

Encoding Structured Information in Gravitational Waves by Controlled Binary-Orbit Modulation

Sean Brady^{1,*}

¹*Independent Researcher*

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Background: Gravitational waves encode the motion of their sources, raising the question of whether deliberately controlled binary motion can carry recoverable information. **Methods:** Two equal masses are kept antipodal while a smooth radial control law produces identical orbital excursions whose timing encodes the integer sequence 2, 3, 5, 7, 11, 13, 17. The two corresponding quadrupole polarizations are calculated from the source motion. A receiver fits the carrier, forms signed residuals, identifies markers, estimates a timing unit, and admits repeated interval packets only after the fixed model and statistical controls are satisfied. Independent numerical integration checks the trajectory and energy balance. **Results:** In a predeclared Gaussian-noise sweep, the full seven-integer payload was recovered in four of six modulated cases, while none of the six matched unmodulated cases passed the packet criteria. At the highest tested noise level, failure occurred in marker extraction rather than carrier fitting. Two chirp- and precession-like nuisance signals also failed to produce repeated packets. The dimensionless construction was mapped to physical binary parameters and Advanced LIGO design sensitivity, with ideal matched-waveform detectability kept distinct from demonstrated packet decoding. **Conclusions:** This study provides a bounded end-to-end demonstration of information encoded through controlled source motion rather than added directly to a waveform, while also quantifying the extreme physical demands of detectable artificial generation.

I. INTRODUCTION

Gravitational waves carry detailed information about the motion of their sources. For a nonrelativistic binary, the leading radiative field is determined by the second time derivative of the source quadrupole moment, while gravitational radiation also drives long-term orbital evolution through energy and angular-momentum loss [1–3]. This raises a straightforward communication question: if a civilization could deliberately control part of a binary’s motion, could it encode a message in the gravitational radiation itself?

Artificial gravitational-wave beacons have been discussed previously. Abramowicz *et al.* considered an engineered object maintained near the Galactic center as a persistent gravitational-wave messenger [4]. A recent review by Wang and Akan surveys proposed generation, modulation, detection, and channel concepts for gravitational communication [5]. The aim here is narrower and more concrete. Rather than asking only whether an artificial source could be detectable, this study asks whether specified controlled binary motion can generate a structured waveform from which a receiver can recover a finite message.

The message is carried only by the *timing* of identical source perturbations. The payload is

$$\mathcal{P} = (2, 3, 5, 7, 11, 13, 17), \quad (1)$$

chosen because the first seven primes provide an easily recognizable mathematical test sequence. The receiver,

however, contains no primality test and is not given the intended payload. It is given only a synchronization/framing rule and must recover the interval values from the waveform.

The experiment separates three questions throughout: (i) whether the controlled source produces a calculable gravitational-wave modulation, (ii) whether an ideal detector with a known template could detect that modulation, and (iii) whether the implemented packet receiver can recover the unknown message. These are different claims and are reported separately.

Figure 1 summarizes the end-to-end calculation.

II. METHODS

A. Controlled binary source

1. Dimensionless reference orbit

The source model contains two equal unit masses with a dimensionless gravitational constant $G_* = 4$. Each mass has a baseline barycentric radius of one and a baseline angular speed of one. The masses remain antipodal,

$$\mathbf{x}_{\pm}(t) = \pm r(t) \mathbf{e}_r(t), \quad \mathbf{e}_r(t) = (\cos t, \sin t). \quad (2)$$

At $r = 1$, their mutual Newtonian attraction supplies the required centripetal acceleration.

Each message marker is a smooth radial excursion centered at time t_k . With $u = t - t_k$,

$$r(t) = \begin{cases} 1 + \frac{(1 - u^2)^4}{16}, & |u| < 1, \\ 1, & |u| \geq 1. \end{cases} \quad (3)$$

* sbnvh@missouri.edu

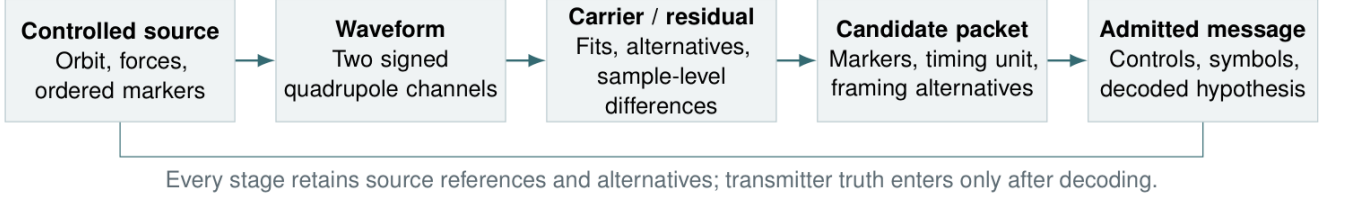


FIG. 1. End-to-end communication chain used in the experiment. The modulation is generated by the controlled orbit. The receiver works from the resulting waveform and does not receive the transmitter’s event schedule or payload.

Within the excursion,

$$\dot{r} = -\frac{u(1-u^2)^3}{2}, \quad (4)$$

$$\ddot{r} = \frac{(1-u^2)^2(7u^2-1)}{2}. \quad (5)$$

The profile joins the circular reference with three continuous derivatives and reaches a maximum radius of $17/16$, a 6.25% excursion from the baseline.

Writing $\mathbf{e}_\theta = (-\sin t, \cos t)$, differentiation of Eq. (2) gives

$$\ddot{\mathbf{x}}_+ = (\ddot{r} - r)\mathbf{e}_r + 2\dot{r}\mathbf{e}_\theta. \quad (6)$$

The companion lies at separation $2r$, so the mutual gravitational acceleration is $-r^{-2}\mathbf{e}_r$. Therefore, the external control acceleration required for the reference motion is

$$f_r = \ddot{r} - r + \frac{1}{r^2}, \quad f_\theta = 2\dot{r}. \quad (7)$$

The second body receives the opposite Cartesian force.

2. Mechanical work

The dimensionless pair energy is

$$E = \dot{r}^2 + r^2 - \frac{2}{r}. \quad (8)$$

The controller power is

$$\begin{aligned} P &= 2(f_r\dot{r} + f_\theta r) \\ &= 2\dot{r}\left(\ddot{r} + r + \frac{1}{r^2}\right) = \frac{dE}{dt}. \end{aligned} \quad (9)$$

The energy rises on the outward half of the excursion and falls during the return. The positive work required per marker is

$$W_+ = \frac{1073}{4352} \simeq 0.2465533 \quad (10)$$

in the dimensionless energy unit. Across the 22 markers used in two repeated packets, the total positive work is $11803/2176 \simeq 5.42417$, with the same amount returned to an ideal reversible controller. Thus the signed net

mechanical work over completed excursions is zero, but the controller must still supply and recover finite power and energy.

Radiation reaction and hardware inefficiencies are not included in the controlled trajectory. Leading circular-orbit radiation losses are estimated separately in Sec. III B.

B. Waveform and message encoding

For the two point masses, the trace-free quadrupole is

$$Q_{ab} = \sum_{\pm} \left(x_{\pm,a} x_{\pm,b} - \frac{r^2}{3} \delta_{ab} \right). \quad (11)$$

In the orbital plane,

$$Q_{xx} - Q_{yy} = 2r^2 \cos(2t), \quad (12)$$

$$2Q_{xy} = 2r^2 \sin(2t). \quad (13)$$

Define

$$A = \dot{r}^2 + r\ddot{r} - 2r^2, \quad B = 4r\dot{r}. \quad (14)$$

The two unscaled face-on quadrupole channels used in the experiment are

$$H_+ = 4[A \cos(2t) - B \sin(2t)], \quad (15)$$

$$H_\times = 4[A \sin(2t) + B \cos(2t)]. \quad (16)$$

When $r = 1$, these expressions reduce to the circular carrier $-8 \cos(2t)$ and $-8 \sin(2t)$. The message-bearing residual is therefore created by the source excursion itself; no marker is added to an independent waveform afterward.

The observation was sampled at $\Delta t = 1/8$ over $0 \leq t \leq 616$, yielding 4929 samples in each polarization. Trigonometric values were rounded to 14 decimal places before the subsequent exact rational arithmetic. An independently constructed Cartesian quadrupole agreed with Eqs. (15)–(16), with a maximum reported discrepancy of 5.87×10^{-14} under this sampling convention.

1. Timing protocol

Each packet begins with four synchronization markers separated by a reference interval. Seven subsequent intervals carry the payload in Eq. (1). The timing unit is

four dimensionless time units, and two complete packets are separated by a 23-unit guard interval. Every marker uses the same excursion shape and strength. Figure 2 illustrates this framing and interval-encoding protocol.

This protocol intentionally keeps the alphabet simple. It does not use amplitude modulation, polarization switching, error-correcting codes, or a second message layer.

C. Receiver and admission rules

The receiver first fits the unmodulated two-channel carrier using 128 quiet calibration samples and then checks the fit on a separate 64-sample quiet holdout. Two carrier families are retained: a joint amplitude/phase model and the same model with one constant offset per channel. The simplest model satisfying the declared holdout criterion is selected.

For each retained carrier model, the receiver forms signed residuals

$$r_{+,i} = y_{+,i} - \hat{y}_{+,i}, \quad r_{\times,i} = y_{\times,i} - \hat{y}_{\times,i}. \quad (17)$$

The residual norm is used only as a marker-detection view; the signed channel residuals remain the underlying quantities.

Candidate marker groups are identified using the fixed threshold and grouping rules established before the follow-up tests. The receiver then searches the declared framing format. It estimates the synchronization unit from the opening markers and computes dimensionless interval ratios

$$\hat{p}_j = \frac{\hat{t}_{j+1} - \hat{t}_j}{\hat{\Delta}}. \quad (18)$$

An interval is assigned to an integer bin only when it lies within the fixed ratio tolerance $3/25$ of that integer. Two disjoint frames with the same seven-symbol sequence are required.

The statistical gate uses the maximum number of disjoint, identical packets found by the complete framing search. For each case, 99 permutations of the detected gap order preserve the gap multiset and repeat the same search. The conditional rank is

$$p_{\text{rank}} = \frac{1 + \#\{T_{\text{null}} \geq T_{\text{obs}}\}}{100}. \quad (19)$$

Admission requires at least two disjoint repeated packets and $p_{\text{rank}} \leq 0.05$. With 99 permutations, the minimum possible rank is $1/100$. This is a conditional test of the observed gap order, not a measure of the astrophysical false-alarm probability.

Transmitter truth is used only after decoding to determine whether the recovered sequence is correct.

III. RESULTS

A. Numerical validation and noise experiment

1. Independent trajectory refinement

The analytic controlled trajectory was checked by an independent fourth-order Runge–Kutta integration of the Cartesian equations of motion. Mutual Newtonian gravity, the feedforward force in Eq. (7), and tracking feedback with gains $k_p = k_d = 4$ were included. The feedback is zero on the exact reference and acts only on numerical deviations.

The numerical acceptance tolerances were frozen before refinement. Coarse runs that decoded the message were not accepted if the dynamical checks failed. Table I shows the refinement history.

At $h = 1/64$, the maximum waveform discrepancy was 2.594×10^{-7} , below the unchanged 10^{-4} waveform tolerance. The matched unmodulated case also passed its numerical checks at the same refinement level.

2. Predeclared Gaussian-noise sweep

Noise was added independently to both channels at per-channel standard deviations

$$\sigma \in \{0.01, 0.05, 0.20\}. \quad (20)$$

Two fixed seeds were used at each level, producing six modulated cases. Each was paired with an unmodulated source generated from the same standard-normal draws at the corresponding noise level. Carrier adequacy was evaluated using the predeclared noise-aware holdout limit $6\sigma + 10^{-10}$; packet thresholds were not returned.

Let δH denote the noiseless modulation, i.e. the difference between modulated and unmodulated waveforms. Two signal-level summaries were reported:

$$\text{SNR}_{\text{RMS}} = \frac{\sqrt{\sum(\delta H_+^2 + \delta H_\times^2)/(2N)}}{\sigma}, \quad (21)$$

$$\rho_{\text{ideal}} = \frac{\sqrt{\sum(\delta H_+^2 + \delta H_\times^2)}}{\sigma}. \quad (22)$$

The second quantity assumes that the complete signal is already known and is included only as a coherent white-

TABLE I. Independent dynamical refinement. The prime source is admitted only at the first step size that satisfies the unchanged state and energy-balance tolerances.

Step	Max. state error	Energy error	Status
1/16	4.849×10^{-6}	2.040×10^{-3}	comparison
1/32	2.902×10^{-7}	1.228×10^{-4}	fail
1/64	1.775×10^{-8}	7.537×10^{-6}	pass

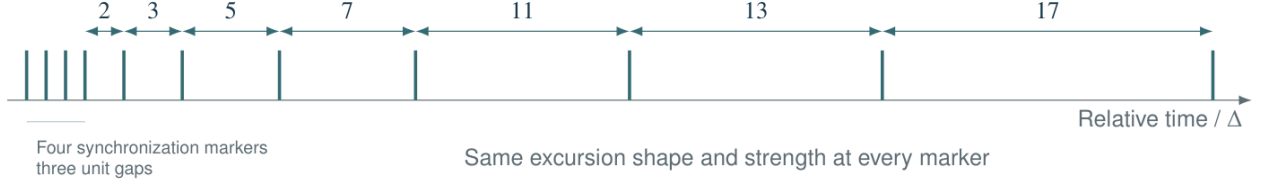


FIG. 2. Timing protocol for one packet. Four equally spaced synchronization markers establish the reference interval. The following seven separations encode 2, 3, 5, 7, 11, 13, 17. The receiver estimates the unit from the synchronization portion and then quantizes the data intervals.

TABLE II. Continuous-source noise sweep. “Recoveries” means exact recovery of all seven intervals. Each noise level uses two fixed seeds and two matched unmodulated controls.

σ	SNR_{RMS}	ρ_{ideal}	Recoveries	Null passes
0.01	37.635	3736.68	2/2	0/2
0.05	7.527	747.336	2/2	0/2
0.20	1.8817	186.834	0/2	0/2

noise reference. Table II summarizes the fixed Gaussian-noise sweep.

At $\sigma = 0.01$ and 0.05, all 22 markers were recovered in both realizations, two repeated packets were found, the permutation rank was 1/100, and the full payload was decoded correctly. All four matched unmodulated controls contained zero accepted markers and were blocked.

At $\sigma = 0.20$, the carrier fits still passed, but noise produced 287 and 324 candidate markers in the two modulated realizations. No repeated packet survived the framing search. The matched unmodulated cases similarly produced many candidate markers but no repeated packets. Thus the observed failure at the highest tested noise level is localized to marker extraction and packet formation rather than the quiet-data carrier fit.

These six injections form a fixed, paired sweep and do not estimate population-level recovery probability.

B. Physical scaling and detector sensitivity

1. Mapping to dimensional parameters

Let each body have physical mass m and barycentric orbital radius r_0 , so the separation is $2r_0$. Equal-mass Newtonian circular motion gives

$$\omega^2 = \frac{Gm}{4r_0^3}, \quad f_{\text{GW}} = \frac{\omega}{\pi}. \quad (23)$$

The physical time corresponding to the dimensionless coordinate is $t_{\text{phys}} = t/\omega$.

For a face-on observer at distance R , the strain convention used here is

$$h_{+, \times}(t) = \frac{Gmr_0^2\omega^2}{c^4 R} H_{+, \times}(t), \quad (24)$$

TABLE III. Illustrative physical source scalings.

	Small compact	Stellar compact
m per body	10^{20} kg	2.78386×10^{30} kg
r_0	25 m	2.0×10^5 m
ω	326.786 rad/s	76.1994 rad/s
f_{GW}	104.019 Hz	24.255 Hz
Two-packet duration	1.885 s	8.084 s
v/c	2.73×10^{-5}	0.0508

so the circular carrier peak is

$$h_{\text{carrier}} = \frac{2G^2m^2}{c^4r_0R}. \quad (25)$$

Equation (24) gives the leading quadrupole mapping for the stated point-mass trajectory [1, 2].

Two illustrative source scales were fixed before evaluation. They are not engineering designs. The first assumes two extremely compact 10^{20} kg objects at $r_0 = 25$ m. The second uses two $1.4M_{\odot}$ compact objects at $r_0 = 200$ km. Table III lists these two dimensional source scalings.

The smaller example should not be interpreted as implying that ordinary matter can be packed or manipulated at that density; it is included only to illustrate the scaling.

2. Strain and ideal known-waveform SNR

The plus-channel modulation is defined as the difference between the controlled and unmodulated sources. Table IV gives representative strain amplitudes.

For an ideal known modulation, a one-detector frequency-domain reference was evaluated against the Advanced LIGO design amplitude spectral density [6]. With $\tilde{h}_k = \Delta t \text{FFT}(h)_k$ and positive-frequency spacing Δf ,

$$\rho^2 = 4\Delta f \sum_k \frac{|\tilde{h}_k|^2}{\text{ASD}(f_k)^2}. \quad (26)$$

Only frequencies covered by the published curve were included. The modulation residual is zero at both ends and was not tapered; the circular carrier was Hann-windowed.

For the stellar compact scaling, the known-modulation reference gave $\rho = 5.26 \times 10^7$ at 1 pc, 5.26×10^4 at 1 kpc,

TABLE IV. Face-on strain scaling. The modulation RMS includes the entire two-packet observation, including quiet intervals.

Source	Distance	Carrier peak	Modulation peak (+)	Modulation RMS (+)
Small compact	1 pc	1.430×10^{-32}	5.639×10^{-33}	6.676×10^{-34}
Small compact	1 kpc	1.430×10^{-35}	5.639×10^{-36}	6.676×10^{-37}
Small compact	1 Mpc	1.430×10^{-38}	5.639×10^{-39}	6.676×10^{-40}
Stellar compact	1 pc	1.385×10^{-15}	5.463×10^{-16}	6.467×10^{-17}
Stellar compact	1 kpc	1.385×10^{-18}	5.463×10^{-19}	6.467×10^{-20}
Stellar compact	1 Mpc	1.385×10^{-21}	5.463×10^{-22}	6.467×10^{-23}

and 52.6 at 1 Mpc. Under the simple $1/R$ scaling, the formal distance at $\rho = 8$ was 6.57 Mpc. This number is *not* a demonstrated message-decoding horizon. Equation (26) assumes the complete modulation waveform is known in advance, whereas the receiver in Sec. II C must discover marker times and packet structure.

For the small compact scaling, the corresponding formal $\rho = 8$ distance is approximately 4.74×10^{-11} pc, only about half a gravitational wavelength at the relevant frequency, so it is not a valid far-zone detection horizon.

3. Radiation losses and control cost

The dimensional force and energy units are $mr_0\omega^2$ and $mr_0^2\omega^2$. For compact astrophysical scalings, the controlled profile therefore implies large actuation requirements. For the stellar compact example, the sampled peak control force is approximately 2.19×10^{39} N per body and the positive mechanical work over 22 markers is approximately 3.51×10^{45} J.

For an equal-mass unmodulated circular binary, the leading quadrupole radiation power and merger time are [2, 3]

$$P_{\text{GW}} = \frac{2}{5} \frac{G^4 m^5}{c^5 r_0^5}, \quad (27)$$

$$t_{\text{merge}} = \frac{5c^5 r_0^4}{32G^3 m^3}. \quad (28)$$

For the stellar compact example, these evaluated to approximately 1.71×10^{42} W and 94.4 s, respectively. The controlled numerical trajectory does not include radiation reaction or the compensating torque and power that a physical controller would need to maintain the assigned orbit. The scaling exercise is therefore a feasibility diagnostic rather than a proposed engineering design.

C. Natural-carrier nuisance tests

Two deterministic, unmodulated nuisance waveforms were predeclared and passed through the same stationary carrier fits and packet search.

The first is a slow chirp with

$$\omega(t) = 1 + 0.1 t/616, \quad \phi(t) = t + 0.05 t^2/616, \quad (29)$$

and amplitude proportional to $\omega^{2/3}$. The second is a precession-like projection with a slowly varying inclination and polarization angle. Neither is intended to represent a full astrophysical inspiral or spin-precession model; both are controlled tests of smoothly evolving carrier structure.

Table V summarizes the two evolving-carrier nuisance tests. Both stationary fits were inadequate, as expected. More importantly, inspection of the resulting residuals showed that neither case generated a repeated packet. Thus these two examples did not produce false message admissions. This result does not estimate a false-alarm rate over an astrophysical source population, and the test set was intentionally small.

IV. DISCUSSION

The experiment establishes a limited but useful result: structured information can be imposed through a controlled binary trajectory and recovered from the resulting quadrupole waveform without inserting symbols directly into the waveform. The receiver can separate an underlying carrier from source-generated residual structure, recover a timing alphabet, and reject matched unmodulated controls under the declared conditions.

The noise sweep also provided a meaningful failure mode. At the two lower noise levels, the full payload was recovered in both realizations. At the highest tested level, carrier fitting still succeeded, but marker extraction became saturated with false candidates and the packet grammar no longer formed a repeated message. This is more informative than a pass/fail threshold alone because it identifies the stage that limits the receiver.

The physical scaling should be interpreted conservatively. A detectable astrophysical-scale modulation does not imply a practical transmitter. The stellar example requires extreme forces and work, has a short leading-order merger time, and omits radiation-reaction control. Conversely, laboratory-scale masses radiate far too weakly for

TABLE V. Evolving-carrier nuisance tests. “Fit adequate” refers to the stationary carrier family used by the receiver.

Case	Fit adequate	Markers	Repeats	Admitted
Slow chirp	no	0	0	no
Precession-like	no	1	0	no

current gravitational-wave detectors. These calculations quantify the enormous technological gap between a mathematically valid communication channel and a practical artificial source.

Several extensions remain open. A more realistic receiver would use detector-colored noise directly in packet recovery rather than only in a known-template sensitivity calculation. The natural-source control set should eventually include inspiral waveforms, precession, eccentricity, glitches, and detector artifacts drawn from realistic distributions. A communication protocol could also add amplitude, phase, or polarization symbols, together with error correction. None of these extensions is required for the narrower result reported here.

V. REPRODUCIBILITY AND COMPUTATIONAL DISCLOSURE

The continuous transmitter, receiver thresholds, noise levels, seeds, nuisance definitions, physical source scalings, numerical tolerances, and the three follow-up test classes were fixed before the reported follow-up suite was evaluated. Failed cases were retained; receiver thresholds were not adjusted after observing the $\sigma = 0.20$ failures.

The waveform and fitting calculations used the explicit numerical conventions described above. The analytic reference trajectory was checked independently by Cartesian integration, and the reported tables were reconstructed from frozen machine-readable results. The dimensional sensitivity calculation used the published Advanced LIGO design curve [6].

VI. CONCLUSION

A smooth, deliberately controlled perturbation of a binary orbit can encode a finite integer message in the timing of its gravitational-wave quadrupole modulation. In the model studied here, the sequence 2, 3, 5, 7, 11, 13, 17 was recovered from two repeated packets after carrier fitting and residual extraction. The same fixed receiver succeeded in four of six predeclared noisy signal cases, admitted none of the six matched unmodulated controls,

and admitted neither of the two evolving-carrier nuisance cases.

The physical scaling exercise illustrates both sides of the idea. Gravitational waves can carry information, but artificial generation at detectable amplitudes is extraordinarily demanding. The present result is best understood as a source-to-message construction and receiver demonstration, not as an engineering proposal. Its main value is to make the communication question concrete enough to test: a message is encoded in controlled mass motion, propagated through the quadrupole waveform, and recovered from the resulting signal under explicit controls.

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DATA AVAILABILITY AND ACCESS STATEMENT

The data, frozen numerical results, and code supporting the findings of this study are available from the corresponding author upon reasonable request.

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The author declares no competing interests.

ETHICS STATEMENT

This study involved no human participants, animals, or identifiable personal data. No ethics approval was required.

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