

# The Cassini Gravitational Wave Experiment

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## ABSTRACT

Doppler tracking experiments using the earth and a distant spacecraft as separated test masses have been used for gravitational wave (GW) searches in the low-frequency ( $\sim 0.0001$ - $0.1$  Hz) band. The precision microwave tracking link continuously measures the relative dimensionless velocity,  $\Delta v/c$ , between the earth and spacecraft. A GW incident on the system produces a characteristic signature in the data, different from the signatures of the principal noises. For 40 days centered about its solar opposition in December 2001, the Cassini spacecraft was tracked in a search for low-frequency GWs. Because of instrumentation upgrades on the spacecraft and on the ground, this joint NASA/ASI collaboration was the most sensitive Doppler tracking experiment to date. The improved sensitivity was mainly due to two technical upgrades. First, the use of a higher radio frequency tracking link (Ka-band, approximately 32 GHz), strongly suppressed noise from radiowave phase scintillation due to plasma irregularities along the line of sight. Second, the use of an advanced tropospheric calibration system allowed calibration/removal of most of the tropospheric phase scintillation. The new instrumentation should also allow broadening of the experiment's band to lower Fourier frequencies, where the GW sources radiate more strongly and may appear with larger SNR. These upgrades support not only the GW experiment, but also a Cassini relativity experiment at solar conjunction and the Cassini radio science experiments at Saturn. Here we describe the experiment, including the transfer functions of the signals and noises to the Doppler observable, and present the noise statistics and compare them with the pre-experiment noise budget.

## 1. LOW-FREQUENCY GRAVITATIONAL WAVES AND THE DOPPLER TECHNIQUE

A very thorough review of gravitational radiation, including detection techniques and expected wave strengths, is given in Ref. 1. Briefly, in General Relativity gravitational waves (GWs) are propagating, polarized gravitational fields which change the distance between separated test masses and shift the rates at which separated clocks keep time. They are characterized by a dimensionless strain amplitude,  $h = \Delta L/L \sim \Delta v/c$  where  $L$  is the fiducial distance between the masses and  $\Delta v$  is the change in relative speed of the test masses caused by the GW. Like electromagnetism, GWs are transverse, have two independent polarization states and propagate at the speed of light. Unlike electromagnetism, GWs are extremely weak. This extreme weakness has two consequences. First, GWs are only generated at potentially detectable levels by extremely massive objects undergoing extremely violent dynamics, i.e. by astrophysical sources. Second, because of the extreme weakness there is negligible scattering or absorption by intervening matter. GWs thus preserve information about the generation of the waves in the deep interiors of astrophysical sources, not about the last scattering surface.

Detection methods depend on the time scale of the radiation<sup>1</sup>. At high frequencies ( $f > 10$  Hz), resonant bars and laser interferometers are used. In resonant bars the GW excites an acoustic wave which is read out with a transducer. In laser interferometers the test masses at the ends of the interferometer arms are perturbed as the GW passes, giving rise to a change in relative arm length and thus a fringe shift. For frequencies lower than about 10 Hz, it becomes prohibitively difficult to isolate any ground-based apparatus from seismic noise and time-variable environmental gravity gradient noise. To search for this longer wavelength radiation all test masses must be put into space.

Until the LISA-era, Doppler tracking of distant spacecraft will continue to be the only broad-band detection method in the low-frequency band. In the Doppler tracking method<sup>2</sup>, the earth and spacecraft act as free test masses. An almost monochromatic radio signal is transmitted from the ground, phase-coherently transponded at the spacecraft, and received on the ground. By comparing the frequencies of the transmitted and received signals the Doppler tracking system measures the relative dimensionless velocity  $2\Delta v/c = \Delta f/f_0$  between the Earth and the spacecraft. A gravitational wave of amplitude  $h$  incident on the system causes Doppler perturbations of order  $h \approx \Delta v/c$ . The waveform is replicated three times in the tracking record<sup>2</sup>. The sum of these three perturbations in the Doppler record is zero; thus the low-frequency band edge is set by pulse cancellation to be  $\sim 1/T_2$  where  $T_2$  is the two-way light time. (This low frequency band "edge" is soft, however; the Doppler response to a signal of duration  $\tau > T_2$  is proportional to  $T_2/\tau$ , giving degraded but non-negligible coupling of the signal even to very low frequencies.) The high frequency band limit is set mainly by the stability of the frequency standard driving the link and by finite signal-to-noise ratio on the downlink. Thus to perform a low-frequency experiment, one needs a large earth-spacecraft distance (for good response to the lowest frequencies), the spacecraft in cruise and as operationally quiet as possible (far from perturbing masses and with minimal unmodeled motion of the spacecraft); high radio frequency and/or multiple links/tropospheric calibration to cancel or calibrate out charged particles/troposphere; and a highly stable ground system driven by a high-stability frequency standard.

## 2. SIGNAL AND NOISE TRANSFER FUNCTIONS

Attempts to detect GWs must deal with other variations in the Doppler record. After all deterministic effects (such as orbital signature) have been removed, the principal sources of variability in the Doppler record are: frequency and timing system (FTS) noise; propagation noise (an extended medium--the solar wind--and media which are localized very close to the antenna--ionosphere and solar wind); thermal noise in the receiver; ground antenna unmodeled motion; ground electronics and FTS distribution; spacecraft transponder noise; spacecraft buffeting; gravitational radiation; and systematic errors. These Doppler variations enter the observable via transfer functions<sup>2,3</sup> which are in general different from the three-pulse response function of the system to gravitation radiation. If "\*" indicates convolution, the time series can be modeled as:

$$y(t) = \Delta f(t)/f_0 = \begin{aligned} & \text{solar wind plasma}(t) * [\delta(t) + \delta(t - T_2 + 2x/c)] + \\ & \text{ionospheric plasma}(t) * [\delta(t) + \delta(t - T_2)] + \\ & \text{troposphere}(t) * [\delta(t) + \delta(t - T_2)] + \\ & \text{ground station mechanical motion}(t) * [\delta(t) + \delta(t - T_2)] + \\ & \text{FTS}(t) * [\delta(t) - \delta(t - T_2)] + \\ & \text{ground electronics}(t) + \\ & \text{receiver thermal}(t) + \\ & \text{spacecraft transponder}(t) * \delta(t - T_1) + \\ & \text{spacecraft buffeting}(t) * \delta(t - T_1) + \\ & \text{gravitational waves}(t) * [(\mu-1)/2] \delta(t) - \mu \delta[t-(1/2)(1+\mu)T_2] + [(1+\mu)/2] \delta(t - T_2) + \\ & \text{systematic errors}(t) \end{aligned}$$

where  $T_1$  and  $T_2$  are the one- and two-way light times to the spacecraft,  $x$  is the distance of a solar wind plasma cloud from the earth, and  $\mu$  is the cosine of the angle between the GW wavevector and a vector with its foot at the earth and its arrow at the spacecraft. The tensor gravitational wave,  $h(t)$  produces a scalar response,  $y(t)$ , in the Doppler time series (which is then convolved with the three-pulse response, above) according to<sup>4</sup>  $y(t) = (1/2) [\mathbf{n} \cdot \mathbf{h}(t) \cdot \mathbf{n}]/(1 - \mu^2)$ , where  $\mathbf{n}$  is the unit vector between the earth and the spacecraft.

Solar wind and ionospheric plasma noises are dispersive (refractive index proportional to wavelength squared<sup>5</sup> and can be suppressed by observing at higher radio frequencies or removed via multi-frequency link observations<sup>6</sup>. Tropospheric scintillation is nondispersive. Antenna mechanical noise is caused by slight physical deformations of the antenna which