IAC-11.C3.1.5

Orbiter Demonstration Plan for Solar Power Satellite of Sandwich Type

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Abstract

We fortunately succeeded in the JAXA/ISAS sounding rocket experiment on the “Furoshiki” deployment, the retrodirective antenna and the crawling robots on the deployed mesh in January, 2006, as we presented the result at the last IAC in Valencia. The S-310-36 sounding rocket was launched to verify our newly proposed scheme to construct huge structures under microgravity condition in space. The rocket experiment had three main objectives, the first objective of which was to verify the Furoshiki deployment system, the second was to test the retrodirective antenna system to correct the distortion of the structures in a long range from space to the ground as mentioned above and the last is a microgravity test of the crawling robots on the deployed mesh.

We are planning the next demonstration for the Solar Power Satellite after the sounding rocket experiment. We are sure the fundamental beam control system of the microwave has been established by the sounding rocket experiment, which is one of the most important and critical issues to realize the SPS. Our next plan is an orbiter experiment to carry out the beam control test with a pilot signal from the ground. We are launching small many satellites to extend the Furoshiki deployment, which can work a test bed to investigate the functions of the Sandwich panels and robotic technologies related to the SPS. We launch many Sandwich panels with the antenna element to work as an active phased array antenna after the construction of the large mesh. Each antenna element, which receives the pilot signal transmitted from the large parabola antenna on the ground, transmits a radio wave of the different frequency from the pilot signal by controlling the output phase to the ground. This space experiment is the first trial in the world to construct the real small Solar Power Satellite.

1. Introduction

The various concepts of the SPS have been proposed. We proposed the SPS with sandwich panels. As shown in Fig. 1, the solar cells generate electricity from the sunlight which is concentrated by the reflector-1 and reflector-2 on the one side of the sandwich panel, while the microwave is transmitted by the power transmission antennas from the other side. The sandwich panel has excellent two advantages.

1. Heavy items can be decreased such as DC transmission line and the rotary joint which connects the electric power from power generation to power transmission system.
2. It is easy to build the Solar Power Satellite because the module structures are simplified.

However, a few issues remain for practical use of the sandwich panel. We describe our developments on the power transmission on the panel. We believe we have advanced one step to achieve the SPS with the sandwich panels by our developments.

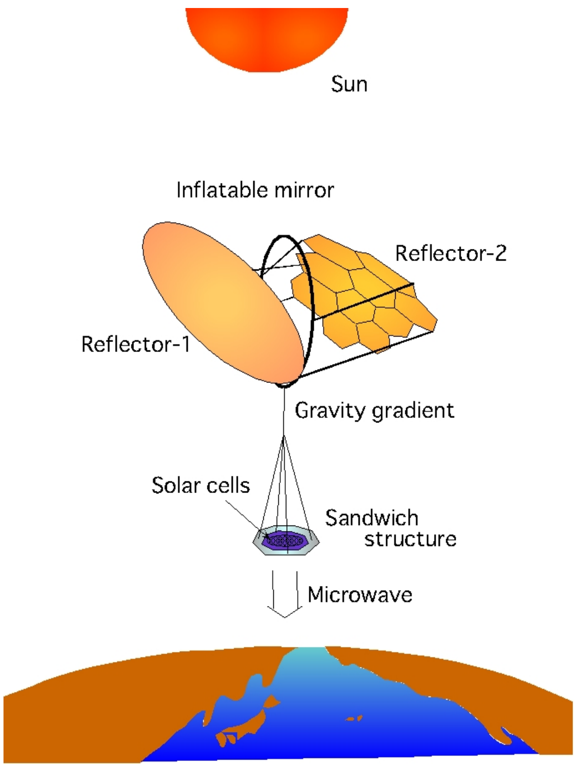

Fig. 1 The concept of the SPS with the sandwich panels

2. Development of the sandwich panel

Two issues which are the heat radiation, transmission power, must be chiefly improved here for the sandwich panel.

It is expected that the temperature of the Solar Power Satellite is high because the conversion efficiency of the solar cell is low. When the conversion efficiency of the solar cell is 35[%], the remaining of the obtained solar energy is changed to heat. We adopt slot antennas as the transmitting antenna on the sandwich panel in order to increase the efficiency of the heat radiation. The slot antenna has a lot of surface area where heat can be radiated compared with other antennas. The detailed design of the slot antenna is described later.

We aim to supply the electric power of 1[GW] as the commercial power supply by the sandwich SPS. We estimate the power transmission beam collection efficiency in rectenna that receives the microwave on the ground is 85[%] and the RF-DC conversion efficiency of rectenna is 90[%]. Therefore, the total transmission power should be about 1.3[GW] in the sandwich SPS. We design the sandwich panel so that the distribution of the transmission power conforms to 10[dB] gauss distribution.

3. Calculation of the transmission power

The size of the sandwich panel is about 50[cm] by 50[cm]. The whole transmitting antenna of the regular hexagon at the diameter of 1[km] is filled with a lot of the panels. The antenna elements are arranged on each panel so that the antenna interval should be 0.75λ anywhere. When the antenna interval is below λ, the grating robe doesn't appear in the antenna radiation pattern. We arrange the antennas at the regular triangle of 0.75λ. This alignment method is called as "triangular array of 0.75λ". We calculate the output electric power and the electric power density of each antenna here. We assume the power transmission antennas are arranged from the center of the regular hexagon in the diameter of 1[km] to the outer as shown in Fig. 2 in order to calculate it easily.

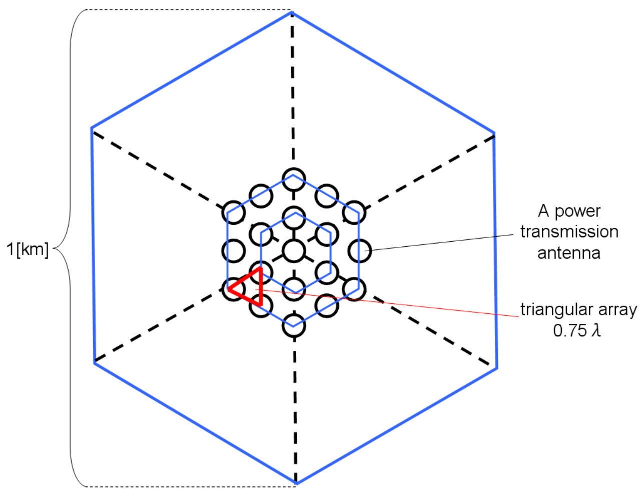

Fig. 2 The power transmission side of the Solar power Satellite

The length of the antenna is $\lambda_g/2$, and the space between the antenna elements is 0.75λ, where λ is 12.2[cm] and λ_g is 7.4[cm] because 2.45[GHz] is used as the frequency of the power transmission wave. Therefore, 0.75λ is 9.2[cm]. The number of the required power transmission antennas can be calculated to be about 89 million.

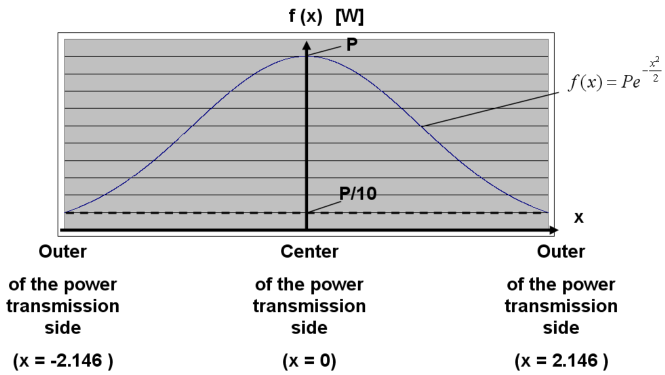

Fig. 3 The electric power distribution radiated from the whole transmitting antenna

The transmission power distribution of antennas on the diagonal of the regular hexagon section is shown in Fig. 3. The maximum output electric power of one antenna is P[W] at the center of the power transmission side of the Solar power Satellite and the minimum output electric power of one antenna is P/10[W] at the edge of the transmitting antenna because it conforms to 10[dB] gauss distribution.

The power P can be obtained by calculating of the total power of the transmitting antenna because we understand the total transmission power of the transmitting antenna is about 1.3[GW] as described above. The power P is 18.7[W]. In other words, the maximum output electric power of one antenna is 18.7[W] (42.7[dBm]). In addition, the maximum electric power density of one antenna is obtained by dividing P by the size of the transmission antenna. The power density is about 4[kW/m^2]. We decide to design the transmitting power from the panel to be 1[kW] on the panel size of 50[cm] by 50[cm] for the practical SPS.

4. Design of the power transmission panel

The whole transmitting antenna of the Solar Power Satellite has the structure of a regular hexagon in the diameter of 1[km]. The transmitting antenna does not consist of one big module but small unit panels, which are about 50[cm] by 50[cm]. We design the thickness and weight of the panel as thin and light as possible because it can reduce the launching cost and the operating cost of the SPS. The reason to divide the transmitting antenna of the Solar Power Satellite with the small unit panels is to detect the phase of the pilot signal from the ground by mounting the phase control system in each module, and to increase the accuracy of the retrodirective beam control. We introduce the antenna element that composes the power transmission panel. The antenna element that composes the power transmission panel is mainly three items as described below.

4.1. Power transmission antenna

The alignment of the power transmission antenna is designed to keep the triangular array 0.75λ. The slot antenna is adopted as the power transmission antenna because slot antenna has a high advantage on the heart radiation. Fig. 4 shows the slot antenna. 2.45[GHz] is the frequency of the power transmission wave.

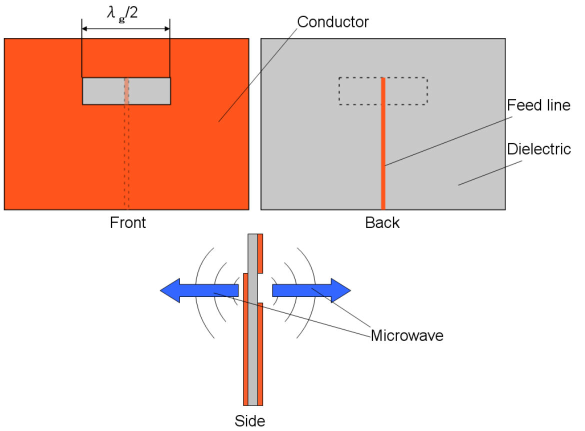

Fig. 4 The slot antenna

The slot array antenna has the simple structure that the conductor on the substrate is cut as the slot. The slot antenna generates the magnetic current by feeding power to the feeding power line, and radiates the power transmission wave by the magnetic current as shown in Fig. 4.

The size of the slot is different from the theoretical estimation because of the influence of the fractional shortening. The actually adjusted size of the slot is 1.1[cm] in length and 3.6[cm] in width. The gain is 4.72[dBi], and VSWR is 1.69. Fig. 5 shows the antenna pattern. The slot antenna radiates the electric wave in both (front and back) directions as shown in Figs. 4 and 5.

4.2. Pilot signal reception antenna

The receiving antenna for the pilot antenna should be installed on the same surface as the transmitting antenna. The slot antenna is used as the receiving antenna for the pilot signal because of the same reason of the transmitting antenna. The frequency of the pilot signal should be 1.225[GHz], which is a just half frequency of the transmitting microwave. The actually adjusted size of the slot is 2.3[cm] in length and 8.0[cm] in width. The gain is 5.68[dBi], and VSWR is 1.89.

4.3. High power FET amplifier

The transmitting power of 42.7[dBm] is necessary in each antenna as described above. Therefore, the high power FET amplifier is required to output to each antenna element. We have already developed the high efficient FET amplifier in our laboratory last year. Table 1 shows the characteristic of the high power FET amplifier. It indicates that the developed high power FET amplifier has the sufficient performances for the practical SPS.

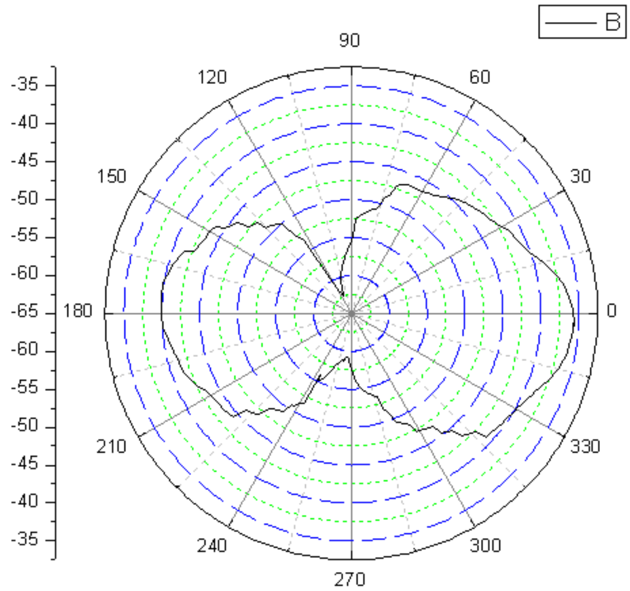

Fig. 5 The pattern of the slot antenna

Table 1. The characteristic of the high power FET amplifier

Input	16.4[dBm]
Output	45.7[dBm]
Drain Efficiency	53.5[%]
Gain	29.3[dB]
Gate Current	1.76[A]
Drain Voltage	50[V]

4.4. Configuration of the power transmission module

The schematic views of the power transmission module are shown in Figs. 6, 7 and 8.

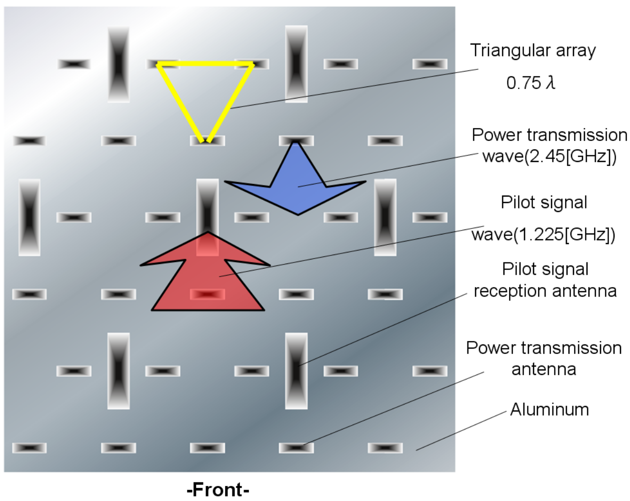

Fig. 6 The design of the power transmission module(front)

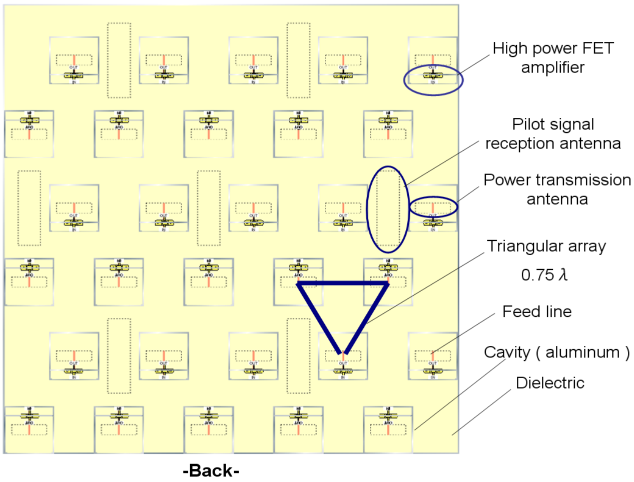

Fig. 7 The design of the power transmission module(back)

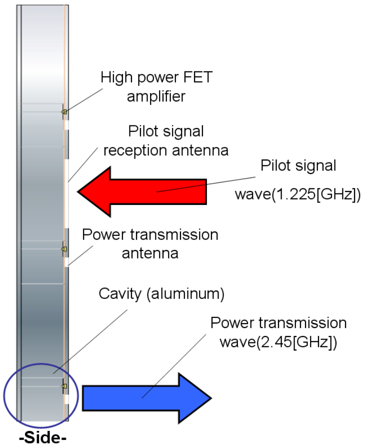

Fig. 8 The configuration of the power transmission module(side)

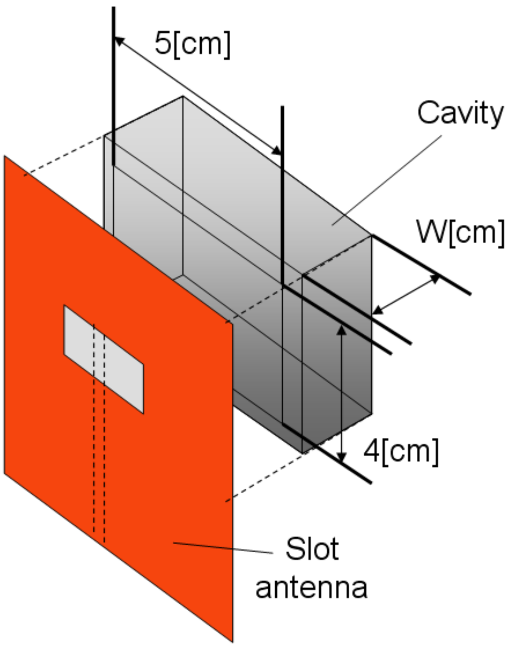

Fig. 9 The slot antenna with cavity

The front of the power transmission module is the simple structure as shown in Fig. 6. The transmission antennas and the receiving antennas are arranged in a regular triangle. As shown in Figs. 6 and 7, the space between the centers of the slots is 0.75λ. The size of the transmission module is adjusted so that the form of a triangular array can be kept between the two modules. The transmission module is 48.24[cm] long, 46.54[cm] wide. The alignment of high power amplifiers and the size of the cavity are limited due to the triangle array configuration. Then, the cavity is 5[cm] long, 5[cm] wide.

4.5. The power transmission antenna with the cavity

The cavity with the slot antenna is needed for the power transmission antenna as mentioned above. Then, we design the slot antenna with the cavity. The cavity is 5[cm] long, 4[cm] wide. Then, we made the slot antenna with the cavity as shown in Fig. 9, and measured the characteristic of the antenna.

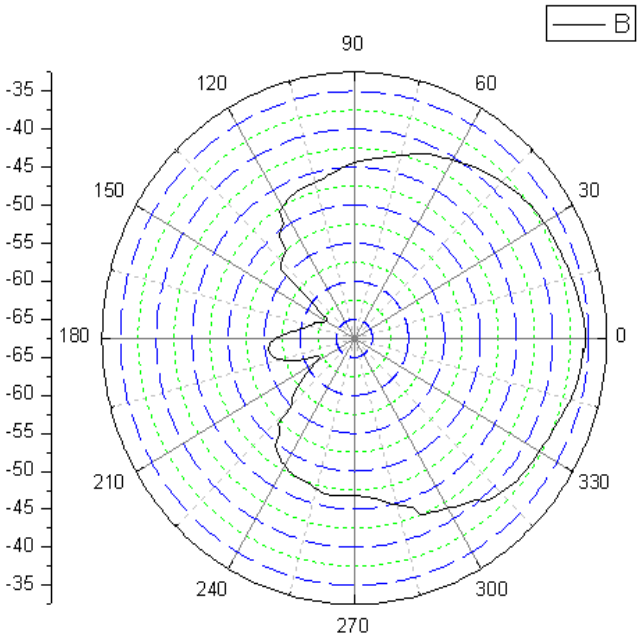

Fig. 10 The pattern of the slot antenna with cavity

We examined the relationship between the thickness W of the slot and VSWR of the antenna element. The result was as shown in Table 2. It shows that the VSWR is the minimum value and reach to the practical level (3 or less) when W is 4[cm]. Therefore, the thickness of the cavity should be 4[cm].

Table 2. The correlation between W and VSWR

W[cm]	VSWR
1	7.42
2	3.72
3	2.81
4	2.46
5	2.70

The gain and the pattern of the slot antenna with the cavity whose thickness is 4[cm] are measured in the anechoic chamber. The gain is 4.62[dBi] and it is rarely different from the gain of the slot antenna without the cavity. Fig. 10 shows the antenna pattern. It indicates that the radiation is one direction compared with the case without the cavity.

5. Next future project

We are planning the next project after the sounding rocket experiment. The next target is an orbiter experiment, because the experimental period by the sounding rocket is too short to verify the developed technologies for the Solar Power Satellite. The objectives of the next experiment should be the first demonstration on the first real demonstration of the Solar Power Satellite. The experimental orbiter is to generate the electric power by the solar cells, to convert it to high power microwave and to transmit the microwave to the ground. That is a small Solar Power Satellite, but it is the real Solar Power Satellite.

The first step is shown in Fig. 11(a) to deploy a huge mesh in the space over 500 m in diameter. In the second step, many sandwich panels, each of which has the solar cells on one side of the panel and the microwave transmitter on the other side, are launched toward the mesh and attached to the allocated position on the mesh. The sandwich panels are desired to be fabricated in the international collaboration. Finally, the first Solar Power Satellite could be realized by assembling a lot of the sandwich panels on the mesh.

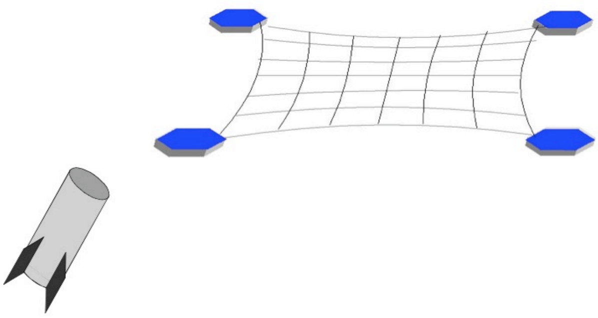

Fig 11(a) First step : Deployment of the huge mesh over 500m in diameter.

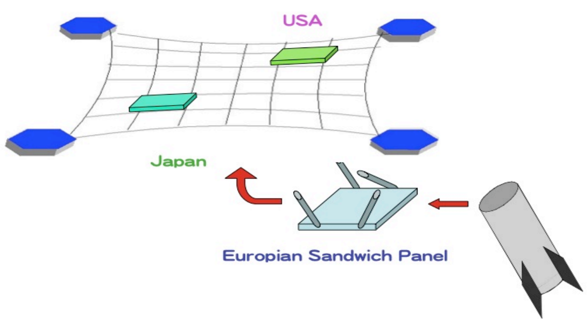

Fig. 11(b) Second step : Launches of many sandwich panels in the international cooperation.

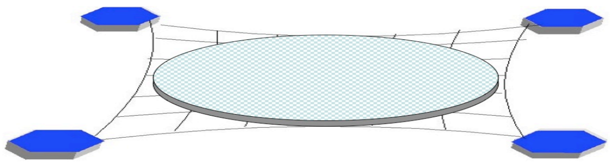

Fig. 11(c) Final step : The first real Solar Power Satellite could be realized.

7. Conclusion

We succeeded in the rocket experiment to develop the new scheme to construct the huge structures for many useful applications using the Furoshiki satellite with the crawling robots. Especially, the new retrodirective antenna system successfully functioned in the rocket experiment. We are now planning the next space demonstration using an orbiter to realize the first real Solar Power Satellite.

We could explain the feature of practical sandwich SPS by describing the concept of SPS with the sandwich panels and the issues for practical use. In addition, we could describe the possibility of the practical use of sandwich SPS by the calculation of the transmission power and the transmission power density of each power transmission antenna. And, we could clarify the design of the power transmission module of sandwich SPS by describing the elements compose the power transmission panel and the configuration of the power transmission module in detail. Moreover, we described the possibility of the practical use of the power transmission antenna by making the slot antenna with the cavity and measuring the characteristic of the antenna.

As mentioned above, the design of the sandwich SPS was described in this thesis, and we could advance the one step to achieve the SPS with the sandwich panels. Also, we are planning the next orbiter demonstration in the near future. We believe that these designs can contribute to practical use of the sandwich SPS.

References

1) S.Nakasuka, R.Funase, K.Nakada, N.Kaya and J.Mankins, "Large Membrane "FUROSHIKI Satellite" applied to Phased Array Antenna and its Sounding Rocket Experiment," Proc. of 54th International Astronautical Congress, 2003.
2) N.Kaya, "A new concept of SPS with a power generator/transmitter of a sandwich structure and a large solar collector," Space Energy and Transportation, Vol.1, No.3, pp.205-213, 1996.
3) N.Kaya, "Development and Demonstration of New Retrodirective Antenna System for Solar Power Satellite of Sandwich Structure," Proc. International symposium on Antenna and Propagation, Vol.3, pp1419-1422, 2000.

4) N.Kaya, Ground Demonstrations and Space Experiments For Microwave Power Transmission, Space Energy and Transportation, No.4, Vol.3&4, 117-123, 1999.
5) N.Kaya, "Development and Demonstration of New Retrodirective Antenna System for Solar Power Satellite of Sandwich Structure," Proc. International Symposium on Antenna and Propagation, Vol. 3, pp1419-1422, 2000.