

THE ROLE OF THE DEEP SPACE NETWORK'S
FREQUENCY AND TIMING SYSTEM IN THE DETECTION OF
GRAVITATIONAL WAVES

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ABSTRACT

A review of the projected role of the Deep Space Network (DSN) in the planned detection of gravitational waves using precision doppler-tracking of deep space vehicles is presented. The review emphasizes operational and configurational aspects; considering: 1. the projected configuration of the DSN's Frequency and Timing System during the experiment, 2. the environment within the DSN provided by the precision atomic standards within the Frequency and Timing System--both current and projected and 3. the general requirements placed on the DSN and the Frequency and Timing System for both the baseline and the nominal gravitational wave experiments.

A comment is made concerning the current probability that such an experiment will be carried out in the foreseeable future.

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I. INTRODUCTION

A variety of astronomical events, both catastrophic and periodic, theoretically result in the generation of gravitational radiation. Of these, periodic events should generate periodic gravity waves while a catastrophic event (although it may be recurring) should result in emission of a "large" gravitational wave-burst.

An example of an event which may be generating periodic gravitational radiation is a star-pulsar binary pair. In such a case, a close examination of radio doppler data from the pulsar¹ may show a gradual decay of the pulsar's orbit and hence allow indirect confirmation of the existence of gravity waves.

Conversely, the gravitational wave bursts which are expected to result from "catastrophic" events such as the collapse of several solar masses of normal matter to form a black hole, may be directly observable by measuring the effect of their passage through the Solar System on some "local" experimental apparatus. Of the various experiments designed to observe such gravity wave bursts, one of the most promising involves the close examination of coherent doppler data which result from the tracking of deep space probes.

This paper will briefly discuss the anticipated effect of the passage of a gravity wave on an experimental configuration consisting of a Deep Space Tracking Station (DSS), a deep space probe and the coherent radio link between them. It will then review the configuration of a prototypical DSS in so far as it is involved with the experiment and in particular examine the varied ways in which the experiment depends upon the frequency stability performance 'environment' which the Frequency & Timing System provides. It will also note the performance constraints which the physical situation places on a DSS and a comparison will be made between these and the capabilities of the Deep Space Network; current (Mark III System), planned (Mark IV-A System) and anticipated (circa 1987-1990).

II. GRAVITATIONAL WAVES

As an idealization, gravitational waves may be envisioned as being small 'ripples' in the shape of spacetime which are propagating outward in all directions from their point of origin--whether periodic or catastrophic.² It is assumed in theoretical analyses of such events that the generators of the waves are at great distances from ourselves and that the gravity waves which are believed to pass through our Solar System are essentially planar. See figure 1 for a graphic representation of the experimental configuration.

In a suitable frame of reference³ (i.e., one which is soluble using the methods of general relativity) the earth and the spacecraft may be regarded as "fixed" and the entire effect of the gravitational wave placed upon the radio link between them. Theoretically, this effect may be regarded as the result of forcing the radio beam to travel through a "changing" spacetime. However, as a mnemonic device, the resultant effect on the experiment of the gravity waves' passage may be thought of in terms of three factors:

1. At Earth: Red-shifting of the frequency output by the Hydrogen Maser (clock speed-up.)
2. At Earth: Physical Buffeting (movement) of the DSS.
3. At Spacecraft: Physical Buffeting of the Spacecraft.

Each of these may be thought of as leading to the introduction of a distinctive, although minute, fluctuation (fractional frequency shift) in the measured doppler shift of the spacecraft. Together with the 'reflections' of effects 1 & 2, these form a unique three-pulse signature for gravitational wave events. See figure 2 for a detailed development of this signature; using this mnemonic device. (Appendix A contains a suggested enhancement of the single spacecraft/single DSS experiment discussed in the body of this paper.)

It results⁴ that for gravitational wave bursts originating from the collapse of normal matter to form a black hole that the amplitude of the burst is related to the burst duration according to:

$$(h) \approx (2 \times 10^{-17}) \times T / (90 \text{ seconds}),$$

where (h) = A dimensionless, polarization-averaged amplitude parameter
and T = The Burst Duration. See figure 3 for a plot of this relation.

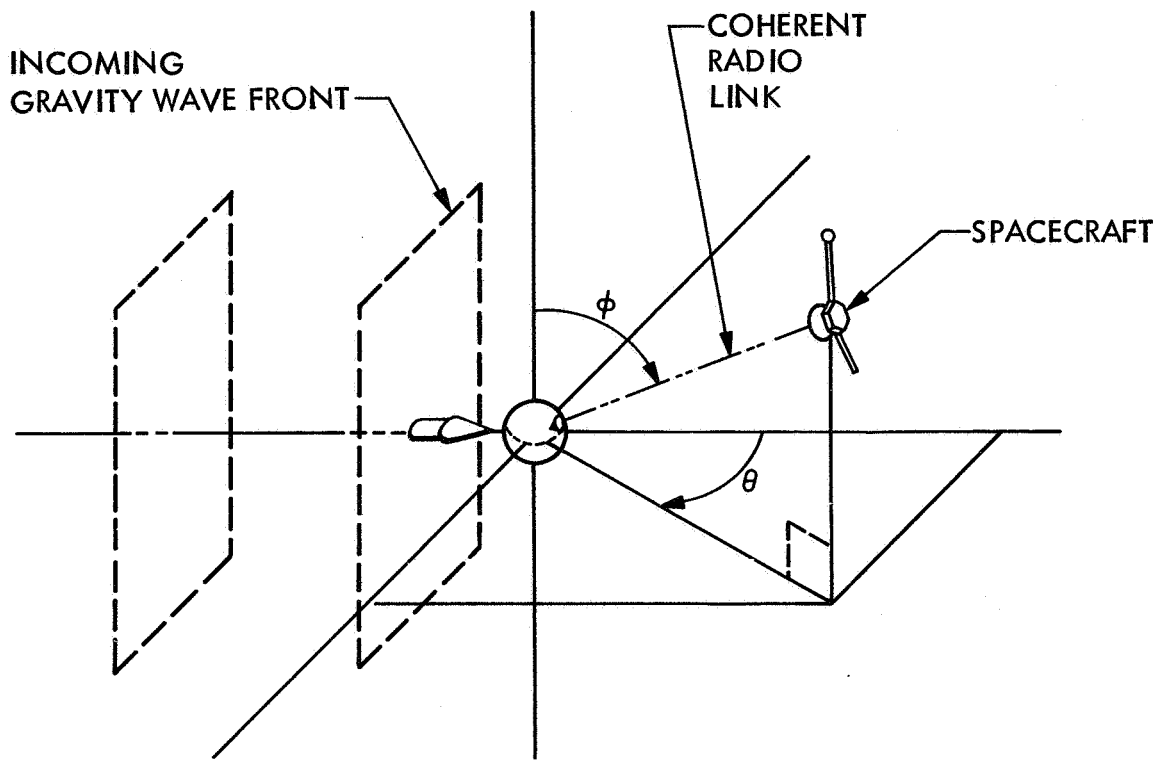
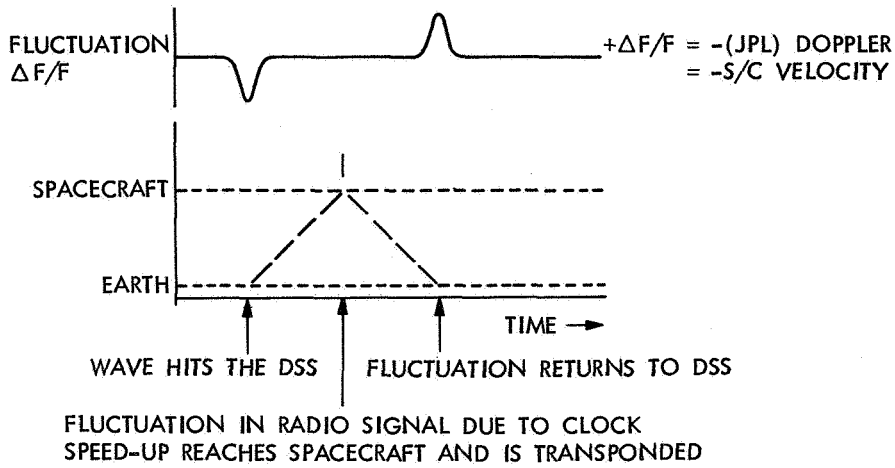
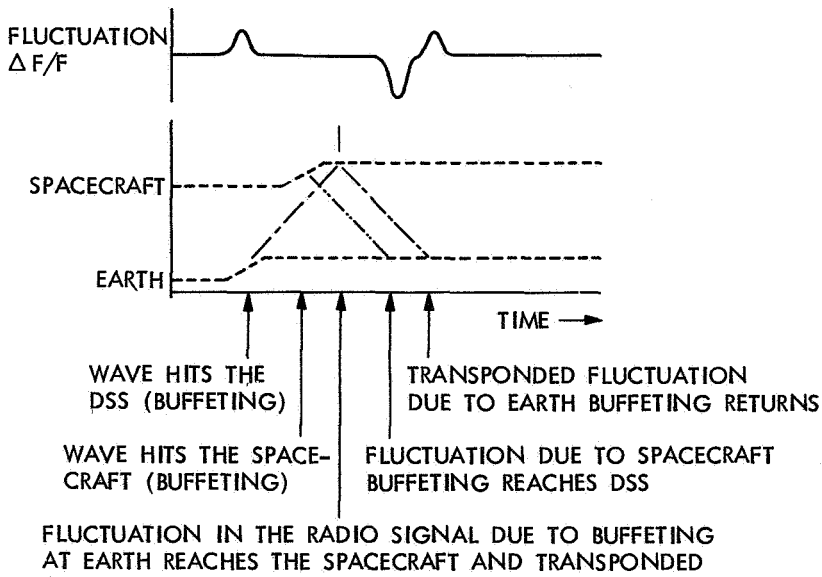


Figure 1. Gravitational Wave Experiment Tracking Geometry.
 Events: 1. Wave passes Earth (causing clock speed-up & buffeting)
 2. Wave passes Spacecraft (causing buffeting.)

1. CLOCK SPEED-UP EFFECT



2. EARTH/SPACECRAFT BUFFETING EFFECT



3. NET GRAVITY WAVE SIGNATURE ($\theta = 60^\circ$)

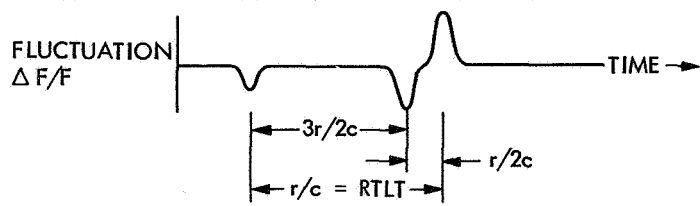


Figure 2. Details of Three-Pulse signature associated with gravity waves
 Note: In point 3, $\theta' = 60^\circ$ refers to the angle θ in figure 1 with $\phi = 90^\circ$.

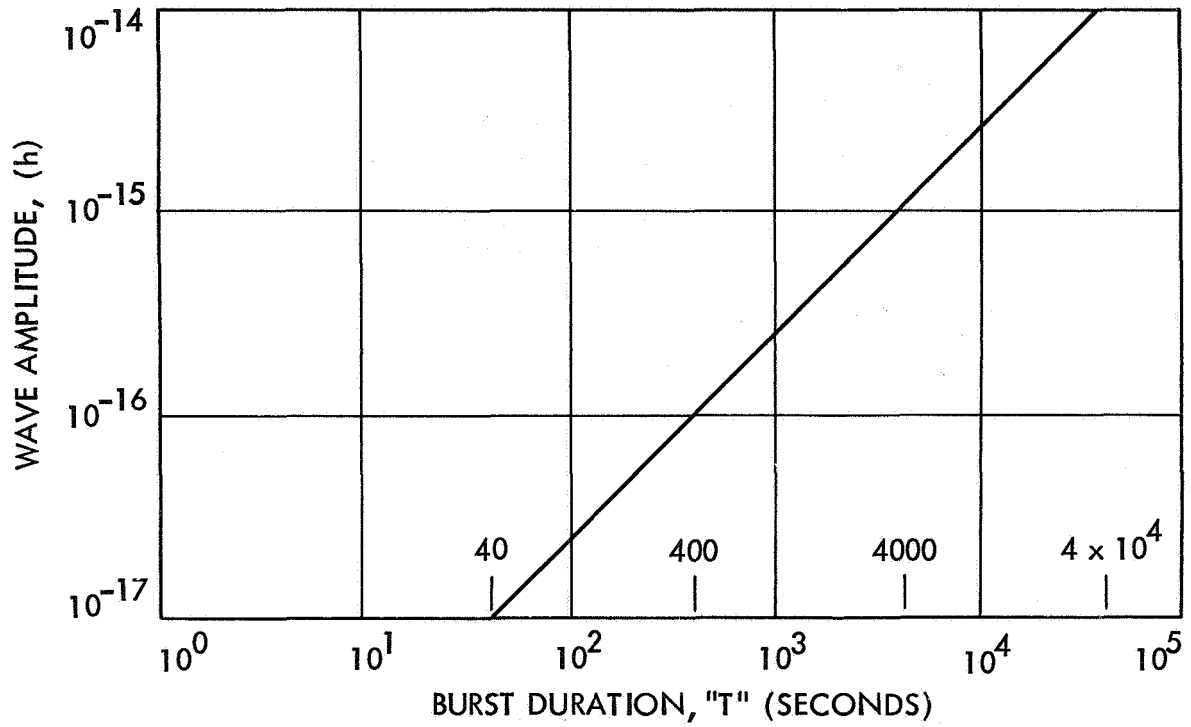


Figure 3. Plot of the Wave Amplitude, (h), vs. Burst Duration, T. (This relation is approximate.)

The anticipated ranges on these parameters are:

$$40 \text{ seconds} \leq T \leq 40,000 \text{ seconds}$$

$$10^{-17} \leq (h) \leq 10^{-14}$$

The range noted above is, however, highly dependent upon certain specific assumptions which were made during its derivation. The actual characteristics of gravity waves may be larger or smaller by some considerable factor. We will consider them as guidelines.

Experimental Constraints

As a result, the following parameters have been suggested as constraints for the Deep Space Network in any attempt to measure gravitational waves⁵:

BASELINE EXPERIMENT : $\Delta F/F \leq 10^{-15}$ Total Measurement System
(Waves with $(h) 10^{-15}$)

$\Delta F/F \leq 10^{-16}$ Each Component (FTS)

for $50 \text{ sec.} \leq T \leq 5000 \text{ sec.}$

DESIRABLE EXPERIMENT : $\Delta F/F \leq 10^{-17}$ Total Measurement System
(Waves with $(h) 10^{-17}$)

$\Delta F/F \leq 10^{-18}$ Each Component (FTS)

for $50 \text{ sec.} \leq T \leq 5000 \text{ sec.}$

III. THE DEEP SPACE NETWORK

Deep Space Tracking Stations (DSS) of the Deep Space Network (DSN) regularly maintain a coherent radio link over a period of hours with the various spacecraft of the Planetary Exploration Program. These stations transmit a precise radio frequency signal which is currently at S-Band (2.3 GHz) to the spacecraft. This "uplink" signal is received by the particular probe and transponded back to the Earth at S-Band (the downlink is the Uplink S-Band Frequency x 240/221) and/or at X-Band (this downlink is at the Uplink S-Band Frequency x 880/221; around 8.3 GHz). These "downlinks" (coherent with each other as well as with the uplink reference) are received by either the transmitting

DSS or by a second DSS which is coherent with the first. The former mode of communication (reception by the transmitting station) is referred to as being "two-way," while the latter (reception by a second DSS) is referred to as being "three-way."

The received frequency will differ (aside from the numerical factor) from the transmitted frequency by the amount of doppler shifting on the transponded signal. This doppler shift is due primarily to two factors:

1. The motion of the Spacecraft relative to the Earth,
2. The motion of the DSS due to the Earth's rotation.

(These factors were removed from the diagrams shown in figure 2.) Further, as we've noted, it is expected that the passage of a gravity wave through the System will result in a distinct fractional frequency shift in the doppler record.* The amplitude of the pulses which make up the signature are very, very small, however, and hence each factor of noise which is inherent in the various components of the experiment is important.

We will list in some detail those points within the system where noise in the Frequency and Timing System's (FTS) outputs may be introduced into the experiment. We will consider in turn:

1. The Frequency and Timing System (FTS)
Primary Component: Hydrogen Maser (H2M)
2. The Receiver/Exciter Subsystem (RCV)
Primary Components: Closed-Loop Receiver (CLR)
Open-Loop Receiver (MMR)
3. The Tracking Subsystem (DTK)
Primary Component: Metric Data Assembly (MDA)
4. The Radio Science Subsystem (DRS)
Primary Component: Occultation Data Assembly (ODA).

See figure 4 for a general block diagram of the configuration of the pertinent sections of a typical DSS during tracking.

*Note: We're not considering media effects here.

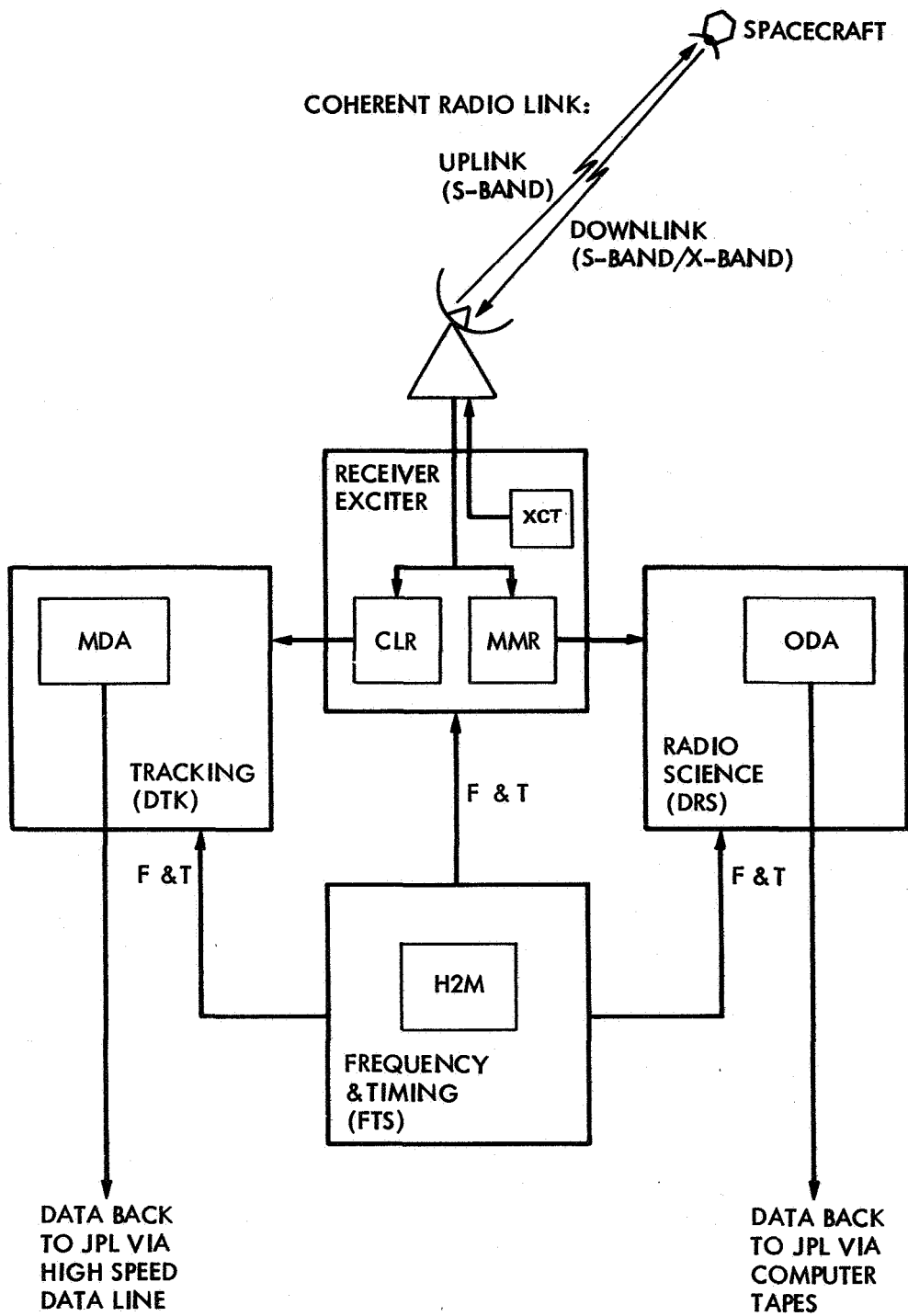


Figure 4. General Block Diagram of DSN Experimental Configuration
 (Note: "F & T" = Frequency and Timing products.)

The Frequency and Timing System

The Frequency and Timing System (FTS) at a Deep Space Station provides virtually all reference frequencies and timing pulses as well as epoch times which are required by the DSS to perform its tracking function. The following are some of the major components of the FTS and their impact on performance. See figure 5 for a current (Mark III) functional block diagram of the FTS. This section will consider the following components of the FTS: The Coherent Reference Generator, the Time Format Assembly and the Hydrogen Maser.

The Coherent Reference Generator

The Coherent Reference Generator (CRG) produces the various reference frequencies which are used in the station's subsystems. Currently the CRG outputs the following frequencies:

- 0.1 MHz
- 1.0 MHz
- 5.0 MHz
- 10.0 MHz
- 10.1 MHz
- 45.0 MHz
- 50.0 MHz
- 55.0 MHz

For the gravity wave experiment, among the most critical of the constraints placed on the CRG's outputs is that they not degrade the coherence of the recorded phase and time in the doppler data within the Tracking System. Problems with the outputs of the CRG can impact this performance in several ways. These include:

1. An increase in the noise of the reference signal can increase the overall noise in the doppler system and thus degrade resolution.
2. Errors in timing pulses can result in varied sample times and resultant doppler jitter. This can cause 'smearing' of the recorded frequencies. (Note, however, that the clocks which generate these pulses are typically noisier than the CRG.)

The stability of the CRG's products is also critical within the Receiver/Exciter Subsystem where they are used at various points to directly mix the incoming signal down into usable ranges.

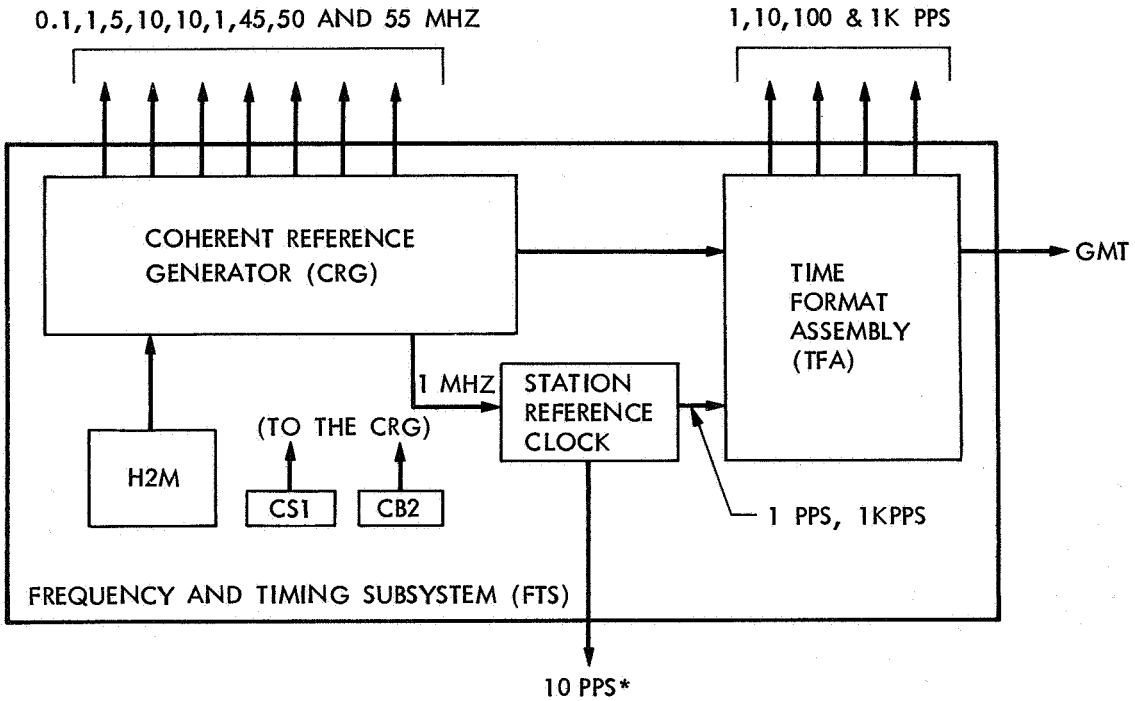


Figure 5. Functional Block Diagram of the Frequency and Timing Subsystem (FTS) showing the various F & T products; Mark III System. (Note: CS1 and CS2 are back-up Cesium Standards, for use in the event of Hydrogen Maser (H2M) failure.)
 *The 10 pps is for the DTK and DRS.

The Time Format Assembly

The Time Format Assembly (TFA) provides precision timing pulses to the various subsystems. TFA outputs include:

Timing Pulses: 1 pps
10 pps
100 pps
1 kpps

Epoch Time Code: GMT

The stability of these pulses depends upon the output of the CRG (see point 2 under Coherent Reference Generator.) Note that some users require a 10 pps reference timing pulse from the Master Clock (see figure 5) rather than from the TFA. (This pulse provides a 10 ns/second rms jitter.)

The Hydrogen Maser

The Hydrogen Maser (H2M) is the central factor in any attempt to utilize the DSN as part of a gravitational wave experiment. Its ultra precision frequency products provide the baseline stability 'environment' upon which the stability of the DSS is determined. And hence, whether an experiment is feasible. Within the maser's cavity, a frequency of 1420 MHz is generated. This is in turn monitored by the unit's instrumentation and used directly in synthesizing several frequency products which are delivered to the CRG. These products are: 0.1 MHz, 1.0 MHz, 5.0 MHz and 10 MHz. In addition, a 100 MHz reference frequency is generated and this will become available to the CRG for use by the open-loop receiver under the Mark-IVA era (1984).

See Table 1 for a Summary of the Specifications imposed upon the Frequency and Timing System by the current requirements of the Deep Space Network. It includes specifications: 1. on the Frequency Standard, 2. between different Deep Space Network Complexes (DSCC's), 3. between the DSN and USNO/NBS, 4. on timing pulses, and 5. on the CRG.

Table 1. Summary of Current Specifications

Knowledge of time synchronization between DSCC's :	<u>±</u> 10 us
Knowledge of frequency offset between DSCC's :	<u>±</u> 3 x 10 ⁻¹³
Frequency Offset between DSCC's maintained within:	<u>±</u> 1 x 10 ⁻¹²
Knowledge of time synch. between DSN & USNO/NBS :	<u>±</u> 5 us

The frequency standard at a DSS (the Hydrogen Maser) must conform to the following stability performance standards:

- 1 x 10⁻¹² for 1 second
- 1 x 10⁻¹⁴ for 10⁴ seconds
- 1 x 10⁻¹⁴ for 12 hours
- 1 x 10⁻¹³ for 10 days

These numbers apply also to CRG outputs (sine waves with harmonic distortion of no greater than 5% for the output frequencies.) In addition, the master clock must provide timing pulses with no more than 10 ns/second rms jitter.

The Receiver/Exciter Subsystem

Within the Receiver/Exciter Subsystem (RCV), there are three components which are of interest in terms of the experiment:

1. The Exciter; which provides the basis for the uplink (S-Band) frequency.
2. The Closed-Loop Receivers which provide the downlink signal to the Doppler Extractor and thence to the Tracking Subsystem (DTK).
3. The Open-Loop, Multi-mission Receivers which provide the downlink signal to the Radio Science Subsystem (DRS).

Each of these rely upon FTS inputs. See figure 6 for a Block diagram of the Receiver/Exciter Subsystem.

Within the Exciter, the primary exciter reference frequency, upon which the uplink is based, is directly derived from a CRG-provided 50 MHz reference frequency.

The Closed-Loop Receivers use a phase-locked loop to follow the downlink signal. The signal is fed by these receivers to the Doppler Extractor where it is mixed with the present output of the Exciter. The resultant signal coming from the Doppler Extractor (whether S-Band or X-Band) is mixed-down using a combination of 1 MHz and 50 MHz frequencies supplied by the CRG. The Closed-Loop Receivers also use the following FTS products; from the TFA: 1, 10, 100 and 1k pps; from the CRG: 0.1 MHz, 1.0 MHz, 5 MHz, 10 MHz, 10.1 MHz, 45 MHz, 50 MHz and 55 MHz. (In short, all of the present CRG outputs are used by the Closed-Loop Receivers in some fashion.)

The Open-Loop Multimission Receiver uses a 50 MHz reference signal supplied by the CRG to mix the signal down into the range of the Narrow Bandwidth filters within the receiver prior to sending the signal to the ODA. This is a particular instance where FTS performance can directly impact data since any noise in the 50 MHz reference frequency will be mixed directly into the signal.

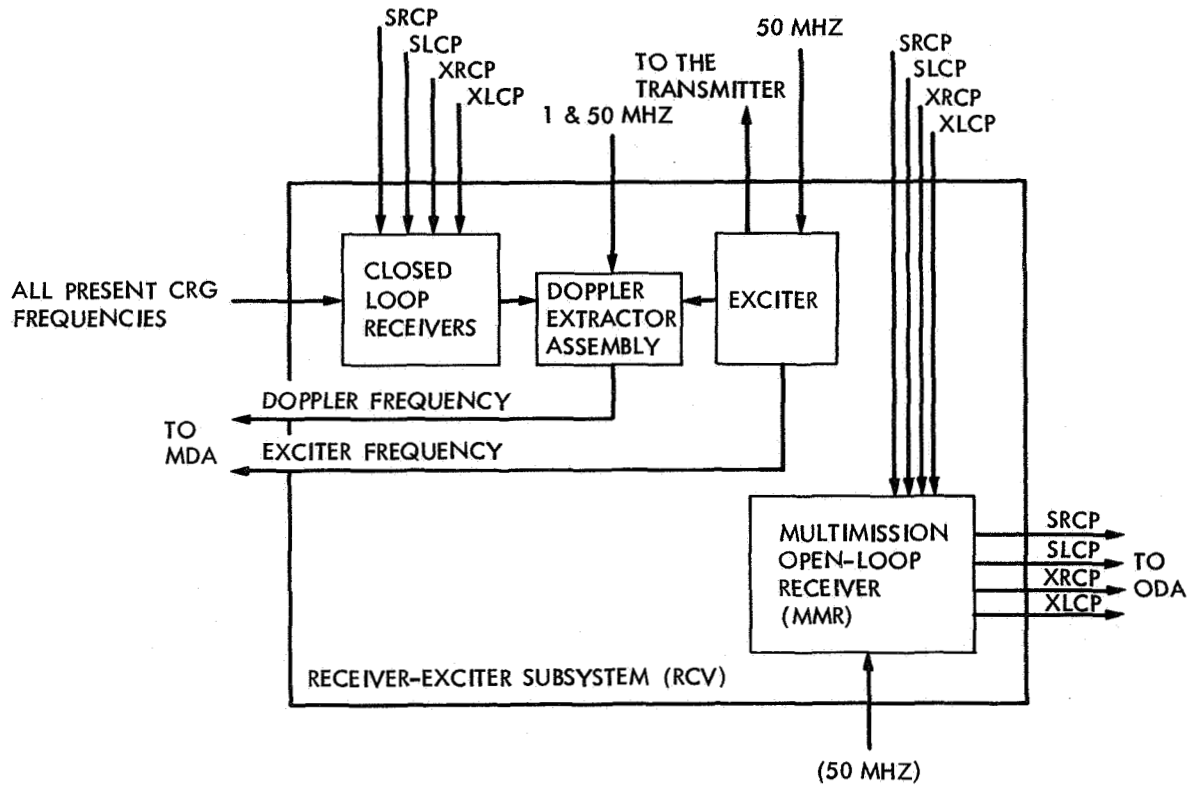


Figure 6. Block Diagram of the Receiver-Exciter Subsystem (RCV). Note that the input frequencies shown are SRCP = S-Band (Right-Circular Polarization), SLCP = S-Band (Left-Circular Polarization), XRCP = X-Band (Right-Circular Polarization) and XLCP = X-Band (Left-Circular Polarization.)

The Tracking Subsystem

The primary user of frequency and timing products in the DSS Tracking Subsystem (DTK) is the Metric Data Assembly (MDA). The MDA utilizes:

1. From the TFA, a) Timing pulses (1, 10, 100 and 1k pps)
b) GMT Epoch
2. From the CRG, a) Frequencies: 1 MHz, 5 MHz and 10 MHz
(to the frequency counters)
3. From the FTS Master Clock, a) 10 pps (to the frequency counters).

Using inputs from the Receiver/Exciter Subsystem, the frequency counters of the MDA measure both the exciter reference frequencies and the resultant doppler frequencies. Following receipt of a timing pulse from the TFA, the frequency counters count radio frequency (RF) cycles and measure any fractional portion of an RF cycle which has occurred. (These counters are driven by the Master Clock's 10 pps reference timing pulse.) The resulting phase data are sent to the MDA's computer (a Mod Comp II/25) for collection and transmission back to the Jet Propulsion Laboratory (in real-time) via High Speed Data Lines (HSDLs). The data is ultimately recorded at JPL. This forms the basis for the closed-loop experiment. See figure 7 for a block diagram of the essentials of the Tracking Subsystem.

The Radio Science Subsystem

The DSS Radio Science Subsystem (DRS), takes the baseband signal provided by the Multimission Receiver, digitizes and then records it on magnetic tapes which are ultimately delivered to JPL. The primary component of the DRS is the Occultation Data Assembly (ODA). See figure 8 for a block diagram of the DRS. From the various frequency and timing products, the DRS accepts:

1. From the TFA, a) Timing pulses (1 pps)
b) GMT Epoch
2. From the CRG, a) Frequencies: 10 MHz (to the ODA)
3. From the FTS Master Clock, a) 10 pps. (to the Freq. Monitor Subassembly).

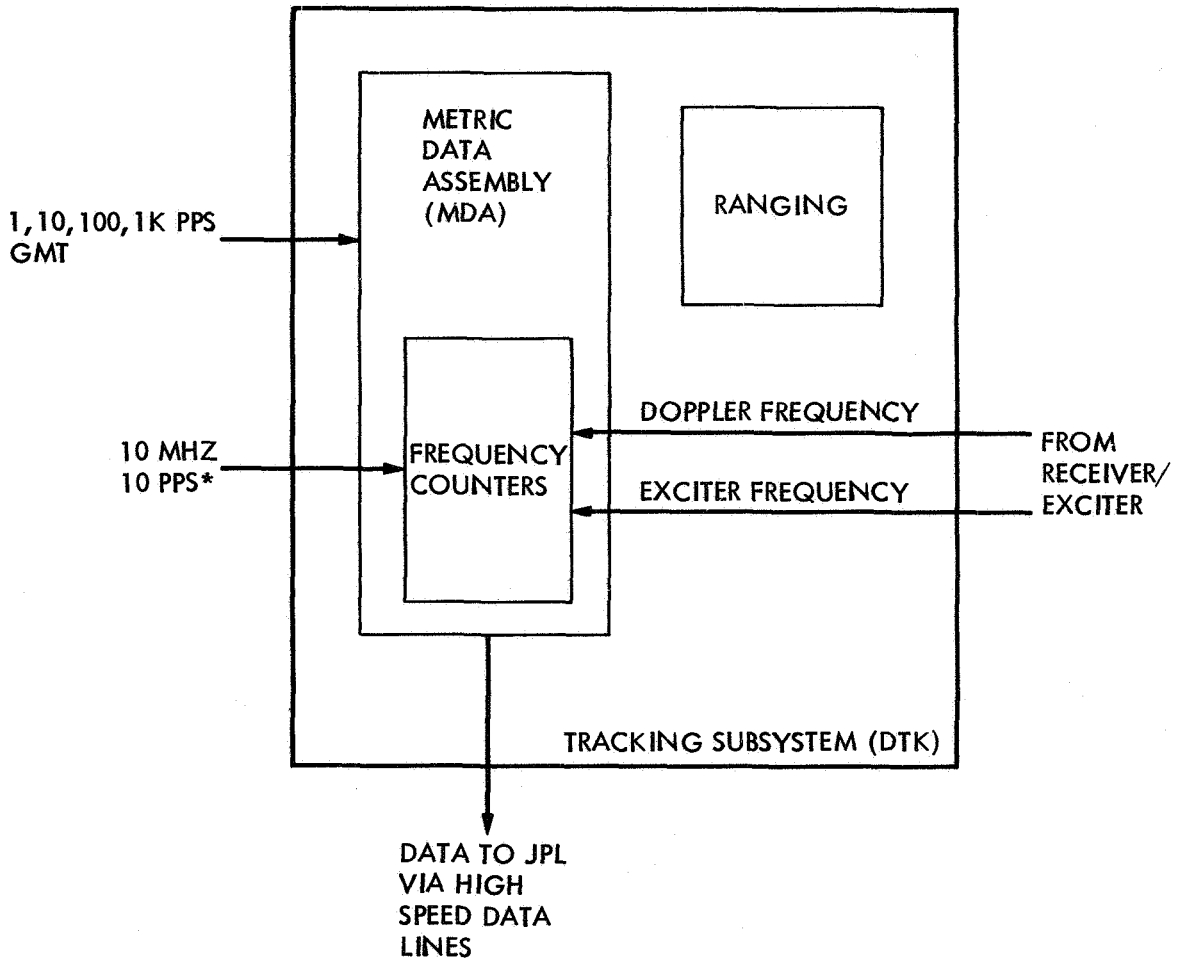


Figure 7. Block Diagram of the Tracking Subsystem (DTK).
 *From the Station Reference Clock.

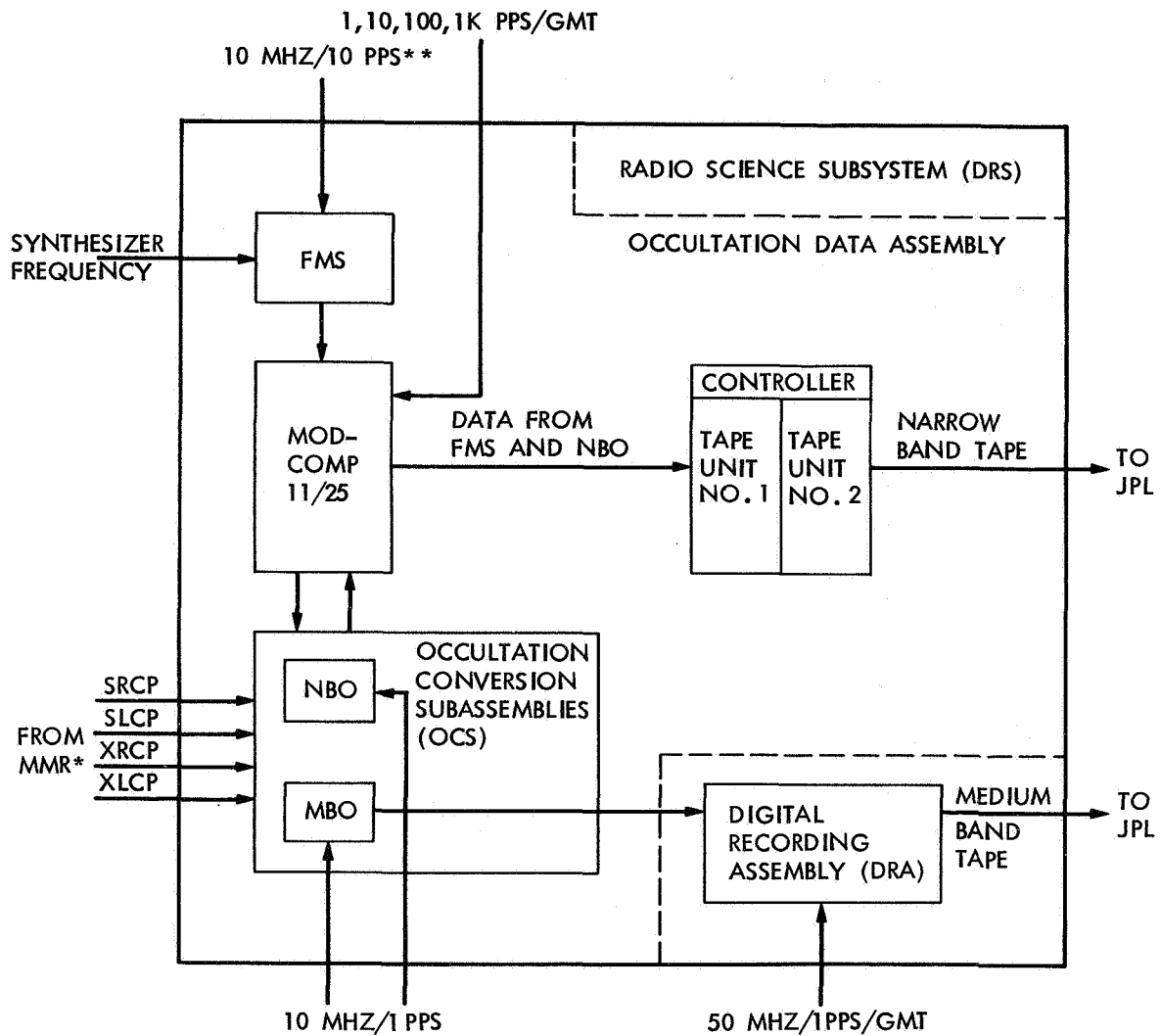


Figure 8. The Radio Science Subsystem (DRS). Note that the following acronyms are used above: "NBO" = Narrow Band Occultation Data Conversion Subassembly; "MBO" = Medium Band Occultation Data Conversion Subassembly; "FMS" = Frequency Monitor Subassembly.

*These frequencies have been mixed down to audio levels.
 **The 10 pps is from the Station Reference Clock.

It is anticipated that during any gravity wave experiment that the DRS will operate in the 'Narrow-Band Mode' due to the narrow bandwidth of the MMR filters which are available in that mode and the resultant high values of the signal-to-noise ratio in the input to the ODA.* (This can be an important factor when the spacecraft being used in the experiment is distant from the Earth.) In the Narrow-Band Mode, the DRS will digitize and format the incoming signal within the ODA's Narrow Band Occultation Conversion Subassembly (NBO). At this point, the experiment can be impacted by FTS performance as the analog-to-digital converters within the NBO rely upon a 10 MHz reference frequency provided by the CRG. Once digitized, the ODA records the data on magnetic tapes which again rely upon the FTS for precision time-tagging. These tapes are ultimately shipped back to JPL.

Planned Capabilities (Mark IVA Era)

In the coming years, a number of changes will be made in the current Frequency and Timing System within the DSN to supply improved mission support. The Mark IVA specifications will include:

CRG Outputs: Sine Waves with Harmonic distortion = 5% at the following frequencies: 0.1 MHz, 1.0 MHz, 5.0 MHz, 10.0 MHz, 10.1 MHz, 45.0 MHz, 50.0 MHz, 55.0 MHz and 100.0 MHz. (The 100 MHz is for the MMR.)

TFA Outputs: Timing pulses with a general stability of 10 ns/sec. rms at: 1 pps, 10 pps, 100 pps and 1 kpps. In addition, an improved 10 pps timing pulse with an rms jitter of 2 ns/sec. will be provided to the MDA/ODA.

Note: The Digital Recording Assembly (DRA) records data taken while the ODA is in the Medium Band Mode. It will not be used during this experiment. (It receives a 50 MHz reference from the CRG.)

*Note: The Narrow Band filters' bandwidths range from
100 Hz to 8180 Hz (S-Band)
100 Hz to 30 KHz (X-Band)

Each Deep Space Communications Complex (DSCC) (as regards this experiment, "DSCC" may be taken as being equivalent to the term "DSS" used previously) will have 2 Hydrogen Maser frequency standards (1 prime and a back-up) as well as 2 Cesium Beam standards (as back-up references.) Each of the Hydrogen standards will continue to have a setability within 7×10^{-15} and will conform to the following stability performance levels⁶.

1×10^{-12}	over 1 second
1×10^{-14}	over 10^4 seconds
1×10^{-14}	over 12 hours
1×10^{-13}	over 10 days.

In addition, critical FTS products will be distributed to the various subsystems via stabilized transmission lines with performance levels comparable to those above. (CRG outputs to be sent via these lines include 5 MHz reference frequencies to the closed-loop receivers and a 100 MHz for the MMR.)

DSN Capabilities circa 1987-1990

Anticipating the requirements of a gravitational wave experiment, the following numbers may be taken to represent the "best-case" capabilities of the DSN's Frequency and Timing System in the 1987-1990 era⁷:

1. Frequency Standards Stabilities better than: 3×10^{-16} for periods $300 \text{ seconds} \leq T \leq 30 \text{ days}$,
2. 10 ns/second rms jitter accuracy timing pulses, with certain 2 ns/second rms jitter pulses for the DTK and DRS.
3. Time Synchronization to ± 10 ns between DSCC's,
4. Time Synchronization to ± 100 ns between the DSN Master Clock and UTC (USNO/NBS).

IV. SUMMARY

Table 2 contains a comparison of the capabilities of the Deep Space Network and the nominal requirements of the gravitational wave experiment.

Table 2. FREQUENCY STANDARD/DELIVERED PRODUCTS DESIRED STABILITIES

DSN Capabilities	$\Delta F/F$	Burst Duration, T
Current (Mark III)	$\leq 3 \times 10^{-13}$	over 10^4 seconds
Planned (Mk IVA)	$\leq 1 \times 10^{-14}$	over 10^4 seconds
Suggested ('87-90)	$\leq 3 \times 10^{-16}$	300 sec. $\leq T \leq$ 30 days

Expt. Requirements	$\Delta F/F$	Burst Duration, T
Baseline Expt.	$\leq 1 \times 10^{-16}$	50 sec. $\leq T \leq$ 5000 sec.
Desirable Expt.	$\leq 1 \times 10^{-18}$	50 sec. $\leq T \leq$ 5000 sec.
Range of Events	10^{-14} to 10^{-17}	40 sec. $\leq T \leq$ 40000 sec.

Although the stability requirements for the "baseline experiment" will not be approached for a number of years, the uncertainties which were involved in the derivation of the Range of Events and the efficacy of current post-processing techniques (which are not discussed here) suggests that experiments should be carried-out during the 1980's. (In point of fact, an experiment is currently being conducted by the DSN using the Pioneer 10 Spacecraft.)

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APPENDIX A

The following is suggested as an enhancement of the utilization of the DSN's Frequency and Timing System in some future gravitational wave experiment:

It has been suggested^{A1} that by tracking two spacecraft simultaneously that the direction of propagation of an incoming gravitational wave could be resolved. (A single spacecraft merely resolves the direction of propagation to within some family of directions which forms a cone.)

Alternately, the simultaneous tracking of a single spacecraft by two stations (one of them in the three-way mode) could also resolve the direction of incidence of the wave via a correlation of the doppler tracking records from the two DSS's. Such a correlation could, if the rise-time of the pulse caused by the gravitational wave were sharp enough, yield the time-delay between the incidence of the plane wave on the two stations. Given that gravitational waves propagate at the speed of light, this yields a second family of directions (i.e., a second cone) and hence could resolve the direction of incidence.

^{A1} R. Hellings; Physical Review D, Vol. 17, #12; (15 June 1978), pp 3158-3163.