NDE: SURFING THE ELECTROMAGNETIC SPECTRUM

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Abstract. Advances in Nondestructive Evaluation demand an arsenal of techniques. This was as true twenty years ago as it is today. As materials and their associated technologies progress, so must the strategy for evaluating the quality of the product. Nondestructive Evaluation is a constant struggle to extract, from classical and quantum physics, the quintessential elements that will optimally address an inspection requirement, apart from purely academic interest. It must work to be useful and thereby advance the field. The electromagnetic spectrum, from Roentgen to Maxwell/Hertz, lies at the foundation of both classical and quantum physics. Not only has NDE plucked pearls from every nook of the spectrum ranging from X-rays to T-rays but also has managed to utilize virtually every known coupling of the spectrum to the classical mechanics of heat and sound. I will “surf” the spectrum to provide a sampling of what NDE has extracted past and present as well as try to couple to its future.

Keywords: Electromagnetic, NDE, Eddy Current, Microwave, Terahertz, Digital Radiography, Laser Ultrasound, Thermal Imaging

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INTRODUCTION

In this overview of electromagnetic (EM) NDE we will be “surfing the spectrum” from the low frequency end, namely radio waves - with application to eddy current - to the high frequency end of the spectrum, x-rays and gamma-rays. We will sample the best NDE technologies in these areas seen through my own eyes – so, apologies in advance for anyone not mentioned since a complete review is out of the scope of this presentation. What is universal is that all this work starts as basic research in NDE that eventually gets utilized, merges, and finally forms an application. Applications are the end game of NDE.

SURFING THE SPECTRUM

What we are going to do is to surf the spectrum, literally. Figure 1 shows the EM spectrum, both from the point of view of wavelength and temperature. Gamma-rays have subnanometer wavelengths and temperatures exceeding billions of Kelvins (K), while microwaves at the other extreme have cm wavelengths and temperatures of the order of 1K. For example, in astronomy there is what is known as the cosmic microwave background radiation, homogeneous throughout the universe, which is about 3K and NDE microwaves and radio fall in that range. So microwaves are very, very low energy and radio waves even lower. The most recently explored area of the NDE EM spectrum is the terahertz (THz) band at about 300 microns wavelength between infrared and microwave and it appears to be the last regime that hasn’t been fully accommodated in NDE.
THE EIGHT-FOLD WAY OF NDE

Here is something interesting I’ve discovered, and this is maybe new - what I call the eight-fold way for NDE (Fig. 2). The “eight-fold way” is the traditional Hindu path to Nirvana or the Buddha. This term was also used in particle physics in the 1970s. Sheldon Glashow used it to describe an eight-fold symmetry in particle physics. This was before the development of the so-called standard model in physics. With respect to NDE, we start by what I call the five pillars of NDE: electricity, magnetism, heat, sound and, of course, since Maxwell unified electricity and magnetism, light. These are coupled in precisely eight ways (not including heat to sound). Of course, quantum mechanics, represented here by the Greek letter, psi, introduces an entire new dimension of couplings and there are hundreds of such couplings. To give examples, we have magneto-optic, electro-optic, thermo-electric, etc, (Fig.2). When one includes quantum mechanical spin effects, there are dozens more. One of special interest to us is Giant Magneto-Resistance (GMR). GMR is currently used for hard drives and is a memory technology based on spin.
THE RADIO SPECTRUM – EDDY CURRENT NDE

Heinrich Hertz first transmitted and received radio waves in 1886. The radio band is defined by frequencies less than 3 GHz, corresponding to wavelengths longer than 10 cm. Eddy current NDE typically deals with frequencies in the kHz-MHz range and thus falls into this band. We borrow here from work done at GE by Dr. Yuri Plotnikov [1-4]. Briefly, eddy current is the use of electromagnetic induction methods for NDE. A coil generates a magnetic field at a radio frequency, either continuous wave or pulsed. A current is generated in the metal through Maxwell’s equations and a reverse current is generated back in the coil. The concept is to look at the complex impedance of this eddy current signal, both the real resistance and the inductive reactance and to relate that to flaws (Fig. 3). This is typically accomplished using some form of balanced electronic bridge. Eddy current is actually a near-field phenomenon – an evanescent “wave”. That is, it’s diffusive, so it’s not really a wave at all. It is critically damped in one cycle. All diffusion phenomena have what is known as a penetration constant or depth. In EM that is the skin depth, δ, related to the “wavelength” as \( \delta = \lambda / 2\pi = 1 / \sqrt{\pi f \mu \sigma} \) where \( \mu \) and \( \sigma \) are magnetic permeability and electrical conductivity respectively. This is true for thermal imaging, for eddy current or any of the EM techniques.

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Z = R + jwL
\]

**FIGURE 3.** Eddy Current method showing bridge detect

**FIGURE 4.** Pulsed Eddy Current (PEC).

The most common application is crack detection. At GE it is used it for turbine blades, disks that carry the turbine blades, dovetails and so on. It is a primary method for finding cracks in metals. Another application uses the eddy current lift-off effect coating thickness measurement as well as a coating integrity measurement. This works if the coating is insulative producing the lift-off gap. Yuri uses pulsed eddy current. Pulsing, like any such pulse method in any field, has certain advantages. The main advantage is it’s spectral content. Just as in thermal imaging, which is my work, when you generate a pulse, an electromagnetic pulse or a heat pulse, it has both low and high frequency content and from the skin depth effect we see that there is deep penetration for the low frequencies and shallow penetration for the high frequencies (Fig. 4).

As a consequence of the different penetration depths, one can literally gate the signal and look at the effect at different depths. This is the same as ultrasound. So, there are certain
commonalities to all of these fields. Gating can be done in ultrasonics, in eddy current and in thermal imaging as well. This has produced all kinds of new imaging effects in all of these fields and allows one to do depth imaging. In this case, an example from Yuri’s work is an aircraft lap splice corrosion panel with rivets (Fig. 5). By analyzing and gating different frequencies, the longer wavelength ones for the deeper imaging and shorter wavelength ones for the shallow imaging, one can literally advance through different layers beneath the corrosion panel and see corrosion at different depths, or the effects of corrosion at different depths.

One of the main advances that Yuri has accomplished in the field is his use of GMR sensors (Fig. 6). Giant Magneto-Resistance sensing is the latest in eddy current technology. These sensors are quantum mechanical devices based on ferromagnetic spin effects and they change their resistance by as much as 10 percent when a magnetic field is present or absent. It’s a huge effect. The Nobel prize was given for this discovery in 2007. What Yuri has done is to create sensor devices consisting of multiple GMR sensors so these are eddy current probes that have a standard pulse generation coil, but the sensor array elements receive local effects so one can create an image. He has developed as many as 512 sensor arrays, 32 x16 elements. This becomes a 2D dimensional scan array and this decreases time of inspection that is the ultimate bottom line. He has cut inspection time down by one-third by going to arrays instead of single element scanning units. Figure 7 shows an example where he uses single element scanning at the top and a GMR element array at the bottom demonstrating a significant improvement in the flaw image in a shorter time.

**FIGURE 5.** Time evolution of the PEC signal.
MICROWAVE NDE

Microwaves are an extension of radio waves and the technology was heavily developed during WWII. The microwave band is defined by frequencies between 3 GHz and 0.1 THz, corresponding to wavelengths between 10 cm and 0.3 cm. Here I borrow from the work of Prof. Reza Zoughi [5] from Missouri University of Science and Technology. There is a tremendous amount of excellent microwave work done in the field, and I have selected only one example. Again, microwaves are subject to the skin effect and so penetration is handled the same way. Microwaves are sensitive to dielectric property variations, local boundary effects, inclusions and gradients of material. Microwaves are polarized, so they are also sensitive to polarization changes. Also one can do microwave imaging in several ways; near-field, far-field, and of course they are sensitive to conduction changes. A typical microwave system is very much like the eddy current system previously described. It uses a balanced bridge arrangement where a directional coupler isolates the return signal from the ingoing signal that is analyzed and eventually displayed (Fig. 8). In the wave modes there is an evanescent mode, just as in eddy current, which is a diffusive mode for the electromagnetic field, and near-field and far-field modes, so you can beam microwaves - something you can’t do with eddy current.
Figure 9 shows typical microwave launching devices or “horns” or waveguides. Waveguides are necessary instead of wires because the frequencies are so high with wavelengths ranging from millimeters to centimeters that the currents are best carried in tuned devices varying in cross-sectional dimension to match the wavelength modes. Applications of microwaves include dielectric analysis, moisture detection, cure monitoring, concrete evaluation and flaw detection, of course. Figure 10 shows an aircraft radome panel with embedded flaws revealed by evanescent microwaves. Figure 11 shows an example of moisture detection in a honeycomb panel. There is water in a honeycomb cell and as the water is drained going from left to right, the signal decreases. Figure 12 is an example of rebar visualization in mortar. During examination of different frequencies, one can get higher resolution at a higher frequency band in the k-band as seen on the right. Reza’s team has recently developed the first real-time
microwave camera. Figure 13 shows a picture of a student holding a thin rubber inclusion sandwiched between two pieces of balsa wood. As the microwaves are beamed through the part, the image is sensed at the right in red while in the background on the PC screen the real-time image is displayed as the part is moved around.

TERAHERTZ NDE

The Terahertz band is defined by frequencies between 3 GHz and 3 THz, corresponding to wavelengths between 3000 microns and 100 microns. Here, I borrow primarily from the work of Dave Zimdars [6-8 ] who is the manager of R&D at Picometrix and Bill Winfree, Manager of the NDE group at NASA, Langley Research Center. Terahertz energies are low - not enough to cause damage to human tissue. I’ve mentioned the so-called terahertz gap and this is an area of the spectrum that’s hard to generate and that’s one of the reasons why it has never been attempted except in the last ten years or so. Instrumentation has evolved to cover this spectrum, mostly through lasers and solid-state terahertz technology. We also have an interesting “privacy issue”. Fig. 14 shows a terahertz image - a scanned image of a man holding a knife wrapped in a newspaper. One can see the knife, a ceramic blade in this case, is exposed - along with the gentleman.

Security is a major application area for terahertz technology. Also, it’s interesting because you cannot only do imaging with terahertz, you can also do spectroscopy simultaneously. So you might get an image of someone holding a weapon, but also you might get an image of someone concealing objects which can be determined to be explosives spectroscopically. This is something that microwaves cannot do, so that’s one of the distinctions between millimeter wave
and terahertz. Terahertz is generated through several approaches. One uses femtosecond lasers where you convert a laser pulse directly through nonlinear materials to terahertz pulses. The backward wave oscillator (BWO) is another way. Femtosecond lasers only can generate microwatts, so power is very low. BWOs are a direct terahertz generator, just like a vacuum tube similar to a klystron, and it can generate on the order of milliwatts and more recently, solid state devices like the quantum cascade laser have been able to develop more than just a milliwatt - on the order of 10s of milliwatts. The disadvantage of the solid state device, the quantum cascade laser, is that it needs to be cooled cryogenically at liquid helium temperatures – a great inconvenience and costly. If they can get that up to liquid nitrogen temperatures, it would be quite good and create a mini-revolution. I don’t believe that’s been achieved yet. Higher power reduces the scan time, so there is a tradeoff between power and scan time. It is a scanning technique right now. It’s not a full imaging beaming technique. Standoff is another challenge - also cost and size. Privacy has already been mentioned. Zimdars and Picometrix have tremendously advanced the field to where compact tabletop systems are available as shown in Fig. 15. The same sort of thing happened to the technology in laser ultrasound and this is directly the result of competition.

Terahertz penetrates a variety of materials: plastic, air, paper, paints. It can be used for coatings or any kind of nonconducting composite. If a composite is conducting, it will absorb terahertz radiation. Water absorbs terahertz radiation. Tissue can absorb terahertz radiation but it’s non-damaging. So, it will penetrate clothing, but it won’t penetrate human tissue as shown in the earlier image.

One of the most interesting applications and an important application for terahertz imaging is the inspection of foam insulation on the Space Shuttle (Fig. 16). That’s really what has made a
big hit. That material is called SOFI - sprayed on film insulation and it is very thick – 50-300 mm. It was the source of the damage that caused one shuttle to fail. They were looking at the foam insulation for some time after that. Dave Zimdars and NASA’s Bill Winfree collaborated on a lot of this work and developed terahertz techniques to look at the bondline of this foam. It could be as much as 8-10 inches thick. There aren’t any NDE techniques that can really penetrate and resolve bondline thicknesses, but terahertz was exactly the right wavelength on the order of 100-300 microns. They use a time domain terahertz system (Fig. 17), where they basically launch a terahertz pulse, similar to what I just showed with Zimdars’ equipment. The pulse penetrates the foam, reflects both off the foam and the metal and comes back into the receiver where it is detected. An example of a typical signal is shown in Fig. 18. The foam reflects a small signal shown at the upper left, signal number 1, and the actual signal as an example of that is shown on the lower right. There, the major reflection from the metal has been removed and that reflection from the metal is shown here in comparison to the small side signal. So, it’s a small signal but nevertheless, it’s there and can be analyzed relatively easily. An example of this kind of imaging for the foam is shown in Fig. 19 and on the left is a physical example of one of the SOFI test panels with inserted artificial flaws which are shown here, imaged by the terahertz waves. Bill Winfree, standing left and Eric Madaras, sitting, at are carrying out the procedure at NASA Langley.

**FIGURE 18.** THz reflections from air gap between foam and metal substrate from simulated disbonds.
Picometrix have gone one step further with terahertz and they have now introduced computer tomography (Fig. 20), a completely new approach to 3D imaging with terahertz waves. The letter P has been engraved in a test phantom panel at different depths and then imaging was performed using a standard construction for computerized tomography resulting in the beautiful image on the right.

**INFRARED NDE**

We move onto infrared NDE. A bit of history: Sir William Herschel discovered infrared radiation in 1800 by placing a thermometer past the visible spectrum while measuring the temperature of the spectrum. I’m selecting from my own work in conjunction with my colleagues, Don Howard and Bryon Knight at the GE Global Research Center [9-12]. There is much work going on in infrared imaging, for example Sonic-IR, but I’m going to select something I know best. In the transient IR technique, an intense flash is applied to a part surface that generates a heat pulse which penetrates the part. One then analyzes the time-temperature evolution at the surface as recorded by the IR camera and downloaded to a PC. A typical system is shown in Fig. 21. Quenchers trim the exponential decay of the light pulse to rectangular for an “ideal” input function. The IR camera, a Flir SC8000, has a 1024 by 1024 array, so it has very high resolution and is very fast (120 FPS and higher). We have very high power with an eight-
lamp system driven by 80 KJ. This will put approximately 40 megawatt peak pulse into a part, so care must be exercised.

The area that we’re developing now for our customers at GE is what I call a Very Large InfraRed imager (VLIR) shown in Fig. 22. This is a huge system and this is just a diagram of it. We have already installed a number of IR systems throughout GE, so the infrared work we’re doing as a team is in fact being used industrially throughout GE right now. We have four systems in the field. NASA has purchased a system at Dryden Flight Research Center so that’s the first time we’ve gone outside of GE. We are working closely with NASA to further develop mutual IR concepts and do research. The methods are further described in the earlier references. The main difference between our methods and others is that we only need to find one point on a time-temperature curve – the “inflection point” which provides us with all the flaw depth information independent of the temperature. An example of a “Depth Image”, produced by flashing a flat bottom hole standard, is shown in Fig. 23. We are using FBH standards in IR very much like those used in ultrasound where a hole is drilled from the bottom of the sample up into the sample, leaving a remnant “plate” thickness which has been flashed from the surface. There
is a time evolution of these flaws – shallow hole appear first and deeper ones last. This effect is represented by colors in a single image. The colors represent depths of holes, blue being the deepest - the thickest top to that hole- and orange being the shallowest. Holes at the same depth have the same colors. Notice that all the holes of the same colors give the same thickness independent of radius. That’s really the advantage and we call that true depth imaging. It’s surprisingly accurate and Fig. 24 shows an example of depth imaging to determine wall thickness in a nickel alloy aircraft engine blade. A typical error is 3% of thickness.

Ceramic composites are ideally imaged by IR, using exactly the same method. We have developed what we term “flaw discrimination”. We can distinguish a delamination from simple porosity in ceramics. Figure 25 shows a U-shaped CMC component (top). The depth image is seen on the bottom right where colors represent the depth of the flaws as seen on the color bar. Shallow delaminations will be red while perfect material shows in blue, meaning the heat has fully gone through the part indicating maximum correct thickness. On the left is the “flaw discrimination image” where green is good, red is a delamination and yellow represents porous regions.

Finally, Fig. 26 shows the VLIR system in the field where one can see the scale. Here the goal is to inspect an engine nacelle component that has a ten-foot dimension. Typically we would do a ten foot part in five foot by five foot shots using four shots, since we prefer better resolution. We have actually imaged the part in a single shot - but at the price of reduced resolution.
THE VISIBLE SPECTRUM – LASER NDE

In-Process Control for Coatings

We move on to the visible spectrum, in particular, laser ultrasonics, a now mature subject of many years of QNDE Special Sessions. I am going to describe some early work of mine at United Technologies Research Center applied to coating measurement [13]. A pulse using a YAG laser is generated that thermo-elastically generates Lamb waves, Fig. 27, in the coating.
We are analyzing the coating as it is being applied, in real time. That was the goal in this case, by analyzing the Lamb waves with a second laser sensor. That sensor was based on a Doppler interferometer that I built at the time (Fig. 28). The Doppler interferometer had a displacement measurement sensitivity of approximately 0.1 Angstrom. Its bandwidth was 20kHz to 20 MHz. This was termed a laser-in/laser-out system and was used on an operating CVD (Chemical Vapor Deposition) reactor. It was actually applied and it worked. We sent both beams (laser generator and interferometer) in collinearly through a quartz window on the reactor. The beams hit the surface of a ceramic component, for example, a blade, on which was being deposited silicon nitride in real time. It was an interesting approach both from a physics standpoint and a materials standpoint.

$$\Delta f_{\text{Doppler}} = 4\pi F \left(\frac{d}{\lambda}\right)$$

- $d$ = surface displacement
- $\lambda$ = sensing wavelength
- $F$ = surface vibration freq

Typical displacement Sensitivity: 0.1 Å (20 kHz – 20 MHz)
The generation laser produced a ring of light that generated both an ingoing and outgoing wave (Fig. 29). The ingoing wave peaked at the center to produce a very large pulse, that was measured by the receiver interferometer system. This was all done at 1400°C. The CVD reactor was operating at essentially white hot temperatures. It was stunning to see a wave moving across a sample coating at 1400°C. The system, shown in Fig. 30, actually worked. On the lower left is the first data coming out of the system where the system is simply turned on and is fully automated. A “Labview” program controlled it and thickness data was accumulated, as is seen on the step-like curve rising as coating accumulated. When the proper thickness is reached - in this case the system was preset at about 150 microns coating thickness – the program shuts the system off. This was the first time a CVD reactor was “in-process” controlled by actual part coating thickness feedback. Here is one thing that never got published. It was a very interesting result, however a publishing error was made and the wrong image was placed in the paper and this was the right one noticed only years later. On the right of Fig. 30 is an interesting example of a Rayleigh wave, shown at the top, slowly evolving into a Lamb wave as the coating builds up. One can see how the coating literally filters components of the spectrum introduced by the Rayleigh pulse travelling across the surface.

Laser Ultrasonics for Industrial Applications

Here, we borrow work from Jean-Pierre Monchalin [16-18]. Figure 31 shows a typical laser ultrasound system concept for polymer composites. Monchalin pushed laser ultrasonics to the edge. He developed and introduced the Fabry-Perot interferometer (Fig. 32) as a detector which revolutionized laser ultrasound because of its so-called étendu, its light gathering efficiency. It didn’t rely on a Rayleigh spot focus like the other techniques did, but could gather unfocused light at a very large angle of divergence. He introduced that in the mid-1980s. The simplicity of current Fabry-Perot receivers, portable, and all fiber optics is also shown in Fig. 32. These
systems used to take up entire benches. Some of the applications of the Industrial Materials Institute include aircraft composite structures inspection and the gauging of steel tubing moving along production lines at feet per second (Fig.33). Here he is shooting a high power pulsed laser beam at the steel tubes. Of course he used ablative methods to generate a longitudinal pulse since it really didn’t matter whether one ablated off a small scar on a thick steel tube or not. It generated a very nice pulse, high signal-to-noise, and he was able to get thickness of tubes and feed back to the mill operation in real time.

**FIGURE** 31. Laser Ultrasound system diagram for composites.

**FIGURE** 32. The original Fabry-Perot interferometer laser ultrasound detector schematic (left) and its modern fiber optic implementation, made by Tecnar (rt).

**FIGURE** 33. Laser ultrasound image of a CF-18 horizontal stabilizer (left) and an application to pipe thickness measurement in a steel mill (rt).
X-RAY, γ-RAY – DIGITAL RADIOGRAPHY (DR)

Finally, we’re getting to the other end of the spectrum, x-rays and gamma rays. X-rays and gamma rays span the range from low energy (keV) to high energy photons (MeV), respectively but not always. There is no qualitative difference. The only real difference is the fact that gamma-rays are usually nuclear decay line-spectra photons, for example, Cobalt 60 and Iridium 192. Otherwise, a gamma-ray might be 1.5 MeV and an x-ray might also be 1.5 Mev or even 9 Mev and they’re still called x-rays, but technically they are gamma-rays.

Here, I’m borrowing again from GE, namely the work of Cliff Bueno [19-21]. The history of x-rays is quite interesting. X-rays were first discovered in 1895 by Roengten in his Crookes’ tubes, Fig. 34, when he saw radiation across the room that went outside the actual tube. Figure 35 shows the very first x-ray ever made of his wife’s ring on her hand. After that, the application to medical uses surged and pushed the technology very rapidly. Shortly after that, General Electric got involved and Coolidge made the first commercial x-ray tube in 1917 (Fig. 35). Not long after that, linear accelerators were developed. These can be either DC or RF devices. Fig. 36 is an example of the first “basement home-made ”, 400 keV, Van de Graff linear accelerator made by the author himself at age 17 as a high school project. The author actually got the proton gun to work beautifully but fortunately the accelerator did not work (due to inadequate proton mean free path from lack of a cold-trap) and consequently no 400 keV x-rays were generated!

A prominent application for x-ray is cracks in thick metals in the nuclear industry and ship industry. Security now is also very important – for example, inspection of cargo containers at shipping ports. Accelerators and x-ray systems are now basically tabletop devices, purchased off-the-shelf. Cliff has developed systems, originally intended for GE Medical, towards industrial NDE applications. This includes a great deal of work on x-ray detection. The premier GE detector is a so-called “flat-panel” device. The device has a 41-cm array of 400-micron

FIGURE 34. Crooke’s tube (left) and first-ever x-ray (rt). FIGURE 35. The GE Coolidge x-ray tube
Silicon/Cesium-Iodide sensors that efficiently convert the x-ray to electron current. Figure 36 shows such a panel and a digital radiographic real-time image of a laptop computer with a number of hidden objects including scissors; saw blade, knife and others. The image scan is taken at 30 frames per second at 150 kV.

CONCLUSION

We have overviewed NDE techniques over the entire electromagnetic spectrum in a few pages by sampling only a handful of contributors. Many deserve much credit for advancing the fields. What is clearly visible is that the traditional methods are rapidly adapting to the latest technologies and instrumentation. This is critical if the field is to remain viable and this appears to be the case. I predict a healthy and exciting future for electromagnetic NDE.

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