Thermal Plume and Primary Radar Refraction

London Oxford Airport raised potential concerns over primary radar refraction caused by thermal plume from solar panels as part of their representations in the examination period (REP4-073).

Thermal effects arising from the proposed Botley West Solar Farm have been assessed to determine whether impacts on the propagation of radar waves over the site are significant, accounting for changes in atmospheric refraction. A temperature change of 1°C has been assumed over the solar panel area, in line with the results of the thermal impact report.

<u>Explanation of Methodology</u>

Radio waves appear to bend downwards as they travel through the atmosphere. This phenomenon is referred to as atmospheric refraction and it means that these waves can travel further along the ground than light waves without being blocked by the horizon.

The calculation of the refractive index of the atmosphere follows the methodology outlined in International Telecommunications Union (ITU) document P.453. A key factor that affects the refractive index, and one that we are interested in, is temperature. Warmer air is less dense than colder air, and so a higher temperature means that the atmosphere is less dense and the refractive index is lower.

This is complicated somewhat by the presence of humidity. Whilst air becomes less dense at higher temperatures, water vapour becomes more dense, which means that where there is a high relative humidity, the refractive index can in fact increase as temperatures increase.

What this does mean is that for a given humidity, it is possible to calculate the refractive index for different temperatures. It is therefore possible to examine how added thermal effects of Botley West Solar Farm will impact the refractive index of radio waves in air passing over the site.

The calculated refractive indices can be converted to effective earth radii using a method set out in ITU P.452. These values can be used to work out the perceived inclination angles of aircraft with and without the thermal effects, and therefore the difference in perceived aircraft height at the radar depending on whether or not the effects are present.

<u>Conclusions</u>

Calculations undertaken suggest that impact significance is negligible, with the maximum change in perceived position of aircraft observed by radar at Oxford Airport expected to be no more than three metres and this is not deemed to be significant relative to the size and speed of a typical aircraft. The modelling has assumed that thermal effects apply to the whole path of propagation, making this a conservative estimate and likely overstating any possible effects.

A summary of the likely differences between perceived height and actual height of aircraft as a result of changes in atmospheric refraction are presented in the table below.

Distance of Aircraft from Radar /km	Change in Perceived Height /m	
	15°C Air Temperature 50% Humidity	15°C Air Temperature 100% Humidity
1	0.00	0.00
5	0.00	0.01
10	0.01	0.02
20	0.03	0.09
50	0.21	0.57
100	0.84	2.27

Detailed Calculations

Radio Refractivity and Refractive Index

Equations used to calculate the refractive index of the atmosphere are given below. These calculations are taken from ITU P.453.

The first step is to find the radio refractivity of the atmosphere. The alternative form of the calculation is used, as presented in Equation 6 of ITU P.453.

$$N = 77.6 \frac{P}{T} - 5.6 \frac{e}{T} + 3.75 \times 10^5 \frac{e}{T^2}$$

Where:

- N is the radio refractivity to be found
- T is the air temperature (K). For example, 15°C is 288.15 K.
- P is atmospheric pressure (hPa). Standard atmospheric pressure is used here: 1013.25 hPa.
- e is pressure coming from water vapour, which depends on humidity H.

It remains to find e, using Equations 8 and 9 of ITU P.453.

Equation 8 sets out the relationship between e and H, where H is relative humidity.

$$e = \frac{H \cdot e_s}{100}$$

Where:

- H is relative humidity (%). A relative humidity of 50% would mean H = 50, not H = 0.5.
- e_s is the saturation vapour pressure (hPa), which depends on air pressure and temperature.

Equation 9 below then allows us to calculate saturation vapour pressure, e_s.

$$e_s = EF \cdot a \cdot exp\left[\frac{\left(b - \frac{t}{d}\right) \cdot t}{t + c}\right]$$

$$EF = 1 + 10^{-4}[7.2 + P \cdot (0.00320 + 5.9 \cdot 10^{-7} \cdot t^2)]$$

Where:

- P is atmospheric pressure (hPa). Standard atmospheric pressure is used here: 1013.25 hPa.
- t is temperature (°C). Note that this lowercase t (°C) is distinct from uppercase T (K).
- a = 6.1121
- b = 18.678
- c = 257.14
- d = 234.5

Notice that in the above calculations:

- a,b,c and d are empirical constants.
- t can be written as t = T – 273.15. (Conversion from Kelvin to degrees Celsius)
- Pressure is assumed to be standard atmospheric pressure of 1013.25 hPa throughout.

The result of these points is that radio refractivity is varied by temperature and relative humidity alone.

Radio refractivity can then be converted to the refractive index by means of Equation 1 of ITU P.453.

$$n = 1 + N \times 10^{-6}$$

It should also be noted that the values of radio refractivity and refractive index calculated so far are applicable to ground level. Equation 11 of ITU P.453 sets out how to obtain these values for different heights above sea level. Here, the refractivity part of the equation is presented, as this is most useful for the purposes of this assessment.

$$N(h) = N_0 \times exp(-h \,/\, 7.35)$$

Where:

- N(h) is the radio refractivity at height h kilometres above sea level.
- h is the height above sea level, in kilometres.
- N_0 is the radio refractivity at sea level.

Effective Earth Radius

The effective earth radius is calculated by taking an Earth radius factor, as given in Equation 5 of ITU P.452.

$$k_{50} = \frac{157}{157 - \Delta N}$$

Where:

- k_{50} is the Earth radius factor.
- ΔN is the absolute value of the loss of radio refractivity in the first kilometre above sea level.

Equivalently,

$$\Delta N = |N(1) - N(0)|$$

with N(1) and N(0) calculated as per Equation 11 in ITU P.453.

The obtained value of k_{50} can then be multiplied by the radius of Earth to obtain the effective Earth radius.

$$a_e = k_{50} a$$

Where:

- a_e is the effective Earth radius.
- k_{50} is the Earth radius factor.
- a is the physical radius of Earth, taken to be 6371km.

Variation in Perceived Aircraft Heights

For a given effective Earth radius, it is possible to calculate, for a given horizontal distance and height relative to the radar, the angle the radar has to look upwards, considering the effective curvature of Earth.

To obtain the change in perceived height, the following steps are taken.

1. Calculate the effective Earth radius without thermal plume.
2. For a given horizontal distance and height of an aircraft, work out the angle which the radar has to look upwards from the horizon to see the aircraft in the absence of thermal plume.
3. Calculate the effective Earth radius with thermal plume.
4. For a given horizontal distance and height of an aircraft, work out the angle which the radar has to look upwards from the horizon to see the aircraft in the presence of thermal plume.
5. Work out the aircraft height required on the Earth radius without thermal plume, such that the angle the radar looks upwards is the same as the angle the radar looks upwards in step 4.
6. Take the difference between the heights calculated without thermal plume in steps 2 and 5. This is the change in perceived height.