Astronomy and Astrophysics Supplement Series, Ulysses Instruments Special Issue, Vol. 92, No. 2, pp. 431-440, Jan. 1992.

Astron. Astrophys. Suppl. Ser. 92, 431-440 (1992)

ASTRONOMY & ASTROPHYSICS
SUPPLEMENT SERIES

JANUARY 1992, PAGE 431

Astron. Astrophys. Suppl. Ser. **92**, 431-440 (1992)

The gravitational wave experiment

B. Bertotti[1], R. Ambrosini[2], S.W. Asmar[3], J.P. Brenkle[3], G. Comoretto[4], G. Giampieri[1], L. Iess[5], A. Messeri[5] and H.D. Wahlquist[3]

[1] Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, Pavia, Italy
[2] Istituto di Radiostronomia, Bologna, Italy
[3] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA
[4] Osservatorio Astrofosico di Arcetri, Firenze, Italy
[5] Istituto di Fisica dello Spazio Interplanetario, Frascati, Italy

Received April 5; accepted April 17, 1991

Abstract. — Since the optimum size of a gravitational wave detector is the wave length, interplanetary dimensions are needed for the mHz band of interest. Doppler tracking of Ulysses will provide the most sensitive attempt to date at the detection of gravitational waves in the low frequency band. The driving noise source is the fluctuations in the refractive index of interplanetary plasma. This dictates the timing of the experiment to be near solar opposition and sets the target accuracy for the fractional frequency change at 3.0×10^{-14} for integration times of the order of 1000 sec. The instrumentation utilized by the experiment is distributed between the radio systems on the spacecraft and the seven participating ground stations of the Deep Space Network and Medicina. Preliminary analysis is available of the measurements taken during the Ulysses first opposition test.

Key words: gravitational waves — solar wind — Doppler measurements.

1. Introduction.

According to relativistic theories of gravitation, gravitational waves will be emitted by most time-varying distributions of matter and energy. The waves are extremely weak and would normally be undetectable experimentally, but sufficiently strong waves can be emitted by very large masses which generate relativistic gravitational fields, or which move with high, near-relativistic, velocities. A variety of known astrophysical objects should be sources of potentially detectable waves : close compact binary stars, supernovae, and the explosive galaxies observed in quasars and active galactic nuclei. More speculative sources include oscillating supermassive black holes formed by gravitational collapse, black hole binaries, and a cosmic background of stochastic gravitational waves that might have been emitted during early epochs in the evolution of the universe (Smarr 1979).

Experimental attempts to detect gravitational waves were initiated in the 1960's, and since then much effort has been devoted to refining the methods to improve sensitivities (Thorne, 1987). Most observers agree that direct detection has not yet been achieved, but they would also agree on the importance of the goal. A successful outcome would verify the most characteristic feature of relativistic gravitation, could discriminate among the alternative theories some of which differ in the properties predicted for the waves, and so would confirm (or disconfirm) general relativity, one of the most fundamental theories of physics. It has also been emphasized many times that viewing the cosmos with gravitational waves would open a new astronomical window allowing observations which are not possible with other signals. Because of their extraordinary weakness gravitational waves are not scattered, absorbed, or deformed in any significant way by ordinary matter which lies in the path to an observer. As a result they would deliver undistorted information about the interior dynamics of relativistic events which are totally obscured by intervening matter from electromagnetic, and even neutrino, observations.

One of the nagging problems for detection experiments is that theoretical estimates of the wave forms, spectral content, and the total amount of gravitational radiation emitted by most of the potential sources are very uncertain (often by several orders of magnitude for the total energy emitted). This is primarily due to the complex dynamics of the sources, as well as to inadequate observational knowledge of the detailed internal structure and motions required to estimate the gravitational luminosity

Send offprint requests to: S.W. Asmar.

(knowledge which may, in fact, be unobtainable except from gravitational wave observations). The only exception to this is compact binaries; in this case the dynamics are sufficiently simple and the observations sufficiently good (especially for binary pulsars) to be able to make theoretical predictions with high precision. While sensitivities have greatly improved, they are still well below the detection threshold for any known objects, such as binaries, whose wave forms and amplitudes can be calculated with confidence. As a consequence, the experimental detection of gravitational waves must be approached as a long-term, evolutionary, program with two aspects: firstly, continuing the development toward detectors with better sensitivity; and secondly, conducting exploratory searches for strong gravitational waves from unknown or unexpected cosmic sources, or perhaps from known objects whose emission cannot be accurately predicted.

The objective of the gravitational wave investigation on Ulysses is to search for low frequency gravitational waves crossing the solar system using the spacecraft Doppler detection method. Because of the great distance to the spacecraft, this method is most sensitive to wave periods between about 100 sec. and 8000 sec., a band which is not accessible to ground-based experiments which are superior for periods below 1 sec. The Ulysses investigation provides several advantages over previous Doppler experiments (see, e.g., (Hellings *et al.* 1981)) which have been limited by observational runs of short duration and by lower sensitivity: (1) it incorporates a higher frequency (X−band) downlink tracking signal so that some noise effects are decreased; (2) it will take advantage of the continuing improvement in the frequency stability of the ground tracking stations of the Deep Space Network (DSN), together with additional tracking support from the highly stable, $VLBI$ and radio astronomy antenna at Medicina in Italy; (3) it has a planned observation sequence of 28 days duration which will provide greater frequency resolution for detection of long-period periodic waves and a higher probability for detection of any occasional gravitational wave bursts from impulsive events.

This investigation will also further the development of the Doppler technique in preparation for subsequent experiments on future planetary missions, such as Galileo and CRAF/Cassini, which will incorporate important advances in the technology of precision Doppler tracking. Thus, the Ulysses gravitational wave experiment is both the most sensitive search for long-period gravitational waves ever accomplished up to the present and an important step along the path toward experiments with greater sensitivity.

2. Doppler detection of low-frequency gravitational waves.

Gravitational waves can be described as strain waves which propagate through space at the speed of light. The wave is represented by a dimensionless symmetric 3-tensor,
$h_{ij}(x,t)$, giving the perturbation of the spatial metric, such that the effect of the wave on any two nearby points is to produce a small time-varying change in their separation $x^i = x_1^i - x_2^i$

$$\delta x_i(t) = \frac{1}{2} h_{ij} x^j \tag{1}$$

In Einstein's theory, gravitational waves are transverse and traceless, so h_{ij} can be written in terms of just two independent polarizations, e^+_{ij} and e^x_{ij} as

$$h_{ij} = h_+ e^+_{ij} + h_x e^x_{ij}$$

where h_+ and h_x represent the corresponding polarization amplitudes. The polarization tensors both satisfy the transverse, traceless conditions

$$e_{ij} k^j = 0 \quad \text{and} \quad e^i_j = 0$$

where k^i is the propagation direction of the wave. Physically, these conditions mean that there is no effect on points separated in the longitudinal direction k^i (Eq. 1), and in transverse directions (in the wavefronts) areas are preserved, i.e., in general relativity gravitational strain waves are actually volume-preserving shear waves (Misner, *et al.*, 1973).

In the spacecraft Doppler tracking method, the earth and a distant spacecraft constitute the two objects whose time-varying separation is monitored to detect a passing gravitational wave. The monitoring is accomplished with high-precision Doppler tracking in which a constant frequency microwave radio signal is transmitted from the earth to the spacecraft (uplink); the signal is transponded (received and coherently amplified) at the spacecraft; and then transmitted back to earth (downlink). The downlink signal is recorded at earth and its frequency is compared to the constant uplink frequency ν_0 to extract the Doppler signal, $\delta\nu/\nu_0$. Since the separation of the earth and spacecraft may be very large, the effect of a gravitational wave on the Doppler signal cannot be determined by using the approximation of Equation (1) which is valid only for nearby points.

A detailed treatment (Estabrook and Wahlquist, 1975) shows that the Doppler signal, $y(t) = \delta\nu/\nu_0$, produced by gravitational waves is given by,

$$\begin{aligned} Y(t) = -\frac{1}{2}(1-\mu)\phi(t) - \mu\phi(t-(1+\mu)\ell/c) \\ +\frac{1}{2}(1+\mu)\phi(t-2\ell/c) \end{aligned} \tag{2}$$

where $\mu \equiv \cos\theta = k^i n^i$ with θ being the angle between k^i and n^i, the unit direction vector of the Doppler link from earth to the spacecraft, a distance ℓ away. Here, $\phi(t)$ is the amplitude of the tensor gravitational wave projected onto the Doppler link

$$\phi(t) = \left(1 - \mu^2\right)^{-1} h_{ij} n^i n^j$$

This characteristic transfer function has some notable features which lead to important requirements for the investigation.

Firstly, the amplitude of the Doopler signal is essentially equal to the gravitational wave projected amplitude $\phi(t)$, up to the geometrical coefficients of order 1. Thus, we have a non-resonant, broadband detector whose geometry-dependent response function can give information about the direction to a source, the polarization properties of the wave, and the detailed wave-form of a gravitational signal. It can also be used to help discriminate gravitational signals from other effects (Armstrong, 1989). In order to take advantage of these properties, however, it is necessary to have long, continuous, 2-way, Doppler tracks extending over many round-trip-light-times (RTLT), $2\ell/c$.

Secondly, the Doppler signal produced by a gravitational wave is zero if k^i and n^i are collinear ($\mu = \pm 1$), again as a consequence of the transverse nature of the waves. Thus, as a gravitational waves detector, the Doppler link has a null response for all frequencies in two particular directions (and also for particular frequencies in any direction), so it is important to repeat the experiment at different epochs (or with different spacecraft), where the geometric relationship to possible cosmic sources may be different.

Thirdly, the sum of the geometrical coefficients of the $\phi's$ in Equation (2) is zero. For wavelengths much longer than 2ℓ (or equivalently, periods much greater than the RTLT), the ϕ's in Equation (2) will become nearly equal and the three terms will tend to cancel out. To sense long-period waves then, we need the spacecraft as distant as possible, while maintaining a sufficiently strong downlink radio signal. The Ulysses mission is ideal in this respect since the spacecraft spends a considerable period of cruise time at large distances from earth.

The effect of a gravitational wave pulse on the Doppler signal from a spacecraft is illustrated in Figure 1. As shown, the wave pulse appears three times in the Doopler record, corresponding to the events of emission and reception of the tracking signal at the earth, and to the retarded time of the transponding event at the spacecraft. The relative amplitudes and time intervals of the three Doppler pulses are determined by the geometrical relationship of the Doppler link to the propagation direction and polarization of the gravitational wave, as given by Equation (2).

3. Noise sources.

The principal sources of noise can be grouped in two classes: those due to the electronic components of the instrumentation onboard the spacecraft and on the ground and those due to the media. The former class is described in Section 4; the latter can be expressed in terms of changes in the total optical path length $\Delta\ell$, defined in terms of the refractive index n by:

$$\Delta\ell = \int \mathrm{d}s\ n$$

so that:

$$\Delta y = \mathrm{d}\Delta\ell / c\mathrm{d}t.$$

There are three contributors to changes in the optical path length. They are: (a) the troposphere, (b) the ionosphere and (c) the solar wind plasma. To appreciate the problem at hand, note that the target accuracy of the experiment, 3.0×10^{-14} at an integration time of 1000 seconds, corresponds to a change of one centimeter in $\Delta\ell$. The tropospheric contribution does not depend on the carrier frequency and cannot be easily distinguished from the gravitational signal, making it particularly difficult to calibrate. It is made up two different terms: the first, given by the integral of the atmospheric density along the path, is proportional to the barometric pressure on the ground in conditions of hydrostatic equilibrium. It produces a change in the optical path which is a function of the elevation and can be fitted away with a suitable atmospheric model. In the first opposition experiment a two parameter exponential model of the atmosphere was used. The changes in this term during a typical station pass can be deduced from measurements of the ground pressure. The second term is proportional to the water vapor content along the ray and, although smaller than the first, is potentially more dangerous because of its variability and unpredictability. Its low level, however, corresponding to about 10^{-14} in the observable and thus below the target accuracy, justifies its neglect in the Ulysses experiment.

The other two contributions are proportional to the electron content along the ray in the ionosphere and the solar wind plasma. Since the refractive index of a low density plasma differs from unity by a term proportional to the square of the wave length of the carrier, they could be eliminated if two carriers were available at two different frequencies. The Ulysses radio system indeed has $S-$ and $X-$bands in the downlink, but only $S-$ band in the uplink. With this "incomplete" system it is possible to measure only the electron content in the downlink, proportional to

$$y_s \nu_s^2 - y_x \nu_x^2$$

and to obtain the sum of the non-dispersive contribution to y (which includes gravitational waves) and the uplink plasma contribution, which is half the total. It turns out that the latter term is much larger than the limiting accuracy of the measuring system for a generic interplanetary spacecraft. However, it has been observed experimentally, and confirmed theoretically, that when the angle between the spacecraft and the anti-solar direction is less than about 10 degrees, the interplanetary contribution is about one order of magnitude less than for generic values of that angle. This is a consequence of the highly supersonic character of the solar wind, which carries along any perturbation in electron density. If the radial solar wind speed is approximately parallel to the ray, any perturbation stays for a long time within the beam and affects the optical path only at frequencies below the relevant band. This dictates both the favorable epoch and the target accuracy for the experiment, i.e. 3.0×10^{-14} for an integration time of the order of 1000 seconds. The ionospheric noise contributes less in this frequency band, even near opposition. The quantitative estimates of the principal noise sources have been combined to give the expected noise spectrum at the first opposition as shown in Figure 2 (Armstrong *et al.*, 1979; Armstrong & Sramek, 1982; Brenkle 1985).

Both the tropospheric and the ionospheric fluctuations differ from site to site, while the interplanetary plasma content of two beams detected at different places is the same. This has suggested the simultaneous use of two receiving stations, as a means to investigate and reduce the local sources of noise and at the same time increasing the amount of acquired data (Iess *et al.* 1987). When the spacecraft is tracked from a station at the Madrid DSN complex the signal is also received at Medicina, thus providing at those times four different observables.

The question arises, since the uplink solar wind plasma is the major noise source in this experiment, is it possible to estimate it from the known downlink electron content? That depends on the signal frequency. Consider two photons, one arriving and one departing the ground station at the same time. They traverse the region within one astronomical unit, where most of the solar wind plasma lies, at times differing by about 1000 sec., thus encountering different electron densities. The corresponding contributions to the optical paths, however, are estimated to be nearly the same for frequencies less than 1 mHz. A rigorous solution of this problem, confirming this estimate, is provided by a formal mathematical estimator, based upon the statistical properties of the solar wind turbulence (see "Doppler tracking of spacecraft with multi-frequency links" by Bertotti, Iess and Comoretto, in preparation). This provides a filtering procedure which will be applied in the data analysis.

4. Instrumentation and doppler extraction system description.

The instrumentation utilized by the Gravitational Wave Experiment is distributed between the Ulysses spacecraft and the ground stations. An S−band signal is transmitted from a ground station to the spacecraft, which then transmits back to the station S− and X−band signals coherent with the uplink. Table 1 shows the frequencies and wavelengths associated with the labels "S−band" and "X−band." This radio communications link, which is used for commanding the spacecraft, receiving telemetry from it, and performing radio navigation, is also used as a science instrument.

The radio frequency system of the Ulysses spacecraft is configured for coherent dual frequency output (S− and X−band) for the Radio Science experiments of the mission. Two-way coherency of the downlink with the uplink is required for the geometry dependence of the experiment as discussed in section 2 and, from the instrumentation point-of-view, to take advantage of the superior phase stability of the ground station hydrogen maser frequency reference as opposed to the on-board free-running oscillator. Dual frequency downlinks are required in order to calibrate the interplanetary media which affects the two frequency bands differently, as explained in Section 3.

TABLE 1. *Ulysses radio Frequency Alocation.*

Link	Band	Frequency (MHz)	Wavelength (cm)
Up	S	2111.607253	14.2
Down	S	2293.148148	13.07
	X	8408.209876	3.57

The radio system consists of two redundant transponders each of which contains an S− band receiver, a modulator, a 5 watt S−band power amplifier, and an X−band exciter. The output of the X-band exciter of each transponder is cross coupled to two redundant traveling wave tube amplifiers which produce a 20 watt strong X−band signal. Either exciter may drive either or both tube amplifiers. Additional cross coupling in the system allows either receiver to drive either or both modulators. The output of each modulator is switchable to drive either the S−band power amplifier or the X−band exciter but not both. So, for the required Radio Science configuration of simultaneous S− and X−band downlinks coherent with the uplink, a selected receiver drives the modulators of both transponders; one modulator then drives the S-band power amplifier and the other drives the X−band exciter and a traveling wave tube amplifier. Modulation is used for telemetry and ranging; however, for critical portions of Radio Science experiments, modulation may be removed in order to maximize the carrier signal strength.

The downlink signals are transmitted via a high gain parabolic antenna aligned with the spin axis of the spacecraft and pointed to earth by a control system using attitude maneuvers. This control requires one attitude reference from a sun-sensor and another reference from conical scanning (CONSCAN) the uplink radio signal. This configuration causes the $S-$band feed of the antenna to be slightly offset from the spin axis.

Two operational spacecraft constraints potentially impact the experiment during solar oppositions. Limits on the minimum tolerable sun-probe-earth angle require careful strategies to maintain proper attitude control. Thermal limitations on-board the spacecraft may occasionally prevent activating dual frequency downlinks.

The worldwide communications complexes of NASA's Deep Space Network are an integral component of the Radio Science instrumentation (Asmar 1990). The network's 70 meter diameter and 34 meter diameter standard antennas are used to track the Ulysses spacecraft. These antennas are equipped with two types of receivers such that after the signal is amplified by the low noise amplifiers, it is received by the "closed-loop" receiver and, when required, also by the "open-loop" receiver. Frequency and timing signals supplied to the station's subsystems are referenced to a hydrogen maser frequency standard. At integration time of 1000 sec., the Allan deviation (a measure of short term frequency stability) of the maser is near 2×10^{-15}, significantly better the experimental target accuracy of $\sigma_y = 3.0 \times 10^{-14}$. The hydrogen maser standard provides reference signals to the closed-loop receivers as well as the local oscillators of the open-loop receiver, as shown in Figure 3.

The closed-loop receiver uses a phase-locked loop, with selectable loop bandwith, to track the carrier signal. The tracking system determines the Doppler shift by comparing the estimated frequency output of the phase-locked loop with a reference from the frequency and timing standard, which is also used to generate uplink carrier. Amplitude information is obtained by sampling of the phase-locked loop automatic gain control voltage.

The open-loop receiver, a superheterodyne receiver, filters and downconverts the carrier signal to baseband where voltages representing the electric field are sampled and recorded by a computer on magnetic tapes. The receiver, which has four channels at the 70 meter stations and two channels at the 34 meter stations, is tuned by frequency predictions based on estimates of the spacecraft transmitted carrier frequency and the Doppler shift. The receiver filters are selectable depending on the uncertainties in the predictions; a 100 Hz filter is used for this experiment. Of the six participating DSN stations, station 12 in Goldstone, California, is not equipped with an open-loop receiver. It is also ordinarily not equipped with a hydrogen maser but one was installed specifically for this experiment.

Due to the better phase stability of the open-loop receivers as well as the flexibility in processing the open-loop data, it is considered the primary data type for the Gravitational Wave Experiment. Doppler information is extracted from the open-loop data by signal detection using software digital phase-locked loop. The signal is scaled to sky frequency and then differenced with a Doppler profile constructed from the spacecraft trajectory information provided by the navigation team. The resulting residuals are further processed in search of signatures of gravitational waves. Note that the accuracy in reconstructing the spacecraft trajectory directly affects the sensitivity of the experiment. The sensitivity of the instrumentation and processing methods described above allow for achieving the goal of $\sigma_y = 3.0 \times 10^{-14}$ at 1000 sec. integration time. The limiting factors in instrumentation-related noise are the σ_y performance of the hydrogen maser and the inherent electronic thermal noise in the hardware, which, given sufficient signal-to-noise ratio is also within the target accuracy.

The largest contributor to the fractional frequency change, $\delta\nu/\nu$, is the Doppler effect produced by the relative motion between the spacecraft and the ground station. It is made up of terms due to earth orbits, earth rotation, spacecraft velocity, and spacecraft spin. The fractional frequency change due to earth orbit is on the order of 10^{-4} over a period of one year, which appears in the data, over a typical station pass, as a slow drift. The peak-to-peak daily change due to earth rotation is 3.1×10^{-6} for a round trip signal, which amounts to 1.9 Hz/second maximum, at $X-$band. The change due to the spacecraft motion is 4×10^{-5} for a period of 5 years, a negligible amount during the cruise phase of the mission. The spacecraft rotation introduces a small but constant bias assuming a perfect alignment of the spin axis with the line-of-sight. The earth rotation, therefore, is the largest contributor to the Doppler effect.

Although this effects is many orders of magnitude larger than the target accuracy of the measurement, it does not appreciably contribute to the noise because it mainly lies at frequencies outside the band of interest and is well understood. To illustrate, the typical phase-locked loop bandwiths for either real-time tracking or software post-processing are between 1 and 10 Hz. So, for a 1 Hz filter, for example, the $\delta\nu/\nu$ at $X-$band is 1.2×10^{-10} which implies, at first glance, that the filter is required to track a signal sweeping at much larger Doppler rates than its relative bandwith. This is accomplished because the Doppler effect is understood and can be predicted to high accuracy that the open-loop receiver is tuned via frequency predictions to remove this effect, and the uncertainty associated with the Doppler is indeed within the target accuracy.

In addition to the DSN antennas, the Medicina station near Bologna, Italy, tracks the Ulysses spacecraft in listen-only mode to acquire additional data for the experiment. This part of the instrument is managed by the

Istituto di Radioastronomia, and is primarily devoted to *VLBI* observations. The Medicina antenna uses a 32 meter diameter reflector, allowing operation up to 22 GHz. The receivers are those of the european and global *VLBI* networks and use cooled GaAs or HEMT FETs. The dual band (S and X) receiver, which is used for the Doppler measurements, is located in a thermostatically controlled box at the primary focus; the operating temperatures at zenith are 115 K at $X-$band and 125 K at $S-$band.

Phase stability, the critical requirement of gravitational wave experiments, has been an important criterion in the design of the receiver chains, in particular the phase calibration system, the microwave synthesizer and, most importantly, the hydrogen maser which controls all the reference frequencies. The MK-III data acquisition system is used to calibrate, sample, format and record the signal on tape. This system, used for *VLBI* observations, can also drive dedicated equipment such as the Digital Tone Extractor, DTE, which is used for tracking the Doppler tone of a spacecraft. The output of the MK-III system is a digitized radio signal with bandwith of 2 MHz, as well as very accurate timing information which is used by the DTE to synchronize the data and its internal digital synthesizer.

The DTE has the purpose of extracting amplitude and phase of a tone of known frequency even when it is buried in wide-band noise and drifts in frequency. It was originally developed at the Jet Propulsion Laboratory and a new version has been developed at the Istituto di Radioastronomia (Comoretto 1991). It includes a digital synthesizer, which generates two signals in quadrature with controlled phases, a multiplier and an integrator producing the sine and cosine components. The synthesizer and the multiplier converts the tone signal to nearly zero frequency and the integrator acts as a low-pass filter, reducing the effective bandwidth to a few hertz.

The DTE is programmed to the expected tone frequency; the measured phase change in two successive integrations is then used to correct the frequency prediction. This is, in effect, a high precision phase-locked loop which can follow any variation of the input frequency to a bandwidth of a few Hz (2.5 Hz in the first opposition test). The data are then recorded on disk. Despite its narrow band, the DTE can track signals with very large frequency drifts. If the drift is not known, it can follow it up to a rate of change of the frequency equal to $B^2/6$, where B is the instantaneous bandwidth. If, as is usually the case, the drift is approximately known, it can be followed up to $B^2/2$; B here is limited by the software to 2.5 Hz, so that the maximum drift is about 3 Hz/sec. The tracking software allows a constant offset and a slowly varying difference between the predicted and the received frequency. For two-frequency observations the control program tracks the signal only in one channel, usually the stronger $X-$band. Since the ratio between the two bands is fixed, the second DTE passively records a band around the derived frequency. Tow other channels are used to record the two tones needed to calibrate the receivers, with a total of four digital tone extractors.

5. The first opposition test.

An extensive test of the Gravitational Wave Experiment as well as the Solar Corona Experiment (Bird *et al.*, 1991) was performed from 3 December 1990 to 5 January 1991. Fourteen objectives were identified for the test (Asmar 1990). They include calibrating and characterizing the overall performance of the radio system, identifying and correcting malfunctions in the ground equipment, and assessing the noise sources to provide an experimental indication of the final sensitivity. 23 dual frequency passes from 6 DSN stations (stations 12 and 14 at Goldstone, 42 and 43 at Canberra, 61 and 63 at madrid) and 9 passes from Medicina were tracked, acquiring about 200 hours of closed-loop data, 150 hours of open-loop data and 120 hours of Medicina Digital Tone Extractor data. Nearly 50% of the data were acquired during 3.5 days of continuous tracking (from 17.30 UT Jan. 1 to 06.00 UT Jan. 5, (1991). The operational objectives of this period included testing the simultaneous 3-way tracking from Medicina and testing stations hand-over procedures, in preparation for the main experiment requiring 28 days of continuous tracking around the second opposition.

In general, the operational procedures, equipment configuration, and interfaces between Medicina and the DSN stations were performed satisfactorily and the test was considered a success. A complete report will be published to document the test results as well as the various minor problems encountered during station configuration and operations.

Due to the close range of the spacecraft, the signal-to-noise ratio, SNR, at the receiving antennas was high, in the range of 56 to 72 dB at $X-$band and 43 to 59 dB at $S-$band, depending on the size of the antenna and the receiver noise temperature. During the first part of the test, however, the nutation of the spacecraft caused large temporal variations (of the order of 20 dB at $X-$band) over 20 second time scales.

The data are at present being analyzed in order to characterize the stability of the Doppler signal. Preliminary results indicate that the target stability, Allan deviation of 3.0×10^{-14} at 1000 second integration times, is seldom reached, while an overall value of 6.0×10^{-14} is often attained. Generally, the system stability exhibited significant differences from pass to pass and from station to station, for reasons still under investigation. Figure 5 shows frequency residuals, not necessarily representative of the whole data set, acquired at Medicina at $S-$ and $X-$bands. The corresponding Allan deviation is shown in Figure 6. The slope of both curves is roughly consistent with a white frequency noise for frequencies exceeding 1 mHz.

Acknowledgements.

The gravitational wave experiment demands extensive and complex collaboration between many scientists and engineers in different organizations and countries. This was demonstrated during the first opposition test for which we thank those who assisted in making it a success. In particular, we thank the Ulysses Project management and Projection Scientists, the spacecraft and navigation teams, and the DSN personnel at JPL and at the stations. We especially appreciate the support of J. Armstrong, P. Bonifazi, C. Collins, P. Eshe, F. Estabrook, R. Garcia, C. Hamilton, R. Herrera, R. Horton, D. Meyer, D. Morabito, R. Rose, A. Vecchio, and B. White.

For the JPL authors, the research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

Armstrong J.W. "Spacecraft Gravitational Wave Experiments" in Gravitational Wave Data Analysis, B.F. Schutz Ed., (Kluwer Academic Publishers, Dordrecht, 1989)

Armstrong J.W., Sramek R.A. 1982, "Observations of tropospheric phase scintillations at 5 GHz on vertical paths," Radio Sci., 17, 1579

Armstrong J.W., Woo R., Estabrook F.B. 1979, "Interplanetary phase scintillation and the search for very low frequency gravitational radiation," Astrophys. J. 230, 570

Asmar S. "Radio Science Handbook" Vol. 1, Jet Propulsion Labotatory Internal Document D-7938, November 1990

Bird M.K., Asmar S.W., Brenkle J.P., Edenhofer P., Pätzold M. and Volland H. "The Coronal-Sounding Experiment," Astron. Astrophys. Supp., this issue

Brenkle J.P. "Interim Giotto, Ulysses and Galileo Doppler Stability - test results," Jet Propulsion Laboratory Internal Document (Interoffice Memorandum number 3394-85-193), 1985

Comoretto G. 1991. "Digital Tone Extractor control and utility programs" Arceti Technical Report N

Estabrook F.B. and Wahlquist H.D. 1975 "Response of Doppler Spacecraft Tracking to Gravitational Radiation", Gen. Rel. Gravitation 6, 439-447

Hellings R.W., Callahan P.S., Anderson S.D., Moffet A.T. 1981 "Spacecraft Doppler gravity wave detection. II Results," Phys. Rev. D, 23, 884

Iess L., Bonifazi P., Bertotti B. and Comoretto G. 1987 "Differential Doppler Tracking of Interplanetary Spacecraft," Il Nuovo Cimento. 10C, 235

Misner C.W., Thorne K.S. and Wheeler J.A. Gravitation, (W.H. Freeman, San Francisco, 1973)

Smaar L.L. Sources of Gravitational Radiation (Cambridge Univ. Press, 1979)

Thorne K.S. "Gravitational Radiation" in 300 Years of Gravitation S.W. Hawking and W. Israel Ed., (Cambridge: Cambridge University Press, 1987)

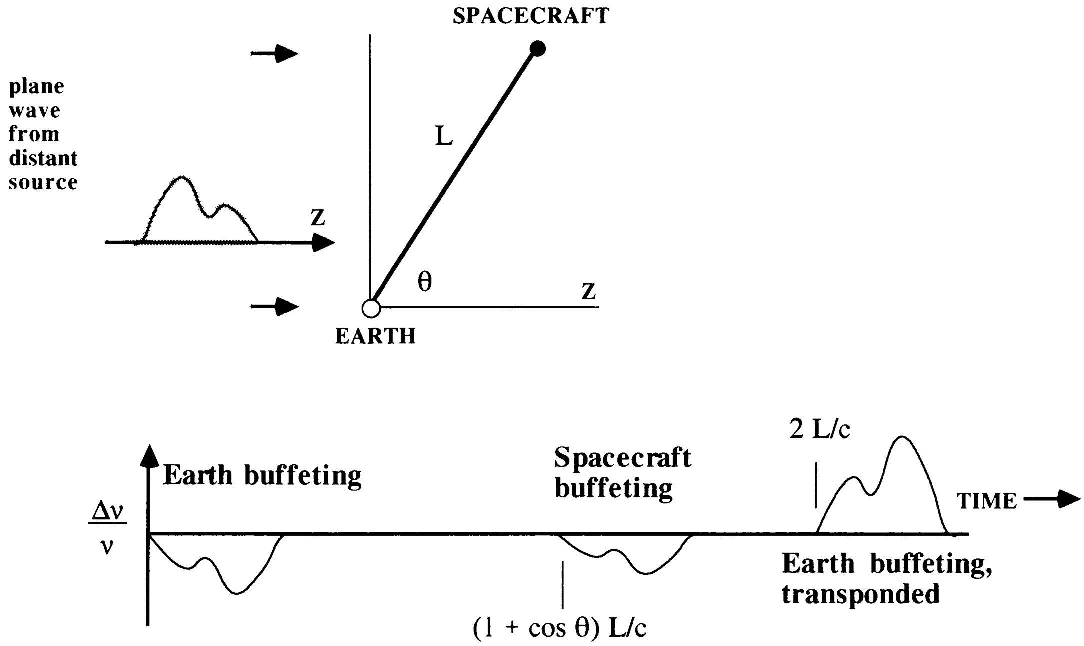

FIGURE 1. Gravitational Wave Detection: Spacecraft Doppler Tracking Method.

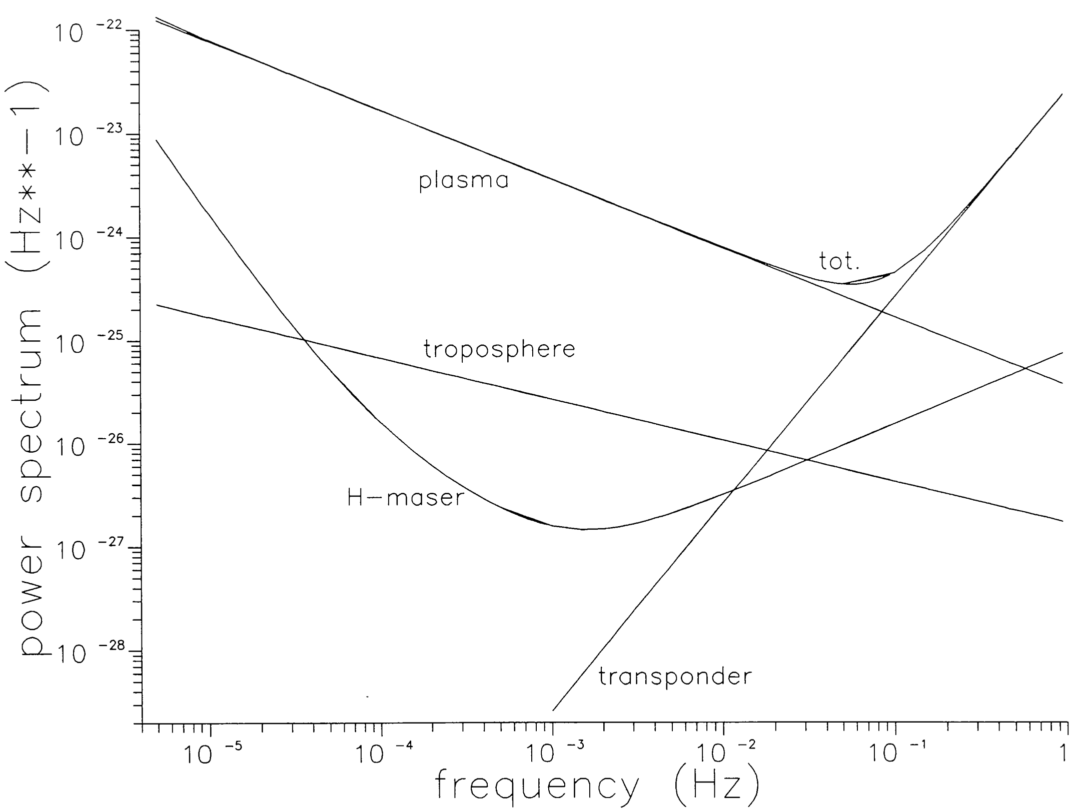

FIGURE 2. Expected Noise Spectrum for the First Opposition Doppler Measurements.

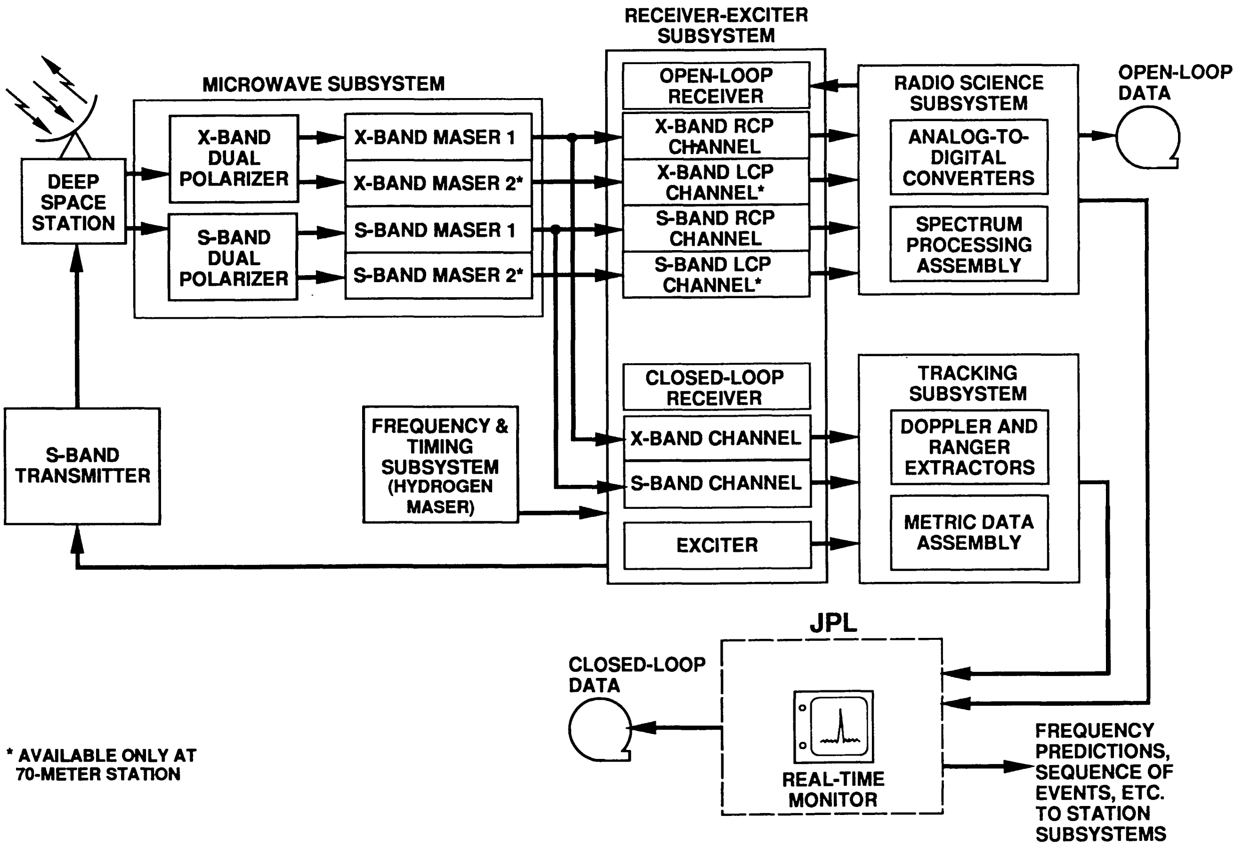

FIGURE 3. Ulysses Radio Science Ground Data System Functional Block Diagram.

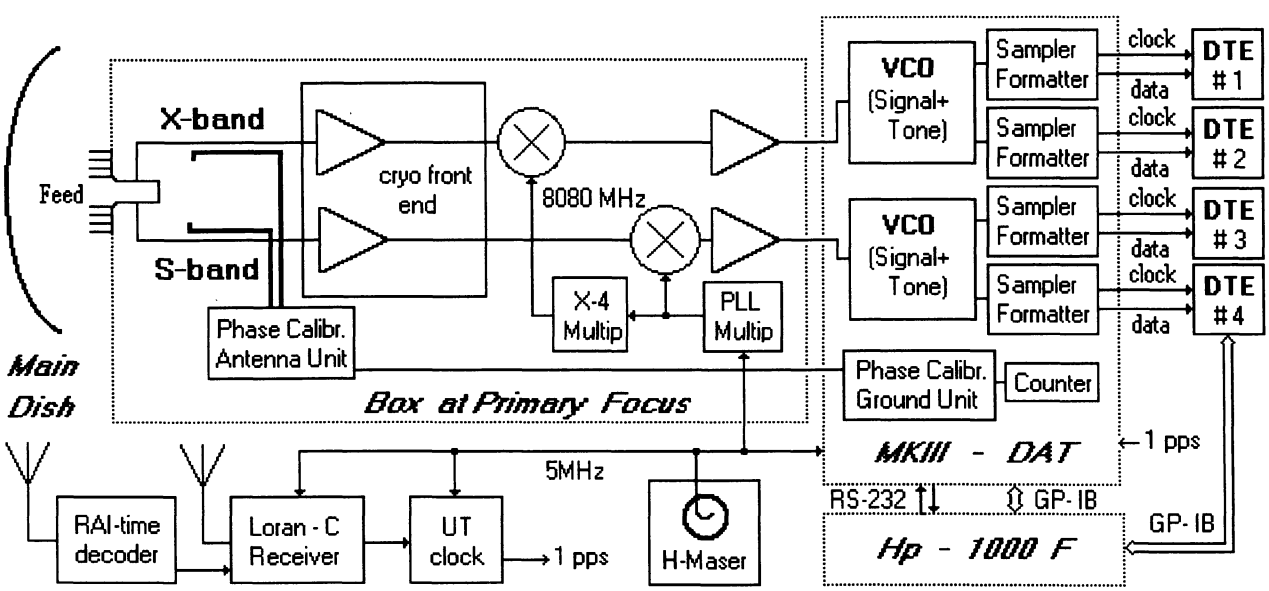

FIGURE 4. Medicina *VLBI* Data Acquisition System Typical Block Diagram.

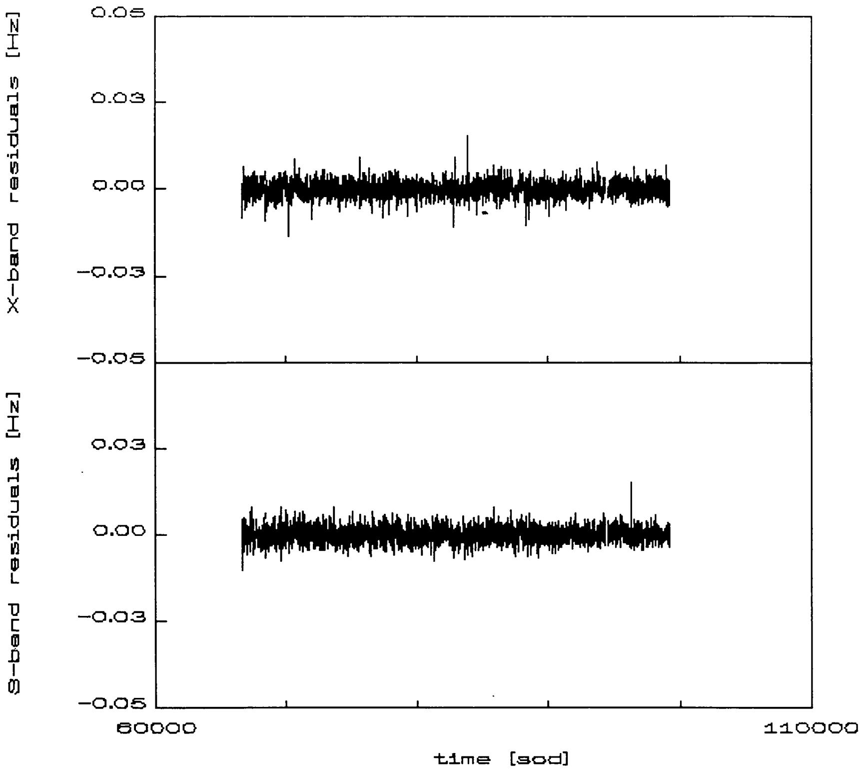

FIGURE 5. Frequency residuals collected at the Medicina *VLBI* antenna equipped with a digital tone extractor on January 2, 1991. Time is expressed in seconds past midnight. Upper curve: X−band, lower curve: S−band.

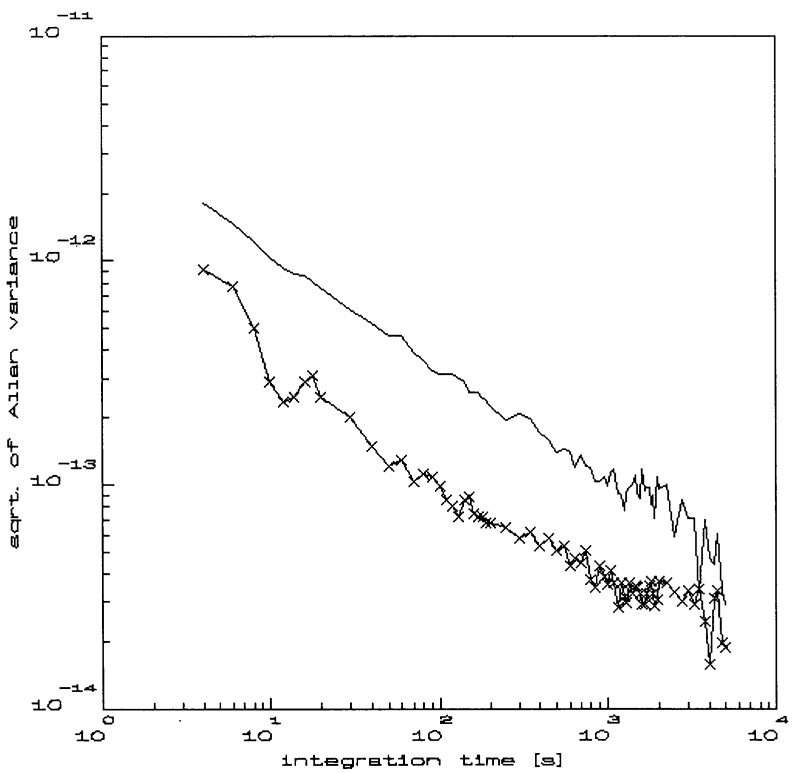

FIGURE 6. Allan Deviation of data shown in Figure 5. Upper curve refers to S−band, lower curve refers to X−band.