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Characterisation of Infrared Sensors for Absolute Unmanned Aerial Vehicle Attitude Determination

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Characterisation of Infrared Sensors for Absolute Unmanned Aerial Vehicle Attitude Determination

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Abstract—**this paper describes the characterisation of infrared sensors used in the attitude control of unmanned aerial vehicles under a range of earth-sky temperature differences.**

***Index Terms*—Unmanned Aerial Vehicle, absolute attitude measurement, infrared sensors.**

I. INTRODUCTION

The use of Infrared (IR) sensors for attitude measurement of spacecraft was first published by researchers at NASA and elsewhere [1-6]. There is at least one commercial aircraft leveler based on IR sensors [7].

Note that the principal idea underpinning the work of these researchers is that we may use the earth-sky temperature differential, particularly with reference to the horizon, to maintain or restore trimmed or level flight.

We now have several years of flight experience using IR sensor based attitude control in our VMC autopilots with this work first being presented in [8]. This paper builds upon the introduction in [9] to show how the IR sensors used may be characterised and how the aircraft attitude may be determined under a range of weather conditions and earth-sky temperature relationships.

If control of the aircraft is to be maintained then it is very important that the pitch and roll angles of the aircraft are not **underestimated** particularly if we wish to adopt reasonable roll and pitch angles (~45°).

II. IR SENSORS

The IR sensors we have used are manufactured by Melexis. There are, however, a number of other similar sensors available including those from Dexter Research and Roithner LaserTechnik. They may have a range of fields of view (FOV), bandwidth and underlying sensor configurations and aperture lenses/diffusers. Most of these aspects can be ignored [9].

To measure the ground-sky temperature difference the sensors are arranged in pairs back-to-back facing outwards. For this paper we have chosen to use sensor heads from FMA Direct [7] because of their convenient packaging. The head contains two sensor-pairs and generates output which corresponds to the difference in temperature seen by the two sensors.

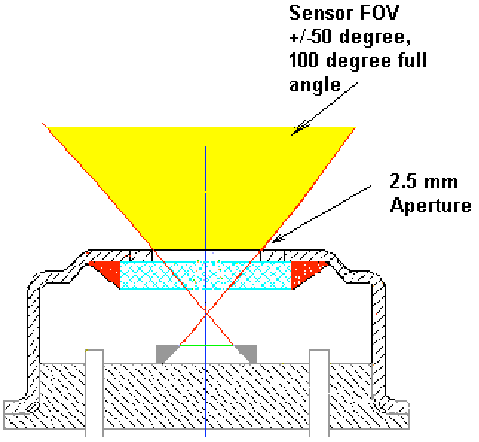

Figure 1 Melexis Sensor Field of View

III. SKY TEMPERATURE PROFILE

A naïve view is that the earth's surface is at close to the ambient temperature and the sky is always very cold relative to the earth's temperature. This is reasonable for a spacecraft above the atmosphere but a little more complicated for aircraft within the atmosphere, particularly those flying at relatively low altitudes or in the presence of scattered cumulous cloud where the FOV intermittently includes cold sky or warmer nearby cloud patches.

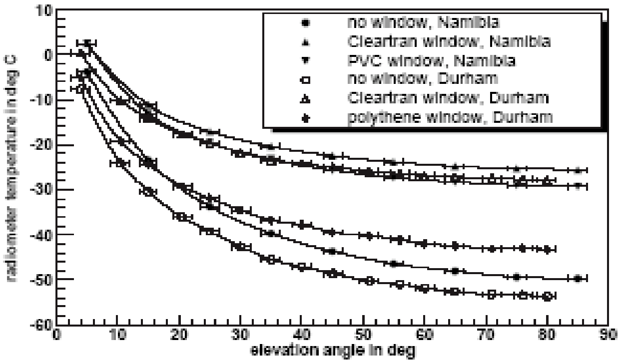

Figure 2 The relation between sky temperature and elevation angle of the radiometer with different window materials. Ambient conditions in Namibia: night time, $T = 16^\circ C$, RH 41%; Durham: afternoon, $T = 5^\circ C$, RH (70 ± 10)% [10].

Figure 2 from [10] shows how sky IR temperature can vary with elevation under different conditions. The sensor used had a FOV of 2.9° and a bandwidth of 8 to 14um (89°C to -66°C). At first the higher night sky temperature in Namibia seems at odds with that of Durham however we speculate that high humidity from the Atlantic Ocean may be the cause.

Other researchers [11] observe that: “The improvements in the infrared and sub-millimetre observing conditions compared to temperate sites are surmised to arise from three principal effects: low temperature, low water vapour content and low levels of particulates. The low temperature results in a reduction of the background sky emission. The low water vapour improves the atmospheric transmission and correspondingly decreases its emissivity. The reduced particulate content of the atmosphere also reduces its emissivity compared to a mid-latitude site”.

Our own measurements in a relatively dry and warm part of Australia confirm that the sky is colder when humidity is low. In fact dry summer nights have very cold sky temperatures while humid days or nights show a much warmer sky.

The data for the graphs of Figure 2 was taken using a Raytek MT-2 Minitemp with a wider FOV of 20º. The form of these graphs accord with those in [10]. It is important to note that hot spots on the ground depart significantly from ambient temperatures and that the sky temperature is seriously affected by clouds. The synthesized output of sensor-pairs shown in Figure 4 also assumes a sensor with a FOV of 20°. Fortunately the wider 100° FOV of the actual IR sensors used in the aircraft serves to average out the peaks caused by ground hot spots and small clouds.

IV. ATTITUDE ESTIMATION

From the measurements in [12] the authors formed a working conclusion that the differential temperature (attitude angle) for the sensor pair may be approximated as shown in Figure 5. In what follows we will present a better means of estimating the aircraft’s attitude.

A. *A better estimation*

While we could attempt to determine formally the function describing the variation of sky temperature with elevation, we observe from Figure 6 and simple curve fitting that it is close to exponential. The sky temperature for a given elevation, maximum sky temperature and ambient/ground temperature can be expressed as:

$$Sky=SkyMax*\exp(-Elevation/90*5.5)-(SkyMax-Ground)$$

Figure 6 shows the sky temperatures for two curves from Figure 2 and the exponential approximation. Integrating over the FOV of each sensor in a sensor-pair we obtain their individual outputs and the difference; Figure 7 shows the results for the Namibia case.

The sensor-pair output for both cases of Figure 6 are given in Figure 8. We observe that when the temperature difference between the sky and ground is high, the output of the sensor-pair approximates a sinusoid. If the temperature difference is relatively low as it may be on a cloudy day then the output is partially flattened.

The sinusoidal approximation in both cases and more generally overestimates the elevation aka roll/pitch angle. In what follows the temperature difference for sensors in a pair should be viewed as synonymous with roll/pitch angle.

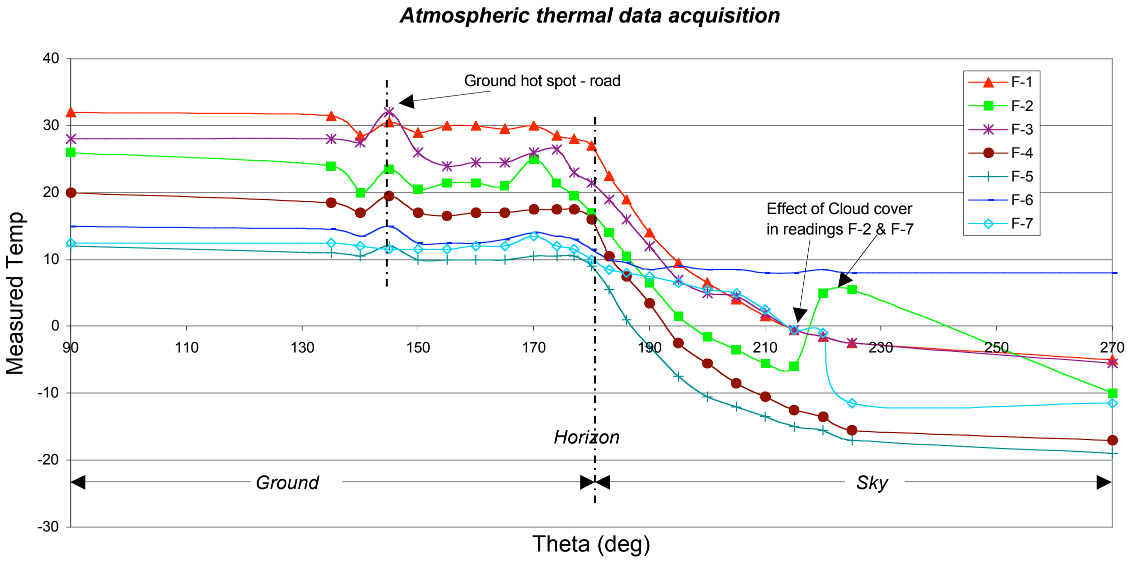

Figure 3 Sky and Ground temperatures for varying attitude, times and weather conditions [10]

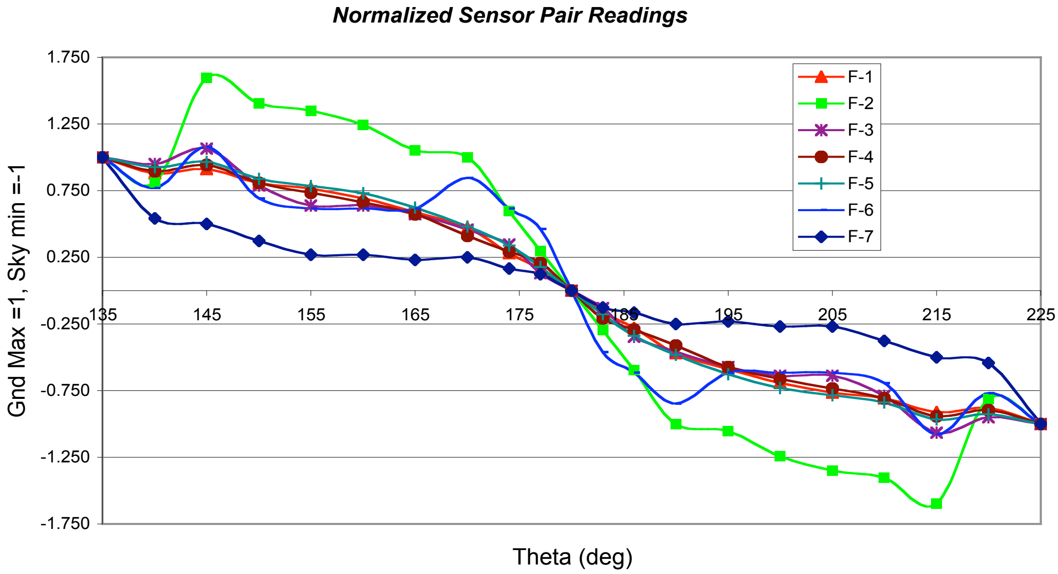

Figure 4 Synthesised sensor-pair readings [10]

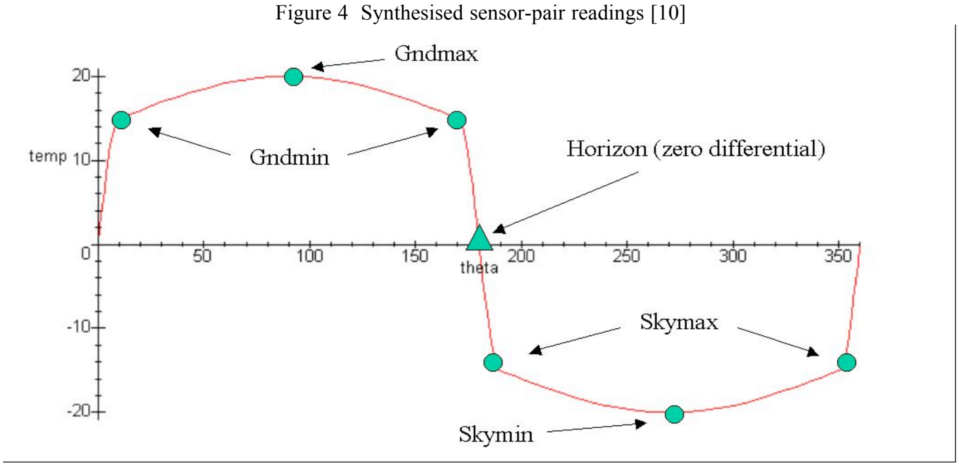

Figure 5 Approximate temperature difference with elevation angle [10]

1) The weakness

Unfortunately the maximum ground-sky difference is not constant varying significantly over periods of seconds to hours. As will be seen later the situation can be further complicated by terrain and clouds.

If the maximum difference is obtained by simply rolling the aircraft before launch to 90° and recording the maximum value of roll sensor-pair output to use for scaling then a decrease in the maximum difference during flight may lead to seriously underestimating the roll/pitch angle. Turning through a large heading change the aircraft will attempt to roll to the maximum roll angle as previously measured which is never reached.

If the initial measured maximum difference is low then the angles will be overestimated resulting in safe but woefully inadequate roll and pitch angles.

2) A solution

Fortunately the simple addition of a third sensor-pair oriented vertically provides continuous monitoring and scaling of the estimated roll/pitch angle. A degree of caution is required as the sensors may not see exclusively ground and sky and the maximum sky/ground range should be filtered with a time constant of a few seconds. If the time constant is too long it is possible to underestimate the attitude angles. For example if we have been flying for a long time under a clear sky then suddenly fly under a cloud the attitude will be **underestimated** if we do not reasonably quickly take into account the range now seen by the vertical sensor-pair. Conversely if we make the time constant too small then we may introduce undesirable noise into the control loops.

The third sensor-pair is used by others to bring aircraft safely to non-inverted trimmed level flight quickly [7]. Full overlapping FOV coverage in all directions, including vertically, adds the prospect of full 3D control [14].

B. Scheme used

While it is simple to construct a lookup table based on the assumptions of constant ground temperature and an exponential sky temperature profile we have elected to date to use a sinusoidal approximation. A lookup table for the inverse sine is used with appropriate scaling based on the maximum output of the vertical sensor-pair. It can be seen (Figures 8 & 9) that this will under normal circumstances **overestimate** the roll/pitch angle. We also limit the maximum available roll to 45°.

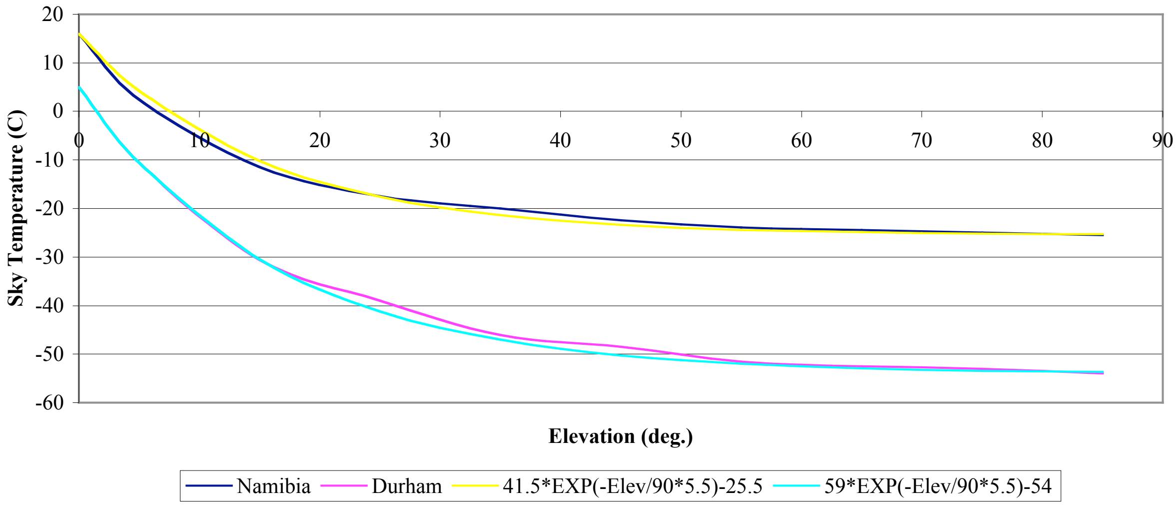

Figure 6 Sky temperature for Durham with a clear window and for Namibia with a PVC window.

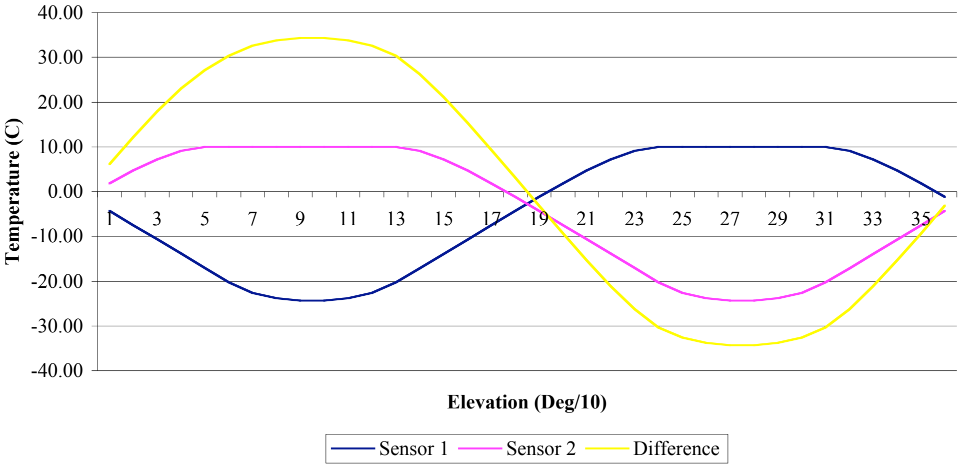

Figure 7 temperature for Namibia for each sensor and the difference over 360° of elevation angles.

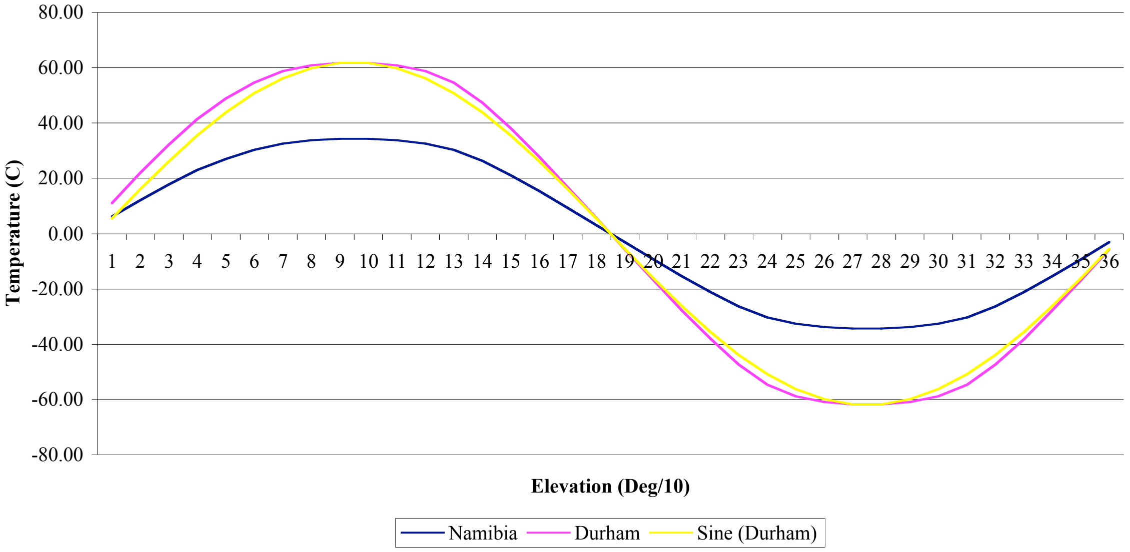

Figure 8 Expected temperature difference for a sensor-pair for Durham with a clear window and for Namibia with a PVC window with Sine function approximation for Durham.

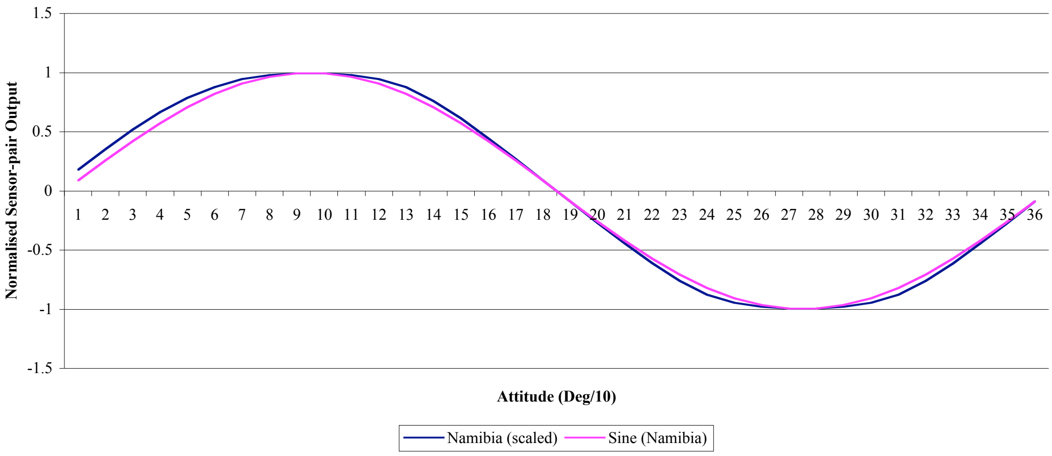

Figure 4 Normalised sensor-pair output expected for Namibia and Sine function approximation.

V. SITUATIONS LIKELY TO CAUSE FAILURE

This section introduces some thoughts on the limitations of this otherwise attractive scheme of directly measuring aircraft pose. In most cases these limitations may be overcome by modest algorithmic changes to qualify the pitch and roll indications up to and including ignoring them and relying upon the intrinsic stability of the aircraft. The positive aspect to these limitations is that they serve to provide a modest degree of terrain and cloud avoidance. We observe this behaviour clearly in practice as the aircraft attempts to bank away from encroaching ridges and clouds.

The output of the sensor-pairs in these circumstances can depart from a simple sinusoidal assumption but are beyond the scope of this paper and will be reported later [14].

1) *False roll determination*

If the aircraft is flying parallel with rising ground or clouds which are above the aircraft's altitude then the computed roll angle will be incorrect.

Assume the ridge/cloud is at 1000M and that the horizon is not obscured in the opposite direction. The horizon will be at a distance of approximately 150Km. If the aircraft is flying on the line between ridge/cloud top and horizon then there will be a roll error of approximately 0.4°; the computed roll will be zero when the aircraft is in fact banked away from the ridge/cloud by 0.4°. This error is of little concern.

If the aircraft is flying below this line then the output of the roll sensor-pair will be lower for a given roll angle as the FOV for both sensors is partially obscured. The roll will be **underestimated**.

If the aircraft is flying below the rim of a valley the roll of the aircraft will be **underestimated**. If the valley walls are rising at an angle greater than half the FOV of the roll sensors and the aircraft is flying level there will be no roll indication; both sensors see ground only and there is no roll control. The vertical sensor-pair will also have the upward looking sensor's FOV partially obscured and thus the sensor gains will be increased. Unfortunately the gain is also increased for the pitch sensor-pair resulting in overestimating pitch although this may only be an issue if flying down a valley which has a dead end!

The inclusion of a yaw gyro and the use of GPS data can disambiguate the above situations usually without recourse to Kalman Filters or other computationally complex solutions.

2) *False pitch determination*

If the aircraft is flying directly towards rising ground or clouds then the pitch sensor will indicate positive pitch when the aircraft is in fact level. The same computation as for roll determination applies with a pitch up of 0.4° being indicated when the pitch from trim is zero.

If the aircraft is below the line connecting the horizon aft of the aircraft to the ridge/cloud ahead then the pitch, while still being indicated as pitch up, will be **underestimated**, with the output of the sensor-pair again falling as the sensor's FOV is partially obscured.

Assume the autopilot strategy is to control airspeed through pitch and altitude from throttle. The aircraft will attempt to correct the falling airspeed by selecting down pitch. The throttle will be increased to maintain altitude. If the aircraft has adequate power to achieve the necessary rate of climb (ROC) then the aircraft may clear the obstacle. Unfortunately the pitch down available to control airspeed is usually limited to around 10° with pitch up limited to slightly less than is possible with the aircraft's maximum ROC. This is 10° down on indicated pitch and so the airspeed may continue to fall if there is insufficient power to maintain altitude at what will be a high and increasing angle of attack as the aircraft approaches the ridge/cloud.

Ideally the waypoints will have been programmed so that the aircraft has climbed to an altitude that will clear the obstacle! If not the best one may hope for is that the aircraft will stall and roll away from the ridge at which point the roll sensor-pair will exaggerate the roll thus perhaps avoiding the obstacle.

3) *Weather issues*

Rain can be a problem as a film of water over a sensor will dominate what that sensor sees. An IR transparent polythene fairing is required to shed any such water. Even with sensors shielded from direct water an air-mass within the FOV which has significant rain in it will distort the temperature profile. Our worst observed effect was immediately following a brief hailstorm where the sudden arrival of very cold hailstones at ground level caused the ground to temporarily appear colder than the sky. This effect was observed in conditions of light fog with horizontal visibility around 1000M. The measured temperatures were a ground temperature of 3C and sky temperature of –2C. It is surmised a much higher level cloud containing the cold hailstones was obscured by the warmer lower cloud. The hailstones then fell through the lower cloud making the ground temperature suddenly drop to -4C while the sky remained at -2. The effect persisted for about 15 minutes and the general visibility was hardly equal to VMC conditions.

VI. CONCLUSIONS

The paper has reported on improvements that may be made to the pitch/roll estimates provided by an IR sensor based attitude measurement scheme. This very simple scheme to directly measure aircraft attitude to within a few degrees has attractions over the more usual inertial measurement based schemes and has been shown to work well in practice [13]. The application of IR sensors to 3D flight control will be presented later [14].

ACKNOWLEDGMENT

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