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# High Frequency Radar Astronomy With HAARP

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**Abstract**—At high frequency, radio waves will interact with space plasmas and surfaces of local astronomical objects, producing an echo that can provide new diagnostic data. The availability of high power radars operating at high frequencies opens a window for the remote investigation of our surrounding space environment. We discuss and illustrate this technique with some specific examples.

## I. INTRODUCTION

Over a period of several years, the High frequency Active Auroral Research Program (HAARP) transmitting array near Gakona, Alaska, has increased in total power from 300 kW to 960 kW (see Fig. 1). In the final configuration the total power of HAARP will be 3.6 MW, making it the most advanced and powerful high frequency (HF) radar facility used for research purposes. The basic science objective of HAARP is to study nonlinear effects associated with ionospheric modification by high power radio waves. These modification experiments are carried out at frequencies in the range 2.8 to 10 MHz. The HAARP phased array is designed to provide agility in power, modulation, frequency selection, and beam forming.

In recent experiments [1],[2],[3], we have begun to utilize the HAARP array for experiments in HF radar astronomy, i.e., to study regions and objects beyond the Earth's ionosphere. The objective of these investigations is to advance and discover new understanding of the physical characteristics and interactions in regions of our solar system that are accessible through high power radio wave transmissions. These regions include the solar corona and coronal mass ejections (CMEs), planetary hard surfaces (e.g., the Moon and asteroids), and astronomical plasmas (solar wind, magnetosphere, dusty plasmas). While our principal research tool will be the high power phased array provided by HAARP, we plan to have access to several other facilities providing state-of-the-art capabilities. We believe that this new window for radar investigations can provide new understanding of solar system phenomena.

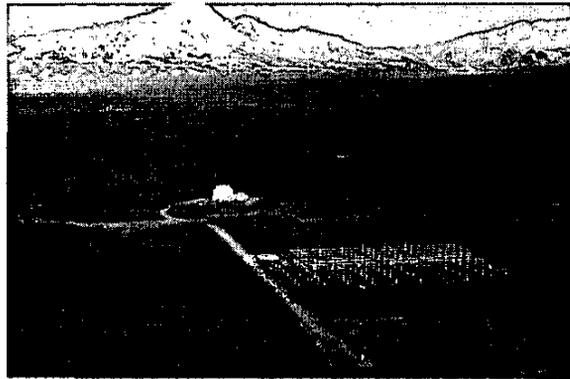


Fig. 1. The HAARP array.

## II. DISCUSSION

In this discussion we review several experiments that illustrate our objectives and approach to HF radar astronomy investigations. Some of these experiments have been done in collaboration with the NASA/WIND satellite and its HF radio wave receiver (the WAVES experiment). The unique orbit of WIND has provided a wide range of radial distances from Earth, including lunar flybys, over which we are able to study the interactions of radio waves transmitted from HAARP. The HAARP-WIND bistatic configuration has allowed new techniques for conducting HF radar experiments beyond the Earth's ionosphere. Other experiments are to be conducted with ground-based receiving arrays, such as the Wink HF array, operated by the University of Texas. We are also planning future experiments utilizing the Low Frequency Array (LOFAR) that will provide a large collecting area array for radio astronomical research.

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## HAARP Radiated Power Density vs Radial Distance in Solar Radii

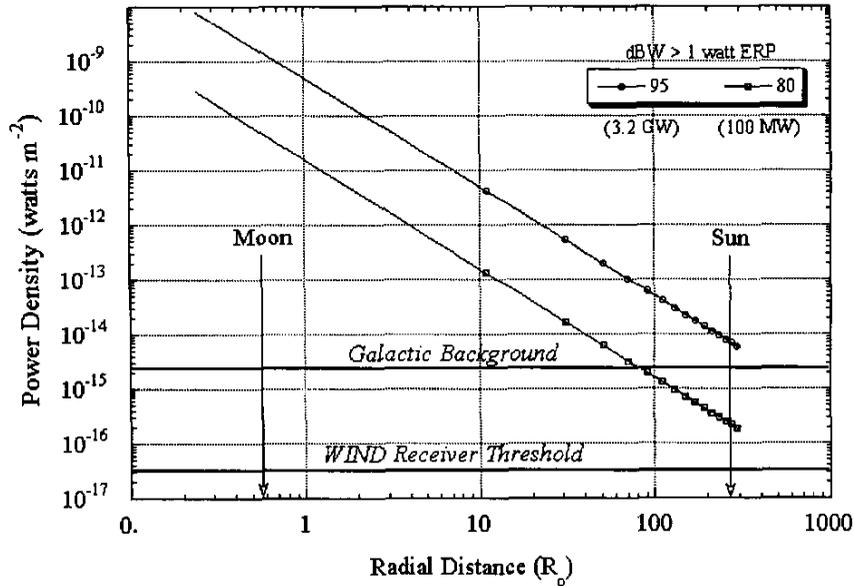


Fig. 2. The HAARP radiated power density versus range in solar radii.

The current and planned effective radiated power (ERP) levels of HAARP can be used to determine the radiated power densities with increasing distance from the Earth. In Fig. 2 we show the power density ( $\text{watts m}^{-2}$ ) expected in terms of distance from the Earth in solar radii ( $R_{\odot}$ ). As a measure of comparison, the receiver threshold for the WAVES experiment on board the WIND satellite is shown. Typically, the cosmic galactic background is the limiting background noise level at the frequencies of HAARP, and this level is also shown. The radial locations of the Moon and Sun show that if a satellite receiver like WAVES were located as far away as the Sun, it would be possible to detect HAARP signals, especially when the final power level of HAARP becomes available. At the current power level of HAARP, it is possible to detect radio waves at levels below the galactic background by using various integration techniques. Thus, for example, future satellite experiments with HF radio wave receivers will be able to perform studies of radio wave scattering in the interplanetary medium between the Earth and the Sun. Similar studies have already begun in the nearby solar wind where WIND is active.

### III. LUNAR ECHO

A specific example of a recent experiment is given in Fig. 3, which shows the ecliptic plane trajectories of the Moon and WIND spacecraft on September 13, 2001, when the spacecraft was approaching the Moon to use lunar gravity for

orbit perturbation. In a 2-hr interval, when the spacecraft was about 40,000 km from the lunar surface, the HAARP array illuminated the Moon with a series of 100-ms pulses at  $\sim 960$  kilowatts at a frequency of 8.075 MHz.

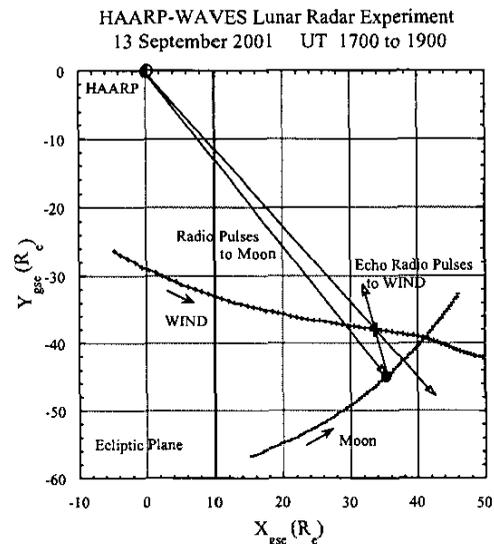


Fig. 3. HAARP pulses at 8.075 MHz received at WIND.

During the experiment, the HAARP transmission beam followed the Moon's apparent motion across the sky in order to keep both WIND and the Moon within the radar beam. Thus, the WAVES radio receiver on board WIND detected both the direct HAARP pulses as they passed by the spacecraft on their way to the Moon and the subsequent echo pulses from the lunar surface.

Fig. 4 shows a 5-s interval of data from this experiment. The timing of HAARP pulse transmissions was arranged so that the direct and echo pulses would not overlap. The echo signals are the lower intensity pulses between the direct pulses.

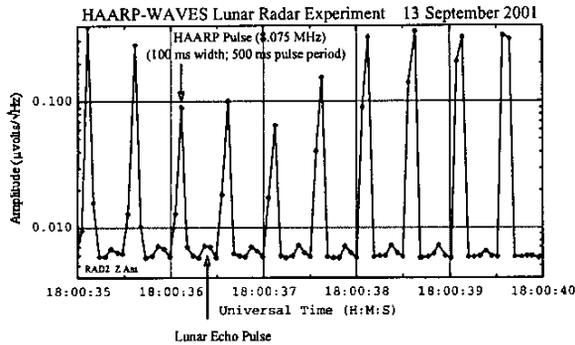


Fig. 4. WIND measurements of the HAARP direct lunar and echo pulses.

The relative intensities of the direct and echo pulses allow us to determine the lunar surface scattering cross-section. From a series of about 2000 radar pulses we are able to determine the lunar radar cross-section (relative to the geometric cross-section of the Moon) as  $\sim 0.15 \pi R_m^2$ , where  $R_m$  is the lunar radius. In addition, we obtained several peaks values of the cross-section at about  $\sim 0.5 \pi R_m^2$ . This experiment was done at the lowest radio frequency that has been used in echo studies of the lunar surface.

#### IV. SOLAR ECHO

The study of the Sun's corona and its dynamical processes is possible with HF radar investigations. The electron densities of the corona and large-scale phenomena like CMEs are such that radio waves in the high frequency range will provide diagnostic echoes. We also expect that the frequency shift imposed on the echo signal from a CME will provide a direct measurement of the earthward-directed velocity, thereby providing a good estimate of the arrival time at Earth. Because CMEs are responsible for the largest geomagnetic storms at Earth, causing power grid blackouts, satellite electronics upsets, and degradation of radio communications circuits, having accurate forecasts of potential CME-initiated geomagnetic storms is of practical space weather interest. The concept of using HF radar to detect CMEs that are moving toward the earth is illustrated in Fig. 5.

#### Solar Radar Detection of Earthward-Directed Coronal Mass Ejections

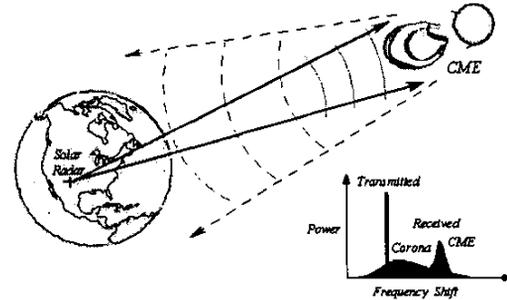


Fig. 5. Concept of detection of coronal mass ejections by solar radar.

A test of solar radar techniques at HF was conducted by an international consortium of interested investigators in recent years [4]. The facilities used were the SURA HF transmitting array in Russia and the UTR2 radio astronomical array in Ukraine. The SURA array is an ionospheric modification facility with power level comparable to that of the present HAARP array. The UTR2 array is currently the world's largest receiving array ( $\sim 150,000 \text{ m}^2$ ) at HF and is used for both solar and galactic radio astronomical studies. The SURA-UTR2 bistatic configuration provided the solar radar for our experiments. In Fig. 6, we show the experiment conducted on 21 July 1996. In this case, the radio wave transmission was done at two frequencies close to 9 MHz with oppositely phased modulation of 20-s ON-OFF. Because of the large range involved, it is possible to transmit for the entire round-trip travel time to the Sun and back (about 16 min) before turning off the transmission and beginning reception of the solar echo. The echo is necessarily very weak and is buried in noise. Thus it is necessary to integrate the full 16-min interval of recorded noise following the transmission in order to detect the echo signal. The upper panel of Fig. 6 shows a 1-min interval of the modulated transmission from SURA. The two lower panels of Fig. 6 shows the dynamic spectra of the signal received at UTR2 after the 16-min integration. Careful examination and comparison of the phase of the power intensity in the two spectra indicate the presence of the expected echo signal. Another way the echo signal may be identified is by integrating the spectral data with respect to frequency so that a total power time-profile is determined. In Fig. 7, we show the resulting time-profile and compare with the opposite ON-OFF phases of the two frequencies transmitted. This figure is equivalent to using pattern recognition to identify the echo signal as containing the same ON-OFF variation as the transmitted signal. The detection of an echo signal from the Sun and the spectral information provide a proof-of-principle test of the radar technique for studying coronal plasma dynamics.

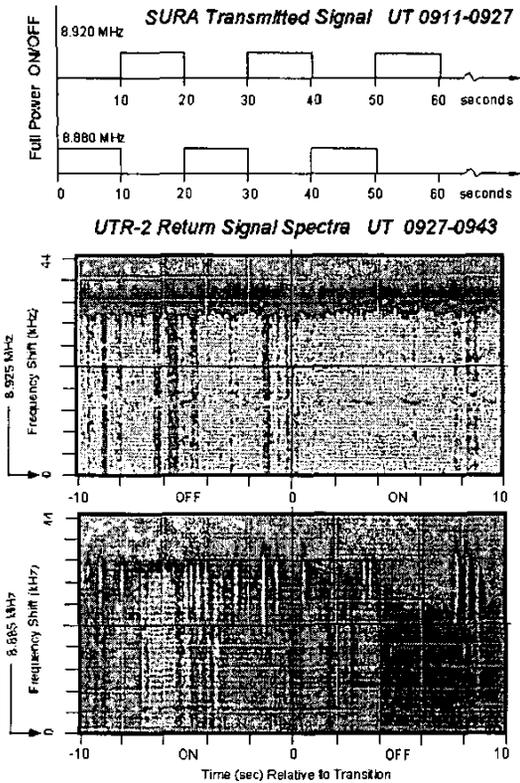


Fig. 6. The SURA/UTR-2 solar radar experiment.

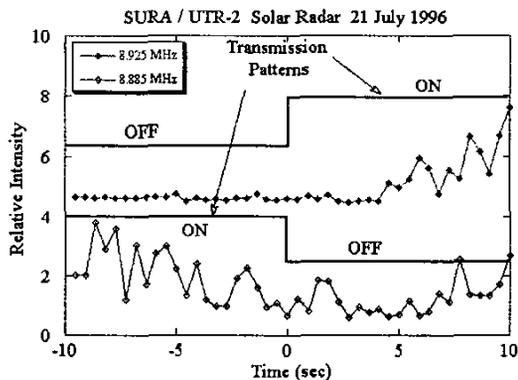


Fig. 7. The integrated solar radar echo.

By increasing both the power transmitted and the area of the receiving array, a solar radar configuration is possible that allows better signal-to-noise ratio than was possible in our initial tests. Of particular interest is the configuration of HAARP with the planned Low Frequency Array. The LOFAR facility will be designed to have an effective receiving area of about 1 km<sup>2</sup> at the frequencies transmitted by HAARP. In this bistatic configuration, HAARP-LOFAR (HALO) will have the performance required for detailed investigations of solar coronal dynamics. This performance is shown in Fig. 8, in which we plot the signal-to-noise ratio for HALO as a function of the integration time required to achieve a specified detection level, such as 5 dB. The plot is based on assuming a thermal background noise level associated with the noise temperature of the Sun at 10 MHz. In addition, two (typical) values of the radar cross-section of the Sun are used along with the present and final power levels of HAARP to calculate the performance curves. The solar radar cross-section is referenced to the geometric cross-section of the visible solar disk. For example, the performance plots show that if LOFAR were available today and used in conjunction with the current power level of HAARP (~0.96 MW), a 5-dB detection threshold would be possible after 10 seconds of integration of an echo signal returned by a solar radar cross-section of 1. With 10-s integration, it is possible to acquire about 96 independent measurements during the 16-min round-trip travel time to the Sun and back. Thus, we are able to resolve time variations in the solar radar cross-section on 10-s time scales, which would provide new information on the plasma dynamics associated with coronal processes, such as CMEs. The performance plots also suggest that for cases where the solar radar cross-section is larger (thus returning a stronger echo), the integration time to achieve the 5-dB threshold can be reduced, thus increasing the time resolution. Other assumptions can be made regarding noise backgrounds and beam sizes and these will result in different performance curves. However, the combination of high power (HAARP) and large effective receiving area (LOFAR) are the principal factors that make possible the remarkable performance indicated.

A facility like HALO would, of course, be used to study many other phenomena of the solar system besides the Sun's corona. Such a ground-based radar observatory would complement space-based studies of the solar system. In Fig. 9, we list some of the solar system phenomena that can be studied with HF radar investigations. This figure illustrates the increasing range of access to solar system astronomical phenomena provided by the high effective radiated power of HAARP.

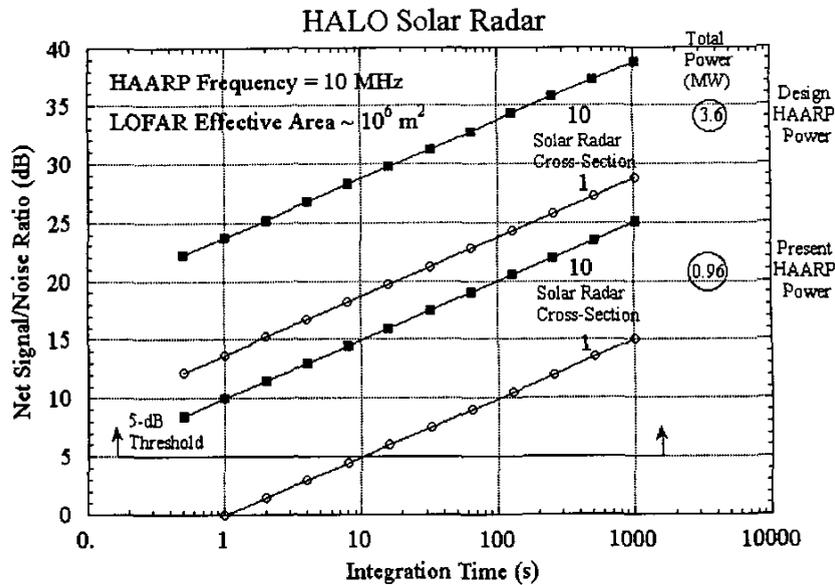


Fig. 8. The performance calculation of the HAARP-LOFAR (HALO) bistatic solar radar.

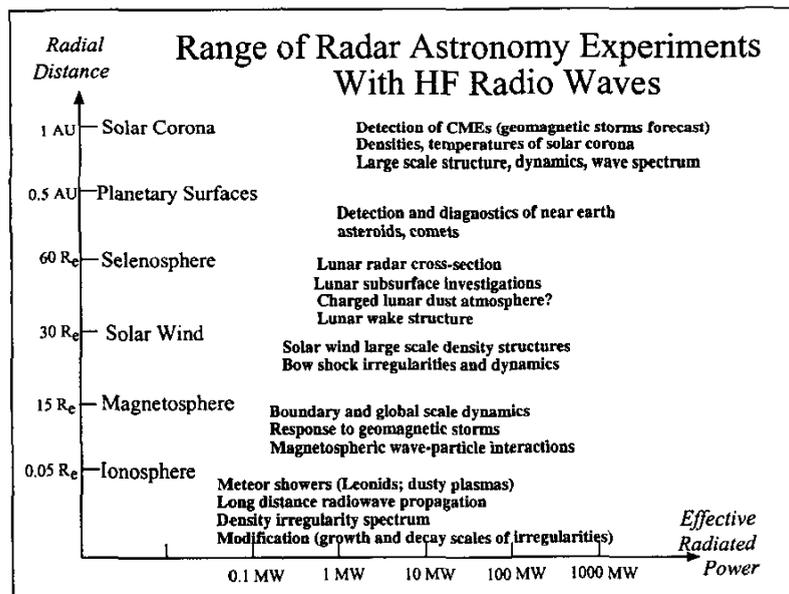


Fig. 9. The research objectives of HF radar astronomy.

## VI. SUMMARY AND CONCLUSIONS

We have discussed a new window on HF radar astronomy and illustrated its use for conducting experiments in our solar system. The high power levels of HAARP have provided access to more distant regions of space and objects within the solar system, allowing new radar experiments in conjunction with large area receiving arrays and satellite HF receivers. The investigations already conducted demonstrate the great versatility of HAARP to address a wide range of scientific problems associated with space plasmas and planetary hard surfaces. We expect to continue and expand our experiments in using the radar echo technique to remotely diagnose and measure our space environment.

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