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Effect of solar power satellite transmissions on radio-astronomical research

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Solar power satellites (s.p.s.) now in the research and development stage are intended to be placed in geostationary orbits where large arrays of photocells will collect solar energy which will be delivered to Earth on a frequency of 2.45 GHz at a power level of 10 GW. The calculations in this paper indicate that severe restrictions will be placed on the use of radio telescopes on Earth for the study of radio emissions from celestial objects. For a single s.p.s. it would be possible to operate with the radio receiver protected by suitable filters at radio frequencies well separated from 2.45 GHz and at angles of look well displaced from the s.p.s. However, operational systems involving many s.p.s. to supply significant amounts of power to Earth would create serious hazards to radio-astronomical research, except possibly in thinly populated areas of the Earth.

1. Introduction

It is now several years since P. Glaser (1968) of the Arthur D. Little Consultancy in the U.S. proposed that solar power should be collected by an orbiting satellite and beamed to Earth by using a microwave transmitter. The concept is based on the consideration that the solar energy flux incident on the atmosphere (1360 W m^{-2}) is several times greater than mean ground level values in Europe and twice the mean flux in the Sahara. Further, at a frequency of 2.45 GHz, radiation penetrates the atmosphere from Space with near unity transmission coefficient under all atmospheric conditions. Therefore, if power is transmitted to Earth from Space at this frequency, there is negligible energy exchange with the atmosphere and a secure 24 h system can be envisaged with the efficiency dependent only on the conversion factors for the solar collector and transmitter in space and the collector on Earth. Substantial encouragement has now been given for the initiation of R. & D. on the system† and in this paper we draw attention to the effects which an operational system might have on important areas of astronomical research.

2. The present proposals for a solar power satellite system (s.p.s.)

In a 1975 presentation to N.A.S.A. of advanced space concepts for the epoch A.D. 1980–2000, Bekey (1975) outlined parameters for a system around which most of the subsequent discussion has centred. The scheme envisages a number of satellites in synchronous equatorial orbits. Each satellite would have solar collecting arrays with dimensions of 13.5 × 4.8 km feeding a 10 GW transmitter that radiates to Earth on a frequency of 2.45 GHz through a 1 km aerial array.

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† In 1978 N.A.S.A. and the U.S. Department of Energy were authorized to commission a $25 M study. Boeing Aerospace and Grumman Corporation are involved in these studies. In the U.K., British Aerospace state that they have a £59000 study contract from the European Space Agency related to this problem (*British Aerospace News* no. 10, March 1978; Press Release 8 Feb. 1978).

The beam would be directed to an antenna on Earth covering 10 × 10 km and it is computed that each system would ultimately deliver 5–10 GW into the terrestrial distribution system. Each satellite would weigh over 11 Mkg and require 20×10^9 photocells, and at the turn of the century it has been estimated that eight satellites of this type could supply the U.K. electrical needs and that 100 could provide one-third of the U.S. electricity requirements. The power density at Earth in the 10 GW, 2.45 GHz beam transmitted from each satellite is computed to be $200\ \mathrm{W\ m^{-2}}$ and we first compare this flux with that received from celestial sources by radio telescopes.

3. INTERFERENCE WITH RADIO TELESCOPES

Terrestrial radio telescopes normally operate over the radio wavelengths from a few centimetres to several metres. Research in the millimetre waveband generally demands special high altitude sites and at the long wave end the ionosphere becomes the limiting factor. By normal standards the signals received from the galaxy and extragalactic objects are extremely weak. The achievable sensitivity varies over the waveband but as a guide for present purposes it may be assumed that most radio astronomical systems today work at sensitivity limits of a few millijansky ($1\ \mathrm{mJy} = 10^{-29}\ \mathrm{W\ m^{-2}\ Hz^{-1}}$). Internationally regulated bands for terrestrial transmitters screen a few frequencies for use in radio astronomy within bandwidths of the order 4 MHz. Thus the incident flux on the antennae at limiting sensitivity is of the order $10^{-23}\ \mathrm{W\ m^{-2}}$. Since the flux from the s.p.s. is of the order 10^{25} times that of the natural radio signals from astronomical objects, it is necessary to enquire whether the operational conditions of the s.p.s. and of radio telescopes lead to any measure of compatibility.

4. OPERATIONAL CIRCUMSTANCES

The feasibility of operating radio telescopes when the 2.45 GHz beams are incident on Earth depends (*a*) on the polar diagram and the sidelobe level of the solar power beam, (*b*) on the polar diagram and the sidelobe level of the radio telescope and (*c*) on the undesired ambient power levels at which the receiver of the telescope can operate. On these points the following information is available.

(*a*) *The polar diagram of the* 2.45 *GHz array*

The 1 km diameter s.p.s. array on 2.45 GHz will have a beam width of approximately 0.02 deg. The flux in the main beam collected by a 10 km 'rectenna' on Earth will be $200\ \mathrm{W\ m^{-2}}$. At the edge of the rectenna the polar diagram of the s.p.s. must be such that the radiation safety standards must be met. These allowable limits at present extend from $100\ \mathrm{W\ m^{-2}}$ in the U.S.A. to $0.1\ \mathrm{W\ m^{-2}}$ in the U.S.S.R. We assume an intermediate value of $1\ \mathrm{W\ m^{-2}}$ at the edge of the collector and that by skilful design and control of the array elements in space the far-out sidelobes could be reduced to -50 dB with respect to the main beam. At a level of $200\ \mathrm{W\ m^{-2}}$ in the main beam the intensity of the far-out sidelobes would then be of the order of $2 \times 10^{-3}\ \mathrm{W\ m^{-2}}$. However, Kassing & Reinhertz (1978) quote a figure 50 times greater of $0.1\ \mathrm{W\ m^{-2}}$ as the achievable diminution of flux from the s.p.s. in the far-out zones. In the present calculations these values of 10^{-1} and $2 \times 10^{-3}\ \mathrm{W\ m^{-2}}$ are taken as the likely maximum and minimum values of the s.p.s. flux in the far-out zones.

(*b*) *The polar diagram of the terrestrial radio telescope*

We are concerned with the power delivered to the focus of the radio telescope from the 2.45 GHz transmissions from the s.p.s., notwithstanding the actual frequency on which the telescope is receiving the signals from celestial objects. The relevant characteristics of the radio telescope are therefore those appropriate to the s.p.s. frequency of 2.45 GHz. For simplicity we take the characteristics of the Mk IA radio telescope at Jodrell Bank. On 2.45 GHz these are: beam width to 3 dB points = 5 arc min, mean sidelobe level to 5° off axis = -30 dB with respect to main beam, sidelobe level beyond 5° = -60 dB with respect to main beam, effective area of the collector = 3×10^3 m^2.

We assume that the telescope is far enough removed (say more than 100 km) from the s.p.s. terrestrial collector that it can be considered to be only in the far-out zone flux of the s.p.s. The power delivered at the focus for the maximum and minimum limits considered in 4 (*a*) can then be calculated for typical circumstances. Table 1 gives the power delivered to the focus for three values of θ – the angle between the axis of the telescope beam and the s.p.s.

TABLE 1. POWER DELIVERED TO THE FOCUS OF THE RADIO TELESCOPE AT DIFFERENT VALUES OF θ FOR TWO LEVELS OF THE FAR-OUT ZONE FIELD OF THE S.P.S.

	s.p.s. field (far-out zone)	
θ/deg	2×10^{-3} W m^{-2}	10^{-1} W m^{-2}
(*a*) $\theta < 0.1$	6 W	300 W
(*b*) $0.5 < \theta < 5$	6×10^{-3}	3×10^{-1}
(*c*) $\theta > 5$	6×10^{-6}	3×10^{-4}

The power delivered to the focus of the telescope from a celestial source (assuming a limiting sensitivity of 10^{-29} W m^{-2} Hz^{-1} and a typical bandwidth of 4 MHz) will be of the order of 10^{-19} W. Thus the power input from the s.p.s. into the telescope focus will be from approximately 10^{14} to 10^{22} times greater than that from the celestial source which it is desired to study.

(*c*) *The characteristics of typical radio-frequency amplifiers in a disturbing field*

With such a great disparity between wanted and unwanted power levels the feasibility of operating a radio telescope even in the far-out field of the s.p.s. depends on the level of rejection of the s.p.s. signal which can be obtained by filtering at the 2.45 GHz frequency. It is possible to provide adequate protection from out-of-band interfering signals for all the stages of a radio receiver except the first. The first stage is typically a parametric amplifier that has been optimized for minimum noise figure so that maximum sensitivity is achieved. Protection of a parametric amplifier by means of a filter results in a degradation in noise performance due to the insertion loss of the filter and the noise that it contributes. The amount of degradation increases with the amount of protection that is required and also as the unwanted frequency approaches the desired frequency.

Measurements have been made of the effect of out-of-band interference on several of the relatively narrow bandwidth (*ca.* 1 %) parametric amplifiers in regular use at Jodrell Bank. Three main effects have been observed:

(i) gain compression for the case where the interfering frequency is within a small percentage of the desired frequency;

(ii) detuning and gain peaking where the frequency separation is greater than in (i);

(iii) cross modulation, i.e. the generation of an inband signal in the parametric amplifier from two out-of-band signals.

Many astronomical observations would be prejudiced by gain changes of 0.01 % and/or spurious in-band components of 10^{-4} times the receiver noise. Interference levels of about 10^{-9} W at the parametric amplifier are sufficient to cause these changes if the frequencies are within a few per cent of one another. Stronger interference can be tolerated if the frequency offset is greater.

Table 2. Filter attenuations required to protect the parametric amplifier from the power levels of table 1

(The maximum and minimum values correspond to the most pessimistic and optimistic estimates respectively of the sidelobe levels from the s.p.s.)

	filter attenuation/dB	
θ/deg	frequency separation < 10 %	frequency separation > 50 %
(*a*) $\theta < 0.1$	100–117	80–97
(*b*) $0.5 < \theta < 5$	70–87	50–67
(*c*) $\theta > 5$	40–57	20–37

5. Filtering requirements

The discussion in the preceding section indicates that the maximum tolerable level of an interfering signal at a parametric amplifier varies from approximately 10^{-9} W for frequencies offset by less than 10 % from the desired signal to approximately 10^{-7} W for offsets greater than 50 %. These data are combined with those from table 1 to deduce the specification of a filter to give the necessary protection to the parametric amplifier. The results are shown in table 2.

Another relevant parameter of a filter is the insertion loss at the desired frequency and the effect of this on signal/noise ratios. The best parametric amplifiers currently achieve system noise temperatures of about 40 K; a filter with an insertion loss of 0.2 dB at room temperature would degrade signal to noise ratios with this system by 40 % and, furthermore, would limit the amount of possible improvement by future developments in parametric amplifiers. It is difficult to combine high rejection and low insertion loss in a filter, especially if the fractional separation of the pass and reject bands is small.

6. Discussion

(i) The following comments may be made on tables 1 and 2.

- (*a*) If a large radio telescope is directed so that an s.p.s. lies within its main beam then the receiver will be damaged unless protected by a filter to ensure that the power level at the parametric amplifier is less than 1 W (a rejection of at least 25 dB at 2.45 GHz for the worst case).
- (*b*) Observations within 5° of an s.p.s. will only be possible with severely reduced sensitivity.
- (*c*) Observations in directions more than 5° away from the s.p.s. but on a frequency within 10 % of 2.45 GHz will have reduced sensitivity because of the filtering requirements. The radio-astronomy band at 2.7 GHz would be affected and also the satellite communication bands at 2.2–2.3 GHz which are also used for radio astronomical observations.

(ii) The estimates in (i) refer to the circumstance where only the fundamental 2.45 GHz signal from the s.p.s. is significant. Any appreciable harmonic content in the signal beamed to Earth would increase the complexity of the filters required and might extend the limitations considered in §6(i) to other frequency bands reserved for radio-astronomy. The seriousness of this cannot be assessed until the characteristics of the space transmitters are defined.

(iii) The calculation of interfering levels and rejection needed have been based on the characteristics of the 250 ft Mk IA radio telescope at Jodrell Bank. These figures may be taken as typical for parabolic reflectors now in use as radio telescopes. For smaller reflectors the area of forbidden sky around an s.p.s. for the various cases considered would increase approximately linearly as the aperture of the telescope decreases. For combinations of radio telescopes used as interferometers or in aperture synthesis networks, the effect of the s.p.s. signal on the system needs more detailed analysis. At best, the restrictions assessed in §6(i), as applied to the smallest aperture telescope in the network would seem to be the limiting factor.

7. Conclusions

The parameters for solar power satellites now under discussion would illuminate radio telescopes situated remotely from the s.p.s. terrestrial collector at power levels at least 10^{20} times greater than those received from the celestial sources now being investigated and several orders of magnitude greater than those from other man made sources. The extent of the inhibition to radio-astronomical research would depend critically on the polar diagram of the space array, the harmonic content of the space transmitter and the number of such power systems operating in space. For a single space station with the best attainable polar diagram and negligible harmonic radiation it should be possible to filter the interfering signal at the radio telescope so that observations would be possible except on frequencies near the band at 2.45 GHz, although investigations of the celestial radiation within several degrees of the satellite would be severely restricted. On the other hand, operational systems requiring several satellites to supply significant amounts of energy to Earth would create serious hazards to radio-astronomical research except in thinly populated areas of the Earth. For example, it is estimated that eight space stations would be required to supply the needs of the U.K. by A.D. 2000. If the terrestrial collectors were distributed over the U.K., then it is unlikely that any site would remain for the satisfactory operation of a radio telescope.

Apart from these direct effects of the space power beam on radio astronomical research it may be noted that other possibilities are now under study which may influence such research. For example, measurements with the Arecibo radio telescope are in progress to determine the possible influence of the 2.45 GHz beam on the electron temperature in the ionosphere (Anon. 1978); and studies at Harvard by Grossi & Colombo (1977) relate to the possibility of weather modification by using a space transmitter at 22.2 GHz. Should this be attempted, then, at least, all research on the water vapour spectral line from celestial sources would be brought to a halt.

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