After Peer Review, Accepted for Publication in the ***Proceedings of the Space, Propulsion and Energy Sciences International Forum (SPESIF*),** 24-27 February, 2009, Edited by Glen Robertson (3rd HFGW Workshop).

Towards a New Era in Gravitational Wave Detection: High Frequency Gravitational Wave Research

Gloria Garcia-Cuadrado

Aerospace Research & Technology Center (CTAE)
Av. Segle XXI s/n CUBIC Building; E-08840
Barcelona, SPAIN
+34 93 664 26 44; gloria.garcia@ctae.org

Abstract. Gravitational Wave Physics is entering into a new age of exploration: low and medium frequency gravitational wave detectors are being planned and built worldwide, and even the first space-based mission for their detection is under way. Interest now is also being focused in the high frequency domain of this new type of radiation, called to host the details about events in the early Universe, among others. The present paper aims at giving a general overview in the field of High Frequency Gravitational Waves (HFGW). The paper is split down into three main parts: the first one will be focused on sources for HFGW as well as fundaments for their detection. The second one will cover different detector architectures being currently proposed. And the third and final part will be devoted to highlighting the potential applications of this new type of radiation.

Keywords: Gravitational Waves; High Frequency Gravitational Waves; Early Universe; Fundamental Physics; Gravitational Waves Detectors; High Frequency Gravitational Waves Applications
PACS: 01.30.Cc; 04.30.-w; 04.80.Nn; 95.55.Ym; 98.80.Bp; 89.20.-a; 89.30.-g; 89.40.-a; 89.70.-a

INTRODUCTION

The present paper aims at giving an overall overview of the current status in High Frequency Gravitational Waves (HFGWs) detection and generation mechanisms, giving also a general introduction to the subject for the newcomers into this field. Thus it is not a paper intended for the publication of research results, but a review paper, relying on the important research of the groups being currently involved in HFGW experiments, to whom we would like to extend our deepest congratulations and admiration for their effort, vision and strength in pursuing and paving the way for an interesting and most promising field in fundamental physics, pushing new applications and technology to the frontiers.

HISTORICAL REMARK

The history of Gravitational Waves (GWs) is traced back from an original suggestion of Jules Henri Poincaré: Poincaré (1905), a French theoretical physicist, celestial mechanic researcher and one of the foremost mathematicians of the 19th century, concluded in 1905 - just a few days before the publication of Albert Einstein's *Special Relativity Theory* paper- that there should exist a kind or radiation related to gravity that should propagate at the speed of light in vacuum (nearly, 300.000 Km/s, generically referred as c). Ten years later, in 1915, Albert Einstein developed the *Theory of General Relativity* in which he deals with the fundamentals of space, time and gravitation (Einstein, 1915).

The development of the first experimental detectors for GWs in the low to medium frequencies is traced back to the pioneering work of Joseph Weber and Robert Forward: In 1963, Dr. Weber built the first resonant GW detector consisting of a 3100 pounds (about 1406 Kg) of aluminum in a cylinder 5 feet long (1.5 m) by 2 feet wide (0.6 m), capable of resonating at frequencies up to 1660 Hz. Although Weber claimed detection of waves in early 1970s, this was not verified. More recently, interest was focused also on the properties of high frequency gravitational waves (HFGWs), defined as those containing components at frequencies between 100 kHz and 100 MHz. Hawking and Israel (1979) defined HFGWs as "those Gravitational Waves having frequencies larger than 100 kHz." One can also find in the literature the term very-high-frequency gravitational waves (VHFGWs), to refer to those components at frequencies between 100 MHz and 100 GHz (Douglass and Braginski, 1979). In the following, we would broadly refer all high frequency components as *High Frequency Gravitational Waves* generically.

The first mention of HFGWs though, seems to be attributed to Baker and Forward when they met back in 1961 at the Lockheed Astrodynamics Research Center in Bel Air, California, after an invitation extended by Baker to Forward to conduct a lecture on the "Weber Bar" that Forward and Joseph Weber were building at the Hughes Research Laboratory in Malibu, California, to detect low-to medium frequency Gravitational Waves (Forward and Baker, 1961). After the lecture, they both commented about building a Laboratory generator and detector for "High-Frequency Gravitational Waves", a term that as far as Baker knows, was the first time the subject had been broached. They concluded during their meeting, that such a project could not be accomplished with the technology available, then in the early 60s. Interestingly enough, approximately 50 years later, the technology seems to be prepared for such detection. First papers specifically on HFGWs date back to the early 60s, in mid 1962, when. Gertzenshtein authored the pioneering paper entitled "Wave resonance of light and gravitational waves" (Gertzenshtein, 1962).

Although the subject is not new for both Gravitational Waves and specifically HFGWs, technology is starting to be prepared for the latter, and thus, they have recently started to be investigated both theoretically and experimentally, with the first suggested methods of generation and detection mechanisms in a laboratory, dating back to the also pioneering work of Woods and Baker (Woods and Baker, 2005).

RATIONAL FOR HFGW RESEARCH

Many are the rationales to stimulate HFGW research:

1 The High frequency band will be complementary to current Low and Medium frequency GWs
2 The characteristic dimensions of the HFGWs devices are of laboratory size (typical lengths range from 1 up to 10 m)
3 There is the possibility of building not just detectors, but also generators of HFGWs also in laboratory size devices.
4 Technological applications for Gravitational Waves rely on the High Frequency domain and are related to communications, imaging and propulsion by means of mixed devices combining HFGWs generators and detectors (emitters and receivers).
5 This new domain will serve as a booster for new technologies appearing in the realm of superconductors, nanotechnology, high-quality factor microwave cavities, ultra-fast science, strong field physics, cryogenic technology or ultra-high sensitivity sensors, among others.
6 HFGWs are cheaper both in construction and in operation. For the sake of illustration, we refer in the following typical characteristics and cost for reference detectors in the Low, Medium and High frequency bands (Li, Baker, Fang and Stephenson, 2007) The Following list provides GW detector's characteristic length (L), frequency (Freq.), sensitivity (GW amplitude in change in meters per meter) and cost for the various GW detectors in operation or planned such as ASTROD, LISA (planned Laser Interferometer Space Antenna), LIGO (existing Laser Interferometer Gravitational-wave Observatory) and two versions of the Li-Baker HFGW detector (I-type and II-type Electromagnetic (EM) detector):

- ASTROD: L ~ 10^8 km; Freq. ~ 10^{-6} - 10^{-3} Hz; Sensitivity ~ 10^{-21} - 10^{-23} ; Cost ~ USD$ 10^8 - 10^9
- LISA: L ~ 5×10^6 km; Freq. ~ 10^{-4} - 1 Hz; Sensitivity ~ 10^{-23} - 10^{-24} ; Cost ~USD$ 10^{10}
- LIGO: L ~ 4 km; Freq. ~ 1 - 10^3 Hz; Sensitivity ~ 10^{-22} - 10^{-24} ; Cost ~ USD$ 10^9
- I-type Electromagnetic (EM) detector (Li-Baker HFGW Detector (Baker, Stephenson and Li, 2007)): L ~ 1 - 8 cm; Freq. ~ 10^9 - 10^{10} Hz; Sensitivity ~ 10^{-30} - 10^{-32} ; Cost ~ USD$ 3×10^6 - 6×10^6

- II-type Electromagnetic (EM) detector: L ~ 1 - 2 m; Freq. ~ 10^8 - 10^{10} Hz; Sensitivity ~ 10^{-30} - 10^{-31} ; Cost ~ USD$ 3×10^6

BUILDING UP THE COMMUNITY

In 2002, Baker traveled to Europe to present his ideas on HFGWs to a varied group of researchers: John Miller at the *International School for Advanced Studies* in Trieste, Italy; Mike Cruise, Dean of Science at *Birmingham University,* England; Professor Giorgio Fontana of the *University of Trento*, Italy; and several others. He recommended that a *HFGW Working Group* was established (Baker, 2002) and, after considerable effort along with Paul Murad, the *Gravitational Wave Conference- International High-Frequency Wave Working Group* was organized in 2003, which attracted over 50 scientists from 14 countries and generated around 25 technical papers on the subject (Baker, 2003). This was the first congress specifically on the topic of HFGWs that served as a kick-off for a worldwide international effort.

GENERATION OF HFGWS

HFGWs are generated in Natural Phenomena and could also be generated in the laboratory. In the following we will sum-up the main HFGWs sources both for natural and for artificial mechanisms.

Sources in Nature for High Frequency Gravitational Waves

Main sources in Nature for Gravitational Waves in the High Frequency domain include:

- *Thermal Gravitational Wave noise of stars:* the working mechanism is the mutual scattering of particles in the star media - thus, this emission can not take place in the space vacuum – (Braginski and Rudenko, 1963; Weinberg, 1972; Galtsov and Gratz, 1974). This applies also to our Sun that should be sending a HFGW flux to the Earth: Galtsov *et al.* (1984) give the estimate due to the photon-Coulomb scattering of a HFGW flux of about 10^{-11} ergcm^{-2}s^{-1} at a frequency of 10^{17} Hz.
- *Electromagnetic to Gravitational Wave conversion in the cosmic media*: similarly to the above case, a media is also needed in this case not being possible the generation by this mechanism in vacuum. Inside the atmospheres of stars or inside ionized gas clouds, electromagnetic to gravitational wave conversion can take place resulting in narrow directed coherent HFGW beams. By this mechanism, an electromagnetic beam can produce a HFGW beam amplified by the quadruple oscillations of atoms in the media (Gertzenshtein, 1962; Zeldovich, 1973; Galtsov *et. al.*, 1984; Servin and Brodin, 2003). The power for such a HFGW beam could be as high as 10^{11}-10^{12} ergs^{-1}
- *Black Hole evaporation*: A family of primordial mini Black Holes created during the very early Universe could evaporate through the so-called "graviton degree of freedom" (GDF) producing a HFGW background (Bekenstein, 1973; Hawking, 1975; Carr, 1976; Zeldovich, 1980). A rotating primordial mini Black Hole could have an enhanced GDF radiation. This source is deemed as a possible component for Dark Matter
- *Primordial Gravitational Waves* (i.e.: those GWs being generated during the origin of the Universe). In the Standard Cosmological Model, a primordial stochastic background of GWs must exist as a result of initial GWs zero quantum fluctuations being amplified by the variable gravitational field of the expanding Universe (Grishchuk, 1988; 2001; and 2003). These backgrounds also exist in other Cosmological models such as Inflation and String Cosmology. All these theories give a non-thermal GW energy density spectrum growing at low frequencies and falling in the high frequency region, with a cut-off around 10^{11} Hz. The issue of relic HFGWs and its relationship to String Cosmology was thoroughly studied by Veneziano (1990) and later by Gasperini and Giovannini (1992). This work continues on today.

Laboratory Sources for High Frequency Gravitational Waves

Many different architectures are being proposed for laboratory generation of HFGWs. We summarize them in the following.

Generation by X-Ray Lasers

These generators emulate the astrophysical GW generation process by means of a pair of orbiting masses (white dwarfs, neutron stars to black holes and combinations of them, in the astrophysical case), with a pair of test masses in the laboratory orbiting each other and experiencing a *jerk*, defined as the time rate of change of the acceleration, being a *jerk* more intense whenever high acceleration changes are involved over very brief time intervals.

These masses or "laser targets" are "jerked" in equal and opposite directions by the impact of equal and opposite intense forces, in this case, X-ray laser pulses which are synchronized and aligned in exactly opposite directions. Following Li and Baker (2005), one can visualize a circle whose diameter is the distance between the laser targets in a plane that is defined by the two coplanar laser beams acting tangential to this circle on the laser targets. Photons then striking the targets will produce a *jerk* on each target mass and together with computer controlled logic system, will generate a HFGW spike each time the laser pulses are repeated.

An X-ray laser of the theoretical specification needed is just on the threshold of state of the art technology. The promise of a "tabletop" X-ray laser was discussed Shelton, et al. (2001). Other technology challenges with X-Ray laser HFGWs generators involve the appropriate endurance of the target masses which would have to withstand the energy release by the laser beams. Proposed materials include gases such as Krypton.

Generation by Piezoelectric or Film Bulk Acoustic Resonators (FBARs)

Similarly to the X-Ray laser case, the Piezoelectric generators simulate also the classical spinning-rod (or dumbbell) or orbiting-mass GW generating systems that are discussed by Baker, Woods and Li (2006).

Basically, an array of synchronized piezoelectric elements (PZTs) such as the Film-Bulk-Acoustic-Resonators (FBARs) found regularly in cell phones, are energized by magnetrons, also a very low cost elements found in day-to-day devices such as microwave ovens. The energy of the magnetrons would produce a *jerk* in the piezoelectric elements (basically fast mechanical displacements in a quadrupole pattern) and the subsequent release of HFGW of an estimated frequency of about 4.9 GHz (Dehnen and Romero, 2003).

It is interesting to point out the fact that usage of PZTs for gravitational wave generation was already brought up by Dr. Weber back in the 1960s (Weber, 1960).

The same concept for PZTs has also been suggested by Baker (2003) using Nanotechnology Micro-Electro-Mechanical (MEMs) elements instead of PZTs.

Generation by a Toroid with an Electromagnetic Field

Grishchuk and Sazhin (1975) suggested the use of an electromagnetic resonator in the form of a torus in which an alternating EM field is excited and can be used as a source of gravitational wave emission.

Generation by Nuclear reactions

Baker and Fontana (2006) suggested that an intense *jerk* on matter could be provided naturally in nuclear reactions involving fission: a fissioning isomer not only rotates at extremely high frequency (~ 3.03×10^{24} s^{-1}), but is also highly deformed in the first stages of fission. Thus one can achieve significant impulsive forces (e.g., 3.67×10^{8} N) acting over extremely short time spans (e.g., 3.3×10^{-22} s). Alternatively, a pulsed particle beam, which could include antimatter, could trigger nuclear reactions and build up a coherent GW as the particles move through a target mass.

The usual difficulty with HFGWs generated by nuclear reactions is the small dimensions involved which are related to the small nuclear reaction volumes (e.g., 10^{-16} m). Such a difficulty could be overcome by utilizing clusters of nuclear material, whose nuclear reactions would be in synchronization through the use of, for example, a computer controlled logic system, and are at a large distance apart, - from meters up to Kilometers-. The effective volume involved is then larger and significant HFGW could be generated, up to 8.5×10^{10} W to 1.64×10^{25} W bursts for the transient asymmetrical spinning nucleus case.

Generation by Quantum, Phenomena: The High Temperature Superconductor Gaser (HTSC Gaser)

In the HTSC Gaser a stimulated emission of gravitons is achieved by coherent gravitational quadrupolar quantum transitions (Fontana, 2004; Fontana and Baker, 2003).

Just as a remark, according to historical nomenclature, the quantum source of gravitational waves has been referred as *GASER* and the quantum of a gravitational wave is referred as the *graviton*.

After recognizing that a quantum source can be developed based on quadrupolar quantum transitions (Halpern, 1964; Ford, 1982), the first serious difficulty in designing a quantum source of HFGW is the identification of a suitable active material, i.e., a material in which those gravitational transitions may take place. According to Fontana (Fontana, 2000), a good candidate could be an orthorombic cuprate High Temperature SuperConductor (HTSC). Later on, a more comprehensive approach to the problem including the details of this proposed HTSC GASER was thoroughly developed by Fontana and Baker (2003).

DETECTION MECHANISMS FOR HFGWS

One of the main challenges concerning the detection of HFGWs is exactly their high frequency nature: from the low to the medium frequency GWs detectors, the ones reaching higher frequencies are interferometers. One might think then of using them for HFGWs detection. The problem is that ultimately, those interferometers are not suited to measuring Gravitational Waves that stretch or shrink the interferometer's arms much more rapidly than the time a photon typically remains inside the optical cavity - which is roughly a millisecond – thus not being appropriate for high frequency signals. That is why new devices for those waves aimed at the high frequency band were started to be considered. Up to now, four groups worldwide are developing HFGW Detectors: one group at the Birmingham University, England, lead by Cruise (2000) another at the INFN Genoa, Italy, lead by Bernard (2002), the Chongqing University, China, lead by Li (2003); and the USA-based group GravWave, lead by Baker (2007). Recently, the last two have merged into a collaboration being the detector jointly developed referred as *the Li-Baker detector* (Li et al., 2008).

Some patents are also already in place: The first patent in HFGWs is from Baker and a business associate of his, Fred Noble, granted as United States Patent 6.160.336 on November 19, 1999. Only a year later, a second patent came, this time authored only by Baker, who was awarded United States Patent Number 6.417.597 for a "Gravitational Wave Generator," filed July 14, 2000. In the following Chapters we will summarize the main fundaments and working principles involving HFGWs detection.

Circular Waveguide Detector

A waveguide ring containing a polarized electromagnetic field will experience a polarization change when a gravitational wave of the same wavelength passes through the waveguide ring. Generally speaking, in the presence of a gravitational wave, an electromagnetic wave can experience changes in its amplitude, frequency, direction of propagation, and polarization. In the case of the Circular Waveguide Detector, if an electromagnetic wave is confined to move in a circular path in the presence of the gravitational wave, a resonant condition exists where the polarization shift is cumulative with successive passes of the circumference, and can thus be noticeable. The circular waveguide detector works best at microwave frequencies. An example of such detector is the one being developed by the Birmingham group (Cruise, 2000). Two have been fabricated so far. The best sensitivity of the instruments is obtained at those frequencies where the noise floor is lowest and it results in about 5×10^{-14} Hz$^{-1/2}$.

Coupled Electromagnetic Cavities

The gravitational wave incident on a pair of tuned resonant cavities will cause those cavities to alter their resonant behavior. In the scheme suggested by Bernard *et al.*, (2001; 2002), HFGWs are detected by coupling two identical high-frequency cavities. Each resonant mode of the individual cavity is then split into two modes of the coupled resonator with different spatial field distribution, and a passing HFGW is sensed by measuring a slight change in the resonance frequency of the two cavities. Similarly to the previous case, the device works best at microwave frequencies. An example of such a detector is the one being developed by the INFN Group. The INFN Genoa detector or *resonant antenna*, consists of two coupled, superconducting spherical harmonic oscillators. The oscillators are designed to have (when uncoupled) almost equal resonant frequencies. The theoretical ultimate sensitivity for GHz frequencies is about 2.2×10^{-22} Hz$^{-1/2}$.

Static Magnetic Field with an EM sense beam

A gravitational wave entering a region filled with a static magnetic field will have a resonant response to a same frequency Gaussian photon beam, creating new photon frequency outputs. The mechanism at work here is referred as the *Inverse Gertzenshtein Effect*. An example of such detector is the one being developed by the joint initiative of GravWave, USA, and the Chongqing University, China, materialized in the *Li-Baker Detector* (Li, *et. al.*, 2003; 2005; 2007; Baker, Stephenson and Li, 2007). In this device, a Gaussian beam (GB) passes through a static magnetic field region. Under a synchro-resonance condition in which the frequency of the GB is set equal to the frequency of the expected HFGW, upon impinge of the HFGW, a Perturbative Photon Flux (PPF) is generated from the background photon flux of the Gaussian Beam. The relatively weak first-order PPF is directed at right angles to the expected HFGW and reflected by a fractal membrane. The resulting reflected PPF (in fact, the signal one detects) exhibits a very small decay in transit to the detector, compared with the much higher decay rate of the background photon flux - which has a typical Gaussian decay rate- allowing therefore for detection of the reflected PPF by a set of microwave receivers.

In a quantum picture of the above process, what is at work is a resonant interaction of the photons (Gaussian Beam) with the gravitons (impinging HFGW), in a background of virtual photons (the statistic magnetic field) which is acting as a catalyst for the interaction, i.e., *the inverse Gertzenshtein effect* above mentioned, involving elastic scattering of the gravitons to the photons in the background of virtual photons which can greatly increase the interaction cross section between the photons and the gravitons. In other words: the interaction may effectively change the physical behavior (such as propagating direction, distribution, polarization, and phase) of the partial photons in the local regions, and there is no need for a resonant conversion of the gravitons to the photons, the latter corresponding to an extremely small conversion rate and thus, even if the net increase of the photon number approaches zero, one still might find an observable effect.

As an historical remark, the idea of a mutual electromagnetic to gravitational wave conversion (EM-GW conversion) in a magnetic field was initially proposed and estimated in the pioneering papers of Gertzenshtein (1962) and Zeldovich (Zeldovich, 1973; Zeldovich and Novikov, 1975) in application to some astrophysical phenomena. This principle has been investigated also with respect to a potential set-up of a magneto-optical GW device (Baker, Davis and Woods, 2005; Li, Baker, Fang, Stevenson, Chen, 2007). In the so-called *Direct Gertzenshtein Effect*, the source of the gravitational radiation is the Maxwell stress tensor: in 1960 Gertzenshtein discovered that a wave resonance solution exists to the general relativity field equations that predict an emitted gravitational wave due to an EM wave propagating through a static magnetic field; In the quantum image, a co-aligned magnetic field acts as a “conversion medium”, transforming some spin 1 particles (photons) to spin 2 particles (gravitons). Conversely, in the so-called *Inverse Gertzenshtein Effect, a* passing gravitational wave in a region filled by a constant magnetic field would induce an electromagnetic wave.

SET OF HFGWS GENERATOR-DETECTOR (EMITTER-RECEIVER)

Applications for HFGWs rely on the possibility of having a set of devices for proper generation and proper detection of this type of radiation. Some architectures have been proposed combining the generators and detectors mentioned in the previous Chapters. Potential combinations could be:

- X-Ray Laser Beam Generator + Li-Baker Detector: The X-Ray Generator is set-up so that the focus or concentration point of the generated gravitational radiation is located at the midpoint between the laser targets. The HFGW detecting system then is located at the HFGW focus, in this case, a Li-Baker detector (Baker and Li, 2005).
- Piezoelectric Generator + Li-Baker Detector. Same idea as above but using a set of PZTs as HFGWs generators (Baker, Woods and Li, 2006)
- X-Ray source entering a Gertzenshtein region + Detector 1 a circular waveguide + Detector 2 a resonant cavity. The X-Ray source could originate from a Synchrotron light source for example. Two sub-options are possible here: The first one involves a short X-ray pulse and a DC magnetic field being used in the generator; the result will be a broad HFGW spectrum at the detector. Alternatively, one could use instead of an X-Ray source, a Microwave carrier wave entering the DC magnetic field region; the result would be a carrier wave (CW) GW signal. The second possibility involves a long X- ray pulse with an AC magnetic field in the generator; in this case one would get a modulated HFGW (Gary, 2005).
- Generator Tokamak (fusion reactor) + Li-Baker Detector. The tokamak should be adapted to Gravitational Wave generation but can rely on current designs such as the DIII-D (General Atomics Tokamak), the JET, (Joint European Torus), or equivalent (Grishchuk and Sazhin, 1975).

TECHNOLOGY UPGRADES

Many technology upgrades are applicable to the above mentioned detectors and generators. Without pretending to be exhaustive, we mention in the following some examples for illustration purposes.

One interesting upgrade for the Li-Baker detector relies on the development of new fractal membranes capable of providing nearly total reflection for the electromagnetic waves within certain frequencies in the GHz band, while providing at the same time nearly total transmission for the photon fluxes for other frequencies in the GHz band. The photon fluxes reflected and transmitted by these new fractal membranes can keep their strength invariant in a distance of one meter from the fractal-membrane's surface (Wen *et al.*, 2002: Zhou et al, 2003; Hou *et al.*, 2005). Another interesting upgrade for the Li-Baker detector consists in using a Gaussian Beam in the X-Ray Band.

Other important technology developments that will serve as upgrades for HFGWs devices will rely on microwave photon detectors capable of being sensitive to one single photon, such as the Quantum Electromagnetic Detection Devices (QED) (Schuster, 2006) which will also help to reduce quantum noise level; and/or the Rydberg Atom Cavity Detector (Baker, Stephenson and Li, 2007). Procedures for detection and data analyses based on Non Demolition Measurements would be also of paramount importance to avoid loss of information (Braginski,, 2007).

It seems also that the *Gertzenshtein Effect* can be enhanced by means of the application of a Fabry-Perot cavity and its efficiency could be improved with the use of an inhomogeneous dielectric (Portilla, Lapiedra, 2001).

Ultra small accelerometers based on MEMs being sensitive to less than a micro*g* would also proof helpful (Waters, Jones, 2004).

Finally, developments of new focusing lens for HFGWs are also promising: Studies by Li and Torr (Li, Torr, 1992; and Torr, Li, 1993) on the propagation behavior of Gravitational Waves inside superconductors, claimed that the phase velocity of GWs in any superconducting material would be about 10^6 ms^{-1}, that is, nearly 300 times less than the phase velocity of GWs in other materials – which is generally assumed to be equal to *c*-. In the language of conventional geometric optics, the above would mean that a superconductor would have a GW refractive index n_g of 300. This will also mean that the wave number would increase by a corresponding factor n_g of 300 times in a superconducting material. This result is of paramount importance for future instruments which may need to be capable to focus, refract, reflect, and in general, manipulate gravitational waves for efficient coupling to generators, transmitters, detectors and other (Woods, 2006).

POTENTIAL APPLICATIONS FOR HFGW

HFGWs are expected to have breakthrough applications in the fields of Communications, Propulsion and Observation (Baker, 2005).

Communications

The working principle for the claimed potential applications of HFGWs for Communication purposes is that Gravitational Waves have a very low cross section for absorption by normal matter and therefore high-frequency waves could, in principle, carry significant information amount with effectively no absorption – contrary to the case of electromagnetic waves -. In this way, HFGWs could represent a broad band, high capacity wireless system and HFGW Communication ground stations could replace an entire communication satellite constellation (Stephenson, 2003; Woods, 2005). Current HFGW detectors are very narrow band. Thus HFGW signal for communication purposes based on current developments will be limited at first stage to narrowband applications, for example time keeping and navigation. When broadband detectors can be developed, the possibility will exist for wideband communications relying on HFGWs communicating directly through the Earth, for example to deeply submerged submarines and other subterranean sites without the need for fiber-optic cable, satellite or microwave relays – a completely new and revolutionary communications means.

Propulsion

The idea underlying potential uses of HFGWs for propulsion is that a HFGW beamed from off board a vehicle (aircraft and even space vehicles) can create gravitational distortions – think of that as “hills” and “valleys”, as Baker has suggested (Baker, 2002) - ; then, the vehicle, would be repelled by, or would fall into those distortions, respectively. The concept of using GWs for propulsion purposes was stated for the first time by Landau and Lifshitz back in 1975 (Landau and Lifshitz, 1975). Propulsion applications for HFGWs are mainly based on the so-called mechanism of *Temporal Quadrupole Rectification* (QR), which operating principle is to create first a HFGW pulse quickly in one direction; then slowly relax; and then, create again back in the opposite. A net Direct Current (DC) GW force requires this quadrupole rectification process, which may be possible in electro-mechanical or nanotechnology HFGW generators, but may not be possible in synchro-resonance generators, such as the ones based on the Gertzenshtein Effect (Stephenson, 2005).

Imaging

HFGWs could allow also for imaging and therefore potential applications may arise in the fields of Earth Observation and surveillance, and space-based observations (a HFGW telescope), among others. This capability would be based in potential changes - even if slight - caused by intervening matter, of the HFGW beam’s polarization, propagation direction, or even extremely slight absorption or scattering. It may then be possible to image directly through the Earth accessing subterranean features, or accessing building interiors, theoretically to a sub-millimeter resolution for HFGWs having frequencies in the THz range.

CONCLUSION

Thorough theoretical development for both Gravitational Waves and High Frequency Gravitational Waves is in place dating back to early 1905. We have also a first indirect proof of their existence, the PSR1913+16, the discovery of which merited a Nobel Prize in Physics in 1993 for the observations conducted during the 70s, by Hulse and Taylor. Being thus a solid theoretical framework in place backing up the field and an indirect evidence for their existence, it is mainly only about technology that the field has not properly progressed yet.

But we are facing interesting times when the technology starts to be at hand both for GW detection and specifically for HFGWs detection but also generation. This new domain will open breakthrough technology applications in communications, observation and propulsion, but also in many other areas thanks to the development of new technology; as well as contributing to breakthroughs in fundamental physics and in our understanding of the Universe.

The development of HFGW technology is almost inevitable. And although long-time development periods are expected of about 30 to 40 years, these are common whenever new technologies are being breached: from the first invention of Edison's Light Bulb in 1879, up to the electrification of all urban America in 1920; or from computers Hollerith's Punch Card Patent in 1889, to the first IBM PC introduced in 1983; or from the Wright Brother's first flight in 1903, to the DC3 rollout in 1935...These are just examples of the fact that technology needs its time to mature into worldwide services and products. We should not be discouraged at the long development time spans, mainly when so much promising applications and new knowledge are waiting for us in the HFGW domain.

ACKNOWLEDGMENTS

The Author would like to express special acknowledgement to Robert M.L. Baker, Jr. for his support, open-mindedness and kind introduction to the HFGW community. The Author wishes also to express special acknowledgement to the local Government of Catalonia (*Generalitat de Catalunya*) for its support in the internal research on Gravitational Waves conducted at the Aerospace Research & Technology Centre (CTAE) under financing line *CIDEM Ajuts a Centres Tecnològics 2007 - Generalitat de Catalunya (CT07-2-0001)*.

REFERENCES

Baker, R.M.L.,Jr., “High-Frequency Gravitational Waves,” *Max Planck Institute for Astrophysics (MPA) Lecture*, May 9, Revised May 15, 2002. Please visit Internet site: http://www.drrobertbaker.com/docs/European%20Lecture%202002%20Revised.pdf. *Last accessed 16 October, 2008*.

Baker, R M.L.,Jr., “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, May 6-9, 2003.

Baker, R. M. L., Jr., Outline of Lecture Delivered to The Max Planck Institute for Astrophysics (MPA) Gauching, Germany, May 9, 2002, 1530-1700 (Unscheduled; Second Revision May 25, 2002) And The National Institute for Nuclear Physics (INFN) Genoa, Italy, May 28, 2002, pp. 1000-1130.

Baker, R.M.L.,Jr., “Generation of High-Frequency Gravitational Waves (HFGW) by Means of an Array of Microand Nano-devices”, in *Gravitational-Wave Conference,* edited by P. Murad and R. Baker, The MITRE Corporation, Mclean, Virginia, May 6-9, 2003.

Baker, R.M.L.,Jr., “Applications of High-Frequency Gravitational Waves (HFGWs)”, in proceedings of *Space Technology and Applications International Forum (STAIF-2005),* edited by M.S. El-Genk, AIP Conference Proceedings, Melville, NY, 2005.

Baker, R.M L.,Jr., Davis, E.W., and Woods, R.C., “Gravitational Wave Radiation Pattern at the Focus of a High-Frequency Gravitational Wave Generator and aerospace Applications”, in proceedings of *Space Technological Applications International Forum, (STAIF 2005),* edited by M.S. El-Genk, American Institute of Physics Conference Proceedings, Melville, New York 746**,** pp. 1315-1322 (2005).

Baker, R.M.L.,Jr., Fang-Yu Li, “High-Frequency Gravitational Wave (HFGW) Generation by Means of X-ray Lasers and Detection by Coupling Linearized GW to EM Fields”, in proceedings of *Space Technology and Applications International Forum (STAIF-2005),* edited by M. S. El-Genk, American Institute of Physics, Melville, New York, Feb. 13-17, 2005.

Baker, R.M.L.,Jr., Woods, R., Fang-yu Li, "Piezoelectric-Crystal-Resonator High-Frequency Gravitational Wave Generation and Synchro-Resonance Detection", in proceedings of *Space Technology and Applications International Forum (STAIF-2006)*; Edited by M. S. El-Genk, American Institute of Physics, Melville, New York, Feb. 12-16, 813, 2006, pp. 1280-1289.

Baker, R.M.L.,Jr., Stephenson, G.V., Fang-yu Li; "Proposed Ultra-High Sensitivity High-Frequency Gravitational Wave Detector", in *2nd HFGW International Workshop Institute for Advanced Studies at Austin (IASA)*, Texas, September 17-20, 2007.

Bekenstein, J.D., *Phys. Rev. D*, 7, p. 2333 (1973).

Bernard, P., *et al.*, (2002), gr-qc/0203024

Bernard, P., *et al.*, Review of Scientific Instruments 72, p. 2428 (2001).

Braginski, V.B.; PNAS , March 2007, vol 104, no.10, pp. 3677-3680.

Braginski, V.B., Rudenko, V.N., 1963, *Scientific notes of Kazan University*, v.123, n 12, pp. .96-108, ed. Kazan University 1963 (in Russian).

Carr, B., *ApJ*, 206, p.8 (1976).

Charles, W. Misner, Kip S. Thorne, John Archibald Wheeler, *Gravitation*, W.H. Freeman and Company; New York.

Cruise, A.M., "An electromagnetic detector for very-high-frequency gravitational waves", in *Class.Quantum Gravity,* Volume 17, pp. 2525-2530 (2000).

Dehnen, H., and Romero-Borja, F., "Generation of GHz - THz High-Frequency Gravitational Waves in the Laboratory" , in *Gravitational-Wave Conference,* edited by P. Murad and R. Baker, The MITRE Corporation, Mclean, Virginia, May 6-9, 2003.

Douglass, D.H., and Braginski, B., "Gravitational-Radiation Experiments," in *General relativity: an Einstein centenary survey* edited by S.W. Hawking and W. Israel, CUP, 1979, pp. 90-137.

Fang-yu Li et al., *First International High-Frequency GW Conference*, edited by P. Murad, The MITRE Corporation, Mclean, VA, USA (2003)

Fang-yu Li, Robert M. L. Baker, "High-Frequency Gravitational Wave (HFGW) Generation by Means of X-ray Lasers and Detection by Coupling Linearized GW to EM Fields", in proceedings of *Space Technology and Applications International Forum (STAIF-2005),* edited by M. S. El-Genk, American Institute of Physics, Melville, New York, Feb. 13-17, 2005.

Fang-yu Li, Robert M. L. Baker, Zhengyun Fang and Gary V. Setephenson, *Second International High-Frequency Gravitational Wave Workshop* Institute for Advanced Studies at Austin, Austin, USA; 2007.

Fang-yu Li, Baker, R.M., Fang Z., Stevenson, G., Chen, Z. gr-qc/0604109 , 2007.

Fontana, G., "Gravitational Radiation and its Application to Space Travel", in proceedings of *Space Technology and Applications International Forum (STAIF-2000)* , edited by M. El-Genk, AIP Conference Proceedings 504, New York, 2000, pp. 1085- 1092.

Fontana, G. and Baker, R. M. L., Jr., "The High-Temperature Superconductor (HTSC) Gravitational Laser (GASER)", in *Gravitational-Wave Conference,* edited by P. Murad and R. Baker, The MITRE Corporation, Mclean,Virginia, May 6-9, 2003, Paper HFGW-03-107.

Fontana, G., "Design of a Quantum Source of High-Frequency Gravitational Waves (HFGW) and Test Methodology", in *Space Technology and Applications International Forum (STAIF-2004),* edited by M. S. El-Genk, American Institute of Physics, Melville, New York, February 8-12, 2004.

Fontana, G., and Baker, Robert M. L., "Generation of Gravitational Waves with Nuclear Reactions", in proceedings of *Space Technology and Applications International Forum (STAIF-2006)*, edited by M. S. El-Genk, American Institute of Physics, Melville, New York, Feb. 12-16, 813, 2006, pp.1352-1358.

Ford, L.H. "Gravitational Radiation by Quantum Systems" in, *Annals of Physics,* 144, pp. 238-248 (1982).

Forward, R.L., and Baker, R. M. L., Jr., "Gravitational Gradients, Gravitational Waves and the 'Weber Bar'," Lecture given at the *Lockheed Astrodynamics Research Center*, 650 N. Sepulveda, Bel Air , California, USA, November 16, 1961. *Lockheed Research Report RL 15210.*

Galtsov, D.V., Gratz Yu.V. 1974, Sov. Phys. Journ.,17, n 12, p.94.

Galtsov, D.V., Gratz Yu.V., Petukhov V.I. 1984, "Radiation of gravitational waves by electrodynamic systems", ed. Moscow University (in Russian).

Gasperini, M., Giovannini,, M.; Physical Review Letters B, Volume 282, 1992, p. 36.

Gertzenshtein, M.E.,, "Wave resonance of light and gravitational waves," *Soviet Physics JETP,* Volume 14, Number 1, 1962, pp. 84-85.

Grishchuk, L.P., Sazhin, M.V., Zh. Eksp. Teor. Fiz. 68, 1569 (1975) [Sov. Phys. JETP. 41, 787 (1976)]; L. P. Grishchuk. Usp. Fiz. Nauk. 121, 629 (1977) [Sov. Phys. Usp. 20, 319 (1977)].

Grishchuk, L.P.1988, Uspekhi Fizicheskih Nauk, 156, 297. (in Russian).

Grishchuk, L.P., Lipunov V.M., Postnov K.A. et. al., 2001, Uspekhi Fizicheskih Nauk, 171, 4. (in Russian).

Grishchuk, L.P., 2003, gr-cq/03005051, 13 May .

Halpern, L., Laurent, B., "On the Gravitational Radiation of Microscopic Systems," *Il Nuovo Cimento*, XXXIII, N. 3, pp. 728-751 (1964).

Hawking, S.W., 1975, Commun. Math. Phys. 43, p. 199.

Hawking, S.W., and Israel, W., "General Relativity: An Einstein Centenary Survey"; Cambridge University Press, Cambridge, 1979, p.98.

Hou B et al., 2005 Optics Express, Volume 13**,** 9149.

Landau, L. D., and. Lifshitz, E. M., “The Classical Theory of Fields”, Fourth Revised English Edition, Pergamon Press, p. 349 (1975).

Li, N. and Torr, D.G., “Gravitational Effects on the Magnetic Attenuation of Superconductors”, in *Phys. Rev. B* 46, pp. 5489-5495 (1992).

Li, F. Y., Baker, R. M L,Jr.,, Zhenyun Fang,. Stephenson, G. V., and Zhenya Chen (2008), Published Online July 30 (Li-Baker Chinese HFGW Detector:) “Perturbative Photon Fluxes Generated by High-Frequency Gravitational Waves and Their Physical Effects,” *The European Physical Journal C. Please visit the Internet site:* http://www.drrobertbaker.com/docs/Li-Baker%206-22-08.pdf. *Last accessed 16 October, 2008.*

Poincaré, Jules Henri (1905), C.R. Ac. Sci. Paris, 140, 1504 and also appears in *Oeuvres*, Volume 9, p. 489, Gauthier-Villars, Paris, 1954.

Portilla, M., and Lapiedra, R.,, “Generation of High Frequency Gravitational Wave”, in *Physical Review D* 63, pp.044014-1 to 044014-7 (2001).

Schuster, D.L.; et al.arXiv:cond-mat/0608693 v1 30 Aug2006.

Servin, M, Brodin G. 2003, gr-qc/0302039 27 Aug.

Shelton, R. K., Ma, Long-Sheng, Kapteyn, H. C., Murnane, M. M., Hall, J. L., and Ye, Jun , “Phase-Coherent Optical Pulse Synthesis from Separate Femtosecond Lasers,” *Science* 293, pp. 1286-1289 (2001).

Stephenson, G. V., “The Application of High-Frequency Gravitational Waves (HFGW) to Communications” in *Gravitational-Wave Conference*, edited by P. Murad and R. Baker, The MITRE Corporation, Mclean, Virginia, May 6-9, 2003

Stephenson, G.V., “Feasibility Study for the Demonstration of the Gertzenshtein Effect”, in proceedings of *Space Technology and Applications International Forum (STAIF-2005).*

Torr, D.G., and Li, N., “Gravitoelectric-electric coupling via superconductivity,” in *Phys. Letts*. 6, pp. 371-383 (1993).

Veneziano, V., “String Theory and Cosmology,” in proceedings of *First Conference on Particles, Strings and Cosmology*, at Northeastern , March, 1990.

Waters, R. L., and Jones, T. E., “Ultra-Sensitive Electro-Optical Accelerometers”, briefing prepared for AFRL, SPAWAR Systems Center, San Diego, California, USA, June 8, 2004, No. 703-696-4214.

Weber,, J., “Detection and Generation of Gravitational Waves”, in *Physics Review* 117, 1, pp. 306-313 (1960).

Weinberg, S., “Gravitation and Cosmology”, 1972, ed. J.Wiley & Sons Inc, NY.

Wen W J et al. 2002 in *Phys. Rev. Lett*. 89 223901.

Woods, R.C., “Manipulation of Gravitational Waves for Communications Applications using Superconductors”, in *Physica C* 433 101-107 (2005).

Woods, R.C., “A Novel Variable-Focus Lens for HFGW”, in proceedings of *Space Technology and Applications International Forum (STAIF-06)*, edited by M.S. El-Genk, AIP Conference Proceedings, Melville, NY, 2006.

Woods, R.C. and Baker, R.M.L., “Gravitational Wave Generation and Detection Using Acoustic Resonators and Coupled Resonance Chambers”, in proceedings of *Space Technology and Applications International Forum (STAIF-05)*, edited by M.S. El-Genk, AIP Conference Proceedings, Melville, NY, 2005.

Zeldovich, Ya.B., in *Sov.Phys. JETP* v.65, p. 1311 (1973)

Zeldovich, Ya.B., Novikov, I.D., “Structure and Evolution of the Universe “, Moscow, 1975.

Zeldovich Ya.B.,1980, in *General relativity*, ed. Hawking S., Israel, Cambridge Univ.Press. (Translation in Russian, p.217, ed. Mir 1983).

Zhou L et al., 2003 *Appl. Phys. Lett*. 82 1012.