Ground Effects obtained from Flight Tests of ALFLEX

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ABSTRACT

The ALFLEX flight experiment was carried out in Woomera in South Australia, and 13 landing trials beginning on July 6, 1996, were conducted. The landing performance of all flying vehicles is strongly influenced by the ground. This paper describes a ground effect analysis method based on the flight experiment data of unmanned non-thrust vehicle, and gives ground effect characteristics of the ALFLEX.

1. Introduction

ALFLEX (Automatic Landing Flight Experiment) is a unmanned, 37% scaled model of HOPE to establish the fundamental technology for the HOPE automatic landing. The flight experiment of ALFLEX was carried out at the Woomera Airport in South Australia, and 13 landing trials were conducted beginning on July 6, 1996.

Ground effects have a strong influence on the landing performance of aircraft since the ground effects have a very large influence on landing aircraft touchdown dispersion and sink rates. Therefore, the wind tunnel tests for examining the ground effect were carried out during the development of ALFLEX. Then, enough simulation calculation was conducted to predict landing performance. It is important to obtain the ground effect characteristics from the flight data, when the effectiveness of the wind tunnel data for the design is evaluated.

To obtain the ground effect characteristics of ALFLEX, we selected the flight data of four flights in which the sink rate does not change abruptly from the 13 test flights. This paper presets a technique to derive the ground effects from flight data of unmanned non-thrust vehicle and then gives the results of using this technique for ALFLEX. Comparison is made between the flight data and wind tunnel ground effects data.

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2. Technique

To quantitatively acquire the ground effect data by the flight test, the aircraft must be perfectly trimmed outside the ground effect regions and it approaches the ground without control. If this flight was done in calm wind condition and the trim of the aircraft was broken as the aircraft nears the ground, its untrimmed condition is caused by the ground effect. The ground effect can be extracted from this phenomenon. However, it is the wind condition is never completely calm, and there is also the danger of touchdown from the nose landing gear due to airframe motion. Therefore, the ground effect data is obtained by a shallow approach method[1)] described below:

- Perfectly stabilize the aircraft at a wing span of 3-5 times.
- Approach at a shallow flight path angle of about 1m/sec sink rate.
- Do not change flaps or engine fan RPM; maintain a constant airspeed with a minimum of control inputs.
- When the aircraft is within about wing height of the ground, hold the pitch attitude constant until touchdown so that the nose landing gear does not hit the ground on touchdown. Do not flare.

Figure 2-1 shows a time history of a typical ALFLEX landing approach used to obtain ground effects. It shows that the approach landing, which is similar to the above-mentioned shallow approach

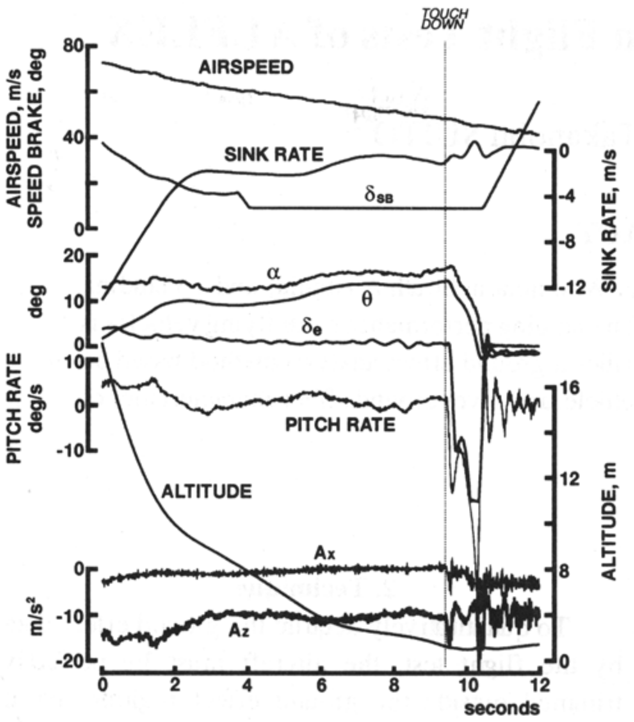


Fig. 2-1 Time History for a ALFLEX Landing Approach

method, is realized. That is to say, the sink rate is constant for about -2m/s at 8m above ground level (AGL), and though a flare is carried out afterward, the angle is small. The approach landing of ALFLEX differs greatly from the shallow approach method in that the airspeed decreases continuously. However, steady motion with a constant acceleration appears to be realized, since deceleration is constant for about -2.4 m/s.

Therefore, when the aircraft nears the ground, its lift coefficient (C_L) and drag coefficient (C_D) are calculated by :

$$C_L = \frac{W}{qS}(A_X \sin\alpha - A_Z \cos\alpha)/g \quad (2.1)$$

$$C_D = -\frac{W}{qS}(A_X \cos\alpha + A_Z \sin\alpha)/g \quad (2.2)$$

where

A_X = X-axis acceleration, forward +

A_Z = Z-axis acceleration, downward +

q = dynamic pressure

The change of coefficients by the ground effect is obtained by subtracting the reference values measured from the ground effect in Eqs. (2.1) and (2.2). The angle of attack (α) and control surfaces may vary during the landing approach, since the conditions trimmed out of ground effect are not exactly maintained owing to the effects of atmospheric disturbance, etc. Therefore, the reference values must be corrected, because this change of the coefficients is not based on the ground effect. It is shown by Eqs. (2.3) and (2.4).

$$\begin{aligned} C_{L_\infty} &= C_{L_{ref}} + \frac{\Delta C_L}{\Delta\alpha}(\alpha - \alpha_{ref}) \\ &+ \frac{\Delta C_L}{\Delta\delta_e}(\delta_e - \delta_{e_{ref}}) + \frac{\Delta C_L}{\Delta\delta_{sb}}(\delta_{sb} - \delta_{sb_{ref}}) \end{aligned} \quad (2.3)$$

$$\begin{aligned} C_{D_\infty} &= C_{D_{ref}} + \frac{\Delta C_D}{\Delta C_L^2}(C_L^2 - C_{L_{ref}}^2) \\ &+ \frac{\Delta C_D}{\Delta\delta_e}(\delta_e - \delta_{e_{ref}}) + \frac{\Delta C_D}{\Delta\delta_{sb}}(\delta_{sb} - \delta_{sb_{ref}}) \end{aligned} \quad (2.4)$$

where

subscript ∞ = out of ground effect (in free air)

subscript ref = trimmed value out of ground effect (reference value)

The change in aircraft pitching moment resulting from ground proximity can be evaluated by the amount of elevator for the elevator angle trimmed out of ground effect, because the pitching moment cannot be directly measured. The pitching moment arises from the change of lift coefficient, speed brake angle (δ_{SB}) and pitch rate (q) during landing approach. Hence the elevator angle (δ_e) in the free air is obtained according to the following equation,

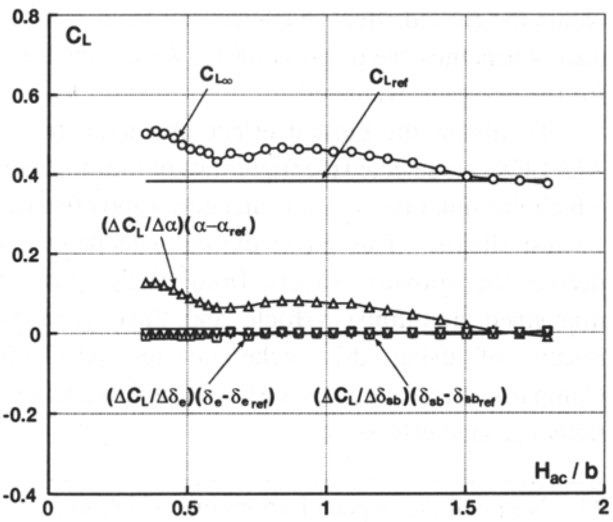


Fig. 2-2 Each Item's Percentage of Eq.(2.3)

because the change of the elevator angle in proportion to the change of the pitching moment is not caused by the ground effect.

$$\delta_{e_\infty} = \delta_{e_{ref}} + \frac{\Delta\delta_e}{\Delta C_L}(C_L - C_{L_{ref}}) + \frac{\Delta\delta_e}{\Delta\delta_{sb}}(\delta_{sb} - \delta_{sb_{ref}}) + \frac{\Delta\delta_e}{\Delta q\bar{c}/2V}\frac{\Delta q\bar{c}}{2V} \qquad (2.5)$$

The reference values used in this ground effect analysis are the average of these quantities from 5m to 6m AGL in which the change of flight path angle is small.

As the proportion of each item after the second term of Eqs. (2.3)-(2.5) is smaller, the good ground effect data can be obtained through the flight test. Figure 2-2 presents the proportion of each item in Eq. (2.3) for lift coefficient. This clearly illustrates that the ALFLEX flight data during landing approach are enough to obtain the ground effect. The change in lift coefficients due to ground effect is determined from the difference between the measured lift coefficient (Eq. (2.1)) and the expected modeled free air lift coefficient (Eq. (2.3)). The change in drag coefficient and elevator angle caused by the ground effect is also obtained in a similar way.

$$\Delta C_{L_{GE}} = C_L - C_{L_\infty} \qquad (2.6)$$

$$\Delta C_{D_{GE}} = C_D - C_{D_\infty} \qquad (2.7)$$

$$\Delta C_{m_{GE}} = -(\delta_e - \delta_{e_\infty})\frac{\Delta C_m}{\Delta\delta_e} \qquad (2.8)$$

The aerodynamic characteristics which is included for the above-mentioned equations was calculated using the wind tunnel test data[2)].

3. Measurement Corrections

The airspeed measured in flight tests includes the position error. In addition, it is necessary to correct the airspeed error caused by the image bound vortex as the aircraft approaches the ground. Though the altitude uses the measured value by the laser tracker whose accuracy is very good, slope and unevenness of the runway are not accounted for. These compensation techniques are clarified below.

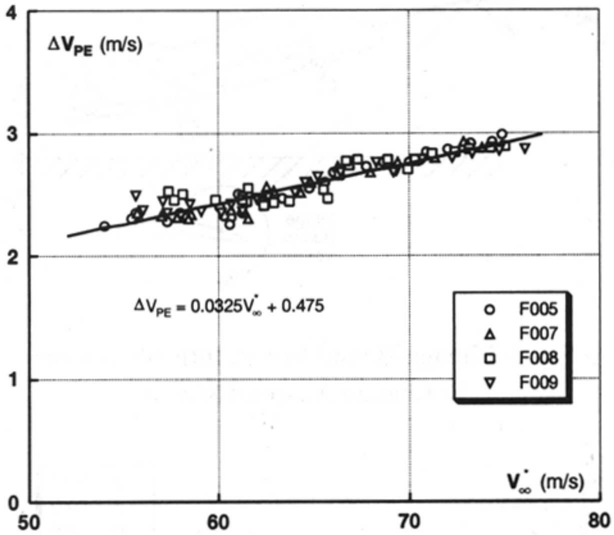


Fig. 3-1 Position Error of Airspeed

3.1 Position Error[3), 4)]

Since the accurate altitude of ALFLEX can be measured by the laser tracker, the static pressure error is obtained from the difference of altitude measured by the laser tracker from the pressure altitude.

The relation between the pressure altitude error (ΔH_{PE}) and static pressure error (Δp_{PE}) is defined by:

$$\frac{\Delta p_{PE}}{\Delta H_{PE}} = \rho g = \rho_0 \sigma g \qquad (3.1)$$

The relation between the static pressure error and the true airspeed error (ΔV_{PE}) is also given by the following equation.

$$\Delta V_{PE} = \frac{-\Delta p_{PE}}{\rho_0 V_\infty^* \left[1 + \frac{\gamma - 1}{2}\left(\frac{V_\infty^*}{a_0}\right)^2\right]^{\frac{1}{\gamma-1}}} \qquad (3.2)$$

where

V_∞^* = instrument corrected true airspeed (include position error)

Figure 3-1 presents the position error of true airspeed obtained with this calibration procedure.

3.2 Runway Slope

It is most important to accurately determine the height above the ground, since the ground effect is an aerodynamic phenomenon generated by the

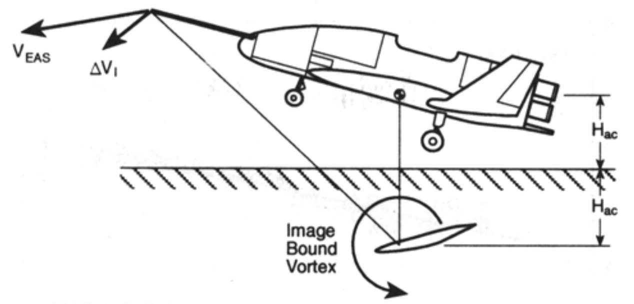


Fig. 3-2 Image-Bound Vortex Influence on the Noseboom Airspeed Sensor

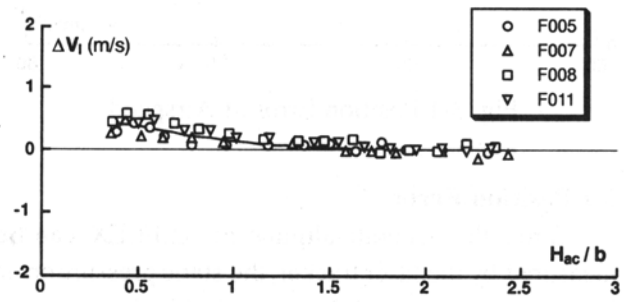


Fig. 3-3 Image-Bound Vortex Effect for Airspeed

interference between flow around the airframe and ground as the aircraft approaches the ground.

There is a radio altimeter which measures the absolute altitude with good accuracy. The radio altimeter, which played an important role in the automatic landing approach, is installed in ALFLEX. However, we cannot use the absolute altitude measured by the radio altimeter, since the bias value fluctuated.

Except for the radio altimeter, the laser tracker was installed as a ground facility which measured the position of the ALFLEX. The ALFLEX position data obtained from the laser tracker is converted into runway coordinate system which uses the end of the runway as the origin. The height above the ground can be calculated from the data of the laser tracker since the slope of the runway is known. The runway slope in the runway coordinate system was measured by using kinematic GPS on the runway center. The height above the ground of ALFLEX can be obtained by subtracting the runway slope from the height calculated from the laser tracker data in the runway coordinate system, because runway slope by measure of the kinematic GPS was given in the 5 ~ 6m interval.

3.3 Image of Bound Vortex

As the aircraft descends to touchdown, airspeed error results from the image of the bound vortex, as illustrated in Fig. 3-2. This airspeed error can be measured from the difference (ΔH_I) between the barometric altitude AGL and absolute altitude. The equation to correct airspeed using the measured pressure altitude error is given by :

$$\Delta V_I = \frac{\Delta H_I}{\dfrac{V_\infty^*}{g}\dfrac{\rho_0}{\rho}\left[1+\dfrac{\gamma-1}{2}\left(\dfrac{V_\infty^*}{a_0}\right)^2\right]^{\frac{1}{\gamma-1}}} \tag{3.3}$$

Figure 3-3 shows this airspeed error induced by the image of the bound vortex.

4. Ground Effect Characteristics

The ground effect data must be analyzed in terms of aircraft mean aerodynamic center height (H_{ac}), because the ground effect is the aerodynamic phenomena as the aircraft nears the ground.

Figure 4-1 shows a representative example of the result of ground effect analysis for lift coefficient. The measured lift coefficient (C_L), lift coefficient in free air (C_{L_∞}) and the change in lift coefficient caused by ground effects ($\Delta C_{L_{GE}}$) in the landing approach are presented in Fig. 4-1. The horizontal axis in this figure is the normalized height defined by mean aerodynamic center height above the ground divided by the wing span (b = 3.295m).

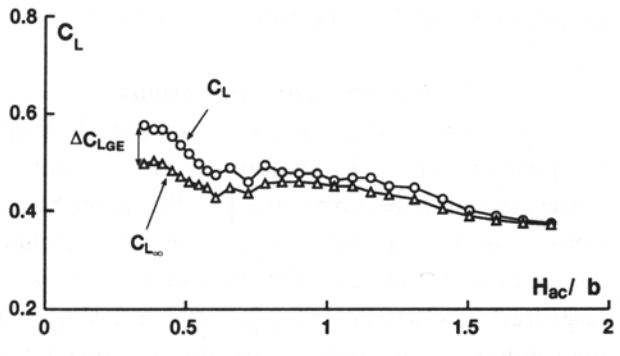
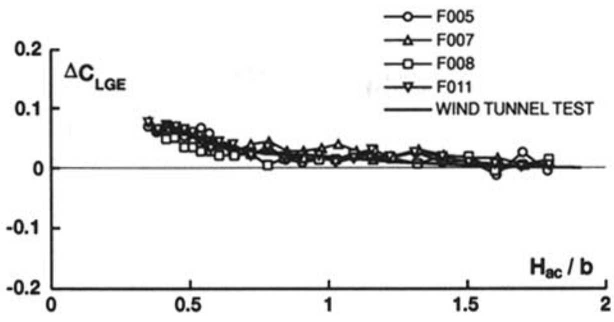
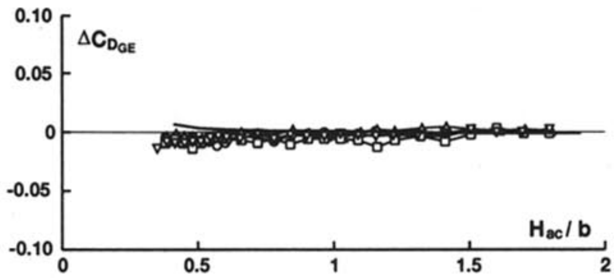


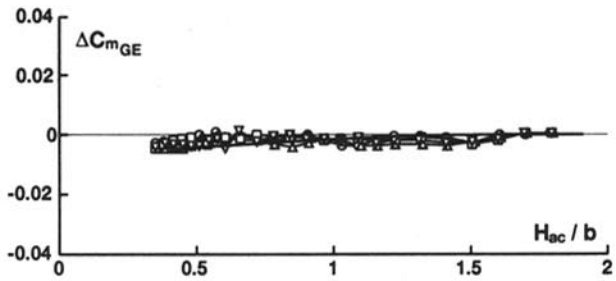
Fig. 4-1 Lift Coefficient during a Landing Approach



(a) Lift Coefficient

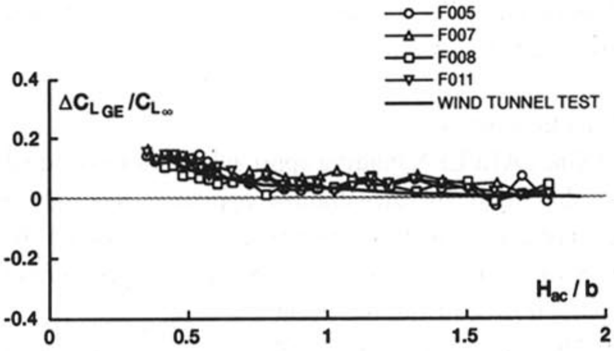


(b) Drag Coefficient

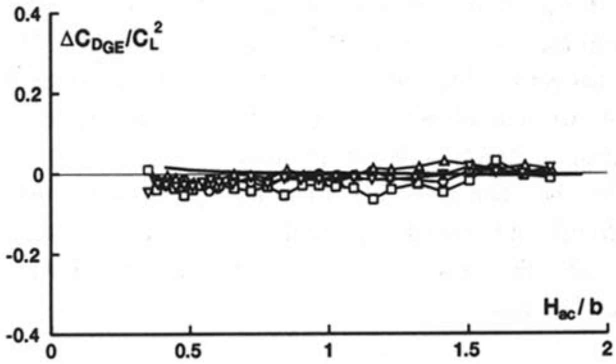


(c) Pitching Moment Coefficient

Fig. 4-2 Ground Effect



(a) Lift Coefficient



(b) Drag Coefficient

Fig.4-3 Ground Effect Characteristics

The change in coefficients caused by ground effects for four flights is shown in Fig. 4-2. Figure 4-3 also presents the percent increase of lift coefficient and the change in drag coefficient normalized by the square of the lift coefficient due to ground effects. This normalization by C_L^2 is logical since the ground effect is expected to cause a reduction in the induced drag which is proportional to C_L^2. The solid line in these figures then shows the ground effect characteristics derived from the wind tunnel tests[5] at $\alpha = 16$ degrees.

As shown in Figs. 4-2 and 4-3, the change of the lift coefficient caused by the ground effects begins to appear at $H_{ac}/b \approx 1.5$ and the change exponentially increases as ALFLEX approaches the ground. The change in lift coefficient due to ground effects is very similar to the ground effect characteristics of conventional aircraft. Though the change in drag and pitching moment coefficients caused by ground effects show a tendency to decrease, the influence by ground effects is small in either case.

The change in lift, pitching moment coefficient caused by ground effect obtained from the flight data agrees well with that obtained by wind tunnel data. The change in drag coefficient due to the ground effect slightly decreases for flight test data and slightly increases for wind tunnel data.

5. Conclusions

A technique for deriving the ground effects from flight data of unmanned non-thrust ALFLEX developed as a cooperative effort between the National Aerospace Laboratory and the National Space Development Agency has been described.

The ground effects characteristics for ALFLEX has also been discussed.

Conclusions:

1) Since ALFLEX landing approach was almost equal to the flight by the shallow approach method to quantitatively acquire the ground effect data by the flight test, it was possible to obtain the ground effect characteristics from the flight test data.

2) The ground effect of ALFLEX begins to appear at a height above the ground of 1.5 times the wing span. The change in lift coefficient due to ground effects exponentially increases as ALFLEX approaches the ground, as it does with conventional aircraft. The change in drag and pitching moment coefficient shows a tendency to decrease. The influence by ground effects is, however, small.

3) The change in lift, drag and pitching moment coefficient caused by ground effect obtained from the flight data agrees well with that obtained by wind tunnel data.

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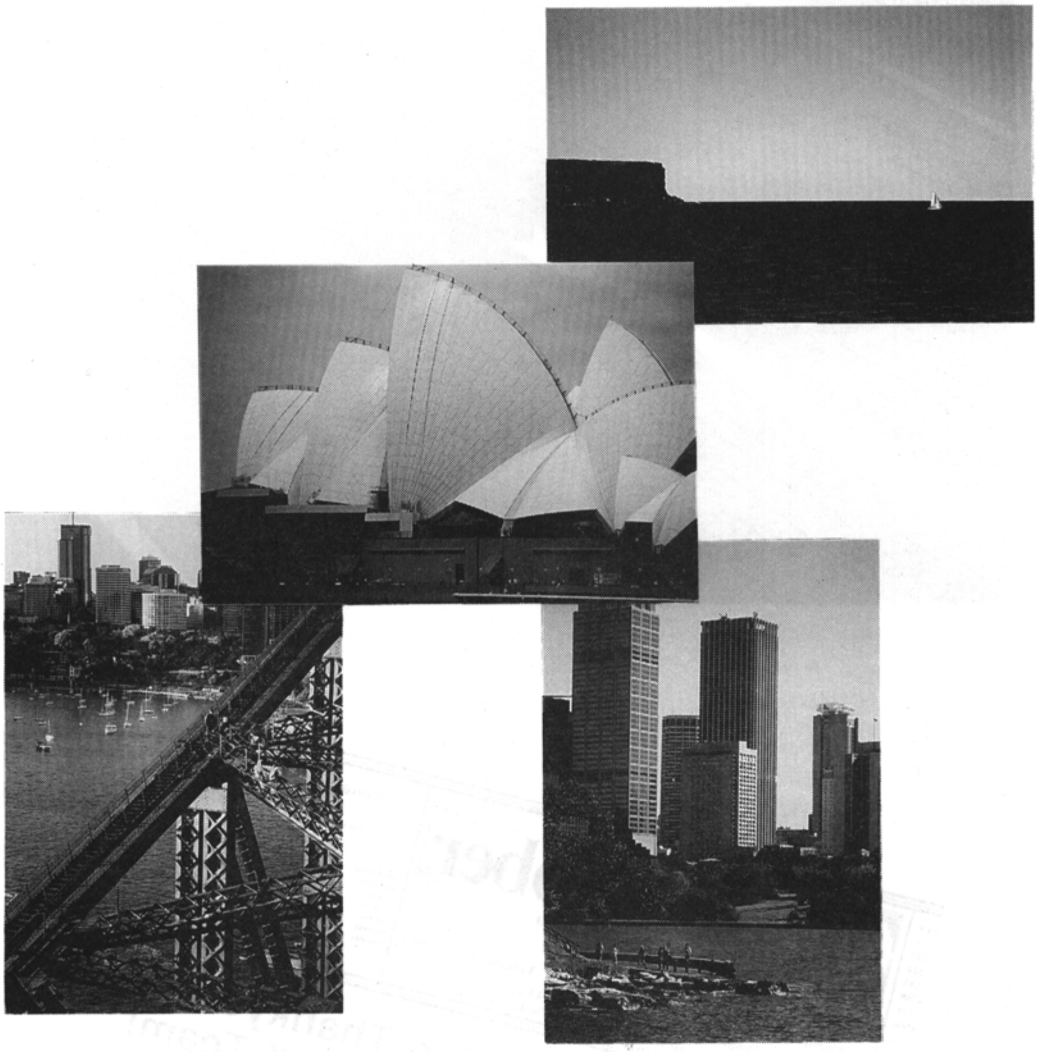

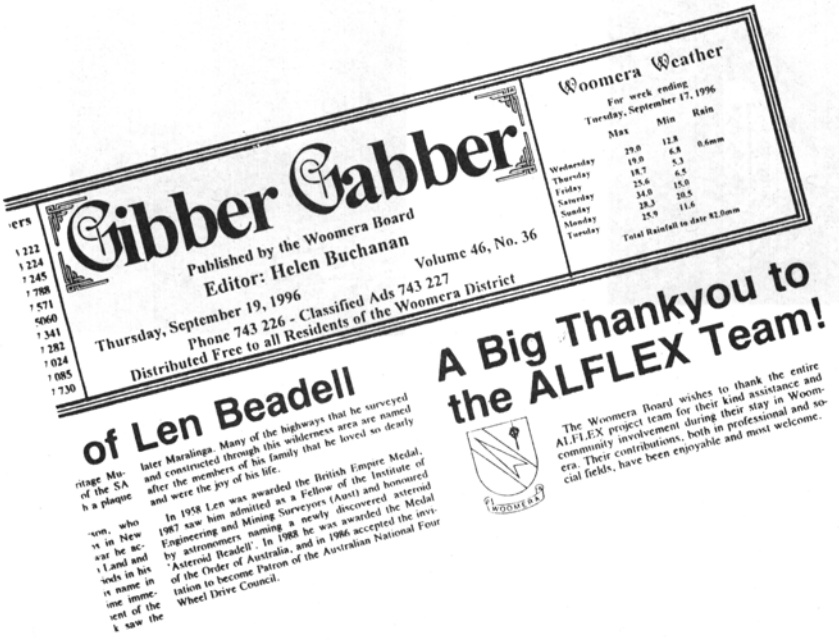

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Woomera Weather

For week ending Tuesday, September 17, 1996

	Max	Min	Rain
Wednesday	29.0	12.8	0.6mm
Thursday	19.0	6.8	
Friday	18.7	5.3	
Saturday	25.6	6.5	
Sunday	34.0	15.0	
Monday	28.3	20.5	
Tuesday	25.9	11.6	

Total Rainfall to date 82.0mm

of Len Beadell

later Maralinga. Many of the highways that he surveyed and constructed through this wilderness area are named after the members of his family that he loved so dearly and were the joy of his life.

In 1958 Len was awarded the British Empire Medal, 1987 saw him admitted as a Fellow of the Institute of Engineering and Mining Surveyors (Aust) and honoured by astronomers naming a newly discovered asteroid 'Asteroid Beadell'. In 1988 he was awarded the Medal of the Order of Australia, and in 1986 accepted the invitation to become Patron of the Australian National Four Wheel Drive Council.

A Big Thankyou to the ALFLEX Team!

The Woomera Board wishes to thank the entire ALFLEX project team for their kind assistance and community involvement during their stay in Woomera. Their contributions, both in professional and social fields, have been enjoyable and most welcome.