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Radiation detection using RADAR

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Defence R&D Canada - Ottawa

Contract Report
DRDC Ottawa CR 2012-164
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Abstract

DRDC Ottawa has been investigating alternative radiation detection techniques under an Applied Research Project (ARP 10dp). As part of this project, proof-of-principle experiments were carried out with the assistance of March Scientific Ltd. The experiments examined the feasibility of two techniques: the use of RADAR to detect the increased free electron density in an elevated radiation field, and the passive detection of microwaves emitted from atomic hydrogen in water vapour. It was shown that the plasma produced by the radiation beam of a high-activity gamma source does result in a small, frequency-dependent phase shift in the microwave signal. Some recommendations are made for future work.

Résumé

RDCC Ottawa a étudié diverses techniques de détection des rayonnements dans un projet de recherche appliquée (ARP 10dp). Dans le cadre de ce projet, des expériences de validation de principe ont été réalisées avec le concours de Mars Scientific Ltd. Ces expériences ont examiné la faisabilité de deux techniques : l'utilisation du radar pour détecter la densité d'électrons libres dans un champ de rayonnement puissant et la détection passive des micro-ondes émises par de l'hydrogène atomique dans la vapeur d'eau. Il a été montré que la présence de plasma produit par le faisceau de rayonnement d'une source de rayons gamma de haute activité se traduit par un petit déphasage en fonction de la fréquence du signal micro-ondes. Certaines recommandations sont formulées en vue de travaux futurs.

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1 Introduction

DRDC Ottawa is currently leading an Applied Research Project (ARP 10dp) on “Development and Testing of Novel Standoff Radiation Systems”. Part of the mandate of this project is to carry out proof-of-principle experiments on alternative radiation detection techniques. In addition, DRDC Ottawa has been actively involved in a number of international collaborations in this area, including two recent NATO study groups: NATO Industrial Advisory Group (NIAG) Sub-Group 112, and NATO Sensors and Electronics Technology (SET) Exploratory Team 65. Canada (DRDC Ottawa) is currently chairing an international task force (ITF-53) under the CBR MOU on “Pre-event standoff radiation detection.

In support of project 10d and ITF-53, DRDC Ottawa will be carrying out an experiment to examine the feasibility of two techniques: RADAR detection of the increased free electron density in a radiation field, and passive detection of microwaves from atomic hydrogen in water vapour. Due to the lack of RADAR expertise within the Radiological Analysis and Defence (RAD) Group at DRDC Ottawa, it was decided that it would be beneficial to enlist the assistance of a RADAR expert in the experiment planning and interpretation of results. March Scientific Ltd. was contracted by DRDC Ottawa to assist with the conduct of these experiments.

The objective of the proof-of-concept study is to determine whether it is technically feasible to remotely identify the presence of radioactivity using microwave or RADAR signals. The study will examine two possibilities: passive detection (radio emissions directly from the radioactive source) and active detection (a radioactive source changes the characteristics of a known radio signal).

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2 Background

The distance at which conventional detectors can detect radiation sources varies widely according to the type and activity of the source, but is typically limited to a few hundred metres at best, and as little as a few centimetres for some sources. Alternate detection methods capable of stand-off detection of nuclear radiation are thus of considerable interest. The primary nuclear radiations (γ -rays, β -particles etc) are attenuated by air ionization and also decrease by the geometrical factor of $1/r^2$. An alternative approach to increase the detection range is to either measure the effect of the radiation on the air near the source or else to detect emission from species created in the vicinity of the source. The radiation ionizes the air surrounding the source resulting in the formation of electrons and new ionic and molecular species. In this study, we are particularly interested in the potential use of microwave detection for stand-off detection.

2.1 Microwave reflection and attenuation

The first observations of the reflection of a radar signal from the radioactive plume above the Chernobyl nuclear power plant were made in 1986 [1]. Subsequently, the presence of the reflected signal was confirmed by other groups [2, 3]. The experiments were made using various types of industrial radars in the centimetre and decimetre ranges. The reflection of the microwave is expected to result from the change in electric permittivity, ϵ , and conductivity, σ , that is associated with the plasma formed by ionization of the gas surrounding the source.

The theory of the propagation of electromagnetic waves in plasma has been well documented [4]. The electromagnetic wave causes the charged particles in the plasma to execute simple harmonic oscillations with amplitude which is directly proportional to its charge, and inversely proportional to its mass. The collective oscillation of the electrons in the plasma are defined by a characteristic frequency called the plasma frequency which is given by

$$f_p = \frac{1}{2\pi} \left[\frac{e^2 N}{\epsilon_0 m_e} \right]^{1/2} \approx 8.97 N^{1/2} \quad (1)$$

At frequencies below the plasma frequency, the electromagnetic wave will be strongly reflected at the boundary of the plasma. Above the plasma frequency, both attenuation and phase shift of the wave occurs. The magnitude of these effects depends on the electron density. Refraction of the wave will also occur at the boundary of homogeneous plasma or in inhomogeneous plasma.

A plane wave propagating in uniform plasma can be described in terms of a complex propagation constant

$$\gamma = \alpha + j\beta \quad (2)$$

where α and β are the attenuation and phase constants. In terms of γ , the complex refractive index can be written as

$$\mu = -\frac{j\gamma c}{\omega} \quad (3)$$

The following formulas are obtained [4] for α and β if account is taken of the effects of collisions with molecular ions and neutral molecules:

$$\alpha = \frac{2\pi f}{c} \left\{ -\frac{1}{2} \left(1 - \frac{80.5N}{f^2 + \nu^2} \right) + \frac{1}{2} \left[\left(1 - \frac{80.5N}{f^2 + \nu^2} \right)^2 + \left(\frac{80.5N}{f^2 + \nu^2} \frac{\nu}{f} \right)^2 \right]^{\frac{1}{2}} \right\}^{\frac{1}{2}} \quad (4)$$

$$\beta = \frac{2\pi f}{c} \left\{ \frac{1}{2} \left(1 - \frac{80.5N}{f^2 + \nu^2} \right) + \frac{1}{2} \left[\left(1 - \frac{80.5N}{f^2 + \nu^2} \right)^2 + \left(\frac{80.5N}{f^2 + \nu^2} \frac{\nu}{f} \right)^2 \right]^{\frac{1}{2}} \right\}^{\frac{1}{2}} \quad (5)$$

In these equations,

e	=	electron charge (Coulombs)
m_e	=	electron mass (kg)
ϵ_0	=	permittivity of free space
N	=	electron density (m^{-3})
ν	=	collision frequency ($\sim 1.5 \times 10^{11}$ /sec at atmospheric pressure)
f	=	microwave frequency (Hz)
f_p	=	plasma frequency (Hz)

If $\nu \gg f_p$ and f , then from equation [4], the attenuation per meter is approximately given by the expression

$$A \left(\frac{dB}{m} \right) \approx 6.5 \times 10^{-17} N$$

Plots of the plasma frequency and attenuation as a function of electron density are shown in Figures 1 and 2. Because of the very high collision frequency at atmospheric pressure the attenuation is essentially independent of frequency at microwave frequencies.

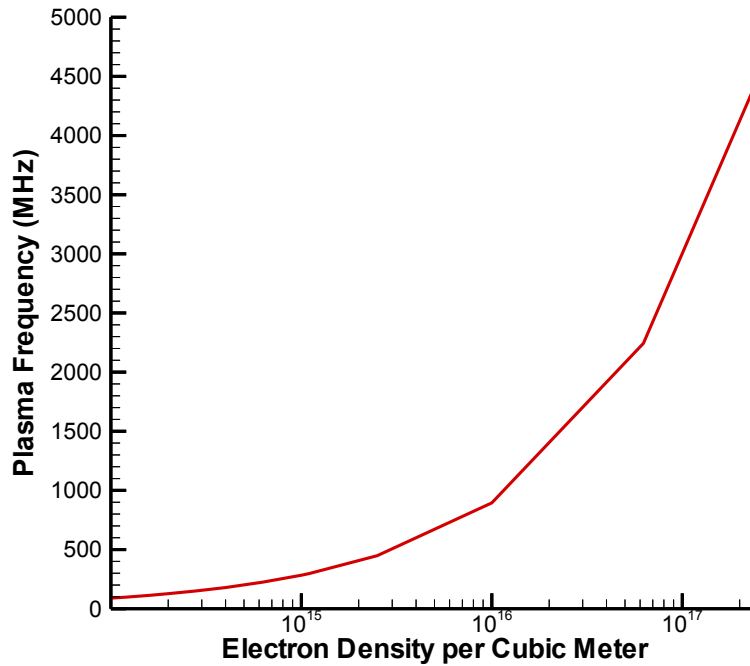


Figure 1: Plasma Frequency as a Function of Electron Density

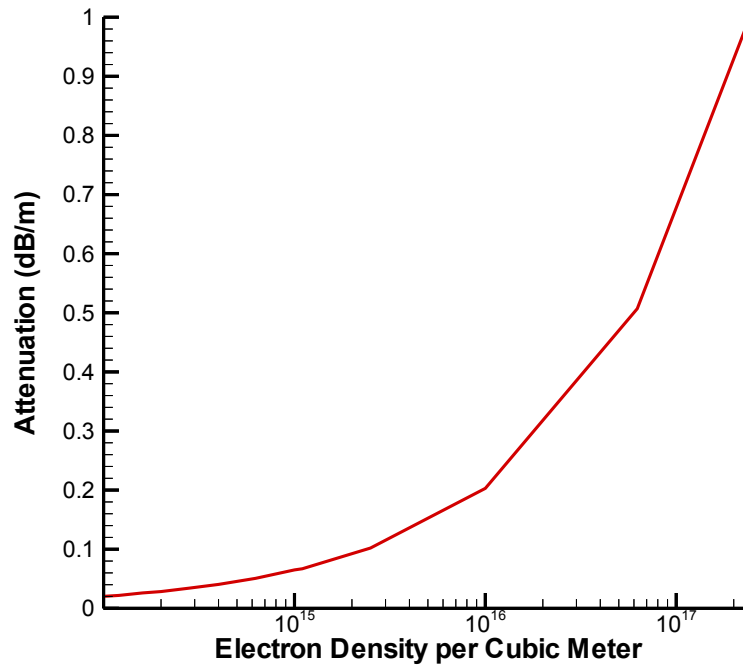


Figure 2: Microwave attenuation as a function of electron density

Microwave attenuation measurements have been used to study the plasma formed in the Aurora test cell [5] and in chemically formed plasmas [6]. Reflection of mm-waves by ionized air has also been reported [7]. Argonne National Lab. has demonstrated the ability to detect a weak radioactive cloud emanating from a nuclear power plant's ventilation stacks during normal operation at a distance of 9 kilometers using mm-waves [8]. Theoretical investigations [9] suggest that this reflection is coming from ion clusters rather than from electrons as the electron density is expected to be too low.

2.2 Hydrogen emission at 1.42 GHz

Atomic hydrogen can be formed in the atmosphere by the radiolysis of water as well as other atmospheric species such as methane, ammonia, molecular hydrogen and formaldehyde. It is known that the atomic hydrogen is a source of spontaneous microwave emission radiation with a wavelength of 21.1 cm which corresponds to a frequency 1420.4 MHz. This microwave emission comes from the atomic transition between the two hyperfine levels of the hydrogen 1s ground state. Long range detection of the microwave emission from atomic hydrogen formed in the radioactive plume from a nuclear reactor has been reported [10-12].

3 Experimental

3.1 Radiation source

The DRDC Ottawa GB-150C cobalt-60 source used in these experiments is in a heavily shielded (lead and steel) position when not being used. The source can be considered ‘off’ at that time. When the source is lifted from its shielding it is moved up into the source chamber. A roughly conical “beam” of gamma-ray radiation is then emitted through a collimator in the chamber as shown in Figure 3.

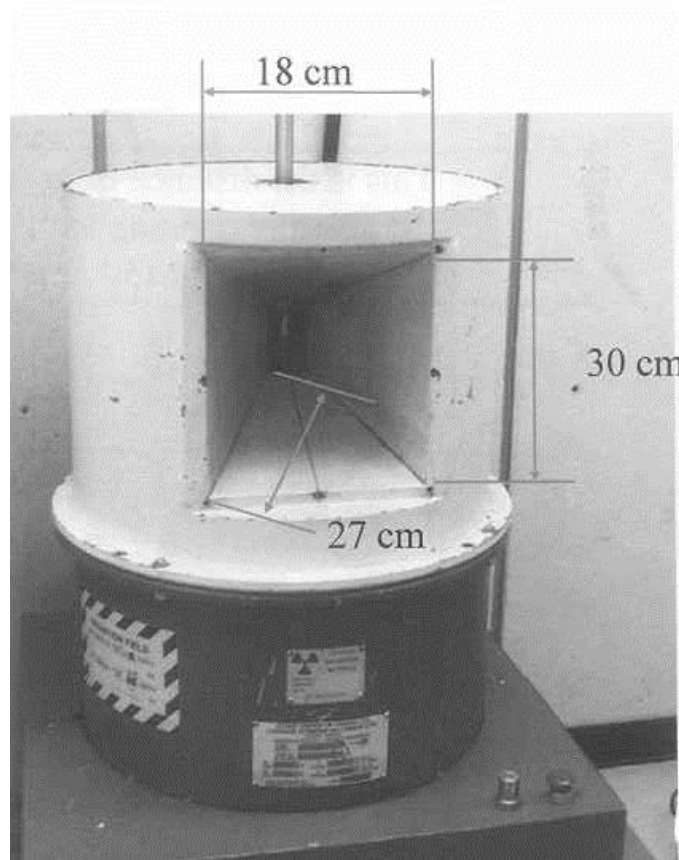


Figure 3: DRDC Ottawa GB-150C Cobalt 60 Source

3.2 Microwave attenuation and reflection measurements

To perform microwave attenuation and reflection measurements, an Agilent E5071B Network Analyzer was used to sweep the frequency and record the network parameters S_{11} and S_{21} over the frequency range from 350 MHz to 2 GHz. A pair of EMCO 3115 1 – 18 GHz broadband horns were used for the radiation and detection of microwaves. Figure 4 shows the set-up of the equipment. The S_{11} and S_{21} data was downloaded from the Network Analyzer and then transferred to a personal computer for analysis. Measurements were made with the radiation beam on and off for comparison.

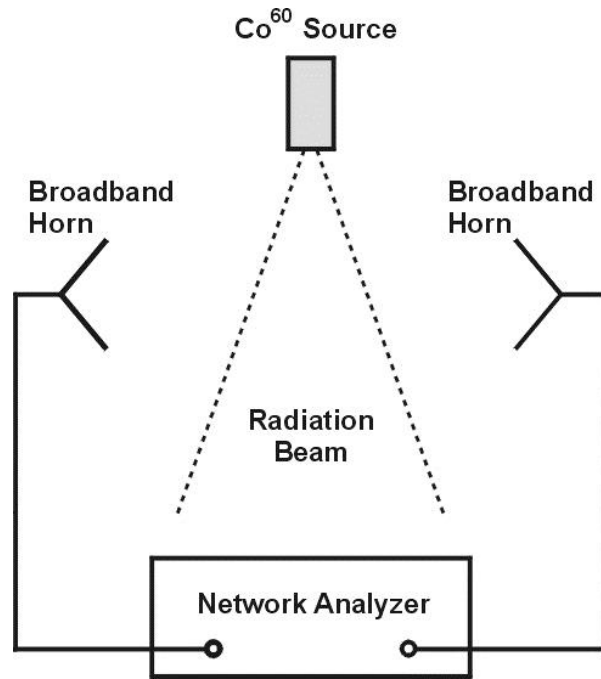


Figure 4: Experimental set-up for microwave attenuation and reflection measurements



Figure 5: Photo of the experimental setup

3.3 Microwave emission measurement

To search for microwave emission from atomic hydrogen at 1.42 GHz, an Anritsu Spectrum Master MS2724C was connected via a coaxial cable to an EMCO 3115 1 – 18 GHz broadband horn that was located in the radiation chamber. A small IF bandwidth was used to maximize instrument sensitivity and a careful search was made in the vicinity of 1.42 GHz. Measurements were made with the radiation beam on and off for comparison.

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4 Results

4.1 October 27, 2011 data

A series of measurements were made to see if significant changes could be detected in the S_{11} and S_{21} readings when the radiation beam was turned on. With the two antennas looking across the beam, measurements were made at various distances from the source and at various separations. S_{11} measurements were also made with one of the antennas looking down the bore site of the beam at several distances from the source. For this series of measurements, reference S_{11} and S_{21} measurements were made and stored in memory. Data was then recorded as log magnitude of (Memory – Signal) both with the beam off and then with the beam on. The first of these measurements was used to get an indication of the noise level in the system. The second measurement confirmed that there was a very significant change in both S_{11} and S_{21} when the beam was turned on as shown in Figure 5. In this and subsequent figures in this section the data has been presented as the difference in magnitude of (Memory – Signal) when the beam off and when the beam is on. After the data was recorded in this fashion, it was realized that, with this method of data presentation, one cannot determine whether there has been an increase or a decrease in the magnitude S_{11} and S_{21} only that there has been a change.

As shown in Figures 5 and 6, quite large changes in S_{11} and S_{21} were observed when the radiation beam was turned on. The change in the S-parameters was larger when the antennas were located close to the source. Figure 7 shows a similar effect for S_{11} data collected on the bore site. As illustrated in Figure 8 however, there seems to be a significant difference in the shape of the curves for data collected across the beam and on the bore site. The across beam data has significantly more intensity at lower frequencies. This is shown more clearly in the difference curve shown in Figure 11. It was later concluded that this difference may be due to the dynamic range available between the S_{11} and S_{21} readings.

Work by Gopalsami et al [11] in the mm-wave range had shown an enhancement of beam attenuation by the insertion of a dielectric cylinder into the beam. To check this, experiments were carried out where the effects of insertion of both a paper and a plastic cylinder were observed. As shown in Figures 9 and 10, no effect was observed at the frequencies used in this experiment.

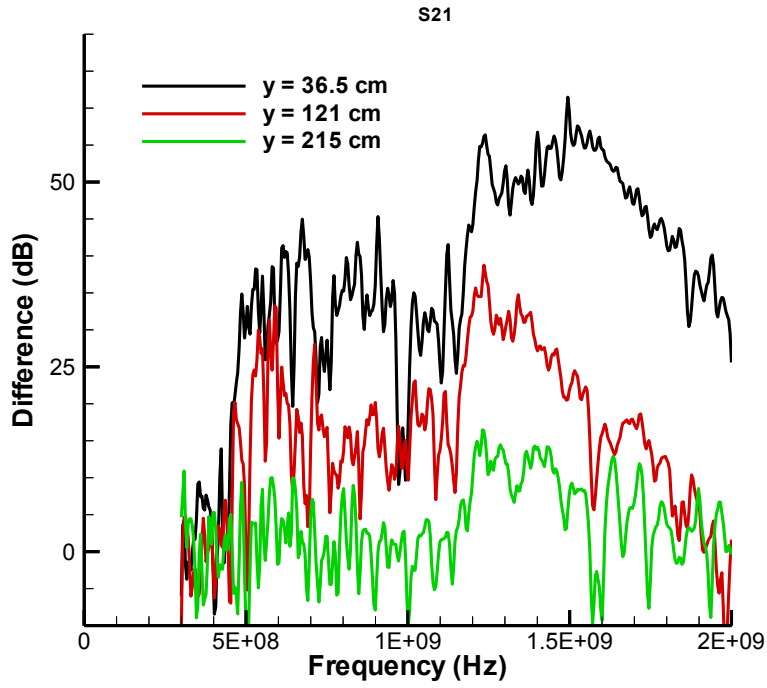


Figure 6: Effect of distance from source on log mag $(M-S)_{21}$: Across beam

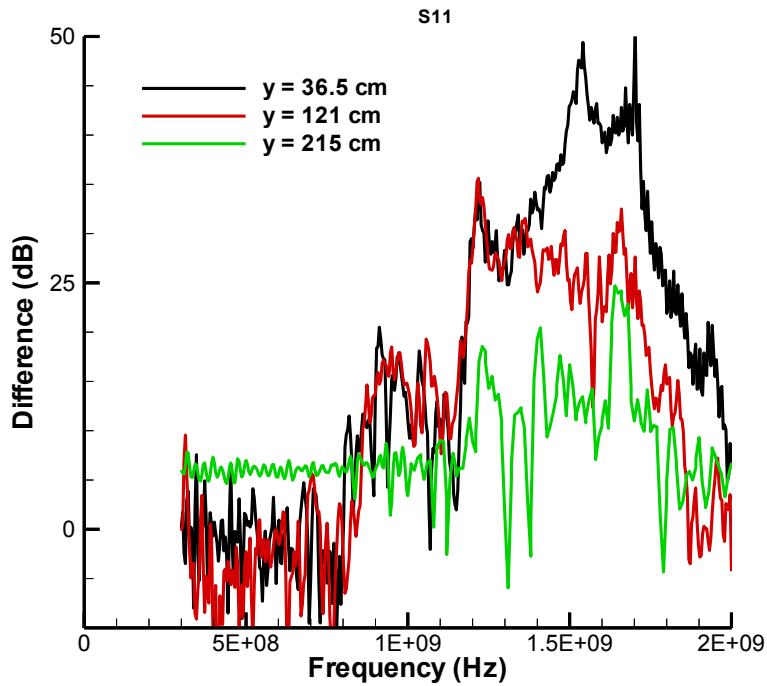


Figure 7: Effect of distance from source on log mag $(M-S)_{11}$: Across beam

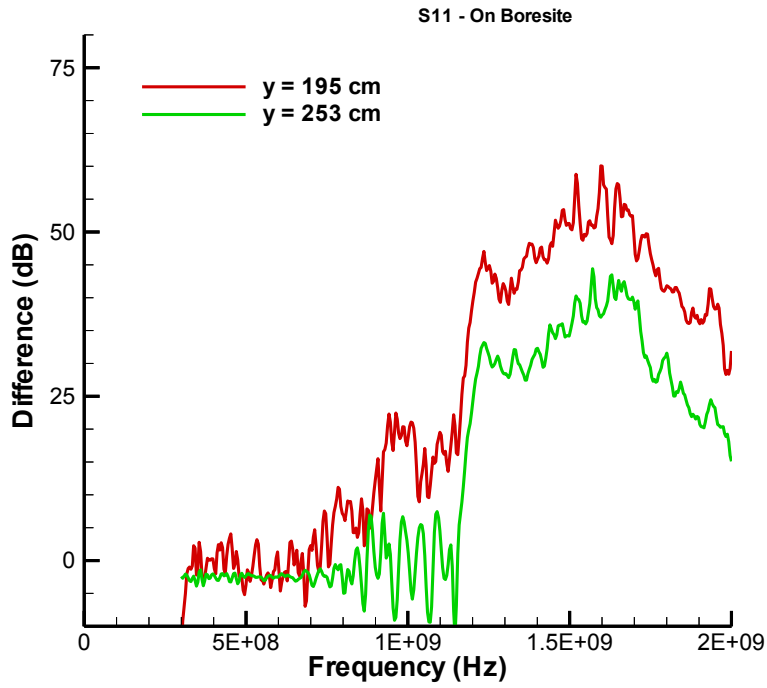


Figure 8: Effect of distance from source on log mag $(M-S)_{11}$: On boresite

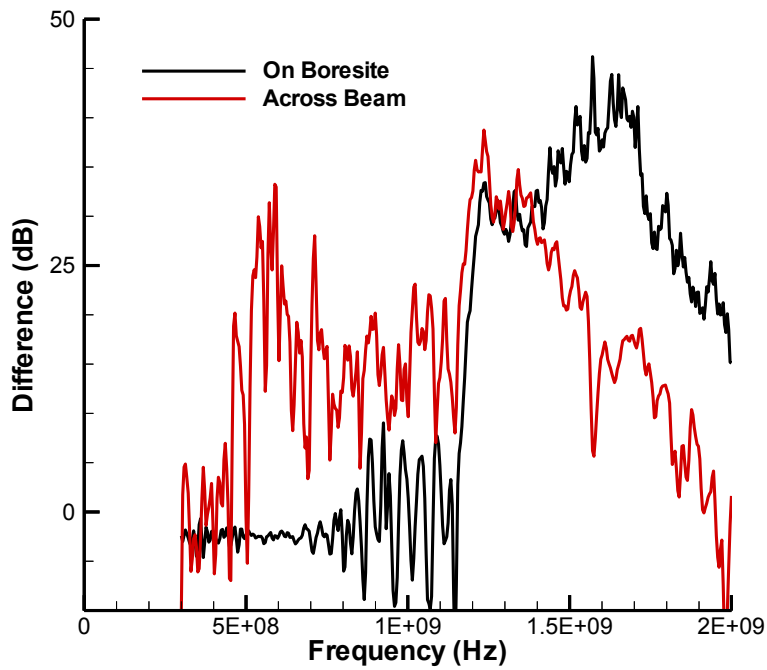


Figure 9: Effect of antenna orientation on signal shape

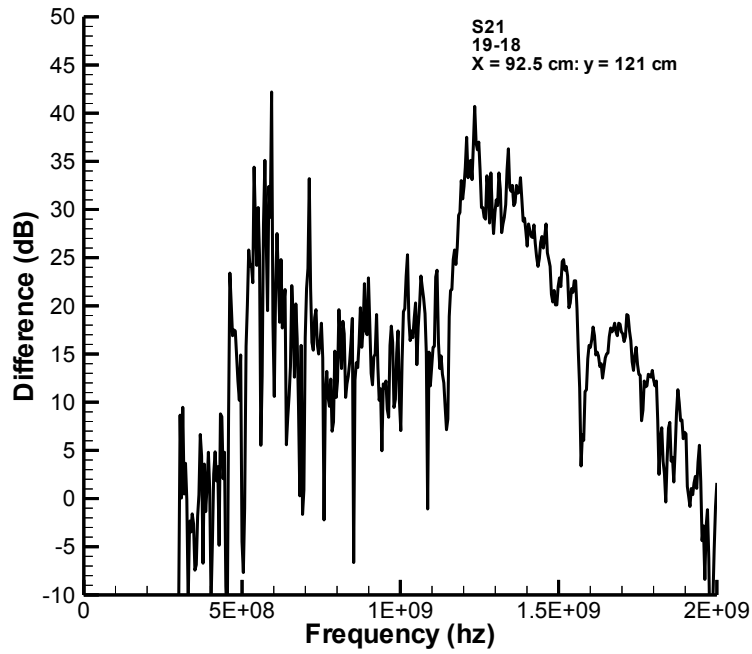


Figure 10: Effect of insertion of a paper cylinder - With cylinder

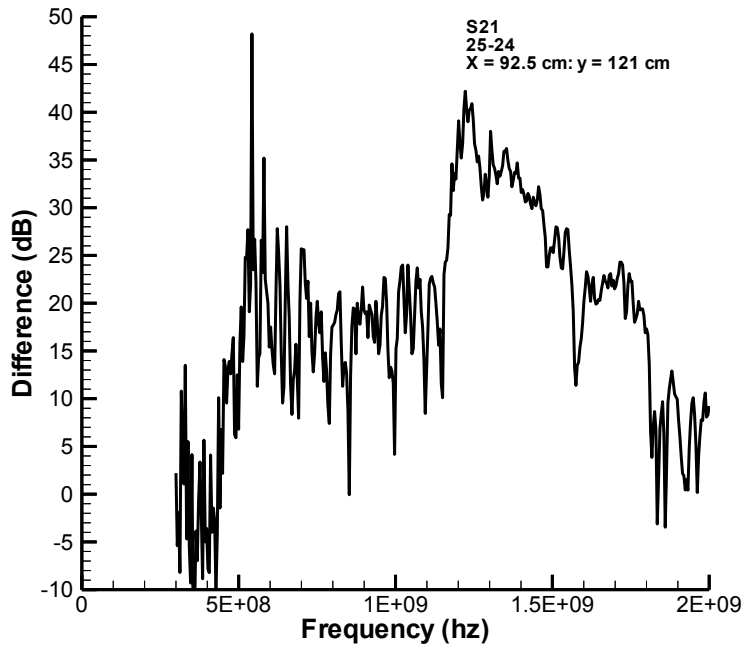


Figure 11: Effect of insertion of a paper cylinder - Without cylinder

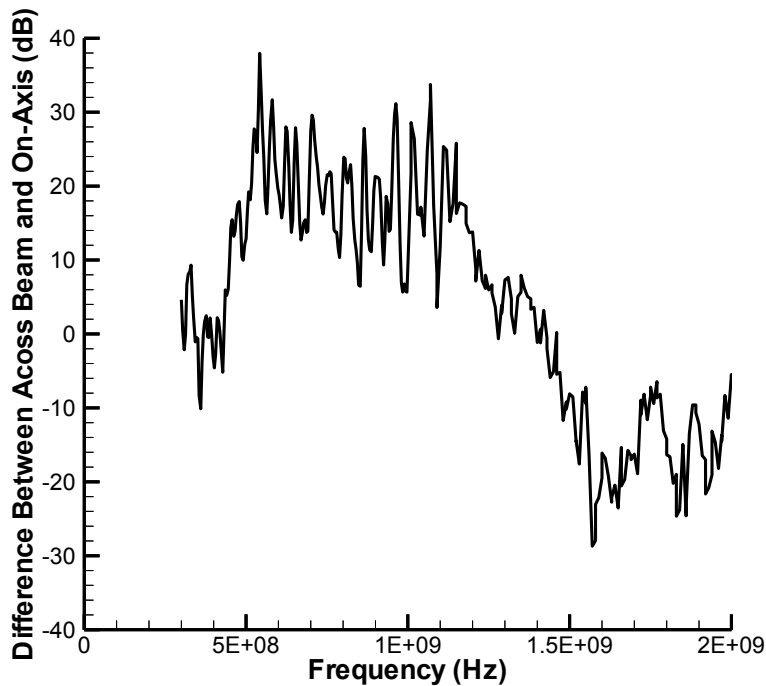


Figure 12: Difference between across beam and on-axis measurement

4.2 November 8, 2011 experiments

In these experiments the equipment was again set up as shown in Figure 4. The one exception was that a new set of cables had to be used as the original cables were no longer available. In order to attempt to determine whether there was an increase or a decrease in the magnitude S_{11} and S_{21} when the radiation beam was turned on, experiments were planned where both log mag (S_{11}) and log mag (S_{21}) were recorded with both the beam on and with the beam off. The difference between the two readings was then calculated numerically. When these experiments were carried out it was discovered that the losses in the new cables were too high to enable the S_{11} data to be recorded. We were able, however, to record S_{21} data. The numerically calculated result for the difference in the magnitude of S_{21} with the beam on and the beam off is shown in Figure 12. The results were surprising as they do not show a consistent change in increase or decrease in S_{21} but rather there is an oscillation around zero. Figure 13 shows that the data recorded on November 8 was consistent with the earlier experiments.

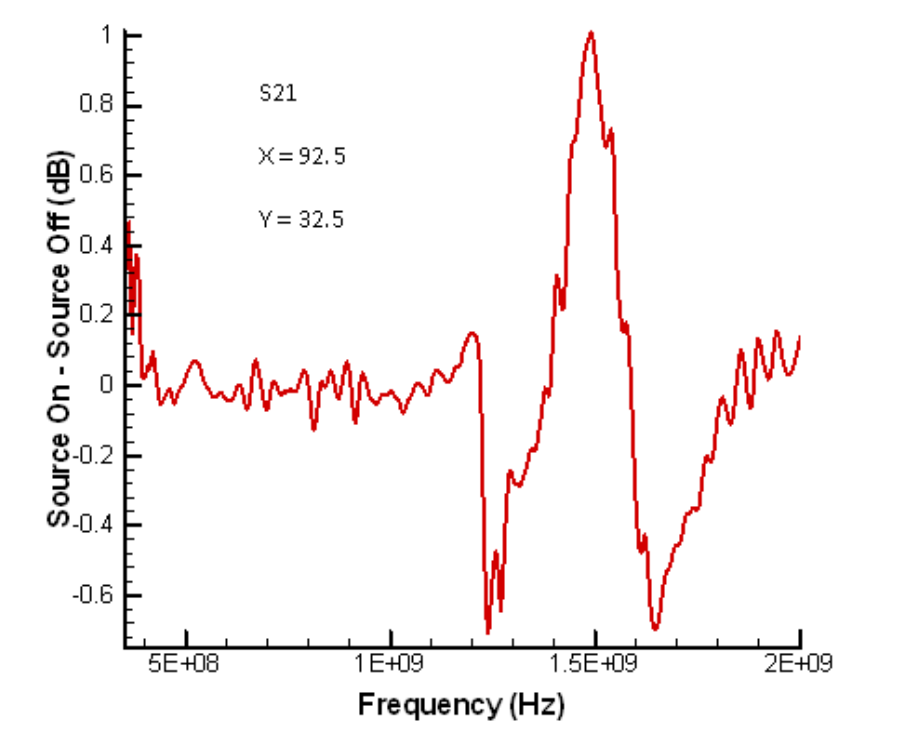


Figure 13: Difference between S_{21} data (source on) - S_{21} data (source off)

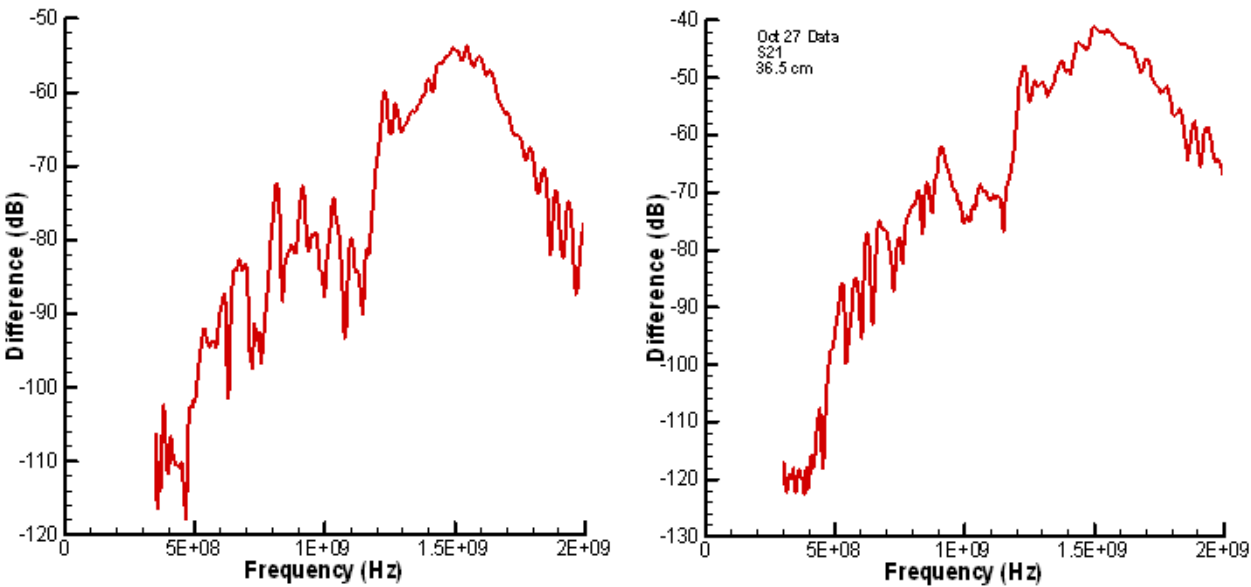


Figure 14: Comparison between Nov 8 Data and Oct 27 Data

4.3 December 7, 2011 data

4.3.1 Microwave attenuation and reflection.

The experiments of November 8 were repeated using a new set of low loss cables that would allow both the S_{11} and S_{21} data to be recorded. These results are shown below for various antenna placements. Figure 14 shows data recorded under the same conditions as used for the November 8 experiments. It is seen that this data is reproducible and the difference between the magnitude of S_{21} with the beam on and the beam off shows the same oscillatory behaviour as seen earlier. The remaining Figures (Figures 16 – 18) show similar behaviour. In general it is noted that the number of oscillations depends on the length of the beam path. The most reasonable explanation for this behaviour seems to be that part of the beam undergoes a small phase shift when the radiation beam is turned on. As noted earlier in Section 3.1, the phase shift associated with the propagation of microwave radiation through the plasma produced by the radiation is expected to be frequency dependent. The small oscillation in the difference in the magnitudes of S_{11} and S_{21} could thus result from part of the beam arriving in and out of phase with the reference signal (i.e. beam off). Figures 17 and 18 show that the measurements are reciprocal as might have been expected.

4.3.2 Passive microwave emission at 1.42 GHz

No signal at 1.42 GHz was detected in these experiments even when a humidifier was inserted into the chamber to increase the humidity.

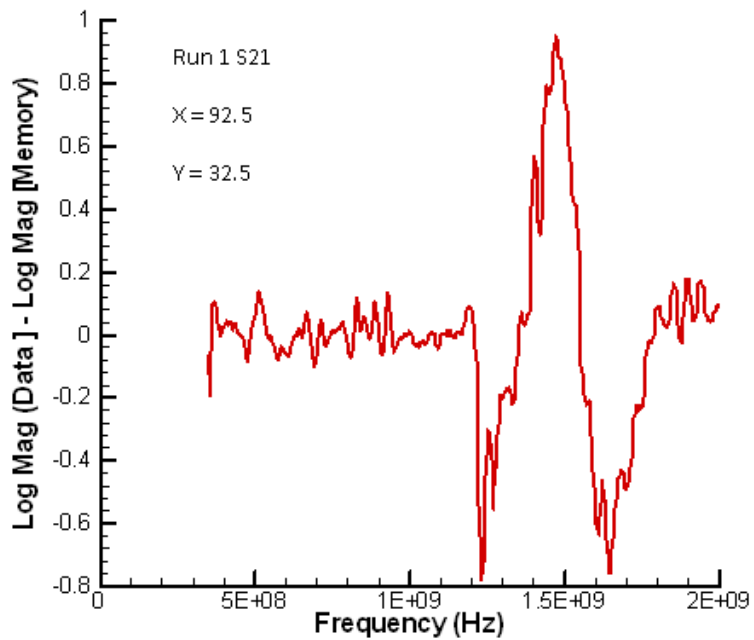
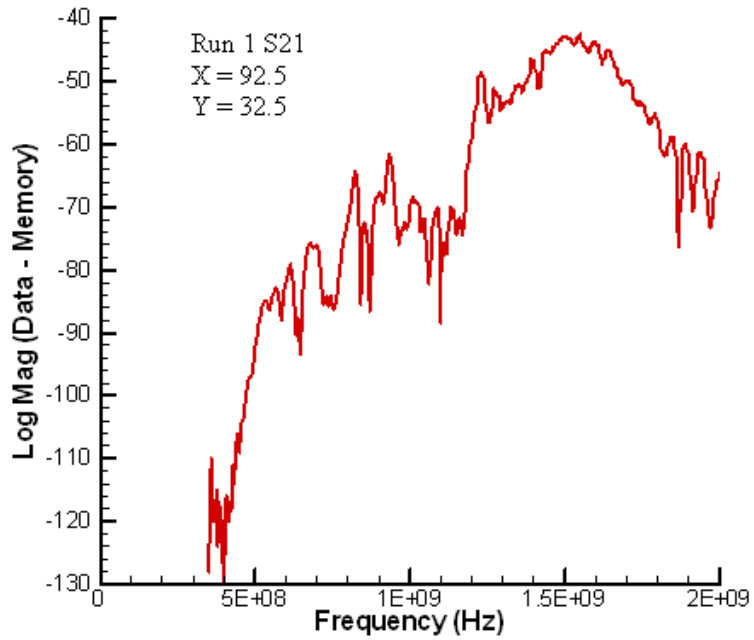


Figure 15: S_{21} data plots for $x = 92.5$ cm, $y = 32.5$ cm

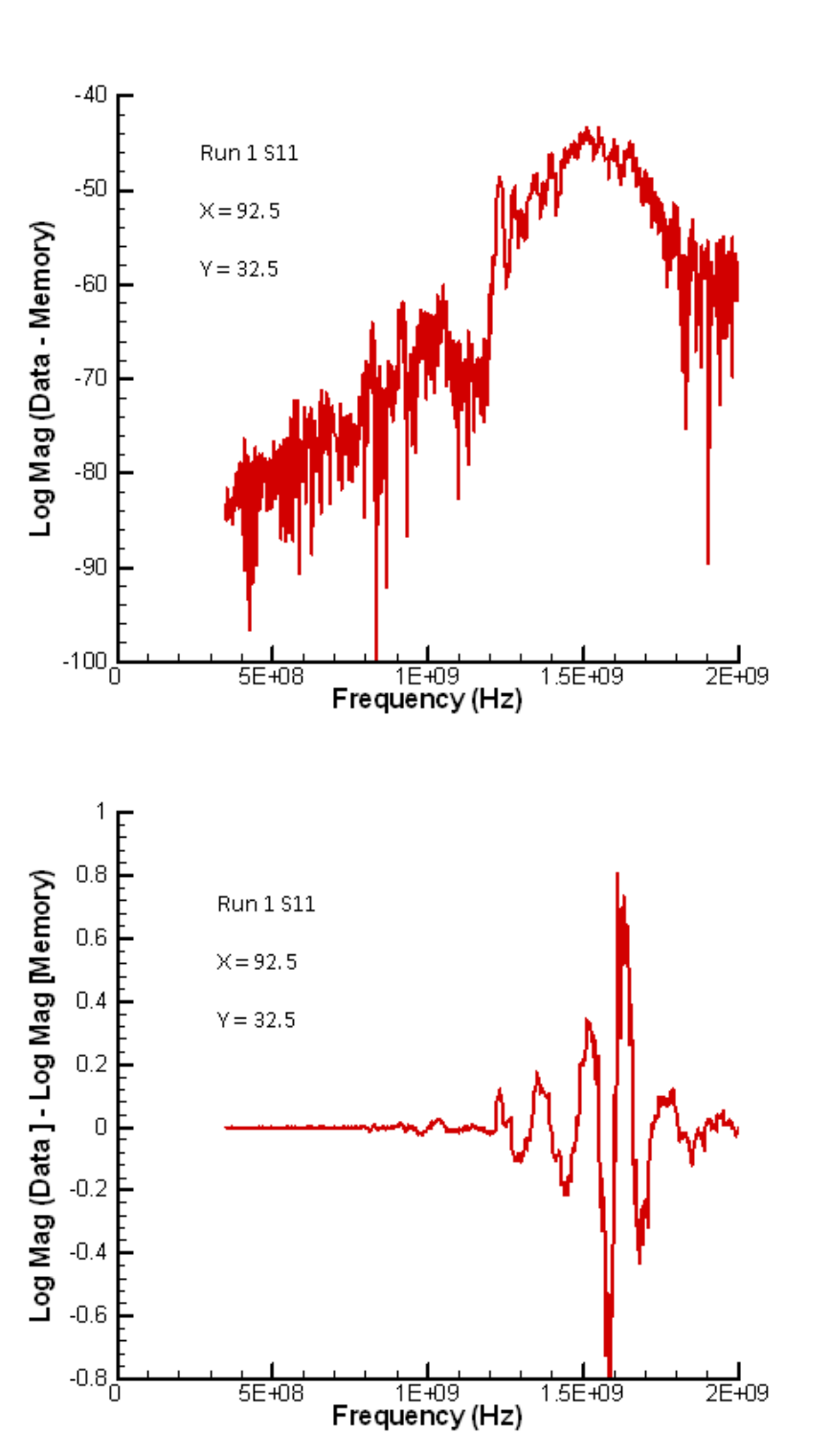


Figure 16: S_{11} data plots for $x = 92.5$ cm, $y = 32.5$ cm

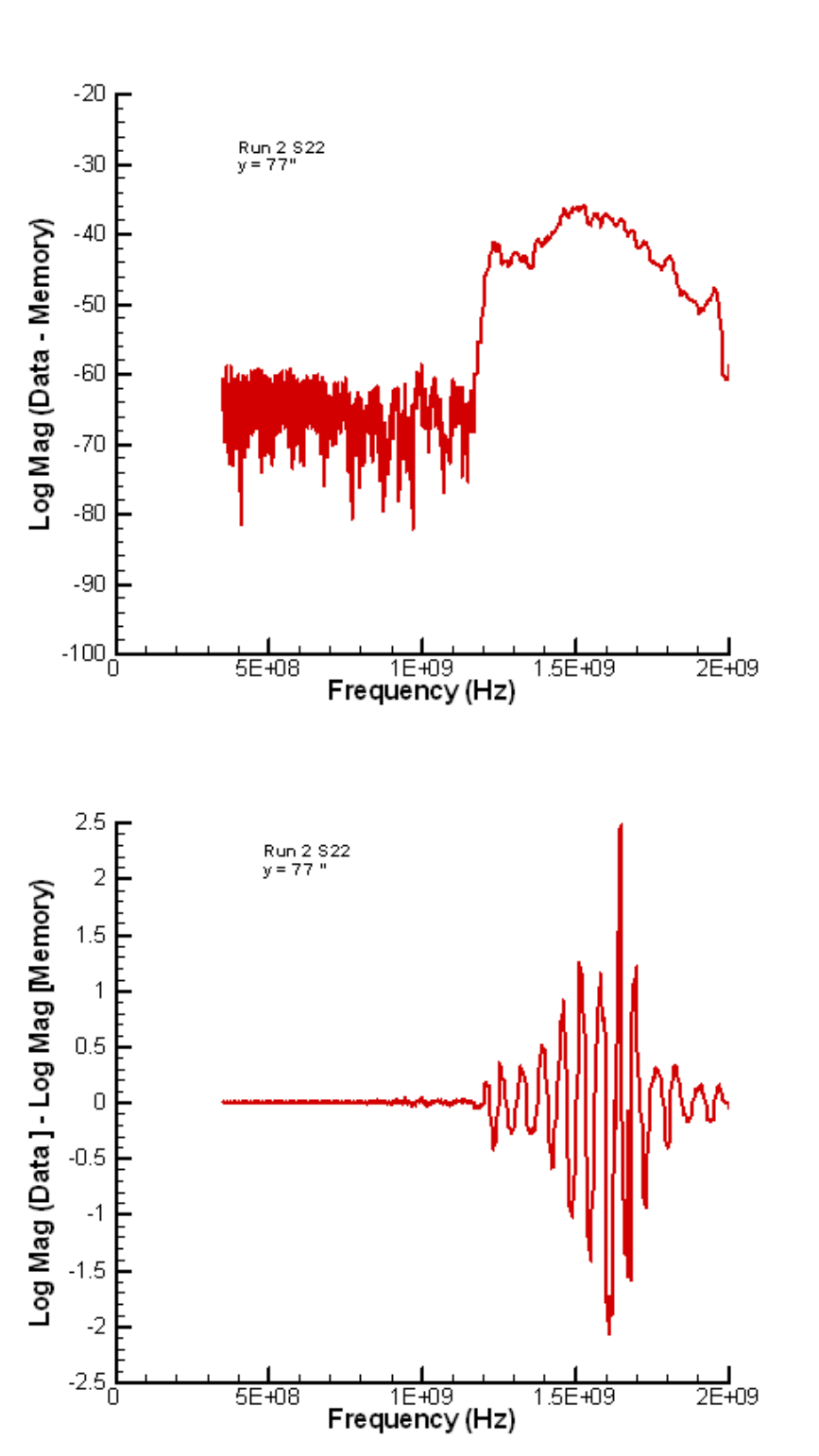


Figure 17: S_{22} data plots for $y = 196$ cm (on boresite)

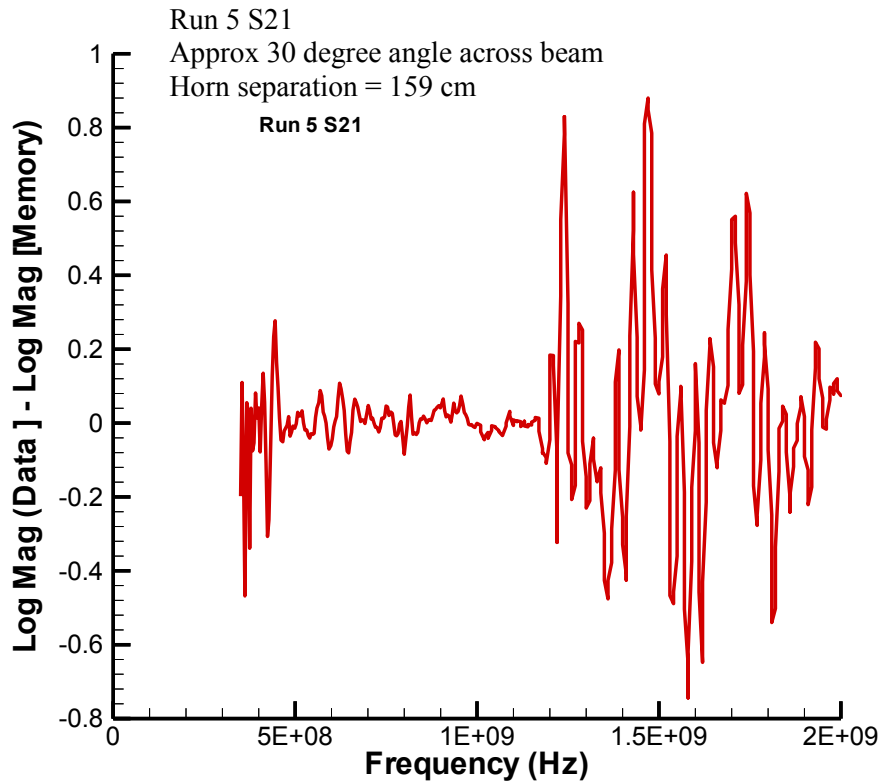
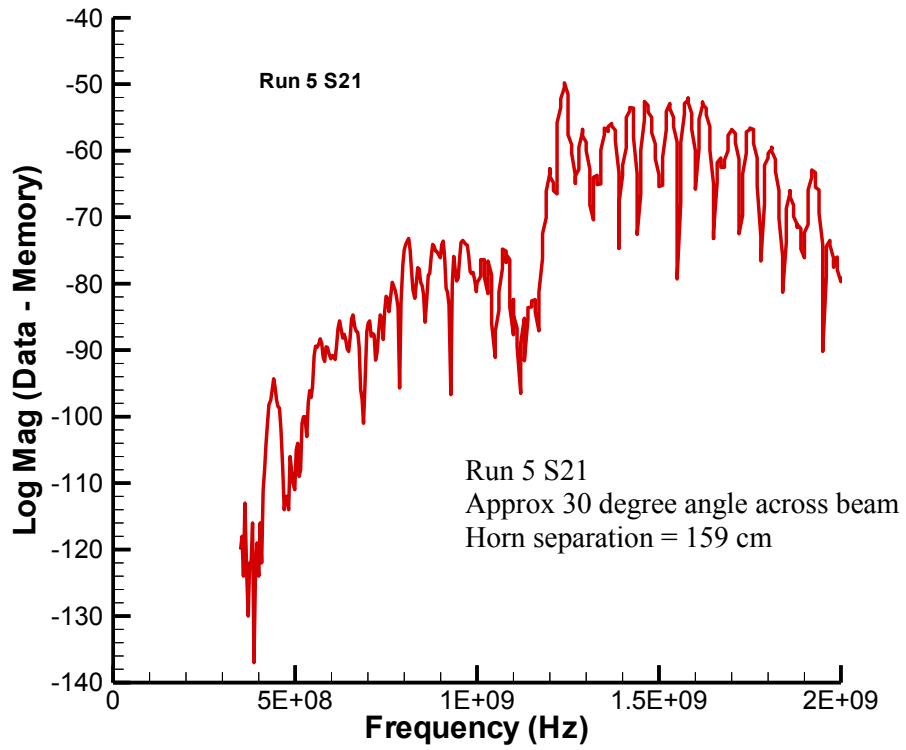


Figure 18: S_{21} data plots for $y = 159$ cm; 30 degree angle across beam

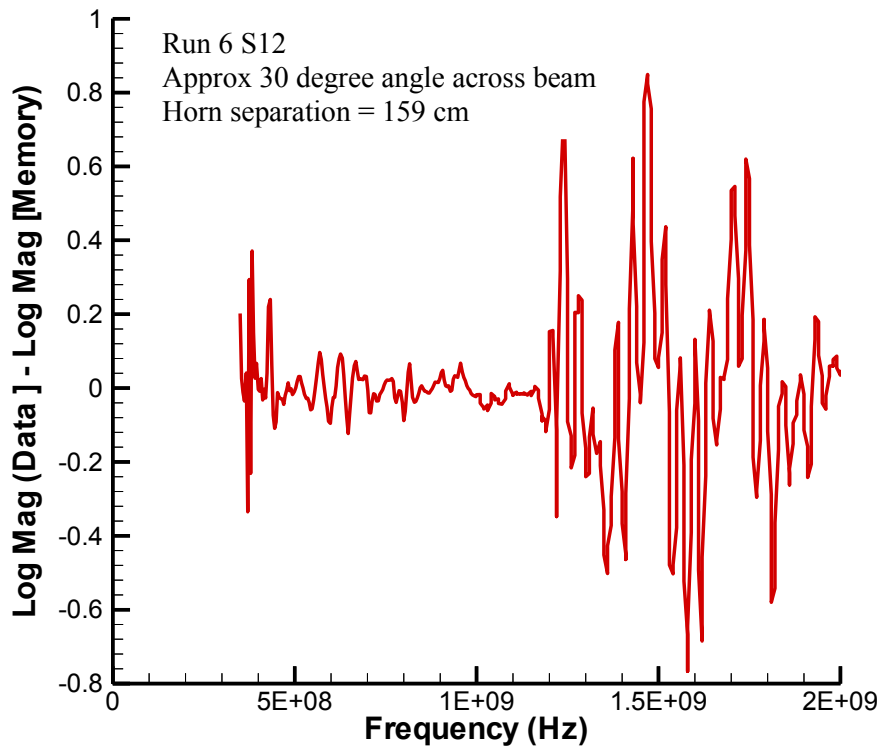
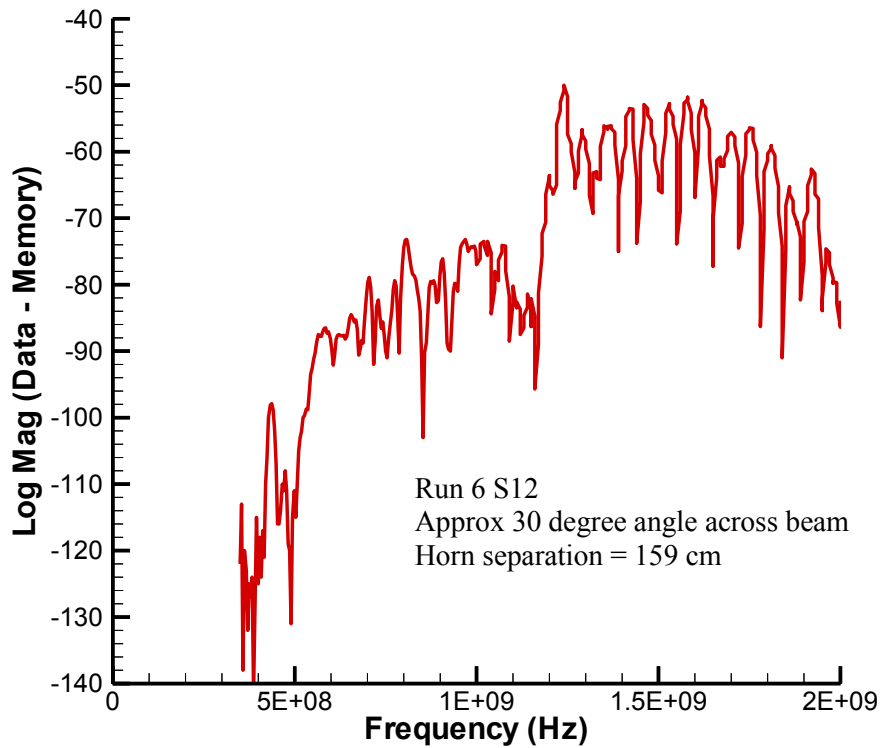


Figure 19: S_{12} data plots for $y = 159$ cm; 30 degree angle across beam

5 Conclusions and recommendations

5.1 Microwave attenuation and reflection

These experiments have shown that microwaves can detect the plasma produced by the radiation beam of the DRDC Ottawa GB-150C cobalt-60 source. Significant changes in the S_{11} and S_{21} signals measured using an Agilent E5071B Network Analyzer were observed. The results seem to indicate that the presence of the plasma produced by the radiation beam causes a small, frequency dependent phase shift in part of the beam. This causes a small oscillation in the received magnitude of the S_{11} and S_{21} signals. There was no indication of significant attenuation or reflection of the signal. The possibility of using phase shifts for stand-off detection of radiation has been discussed previously by Peurrung [17].

5.1.1 Recommendations for future work

Based on some calculations that were made in the early stages of this project, it was anticipated that the free electron densities would be high enough that the plasma frequency would be of the order of 500 MHz and that significant reflection of the microwaves would occur at frequencies lower than this. Further analysis revealed that these calculations were based on some false assumptions, and that accurately estimating the equilibrium free electron density around the GB-150C source was not a straightforward exercise. A first-order estimate taking into account ion production rates and typical free electron lifetimes made it clear that the free electron density would be much lower than first estimated. In spite of this conclusion the decision was made to investigate the transmission characteristics of microwaves in the plasma generated by the radiation source over the frequency range of 350 MHz – 2 GHz.

As discussed above, small but significant changes in the S_{11} and S_{21} signals measured using an Agilent E5071B Network Analyzer were observed. These changes appear to result from small phase shifts as the microwaves propagate across the beam. There was no indication of a significant attenuation or reflection of the signal over the frequency range examined. Based on these results, the use of microwaves in this frequency range for stand-off detection of radiation does not appear particularly promising although it should be noted that detection of the large radiation plumes above a nuclear reactor has been detected using microwaves in this frequency range. Detection of radiation over a widely dispersed area may thus be possible.

The following additional work could be considered in the future:

1. Examination of RADAR reflection from the plume over an operating nuclear reactor. These experiments might be done, for example, on the plume above one of Ontario's CANDU reactors.
2. Measurements at higher frequencies. In particular it is noted that measurements in the mm range have shown some success. Gopalsami et al [7] have reported using microwaves in the radiation in the 26.5 – 40 GHz for the remote sensing of ionized air and scientists at Argonne National Laboratory have reported [8] the detection of the weak radioactive cloud emanating from a nuclear power plant's ventilation stacks during normal operation at a distance of 9

kilometers. Based on other reported measurements, these measurements were probably made at a frequency of 94 GHz.

3. Microwave Attenuation and Reflection in the Presence of a Magnetic Field.

Based on work described in US patent 4,989,006, the absorption of microwaves can be greatly enhanced at certain frequencies by the presence of a magnetic field. In the presence of a magnetic field, there is a large attenuation [14] of microwaves propagating through plasma at the cyclotron frequency. This phenomenon could potentially be used to develop a system to detect radioactive contamination.

4. Ultra Wide Band (UWB) Propagation Measurements

It would be useful to investigate the potential of using UWB propagation measurements for the characterization of plasmas. Some work is available in this area [15,16]

5.2 Passive microwave emission at 1.42 GHz

In spite of our failure to detect passive emission from hydrogen at 1.42 GHz, previous work has shown that it can be detected at long range in the radioactive plumes above a nuclear reactor. It seems probably that the difference in the measurements is related to the much larger volume of the radioactive plume from the reactor. Further study is recommended if a much more dispersed (larger volume) radiation source can be found.

5.2.1 Recommendations for future work

Further study is recommended if a much more dispersed (larger volume) radiation source can be found. These experiments might be done, for example, by looking at the emission from the plume above one of Ontario's CANDU reactors.

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DRDC Ottawa has been investigating alternative radiation detection techniques under an Applied Research Project (ARP 10dp). As part of this project, proof-of-principle experiments were carried out with the assistance of March Scientific Ltd. The experiments examined the feasibility of two techniques: the use of RADAR to detect the increased free electron density in an elevated radiation field, and the passive detection of microwaves emitted from atomic hydrogen in water vapour. It was shown that the plasma produced by the radiation beam of a high-activity gamma source does result in a small, frequency-dependent phase shift in the microwave signal. Some recommendations are made for future work.

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