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Advanced Space Propulsion Based on Vacuum (Spacetime Metric) Engineering

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Advanced Space Propulsion based on Vacuum (Spacetime Metric) Engineering

Prepared by:

(b)(3):10 USC 424

Defense Intelligence Agency

Author:

(b)(6)

Administrative Note

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Advanced Space Propulsion Based on Vacuum (Spacetime Metric) Engineering

Preface and Introduction

A theme that has come to the fore in advanced planning for long-range space exploration in the future is the concept that empty space itself (the quantum vacuum, or spacetime metric) might be engineered to provide energy/thrust for future space vehicles. Although far reaching, such a proposal is solidly grounded in modern physical theory, and therefore the possibility that matter/vacuum interactions might be engineered for spaceflight applications is not a priori ruled out (Reference 1). Given the current development of mainstream theoretical physics on such topics as warp drives and traversable wormholes that provides for such vacuum engineering possibilities (References 2-6), provided in this paper is a broad perspective of the physics and consequences of the engineering of the spacetime metric.

The concept of "engineering the vacuum" found its first expression in the mainstream physics literature when it was introduced by Nobelist T. D. Lee in his textbook *Particle Physics and Introduction to Field Theory* (Reference 7). There he stated, "The experimental method to alter the properties of the vacuum may be called vacuum engineering.... If indeed we are able to alter the vacuum, then we may encounter new phenomena, totally unexpected." This legitimization of the vacuum engineering concept was based on the recognition that the vacuum is characterized by parameters and structure that leave no doubt that it constitutes an energetic and structured medium in its own right. Foremost among these are that (1) within the context of quantum theory, the vacuum is the seat of energetic particle and field fluctuations and (2) within the context of general relativity, the vacuum is the seat of a spacetime structure (metric) that encodes the distribution of matter and energy. Indeed, on the flyleaf of a book of essays by Einstein and others on the properties of the vacuum, there is the statement, "The vacuum is fast emerging as the central structure of modern physics" (Reference 8). Perhaps the most definitive statement acknowledging the central role of the vacuum in modern physics is provided by 2004 Nobelist Frank Wilczek in his book *The Lightness of Being: Mass, Ether and the Unification of Forces* (Reference 9):

"What is space? An empty stage where the physical world of matter acts out its drama? An equal participant that both provides background and has a life of its own? Or the primary reality of which matter is a secondary manifestation? Views on this question have evolved, and several times have changed radically, over the history of science. Today the third view is triumphant."

Given the known characteristics of the vacuum, one might reasonably inquire why it is not immediately obvious how to catalyze robust interactions of the type sought for spaceflight applications. For starters, in the case of quantum vacuum processes, uncertainties regarding global thermodynamic and energy constraints remain to be clarified. Furthermore, it is likely that energetic

components of potential utility involve very-small-wavelength, high-frequency field structures and thus resist facile engineering solutions. With regard to perturbation of the spacetime metric, the required energy densities predicted by present theory exceed by many orders of magnitude values achievable with existing engineering techniques. Nonetheless, one can examine the possibilities and implications under the expectation that as science and its attendant derivative technologies mature, felicitous means may yet be found that permit the exploitation of the enormous, as-yet-untapped potential of engineering so-called "empty space," the vacuum.

This paper introduces the underlying mathematical platform for investigating spacetime structure, the metric tensor approach. It then outlines the attendant physical effects that derive from alterations in the spacetime structure. Finally, the paper examines these effects as they would be exhibited in the presence of advanced aerospace craft technologies based on spacetime modification.

I. Spacetime Modification – Metric Tensor Approach

Despite the daunting energy requirements to restructure the spacetime metric to a significant degree, one can investigate the forms that such restructuring would take to be useful for spaceflight applications and determine their corollary attributes and consequences. Thus we embark on a “Blue Sky,” general-relativity-for-engineers approach, as it were.

As a mathematical evaluation tool, the *metric tensor* that describes the measurement of spacetime intervals is used. Such an approach, well known from studies in general relativity (GR), has the advantage of being model independent—that is, it does not depend on knowledge of the specific mechanisms or dynamics that result in spacetime alterations but rather only assumes that a technology exists that can control and manipulate (that is, engineer) the spacetime metric to advantage. Before discussing the predicted characteristics of such engineered spacetimes, beginning in Section III, a brief mathematical digression for those interested in the mathematical structure behind the discussion to follow is introduced.

As a brief introduction, the expression for the four-dimensional line element ds^2 in terms of the metric tensor $g_{\mu\nu}$ is given by

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu \quad (1)$$

where summation over repeated indices is assumed unless otherwise indicated. In ordinary Minkowski flat spacetime, a (four-dimensional) infinitesimal interval ds is given by the expression (in Cartesian coordinates)

$$ds^2 = c^2 dt^2 - (dx^2 + dy^2 + dz^2) \quad (2)$$

where the identification $dx^0 = cdt$, $dx^1 = dx$, $dx^2 = dy$, $dx^3 = dz$ is made, with metric tensor coefficients $g_{00} = 1$, $g_{11} = g_{22} = g_{33} = -1$, $g_{\mu\nu} = 0$ for $\mu \neq \nu$.

For spherical coordinates in ordinary Minkowski flat spacetime

$$ds^2 = c^2 dt^2 - dr^2 - r^2 d\theta^2 - r^2 \sin^2 \theta d\phi^2 \quad (3)$$

where $dx^0 = cdt$, $dx^1 = dr$, $dx^2 = d\theta$, $dx^3 = d\phi$, with metric tensor coefficients $g_{00} = 1$, $g_{11} = -1$, $g_{22} = -r^2$, $g_{33} = -r^2 \sin^2 \theta$, $g_{\mu\nu} = 0$ for $\mu \neq \nu$.

As an example of spacetime alteration, in a spacetime altered by the presence of a spherical mass distribution m at the origin (Schwarzschild-type solution), the above can be transformed into (Reference 10)

$$ds^2 = \left(\frac{1 - Gm/rc^2}{1 + Gm/rc^2} \right) c^2 dt^2 - \left(\frac{1 - Gm/rc^2}{1 + Gm/rc^2} \right)^{-1} dr^2 - (1 + Gm/rc^2) r^2 (d\theta^2 + \sin^2 \theta d\phi^2) \quad (4)$$

with the metric tensor coefficients $g_{\mu\nu}$ modifying the Minkowski flat-spacetime intervals dt , dr , and so forth, accordingly.

As another example of spacetime alteration, in a spacetime altered by the presence of a *charged* spherical mass distribution (Q, m) at the origin (Reissner-Nordstrom-type solution), the above can be transformed into (Reference 11)

$$ds^2 = \left(\frac{1 - Gm/rc^2}{1 + Gm/rc^2} + \frac{Q^2 G / 4\pi\epsilon_0 c^4}{r^2 (1 + Gm/rc^2)^2} \right) c^2 dt^2 - \left(\frac{1 - Gm/rc^2}{1 + Gm/rc^2} + \frac{Q^2 G / 4\pi\epsilon_0 c^4}{r^2 (1 + Gm/rc^2)^2} \right)^{-1} dr^2 - (1 + Gm/rc^2)^2 r^2 (d\theta^2 + \sin^2 \theta d\varphi^2) \quad (5)$$

with the metric tensor coefficients $g_{\mu\nu}$ again changed accordingly. Note that the effect on the metric due to charge Q differs in sign from that due to mass m , leading to what in the literature has been referred to as *electrogravitic repulsion* (Reference 12).

Similar relatively simple solutions exist for a spinning mass (Kerr solution) and for a spinning electrically charged mass (Kerr-Newman solution). In the general case, appropriate solutions for the metric tensor can be generated for arbitrarily engineered spacetimes, characterized by an appropriate set of spacetime variables dx^μ and metric tensor coefficients $g_{\mu\nu}$. Of significance now is to identify the associated physical effects and to develop a table of such effects for quick reference.

We begin by simply cataloging metric effects—that is, physical effects associated with alteration of spacetime variables—saving for Section IV the significance of such effects within the context of advanced aerospace craft technologies.

II. Physical Effects as a Function of Metric Tensor Coefficients

In undistorted spacetime, measurements with physical rods and clocks yield spatial intervals dx^μ and time intervals dt , defined in a flat Minkowski spacetime, the spacetime of common experience. In spacetime-altered regions, dx^μ and dt are still chosen as *natural* coordinate intervals to represent a coordinate map, but now *local* measurements with physical rods and clocks yield spatial intervals $\sqrt{-g_{\mu\nu}} dx^\mu$ and time intervals $\sqrt{g_{00}} dt$, so-called *proper* coordinate intervals. From these relationships a table of associated physical effects to be expected in spacetime regions altered by either natural or advanced technological means can be generated. Given that, as seen from an unaltered region, alteration of spatial and temporal intervals in a spacetime-altered region result in an altered velocity of light, from an engineering viewpoint such alterations can in essence be understood in terms of a variable refractive index of the vacuum (see Section III below) that affects all measurement.

TIME INTERVAL, FREQUENCY, ENERGY

Begin by considering the case where $\sqrt{g_{00}} < 1$, typical for an altered spacetime metric in the vicinity of, say, a stellar mass, as expressed by the leading term in Equation (4). Local measurements with physical clocks within the altered spacetime yield a time interval $\sqrt{g_{00}} dt < dt$; thus an interval of time dt between two events in an undistorted spacetime remote¹ from the mass—say, 10 seconds—would be judged by local (proper) measurement from *within* the altered spacetime to occur in a lesser time interval, $\sqrt{g_{00}} dt < dt$ —say, 5 seconds. From this one can rightly infer that, relatively speaking, clocks (atomic processes and so forth) within the altered spacetime run slower. Given this result, a physical process (for example, interval between clock ticks, atomic emissions) that takes a time Δt in unaltered spacetime slows to $\Delta t \rightarrow \Delta t / \sqrt{g_{00}}$ when occurring within the altered spacetime. Conversely, under conditions (for example, metric engineering) for which $\sqrt{g_{00}} > 1$, processes within the spacetime-altered region are sped up. Thus the first entry for a table of physical effects (see Table 1) is made.

Given that frequency measurements are the reciprocal of time duration measurements, the associated expression for frequency ω is given by $\omega \rightarrow \omega \sqrt{g_{00}}$, our second entry in Table 1. This accounts, for example, for the redshifting of atomic emissions from dense masses where $\sqrt{g_{00}} < 1$. Conversely, under conditions for which $\sqrt{g_{00}} > 1$, blueshifting of emissions would occur. In addition, given that quanta of energy are given by $E = h\omega$, energy scales with $\sqrt{g_{00}}$, as does frequency, $E \rightarrow E \sqrt{g_{00}}$, our third entry in the table. Depending on the value of $\sqrt{g_{00}}$ in the spacetime-altered region, energy states may be raised or lowered relative to an unaltered spacetime region.

¹ An observer at "infinity."

Table 1. Metric Effects on Physical Processes in an Altered Spacetime as Interpreted by a Remote (Unaltered Spacetime) Observer

Variable	Typical Stellar Mass ($g_{00} < 1, g_{11} > 1$)	Spacetime-Engineered Metric ($g_{00} > 1, g_{11} < 1$)
Time Interval $\Delta t \rightarrow \Delta t/\sqrt{g_{00}}$	Processes (for example, clocks) run slower	Processes (for example, clocks) run faster
Frequency $\omega \rightarrow \omega\sqrt{g_{00}}$	Redshift toward lower frequencies	Blueshift toward higher frequencies
Energy $E \rightarrow E\sqrt{g_{00}}$	Energy states lowered	Energy states raised
Spatial $\Delta r \rightarrow \Delta r/\sqrt{-g_{11}}$	Objects (for example, rulers) shrink	Objects (for example, rulers) expand
Velocity $v_L = c \rightarrow c\sqrt{g_{00}/-g_{11}}$	Effective $v_L < c$	Effective $v_L > c$
Mass $m = E/c^2 \rightarrow (-g_{11}/\sqrt{g_{00}})m$	Effective mass increases	Effective mass decreases
Gravitational "force" $f(g_{00}, g_{11})$	"Gravitational"	"Antigravitational"

Spatial Interval

Again, by considering the case typical for an altered spacetime metric in the vicinity of, say, a stellar mass, then $\sqrt{-g_{11}} > 1$ for the radial dimension $x^1 = r$, as expressed by the second term in Equation (4). Therefore, local measurements with physical rulers *within* the altered spacetime yield a spatial interval $\sqrt{-g_{11}} dr > dr$; thus a spatial interval dr between two locations in an undistorted spacetime—say, remote from the mass—would be judged by local (proper) measurement from within the altered spacetime to be greater. From this one can rightly infer that, relatively speaking, rulers (atomic spacings and so forth) within the altered spacetime are shrunken relative to their values in unaltered spacetime. Given this result, a physical object (for example, atomic orbit) that possesses a measure Δr in unaltered spacetime shrinks to $\Delta r \rightarrow \Delta r/\sqrt{-g_{11}}$ when placed within the altered spacetime. Conversely, under conditions for which $\sqrt{-g_{11}} < 1$, objects would expand—thus the fourth entry for the table of physical effects.

Velocity of Light in Spacetime-Altered Regions

Interior to a spacetime region altered by, say, a dense mass (for example, a black hole), the locally measured velocity of light c in, say, the $x^1 = r$ direction is given by the ratio of locally measured (proper) distance/time intervals for a propagating light signal (Reference 13).

$$v_L^i = \frac{\sqrt{-g_{11}} dr}{\sqrt{g_{00}} dt} = c \tag{6}$$

From a viewpoint *exterior* to the region, however, from the above one finds that the remotely observed *coordinate* ratio measurement yields a different value

$$v_L^r = \frac{dr}{dt} = \sqrt{\frac{g_{00}}{-g_{11}}} c \quad (7)$$

Therefore, although a local measurement with physical rods and clocks yields c , an observer in an exterior reference frame remote from the mass speaks of light "slowing down" on a radial approach to the mass owing to the ratio $\sqrt{g_{00}/-g_{11}} < 1$. Conversely, under (metric engineering) conditions for which $\sqrt{g_{00}/-g_{11}} > 1$, the velocity of light—and exotic-technology craft velocities that obey similar formulas—would appear superluminal in the exterior frame. This gives our fifth entry for the table of physical effects.

Refractive Index Modeling

Given that velocity-of-light effects in a spacetime-altered region, as viewed from an external frame, are governed by Equation (7), it is seen that the effect of spacetime alteration on light propagation can be expressed in terms of an optical refractive index n , defined by

$$v_L^r = \frac{c}{n}, \quad n = \sqrt{\frac{-g_{11}}{g_{00}}} \quad (8)$$

where n is an effective refractive index of the (spacetime-altered) vacuum. This widely known result has resulted in the development of refractive index models for GR (References 14-17) that have found application in problems such as gravitational lensing (Reference 18). The estimated electric or magnetic field strengths required to generate a given refractive index change given by standard GR theory (the Levi-Civita Effect) can be found in (Reference 19).

In engineering terms, the velocity of light c is given by the expression $c = 1/\sqrt{\mu_0 \epsilon_0}$, where μ_0 and ϵ_0 are the magnetic permeability and dielectric permittivity of undistorted vacuum space ($\mu_0 = 4\pi \times 10^{-7}$ H/m and $\epsilon_0 = 8.854 \times 10^{-12}$ F/m). The generation of an effective refractive index $n = \sqrt{-g_{11}/g_{00}} \neq 1$ by technological means can from an engineering viewpoint be interpreted as manipulation of the vacuum parameters μ_0 and ϵ_0 . In GR theory, such variations in μ_0 , ϵ_0 and hence the velocity of light, c , are often treated in terms of a "TH $\epsilon\mu$ " formalism used in comparative studies of gravitational theories (Reference 20).

As discussed below, a number of striking effects can be anticipated in certain engineered spacetime regions.

Effective Mass in Spacetime-Altered Regions

In a spacetime-altered region, $E = mc^2$ still holds in terms of local ("proper coordinate") measurements, but now energy E and the velocity of light c take on altered values as observed from an exterior (undistorted) spacetime region. Reference to the definitions for E and c in Table 1 permits one to define an effective mass as seen from the exterior undistorted region as therefore taking on the value $m \rightarrow m(-g_{11})/\sqrt{g_{00}}$, providing a sixth entry for our table. Depending on the values of g_{00} and g_{11} , the effective mass may be seen from the viewpoint of an observer in an undistorted spacetime region to have either increased or decreased.

Gravity/Antigravity "Forces"

Strictly speaking, from the GR point of view, there are no gravitational "forces" but rather (in the words of GR theorist John Wheeler) "matter tells space how to curve, and space tells matter how to move." (Reference 21) As a result, Newton's law of gravitational attraction to a central mass is therefore interpreted in terms of the spacetime structure as expressed in terms of the metric tensor coefficients, in this case as expressed in Equation (4) above. Therefore, in terms of the metric coefficients, gravitational attraction in this case derives from the condition that $g_{00} < 1, |g_{11}| > 1$. As for the possibility for generating "antigravitational forces," noted in equation (5), inclusion of the effects of charge led to metric tensor contributions counter to the effects of mass—that is, to *electrogravitic repulsion*. This reveals that conditions under which, say, the signs of the coefficients g_{00} and g_{11} could be reversed would be considered (loosely) as antigravitational in nature. A seventh entry in Table 1 represents these features of metric significance.

III. Significance of Physical Effects Applicable to Advanced Aerospace Craft Technologies as a Function of Metric Tensor Coefficients

As in Section III, metric tensor coefficients define the relationship between locally and remotely observed (that is, spacetime-altered and unaltered) variables of interest as listed in Table 1, and in the process define corollary physical effects. Table 1 thereby constitutes a useful reference for interpreting the physical significance of the effects of the alteration of spacetime variables. The expressions listed indicate specific spacetime alteration effects, whether owing to natural causes (for example, the presence of a planetary or stellar mass) or as a result of *metric engineering* by advanced technological means as might be anticipated in the development and deployment of advanced aerospace craft.

TIME ALTERATION

With regard to the first table entry (time interval), in a spacetime-altered region, time intervals are seen by a remote (unaltered spacetime) observer to vary as $1/\sqrt{g_{00}}$ relative to the remote observer. Near a dense mass, for example, $\sqrt{g_{00}} < 1$, and

therefore time intervals are seen as lengthening and processes as running slower,² one consequence of which is redshift of emission lines. Should such a time-slowed condition be engineered in an advanced aerospace application, an individual who has spent time within such a temporally modified field would, when returned to the normal environment, find that more time had passed than could be experientially accounted for.

Conversely, for an engineered spacetime associated with an advanced aerospace craft in which $\sqrt{g_{00}} > 1$, time flow within the altered spacetime region would appear sped up to an external observer, while to an internal observer external time flow would appear to be in slow motion. A corollary would be that within the spacetime-altered region, normal environmental sounds from outside the region might cease to be registered, since external sounds could under these conditions redshift below the auditory range.

An additional implication of time speedup within the frame of an exotic craft technology is that its flightpath that might seem precipitous from an external viewpoint (for example, sudden acceleration or deceleration) would be experienced as much less so by the craft's occupants. From the occupants' viewpoint, observing the external environment to be in relative slow motion, it would not be surprising to consider that one's relatively modest changes in motion would appear abrupt to an external observer.

Based on the second entry in Table 1 (frequency), yet another implication of an accelerated timeframe due to craft-associated metric engineering that leads to $\sqrt{g_{00}} > 1$, frequencies associated with the craft would for a remote observer appear to be blueshifted. Corollary to observation of such a craft is the possibility that there would be a brightening of luminosity due to the heat spectrum blueshifting up into the visible portion of the spectrum (see Figure 1).

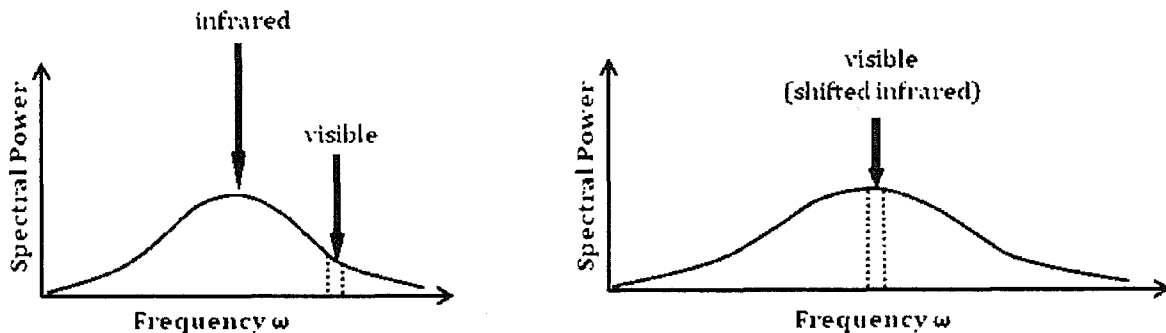


Figure 1. Blueshifting of Infrared Heat Power Spectrum

With regard to the third entry in Table 1 (energy), in a spacetime-altered region, energy scales as $\sqrt{g_{00}}$ relative to a remote observer in an undistorted spacetime. In the vicinity of a dense mass where $\sqrt{g_{00}} < 1$, the consequent reduction of energy bonds correlates with observed redshifts of emission. For engineered spacetimes associated with advanced craft technology in which $\sqrt{g_{00}} > 1$ (accelerated timeframe case), a

² In the case of approach to a black hole, to stop altogether.

craft's material properties would appear "hardened" relative to the environment owing to the increased binding energies of atoms in its material structure. Such a craft could, for example, impact water at high velocities without apparent deleterious effects.

SPATIAL ALTERATION

The fourth entry in Table 1 (spatial measure) indicates the size of an object within an altered spacetime region as seen by a remote observer. The size of, say, a spherical object is seen to have its radial dimension, r , scale as $1/\sqrt{-g_{11}}$. In the vicinity of a dense mass $\sqrt{-g_{11}} > 1$, in which case an object within the altered spacetime region appears to a remote observer to have shrunk. As a corollary, metric engineering associated with an advanced aerospace craft to produce this effect could in principle result in a large craft with a spacious interior appearing to an external observer to be relatively small. Additional dimensional aspects, such as potential dimensional changes, are discussed below in "Refractive Index Effects."

VELOCITY OF LIGHT/CRAFT IN SPACETIME-ALTERED REGIONS

Interior to a spacetime-altered region, the locally measured velocity of light, $v_L^l = c$, is given by the ratio of (locally measured) distance/time intervals for a propagating light signal, as expressed in Equation (6) above. From a viewpoint exterior to the region, however, the observed coordinate ratio measurement can yield a different value v_L^c greater or less than c as given by the fifth entry in Table 1 (velocity). As an example of a measurement less than c , one speaks of light "slowing down" as a light signal approaches a dense mass (for example, a black hole.) In an engineered spacetime in which $g_{00} > 1$, $|g_{11}| < 1$, however, the effective velocity of light v_L^c as measured by an external observer can be $> c$.

Given that velocities in general in different coordinate systems scale as does the velocity of light—that is, $v \rightarrow \sqrt{g_{00}/-g_{11}}v$ —for exotic propulsion an engineered spacetime metric can in principle establish a condition in which the trajectory of a craft approaching the velocity of light in its own frame would be observed from an exterior frame to exceed light speed—that is, exhibit motion at superluminal speed. This opens up the possibility of transport at superluminal velocities (as measured by an external observer) without violation of the velocity-of-light constraint within the spacetime-altered region, a feature attractive for interstellar travel. This is the basis for discussion of warp drives and wormholes in the GR literature (References 2-6). Therefore, although present technological facility is far from mature enough to support the development of warp drive and wormhole technologies (Reference 22), the possibility of developing such technologies in the future cannot be ruled out. In other words, effective transport at speeds exceeding the conventional speed of light could occur in principle, and therefore the possibility of reduced-time interstellar travel is not fundamentally ruled out by physical principles.

REFRACTIVE INDEX EFFECTS

When considering metric-engineered spacetime associated with exotic propulsion, a number of corollary side effects associated with refractive index changes of the vacuum structure emerge as possibilities. Expected effects would mimic known refractive index effects in general and can therefore be determined from known phenomena. Indistinct boundary definition associated with "waviness" as observed with heat waves off a desert floor is one example. As another, a light beam may bend (as in the GR example of the bending of starlight as it grazes the sun; see Figure 2) or even terminate in mid-space. Such an observation would exhibit features that under ordinary circumstances would be associated with a high-refractive index optical fiber in normal space (well-defined boundaries, light trapped within, bending or termination in mid-space). Additional observations might include apparent changes in size or shape (changes in lensing magnification parameters). Yet another possibility is the sudden "cloaking" or "blinking out," which would at least be consistent with strong gravitational lensing effects that bend a background view around a craft, though other technical options involving, for example, the use of metamaterials, exist as well.

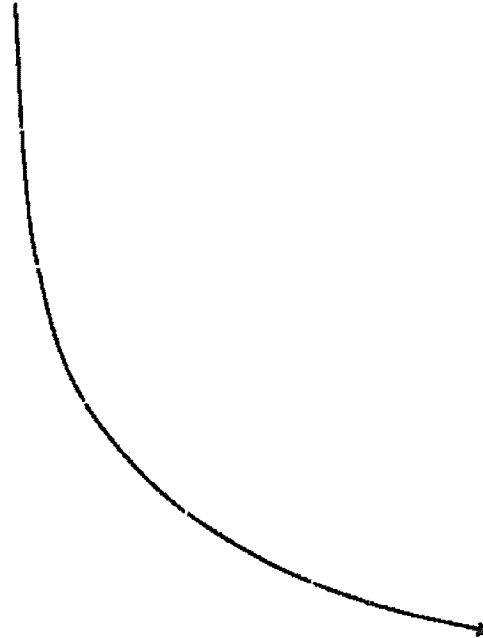


Figure 2. Light-Bending in a Spacetime-Altered Region

EFFECTIVE MASS IN SPACETIME-ALTERED REGIONS

As noted in the preceding sections, spacetime alteration of energy and light-speed measures leads to an associated alteration in the effective mass of an object in a spacetime-altered region as viewed from an external (unaltered) region. Of special interest is the case in which the effective mass is decreased by application of spacetime metric engineering principles as might be expected in the case of metric engineering for spaceflight applications (reference last column in Table 1). Effective reduction of inertial mass as viewed in our frame of reference would appear to mitigate against untoward effects on craft occupants associated with abrupt changes in movement. (The physical principles involved can also be understood in terms of associated coordinate transformation properties as discussed above.) In any case, changes in effective mass associated with engineering of the spacetime metric in a craft's environs can lead to properties advantageous for spaceflight applications.

GRAVITY/ANTIGRAVITY/PROPULSION EFFECTS

In the GR ansatz gravitational-type forces derive from the spacetime metric, whether determined by natural sources (for example, planetary or stellar masses) or by advanced metric engineering. Fortunately for our consideration of this topic, discussion can be carried out solely based on the form of the metric, independent of the specific mechanisms or dynamics that determine the metric. As one exemplar, consider Alcubierre's formulation of a "warp drive," a spacetime metric solution of Einstein's GR field equation (References 2, 22). Alcubierre derived a spacetime metric motivated by cosmological inflation that would allow arbitrarily short travel times between two distant points in space. The behavior of the warp drive metric provides for the simultaneous expansion of space behind the spacecraft and a corresponding contraction of space in front of the spacecraft (see Figure 3). The warp drive spacecraft would thus appear to be "surfing on a wave" of spacetime geometry. By appropriate structuring of the metric, the spacecraft can be made to exhibit an arbitrarily large apparent faster-than-light speed as viewed by external observers without violating the local speed-of-light constraint within the spacetime-altered region. Furthermore, the Alcubierre solution showed that the proper (experienced) acceleration along the spaceship's path would be zero, and that the spaceship would suffer no time dilation—highly desirable features for interstellar travel. In order to implement a warp drive, one would have to construct a "warp bubble" that surrounded the spacecraft by generating a thin shell or surface layer of exotic matter—that is, a quantum field having negative energy and/or negative pressure. Although the technical requirements for such are unlikely to be met in the foreseeable future (Reference 22), the exercise nonetheless serves as a good example for showcasing attributes associated with manipulation of the spacetime metric at will.

The entire discussion of the possibility of generating a spacetime structure like that of the Alcubierre warp drive is based simply on assuming the form of a metric (that is, $g_{\mu\nu}$) that exhibits desired characteristics. In like manner, arbitrary spacetime metrics to provide gravity/antigravity/propulsion characteristics can in principle be postulated. What is required for implementation is to determine appropriate sources for their generation, a requirement that must be met before advanced spaceship technology based on vacuum engineering can be realized in practice. The difficulties, challenges, and options for meeting such requirements can be found in the relevant literature (Reference 22).

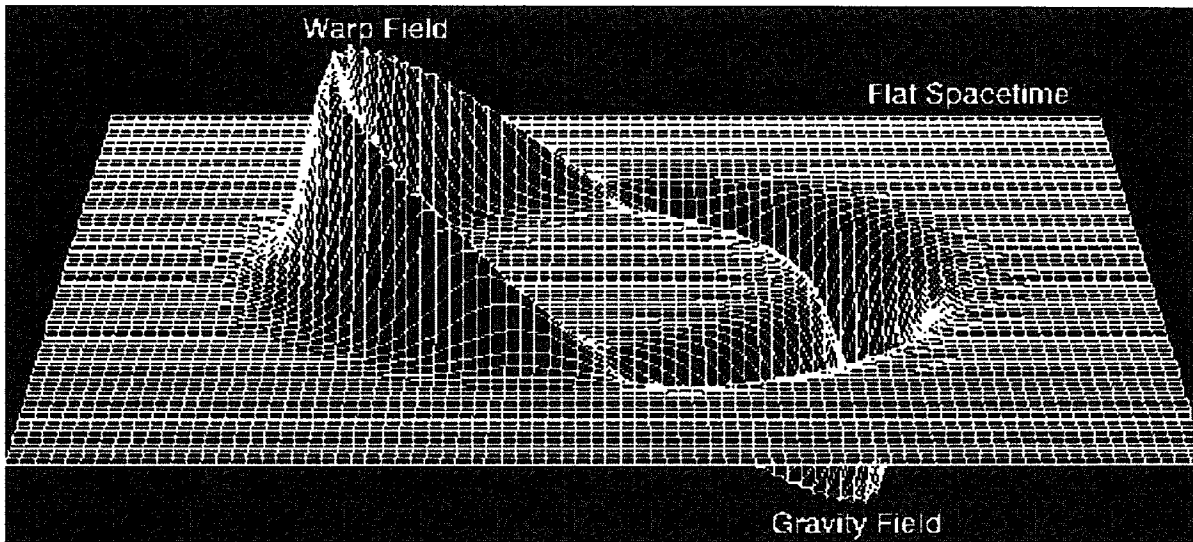


Figure 3. Alcubierre Warp Drive Metric Structure

IV. Discussion

This paper has considered the possibility—even likelihood—that future developments with regard to advanced aerospace technologies will trend in the direction of manipulating the underlying spacetime structure of the vacuum of space itself by processes that can be called vacuum engineering or metric engineering. Far from being simply a fanciful concept, a significant literature exists in peer-reviewed, Tier 1 physics publications in which the topic is explored in detail.³

The analysis presented herein, a form of general relativity for engineers, takes advantage of the fact that in GR a minimal-assumption, metric tensor approach can be used that is model-independent—that is, it does not depend on knowledge of the specific mechanisms or dynamics that result in spacetime alterations but rather only assumes that a technology exists that can control and manipulate (that is, engineer) the spacetime variables to advantage. Such an approach requires only that the hypothesized spacetime alterations result in effects consonant with the currently known GR physics principles.

In the metric engineering approach, the application of the principles gives precise predictions as to what can be expected as spatial and temporal variables are altered from their usual (that is, flat space) structure. Signatures of the predicted contractions and expansions of space, slowdown and speedup of time, alteration of effective mass, speed of light and associated consequences, both as occur in natural phenomena in nature and with regard to spacetimes specifically engineered for advanced aerospace applications, are succinctly summarized in Table 1.

Of particular interest with regard to innovative forms of advanced aerospace craft are the features tabulated in the right-hand column of Table 1, features that presumably describe an ideal craft for interstellar travel: an ability to travel at superluminal speeds

³ See Reference 1 for a comprehensive introduction to the subject with contributions from lead scientists from around the globe.

relative to the reference frame of background space, energy bonds of materials strengthened (that is, hardened) relative to the background environment, a decrease in effective mass vis-à-vis the environment, an accelerated timeframe that would permit rapid trajectory changes relative to the background rest frame without undue internal stress, and the generation of gravity-like forces of arbitrary geometry—all on the basis of restructuring the vacuum spacetime variables. As avant garde as such features appear to be, they are totally in conformance with the principles of general relativity as currently understood. A remaining challenge is to develop insight into the technological designs by which such vacuum restructuring can be generated on the scale required to implement the necessary spacetime modifications.

Despite the challenges, sample calculations as presented herein indicate the direction of potentially useful trends derivable on the basis of the application of GR principles as embodied in a metric engineering approach, with the results constrained only by what is achievable practically in an engineering sense. The latter is, however, a daunting constraint. At this point in the consideration of such nascent concepts, given our present level of technological evolution, it is premature to even guess about an optimum strategy, let alone attempt to form a critical path for the engineering development of such technologies. Nonetheless, only through rigorous inquiry into such concepts can one hope to arrive at a proper assessment of the possibilities inherent in the evolution of advanced spaceflight technologies.

¹ See, for example, a series of essays in the compendium *Frontiers of Propulsion Science*, Eds. M. G. Millis and E. W. Davis, AIAA Press, Reston, Virginia (2009).

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