simultaneously, recent disruptions in the supply chain point to instances where the global supply chain has experienced shortages due to:
  - Single material sources or
  - Large markets shares of a particular material

Supply Chain Challenge Examples

Texas 2021 Winter Storm

- Adverse affects on power grid have affected worldwide polymer production
- Freeze in TX shut down chemical plants used as part of polymer production

(Taken from Weather.gov)

U.S. Foreign Dependance for Precious Metals

- U.S. Geological Survey (USGS) reported that United States was 100% dependent on foreign sources for 20 of the 90 material commodities that USGS tracks
- Biggest importers are:
  - China
  - Canada
  - Brazil
  - South Africa

Supply Chain Challenges

USGS determined reliance on foreign countries for materials used in military and consumer electronics and shielding (taken from USGS.gov)

Commodity	Percent	Major import sources (2012–15)
ARSENIC	100	China, Japan
ASBESTOS	100	Brazil
CESIUM	100	Canada
FLUORSPAR	100	Mexico, China, South Africa, Mongolia
GALLIUM	100	China, Germany, United Kingdom, Ukraine
GRAPHITE (natural)	100	China, Mexico, Canada, Brazil
INDIUM	100	Canada, China, France, Belgium
MANGANESE	100	South Africa, Gabon, Australia, Georgia
MICA, sheet (natural)	100	China, Brazil, Belgium, Austria
NIOBIUM (columbium)	100	Brazil, Canada
QUARTZ CRYSTAL (industria	100	China, Japan, Romania, United Kingdom
RARE EARTHS	100	China, Estonia, France, Japan
RUBIDIUM	100	Canada
SCANDIUM	100	China
STRONTIUM	100	Mexico, Germany, China
TANTALUM	100	China, Kazakhstan, Germany, Thailand
THALLIUM	100	Germany, Russia
THORIUM	100	India, France, United Kingdom
VANADIUM	100	Czech Republic, Canada, Republic of Korea, Austria
YTTRIUM	100	China, Estonia, Japan, Germany

GEMSTONES	99	Israel, India, Belgium, South Africa
BISMUTH	95	China, Belgium, Peru, United Kingdom
TITANIUM MINERAL CONCENTRATES	91	South Africa, Australia, Canada, Mozambique
POTASH	90	Canada, Russia, Chile, Israel
GERMANIUM	85	China, Belgium, Russia, Canada
STONE (dimension)	84	China, Brazil, Italy, Turkey
ANTIMONY	83	China, Thailand, Bolivia, Belgium
ZINC	82	Canada, Mexico, Peru, Australia
RHENIUM	81	Chile, Poland, Germany
GARNET (industrial)	79	Australia, India, South Africa, China
BARITE	78	China, India, Morocco, Mexico
FUSED ALUMINUM OXIDE (crude)	>75	China, Canada, Venezuela
BAUXITE	>75	Jamaica, Brazil, Guinea, Guyana
TELLURIUM	>75	Canada, China, Belgium, Philippines
TIN	75	Peru, Indonesia, Malaysia, Bolivia
COBALT	74	China, Norway, Finland, Japan
DIAMOND (dust grit, and powder)	73	China, Ireland, Romania, Russia
PLATINUM	73	South Africa, Germany, United Kingdom, Italy
IRON OXIDE PIGMENTS (natural)	>70	Cyprus, France, Austria, Spain
IRON OXIDE PIGMENTS (synthetic)	>70	China, Germany, Canada, Brazil
PEAT	69	Canada
SILVER	67	Mexico, Canada, Peru, Poland
CHROMIUM	58	South Africa, Kazakhstan, Russia
MAGNESIUM COMPOUNDS	53	China, Brazil, Canada, Australia
ALUMINUM	52	Canada, Russia, United Arab Emirates, China
IODINE	>50	Chile, Japan
LITHIUM	>50	Chile, Argentina, China
SILICON CARBIDE (crude)	>50	China, South Africa, Netherlands, Romania
ZIRCONIUM MINERAL CONCENTRATES	>50	South Africa, Australia, Senegal
ZIRCONIUM (unwrought)	>50	China, Japan, Germany
BROMINE	<50	Israel, China, Jordan
MICA, scrap and flake (natural)	48	Canada, China, India, Finland
PALLADIUM	48	South Africa, Russia, Italy, United Kingdom
TITANIUM (sponge)	41	Japan, Kazakhstan, China
SILICON	38	Russia, China, Canada, Brazil, South Africa
COPPER	34	Chile, Canada, Mexico
LEAD	30	Canada, Mexico, Republic of Korea, Peru
VERMICULITE	30	Brazil, South Africa, China, Zimbabwe
MAGNESIUM METAL	<30	Israel, Canada, China, Mexico
NITROGEN (fixed)—AMMONIA	28	Trinidad and Tobago, Canada, Russia, Ukraine
TUNGSTEN	>25	China, Canada, Bolivia, Germany
NICKEL	25	Canada, Australia, Norway, Russia

Conclusions

- Much of the U.S. military arsenal contains integrated electronic components.
- The U.S. industrial (civilian) and military infrastructures are intimately tied.
- **<u>All these need to be protected from unwanted EM and EMI.</u>**
- Wrapped within the existing and upcoming requirements for new weapon systems is ensuring that R&D into new materials, existing materials, and new engineering methodologies is available.
- These new materials and methodologies will continue to allow:
  - Protecting civilian and military infrastructure
  - Holding near peer adversaries at bay
  - Allowing U.S. forces to leverage military superiority

Image Credits

Slide 3 – https://www.defense.gov/Explore/News/Article/Article/1561238/soldiers-train-to-detect-defend-against-electronic-warfare/

Slide 3 - https://hpc.mil/index.php?option=com_content&view=article&id=64&Itemid=225

Slide 4 – https://science.nasa.gov/ems/03_behaviors

Slide 4 – https://science.nasa.gov/ems/02_anatomy

Slide 5 – https://www.army.mil/article/197260/army_scientist_studies_thunderstorms_to_improve_battlefield_missions

Slide 5 - https://www.army.mil/article/131727/armys_key_mid_tier_radio_moves_forward_with_tests

Slide 7 – NASA – RBSP L-14 Briefing Materials

Slide 7 - https://sdo.gsfc.nasa.gov/

Slide 12 – AFRL SBIR Report, Phase I – Topic AF151-008 (Contract FA8051-15-P-0012)

Slide 13 – https://www.af.mil/News/Article-Display/Article/2511792/army-partners-with-air-forces-thor-f

Slide 13 - https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104516/rq-4-global-hawk/or-base-defense/

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Slide 14 – https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104482/b-2-spirit/

Slide 14 - James. E. Burke, “UWB Radiating Using Explosive Pulse Power from M4 Rifle,” RDECOM, Distribution A

Slide 15 – https://obamawhitehouse.archives.gov/blog/2016/05/02/weight-one-mission-recounting-death-usama-bin-laden-five-years-later

Briefing for the Joint Commission on Technologies and Science (JCOTS), Transoceanic Subsea Cables and Broadband Expansion in Virginia, 2017 (dls.virginia.gov)

Slide 16 – https://www.nasa.gov/mission_pages/sunearth/spaceweather/index.html

Slide 19 – https://www.nist.gov/image/faraday-cage.jpg

Slide 20 – Peter D. D. Schwindt, “Person-sized shields for biomagnetic measurements,” 21st Intl. Conf. on Biomagnetism (2018), Sandia.gov

Slide 21 – N. Keyana, A. Bahraman, W. Hatch, K. Dang, and L. Giersch, “Mechanical Design and Configuration of Penetrations for the Europa Clipper Avionics Vault Structure,” NASA.gov

Slide 24 - https://newsreleases.sandia.gov/metamaterials/

Slide 24 - https://microdevices.jpl.nasa.gov/capabilities/advanced-detectors/novel-materials-and-detectors

Image Credits

Slide 26 – Donnell and Motes – White Paper, 2020.

Slide 28 - https://als.lbl.gov/2d-mxene-shows-evidence-of-a-magnetic-transition/

Slide 30 - https://www.army.mil/article/217433/3d_printing_technology_enhancing_logistics_for_army

Slide 32 - https://www.weather.gov/lub/events-2021-2021010-snow

Slide 33 - https://www.usgs.gov/news/risk-and-reliance-us-economy-and-mineral-resources