Analysis of the Demonstration of the Gertsenshtein Effect

Gary V. Stephenson

Seculine Consulting,16501 SE 57th Place, Bellevue, WA 98006
425-443-8651, Seculine@Comcast.net

Abstract. A possible demonstration configuration of the Gertsenshtein Effect is analyzed. In 1960, using only General Relativity, the Russian theorist M. E. Gertsenshtein described the revolutionary concept that light passing through a strong magnetic field will produce a gravitational wave via wave resonance. The generation and control of gravitational waves would enable significant and dramatic advances in space communication and propulsion. Such advances would be highly valuable to the human and robotic exploration of space. This paper focuses on one method for a near term demonstration of the Gertsenshtein Effect using system components that are within the current state of the art. Light sources such as X-ray lasers and synchrotrons are investigated for suitability. Pulsed light sources may strengthen the effect, as will inhomogeneous index targets, which have also been predicted to strengthen the conversion efficiency to gravitational waves (GW). Various sources of strong magnetic fields are also investigated since this is a requirement for the Gertsenshtein Effect. While a DC field is the baseline, AC magnetic fields are also explored as they may act to provide a source of modulation for the effect in the case of a continuous wave light source. A number of existing GW detectors are reviewed in the context of how they could be applied to measuring the gravitational waves produced by the Gertsenshtein Effect.

INTRODUCTION

In 1960, motivated by the astronomical implications of possible observation, the Russian theorist M. E. Gertsenshtein described the revolutionary concept that gravitational waves passing through a strong magnetic field will produce light waves via wave resonance (Gertsenshtein, 1962). Conversely, in the same paper Gertsenshtein outlined the concept that light passing through a strong magnetic field will produce gravitational waves, using the same wave resonance technique. While astronomers have concerned themselves mostly with the former effect (Zeldovich, 1983), the latter effect, creating GW, has enjoyed a recent resurgence of interest due in part to the theoretical efforts of Li, Portilla, and Navarro (Li, 2000; Portilla, 2001; Navarro, 2004). While the effect has thus far been too small to test, recent technology advances make now make such a demonstration worth considering. This is the topic of the present paper.

CONCEPT DEFINITION

This paper explores the possibility of experimentally demonstrating the Gertsenshtein Effect. In 1960, Gertsenshtein noted that according to general relativity electromagnetic (EM) and gravitational waves (GW) propagate at the same speed, are linearly related, and that wave resonance between them is therefore possible (Gertsenshtein, 1962). Gertsenshtein went on to solve Einstein's field equations for the case of a uniform, constant magnetic field. This solution has become known as the "Gertsenshtein Effect" and is represented in Figure 1.

From a quantum mechanics perspective, a co-aligned magnetic field acts as a "conversion medium," transforming some spin 1 particles (photons) to spin 2 particles (gravitons). Conservation of angular momentum is maintained through interaction with the magnetic field in each conversion event.

Due to the extremely poor coupling between mass-energy and gravitational waves, the Gertsenshtein Effect has never been demonstrated. However, in the 45 years since the effect was first conceived in an astronomical context, technological advances such as synchrotron x-ray light sources, superconducting electromagnets, optimized targets,

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and ultra-sensitive coupled cavity detectors may now permit us to attempt the laboratory demonstration of this effect here on Earth. Several possible experimental configurations are explored here in further detail.

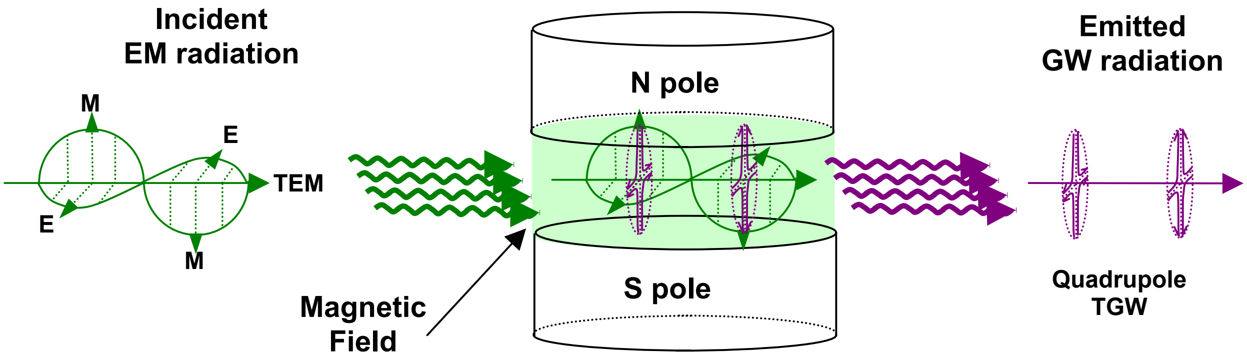


FIGURE 1. The Gertsenshtein Effect (Gertsenshtein, 1962).

A block diagram of one proposed experimental setup is included as figure 2. This demonstration would consist of two main components: the generation of GW, and the detection of GW. The experiment would necessarily be collocated near a source of high frequency x-ray light, such as a synchrotron or linear accelerator. This x-ray source would serve as the incident EM light source. The light would be directed to strike a target immersed inside a strong magnetic field, and gravitational waves would presumably be generated at that point. A number of GW detectors may be co-aligned to improve the odds of experimental success. Given the sensitivity of the HFGW detectors, a faraday cage is recommended to cut down on stray incident EM radiation and guard against false positives. One way to ensure that detections are from GW, and not EM, is to switch off and/or modulate the magnetic field, since the strength of the resultant GW is a function of the magnetic field strength.

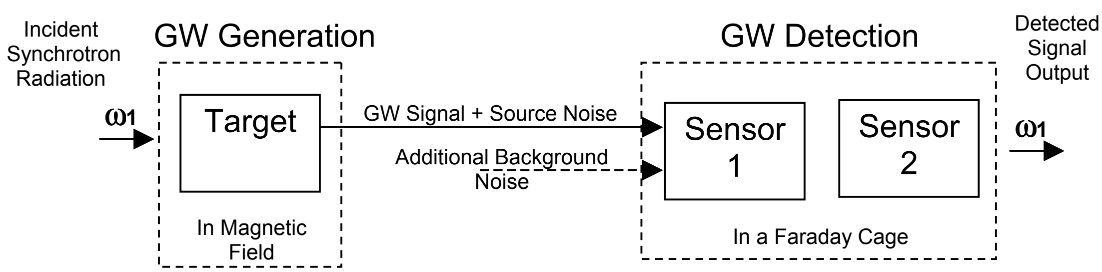


FIGURE 2. Experimental Setup Block Diagram.

The Gertsenshtein Effect may be further strengthened by the optimization of a target within the magnetic field. This was discovered by Portilla and Lapiedra, who published a work to better quantify the Gertsenshtein Effect (Portilla, 2001). Their paper resulted in equation (1), which highlights the parameters important for overcoming the very poor EM to GW coupling.

$$L_G = \frac{(84\pi)\, G\, H^2 \Delta F_E}{5c^4(n_I^{\,2}-1)K^4} \tag{1}$$

For the Gertsenshtein Effect, GW strength goes as the square of the magnetic field strength, which assigns a high importance to a strong super conductor (SC) electromagnet. F_E, incident electromagnetic flux, should be as high as possible. Among the most powerful light sources in the world are the Xray light sources produced by synchroton radiation, so called Synchroton Light Sources (SLS). Because of their large instantaneous flux, SLS radiation would be the light source of choice for a Gertsenshtein Effect demonstration.

Incident index of refraction n_I also appears in equation (1). If this term is correct, incident index in the denominator should be made as low as possible by pumping down the target area to a near vacuum. The index of the target itself should be optimized by making it very high, and non-uniform. Portilla and Lapiedra found that both index and non-uniformity affect the value of the dimensionless parameter Δ. See figure 3 for a diagrammatic representation of a recommended target.

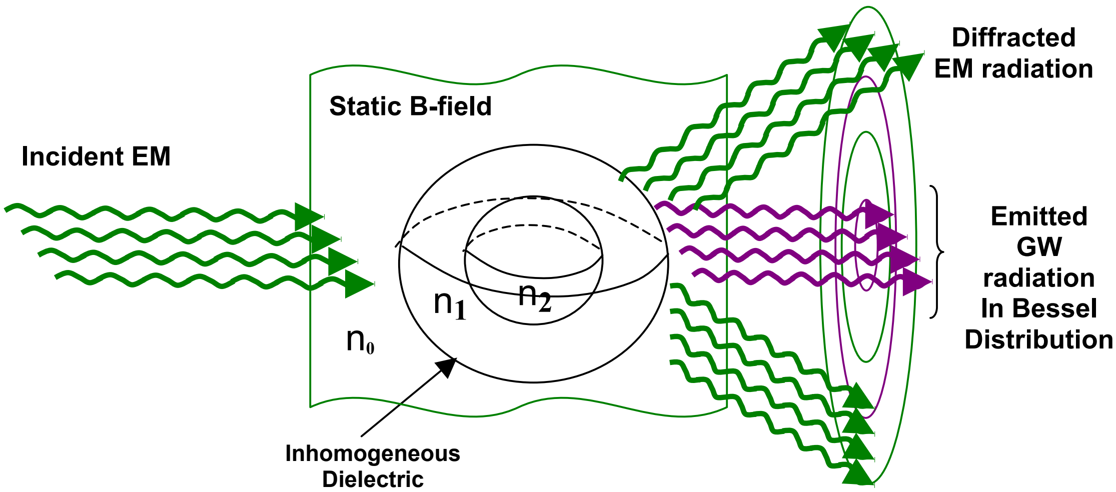


FIGURE 3. Inhomogeneous Radiation Target (Portilla, 2001; Stephenson, 2003).

A quantitative measure of the strength of the Gertsenshtein Effect has been calculated (Navarro, 2004) be reducing the expression of equation (1) to a ratio of generated GW power to incident EM power. The simplified expression from this reference (Navarro, 2004) is shown in equation (2) below:

$$Pg/Pw = 5 \times 10^{-9}(B/1\ \text{Tesla})^2(10^{-9}\ \text{Torr} / P)^2\ (2\pi x 10^{10}\ \text{Hz}/\omega)^2 \tag{2}$$

For a UV Synchrotron Light Source with $Pw = 10^6$ W and $\omega = 2\pi x\ x10^{12}$ Hz, a magnetic field with field strength B = 10 Tesla, and an incident index of refraction resulting from a vacuum at a pressure level of $P = 10^{-9}$ Torr, the generated gravitational wave power is predicted to be on the order of 50μW. This signal level should be within the reach of HFGW detectors. One complicating factor is that while synchrotron light sources are desirable from a signal strength point of view, strong gravitational waves are ineffective for demonstration purposes if they can not be detected, and current detectors are not designed to operate at frequencies above the microwave range. See references (Ingley, 2001; Bernard, 2001; Li, 2000) for descriptions of state of the art detectors.

There are two possible solutions to the frequency cutoff problem in the current state of the art detectors. The first method is to use a very short, sharp impulse function as an EM input. It is known theoretically that an impulse function input into any system is spread into a broad spectrum of frequencies, the "impulse response function," due to the transfer function of the system. Aside from demonstrating the generation of gravitational waves, such an approach would have scientific benefit, were the detectors able to tune over a range of frequencies, in providing insight into the fundamental physics of the conversion process. This first approach may be designated the "short pulse" option, and is depicted in figure 4. Detectors depicted in this figure represent the circular waveguide (Ingley, 2001) and the resonant cavity pair (Bernard, 2001).

The second approach would take advantage of high field strength low frequency AC magnetic field sources by using one as a modulation source. Since gravitational wave generation is a function of magnetic field strength, it follows that a magnetic field may be used as an amplitude modulation and/or pulse modulation source. In this case the detectors could be tuned to detect only the GW energy at the frequency of the modulation, and not the energy left in the carrier frequency. This would require light pulses long enough to be modulated, and is designated in figure 5 as the "long pulse" option.

Left to future study is a comparison of the advantages and disadvantages of each of the two described approaches in terms of generation and detection viability, and recommendations regarding which approach should be stressed in any follow-on demonstration.

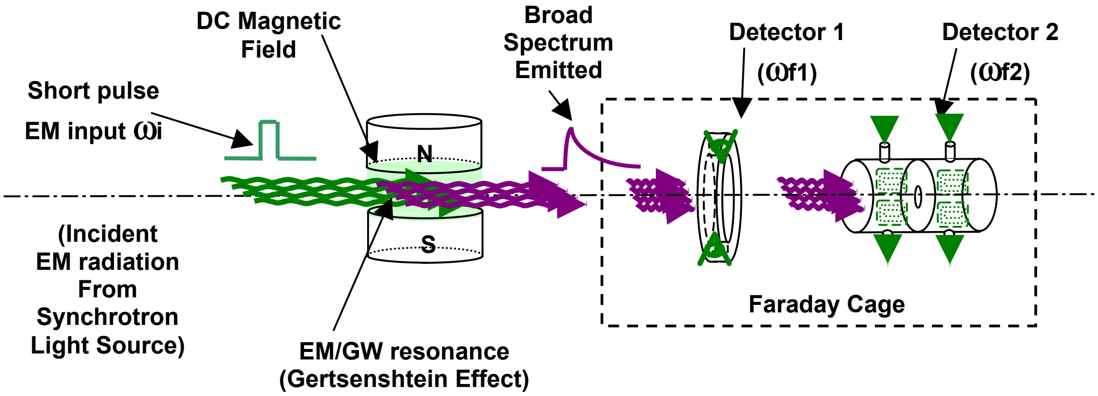


FIGURE 4. Short Pulse Demo Option.

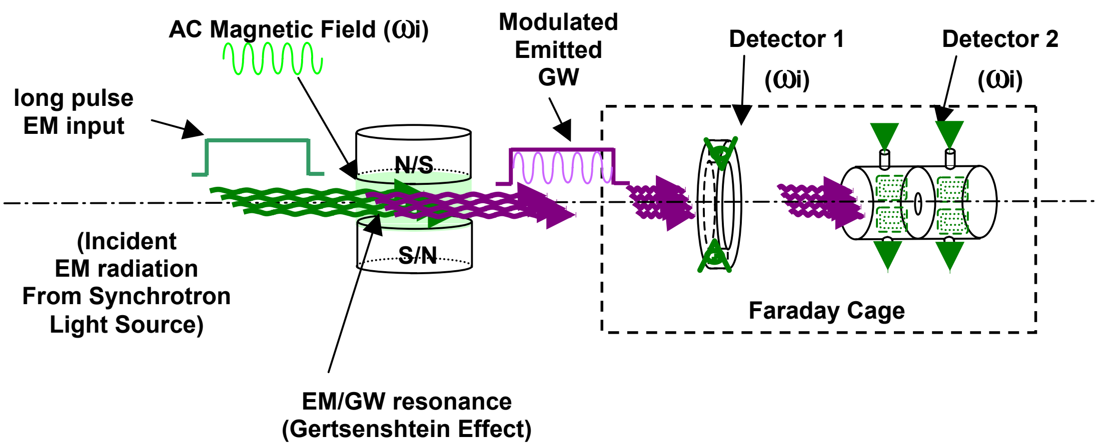


FIGURE 5. Long Pulse Demo Option.

OBJECTIVES

A successful demonstration of the Gertsenshtein Effect would enable dramatic improvements in the quality and execution of space exploration missions. In general, demonstration of the Gertsenshtein Effect would prove the feasibility of HFGW technology, and the potential value of HFGW technology could then be realized via application to the objectives of space exploration, including enabling deep space communication, navigation, and possibly even propulsion.

Application to Communication and Navigation

Prior work (Stephenson, 2003) pointed out that GW communication would have certain advantages, most obviously that line of sight would not be an issue, as GW passes through mass with very little refraction or scatter, as depicted in figure 6.

However, even prior to improving the initially poor bandwidth expected with GW communication, NASA could immediately use the technology to make improvements in very long baseline interferometry. This is a technology that requires a precise knowledge of relative positions of receiving stations with respect to one another. Because GW pass directly through mass at very nearly the speed of light, it may be possible to dramatically extend the size and scope of terrestrial visible/IR telescope interferometry in a way that is currently only done with telescopes that are in laser line of sight.

Similarly, even a very low bandwidth HFGW technology could have an equally dramatic effect on time keeping, a function critical to defense applications such as navigation and threat geolocation using time difference of arrival. Every user on the globe could listen to one central time signal broadcast station and use it as a universal reference. With multiple stations absolute time could be precisely approximated, as could position. This could be done without the use of a single satellite, rendering the GPS system completely obsolete.

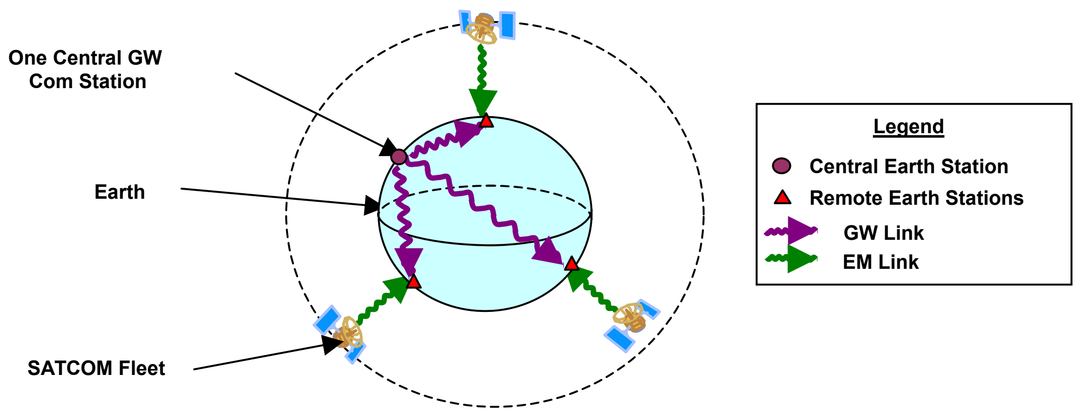


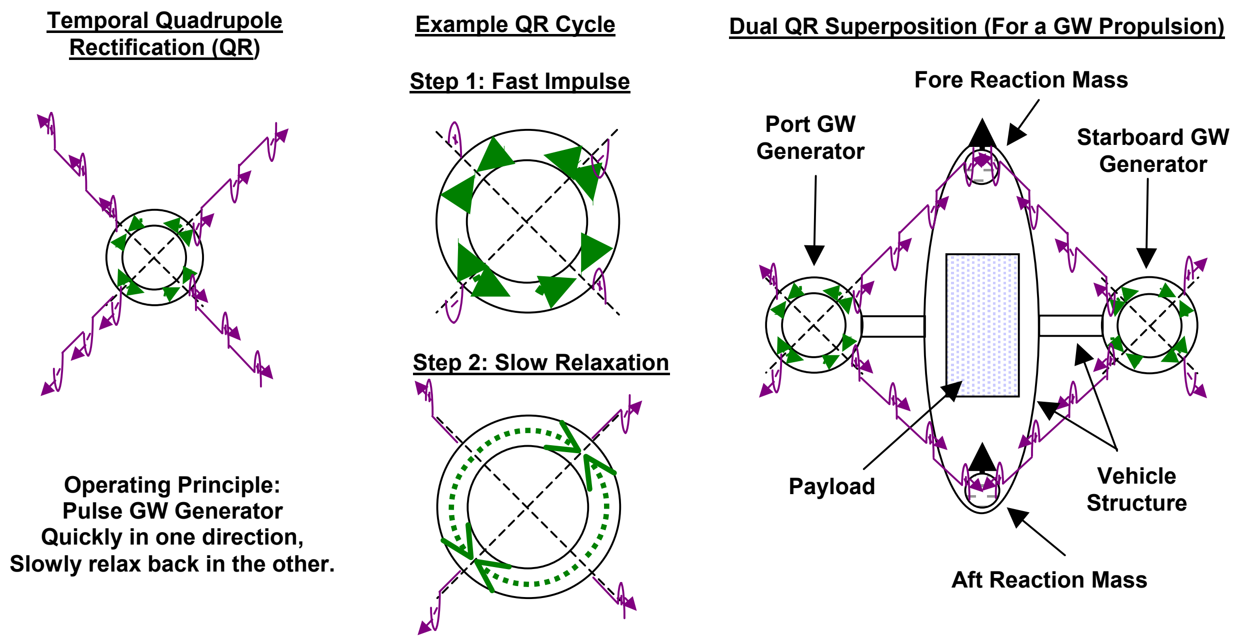
FIGURE 6. Application of HFGW to Communication and Navigation (Stephenson, 2003).

Application to Space Propulsion

Space propulsion is another area of future application. While it may take longer to develop this technology, the payoff is potentially greater. The conceptual details of one possible drive configuration are depicted in figure 7.

In order to be useful in creating an unbalanced force, the GW generators must be operated in a temporally asymmetric way. If a rotary GW generator, such as an EM resonant torus (Grischuk, 1975), a nanotechnology spindle (Baker, 2000; Baker 2004), or a non-rotating ring of jerking masses (Baker, 2003; Baker 2004) is run quickly in one direction but very slowly in the other, then the coupling to GW and hence to mass will effectively be "rectified" such that in any selected direction, the same polarity of quadrupole is emitted over and over. This may be referred to as quadrupole rectification (QR). Note that both polarities are still present, but if one is careful about how the GW radiator is excited, the coupling to GW during the fast polarity is much stronger than for the slower polarity signal. A similar technique to the non-rotating jerked ring has also been recently described using X-ray lasers as an acceleration impulse source (Baker, 2005).

If two GW generators operating in a QR mode are oriented at a right angle with respect to one another, they will be oriented such that they will balance each other out. Furthermore they will create, through superposition, a gravitational "well" in front of the axis of symmetry, and a gravitational "bump" in the back of the same axis, that is, they will create beneficial undulations in space time. This has all the characteristics of the long sought "gravitational dipole" needed to both pull a ship from the front and push it from the back, resulting in an unbalanced force. Note however that conservation of momentum is still maintained, since an equal amount of "waste" gravitational wave energy is being dumped overboard in directions away from the ship. This design is therefore at best 50% efficient, even assuming perfect coupling to GW energy. There are very likely to be many other more elegant solutions than this, but this does serve the point that there is no logical or physical reason why GW propulsion could not be developed. Nevertheless, the application of GW to propulsion will be a formidable engineering challenge.



(a) Quadrupole Rectification. **(b)** QR Cycle. **(c)** Dual QR Propulsion.

FIGURE 7. The Application of Quadrupole Rectification to Space Propulsion.

CONCLUSIONS

Given very strong light sources such as those available at a synchrotron, strong DC and AC magnetic fields, and sensitive HFGW detectors, it may now be feasible to attempt the demonstration of the Gertsenshtein Effect. The Gertsenshtein Effect would be one way to produce gravitational waves, which would find applications in the areas of communication, navigation, and possibly propulsion.

The current state of knowledge in the area of HFGW has recently been summarized in the proceedings of the International High Frequency Gravitational Wave (HFGW) Working Group that met at Mitre in McLean, Virginia from May 6th through May 9th, 2003. During the conference papers were presented on all the components that would be required for a demonstration of the Gertsenshtein Effect. In the case of generators, theoretical work on terrestrial GW generators dates back to at least 1975 (Grishchuk, 1975), but the generators can not be demonstrated without demonstrating an end-to-end gravitational effects test. All the building blocks are in place for a hardware demonstration of the Gertsenshtein Effect, but experimental verification can not be parsed any smaller than the demonstration in question.

Future technology readiness analysis, performed in advance of any experiment, could improve the probability of success. Industry proven system engineering methodology can be used in the systems architecture and feasibility analysis of any proposed experiment. A ROM (Rough Order of Magnitude) capabilities compilation should be assembled for the light sources, magnets, and detectors based on source surveys. End-to-end functionality analyses must be performed, in this case by performing signal link budgets and signal-to-noise ratio (SNR) estimates. Finally, a top level risk assessment has to be conducted to determine where the risk outliers are, and a risk mitigation plan should be developed to guide future work.

NOMENCLATURE

L_G = Gravitational Luminosity (W)
G = Gravitational Constant (6.672x10^{-12} N/m^{2}Kg^2)
H = Magnetic Field (T)

Δ = target index parameter constant
F_E = incident EM flux (W/m^2)
c = speed of light (m/s)
n_I = index of refraction
K = wave number (m^{-1})

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