What Poincaré and Einstein have Wrought: a Modern, Practical Application of the General Theory of Relativity (The story of High-Frequency Gravitational Waves)

(Paper HFGW-03-101, Gravitational Wave Conference, The MITRE Corporation, McLean, Virginia, USA, May 6-9, 2003)

by

Robert M. L. Baker, Jr.†

ABSTRACT

The history of gravitational waves is traced from the original suggestion of Jules Henri Poincaré, the general theory of Albert Einstein, and the pioneering analyses of Joseph Weber and Robert Forward. Today we are discovering new means to generate and detect High-Frequency Gravitational Waves (HFGW) in a terrestrial laboratory due to technological advancements. The validation of Einstein's gravitational wave (GW) theory by Hulse and Taylor, for which they received the Nobel Prize, and the studies of possible relic or primordial HFGW to be detected in the cosmic background, and other celestial sources of much lower frequency GW, are discussed. The seemly insurmountable barriers to laboratory GW generation are shown to be breached through the use of new technology including high-temperature superconductors, nanotechnology, and ultra-fast science. Some twenty devices that have been proposed for the laboratory generation of HFGW since 1960 and three new HFGW detectors are briefly described. Finally, one quite practical and some more speculative applications of HFGW are presented as the result of the theoretical potential for generating between one kilowatt and one megawatt of HFGW according to four of the papers presented at this Conference.

1. INTRODUCTION

This introductory presentation today concerns an exciting new concept: the laboratory generation, detection and utilization of *High-Frequency Gravitational Waves* (HFGW). **This is the *clarion* call**:

? *today*, we have the unique **opportunity** to study and utilize the gravitational-wave phenomenon predicted by Poincaré and Einstein decades ago because of recent advances in technology.

? *today*, we have the **means** to generate HFGW and to detect it in the laboratory because of the availability of at least three new HFGW detectors. And we now,

? *today*, have the **motivation** to apply HFGW to communication, space propulsion, physics, imaging and, in general, the motivation for the laboratory study of HFGW!

---

† Senior Consultant, GRAVWAVE® LLC and Transportation Sciences Corporation. 8123 Tuscany Avenue, Playa del Rey, California 90293, USA. Telephone: (310) 823-4143. E-mail: bakerjr@attbi.com.

But first, allow me to tell you a bit about myself and how my interest in HFGW developed:

In the 1960s a Dr. Robert L. Forward contacted me regarding a "Satellite Librations" paper I coauthored in the 1950s. He was interested in something called "gravitational waves" and his Ph.D. thesis was the design of a resonance device to detect them developed by a Joseph Weber called the "Weber Bar." He was working at the *Hughes Research Laboratories* in Malibu, California and I invited Dr. Forward, who turned out to be an early pioneer in the field of gravitational radiation, to deliver a lecture to my staff. We were all intrigued with the possibility of sensing **low-frequency gravitational waves** (LFGW) with frequencies on the order of a **KHz or less** using the Weber Bar. I was also intrigued by the possibility of generating **high-frequency gravitational waves** exhibiting frequencies of a **GHz or more**. In fact, Dr. Forward coined the name High-Frequency Gravitational Waves or HFGW to refer frequencies greater than those predicted to be generated by celestial sources. The HFGW frequency bands were specifically defined by D. H. Douglas and V. B. Braginsky in 1979 (their effort was supported by the *National Science Foundation* and *Ministry of Higher Education USSR*) and presented in Chapter 3 of Hawking and Israel [10]. Specifically, HFGW was defined to be above 100 KHz (suggested by Douglas and Braginsky to be "Man-made?") and taken by a majority of those interested in HFGW today to be inclusive of very high frequency and ultra high frequency gravitational waves. At the time, however, I saw no practical means to generate the HFGW. But before continuing the story of high-frequency gravitational waves lets look at the theory of gravity.

2. BRIEF HISTORY OF GRAVITATIONAL WAVES

According to a thumbnail sketch of Einstein's theory of general relativity, time and space disappear with material things. That is, matter (a star to an atomic nucleus) is inseparably connected by time and space and *vice versa* within the fabric of what Einstein called a *spacetime continuum*. "Things" are all but hills, valleys, and holes in the fabric of Einstein's spacetime. This is a very exotic concept and most of us are hard pressed to visualize it! It is **not** in our range of experience. Nevertheless, let us look at a simple example: Consider two explorers starting out at different points on the equator and heading due North. As they proceed North they will get closer together – they are in a sense "attracted" to each other. This "attraction" is really a property of the geometry! Geometry is everything! We observe that the planet Mercury's perihelion (closest point to the Sun) is shifting and that light is bent by the Sun's "gravity". But it's all geometry like a bowling ball in the middle of a rubber sheet with a baseball rolling around it – like a roulette ball that never comes to rest.

But what are *gravitational waves?* Please see Fig. 1A. Let us first consider the only truly visible waves that we perceive: *water waves*. Such waves are disturbances or undulations on or in a medium: *the water*. They exhibit an amplitude or height, a frequency that is dependent on the time between the passages of wave crests by some point, and they propagate with a speed across a fluid surface that is variable and depends upon a number of factors. They can be sensed, for example, by the motion of a buoy or leaf on the water. Although we usually don't see them, we also are familiar with *sound waves*. Such waves propagate as compressions and rarefactions in a gas media – usually air. They have an amplitude according to the strength of the compressions and rarefactions, a frequency that is related to the time between the passages of the sound wave front by some point, and a speed that is variable like water waves. They can be sensed by, for example, the motion of a diaphragm in a microphone. We also have some familiarity with *electromagnetic waves* like radio, microwaves, light, X-rays, etc. Such waves seem more sophisticated and depend upon the propagation of undulations in an electromagnetic (EM) field that also exhibit a frequency like the other waves but, according to Einstein, propagate at a **constant speed**, $c \sim 3 \times 10^8$ [m/s]. Also there is no true *medium* for EM waves, although at one time, prior to the famous Michelson-Morley experiment and the acceptance of Einstein's special theory of relativity, most scientists thought that there was such a medium called the "aether" or "ether." EM waves can be sensed by, for example, the motion of electrons in a photocell.

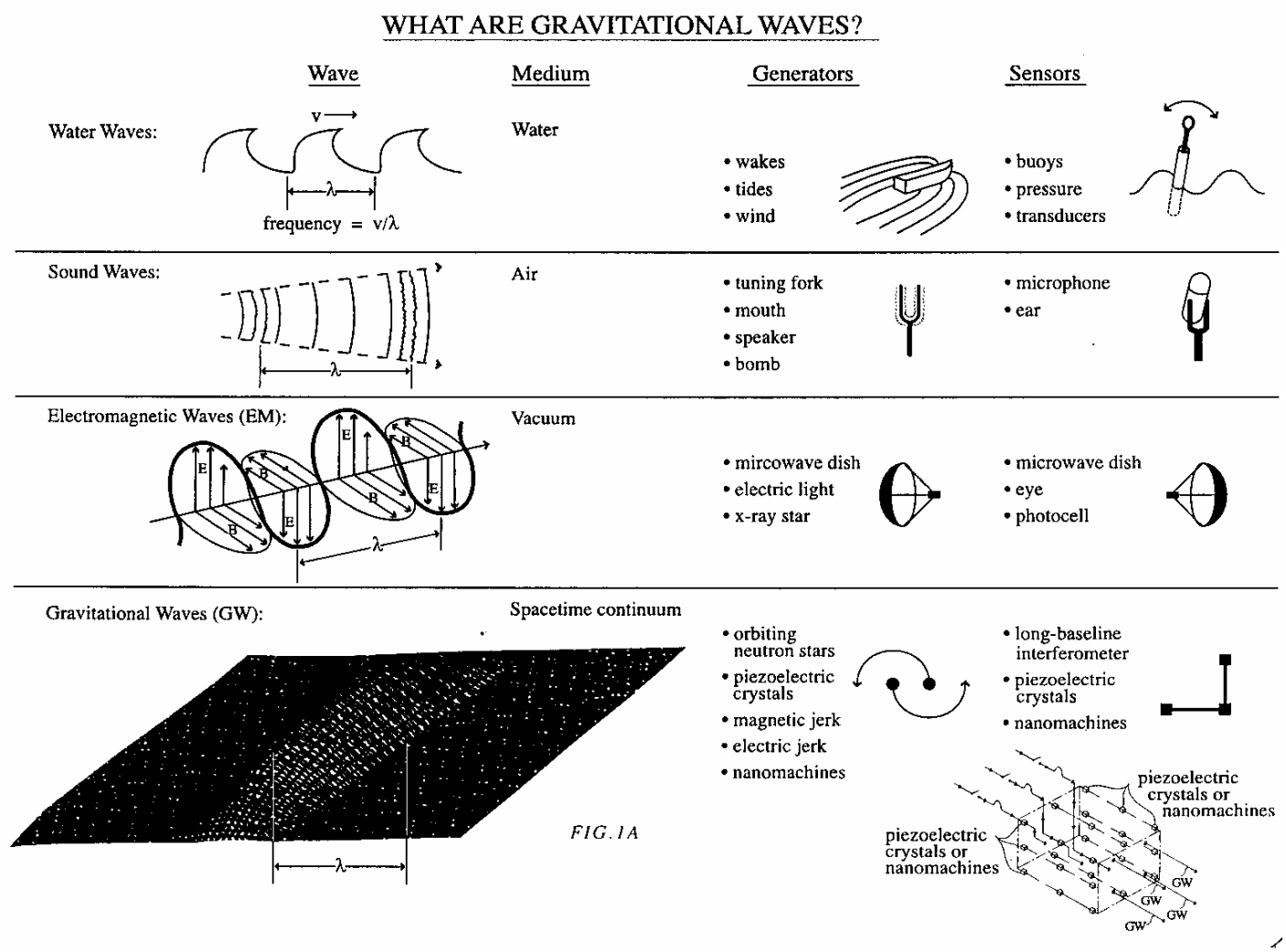

Figure 1A

Gravity itself propagates as an attractive force and there are waves of gravity that generate tides and gravitational perturbations on all masses, e.g., planets and spacecraft. Such waves of gravity are measured to have a constant speed that is likely to be the speed of light, c . Waves of gravity can be sensed by, for example, the motion of a mass in an accelerometer. There exists a wavelike and particle-like expression for waves and the particle-like expression for a wave of gravity is the *graviton*. The particle expression for an EM wave is the *photon*. In Einstein's General Theory of Relativity I have already noted that geometry is everything and that the geometry that Einstein developed consists of a fabric whose dimensions involve the usual three dimensions of space, but with the addition of *time*, which in his theory is no longer a fixed uniformly increasing quantity. Thus Einstein theorized a revolutionary *spacetim*e fabric or continuum. The undulations or waves propagated in this fabric he called *"gravitational waves"* and he theorized that they propagate at the speed of light. Gravitational waves can be sensed by, for example, the change in lengths measured by extremely sensitive interferometers. The particle expression for these waves in the spacetime continuum is the *gravitational instanton* or just *"instanton."* A more complete discussion of instantons can be found in Conference paper HFGW-03-107. (By the way, the term "gravity waves," strictly speaking, refers to water waves in which buoyancy acts as a restoring force, as opposed to relativistic "gravitational waves" as referred to in this paper.)

At this point I should note that in the 1960s to 1980s there was considerable skepticism concerning the existence of gravitational waves and consequently little attention was paid to the literature concerning the

laboratory generation of GW. In this regard, as an historical note, Jules Henri Poincaré, a French theoretical physicist, celestial mechanic and one of the foremost mathematicians of the 19th century concluded in 1905 (a few days before the publication of Albert Einstein's special relativity paper) that Newton's laws needed modification and that there should exist *gravitational waves* that propagate at the speed of light. Albert Einstein developed *The Theory of General Relativity* in 1915 and in 1918 developed an equation (the quadrupole) that provided an approximation to the intensity of gravitational waves (GW). Some scientists believed that these waves in Einstein's revolutionary spacetime continuum were unobservable artifacts of his theory. The indirect evidence obtained by R.A. Hulse and J. H. Taylor concerning their observations of a contracting binary star pair, which perfectly matched Einstein's GW theory, garnered them the 1993 *Nobel Prize* and the skepticism concerning GW evaporated.

Almost immediately after the Hulse and Taylor revelation, many proposals were brought forward to detect celestially generated GW. One of the most famous is the Laser Interferometric Gravitational Observatory or LIGO. These and other GW detectors are being built or are in operation throughout the world at a cost of about a billion dollars. At this point it is important to focus on the frequency bands of GW. A celestial source relies on the motion of extremely massive objects to produce a time rate of change of acceleration to generate GW. Such motions complete their cycles in days down to milliseconds. Thus they generate very long wave lengths (often measured in astronomical units) at very low frequencies (e.g., down to micro Hertz) or LFGW. Laboratory generation of GW, on the other hand, utilizes a very strong electromagnetic or nuclear force operating at very high frequencies – GHz to QHz (10^{15} Hertz; the term Quadrahertz, QHz, is preferred over the term Petahertz or PHz) and above; this is ***HFGW***. Thus the technologies for generation and detection of LFGW and HFGW are totally different – as different as 60 Hz alternating current equipment design is from microwave radar design. Thus we have introduced the term *High-Frequency Gravitational Waves* or HFGW as the descriptor of the very special technology that this Conference is all about.

3. THE ESSENCE OF HFGW

Due to the misconception that it requires the utilization of a very weak gravitational force to generate GW (possibly engendered by the unfortunate term "graviton" as the particle manifestation of GW in Einstein's spacetime continuum rather than the preferred term, "*instanton*") most scientists were ill disposed to acknowledge the possibility of the laboratory generation of GW. Furthermore, most of today's scientists were exposed to the impossibility of the use of a spinning rod in a laboratory to generate gravitational waves from reading their first textbook on the subject and have not considered other generation means. On the other hand, as will become most evident during the course of this Conference, there is ample evidence that the laboratory generation of gravitational waves has been thoroughly studied by dozens of scientists and many of the devices that they have suggested are both feasible and practical if we take advantage of recently developed technology. To be sure there are some very sophisticated and exact computer simulations of the generation of gravitational waves. Please see, for example, the quadrupole approximation utilized herein by me and, for example, at this Conference by Dehnen and Romero-Borja (paper HFGW-03-102), Rudenko (paper HFGW-03-113), and others is probably less exact than computational simulations. On the other hand, the computer simulations are less relevant to the devices involved in the generation and detection of HFGW in the laboratory. These computer simulations describe GW generation by strong-field astrophysical phenomena (e.g., neutron stars, black holes, etc.), coupled spacetime and general relativistic hydrodynamic equations, and are usually restricted to gravitational forces; not non-gravitational forces involved in laboratory HFGW generation.

To illustrate the engineering challenge of generating HFGW I will present without proof (such proof or derivation is provided in Conference paper HFGW-03-117) a fundamental equation to compute the power of a HFGW source under certain situations. It is basically a form of the classic *quadrupole equation* and in MKS units the power of a HFGW source is given by

$$P = 1.76\text{x}10^{-52}\,(2r?f/?t)^2 \text{ [watts]}, \quad (1)$$

where ?f and ?t are the change in force [N] over a very short time [s] or a "*jerk*" and *r* is the radius of gyration [m] of a system of masses. Thus the smaller that ?t is and, therefore, the higher the frequency is, the stronger is the HFGW. Equation (1) is an approximation and is only strictly valid for speeds of the system much

less than the speed of light and, possibly, for r « $?_{GW}$ where $?_{GW}$ is GW wavelength. Because of the very small coefficient in Eq. (1), a very large ?f and/or a very small ?t is required. A large ?f implies the use of strong electromagnetic or nuclear forces rather than weak gravitational force. The electromagnetic forces are 10^{42} to 10^{44} stronger than gravitational forces and strong nuclear forces are about 300 times stronger than that. A small ?t implies a high HFGW frequency. Together they result in a very large jerk. The engineering challenge is to create a very strong high-frequency jerk of, say, electrons in a superconductor or in the walls of a resonance chamber, a piezoelectric crystal, or the coordinated jerk of micro- and nano-machines, or small magnets without generating too much heat or disruptive accelerations or overpowering EM radiation. Seven papers at this Conference address the engineering solutions to this challenge.

A word about the term *quadrupole* is in order: one of the basic physical processes for generating a gravitational wave is the third (or higher) time derivative of the motion of a mass, termed a "jerk" or ?f/?t, where ?f is, again, an increase in force, f, on the mass carried out over a small time interval, ?t. That physical process produces a gravitational wave with a power given by, for example, the quadrupole approximation, Eq. (1) (as already noted it was originally derived by Einstein), or it could be determined directly from the special and general relativity equations (using a computer-implemented numerical integration as, for example, discussed in Ashby, *et al* [1]). The quadrupole is the lowest-order solution to the GW propagation problem and mass motions that have quadrupole moments are the most effective GW generators. That is, the quadrupole itself is not the physical process at all, but only one means of establishing the power of the gravitational wave – the lowest-order solution. Other algorithms, often most complicated, can define other GW properties such as direction, polarization, constructive and/or destructive interference, etc. This situation is similar to Newton's Laws, which govern the physical process of planetary motion. The effect of that motion can be computed using, for example, the two-body approximation, or it could be determined directly from the equations of motion described by Newton's Laws, using a computer-implemented numerical integration. The two-body approximation itself is not the physical law at all, but only one means of approximately describing the resultant motion – a "lowest-order solution." In the case of a nuclear-reaction-generated gravitational wave, in which a nuclear particle is ejected from a nucleus, it is like a small rocket, or in the case of electrons shaken in a resonance cavity, plasma beam, superconductor, etc., it is like a jerk. In the first case there is a third time derivative of the motion of the nucleus. In the second case there is a third-time derivative motion of the electron, which produces a gravitational wave whose power can be estimated, for example, by the quadrupole approximation of Eq. (1). Thus when I mention a "quadrupole-produced gravitational wave" I'm really implying the fundamental physical concept of the jerk and not the computational means for establishing the power of the gravitational wave or a lowest-order solution. As far as a harmonic motion of a mass or a pair of masses is concerned (harmonic oscillator), gravitational waves are generated. Just as in the case of a pendulum, the usual descriptor of harmonic motion, there exists a third time derivative of the pendulum bob. It is the jerk of that bob that produces the gravitational wave, which can be estimated using a quadrupole approximation or computed exactly by means of a rather complicated solution of the equations of special and general relativity. There are some circumstances that involve symmetrical jerks, such as those occurring during a stellar explosion, that do **not** generate GW and this null result is discussed in Conference paper HFGW-03-117.

4. DETECTORS

Let us consider three currently proposed detectors of HFGW.

4.1 Spacetime Curvature Detector

In a spacetime-curvature detector, developed by A. M. Cruise of *Birmingham University*, the interaction between HFGW and the polarization vector of an electromagnetic (EM) wave is utilized in which the polarization vector rotates about the direction of EM propagation. When a resonance condition is established with the EM wave always experiencing the same phase as the HFGW, then the effect is cumulative and can be enhanced linearly by repeated EM circuits of a closed loop or waveguide. A prototype detector has been fabricated by Richard Ingley at *Birmingham University*. The loop is about a meter in length and can detect 200 MHz HFGW. A smaller loop could detect 3 GHz or even higher frequency HFGW. If the loop is cooled or coated with a semiconductor, then the device's sensitivity increases. A small probe is introduced into the loop or waveguide to detect the EM polarization that is sensitive to the curvature of spacetime created by the passage of a HFGW.

4.2 Coupled Resonator Detector

Since 1978 superconducting microwave cavities have been proposed as sensitive detectors of HFGW. As will be discussed by Chincarini and Gemme at this Conference (paper HFGW-03-103) the interaction of HFGW with cavity walls, and the resulting motion or jerk, induces the transition of some EM energy from an initially excited cavity mode to an adjacent empty cavity. The energy transfer is at a maximum when the frequency of the HFGW is equal to the frequency difference of the two cavity modes. Several such superconducting cavities of spherical shape have been fabricated at *INFN Genoa*, Italy and small-sized ones, on the order of a centimeter in size, could be sensitive to GHz HFGW. Since the coupled cavities are of a dimension smaller than a HFGW wavelength it may be possible in future to construct an array of them (possibly out of carbon nanotube pairs) in order to enhance overall sensitivity or to sense a HFGW focal-plane image to be discussed in subsection 5.3.

4.3 Superconductor Detector

Li, Tang, and Shi (paper HFGW-03-108) propose a HFGW detector that involves the response of a Gaussian beam passing through a superconductor having a static magnetic field impressed upon it. They find that under the proper resonant conditions, the first-order perturbative power fluxes will contain a "left circular" wave and a "right circular" wave around the axis of the Gaussian beam. For HFGW in the GHz to THz range the corresponding perturbative photon flux would be large enough to detect such HFGW and lead to very sensitive HFGW receivers. The detectors could even be sensitive to extremely high-frequency gravitational waves, e.g., a QHz (or Peta Hertz).

5. APPLICATIONS

For the engineer the prospect for the application of HFGW is more exciting and compelling than even the prospect for the epoch-making experiment to generate and detect HFGW in the laboratory. In the following subsections I will discuss, quite generally, the applications of HFGW to communication, propulsion, physics, and imaging. During the course of this Conference each of theses applications will be expanded upon.

5.1 *Communication:*

As was mentioned, at least three HFGW detectors or "receivers" are under development and two are now functional {please see Ingley and Cruise [2] and Chincarini and Gemme (paper HFGW-03-103)}. Together with HFGW generators or "transmitters" (seven of them are to be described in this Conference) these detectors can be linked in order to carry information at high frequencies/bandwidths (THz to QHz and above – *the higher the frequency the more efficient is the HFGW generation)*. A rather complete analysis of HFGW communication is given by Stephenson (paper HFGW-03-104) and by Lewis (paper HFGW-03-109).

Like the gravitational field itself, GW passes unattenuated through *all* material things and can, for example, reach deeply submerged submarines. As Thomas Prince (Chief Scientist, NASA/JPL and Professor of Physics at *Caltech*) recently commented to me: "Of the applications (of HFGW), communication would seem to be the most important. Gravitational waves have a very low cross section for absorption by normal matter and therefore high-frequency waves could, in principle, carry significant information content with effectively no absorption unlike any electromagnetic waves." Such a HFGW communication system would represent the **ultimate wireless system** -- point-to-multipoint QHz communication without the need for expensive enabling infrastructure, that is, no need for fiber-optic cable, satellite transponders, microwave relays, etc. Antennas, cables, and phone lines would be a thing of the past!

5.2 *Propulsion:*

Landau and Lifshitz [3], on page 349 of their fundamental treatise state: **"Since it has definite energy, the gravitational wave is itself the source of some additional gravitational field... its field is a second-order effect ... But *in the case of high-frequency gravitational waves the effect is significantly strengthened* ..."** Thus it is possible to change the gravitational field near an object by means of HFGW and move it. Bonner and Piper [4] state: "Loss of mass and gain in momentum arises ... because of the emission of

quadrupole or octupole GW." Thus, according to them, one has the potential of propelling a craft by means of GW. Fontana, in his Conference paper HFGW-03-111, quotes theories that predict HFGW can be employed for propulsion, that is, the generation of space-time singularities (see also Ferrari [5]) with colliding beams of HFGW and could be a form of "propellantless propulsion." The concept is that HFGW energy beamed from off board can create gravitational distortions, that is, "Hills" and "Valleys" in the spacetime continuum that the spacecraft or other vehicle is repelled by, or "falls into," or "falls toward." Again, HFGW is proposed as propulsion means!

5.3 *Physics:*

When high-intensity HFGW is focused by means of a High-Temperature Superconductor or *HTSC* lenses to dimensions of a few microns, GW-driven nuclear phenomena, including quantum jitter, may occur. As discussed in [7], it is hypothesized (along with Greene [8]) that since the smaller particles have a more detailed structure they are more fragile and susceptible to space-time geometry warp or tear caused by gravitational stress related to a large gravitational-energy or HFGW flux. It is also recognized [9] that as the focused intensity of lasers (or possibly HFGW) increases from 10^{20} to 10^{26} .[watts/m^2] photoexcitation of low-lying nuclear levels, photonuclear and ion-induced reactions, and pion production can occur. Utilizing a HTSC lens for concentrating HFGW power the theoretical **ten-megawatt** pulse output predicted in HFGW-03-107, **380-kilowatt** continuous power predicted in HFGW-03-117, **11-kilowatt** continuous power predicted in HFGW-03-106, and the over **one-kilowatt** pulse power predicted in HFGW-03-113 could be concentrated to provide HFGW fluxes in excess of 10^{20} [watts/m^2].

5.4 *Imaging:*

Lower diffraction for HFGW allows for imaging using the refractive properties of a *HTSC* for use in communications, propulsion, and optics. {Such refractive properties were first found by Ning Li and David G. Torr [6].} Theoretically, one can image (resolve) two point sources whose angular separation, a_d, (the diffraction limit) is given by

$$a_d = 1.22?_{GW}/d \quad \text{[radians]}, \qquad (2)$$

where d is the diameter of the aperture of the optical device. Thus the smaller $?_{GW}$ is (and, of course, the higher the HFGW frequency is) the greater the resolution. Refractive properties of HTSC, as established by the pioneering analyses of Ning Li and David Torr, also open up the possibility of a **HFGW Telescope**. It may be possible to intensify any anisotropic relic cosmic background features that may exist (MHz to THz) and possibly image HFGW celestial point sources such as: rapid stellar compression shock waves (jerks) and even more speculative, nearer, relic mini black holes – a candidate for *Dark Matter*. The *Big Crunch/Big Bang* theories developed in Conference paper HFGW-03-115 could be tested. Dr. John Miller, a professor both at the *University of Oxford* and the *International School for Advanced Studies* (ISAS), Trieste, Italy and a well-known astrophysicist, made the following observations: although originally he was quite skeptical, now he realizes that there might be a possibility of generating HFGW in the laboratory ... now he felt that this may be quite feasible. With regard to the HFGW Telescope, he suggested to me on May 4, 2002 that: **"It has been the fashion to look for celestial sources of rather low-frequency GW... now my eyes are opening to the possibility of celestial sources of your high-frequency GW."**

If intervening matter between the HFGW generator and detector causes a change (even a very slight one) in HFGW polarization, direction (refraction), frequency (dispersion) or results in extremely slight scattering or absorption, then it may be possible to develop a HFGW "X-ray" like system. It may, in fact, be possible to image directly through the Earth and view subterranean features in three dimensions, such as geological ones, to a sub-millimeter resolution (for THz HFGW) as will be discussed in Conference paper HFGW-03-120.

6. CONCLUSIONS

We now have reached a time when an experiment to generate and to detect HFGW is feasible. There are several HFGW generators that have been proposed – seven at this Conference. These are to be reported on and they are at various stages of development. Thus it is recommended that government- and/or industry-supported experiment or experiments be planned in the next twelve months. It is also recommended that during the course of the planned experiment, communications, propulsion, physics, and imaging applications be explored and experimental parameters for them be established. Like all development projects, the time to fruition is inversely proportional to the development effort that is mounted. **Given a significant development effort, HFGW technology is likely to evolve in a matter of a few years not a few decades.** I encourage you to continue the international composition of the HFGW Working Group (seven countries are represented here today). I also encourage the continuation of the interdisciplinary nature of this group. We bridge the technical spectrum from theoreticians, through experimentalists, to engineers. Although we may differ on goals (epoch-making experiment to amazing applications) and even nomenclature (intensity of HFGW measured in terms of strain, meters per meter, or in terms of flux, watts per square meter) we are a cohesive yet diverse group. ***We are joined by the common commitment to pursue an exciting new technology: High-Frequency Gravitational Waves!***

REFRENCES

[1] , S. F. Ashby, Ian Foster, James M. Lattimer, Norman, Manish Parashar, Paul Saylor, Schutz, Edward Seidel, Wai-Mo Suen, F. D. Swesty, and Clifford M. Will (2000), "A Multipurpose Code for 3-D Relativistic Astrophysics and Gravitational Wave Astronomy: Application to Coalescing Neutron Star Binaries," *Final Report for NASA CAN NCCS5-153*, October 15, 30 pages).

[2] R. M. J. Ingley and A. M. Cruise (2001), "An Electromagnetic Detector for High Frequency Gravitational Waves," *4th Edoardo Amaldi Conference on Gravitational Waves*, Perth, Australia, July.

[3] L. D. Landau and E. M. Lifshitz (1975), *The Classical Theory of Fields*, Fourth Revised English Edition, Pergamon Press, pp. 348, 349, and 355-357.

[4] W. B. Bonnor and M. S. Piper (1997), "The gravitational wave rocket," *Class. Quantum Grav.*, Volume 14, pp. 2895-2904.

[5] Valeria Ferrari (1988), "Focusing process in the collision of gravitational plane waves," *Physical Review D*, Volume 37, Number 10, 15
May, pp. 3061-3064.

[6] Ning Li and Douglas G. Torr (1992), "Gravitational effects on the magnetic attenuation of super conductors," *Physical Review B*, Volume 46, Number 9, p. 5491. (HFGW refraction).

[7] Robert M. L. Baker, Jr. and Paul A. Murad (2003), "Cosmology and the door to other dimensions and universes," *39th AIAA/ASME/SAE/ASEE Propulsion Conference*, Huntsville, Alabama, July 22.

[8] Brian Greene (1999), *The elegant universe*, Norton, New York, p. 129.

[9] K. W. D. Ledingham, P. McKenna, and R. P. Singhal (2003), "Applications for nuclear phenomena generated by ultra-intense lasers," *Science*, Volume 300, p.1107.

[10] S. W. Hawking and W. Israel (1979), *General Relativity: An Einstein Centenary Survey*, Cambridge University Press, Cambridge, Table 3.2, p. 98.