NOTES ON THE PROPOSED 94.5GHz SPACE BASED CLOUD PROFILING RADAR AND ITS IMPACT ON MM-WAVE RADIO ASTRONOMY.

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1. Introduction

These notes were written and distributed in hand written form to various interested parties during the October 7th-16th meeting of WP7 at the ITU Geneva. They were written as a result of an *ad hoc* meeting between radio astronomers of WP7D and proponents of the Cloud Profiling Radar (CPR) of WP7C as a way of establishing whether the radio astronomy community, as represented by the author, truly understood the CPR proposal and as a way of conveying to the radar proponents, certain precautions they might adopt, and certain design features they might avoid, to minimize the impact of their radar on radio astronomical observation.

The original notes are presented here in tidied up form and with the addition of a specific suggestion for the shape of the radar pulse. The author has made a quantitative study of the power spectrum of this pulse shape and this also is presented.

2.Science

The purpose of the Cloud Profiling Radar is to determine the Earth's albedo and radiation balance, by measuring the distribution of cloud with height on a global basis.

The water droplets in clouds are very small compared to the wavelength (λ=3.2mm) of the proposed radar. In this circumstance the radar echo goes as $1/\lambda^4$ and is due to *Rayleigh Scattering*.

A second echoing mechanism is from ice particles. They may be very much bigger than the water droplets but they are still small compared to the wavelength and so they too echo by *Rayleigh Scattering*.

3. Radar System Parameters

Many of the parameters quoted are approximate but they are thought to be representative of likely system parameters.

3.1 Orbit

Circular at 400 -> 600 km height.

Nominal height taken as 450 km.

Orbital period depends upon height ~95 min

Orbital inclination i $\approx 90^0$. Needs to be $\sim 95^0$ to be sun-synchronous.

?

3.2 Transmitter

Power 1000 -> 1500 W (on pulse)		1000 W
Pulse length		3.3 μs
Duty factor		~1%
Pulse repetition frequency (PRF)		~3000 ~~kHz~~ ? 3 kHz
Interpulse interval = duration of cyclic timebase		330 μs
Polarization		Linear
Antenna gain	3.24×10^{6} ->	+65dBi
Antenna sidelobe level at 19^{0} off boresight		0dBi
Antenna sidelobe level far off boresight		-10dBi
Direction (possibly 20^{0} off nadir)		Nadir
Footprint	circular	1 km dia
Frequency (possibly 30 carrier frequencies 1MHz apart)		94.5 GHz
Wavelength		3.2 mm

3.3 Radar Parameters

Range resolution (3.3 μs)	~500 m
Time of flight of pulses (450 km)	~3 ms
Height range of cyclic timebase (330 μs)	~50 km
Number of pulses in flight	~9

4. Radio astronomy system parameters.

4.1 Radio Telescope.

A 30 metre diameter dish is the largest that need be considered since for a larger antenna the satellite will begin to be in the near field. Such an antenna becomes defocused and does not deliver any more power into the radio astronomy receiver.

For λ = 3mm, beamwidth $\sim 1.22\,\frac{3\times10^{-3}}{30} = 1.22\times10^{-4}$ = 0.4 arcmin

Diameter	30m	
Antenna gain	+88.5dBi	Width of beam at 5.. distance = 50 m
Antenna gain 19^{0} off axis	0dBi	Satellite speed 7k..
Antenna gain far off axis	0dBi (by convention)	

On [illegible] covers 0.5km at [illegible]

3.3μS, 0.7W = 2.3×10^{-6} Joules

Tsystem ~ 100 [illegible]

4.2 Radio astronomy receiver.

Receiver is cryogenic SIS mixer		
Noise temperature		100K
Damage level	10mW:	-20dB(W) possibly less
Mixer saturation level	~1nanoW:	-90dB(W)
Receiver IF bandwidth		~1GHz

Threshold Interference Level for Input Power ΔP_H for spectral line observation (88600, 98000, 115000 MHz)taken from Table 5 in Chapter 4, p21 of the ITU-R *Handbook on Radio Astronomy.*

-204dB(W) in a spectrometer channel of Δf = 1000kHz bandwidth.

4.3 Path loss.

The free-space path loss for various heights of circular orbits are shown in Fig 1 where the horizontal scale is linear in fraction of visible sky.

Space path loss for 450km at λ = 3.2mm is 185dB

5. Calculations.

5.1 Case 1. Main beam of satellite antenna -> main beam of telescope: Fig 2a.

This is nominally an extremely rare event. However it should be noted that the radar is pointing to the nadir and some telescopes are parked in the zenith when they are not observing. This practice could very greatly increase the chance of this worst case occurring.

Transmitter power on pulse	+30dB(W)
Radar antenna gain	+65dBi
Path loss	-185dB
Telescope antenna gain	+88.5dBi
Received power on pulse	-1.5dB(W)

The on-pulse received power is ~0.7 watts. This is 18.5dB above the nominal level at which SIS mixers are expected to burn out. There is a chance that a notch filter might be possible that would cut out the radar enough to protect an SIS mixer sufficiently from burn out: i.e ~-20dB notch, but it is not certain.

5.2 Case 2. Main beam of satellite -> Sidelobe of telescope: Fig 2b.

This case can only occur when the satellite passes directly overhead of the radio observatory, assuming a nadir pointing satellite. It is a relatively rare event.

Assume the telescope is more than 19^0 away from the zenith so that its gain is reduced to 0dBi. So add -88.5dB to the case 1 result:-

	-1.5
for the telescope gain	-88.5
	-90.0dB(W)

This level of interference just takes the SIS mixer to the onset of the non-linear regime. It only occurs on-pulse and it is a situation that cannot endure for more than ~1/3 sec because of the speed with which the radar footprint moves over the ground. (Footprint is ~1km in diameter and it moves as fast as the orbital velocity of the satellite: about 7km/s.)

Duration < 0.1 sec notes on p 2. Duration mentioned: << 1 ...

5.3 Case 3. Sidelobe of satellite -> Main beam of telescope: Fig 2c.

This case occurs more frequently than Case 2. It occurs when the satellite happens to pass through the main beam of the telescope which however is more than 19^0 from the zenith. This condition ensures that it is the radiation in the satellite's side-lobes that is received. In this case the power received is found by subtracting the radar antenna gain from the result of Case 1.

	-1.5dB(W)
for the satellite antenna	-65dB
	-66.5dB(W)

This case requires the satellite to be more than 19^0 from the zenith at the radio observatory. So the slant range is increased by a factor of at least $1/\cos(19^0)$, but as this gives only 0.25dB additional path loss I ignore it.

The main point in this case is that the received on-pulse power is certainly way above the level that saturates an SIS mixer.

5.4 Case 4. Side-lobe of Satellite -> Side-lobe of telescope: Fig 2d.

Here I assume that the satellite antenna is pointing 19^0 or more from the direction towards the radio telescope and the telescope is pointing more than 19^0 away from the direction of the satellite. This will be a frequent occurrence. To the result of Case 1 we add:

	-1.5dB(W)
for gain of the telescope	-88.5dB
for the satellite antenna	-65.0dB
	-155.0dB(W) (on pulse)

Here there is no question of the SIS mixer being driven non-linear.

This received power must be compared with the total power in the radio astronomy receiver which is kTB.

k = Boltzmann's constant = 1.38×10^{-23} joules/^{0}K
T = 100^0K
B = 1GHz being the overall IF bandwidth

Noise power = 1.38×10^{-12}W => -118dB(W)

In this case the on-pulse power of the radar is -37dB relative to the total power in the IF amplifier and it is therefore negligible from the point of view of main IF amplifier saturation.

However a spectrometer on the end of the main IF is assumed to have a 1 MHz bandwidth. In such a spectrometer channel the receiver noise power is

1GHz to 1MHz change of bandwidth	-118dB(W) -30dB -148dB(W) (RX noise)

We see that in one spectrometer channel the on-pulse power is only -7dB relative to the noise. So it represents a 20% increase of power in the channel and it is +49dB relative to the radio astronomy interference threshold of -204dB(W). However it is the on-pulse power. If the radar duty factor is 1% then the *mean power* will be a further 20dB down:

1% duty factor	-155dB(W) (on pulse) -20dB -175dB(W) (mean)

and this is now +29dB, still nearly eight hundred times, above the radio astronomy threshold level.

5.5 Other factors that may decrease the level of the interference.

5.5.1. The figure of -175dB(W) given above is based on the satellite antenna gain of 0dbi at the 19^0 off-axis point. If the far side-lobe gain level of -10dBi is used, then the mean signal level is reduced to

far out satellite side-lobe level of -10dBi	-175dB(W) -10dB -185dB(W)

5.5.2. If the radar pulses are cycled around 30 carrier frequencies mutually spaced by 1MHz, then 30 spectrometer channels will successively receive the peak of the radar spectrum. Thus each individual channel will receive only 1/30 of the mean power. This reduces the mean power in each of the affected channels by 15dB

-185dB(W)
-15dB
-200db(W)

5.5.3. The radio astronomy threshold level for interference is based on an assumed 2000s integration time. Now even a satellite pass that goes directly overhead of a radio observatory takes only ~660seconds from horizon to horizon, and this is 1/3 of the standard integration time. This introduces a further -5dB to obtain the mean interference power level averaged over 2000sec.

-200dB(W)
-5dB
-205dB(W)

5.5.4. Over the duration of an horizon to horizon *apparition* of the satellite the range changes considerably, and therefore so does the space path loss. This is shown in Fig 1. There is no easy way to find a typical additional loss due to this variable because it depends so much on the geometry of each pass. But it is easy to understand that a LEO satellite will appear most of the time at low elevation (large zenith distance) and at relatively large range. So this factor will introduce a further average power loss of several dB.

[It should be noted that at 30^0 elevation (60^0 zenith distance), which is the elevation which divides the sky in two, the free-space path loss is increased by 5dB relative to the zenith.]

5.5.5. As well as the free space path loss there will be additional atmospheric loss when the satellite appears at low elevation at the radio observatory and this will give additional protection to the radio telescope. In calculating the atmospheric attenuation however it should be noted that mm-wave observatories are ideally placed at high altitude sites specifically chosen for low atmospheric attenuation. Furthermore atmospheric attenuation is highly variable so that the most valuable observing time is to be had on those occasions when the atmospheric attenuation is exceptionally low. It would therefore be quite inappropriate to use some average standard atmosphere based on sea-level values to compute the protection provided by atmospheric attenuation. The observatory sites are chosen to get away from such standard conditions. Of course to minimize the effect of atmospheric attenuation on the radio astronomy observations themselves, they are for preference conducted at the highest possible telescope elevation that the latitude of the observatory and the positions of the radio sources in the sky will permit. For these reasons I deem it prudent to ignore the contribution provided by atmospheric attenuation.

6. The Radio Astronomy Threshold Interference Level.

In §5.4 the mean noise power in a 1MHz bandwidth spectrometer channel was calculated to be -148dB(W). The Threshold Interference Level is stated to be -204dB(W). It is instructive to see how one gets from the one to the other.

The "noise" fluctuation as a result of an integration for time T is

$$\frac{1}{\sqrt{BT}} \text{ times the total noise,}$$

so with B=1MHz and T=2000s $\sqrt{10^6 \times 2000} = 0.45\times10^5 \Rightarrow -46.5\text{dB}$

$$\begin{array}{r} -148\text{dB(W)} \\ -46.5\text{dB} \\ \hline -194.5\text{dB(W)} \end{array}$$

The Radio Astronomy threshold is set 10dB below this RMS fluctuation level.

$$\begin{array}{r} -194.5\text{dB(W)} \\ -10\text{dB} \\ \hline -204.5\text{dB(W)} \end{array}$$

which is within 0.5dB of the stated level.

7. Discussion.

The additional factors mentioned in §5.5 bring the mean interference power level to below the stated Radio Astronomy interference threshold level for spectrometry. It must be recognized however that the assumed condition, that both the satellite and telescope beam axes be more than 19^0 away from the mutual line-of-sight, will frequently be violated, since a cone of 19^0 includes a solid angle which is $100\times(1-\cos(19^0)) = 5.5\%$ of the sky. However if the radio observatory is provided with an ephemeris for the satellite, so that the telescope can be steered in such a way as to avoid violating that condition, or so that integrations may be suspended for the few tens of seconds required to prevent contamination of the data when it cannot be avoided, it should be possible for observations to be conducted in a frequency band that includes the radar frequency.

Because an SIS mixer receiver is inherently wide band, the limitation imposed by SIS nonlinearity applies whatever band of frequencies is being observed, whether or not it includes the radar frequency. However provided the on-pulse radar signal level is below the SIS nonlinearity limit there is the possibility of observing in neighbouring bands which do not include the radar frequency. This does not require that both satellite and the telescope point more than 19° away from the mutual line-of-sight. As we have seen in §5.4 satisfying that condition reduces the received signal to -155dB(W), but now we see that one or other or both can be pointing closer, provided that the sum of the gains of the two antennae do not exceed +65dB along the mutual line-of-sight. The signal strength would now severely saturate the IF amplifier were it not at a frequency which can be rejected by filters placed after the mixer but before the main IF gain stages.

In this case we envisage a power of -90dB(W) on-pulse or -110dB(W) mean, but what becomes important is the width of the guard band that is needed to ensure that the far-out-sideband power of the radar has fallen by the further ~100dB or so needed to reach the Radio Astronomy Threshold Interference Level. So we turn to the question of the power spectrum of the radar.

8. Power spectrum of the radar.

Provided the PRF is constant the radar emits a spectrum which consists of lines mutually spaced by 3.3kHz. The envelope of this line spectrum is set by the shape of the individual pulses and it is the square of the modulus of the Fourier transform of the pulse amplitude profile. For a 3.3μs pulse most of the energy lies in a 600kHz band, unless some form of *within-pulse* pulse compression scheme is used: i.e. chirp or pseudo random phase coding. However some small fraction of the power goes into far-out-sidebands. These can be expected to form a series of "lobes" of width ≈ 300kHz being the reciprocal of the pulse length. The rate of decay of the envelope of the far-out sidebands depends on the smoothness of the pulse profile. For an ideal rectangular pulse this would be -20dB/decade of frequency offset from the carrier. A trapezoidal pulse shape has been suggested. This, being a profile which is discontinuous in its first derivative, has a power spectrum envelope which decays at -40dB/decade of frequency offset. In reality of course the pulse shape will not have sharp corners and this means that the rate of fall off will increase at frequencies many "side-lobes" away from the carrier where the level has already fallen a long way.

It is extremely difficult to predict the precise shape of the power spectrum at frequencies beyond the point at which the level has already fallen by 40dB, as this implies ability to specify the shape of the pulse to better than 1% in amplitude. All that can be stated with confidence is that the asymptotic slope of the far out side-bands falls as $f^{-2(n+1)}$ where n is the order of the first discontinuous derivative of the pulse profile. It is unlikely that n would be less than 2.

9. Operation of the Transmitter.

The use of either a TWT (Travelling Wave Tube) or an EIA (Extended Interaction Amplifier) is being considered for the radar transmitter.

To save power the amplifier beam will have to be gated off between transmitter pulses. It also needs to be switched off completely to prevent it generating high level noise during receive time. It will furthermore be necessary to switch off the drive to the power amplifier so that no carrier frequency signal exists anywhere within the satellite whilst the radar is in receive mode. It would therefore be appropriate to gate the power amplifier beam ON for say 4.0μs and to shape the RF drive pulse within this interval.

A suitable form of pulse is proposed in Fig 3. It's duration at half height is 3.30μs but it's overall length is 3.96μs. It's leading and trailing edges are both 0.66μs and are each composed of parabolic sections. It was generated, in the mathematical sense, by convolving a 3.3μs rectangular pulse twice with a rectangular pulse of 0.33μs. The result is a shape that is discontinuous only in it's 2nd derivative: (n = 2). The envelope of its far-out power spectrum therefore decays as -60dB/decade of frequency offset. The corresponding power spectrum is shown in Fig 4. It is described by

$$P(f) = \left(\mathrm{sinc}(fT)\times\mathrm{sinc}(fT/10)\times\mathrm{sinc}(fT/10)\right)^2 \qquad (1)$$

where $\mathrm{sinc}(x) = \frac{\sin(\pi x)}{(\pi x)}$ and T = 3.3μs and f is frequency offset in MHz.

It will be seen that the spectral power density (SPD) has fallen to -100dB at about 20MHz from the carrier. This 20MHz is then the guard bandwidth mentioned at the end of § 7, required for the radar spectrum to fall from the SIS saturation level to the Radio Astronomy Threshold Interference Level.

Such a pulse would allow the radar to operate within a frequency assignment of only 75MHz computed as

center frequency to -100dB level	20×2	40MHz
± 2.5 MHz for orbital Doppler shift	2.5×2	5MHz
30×1 MHz for frequency hopping		30MHz
		75MHz

No significant extra bandwidth need be provided for transmitter frequency tolerance.

10. Conclusion.

The previous discussion has shown that provided a number of conditions are met it will be possible for a radio telescope to continue observation for *much* of the time that the radar satellite is above the horizon. The main condition is that the radar and telescope beams should be sufficiently out of alignment for the interfering signal to be small compared to the total noise in the radio astronomy IF amplifier. Relatively large angular separation is needed if the radar frequency lies within the observing band. If the radar frequency lies outside the observing band, the beams can be allowed to come closer aligned but extra protection in the form of filtering then needs to be incorporated in the radio astronomy IF amplifier. Whatever the observing frequency, the beams must not become so aligned that the SIS mixer is driven into saturation.

If the radar uses the proposed 30×1MHz frequency hopping scheme, then the main peak of the interfering spectrum is spread over 30MHz and this lowers the level of the mean interference into any one particular 1MHz spectrometer channel. If it is not used, the radar will be be a prominent source of interference in at least one channel. How many channels are affected depends on the spectrum of the radar pulses.

It has been shown that quite simple shaping of the radar pulses makes it possible for the far-out sidebands to fall to -100dB at about 20MHz from the carrier. So it should be sufficient for the radar to operate within a frequency allocation of 75MHz for the frequency hopping scheme or within 45MHz if only one carrier is used.

Certain modifications to the radar would markedly worsen the interference to radio astronomy. These are:-

1. Use of a non-nadir pointing radar antenna.
2. Use of a transmitter duty factor of substantially more than 1% such as might be used in a pulse compression scheme.
3. Use of significantly wider frequency hopping than the proposed 30×1MHz scheme.

The reason for three is that one way a radio astronomy observatory could work in the presence of the radar pulses, is by receiving them and locking on to them using an auxiliary antenna and receiver, and in that way generating blanking pulses for the main radio astronomy receiver. The wider the bandwidth of the hopping, the worse the signal to noise ratio in this auxiliary system.

The introduction of a Cloud Profiling Radar will certainly be an inconvenience to radio astronomical observation but provided good neighbourly care is taken in the design of the radar to avoid design features that would exacerbate the problem, it should be possible for both scientific activities to work simultaneously.

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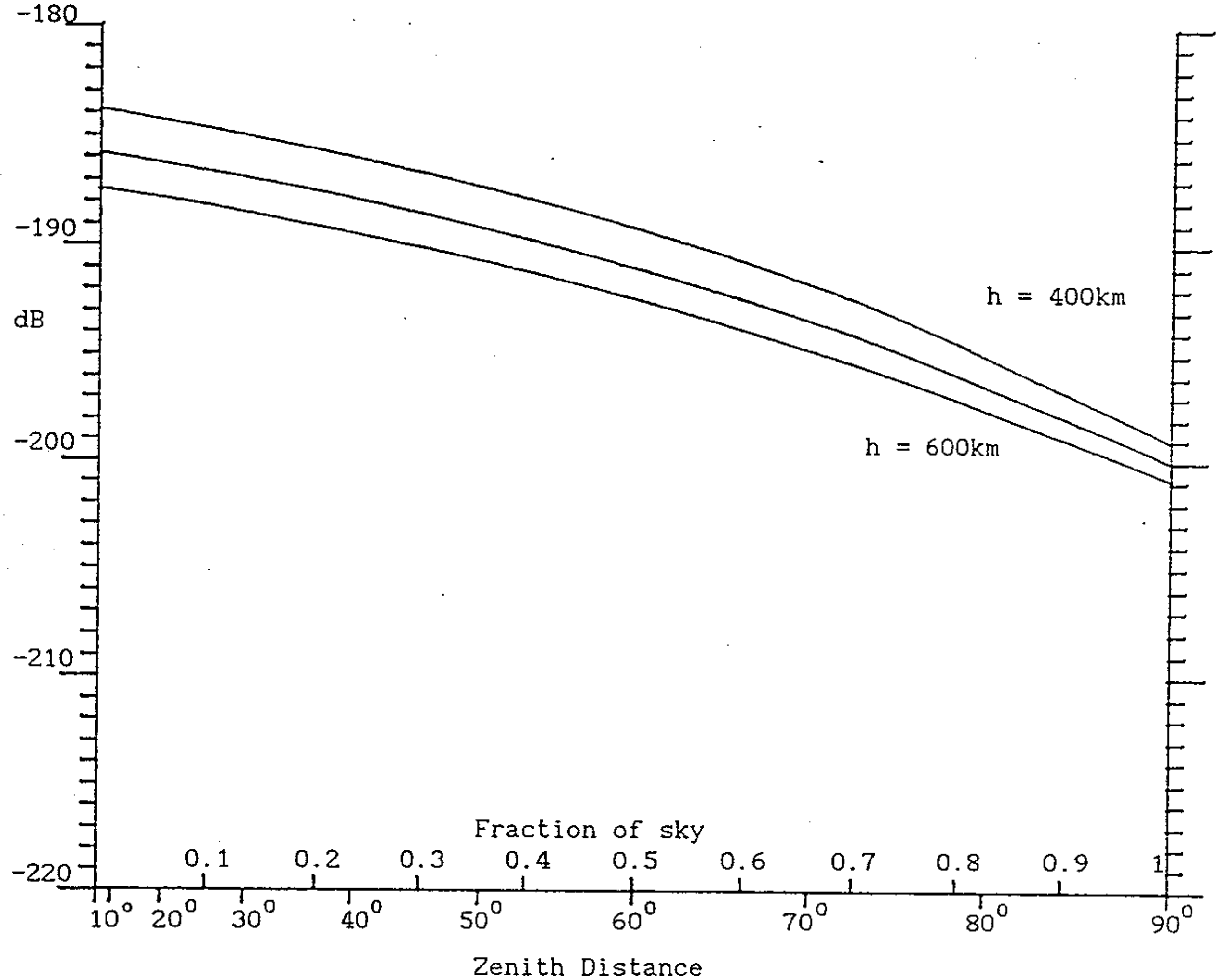

Fig 1. Plot of path loss (dB) versus fraction of sky measured from the zenith, for satellites in circular orbit at heights of 400, 500 & 600 km.

path loss = $20\log_{10}\left(\frac{\lambda}{4\pi r}\right)$dB λ=3.2mm   r = slant range in metres.

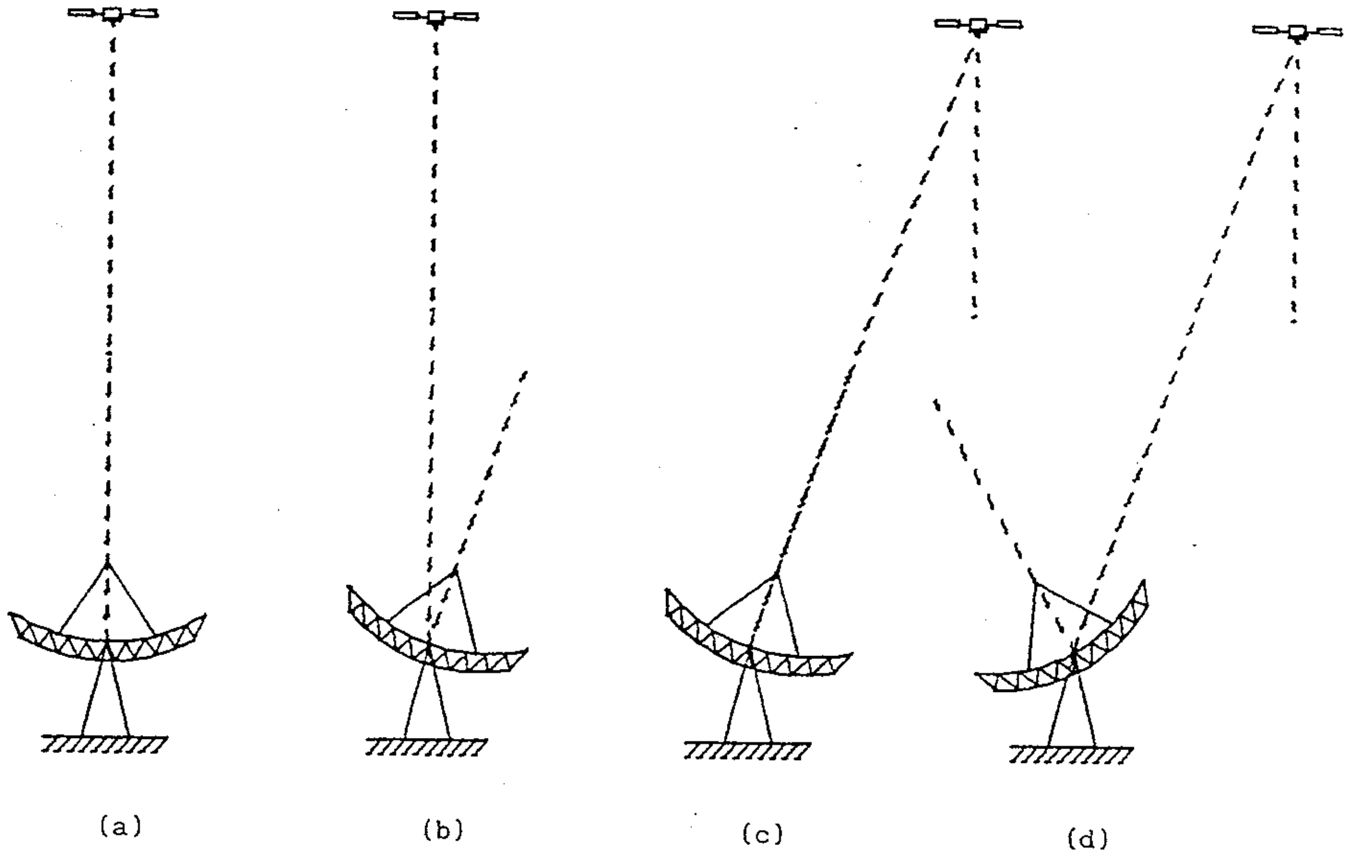

Fig 2. The four configurations of radar satellite and radio telescope considered in §5.

(a) Case 1. Main beam of satellite -> main beam of telescope: -1.5dB(W).

(b) Case 2. Main beam of satellite -> sidelobe of telescope: -90dB(W).

(c) Case 3. Sidelobe of satellite -> main beam of telescope: -66.5dB(W).

(d) Case 4. Sidelobe of satellite -> sidelobe of telescope: -155.0dB(W).

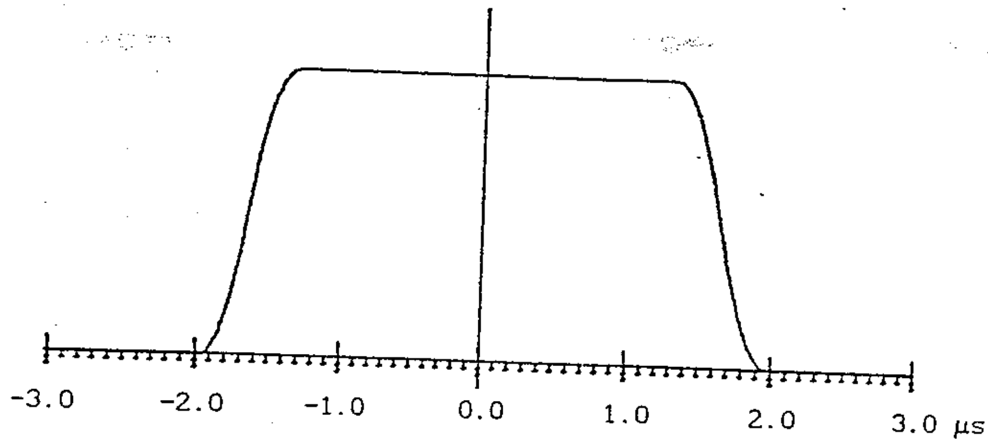

Fig 3. Proposed pulse shape. The amplitude is described by

$$v(t) = \Pi(t/T)*\Pi(10t/T)*\Pi(10t/T) \text{ where } t \text{ is in } \mu s \text{ and } T=3.3\mu s.$$

It has total duration 3.96μs and is discontinuous only in its 2nd derivative. (* denotes convolution.)

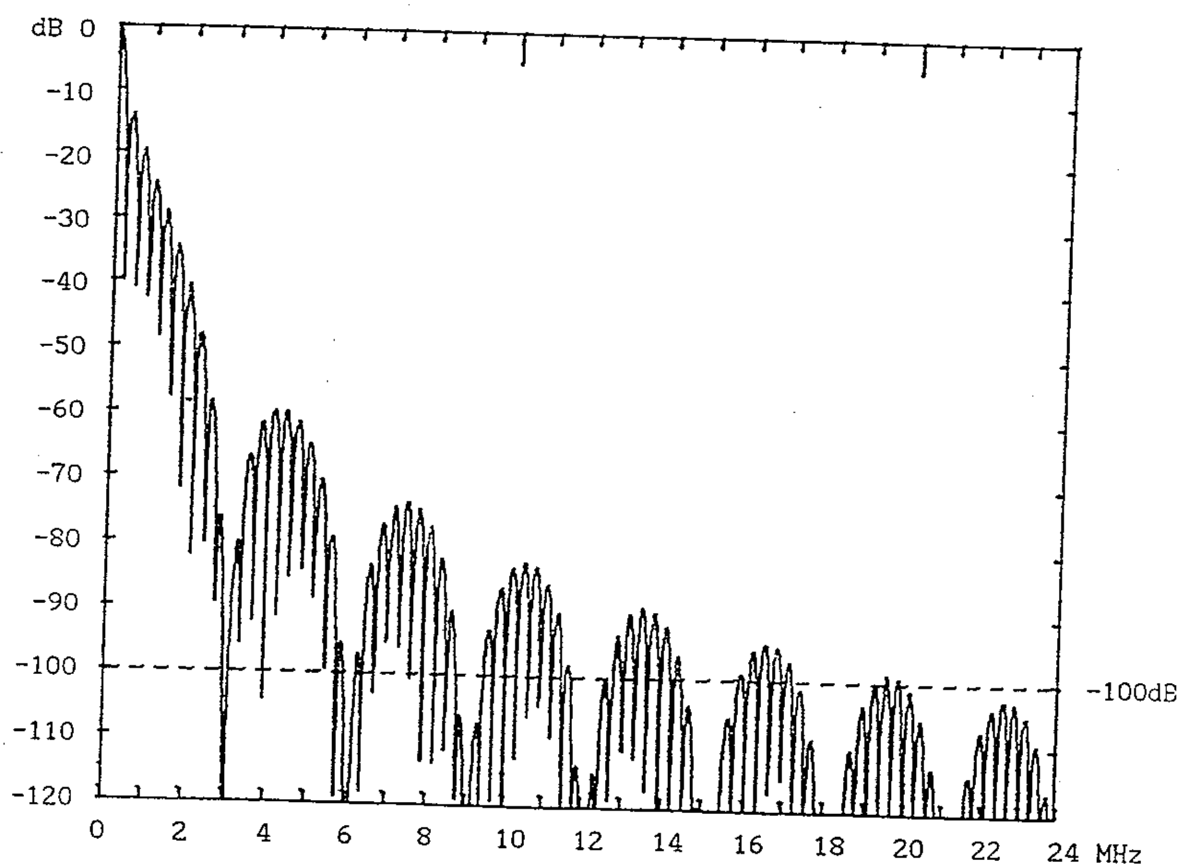

Fig 4. Spectral Power Density (SPD) in dB versus MHz, of the pulse proposed in Fig 3.
The fine "lobes" have width 300kHz and the coarse 3.0MHz.
The level has fallen to -100dB at 20MHz from the carrier.
The line structure at multiples of the PRF are not shown.