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ISY-METS Rocket Experiment

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Abstract: The ISY-METS (International Space Year-Microwave Energy Transmission in Space) rocket experiment was promoted by the SPS (Solar Power Satellite) Working Group of the Institute of Space and Astronautical Science (ISAS) in Japan. The ISY-METS is an advanced version of our previous MINIX rocket experiment. Its purposes are to verify a newly developed microwave energy transmission system for space use and to study nonlinear effects of the microwave energy beam in the ionospheric plasma environment. The S-520-16 sounding rocket carrying instruments for the ISY-METS was successfully launched at 16:00 on February 18, 1993 from the Kagoshima Space Center of the ISAS. All the instruments functioned perfectly. A high power microwave of about 800 W was transmitted by a newly developed active phased array antenna installed on a mother section of the rocket payload accurately toward a separated daughter one. The wave observation in the HF range indicated that natural plasma waves are enhanced by the microwave energy through nonlinear interactions.

1. INTRODUCTION

Higher human activities naturally need much higher power availability. Thus, the demand of power will continuously increase toward the next century, so that the power shortage will occur on the ground. To overcome the shortage an idea of the Solar Power Satellite (SPS) was proposed by P.E. Glaser in 1968 [1]. The SPS can supply a huge electric power generated by solar cell to the ground in the form of microwave. Thus, the microwave wireless energy transmission is one of the most key technologies for the SPS. It is useful not only for the SPS but also for much smaller scale energy transmissions from power satellites to other spacecraft and for many other ground-based applications.

Further investigations and developments are required to establish the technology of wireless power transmission. The control of microwave energy beam is important to accurately aim at its receiving antenna regardless of any distortion of antenna structure and of moving target location at a high speed. An active phase array antenna is the most flexible and desirable to meet the requirement of energy transmission with high pointing accuracy. However, such an active phased array antenna has not yet been developed for the wireless energy transmission.

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Since the space environment is not in perfect vacuum but is filled with plasma, the propagation characteristics of microwave energy beam is not so simple as in the vacuum. A highly intense electric field of the microwave beam causes a modification of the medium in such a way that the beam suffers a filamentation of itself. This will be a serious problem for long-distance energy transmission as the nonlinear plasma nature will modify the propagation path and thus give rise to a mistransmission to a wrong target other than the receiving site. Such filamentation instabilities have not been studied well and no quantitative prediction is available. Much experimental works are necessary as well as theoretical ones. We succeeded in the MINIX (Microwave lonosphere Nonlinear Interaction eXperiment) rocket experiment in 1983 to study associated nonlinear plasma effects of the high power microwave energy beam in the space environment [2, 3, 4]. The interesting and useful results about nonlinear plasma wave excitations were obtained, though the microwave was transmitted by a simple system driven by a magnetron.

We believe nothing is more effective for the promotion of relevant technologies than to operate step-by-step experiments and thus accumulate critical data. We have newly developed an active phased array antenna for the microwave energy transmitter in the MILAX (MIcrowave Lifted Aircraft eXperiment) demonstration [5] and ISY-METS rocket experiment. In this paper, we will describe the summary and initial results of the ISY-METS.

We have changed the name of our rocket experiment from our original naming of METS to ISY-METS, because it was nominated by the Power Committee of IAF as one of the Space Power Test Projects in the International Space Year, 1992.

2. Objectives of the ISY-METS rocket experiment

The ISY-METS rocket experiment has the following two objectives. One is an in situ demonstration of the microwave energy transmission to verify the technological capability of the newly developed active phased array antenna in the space environment. The microwave energy transmission using a computer control system was conducted toward the daughter section as a target. An attempt of energy concentration on one point in space was also made using the beam steerability by computer controlled phase shifters. We also succeeded in a ground-based energy transmission test of the developed system by using a small model airplane before the rocket launch. The airplane flew around at a height of about 10 m only by the received microwave energy. The space and ground tests can provide a good opportunity of demonstrating a feasibility of the wireless energy transmission.

The other objective is to study nonlinear plasma effects of the high power microwave energy beam in the space environment. If the microwave intensity is of the order of that used in the usual telecommunication, very little effect to the ionospheric plasma would be expected. However, the microwave power density for the power transmission is twelve orders of magnitude higher than that for the telecommunication. Therefore, strong nonlinear effects are expected such as plasma heating [6] and nonlinear scattering which cause excitations of various plasma waves [7, 8]. The

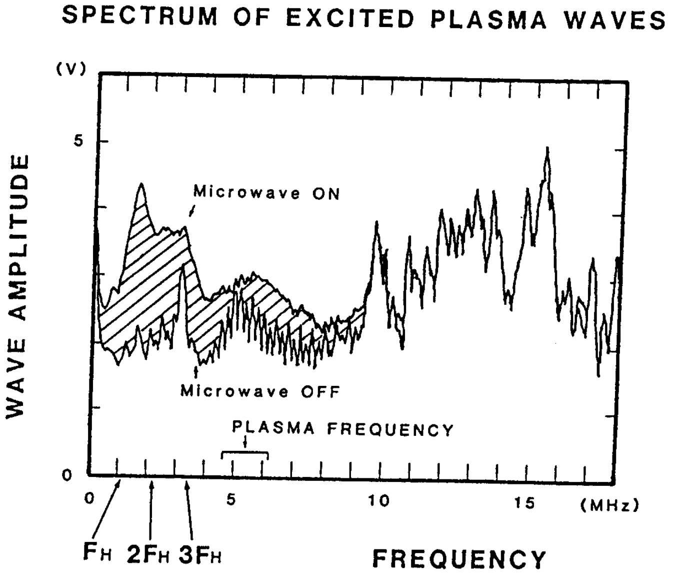

Fig. 1. Dynamic spectrum of plasma waves observed by HF receiver in the MINIX.

ISY-METS rocket experiment provides an unique opportunity of an advanced scientific research on this subject.

A similar rocket experiment was carried out in 1983 by the name of MINIX. The MINIX was the first successful rocket experiment dedicated to the study of the microwave energy transmission in space. Its primary objective was to study the nonlinear reaction of the space plasma environment to the intense energy beam in the form of the microwave at a frequency of 2.45 GHz. Though the microwave was transmitted by a very simple truncated waveguide connected to a magnetron used in home microwave ovens, the experiment provided interesting and useful results concerning nonlinear plasma wave generation. The MINIX was carried out by a daughter-mother rocket, which was separated near the apogee of the trajectory. The diagnostic package to measure the plasma reactions of the microwave was installed on the daughter section, while the microwave transmitters were on the mother. The microwave at a power of 780 W was transmitted intermittently into the ionospheric plasma. The observed wave spectrum shown in the Fig. 1 indicates the excitations of plasma waves in the HF range by the microwave, judging from comparison with the natural wave spectrum. Two types of plasma waves were excited around the odd half of a local electron cyclotron frequency and around a local electron plasma frequency.

3. Organization of the METS research group

A research group to promote the ISY-METS rocket experiment was organized as one of the sub-groups in the SPS Working Group of ISAS in 1991, which was organized under the Engineering Committee of ISAS to investigate the future SPS. The research area of the SPS Working Group covers scientific and engineering subjects to realize the SPS and to predict environmental phenomena caused by the SPS.

Since the ISY-METS rocket experiment was nominated by the Power Committee of the International Astronautical Federation (IAF) as one of the Space Power Test Projects in the International Space Year, 1992, we naturally need international collaborations and supports. We called for the international participation by announcing the ISY-METS project. It is also essential for the SPS to establish international cooperative relationships.

Seven researchers and one company have applied to our announcement of opportunity for the ISY-METS experiment as follows:

1. P.E. Glaser, Vice President, Arthur D. Little, USA.
2. P. Koert, Chief Engineer, ARCO Power Technologies Inc., USA.
3. K. Chang, Prof., Texas A&M University, USA.
4. B. Thide, Prof., Swedish Inst. Space Physics, Sweden.
5. J-S. Chang, Prof., McMaster Univ., Canada.
6. V.Prisnjakov, Prof., Dniepropetrovsk State Univ., CIS.
7. V.Vanke, Prof., Moscow State Univ., CIS.
8. Aerospace Division, Nissan Motor Co., Japan.

Various kinds of participation in the ISY-METS were expected as international collaborations. Because Profs. B. Thide and J-S. Chang showed an interest in the plasma physics, we are planning to work together on the data analysis of the ISY-METS in the future. The applicants, except for two, have an interest in the microwave energy transmission. The International Space University (ISU), which conducted a Space Solar Power Program design project in Japan in 1992, arranged for NASA support for the design and construction of an ISU/Texas A&M space rectenna. The proposal of the ISU/Texas A&M university was accepted to actually install their rectenna on the METS rocket for reception of the microwave transmitted from the mother section in space.

4. Development of the ISY-METS Instruments

The microwave power transmission needs a huge transmitting antenna to concentrate the microwave energy on the receiving antenna. The huge antenna is likely distorted due to many kinds of thermal sources and mechanical vibrations. The active phased array antenna is an essential technique for the wireless power transmission, because it can control phase shifters to correct wrong phases occurred by any distortion of the antenna. Besides, it can accurately steer the microwave beam toward moving targets, and concentrate the microwave energy on one point. The concentration to make a very strong electric field can make it possible to perform various experiments on nonlinear interactions between the microwave and the ionospheric plasma. Thus, we have newly developed a microwave transmission system of the active phased array antenna for the space experiment.

The ISY-METS was planned to use a mother-daughter rocket similar to the previous MINIX. The mother section was mainly used for the MicroWave high-power Transmitter (MWT), while the daughter section carried a MicroWave Receiver (MWR: rectenna) and diagnostic packages to detect plasma responses. The

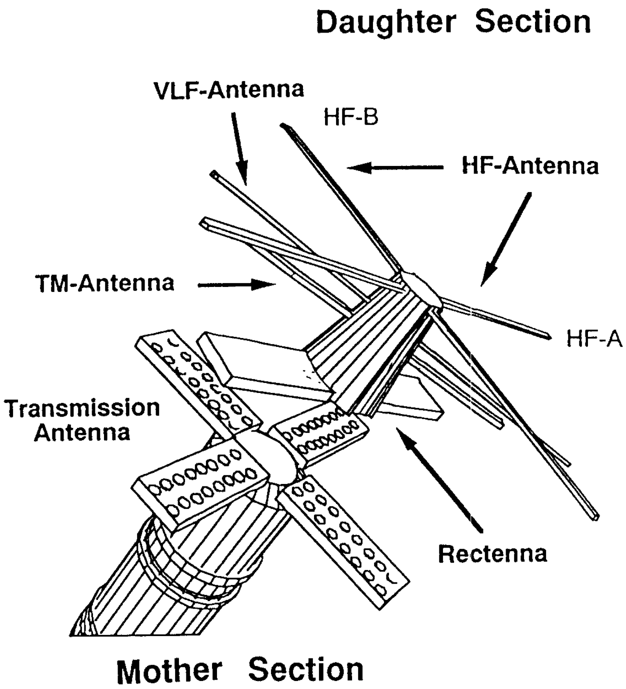

Fig. 2. Conceptual configuration of the ISY-METS payload section

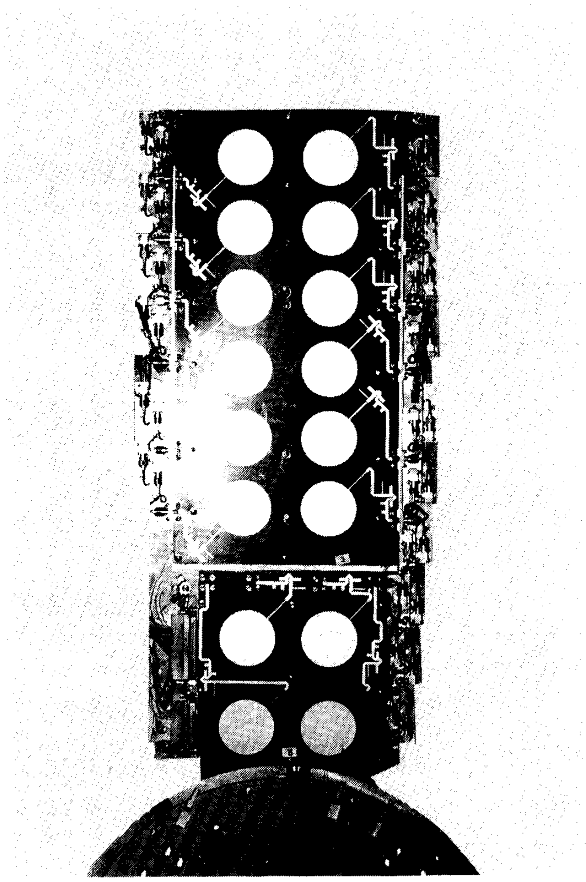

Fig. 3. Picture of the MWT paddle

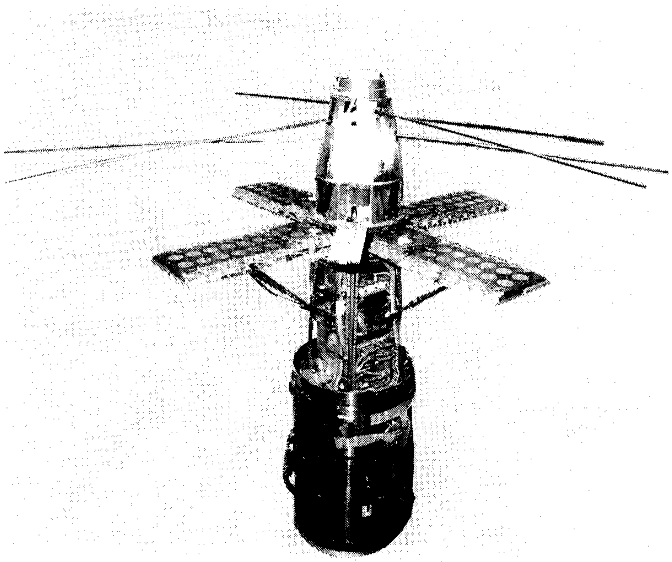

Fig. 4. Picture of the ISY-METS payload with the deployed antenna paddles

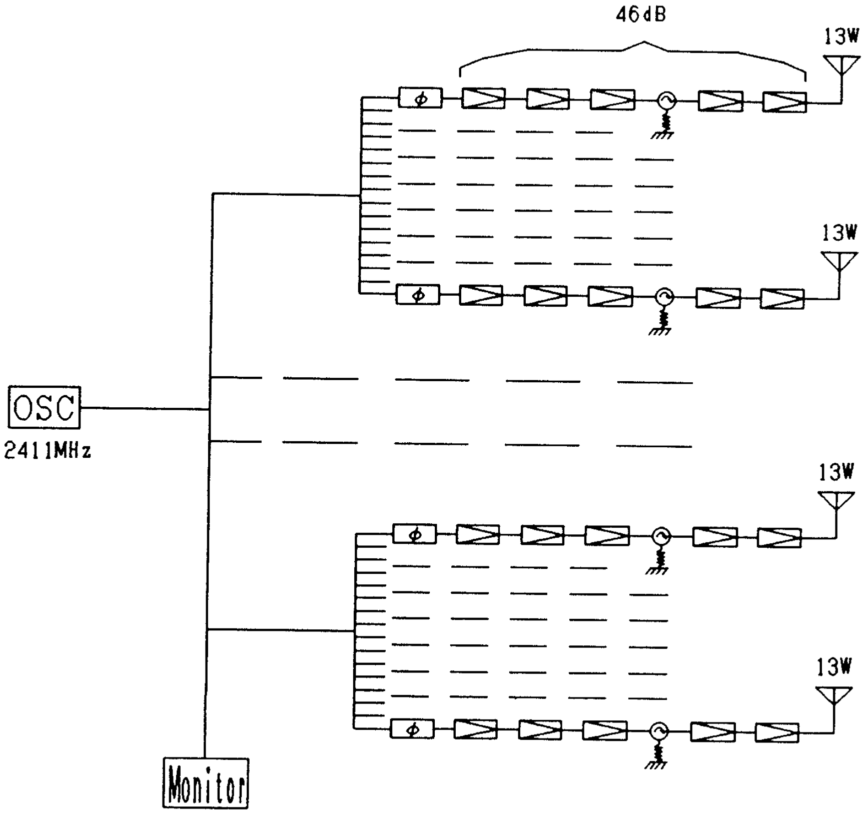

Fig. 5. Block diagram of the MWT

conceptual configuration of the ISY-METS payload section is shown in Fig. 2.

The new transmitter system can radiate a stable and purely monochromatic microwave of 2.41 GHz. The transmitting antenna consists of four antenna paddles as shown in Fig. 3, each mounting sixteen circular microstrip antennas of a linear

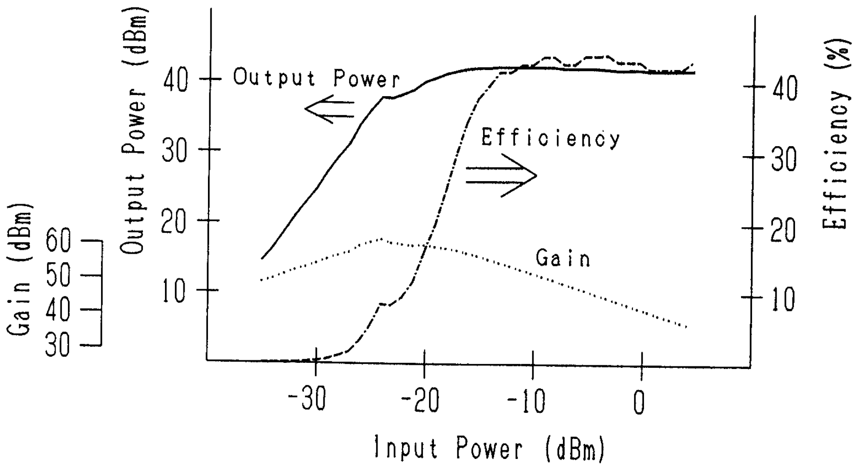

Fig. 6. Output power, efficiency and gain of the amplifiers

polarization with a microstrip feeder. The antenna paddles are deployed in a cross shape on the top of the mother section. Figure 4 shows a picture of the deployed antenna paddles.

A block diagram of the transmitter system is shown in Fig. 5. The microwave generated by an oscillator is distributed to four antenna paddles and a power monitor. The distributed microwave is divided to sixteen high gain amplifiers through a power divider. Each of the high gain amplifiers is composed of five-stages of GaAs-FET amplifiers with a 4-bit digital phase shifter. A 200IB FET is used for the last stage of the amplifiers. The 200IB FET is an amplifier of an F-class type, which can amplify the microwave with a very high efficiency to an output power above 13W. The typical output power, efficiency and gain of the five-stage amplifiers are shown in Fig. 6. It indicates the amplifier can output a power of 16W in an efficiency of 42%. The maximum efficiency of our 200IB FET reaches 64%, though the average efficiency is about 40%.

Output phases of the transmitting microwave are controlled by the 4-bit digital phase shifters, which are composed of three switched line type phase shifters and a loaded line type one. The phase shifters in the ISY-METS are controlled not by a retrodirective antenna but by a computer. The reason is that the computer control system can adequately change both of the power density and the direction of microwave for technical and scientific purposes, while the retrodirective antenna can focus the microwave only to the pilot signal transmitter.

An optical position sensitive detector is installed to measure relative direction between the mother and daughter sections. The computer determines the most suitable direction of microwave beam from the data of the position sensitive detectors, separation speedometer and magnetometers. The transmitting phases of the antenna elements are individually calculated with the distances between the antenna elements and the concentrated point.

Preparatory functional checkouts for the microwave transmitter were performed in the radio anechoic chamber of the Communication Research Laboratory (CRL).

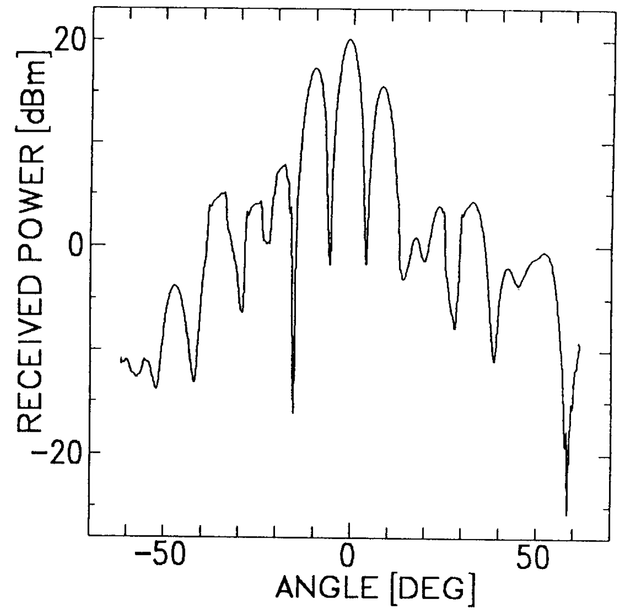

Fig. 7. Antenna pattern of the MWT

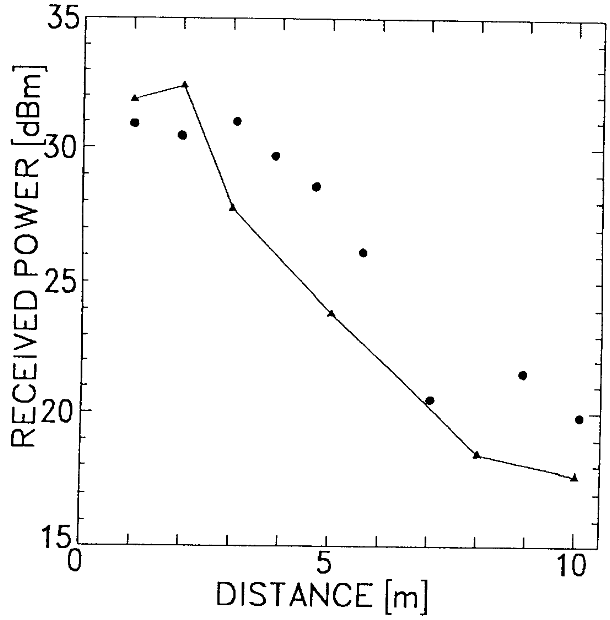

Fig. 8. Received power by a dipole antenna at different distances

Figure 7 shows the measured radiation pattern when the microwave is concentrated on one point 10 m apart from the antenna. The level of the first side-lobes are high due to the cross shape of the transmitting antenna. The results, however, show that the radiation patterns of the transmitting antenna are almost consistent with the calculated ones. They indicate the active phased array antenna has a capability of focusing the microwave energy around a specific spatial point by controlling the digital phase shifters independently. Figure 8 shows concentrated power received by a dipole antenna at different distances from the transmitting antenna by a solid line, while circles indicate the flight data described later. It indicates the high power of 32.5 dBm

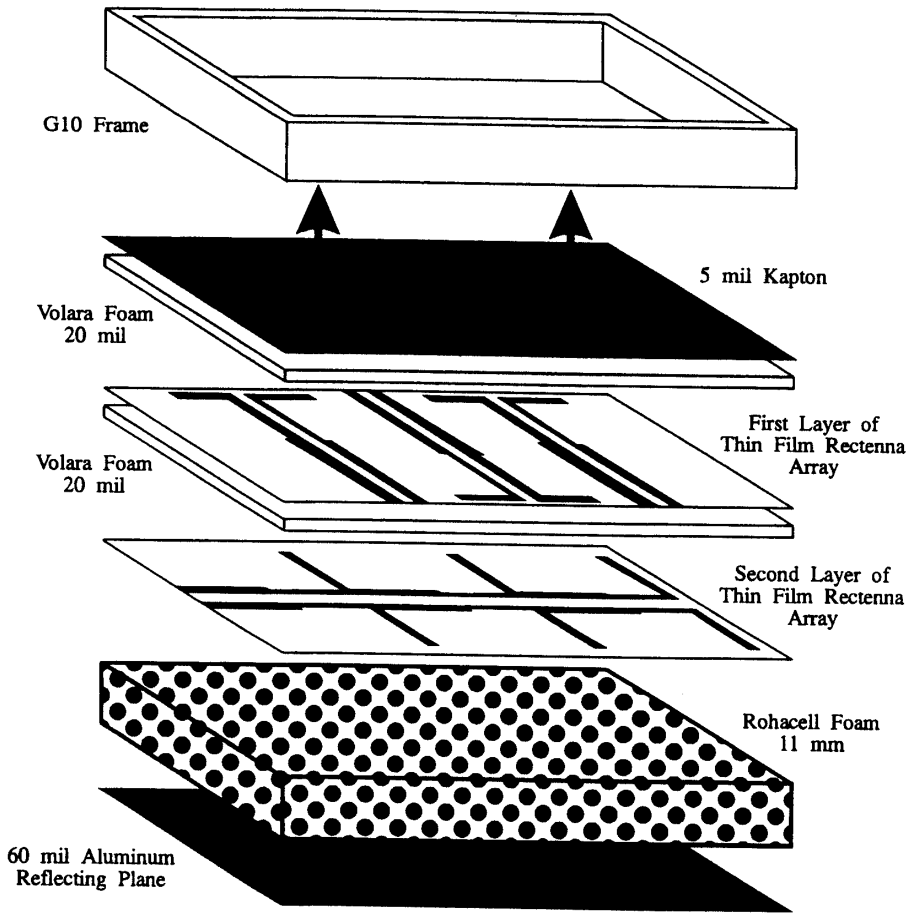

Fig. 9. Structure of the rectenna developed by ISU/Texas A&M University

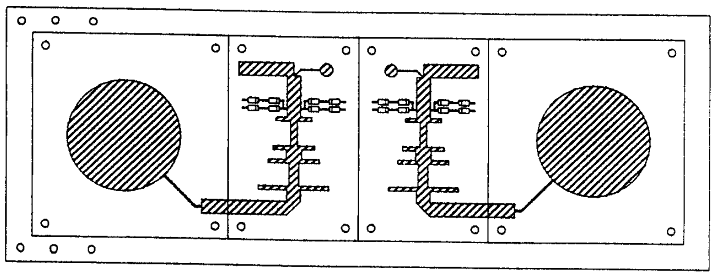

Fig. 10. Structure of the rectenna developed by CRL

can be concentrated at a distance of 2m.

Two types of the rectenna were installed on the daughter section to receive the microwave transmitted from the mother section. One was developed by the research group located at Texas A&M University, while the other was by the CRL. The ISU/Texas A&M University rectenna shown in Fig. 9 was composed of a pair of three dipole antenna arrays. On the other hand, the rectenna of the CRL was composed of two circular microstrip antennas shown in Fig. 10.

The diagnostic package consists of four scientific instruments to observe plasma phenomena excited by the high power microwave. In order to reveal nonlinear interactions between the high power microwave and the ionospheric plasma, they can measure parameters of plasma (electron density and electron temperature) and plasma waves in a HF range of 500kHz to 10MHz, and a VLF one of 100Hz to 15kHz. The antennas of the HF, VLF and Impedance probe were installed on the top of the daughter section.

5. Experimental Operations

The sequence of experiment in flight consists of two experimental phases (see Fig. 11). All the antennas for plasma observation and microwave receiver except the microwave transmitting antenna paddles are deployed soon after a nose cone is released from the rocket at 55 sec after the launch. The antenna paddles are deployed 2 sec later so that the first phase of the experiment starts to examine the nonlinear plasma wave excitations in the natural ionosphere while the daughter section is kept to connect with the mother during the first phase.

The microwave energy can be concentrated into one point near the daughter section to effectively observe the nonlinear plasma instabilities. Four experimental modes of the microwave transmission are planned to observe characteristics of excited plasma waves. The microwave is transmitted in two fixed directions, one of which is normal to the antenna and the other is at an oblique angle of 30 degrees from the normal direction. The microwave is concentrated in points along the geomagnetic field from the daughter section in the third experimental mode in order to examine parallel propagation of the plasma waves. The microwave is also concentrated in points perpendicular to the geomagnetic field to examine perpendicular propagation in the fourth mode.

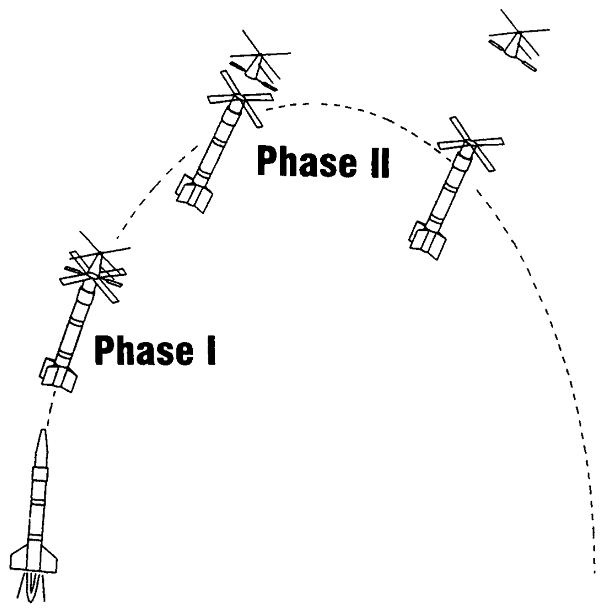

Fig. 11. Experimental schedule of the ISY-METS

The daughter section carrying the diagnostic package is separated in the next experimental phase at 222 sec by very weak springs as slowly as possible from the mother, because the effective area for the experiment with the intense microwave field is very limited only in the vicinity of the transmitter. The direction of the microwave beam is controlled toward the rectenna onboard the daughter for the energy transmission demonstration. The transmitting phases of all the antenna elements are calculated by the computer by measuring the relative separation speed and the direction of the daughter section. The distance between the daughter and the mother sections can be calculated with the separation speed, because the daughter section goes away in the inertial motion. The direction of the daughter section can be measured with a two-dimensional position sensor.

6. The initial results of the experiment

All the instruments installed on the S-520-16 sounding rocket worked perfectly. The microwave transmitting antenna paddles and all the antennas for the plasma diagnostics were deployed on schedule.

The MicroWave transmitter (MWT) began to radiate the microwave of approximately 800 W from 65 sec after the launch. The microwave was intermittently transmitted with each interval of 7 sec followed by 3 sec pause in order to distinguish the effects by the microwave from natural phenomena.

One example of the dynamic spectra of the plasma waves in the HF range is shown in Fig. 12. The ordinate is the relative level of the observed power, while the horizontal axis is the frequency up to 10 MHz. The left panel in the figure indicates the dynamic spectrum of the ionospheric plasma illuminated by the high power microwave for 7 sec from 20 sec after separation, while the center one shows the spectrum in the natural ionosphere. The right panel shows the difference between the left panel and the center one. The center panel shows the existence of the natural plasma waves in a frequency range from 3.5 to 5.5 MHz around a local electron plasma frequency. Note that the altitude profile of the electron density measured by the impedance probe is shown in Fig. 13. It is clear that the natural plasma wave was enhanced by the microwave as shown in the left and right panels.

The excitations of two types of the plasma waves were observed in the MINIX shown in Fig. 1. One is those around the local electron plasma frequency. The other is

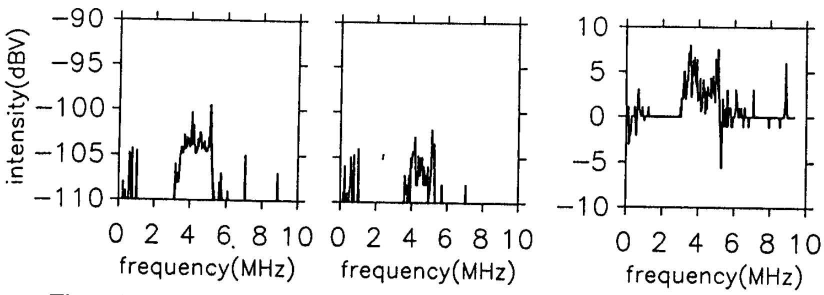

Fig. 12. Dynamic spectra of the plasma waves in the ISY-METS

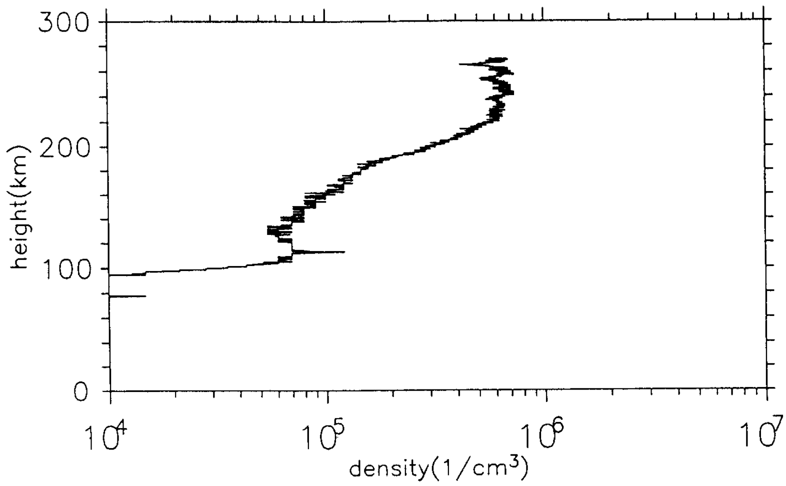

Fig. 13. Altitude profile of the electron density

around the odd half of the local electron cyclotron frequency which decreases with the increase of rocket altitude. The former is supposed to be the same as the plasma wave observed in the ISY-METS. However, the latter was not detected in the ISY-METS. The truncated waveguide antenna used as the transmitting antenna in the MINIX had a so small aperture of the antenna (95 mm×55mm) that the local electric field on the aperture (15W/cm^2) is 150 times as strong as the maximum power density (0.1W/cm^2) concentrated by the active phased array antenna of the ISY-METS. It is resonable to infer that the plasma wave around the odd half of the electron plasma frequency observed in the MINIX was excited by the extremely strong electric field around the aperture of the antenna.

The daughter section was separated by the weak springs from the mother at 222 sec after the launch. The relative speed between the daughter and mother was measured to be 8.6 cm/sec. The daughter section shifted away almost along the symmetrical axis of the mother section. The attitude of the daughter was not changed by the separation, so that the rectenna kept facing the transmitting antenna. The MWT resumed the microwave transmission 10 sec after the separation. The power levels received by the rectennas are shown by circles in Fig. 8, which indicates that the output of the rectenna is higher than the power levels obtained in the pre-launch test. Because the higher voltage of the batteries was supplied to the MWT than that of the power supply used for the pre-launch test. The results verified that the MWT functioned perfectly in space, because the received power decreased with increasing distance between the daughter and mother sections agreeing to the pre-launch test.

7. Conclusion

We succeeded in the development of the active phased array antenna which is the essential technique for the microwave energy transmission. It was installed on the S-520-16 rocket to verify the performance of the microwave beam control in space. The microwave transmitted from the mother section was successfully received by the rectennas on the daughter one, which was separated at a speed of 8.6 cm/sec.

It is also a very important objective of the ISY-METS to examine the nonlinear interactions between the high power microwave and the ionospheric plasma. The HF receiver showed the clear differences in the frequency spectra of the plasma waves when the microwave transmission was on and off. The data obtained by the ISY-METS will be investigated in detail to bring us new information not only on the nonlinear plasma physics but also useful data for the future Solar Power Satellite.

Acknowledgement

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