After peer reviews, accepted for publication in the *Proceedings of the Space Technology and Applications International Forum (STAIF-2007),* edited by M. S. El-Genk, American Institute of Physics, Melville, New York, Feb. 12-15, 2007, Paper 184

Reviewer's Comments

Your paper was submitted for peer review. Below are the reviewer's comments, provided for your information. Reviewer's names have been omitted:

Reviewer's Comments on Log No. 184

Reviewer #1:

The author provides an excellent overview of the potential application of high-frequency gravitational waves (HFGWs) to a variety of surveillance missions. These missions would include, but not be limited to, geophysical surveys and detections of underground petroleum or mineral resources, military surveillance of enemy movements or uncovering of clandestine enemy operations, detection of hidden weapons of mass destruction, etc., while using a form of radiation (HFGWs) that is unfettered by the intervening Earth. The author proposes that HFGW surveillance systems could be both ground-based and space-based platforms, and shows concept schematics of such systems.

The paper is very good except that it would be even better if the author were to provide two or three key equations that are representative of HFGW optics parameters that appeal to surveillance applications. These should be accompanied by a few engineering-physics numbers that the reader could use to better understand the HFGW optics in application to said surveillance missions.

Reviewer #2:

The paper represents an original work that substantially adds to the academic knowledge base in this area of research.

I have the following detailed comments:

1) Please quantify phase change / polarization change of GW vs. transmission mass profile per MTW (1973) referenced.

2) Please address - would GW scatter / backscatter account for the so called "Solar Eclipse Anomaly"? See Ref below:

- Qian-shen Wang, Xin-she Yang, Chuan-zhen Wu, Hong-gang Guo, Hong-chen Liu, and Chang-chai Hua, "Precise measurement of gravity variations during a total solar eclipse," *Phys. Rev. D* **62**, 041101(R) (2000).

3) It is not clear why HFGW radiators and detectors need to be in orbit - just for a longer baseline / better geometry? What is the sensitivity to baseline length, and would it justify the expense of placing these radiators and detectors in orbit onboard satellites?

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Reviewer #3:

This paper utilizes the results of prior papers on the detection and generation of high-frequency gravitational waves whose frequency bands include high-frequency, very high frequency and ultra high frequency gravitational radiation. The two Chinese detectors referenced include a paper to be presented in February 2007 (and to be published in the Proceedings volume) that I could not consider, a paper "in press" that I also could not consider (if it is not actually published before the Proceedings then it should be eliminated from the reference list), and a paper by Baker, Woods and Li that I did look at. The analyses of the detection scheme in that latter paper, although quite complicated, seems correct and detector sensitivities to GW amplitudes of 10^-32 seem attainable.

The paper also presents the details of a GW generator and relies on a formulation of the quadrupole based upon a recently published paper (Baker, 2006). I also checked the analyses in that paper. As far as I can determine the results there are correct and the "quadrupole formalism", although derived in a different fashion, does correctly provide for an r-squared (distance of the GW focus from the GW radiators) increase in GW power at the focus. Although more theoretical analyses are called for, it appears that there is no apriori reason to assume that r cannot be far larger than the GW wavelength --at least there is no reason to believe that no GW radiation is produced or that the quadrupole does not hold for this region.

The author correctly points out that the polarization angle is fixed in a plane that includes the GW radiators, but his calculation of the precision to which this plane is fixed, during an observation span, to a "yoctoradian" is far too conservative. With high-precision station keeping of GW radiators on geosynchronous orbits, it should be on the order of 10^-30 to 10^-40 radians.

The paper has stunning ramifications in the world of surveillance and deserves publication.

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Surveillance Applications of High-Frequency Gravitational Waves

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Abstract. This paper explores the possibility of utilizing a novel means of imaging to establish a system of surveillance – a system that may allow for the observation in three-dimensions of activities within and below structures and within the Earth and its oceans. High-Frequency Gravitational Waves (HFGWs) pass through most material with little or no attenuation; but although they are not absorbed their polarization, phase velocity (causing refraction or bending of GWs) and/or other characteristics can be modified by a material object's texture and internal structure. For example, the change in polarization of a GW passing through a material object is discussed in Misner, Thorne, and Wheeler (1973). Specifically, "If the wave is a pulse, then the backscatter will cause its shape and polarization to keep changing ..." Such an assertion will need to be verified both theoretically and experimentally, but the potential payoffs are enormous. Applications of this technology include satellite-based surveillance systems to image subterranean weapons of mass destruction or WMDs, personnel of interest inside and behind buildings, deeply submerged submarines, hidden missiles and rockets, oil and mineral deposits, etc. as well as acoustical surveillance. The Laser Interferometer Gravitational Observatory or LIGO and other interferometer detectors cannot detect HFGWs due to the HFGW's short wavelengths as discussed by Shawhan (2004). Long-wavelength gravitational waves having thousand and million meter wavelengths, which can be detected by LIGO, are of no practical surveillance value due to their diffraction and resulting poor resolution. Short HFGW wavelengths of a few meters to fractions of a millimeter and the sensitivity of the HFGW generator-detector system to polarization angle changes of yoctoradians to 10^{-40} radians could afford suitable resolution for practical surveillance systems.

Keywords: Surveillance, imaging, gravitational waves, HFGW, high-frequency gravitational waves, very high-frequency gravitational waves, ultra high-frequency gravitational waves, weapons of mass destruction, LIGO, submarines, stealth technology, hidden rockets and missiles, electronic cloaking, eavesdropping, polarization.

PACS: 95.55 Ym, 95.85 Sz.

INTRODUCTION

The objective of this paper is to explore the possibility of utilizing a novel means of imaging to establish a system of surveillance – a system that may allow for the observation in three-dimensions of activities and materials within and below structures and within the Earth and its oceans. Gravitational waves, including high-frequency gravitational waves or HFGWs, pass through most material with little or no attenuation; but although they are not absorbed their polarization, phase velocity (causing refraction or bending of gravitational rays), backscatter, and/or other characteristics can be modified by a material object's texture and internal structure. For example, the change in polarization of a GW passing through a material object is discussed in Misner, Thorne, and Wheeler (1973). Specifically, "In the real universe there are spacetime curvatures due not only to the energy of gravitational waves, but also more importantly to the material content of the universe (material objects and structures) ... its wavelength changes (gravitational red shift) and it (gravitational wave) backscatters off the curvature to some extent. If the wave is a pulse, then the backscatter will cause its shape and polarization to keep changing ..." It is difficult to establish theoretically the actual magnitude of the changes and to quantify them relative to the transmission mass profile in advance of the HFGW generation/detection laboratory experiment. One exception is the theoretical analyses of Li and Torr (1992) who predict that "…Cooper pairs in superconductors will form a superconducting condensate characterized by a (HFGW) phase velocity … (which) can be predicted for the first time as ~ 10^6 m/s…" versus their speed in a vacuum of $3x10^8$ m/s (light speed), which leads to an index of refraction of about 300. Such assertions will need to be verified both theoretically and experimentally, and actual estimates of the effect of various intervening materials between the HFGW generator and detector established. This is especially true in the case of Li and Torr's analyses that have been challenged by Kowitt (1994) and Harris (1999), but taken more seriously by Woods (2006). Woods (2007) has developed a system of HFGW optics, utilizing high-temperature superconductors (HTSCs) that may be capable of enhancing the surveillance imaging. It is recognized that the use of low-frequency gravitational waves or LFGWs, having frequencies less than 100 kHz and wavelengths of many hundreds or millions of meters (Hawking and Israel, 1979), do not have sufficient resolution for effective imaging and surveillance.

GENERAL CONCEPT

As indicated above, the general concept is to image the texture and internal structure of a material object that is interposed between a source or sources of gravitational waves and a detector or detectors of gravitational waves. Thus the detectors can reveal the texture and internal structure of the material object in a similar, although substantially different way than X-rays do in the electromagnetic-wave spectrum. In order to avoid diffraction the GWs should be of relatively short wavelength or high frequency, e.g., HFGWs as defined by Hawking and Israel (1979) to have frequencies of 100 kHz to 100 MHz. Very high-frequency gravitational waves (VHFGWs) have frequencies of 100 MHz to 100 GHz and, presumably, ultra high-frequency gravitational waves (UHFGWs) have frequencies above 100 GHz (theoretically generated by lasers as discussed by Baker, Li, and Li, (2006)). The generic term HFGWs describes all three of these bands. Experiments to determine the efficacy of the HFGW imaging application will involve the placement of various materials and substances between an HFGW generator and detector and observe the change in the HFGW signal. In the case of X-rays this electromagnetic (EM) radiation is far less penetrating than the gravitational radiation and ordinarily the absorption of the EM or X-ray waves precludes the imaging of the texture and internal structure of large intervening material objects, such as a building or the Earth itself, between the X-ray generator or source and the detector or film. Gravitational waves (GWs) can, in fact, propagate directly through the Earth and are not absorbed. As noted, the resolution of such imaging is dependent upon the wavelengths of the GWs: the shorter the wavelength (and higher the frequency) the less diffraction and the greater the resolution. LFGWs, such as those produced by most astrophysical sources and measured, for example by the Laser Interferometer Gravitational Observatory or LIGO, are many thousands or millions of meters in length, have very poor resolution and cannot possibly reveal the detailed texture and internal structure of material objects of practical interest. Thus HFGWs, whose wavelengths are less than a few hundred meters to small fractions of a millimeter, are required for useful GW image applications. These applications might include imaging deeply submerged submarines, possibly with HTSC tags, or weapons of mass destruction (WMDs) possibly involving HTSCs utilized in their construction or oil or mineral deposits as sketched notionally in Fig. 1, WMDs secreted under buildings or hidden missiles and rockets as in Fig. 2 or personnel inside (or behind) buildings as in Fig. 3. Even acoustical surveillance (eavesdropping) is conceivable if material vibrations are sensed by the passage of HFGWs through the vibrating material.

IMPORTANT FEATURES OF HFGW GENERATORS

It is important to recognize two features of the HFGW generators either piezoelectric-crystal based (Baker, Woods and Li, 2006) or laser-pulse based (Baker, Li and Li, 2006): (1) Their polarization is a constant and known value (unlike most rotating star astrophysical sources) and the detection of intervening material that very slightly modifies the GW polarization (sensitive to yoctoradians, 10^{-24} radians, or potentially even smaller polarization angle changes on the order of 10^{-40} radians) can be accomplished. (2) Even more importantly, as exhibited in Fig. 1, the focus of the HFGW source (or generator) if the GW radiators are space based and far apart (Baker, 2006), can be remotely moved to almost any location in, on or above the Earth's surface (Baker, Woods and Li, 2006). For example, if two HFGW radiators are situated on geosynchronous orbits as in Fig. 1 and the HFGW radiators phase is slightly offset, then the HFGW focus or source (exhibiting a peanut-shaped radiation pattern as discussed in Baker, Davis, and Woods (2005) and derived in Landau and Lifshitz (1975)) can be moved away from their midpoint. Also by slightly modifying the radiator's orbital position and/or orientation relative to the Earth, the focus can be positioned almost anywhere on or under the Earth's surface as in Figs. 1, 2, and 3. The HFGW focus can be rapidly moved from one location to another by computer control of the timing and/or orientation of the gravitational radiators comprising the generator so that several "targets" or "objects of interest" such as WMDs, hidden missiles and rockets, personnel, deeply submerged submarines, mineral/oil deposits, etc. can be imaged per second by time sharing a single HFGW-radiator pair and multiple HFGW detectors on surveillance orbits will provide even more coverage.

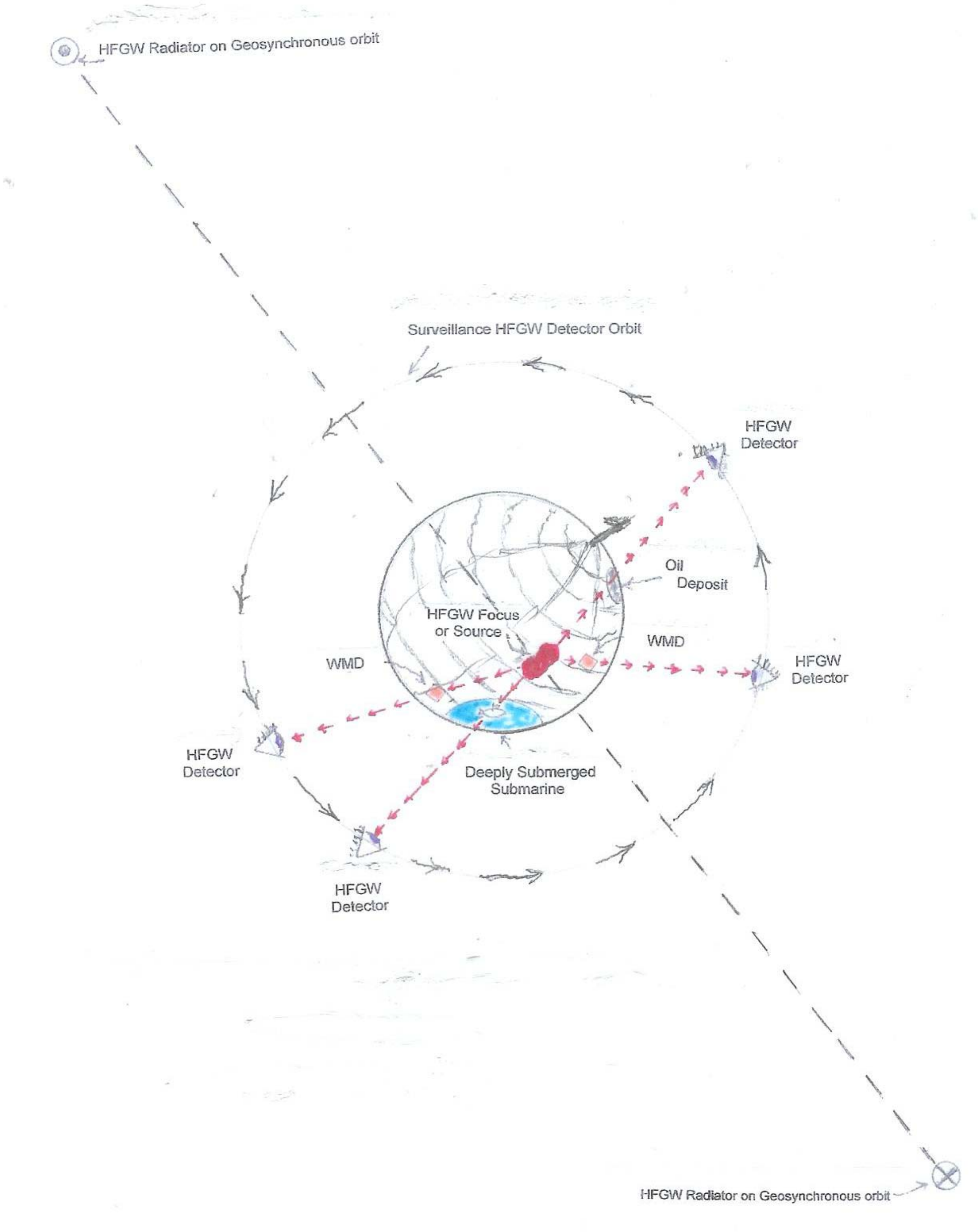

FIGURE 1. Notional Schematic of HFGW Global Surveillance System.

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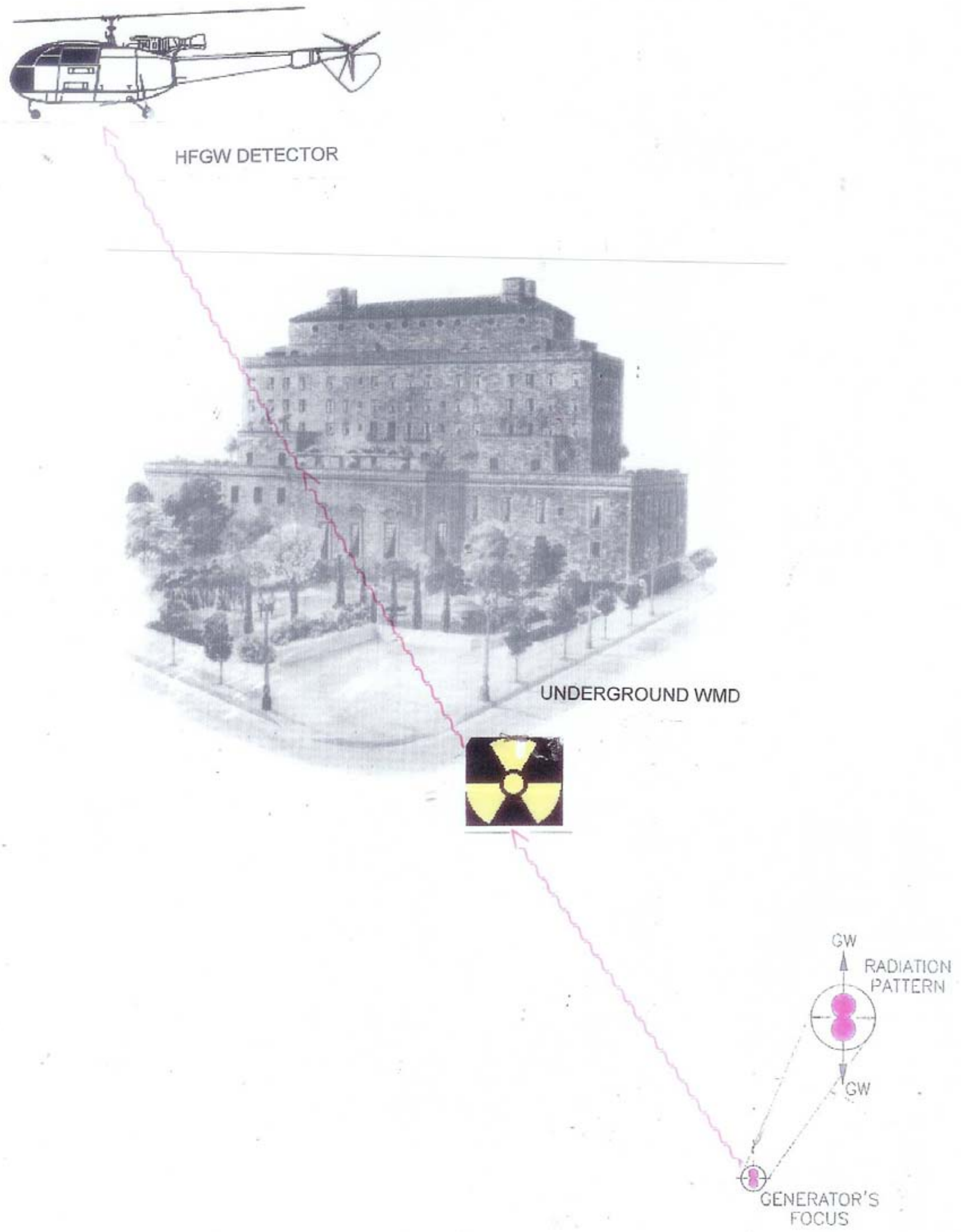

FIGURE 2. The GW Generator-Detector System on Either Side of an Underground Object of Interest.

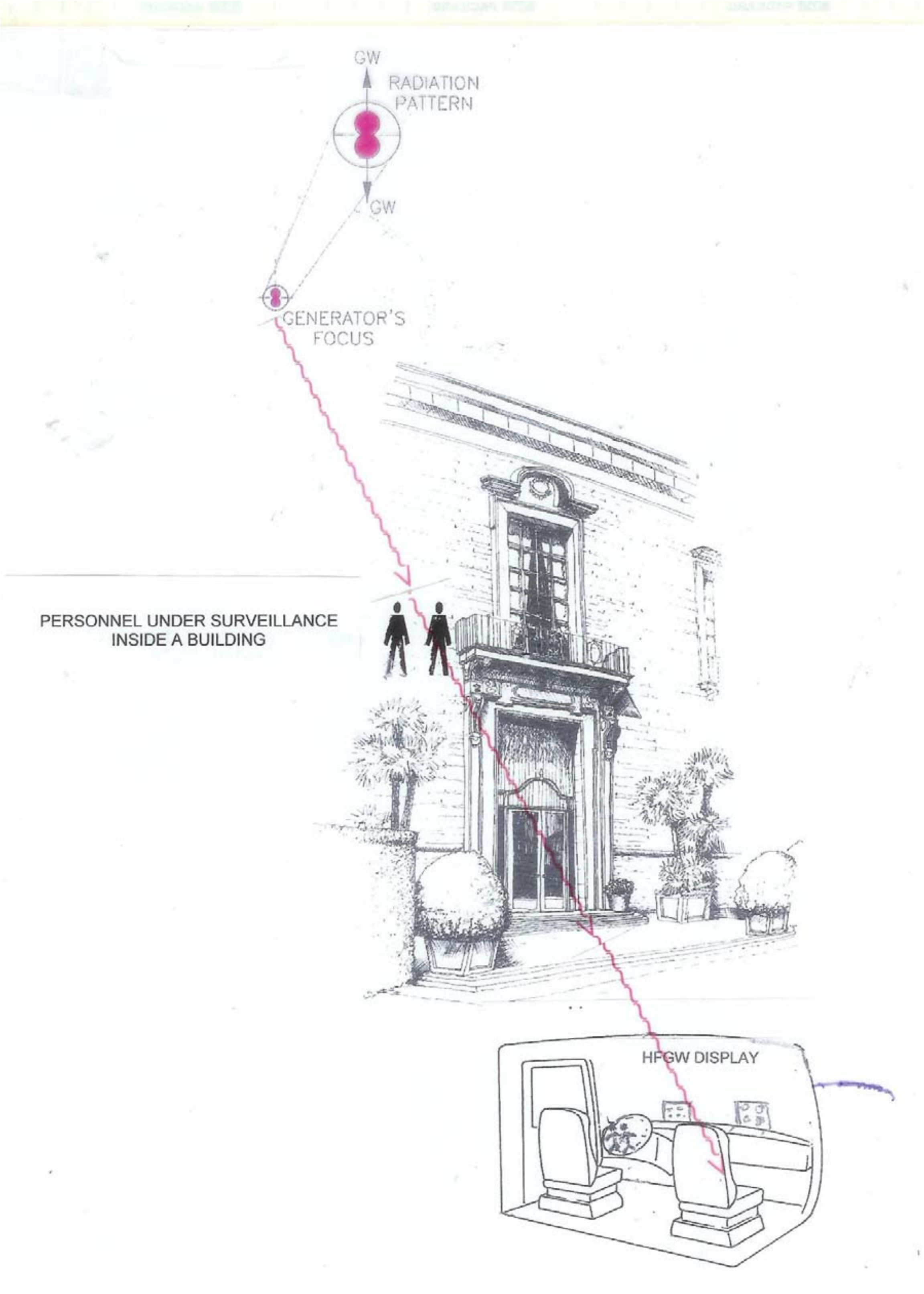

FIGURE 3. The GW Generator-Detector System on Either Side of Individuals of Interest within a Building.

Multiple gravitational-wave generators and/or detectors, which can be in motion relative to the material object, can be utilized to provide a stereoscopic or three-dimensional view of the material object's texture and internal structure and/or suppress or screen out unwanted features of the material object's texture or internal structure between the generator and detector. It may also be possible to utilize an interferometer array of HFGW transmitters and detectors, having specific time delays, to obtain stereoscopic measurements and even reveal three-dimensional motion of an object under surveillance. A specific example of a gravitational-wave generator/detector system is as follows: In this example the gravitational-wave generator or generators will be situated on one side of the Earth, at or near sea level, for example near Chongqing, China, whereas the detector or detectors as shown in Fig.1 can be spacebourne. Thus the detector(s) motion relative to the material object as, for example, if they are carried onboard a Earth-satellite moving about 200 km above sea level on the side of the Earth opposite the generator, for example, over Argentina, would allow for stereoscopic imaging. In this regard, use of variable-focus HTSC lenses as proposed by Woods (2007) could allow for the focusing of HFGW beams on specific objects of interest if collocated with the HFGW generator or its focus and could improve resolution if collocated with the detector or detectors. It should also be noted that HFGW imaging could, in theory, defeat the recently proposed EM cloaking or stealth techniques (Leonhart, 2006; Pendry, Schurig and Smith, 2006).

OPERATIONAL CONSIDERATIONS

There exist four major operational considerations for a possible HFGW surveillance system: (1) the generator, (2) the placement of the remote focus of the generator, (3) the change (if any) in HFGWs as they pass through an object of interest that would disclose the object's features or signature, and (4) the HFGW detector including any associated optics and display equipment.

(1) As a first assumption we will take the resolution of a HFGW surveillance system as one centimeter so that the HFGW wavelength, λ_{GW}, would be about this same length. Thus the HFGW frequency, ν , would be

$$\nu = c/\lambda_{GW} = 3x10^8/0.01 = 3x10^{10}\ \text{Hz} = 30\ \text{GHz}, \qquad (1)$$

which is well above audio frequencies enabling possible acoustical surveillance. Both the proposed piezoelectric or Film Bulk Acoustical Resonator or FBAR-cluster HFGW generator at about $\nu = 4.9$ GHz (Baker, Woods and Li, 2006) and the proposed laser HFGW generator at about $\nu = 29$ THz (Baker, Li and Li, 2006) would be capable of suitable HFGW wavelengths for the desired resolution. The power of these generators, P, has been computed based upon the quadrupole equation as derived in Baker (2006) for astronomical GW sources:

$$P = 2G(2\delta m)^2 r^4 \omega^6/45c^5 = 1.76\times10^{-52}(2r\Delta f/\Delta t)^2\ \text{W}, \qquad (2)$$

where G is the universal gravitational constant, δm is the mass of a GW radiator element, r is the distance of the radiator to the GW focus, ω is the angular rate of two radiator masses if they are on orbit, c is the speed of light, Δf is the jerk or shake or impulsive force on δm and Δt is the time interval over which Δf is applied to δm. The question here is to what degree this quadrupole formalism of Eq. (2) holds for $\lambda_{GW} \leq r$. From Eq. (2) it can be seen that the larger r (or the distance of the GW radiators from the GW focus) the greater the GW power by the square of r.

(2) As analyzed by Landau and Lifshitz (1975), the focus of gravitational-wave (GW) generation is midway between the GW radiators. In their case the radiators were orbiting masses whose quadrupole related jerks or shakes were due to the shift in the centrifugal-force vector as the masses move along their orbit. For a circular orbit the focus was midway between the radiators and for an elliptical orbit the focus was shifted closer toward one of the radiators. In the case of the aforementioned HFGW generators, the radiators' jerks are not due to centrifugal-force change, but due to impulsive forces occasioned by the piezoelectric crystals in one generator and impulsive forces on laser targets in the other generator. The GW-generation process is described for astrophysical applications in Baker (2006). Thus it is possible to establish the HFGW focus in different locations relative to the GW radiators depending upon the timing of the jerks and their direction in the two radiators. By situating the radiators on each side of the Earth, for example by placing them on board geosynchronous satellites, 12 hours

apart, or on the Moon and at the L_3 libration point, the HFGW focus can be established at almost any location over, on or below the surface of the Earth and the power of the HFGWs is greatly increased by the larger *r*. The GW radiation pattern for the orbiting masses is according to the analyses of Landau and Lifshitz (1975) peanut shaped with an axis normal to the orbit plane at the midpoint focus. The derivation of Baker, Davis and Woods (2005) utilizes an identical analysis method, but for stationary jerking GW radiators. The equation from this latter reference for the HFGW radiation pattern is:

$$I\,(\theta) = 7.55\text{x}10^{-6}P\,(1 + 6\cos^2\theta + \cos^4\theta)\ \text{ W deg}^{-2}, \tag{3}$$

where *I* is the HFGW intensity in watts per square degree and θ is the polar angle measured at the HFGW focus from the normal to the plane defined by the two equal and opposite jerks of the GW radiators, that is the Δf vectors as shown into and out of Fig. 1 at the extremes of the line connecting the HFGW radiators on their geosynchronous orbit. Note that Eq. (3) describes only a section of the peanut-shaped radiation pattern of Landau and Lifshitz (1975) since the radiators are effectively stationary (at least over any reasonable observation time interval, which could be as short as Δt or nanoseconds or femtoseconds in length). The "thickness" of the radiation pattern is defined by the diffraction of the HFGW. It is important to emphasize that the polarization of the HFGW is almost constant. In the case of orbiting GW radiators discussed by Landau and Lifshitz (1975) the polarization shifts as the radiators move on their orbit and in one-half orbital period the figure-8 shaped radiation sections will trace out an entire surface-of-revolution, peanut-shaped radiation pattern.

(3) Due to the Gertsenshtein effect GWs generate EM waves and GWs could, in principle, be modified by material in a HFGW beam due to this effect. On the other hand, the effect requires a very large static magnetic field and produces very small amounts of EM radiation (Baker, Woods, and Li, 2006). Thus HFGWs passing through only very special electrical circuits would have such an effect. Scattering of GWs by intervening material also would probably only have small effects unless the intervening material was extremely massive such as a star, black hole or galaxy. As already mentioned superconductors quite probably cause refraction or reflection of HFGWs (Baker, 2004; Baker, Davis and Woods, 2005) so that devices or materials involving superconductors could be "visible" as HFGWs passed through them; but this is a very special class of material. It is suggested here, to be proven by experiment, that materials in the path of HFGWs might change the GWs polarization. As already mentioned, the HFGW generators so far theorized (Baker, Li and Li, 2006; Baker, Woods and Li, 2006) produce HFGWs having a single and constant polarization angle. Furthermore, fractal membranes are extremely sensitive to HFGW polarization angle according to Baker, Woods and Li (2006). The polarization angle of an HFGW generator whose GW radiators are located on a geosynchronous orbit, at a distance of $r = 3.8\text{x}10^7$ m, is essentially constant (it moves in a slowly rotating framework that is stationary with respect to the rotating Earth). Assuming a nanosecond observational interval or "snapshot" and a random orbital speed (perhaps caused by micrometeorite impacts) of 10^{-7} ms^{-1}, the random and unpredictable location motion of the geosynchronous satellites during observations would be about $\Delta s = 10^{-16}$ m. The HFGW polarization-angle steadiness can be defined as $\Delta\varphi = \Delta s/r = 10^{-16}/3.8\text{x}10^7 = 2.6\text{x}10^{-24}$ radians = 2.6 yoctoradians. Utilizing ultra-high-precision orbit determination and station keeping and a lunar and L_3 based system, the polarization angle of the generated HFGW could be defined and held constant during observation intervals or "snapshots" to afford 10^{-30} to potentially less than 10^{-40} radian sensitivity. This sensitivity is theoretically about the sensitivity of a laser-calibrated fractal-membrane HFGW detector to polarization angle change. It is recognized that it is not necessary to define the polarization angle φ accurately, but only sense its *change*. Thus HFGW imaging utilizing the change in polarization angle of material or devices irradiated by HFGWs would probably be the most useful if HFGW detectors involving fractal membranes were introduced. Perhaps electronics associated with weapons of mass destruction (WMDs) and the electronics associated with hidden missiles and rockets and other weapons would produce the most distinguishing signatures? Only the core-technology HFGW generation-detection laboratory experiment will resolve the question and allow for the development of equations and optical parameters that influence surveillance applications.

(4) As of this writing there exist four HFGW detectors fabricated or designed. First, the *Birmingham University* detector (Ingley, 2005). At $\nu = 3\text{x}10^{10}$ Hz or 3 GHz the minimum detectable HFGW amplitude is A ~ $3\text{x}10^{-19}$ meters per meter (strain). Second, the *INFN Genoa* detector (Chincarini and Gemme, 2003, Fig. 6). At $\nu = 10^9$ or 1 GHz the minimum detectable HFGW amplitude is A = 10^{-21} to 10^{-22} meters per meter (strain). Third, the open

cavity *Chongqing University* detector (Li, Baker and Fang, 2007, Table 1). At $\nu = 10^{10}$ or 10 GHz the minimum detectable HFGW amplitude is $A \sim 10^{-26}$ meters per meter (strain). Forth, the fractal membrane *Chongqing University* detector (Baker, Woods and Li, 2006, Table 2). At $\nu = 4.9 \text{ x}10^{9}$ Hz or 4.9 GHz the minimum detectable HFGW amplitude for a laboratory-size detector and generator apparatus is $A = 3\text{x}10^{-32}$ meters per meter (strain) and at $\nu = 10^{10}$ or 10 GHz the minimum detectable HFGW amplitude is $A = 6.62\text{x}10^{-32}$ meters per meter (strain). The HFGW lens proposed by Baker (2004), the Fresnel reflectors and lenses proposed by Baker, Davis and Woods (2005) and the variable-focal-length HTSC lens systems proposed by Woods (2006; 2007) for HFGW optics might greatly benefit the resolution and sensitivity of HFGW surveillance systems.

CONCLUSIONS

High-Frequency Gravitational Waves (HFGWs) might be utilized in a satellite-based surveillance system to image subterranean WMDs, personnel of interest inside and behind buildings, deeply submerged submarines, oil and mineral deposits, hidden missiles and rockets, etc. and provide for acoustical surveillance or eavesdropping. LIGO and other interferometer detectors (such as the Advanced LIGO, GEO600, Laser Interferometer Space Antenna or LISA, etc.) cannot detect HFGWs due to the HFGW's short wavelengths as discussed by Shawhan (2004). The currently available *Birmingham University* (Ingley, 2005) and *INFN Genoa* (Chincarini and Gemme, 2003) detectors and may not yet be sensitive enough, but two Chinese detectors under development at *Chongqing University* (Li, Baker; Fang, 2007) are possibly of sufficient sensitivity to have good image quality utilizing these detectors' yoctoradian to potentially less than 10^{-40} radian sensitivity to changes in polarization angle. Experiments utilizing them will determine their efficacy as it is not possible to theoretically predict their capability in advance of such experiments except in the case of superconductors. Since the distance of the focus from the HFGW radiator r can theoretically be $>> \lambda_{GW,}$ the HFGW wavelength (Baker, 2006), one could, in principal, place HFGW radiators at great distances apart such as on a geosynchronous orbit as in Fig. 1 or on the Moon and the L_3 libration point, with their focus remotely placed anywhere within or above the Earth's surface. The Chinese have an active program to develop core technology for the laboratory generation and detection of HFGWs (Baker, Woods and Li, 2006 and P. R. China Patent granted to Baker, 2005) and could possibly develop these surveillance applications within this decade.

NOMENCLATURE

A = amplitude of gravitational wave (meters/meter)
c = speed of light = 3x10 ms^{-1}
G = universal gravitational constant = $6.67423\text{x}10^{-11}$ ($\text{m}^3/\text{kg-s}^2$)
I = HFGW intensity, W per square degree
P = power of a gravitational wave, W
r = distance from a GW focus and a GW radiator, m
s = distance along an orbital path, m
δm = small mass undergoing a change in acceleration or jerk or shake, kg
Δ = small increment
Δf = change in force, N
Δt = time interval over which Δf is applied, s
θ = polar angle measured at the HFGW focus from the normal to the plane defined by the two equal and opposite jerks of the GW radiators, degrees
φ = polarization angle, radians
λ_{GW} = gravitational wavelength, m
ν = frequency of a gravitational wave, s^{-1}
ω = rotational rate of a pair of massive objects on orbit or a rod, radians/s

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