N90-19954

34-90

EARTH-ORBITING RESONANT-MASS GRAVITATIONAL WAVE DETECTORS

HO JUNG PAIK
Department of Physics and Astronomy
University of Maryland, College Park, MD 20742

MI 9/5

ABSTRACT

Earth-based gravitational wave detectors suffer from the need to support the large antenna masses against the earth's gravity without transmitting a significant amount of seismic noise. Passive vibration isolation is difficult to achieve below 1 Hz on the earth. Vibration-free space environment thus gives an opportunity to extend the frequency window of gravitational wave detection to ultralow frequencies. The weightless condition of a space laboratory also enables construction of a highly symmetric multimode antenna which is capable of resolving the direction of the source and the polarization of the incoming wave without resorting to multiantenna coincidence. In this paper, we consider two types of earth-orbiting resonant-mass gravitational wave detectors. One is a skyhook gravitational wave detector, proposed by Braginsky and Thorne (1985). The other is a spherical detector, proposed by Forward (1971) and analyzed by Wagoner and Paik (1976).

I. SKYHOOK GRAVITATIONAL WAVE DETECTOR

The skyhook detector is an extension of the shuttle-borne skyhook, proposed by Colombo *et al.* (1974), now known as Tethered Satellite System. As a gravitational wave detector, two end masses (mass m_o each) are connected by a long, thin cable (length L) to form a dumbbell antenna with a spring at its center (fundamental longitudinal resonance frequency $\omega_o/2\pi$ and quality factor Q). As it orbits the earth, the cable would be stretched radially by the earth's tidal gravitational field. Gravitational waves would pull the masses apart and together in a oscillatory fashion. Their motion would be transmitted to the spring by the cable and a sensor would monitor the spring's resulting motion. Due to the relatively large motion produced in the spring, the sensor noise is deemed negligible, thus making the skyhook a broadband detector.

Four serious noise sources have been identified for the skyhook: Nyquist noise produced by the fluctuating part of the skyhook's internal dissipation, fluctuations in the cable length produced by fluctuations in solar and earth heating, fluctuating forces due to the gravity gradients of the high harmonics of the earth, and fluctuating electric and magnetic forces. In order to have a detection bandwidth of 10 mHz to 100 mHz, one could choose $m_o = 20$ kg, $L = 25$ km, $\omega_o/2\pi = 35$ mHz and $Q = 10^5$. The Nyquist noise expressed in gravitational-wave units is

$$h_N = \left(\frac{32}{\pi} \frac{kT\omega_o}{mL^2\omega^3 Q} \right)^{1/2} = 3 \times 10^{-17} \left(\frac{f}{30 \text{ mHz}} \right)^{-3/2} .$$

In order to keep the noise due to fluctuations in heating below this level, the fractional oscillation in irradiating heat flux must either be below 3×10^{-6} or be monitored to this sensitivity by an instrument on board the skyhook. The gravity gradient noise could be made negligible by choosing an altitude greater than 1,000 km. A nonconducting cable is proposed to minimize the effect of electric and magnetic fields. During some micropulsations, the disturbance is expected to greatly exceed the level given by the Nyquist noise. Thus, it will be necessary to carry on board the skyhook one or more electric field probes to monitor the vertical gradient of the vertical electric field fluctuations. The skyhook altitude must also be chosen to be below 6,000 km to maximize the time spent in quiet E-field regions.

The skyhook could be a relatively inexpensive broadband earth-orbiting detector, with sensitivity $h \cong 3 \times 10^{-17}$ in the frequency band 10 to 100 mHz, intermediate between present detectors (spacecraft Doppler tracking and earth modes) and the envisioned interferometric systems.

II. FISH-EYE GRAVITATIONAL WAVE TELESCOPE

Present Weber-bar antennas, laser interferometers, and Doppler tracking systems are all single-degree-of-freedom detectors of gravitational waves. As a result, many detectors in various orientations have to be used in coincidence to discriminate against nongravitational disturbances and to construct the direction of the source and the polarization of the waves. This problem could be overcome by using a resonant-mass detector whose modes exhibit the highest degree of degeneracy; *i.e.*, a spherically symmetric mass. A sphere has five degenerate quadrupole modes. By measuring the amplitudes of these five modes simultaneously, one could determine the four unknowns: the source direction (θ, ϕ) and the amplitudes of two independent polarizations of the wave $(\psi_+, \psi_\times)$. The remaining fifth degree of freedom could be used to reject nongravitational disturbances. The monopole mode of the sphere could also be monitored to have further anticoincidence rejection and to test theories, such as the Brans-Dicke theory, that predict existence of a scalar wave. The sphere is equally sensitive to waves coming from any direction, due to its symmetry, thus making the antenna a unique "fish-eye gravitational wave telescope."

Operation of such a spherical detector in a terrestrial laboratory is hampered on account of the difficulty of supporting the system against gravity without violating the spherical symmetry. In space, the antenna can float inside a spacecraft, providing excellent vibration isolation without disturbing the mode characteristics of the sphere. It is, however, difficult to improve the sensitivity of a lumped resonant-mass detector much beyond those of earth-based detectors due to a practical limit in putting a large mass into an earth orbit.

We consider, as an example, an aluminum sphere with radius (R) of 1.2 m, which will have a mass (M) of 2×10^4 kg and the quadrupole mode frequency $(\omega_2/2\pi)$ of 1 kHz. The quantum-limited sensitivity of this detector is

$$h_{QL} = \left(\frac{2\hbar}{M\omega_2 R^2}\right)^{1/2} \cong 10^{-21}$$

By cooling the antenna to 1 K and efficiently matching its output to a quantum-limited SQUID, one could achieve this sensitivity. If the sensitivity of $h \cong 10^{-21}$ is found to be sufficient to detect bursts of gravitational waves, an orbiting gravitational wave observatory carrying a fish-eye telescope could be constructed.

REFERENCES

Braginsky, V. B., and Thorne, K. S. 1985, *Nature*, **316**, 610.

Colombo, G., Gaposchkin, E. M., Grossi, M. D., and Weiffenbach, G. L. September 1984, "Shuttle-borne Skyhook: A New Tool for Low-Altitude Research," Smithsonian Astrophysical Observatory Reports in Geoastronomy, No.1.

Forward, R. L. 1981, *Gen. Rel. and Grav.*, **2**, 149.

Wagoner R. V., and Paik, H. J. 1977, in *Experimental Gravitation* (Academia) (Nazionale dei Lincei, Rome).

DISCUSSION

SHAPIRO: What analysis has been carried out (re: the proposed skyhook gravitational wave detector) to show that the (broad band) plasma processes in the vicinity of the skyhook will not cause serious problems?

PAIK: The disturbance by the ambient electromagnetic field has been considered. I am not sure whether the plasma processes have been fully analyzed.

SCHUTZ: Why do you only need to go down to 1°K? Isn't the noise at that temperature still larger than the quantum limit?

PAIK: It depends on the quality factor of the antenna and the bandwidth. For a detector with Q of 10^8 and a fractional bandwidth $\Delta f/f$ of 0.1, cooling to 1°K is enough to reach the quantum limit. If one cools down the antenna further, requirement on the transducer Q and coupling will be reduced.

ANDERSON: With regard to the skyhook, when we looked at this, we came to the conclusion that it was necessary to know the gravity gradient field of the Earth to 4 or 5 orders better than it is presently modelled. We therefore came to the conclusion that it might possibly work as a gravity gradiometer for earth gravity modelling--but not as a good gravitational wave detector. Is that so?

PAIK: In fact, Braginsky and Thorne point out that the skyhook is a very good gravity gradiometer for earth gravity. But, by putting the skyhook at high enough altitude, above 1,000 km according to their calculation, they bring down the effect of the earth's gravity gradient to the level of $h=10^{-17}$.

BERTOTTI: I wonder if the noise produced by the low order harmonics of the gravity field of the earth has been studied in the skyhook gravitational wave detector. Since the orientation of the wire will change, there is an additional change in tension due to unknown harmonics.

PAIK: Yes. This gravity gradient effect is attenuated exponentially as a function of altitude. There is a pendulum mode of the skyhook, which makes the end masses rock sideways. However, the additional time-varying tension due to this motion will be narrow-banded.

WEISS: Could you explain the relative merits in sensitivity and costs of putting a spherical antenna in space vs. putting cylindrical bar antennas on the ground. What cannot be done on the ground that must be done in space?

PAIK: In principle, five or six bar detectors oriented in proper directions may accomplish the same purpose as a spherical antenna. However, it may not be easy to support them against the Earth's gravity in various required orientations in three dimensions on Earth.