High Frequency Gravitational Waves

October 2008

JSR-08-506

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
October 2008

2. REPORT TYPE
Technical

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
High Frequency Gravitational Waves

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
D. Eardley et al.

5d. PROJECT NUMBER
13089022

5e. TASK NUMBER
PS

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

The MITRE Corporation
JASON Program Office
7515 Colshire Drive
McLean, Virginia 22102

8. PERFORMING ORGANIZATION REPORT NUMBER
JSR-08-506

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of the Director of National Intelligence
Defense Intelligence Agency
Washington, DC 20511

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

JASON was asked by staff at the National MASINT Committee of ODNI to evaluate the scientific, technological, and national security significance of high frequency gravitational waves (HFGW). Our main conclusions are that the proposed applications of the science of HFGW are fundamentally wrong; that there can be no security threat; and that independent scientific and technical vetting of such hypothetical threats is generally necessary. We conclude that previous analysis of the Li-Baker detector concept is incorrect by many orders of magnitude; and that the following are infeasible in the foreseeable future: detection of the natural "relic" HFGW, which are reliably predicted to exist; or detection of artificial sources of HFGW. No foreign threat in HFGW is credible, including: Communication by means of HFGW; Object detection or imaging (by HFGW radar or tomography); Vehicle propulsion by HFGW; or any other practical use of HFGW. For the relatively weak fields in the lab, on the Earth, or indeed in the solar system (far from the cutting-edge science of black holes of the Big Bang), the general theory of relativity and its existing experimental basis are complete, accurate and reliable.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified	UL		Dr. Ronald Pandolfi **19b. TELEPHONE NUMBER** *(include area code)* 703-907-0862

Contents

Abstract

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1 EXECUTIVE SUMMARY

JASON was asked by staff at the National MASINT Committee of ODNI to evaluate the scientific, technological, and national security significance of high frequency gravitational waves (HFGW). Our main conclusions are that the proposed applications of the science of HFGW are fundamentally wrong and that there can be no security threat. More generally we observe that independent scientific and technical vetting of such hypothetical threats is generally necessary.

In particular we conclude:

1. Previous analysis of the Li-Baker detector concept is incorrect by many orders of magnitude
2. The following are infeasible in the foreseeable future:
   (a) Detection of the natural "relic" HFGW, which are reliably predicted to exist
   (b) Detection of artificial sources of HFGW
3. No foreign threat in HFGW is credible, including:
   (a) Communication by means of HFGW
   (b) Object detection or imaging (by HFGW radar or tomography)
   (c) Vehicle propulsion by HFGW
   (d) —or any other practical use of HFGW.
4. For the relatively weak fields in the lab, on the Earth, or indeed in the solar system (far from the cutting-edge science of black holes of the

Big Bang), the general theory of relativity and its existing experimental basis are complete, accurate and reliable.

2 INTRODUCTIONS AND OVERVIEW

The subject of High Frequency Gravitational Waves (HFGW) has attracted considerable interest in the US government over the last few years. In September 2007, HFGW came to the attention of the National MASINT Committee of ODNI; in turn, staff at this committee asked JASON to review both the underlying science and technology of HFGW, and their implications for national security. JASON hosted briefings during June 17-18, 2008 from individuals both inside and outside the US government, and also collected about a thousand pages of printed or electronic material. This report gives our conclusions and supporting analyses, after having considered this input. Classified topics and conclusions are presented in the accompanying classified appendix.

Gravitional waves (GW) are a firm prediction of Einstein's general theory of relativity, but — due to their weakness — have never been directly detected experimentally. Measurement of their indirect effects on the orbits of certain binary neutron stars was a major experimental triumph, and merited the award of a Nobel Prize in Physics [4]; these measurements agree with theory to better than 1%. Ongoing ambitious experiments to directly detect gravitational waves from astrophysical sources involve long-baseline laser interferometers [1, 2] for GW at frequencies at 10-1000 Hz; planned satellite missions[3] could detect GW in the 0.0001-1 Hz band. The term HFGW has come to mean gravitational waves at much higher frequencies of several GHz, say 10GHz to be specific. These have never been detected.

Meanwhile, a wide variety of other experiments have confirmed the general theory of relativity, and give great confidence to our predictions about the physical properties of GW, whenever they are actually detected [5, 6, 7]. In particular, possible artificial sources of GW can be confidently modelled, and turn out to be terribly weak. Thus the “Hertz Experiment” — an artifical source sending waves to a laboratory detector — has never been accomplished for GW, and predictably so. The aforementioned detection experiments all plan to use astrophysical sources of GW.

Unfortunately, relativity and gravitation theory have, over the last century, been the subject of a great deal of pseudo-science, in addition to real science. Therefore, in evaluating ambitious claims about gravitational applications, one must consider the possibility that the claims are misguided and wrong. For a lucid introduction to pseudo-science and its pitfalls, see Feynman [8]. There is no substitute for seeking expert scientific and technical opinion in such matters.

Our main conclusions are that the proposed applications of the science of HFGW are fundamentally wrong and that there can be no security threat. More generally we observe that independent scientific and technical vetting of such hypothetical threats is generally necessary.

In Section 3 we shall review the physics background for HFGW, and estimate the magnitude of its effects. Section 4 analyzes the proposed HFGW detector. Section 5 evaluates the proposed practical applications of HFGW technology. Finally, Section 6 gives our conclusions and recommendations.

We are especially grateful to Ronald Pandolfi and Mark Pesses of ODNI for their continued help in arranging briefers and documentation; they were ably assisted by Paul Flemming and Sara Shelton. We benefited from briefings by Robert Baker, Gary Stephenson, Paul Murad, Patricia Walters, Ronald Pandolfi, Kevin Pollpeter, and Mark Pesses.

3 PHYSICS BACKGROUND ON HFGWs

Einstein's theory of General Relativity [5] is the widely accepted basis for our understanding of gravity. A great variety of different experiments [6, 7] confirm its predictions, and indeed, modelling of general relativisitic effects is essential to the correct operation of the GPS system and to the tracking of interplanetary spacecraft.

3.1 Gravity and gravitational waves

Newton's formulation of the theory of gravity,

$$\overrightarrow{F}_{12} = -\frac{M_G(1)\ M_G(2)}{r_{12}^2}\left(\frac{\overrightarrow{r}_{12}}{r_{12}}\right) \tag{3-1}$$

$$\overrightarrow{F} = M_I \overrightarrow{a} \tag{3-2}$$

$$M_I = M_G \tag{3-3}$$

for two spherical gravitating masses $M_G(1)$ and $M_G(2)$ is equivalent to the "non-relativistic" gravitational field description

$$\overrightarrow{\nabla} \cdot (\overrightarrow{\nabla} \hat{h}) = \frac{4\pi G}{c^2}\, \rho_G \tag{3-4}$$

$$c^2 \rho_G \overrightarrow{\Delta} \hat{h} = \rho_I \overrightarrow{a} \tag{3-5}$$

$$\rho_I = \rho_G \tag{3-6}$$

in which a non-dimensional "potential" $\hat{h}$ has been chosen to agree with the mathematical language used for it in General Relativity. Here M_I and M_G are the inertial and gravitational masses respectively, and ρ_I and ρ_G are the distributions of these masses. Equations (3-4) and (3-5) are an instantaneous action-at-a-distance description which is inconsistent with the constraints of Special Relativity.

In General Relativity (which is generalizes Newton's theory) Equations (3-4) - (3-6) become

$$\left(\nabla^2 - \frac{\partial^2}{c^2\,\partial t^2}\right)\hat{h}_{\mu\,\nu} = \frac{4\pi G}{c^2}\,\hat{T}_{\mu\,\nu} \tag{3-7}$$

with

$$\hat{T}_{\mu\,\nu} = 2\left[T_{\mu\,\nu} - \frac{g_{\mu\,\nu}}{2}\,T\right]/c^2 \tag{3-8}$$

$T_{\mu\,\nu}$ is the complete relativistic stress-energy tensor of everything including the gravitational field itself, and T is its trace. ($g_{\mu\,\nu}$ is the Minkowski metric tensor of Special Relativity plus $\hat{h}_{\mu\,\nu}$.) Confirmed predictions include the equivalence principle $\rho_I = \rho_G$ (to better than 10^{-10}), the calculated value for the bending of light passing near the sun and gravitational lensing of light in other parts of the Universe, many solar system observations, and remarkably accurate observations of neutron star binaries.

The full content and implications of General Relativity are not needed for any of the HFGW predictions to be considered below. For example the quantum energy density in a vacuum is negligibly small compared to the other important matter and field contributions to $T_{\mu\,\nu}$ in our local environment. All of the HFGW amplitudes of interest here are so small that their contributions to energy density can be neglected in $\hat{T}_{\mu\,\nu}$[1].

In a vacuum with only $\hat{h}_{\mu\,\nu}$ present the RHS of Equation (3-7) vanishes,

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[1] On the laboratory scale (M $\sim$ kg; L $\sim$ cm) $\hat{h} <$ GM / Lc^2 $\sim 10^{-25}$. The gravitational potential $\hat{h}$ at the earth's surface is 10^{-9} and there is no hint of any problem with Equations (3-7) - (3-8)

leaving the familiar free field wave equation[2]

$$\left(\Delta^2 - \frac{1}{c^2}\,\frac{\partial^2}{\partial t^2}\right)\hat{h}_{\mu\,\nu} = 0 \tag{3-9}$$

The robustness of the basic theory for the HFGWs discussed below is even more robust than that of General Relativity. Hypotheses about changes in gravity and $T_{\mu\,\nu}$ from string theory might change it at length scales $\ll 1$ cm and some have proposed changes at huge (astronomical/cosmological) scales but neither would change Equations (3-7) on the scales of interest here.

Because we are concerned with such small HFGW intensities it is often constructive to describe these flows as a flow of gravitational quanta (gravitons). Gravitons are a necessary consequence of Quantum Mechanics applied to Equation (3-9) and bear the same necessary relationship to Equations (3-9) and (3-7) as photons do to electromagnetic fields. In particular

$$E\ (\text{graviton}) = \hbar\ \omega = \hbar\ \mathrm{c}\ \mathrm{k}, \tag{3-10}$$

with $\omega = 2\pi\times$ frequency and $k = 2\pi/\lambda$.

Figure 1 shows the electromagnetic-gravity field interactions in Equation (3-7) as (static gravity or graviton) - (photon or static electromagnetic field) interactions.

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[2] This equation was well known before Special Relativity as the Helmholtz equation. Indeed, studies of gravity in Special Relativity led Nördstrom (1913) to propose the simplest Lorentz invariant guess, $(\nabla^2 - \frac{1}{c^2}\,\frac{\partial^2}{\partial\, t})\hat{h} = 4\pi G\ T/c^2$, before the introduction of General Relativity by Einstein in 1916. This had to be discarded after the solar bending of light observation (1919), because $T = 0$ for electromagnetic waves, or any solution of Maxwell's equations, and no light bending should be observed in such a scalar gravity theory. Einstein presumably knew about this proposal but rejected it on theoretical grounds. A vector $\hat{h}_\mu$ model, a close analog to electromagnetic theory, would have been a non-starter since in it like particles repel. The pure tensor model gives like-mass attraction and agrees with all other observations.

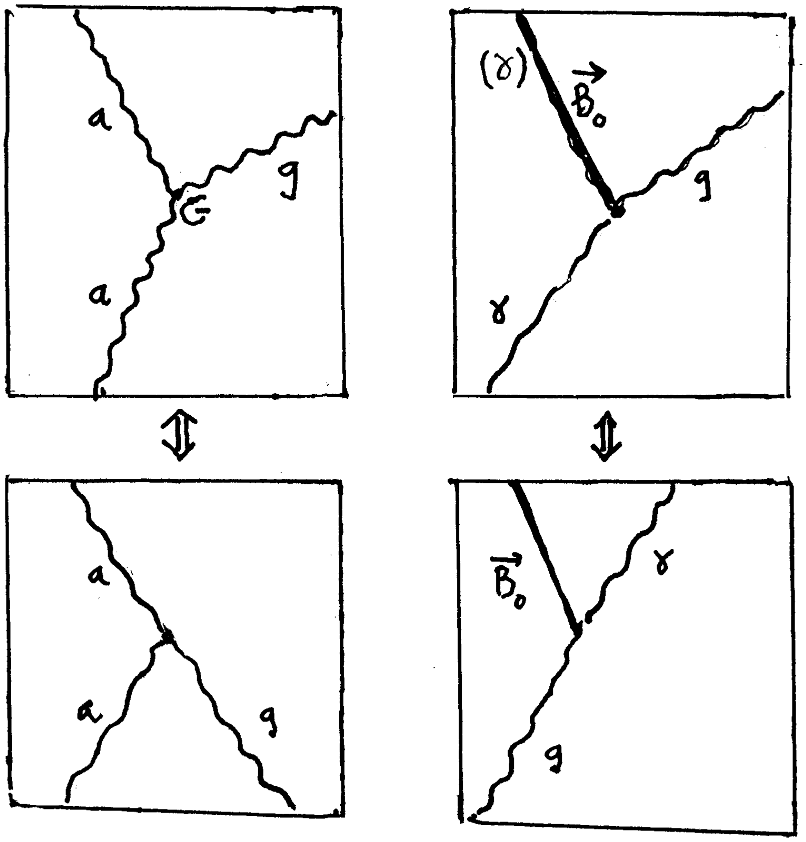

Figure 1: Feynman diagrams of quantum (graviton/photon) reactions in quantized gravitational field versions of General (and Special) Relativity. $\gamma \equiv$ HF electromagnetic field or static field ($\vec{B_0}$); $g \equiv$ graviton: $A \equiv$ any particle.

3.2 Backscatter of a HFGW by Matter (HFGW Radar)

It follows from Equations (3-7) and (3-8) that the backscattered fraction (R) of a HFGW incident on a half-space discontinuity in mass density ($\Delta\ \rho$) is about

$$R \sim \left(\frac{4\pi G\ \Delta\ \rho}{\omega^2}\right)^2 \sim 10^{-52} \qquad \text{(3-11)}$$

where the numerical value of $|\Delta\ \rho| \sim 1$ g cm^{-3} and $\omega \sim 10^{10}$ s^{-1}. (This follows, of course, just from Equation (3-7) or any theory whose main gravitational interaction involves only G, c, and ρ.)

We note that such a tiny reflection R means that the backscattering cross-section

$$\sigma_{\text{HFGW radar}} \sim 10^{-50} \sigma_{\text{HF electromagnetic wave radar}} \tag{3-12}$$

Thus targets are essentially "invisible" to HFGW radar quite aside from the extraordinarily low efficiency of any proposed radar beam generator and detector. To reflect a single HFGW graviton takes 10^{50} incident gravitons. This is 10^{33} ergs of incident HFGW radiation, equivalent to all the electric power now generated on the earth for 10^8 years!

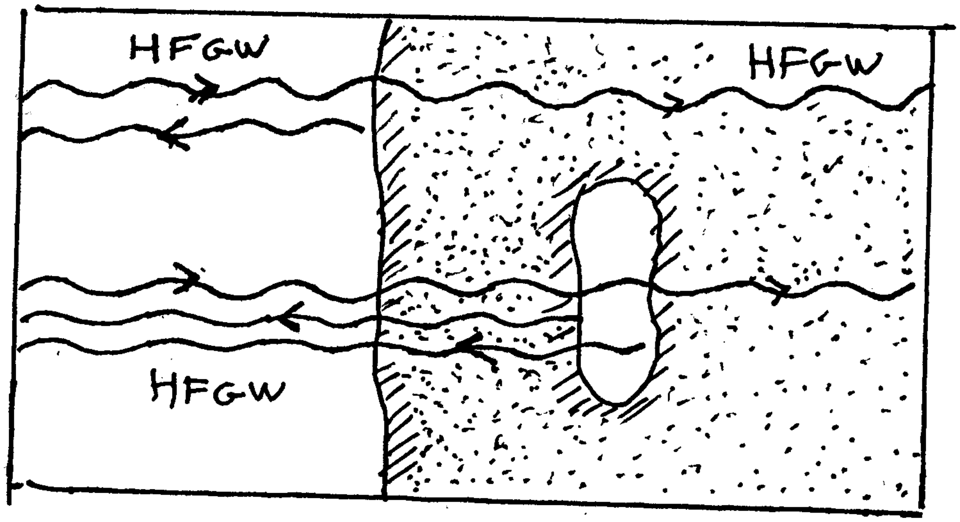

Figure 2: Reflection of a HFGW at discontinuities in matter density.

3.3 Terrestrial HFGW Generators

A basic mechanism for generating a HFGW is the direct conversion of an electromagnetic wave into a gravitational one of the same frequency by a strong static magnetic field ($\overrightarrow{B_0}$). This Gertsenshtein [9] process is idealized in Figure 3. The GW power out, $P_{G\,W}$ (out), is proportional to the electromagnetic wave incoming power P_{EMW} (in):

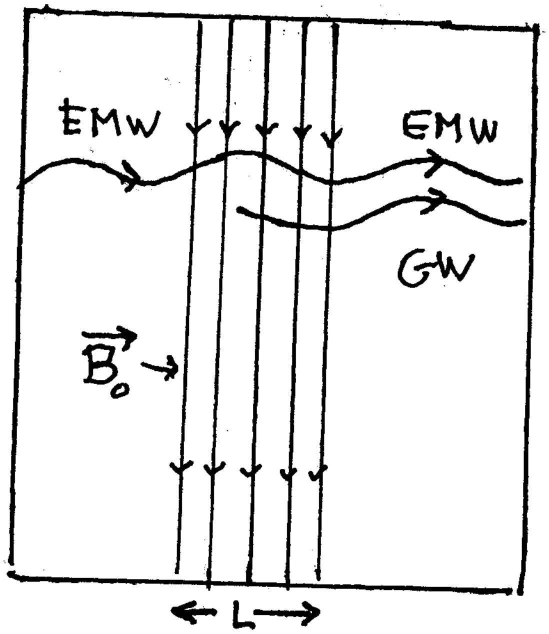

Figure 3: Gertsenshtein HFGW generation by EMWs passing through a constant magnetic field B_0,

$$P_{GW}\ (\text{out}) = \mathcal{F}\ \mathrm{P}_{\mathrm{EMW}}\ (\text{in}) \tag{3-13}$$

$$\mathcal{F} = \frac{4\,\pi\,G\,B_0^2\,L^2}{c^4}\ \sim\ 10^{-35} \tag{3-14}$$

for $B_0 = 10^5$ Gauss and $L^2 = 10^3$ cm^2. Equivalently

$$P_{GW}\ (\text{out}) = \frac{4\,\pi\ \mathrm{G}\ \mathrm{B}_0^2\ \mathrm{U}}{\mathrm{c}^3}\ \mathrm{L}, \tag{3-15}$$

where U is the total EMW energy in the volume (V) in which the EMW passes through $\vec{B}_0$.

$$u = \frac{U}{V}$$

is the energy density in that region.

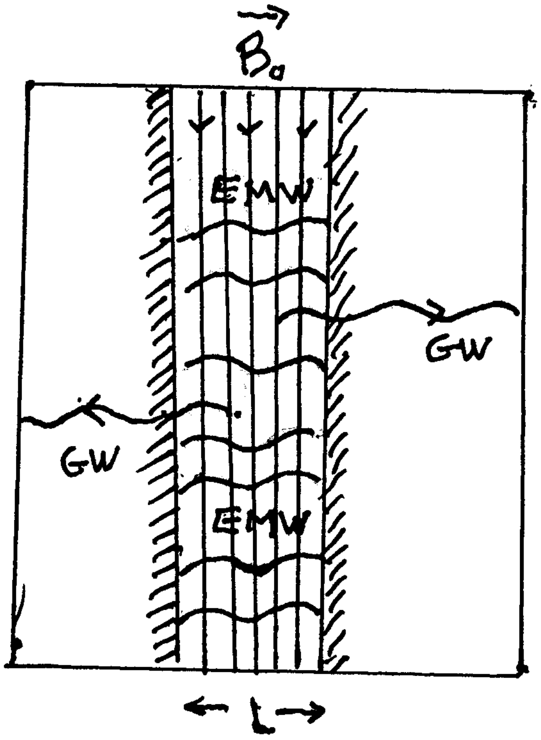

Figure 4: HFGW generation by standing wave electromagnetic modes in a cavity.

For the geometry of Figure (3) in which the passage of the EMW through $\vec{B}_0$ is not otherwise interrupted

$$U = P_{\mathrm{EMW}} \text{ (in) L/c.} \tag{3-16}$$

For $P(\text{in}) \sim 10$ kW, and $L = 30$ cm, $U = 10^{-5}$ joules. If the EMF is contained as a normal mode within V, U can be very much larger. However, there are various limits to U which are independent of the available EMW power. For a cavity with EM dissipation time τ

$$\omega\,\tau \equiv Q \tag{3-17}$$

the heat loss rate

$$\dot{H} = \frac{U}{\tau} = \frac{U\,\omega}{Q} \tag{3-18}$$

For a (generous) cooling rate from an exterior coolant flow around a copper cavity $\dot{H} \sim 10^6$ watts, $Q \sim 2 \times 10^3, U_{\rm max} \sim 2 \times 10^{-1}$ joules and

$$\text{Max P}_{\rm GW}\text{ (out)} \ \sim 2 \times 10^{-27}\text{ watts} \sim 2 \times 10^{-2}\text{ graviton/sec.} \tag{3-19}$$

(We note that it would take a continual EM power input of one MWatt to maintain this tiny GW output.)

If we replace the copper-walled cavity by one with superconducting walls τ may increase from the $\sim 10^{-7}$ sec of Cu by a factor $\sim 10^7$. However, $U_{\rm max}$ could not increase by nearly such a factor, even if we ignore any problems of maintaining superconductivity near the huge $\overrightarrow{B_0}$, and keeping the very low temperature needed. The u inside the superconducting cavity would be limited by unacceptable electron emission from a mode's strong electric field perpendicular to a wall:

$$E_\perp \ < \ \frac{50 \times 10^6\text{ volts}}{\text{meter}} \tag{3-20}$$

This implies

$$u \ \sim E_\perp^2/8\pi < 10^7\text{ erg cm}^{-3}. \tag{3-21}$$

Then with an assumed $V \ \sim 3 \times 10^3\text{ cm}^3$

$$\text{Max P}_{\rm GW}\text{ (out)} \sim 10^{-23}\text{ watts} \sim 10^2\text{ graviton/sec} \tag{3-22}$$

Even if this crucial limit is ignored there would be a limit to u from the maximum mechanical strength of the container confining the electromagnetic modes:

$$u_{\max} \sim 10^{10} \text{ dyne/cm}^2. \tag{3-23}$$

The limit of Equation (3-23) and $V \sim 3 \times 10^3$ cm^3 gives $U_{\text{Max}} \sim 3 \times 10^6 J$ and

$$P_{GW} \text{ (out)} \sim 10^{-20}\text{watts} \sim \ 10^5 \text{ graviton/sec} \tag{3-24}$$

Finally we could ask the ultimate limit when, instead of $\overrightarrow{B_o} \sim 10^5$ Gauss and EM waves V is filled with moving masses, EM energy, etc. all contained within $V \sim 3 \times 10^3$ cm^3 to the limit where the container explodes. Then

$$P_{GW} \text{ (out)} \sim 10^{-18}\text{watts} \sim \ 10^7 \text{ graviton/sec.} \tag{3-25}$$

The graviton flow at a target a distance d away is

$$\frac{P_{GW} \text{ (out)} \times \text{b}}{4\ \pi\ d^2} \tag{3-26}$$

where d is the distance to the target and b a directional beaming factor[3] which we take $\sim 10^2$. Then for $d > 1$ km the maximum flux at a target

$$f \ < \ 10^{-9} \times (10^7) \ \frac{\text{graviton}}{\text{cm}^2 \text{ sec}} \tag{3-27}$$

for the unrealistically large limit of Equation (3-25).[4] Increasing V to 10^7 cm^3 would still limit

$$f \ < \ 30 \text{ gravitons/cm}^2\text{/sec.} \tag{3-28}$$

Almost none will be stopped or converted within the target. (But even if they were their total impulse would cause no damage to any part of it.)

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[3] Beaming can be arranged using the principles of phased arrays — one would have to match the phase velocities of the EMW and the GW to a few percent

[4] And this is only 10^{-12} of the expected (but still undetected) flux of cosmic gravitons from the Big Bang.

3.4 HFGW Detectors

Proposed HFGW detectors have generally been based upon versions of the inverse Gertsenshtein process.[5] The most elementary one is that in Figure 5. As in Equations (3-13) and (3-14)

$$P_{EM}\ (\text{out}) = \mathcal{F}\ \mathrm{P_{GW}}\ (\text{in}) \tag{3-29}$$

and

$$\mathcal{F} = 10^{-35} \text{ for } \mathrm{L}^2 = 10^3 \text{ cm}^2 \text{ and } \mathrm{B}_0 = 10^5 \text{ Gauss.}$$

For the maximum HFGW generator production of 10^2 graviton/sec of Equation (3-22), and $b \sim 10^2$ and $d \sim 10$ m in Equation (3-26), and a detector area transverse to the beam $(\hat{A}) = 10^4 \mathrm{cm}^2$

$$P_{EM}\ (\text{out}) \sim 10^{-34} \text{ EM photons/sec} \equiv \dot{\mathrm{N}}_\gamma$$

with an average interval between photons

$$\hat{t}_\gamma = \frac{1}{\dot{N}_\gamma} = 10^{34} \text{ sec.} \tag{3-30}$$

Such a small photon flow would, of course, never be observed, no matter what plausible changes are made in HFGW generator, d, b, or $\hat{A}$. However proposals have been made to decrease this interval by very great factors.

One such proposal introduces an additional EMW_0 with the same frequency as the GW and the very weak EMW it generates in passing through the strong $\overrightarrow{B_0}$ region. This is well understood "homodyning" of the weak signal. It does not increase a signal to noise ratio when the noise is the minimal photon noise from quantization. If we consider the simple geometry of

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[5] Efficiency for electromagnetic conversion of gravitons to photons is generally proportional to the electromagnetic energy density in the detector. For proposed Gertsenshtein detectors $B_0^2/8\,\pi \sim 40$ joules/cm^3 and this is already close to the maximum containable EM energy density (Sec 2). We consider below, therefore, only such HFGW detectors.

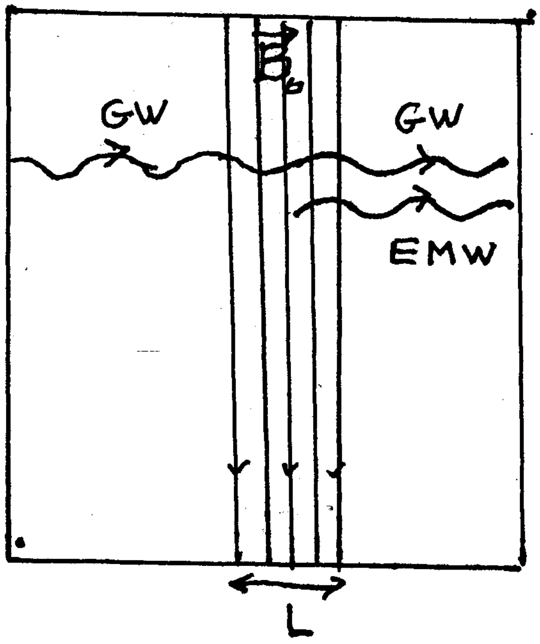

Figure 5: Inverse Gertsenshtein conversion of HFGWs to EMWs of the same frequencies.

Figure 6 with the electromagnetic waves electric field normal to the plane of wave propagation and $\overrightarrow{B_0}$, there are two possibilities for interference between E_{GW}, the electric field of the EMW generated by the GW and E_0. In one the original propagation directions are coincident. Then the total field ($\overrightarrow{E}_T$)

$$\overrightarrow{E}_T = \overrightarrow{E}_0 + \overrightarrow{E}_{GW},$$

with $\overrightarrow{E}_T$ the homodyning field and $\overrightarrow{E}_{GW}$ that from GW conversion along the common trajectory. If $\vec{E}_{GW}$ reaches the photon detector so must $\vec{E}_0$. That detector's photon counting rate

$$\dot{N}_d \ \propto \ |\overrightarrow{E}_T|^2 = \left(|\overrightarrow{E}_0|^2 + 2\overrightarrow{E}_0 \cdot \overrightarrow{E}_{GW} + |\overrightarrow{E}_{GW}|^2\right) \tag{3-31}$$

After a long time t the collected number of photons

$$N_d = \dot{N}_0 t + 2(\dot{N}_0 \ \dot{N}_{\mathrm{GW}})^{1/2} \ t \ \cos\delta + \dot{N}_{GW} \ t \tag{3-32}$$

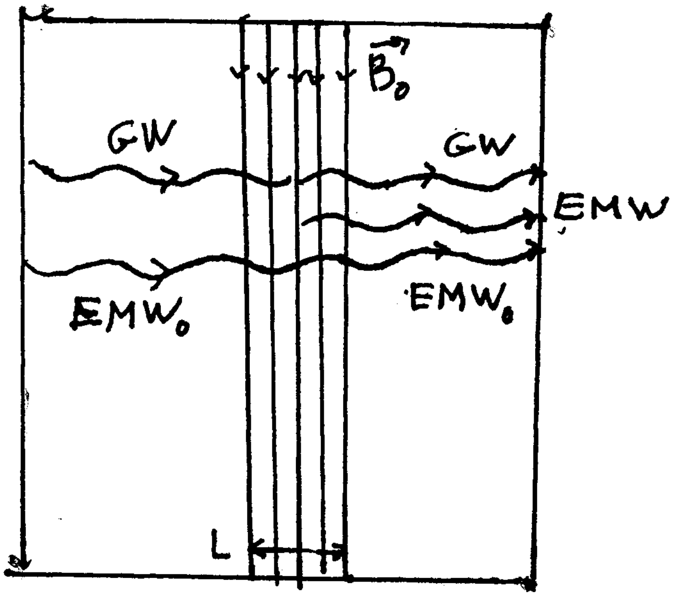

Figure 6: Homodyning of weak EMW with much stronger EMW_0.

with $\dot{N}_0$ the counting rate when $\dot{N}_{\mathrm{GW}} = 0$ and $\dot{N}_{\mathrm{GW}}$ the very much smaller rate when $\dot{N}_0 = 0$. A non-zero $\cos\delta$ can arise from phase match between $\overrightarrow{E}_0$ and $\overrightarrow{E}_{GW}$.

The large $N_0 = \dot{N}_0 t$ is the expectation value of a Poisson distribution of width $N_0^{1/2}$ which is intrinsic to the quantum (photon) distribution in the classical wave description.

The main $\dot{N}_{\mathrm{GW}}$ contribution to the detector counts $(2\ (\dot{N}_0 \dot{N}_{\mathrm{GW}})^{1/2} \cos\ \delta\ t)$ must be significantly larger than this fluctuation $(\dot{N}_0 t)^{1/2}$ for the signal/minimal photon noise ratio to exceed unity:

$$(\dot{N}_0\ \dot{N}_{\mathrm{GW}})^{1/2}\, t\ > (\dot{N}_0\ t)^{1/2}. \tag{3-33}$$

Then

$$t\ >\ 1/\dot{N}_{\mathrm{GW}} = \hat{t}_\gamma, \tag{3-34}$$

i.e., it will still take the $\hat{t}_\gamma$ of Equation (3-30) to identify with any confidence a single EMW photon from incoming GW graviton conversion.

If the $\overrightarrow{E}_0$ photons differ enough in direction from the $\vec{E}_{\mathrm{GW}}$ ones so that they do not reach the detector the photon fluctuations $|\overrightarrow{E}_0|^2$ term of Equation (3-31) could be absent, but so would $2\overrightarrow{E}_0 \cdot \overrightarrow{E}_{\mathrm{GW}}$ so that again $t \sim 1/\dot{N}_\gamma$. The history of this interference term before the detector is reached is not relevant: $t \sim 1/\dot{N}_{\mathrm{GW}}$ whether or not $\overrightarrow{E}_0$ reaches the photon detector with $\overrightarrow{E}_{\mathrm{GW}}$ or what its magnitude there is as long as it gives the minimal fluctuation in photon number as the major noise source at the EMW detector.

If instead of $\overrightarrow{E}_0$ with the same frequency at the EMW from HFGW conversion (homodyning), the $\overrightarrow{E}_0$ wave has a different frequency (ω') and the detector admits $\omega \pm \omega'$ (heterodyning) the quantum limit still gives the same needed t (to within a factor 2) for a signal to noise ratio exceeding one; see Marcuse [13] (Eqs. 6.5–14,6.5–17) with the minimum bandwidth $B \sim t^{-1}$ achieved over a time t,

A second kind of proposal for greatly increasing the photon counting rate from graviton → photon conversion is to contain the conversion volume within reflecting walls for EMWs. This is similar to the same sort of proposal to increase the efficiency of Gertsenshtein conversion of photons to gravitons in Figure 3. It differs, however, in that the containing cavity does not reflect the gravitons which are the source for conversion, but only the photons which are the product of it.

If we start with an empty cavity with mode decay time τ and a resonance frequency $\omega_0 = \omega$ (or at least $|\omega - \omega_0| < \omega_0/Q$) the cavity will initially fill with EM mode energy (U) at a rate

$$\dot{U} \sim \frac{\hbar\,\omega_0}{\hat{t_\gamma}}\left(\frac{ct}{L}\right) \tag{3-35}$$

which will continually increase until a steady state is reached at $t \sim \tau \equiv$

Q/ω. (U is not limited in the cavity detector by the considerations of Sec 3. because it is always so tiny in comparison to those in a GW generator).

At $t = \tau$ a maximum photon counting rate

$$\dot{N}_\gamma \sim \frac{1}{\hat{t}_\gamma} \left(\frac{c\,\tau}{L}\right) = \frac{Q}{\hat{t}_\gamma} \tag{3-36}$$

if cavity photons are counted instead of being dissipated in the cavity walls.

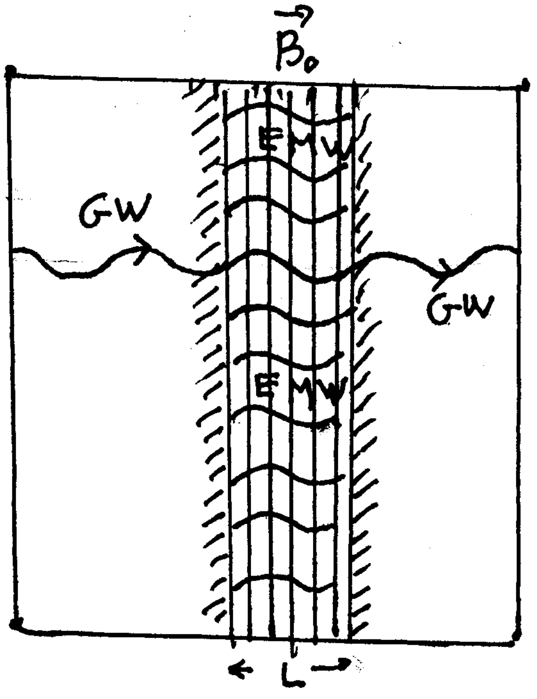

Figure 7: GW conversion on $\vec{B}_0$ pumping a resonant cavity with the same frequency.

If, unphysically, finite cavity mode decay time did not limit $\dot{N}_\gamma$ we might still note how long (t_1) it would take for the expected number of GW induced photons inside the cavity to reach one, i.e.

$$1 = \frac{U}{\hbar\,\omega_0} = \left(\frac{c\,t_1}{L}\right) \frac{t_1}{\hat{t}_\gamma}. \tag{3-37}$$

Then

$$t_1 \sim \left[(\frac{L}{c})\,\hat{t}_\gamma\right]^{1/2} \sim 10^{12}\ \text{sec}. \tag{3-38}$$

However, finite $\tau = (Q/\omega)$ does limit the cavity U. The maximum expected value for GW induced photon number in the cavity never approaches unity. Instead

$$\frac{U_{\max}}{\hbar\,\omega_0} \sim \left(\frac{\tau}{\hat{t}_\gamma}\right)^2 \ll 1 \tag{3-39}$$

A copper-walled cavity with $Q \sim 2\times10^3$ would decrease the time interval between GW induced photons in the cavity, but only to

$$\hat{t}_\gamma/Q \sim 10^{31}\ \text{sec.} \tag{3-40}$$

The largest plausible τ would be for a cavity with superconducting walls. Then τ might reach, say, 10 seconds ($Q \sim 10^{11}$). Then

$$\hat{t}_\gamma/Q \ \sim\ 10^{23}\ \text{sec,} \tag{3-41}$$

still essentially an infinite time between photon counts.

If the cavity GW induced photon energy were homodyned (or heterodyned) by introducing additional resonant mode electromagnetic field energy the photon number fluctuations in that energy would again not allow interference to increase the time interval for signal/photon noise > 1 to be less than the $\hat{t}_\gamma/Q$ of Equations (3-40)- (41).

The photon counting rates for confident detection of graviton-induced photons from proposed HFGW generators and detectors is so small that development of HFGW communication links is not a reasonable prospect.

The graviton interception-transformation rate at a large cooperative target (specially designed to detect gravitons) $\ll 10^{-20}$ [cf Equations (3-29) and (3-36)]. When combined with the comparably small fraction for photo → graviton efficiency in HFGW generators this implies that to deposit even an ergs worth of HFGW gravitons in a target requires $\gg 10^{40}$ ergs of electric power input to a HFGW generator. This is more than total energy from electric power generation on the earth ($< 10^{12}$ watts) for longer than the age of the Universe.

Use of HFGW beams for destroying, deflecting, or compromising distant targets (or close ones) has no promise.

4 ANALYSIS OF THE LI-BAKER DETECTOR PROPOSAL

The JASON study was motivated by proposals to the US government by a group centered around the company GravWave® LLC, the CEO of which is Dr. Robert M.L. Baker, Jr. An important proposal is a concept for a detector of HFGW, by Baker and Dr. Fangyu Li of Chongqing University, China; see [10, 11, 12] and references cited therein. These references project a detector sensitivity many orders of magnitude greater than detectors constructed or proposed by other research groups around the world. In turn, the various practical applications proposed by the Li-Baker group depend crucially upon this high claimed sensitivity. We therefore have analyzed the Li-Baker detector proposal in detail to determine its possible sensitivity.

4.1 Physics analysis

The proposal [10, 11, 12] estimates a sensitivity about 10^{25} times greater than the predictions of Equations (3-30), and (3-34). This comes from the proposed introduction of a homodyning reference beam with electric field strength $|\overrightarrow{E}_0| = 1.17 \times 10^3$ volts/m to be added to an

$$E_{GW} \sim \hat{h} \, B_0 \, \frac{\omega \, L}{c} = 10^{-22} \text{ volts/m} \tag{4-42}$$

for $\hat{h} = 3 \times 10^{-32}$, $B_0 = 10^5$ Gauss, $\frac{\omega \, L}{c} = 10$. For these parameters the magnitude of the $2\overrightarrow{E}_0 \cdot \overrightarrow{E}_{\mathrm{GW}}$ term in Equation (3-31) is larger than the unboosted signal $|\overrightarrow{E}_{GW}|^2$ by a factor 10^{25}. But the very much larger photon noise from $|\overrightarrow{E}_0|^2$ is neglected because, it is claimed, E_0^2 does not reach the photon detector. This claim is physically untenable. There is no way to detect the power in the "interference term" $2\overrightarrow{E}_0 \cdot \overrightarrow{E}_{\mathrm{GW}}$ if E_0^2 is not there at the same time. Indeed, by itself the interference term could even be negative at the detector if $|\overrightarrow{E}_0|^2$ is diverted from reaching the detector at the same time, a rather meaningless prediction when the larger $|\vec{E}_0|^2$ is not also present. The assumed "fractal membrane" could not separate the $\overrightarrow{E}_0$ and $\overrightarrow{E}_{\mathrm{GW}}$ beams if they were initially exactly parallel. Indeed, the magical power of a fractal membrane is limited by the same physics as constrains optical or microwave mirrors or lenses.

4.2 Technical Analysis

In the proposed Li-Baker experiment, [10, 11, 12, 15] an intense steady magnetic field is used to convert a gravitational wave into a photon of the same frequency. This is proposed for use to detect relic gravitational radiation as well as to detect GW generated in the laboratory.

The instrumentation can be simplified in principle to be just an intense magnetic field on the order of 9 tesla viewed by a detector of microwave photons. Since the photons are generated along the direction of the gravity wave, with an efficiency and hence an intensity that is proportional to the square of the magnetic field component in that direction, one could align the detector of mm-wavelength photons with the field, or if that were inconvenient, one could put in a metallic reflector to deflect the generated photons at nominally right angles to the magnetic field. One could even use a fractal membrane, but without the mystical powers attributed to it.

The relic GW can be approximated by a thermal bath of gravitons at 2 degrees K, and, aside from spin, the flux would be that (into a hemisphere) of electromagnetic radiation given by a Stefan-Boltzmann constant of $5.67 \cdot 10^{-8}$

$m^{2\mathrm{deg}^4}$. So the incidence of GW over a region of 10 cm×10 cm would be just about 10 nW.

The conversion coefficient from graviton to photon is approximately 10^{-38}, so for a region 10 cm×10 cm, we would have an emergent photon flux of 10^{-46} W. At the peak of the distribution (about 4 kT or 8 degK), the graviton or the photon would have an energy of 10^{-22} J, so that it would be necessary, on the average, to wait a time of 10^{24} s for a photon to be emitted from the region of 9-T magnetic field by the inverse Gertsenshtein Effect.

This is a long time. Since a year is $3 \cdot 10^7$ s, and the age of the universe is less than 10^{18} s, one would either have to wait 10^6 ages of the universe (beyond the funding horizon of any federal agency) or replicate the experiment some 10^{17}-fold to obtain one photon per year.

In calculating the emission rate of photons from the inverse-Gertsenshtein [9] converter, we are simply scaling the conversion of an intense beam into a similar classical beam of photons, as could be done, for instance, in going from the classical photoelectric effect to the quantum photoelectric effect.

The technical requirements are substantial to detect individual photons in this range, but the emission rate is the fundamental problem. First, one would need to reduce the emission of photons from the boundaries of the converter to a level comparable with or less than the gravitational conversion rate. We have already identified the rate of thermal emission for a body at 2 degK as 10^{-8} W. We need to measure 10^{-46} W, so the temperature of the environment needs to be reduced essentially to reduce the thermal flux by the conversion factor of 10^{-38}. Since the emission falls off exponentially with ratio of photon energy to ambient temperature, a factor 10^n would be obtained by a ratio of photon energy to temperature of $2.3n$, where 2.3 is the natural log of 10. Reducing the ambient temperature by a factor 87 below 2 degK would do the job, or to a temperature of about 20 mK.

Of course, the detector would need to be at that same temperature and be noise-free.

But it is absolutely not worth worrying about the temperature of the enclosure and the noise added by the detector unless a scheme can be found that with 100% noise free and efficient detection of photons, one can expect a signal in a reasonable time.

4.3 Analysis of the fractal Membrane

In this subsection we analyze the fractal membrane (FM) that is proposed for use in the Li- Baker approach for detecting GHz gravitational waves. The magical properties of the FM are discussed in the G.V. Stephenson briefing[15].

Here, Stephenson finds that the FM gives a contribution to the Q of the system of $3.4 \cdot 10^{21}$ in the radial direction and gives an antenna gain of $6.3 \cdot 10^{4}$ (at beam center) as a function of angle. In other papers, the FM is assumed to give a high concentration of the signal onto the detector and an enormous discrimination against background photons.

Essentially none of this is valid.

Furthermore, the FM is immersed in the Gaussian beam (GB) of microwave energy, and, like the rest of the detector, is supposed to be maintained at 20 mK in order not to contribute to the thermal background of microwave photons.

The FM is variously portrayed as being made of superconductor, stainless steel, or copper. But its immersal in a steady magnetic field of 9T would preclude its being superconducting. Worse, the losses in the membrane are incompatible with the intense microwave radiation of the GB, in view of the surface currents that must flow in the FM, induced by the microwaves of the GB.

It is true that an FM can be used as a lens for microwaves, but as a lens it is not magic. It performs a linear operation on the electromagnetic field and could thus, at best, provide a diffraction-limited image of a source at an image point. If the source is distributed along an interaction length in the steady magnetic or microwave field, not all of these geometrically spread sources can be imaged onto the same detector point from the same direction. Effectively breaking up the FM into a series of lenses along the interaction region, in order to image the photons on the same detector increases the diffraction spread from each of the lenses.

Furthermore, there is a magnification that comes from the use of a single FM or lens that might be at a distance of 3.5 cm from the source and providing an image at ten times that distance. A perfect lens or its equivalent as an FM would then have a magnification in both transverse dimensions of the order of ten, which in this case is no better than allowing free divergence of the photons without optics at all.

More generally, the FM cannot reduce the phase space occupied by the microwave energy.

An ordinary microwave lens or FM placed halfway between the source and detector could serve to increase the fraction of the energy that falls on the detector, but it is fantasy to imagine that any kind of strict alignment is required or beneficial to focus microwave energy onto a micron-sized detector.

In just the same way that the FM or any lens cannot focus microwaves from a distributed volume onto a point, neither can the lens or FM discriminate highly against photons coming from another region.

The focal size of the FM is also misunderstood, being given as $\lambda/2\pi$, but that is below the minimum focal size, and assumes that the FM or lens subtends a very large solid angle at the detector. For instance, if the detector is at a distance of 1 m, then the FM or lens must be at least 1 m in extent, and must also be more or less uniformly illuminated.

Indeed, a multi-element focusing system can accomplish this, but in no way can it be done by a single element such as an FM at substantial standoff from the receiving focus.

4.4 Possible increases to RF power

This subsection will discuss some further technical aspects of HFGW detectors and related physical effects, based on briefings [12, 15] and related reports.

Stephenson[15] assumes a GB resonator with 10^{13}J of stored energy, probably in less than a liter volume—so 10^{10} J/cc or 10^{17} erg/cc. This corresponds to an electric field such that $E^2/8\pi = 10^{10}$, or $E = 5 \cdot 10^5$ esu/cm or 150 MV/cm or 1.5 GV/m. The maximum RF field achieved in particle accelerators after 60 years of dedicated, inspired work is about 30 MV/m or 0.3 MV/cm. The electromagnetic field assumed by Stephenson and colleagues is 50 times as large, and the energy density 2500 times as large. Long before the field can reach this value, the electromagnetic field will be destroyed by tearing electrons out of the materials of the cavity—“field emission”.

Now we address further the assumption that the electromagnetic energy content of the apparatus can be 10^{13} J. This is supposed to be derived from an RF generator of 10^5 W, operating for 10^3 s, into a cavity with a Q of 10^5. In fact, multiplying these numbers does give 10^{13} J, and the dimensions are even correct. But that is the only thing that is correct about this fantasy. In fact, 10^{13} J is 2.4 kilotons of energy, and would require a containing stress of 10^5 MBar (a million times atmospheric pressure!).

First, a generator of 10^5 J operating for 10^3 s consumes 10^8 J and at 100% efficiency would provide 10^8 J of microwave energy. So the maximum that could be radiated or stored would be 10^8 J instead of 10^{13} J.

But a cavity Q of 10^5 simply means that the residence time of electromagnetic energy in the cavity of about one wavelength in size is 10^5 oscillation times instead of about 1 cycle of the RF period. Since the oscillation time of a 5 GHz electromagnetic wave is 0.2 ns, the cavity residence time would be about $2 \cdot 10^{-5}$ s. A 10^5 W generator operating continuously would then provide about 2 J of energy content in the apparatus, no matter how long it operated. There is quite a difference between 2 J and the assumed 10^{13}J.

Beyond all of these specific problems, we address the suggestion that even though HFGW are not useful with our present understanding of general relativity, such experiments should be supported because if scientific understanding were wrong, and HFGW were easier to generate and to detect than is believed by the standard theory, there would be adverse national security consequences. One can always imagine something different, but it is clear that the work should be put in the hands of a team that understands both gravitational radiation and experimental physics.

Lastly, we make the following two comments on experimental details as provided in “Proposed Ultra-High Sensitivity High-Frequency Gravitational Wave Detector” [10].

The calculation for the required gas pressure is ridiculous. It assumes that the interaction of a microwave photon with an atom of hydrogen or helium has a cross section that is the physical cross section of the atom. If this were so, microwaves could not propagate through ordinary atmospheric air. It is simply and grossly the wrong calculation.

In this paper [10], mention is made of the possibility that superconductors could reflect gravitational radiation, and elsewhere there are proposals to use superconductors as lenses to focus gravitational waves. There is absolutely no reason why there should be any enhanced interaction between superconducting matter and gravitational waves.

5 ANALYSIS OF PROPOSED APPLICATIONS

Finally, it will be necessary to address the applications proposed for gravitational waves (GW), such as communication, imaging of the interior of the Earth, propulsion of spacecraft, and provision of super-accurate timing with an estimated value of $50 B over ten years.

In connection with earth imaging, mention is made of a required phase sensitivity to GW of 10^{-40} radian, but even if the system were available to detect this, there would need to be at least 10^{80} gravitons to define such a sensitivity, and this would correspond then to a beam energy of, which would represent the conversion of 10^{33} grams of energy into gravitational radiation. The mass of the Earth is 6×10^{27} g.

The thought of using GW traveling at the speed of light to provide propulsion by the attraction of a GW focus ahead of the spacecraft is particularly inept. To provide an acceleration of 1 g (10 m/s^2) by the attraction of focused GW 100 m ahead of the craft would require the generation and focusing of 10^{38} Watts of GW; this would require more than 10^{25} times the world's total power consumption.

And finally, the much touted value of $50 B for increased timing accuracy by the use of GW signaling first of all depends on a means to generate the GW and to detect the GW, but the system is fundamentally flawed unless all the communication is by GW as well, traveling then in straight lines. If GW signals were used to try to synchronize microwave communications through the ionosphere and atmosphere, even though some kind of absolute timing might be achieved with GW, what is necessary is timing with respect to the electromagnetic signals, the path of which varies with atmospheric conditions.

Absolute time synchronization is even less relevant in systems that are connected by cables or fiber optic, because the transit time varies with temperature and other environmental conditions. Time distribution via gravity waves will not be achieved and would not be valuable.

We saw a report on the "Economic Benefit of HFGW for Timing," that claimed if HFGW could be used for this purpose, it would have an economic benefit of $50 B, for instance by increasing the number of points that could be used in an amplitude-phase modulated communications system. Of course, this is nonsense, because any such improvement can be achieved by adaptively synchronizing the phase, which is in fact usually done. And the idea that one could have a small HFGW detector (and source) is not extrapolation but hallucination.

It is extremely unlikely that there would be any economic benefit, or any useful applications of HFGW, even if HFGW could be produced and detected in the laboratory as claimed. These benefits and applications are so far from realization that "unlikely" (in the intelligence analyst's lexicon) is a totally inappropriate exaggeration.

6 CONCLUSIONS AND RECOMMENDATIONS

Our analysis of the proposed detectors and applications shows that previous analyses [10, 11, 12, 15] of them have been badly incorrect, and that they are infeasible by many orders of magnitude. Most importantly, previous analyses of the proposed detector use a badly incorrect estimation of the sensitivity of a homodyne detector, and are the resulting sensitivity estimates are too optimistic by more than 20 orders of magnitude. Similar errors occur throughout the analyses that we have seen in this study. Notably, this error does not concern gravitaton physics directly; it is an error of electrical engineering of the proposed detector. None of the proposed applications that were briefed to us, or which we have read about, are remotely possible in the foreseeable future. Therefore these proposals belong to the realm of pseudo-science, not science.

Oue main conclusions are that the proposed applications of the science of HFGW are fundamentally wrong, and that there can be no security threat.

In particular we conclude:

1. Previous analysis of the Li-Baker detector concept is incorrect by many orders of magnitude
2. The following are infeasible in the foreseeable future:
    (a) Detection of the natural “relic” HFGW, which are reliably predicted to exist
    (b) Detection of artificial sources of HFGW

3. No foreign threat in HFGW is credible, including:
   (a) Communication by means of HFGW
   (b) Object detection or imaging (by HFGW radar or tomography)
   (c) Vehicle propulsion by HFGW
   (d) —or any other practical use of HFGW.
4. For the relatively weak fields in the lab, on the Earth, or indeed in the solar system (far from the cutting-edge science of black holes of the Big Bang), the general theory of relativity and its existing experimental basis are complete, accurate and reliable.

We recommend that independent scientific and technical vetting of such hypothetical threats is generally necessary.

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