Slide Rules and Other Mechanical Calculating Devices in Aviation

Ronald van Riet

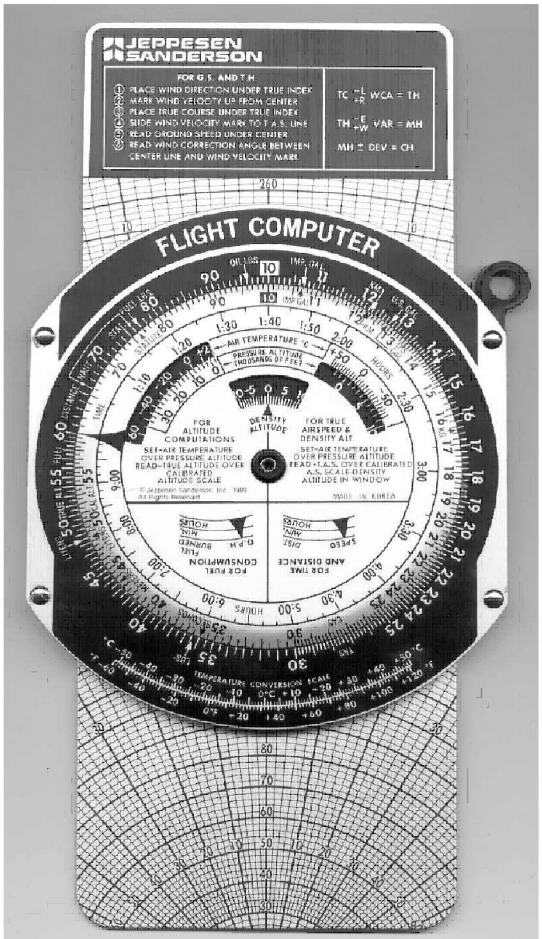


Figure 1. The E6B Flight Computer.

Rationale

It is perhaps surprising to see a high-tech area like aviation being the last stronghold for mechanical calculators, to the extent that a type of circular slide rule (the ubiquitous E6B flight computer) is mandatory at every pilot's exam, both in the USA and elsewhere. Even in this era of GPS, moving maps and other electronic calculators, mechanical flight computers are here to stay for at least a good many years.

Several articles in the (slide rule) collecting press have appeared in the past on these types of slide rules (see abbreviated bibliography at the end), but these have mostly treated the subject from the point of view of a collector. Discussions with fellow collectors (most notably IJzebrand Schuitema) have proven that there is a need to approach such slide rules from the point of view of the user: the pilot, navigator, or loadmaster. The current article is an overview; future articles could describe the use of these devices in more detail. The writer invites the readers to propose subjects for such in-depth articles.

Introduction

The E6B (originally a US military designation, but long since generic for a general-purpose type of flight computer) has been manufactured by literally dozens of companies in hundreds of variations. Most of these manufactures are US-based, Jeppesen being the best known. In Europe some types are also well known for their high quality and precision, e.g., the British Pooley's CRP series and the German Aristo Aviat. We have even seen at least two Dutch manufacturers: Mercator (types B-3, B-4, and 100) and Holland Aviation with its Polestar.

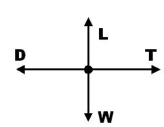
The use of mechanical calculators can be subdivided in a number of areas, each of which will be briefly treated in this document:

1. Weight and balance
2. Performance
3. Wind correction
4. Flight time, Endurance
5. Conversion of different units
6. True altitude
7. True airspeed
8. Density altitude
9. Various applications

Unless explicitly mentioned, all examples given are taken from my own collection of flight computers.

1. Weight and Balance

In straight and level flight, four forces act upon an aircraft: Thrust **T** equaling Drag **D**, Lift **L** equaling Weight **W**.



The maximum weight is usually limited by the available thrust and by construction factors.

Moreover, the Center of Lift (CL) has to coincide with the Center of Gravity (CG). CL can be varied within relatively small limits by aerodynamical means, meaning that the CL has to be within strict limits as well. Should an airplane try to take off with its CG too far forward, it will not be able to rotate and cannot get airborne; with the CG too far aft, the plane may become airborne but will be extremely difficult to control with a high chance of crashing. The limits are calculated theoretically and verified experimentally and although some safety margin is always calculated in, it is strictly forbidden—as well as highly unwise—to attempt to take off with the CG outside the limits.

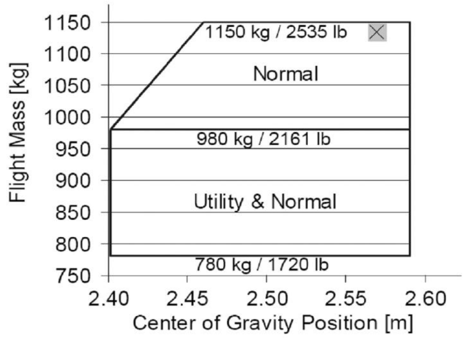


Figure 2. Weight and Balance Diagram.

The picture shows a typical weight-and-balance diagram for a modern light aircraft, showing that the forward/aft limits of the CG are typically dependent of actual weight.

I will give two examples of devices used in determining the weight and balance for an aircraft:

1. Light aircraft manufacturer Piper has issued a number of mechanical devices for its larger aircraft directly showing the weight-and balance diagram. Using slots in sliding overlays, the user can enter the effects of pilots, passengers, baggage and fuel to prove that the weight and balance is inside the proper envelope; in case of problems, adjustments can easily be made to correct the situation. The picture shows such a device for the twin-engined PA-32 Twin Comanche.

   My collection contains nine different graphical calculators like this, I know of four more and I estimate that about 25 different devices of this type have been developed.

2. Widely known are the load adjusters, devices made by Cox & Stevens (later acquired by Revere Corp. of America), basically a relatively conventional slide rule used to determine the correct load and balance. More than 1200 different types have been made (the highest known number is 1216 for the E-3A, the AWACS early warning airplane), one each per type of aircraft; sometimes more than one in case of variants with different specifications. Very subtle differences must exist between the versions for the B-17E & F with the addition "revised" and another one with the addition "modified". Depicted below is a load adjuster for the WWII vintage B-29/B-29A bomber.

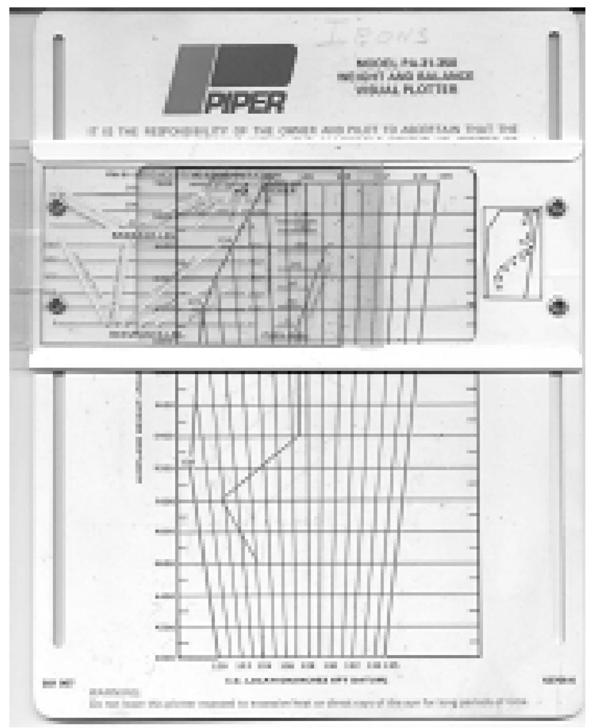


Figure 3. Piper Weight and Balance Plotter.

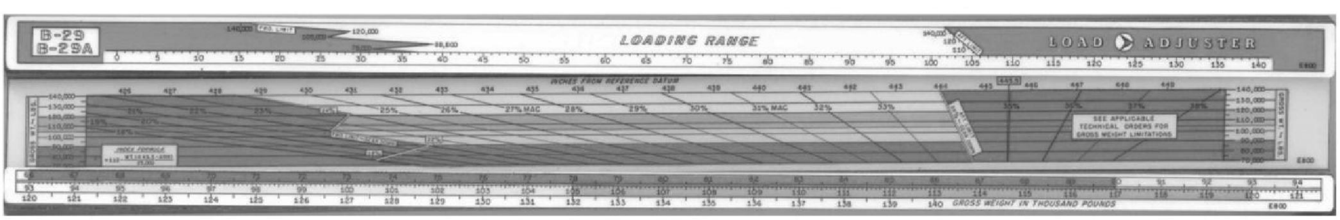


Figure 4. Load Adjustor for the American B-29 Bomber.

Most load adjusters were for military types, but some have been made for civil types: the oldest load adjuster known to me is number 163 from 1939 for a Sikorski S-42 flying boat (Collection IJzebrand Schuitema).

Load adjusters are widely available at eBay and elsewhere but in general only a very limited number of aircraft types can be found; prices vary greatly depending on popularity of the aircraft type more than on anything else.

Figure 5. Wright R-9 Performance Computer.

2. Performance

Aircraft performance is obviously based on engine performance, so slide rules have been created to calculate the engine power as a function of rpm, manifold pressure, temperature and density of outside air, and possibly turbocharger setting. Such a slide rule was manufactured by Beechcraft for the Wright R-9 engines with which several of its aircraft were equipped (see picture).

In many cases, the actual aircraft performance is taken from tables in the pilot's operating manual using the resulting power as main input.

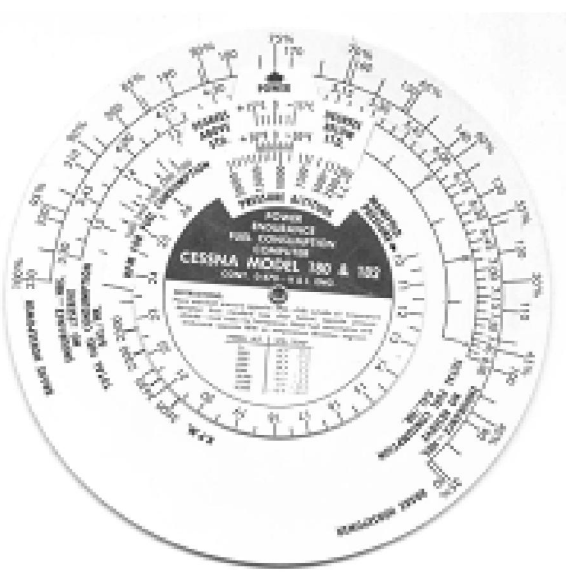


Figure 6. Cessna Performance Computer.

One manufacturer of light planes, Cessna, has developed a large series of slide rules to combine these steps: they take into account all the above-mentioned engine performance variables, and then add the aircraft parameters, including fuel capacity, to calculate directly endurance and other related values.

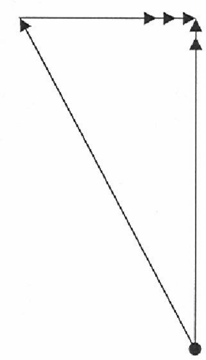
Cessna has built dozens if not hundreds of different aircraft types (over successive years often with slightly different engines) and such computers are available for many of these: I would expect there to be at least 100 different types.

Dozens of other completely different types of performance calculators have been developed, mostly in the USA and in the UK, but any treatment of these falls outside the scope of an overview article.

3. Wind Correction

When navigating in moving air, it is important to calculate the effect of the air movement (more commonly known as wind effect): both sidewind and head/tailwind have to be taken into account. Graphically, this can be depicted by a wind triangle consisting of the following three vectors:

- Single arrow: aircraft heading;
- Double arrow: ground track;
- Triple arrow: wind vector.



The diagram above shows a somewhat extreme case that I came across a few years ago: My plane had a true airspeed of 120 kts, I had to fly due north and the wind was blowing from the west at 60 kts. This is a simple example to calculate: a rectangular triangle with angles of 30 and 60 degrees. With three variables known (two lengths and an angle), it is possible to calculate the remaining unknowns, resulting in a drift of 30 degrees and a ground speed of 104 kts ($120 \times \frac{1}{2}\sqrt{3}$).

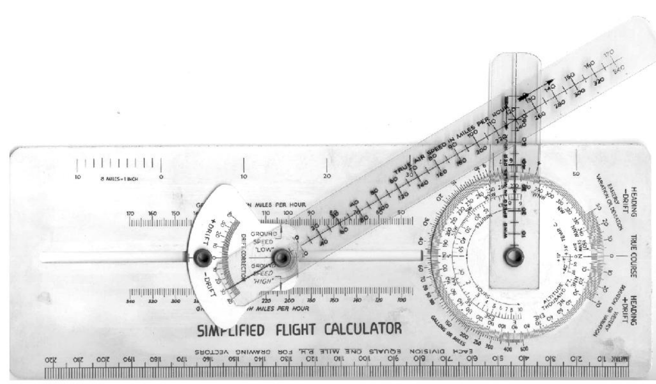


Figure 7. Simplified Flight Calculator.

The most direct method is using dedicated wind correction computers like the 1942 vintage "Simplified Flight Calculator". It gives a direct graphical representation of the wind triangle. Readout is straightforward and exact. The main disadvantage is that it can be somewhat difficult to operate (especially with cold hands/gloves) and it is fragile. The British military Mark II (pre-WWII) operated along the same lines.

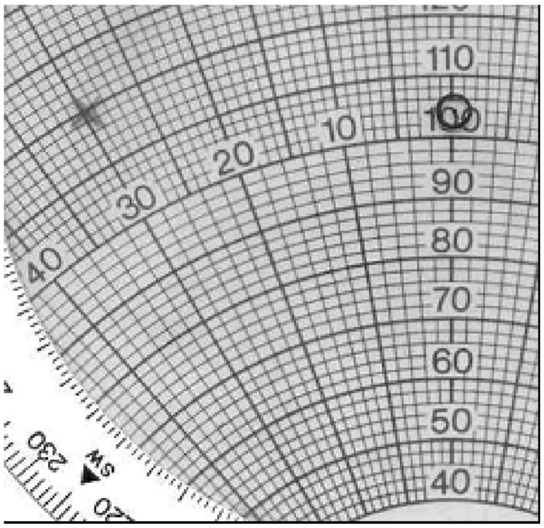


Figure 8. Wind Triangle on E6B.

The wind slide as used in the E6B was pioneered in 1935 by Philip Dalton and has become the most widely used method of calculating the wind triangle. When I tried the above-mentioned example, I was surprised to see that a standard E6B could not handle this problem: the low speed side could not handle 60-kt winds, whereas the high speed side could not handle 120-kt airspeeds. A variant (the 1953 vintage AN-5834-1A) can handle the problem, although with low accuracy.

The Aristo Aviat series or the Pooley/Airtour CRP series perform much better (the picture shows the wind triangle on an Airtour CRP-5). Both these series truly seem to live up to their fame as being the cream of the E6B-type flight computers.

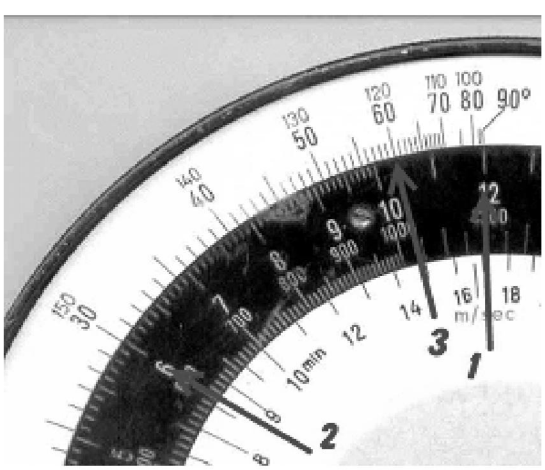


Figure 9. Wind Triangle on DR2.

Most flight computers use some form of graphical representation to solve the wind triangle problem.

An interesting and different approach was taken by the German WWII vintage Dreieckrechner (DR2), which has an added sine scale to perform directly the calculations for the wind triangle as follows: set wind angle (90°) against airspeed (120 kts) (1), opposite wind speed (60 kts) read drift angle (2: 30°), subtract drift angle from wind angle (60°) and read ground speed opposite (3: 104 kts).

Russian and other Eastern bloc flight computers, including the linear NL10M and its Polish equivalent, the Skala SN-3m, have since used the principle used by the DR2.

Because the DR2 is special in covering two decades (1 to 100) instead of just one decade as any other flight computer does, it gives direct values both for small and for large drift angles. This is different than the MB-9, which also has a sine scale for this purpose, but which covers only one decade; hence the sine scale spirals twice and one has to be very careful to use the correct sine value when calculating drift angles.

4. Flight Time, Endurance

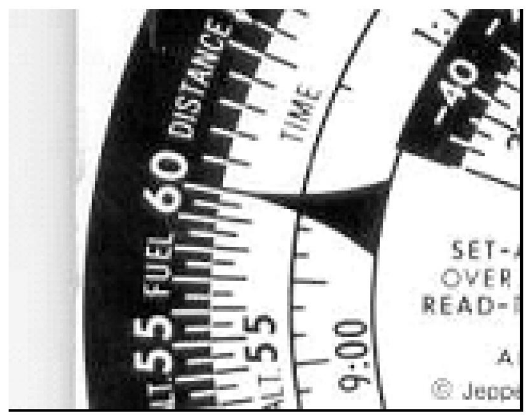


Figure 10. Hour Gauge Mark on E6B.

These answer questions like: "when flying at 120 kts, how long will it take me to fly a distance of 300 miles" or "with a fuel consumption of 9 gallons per hour, how long can I fly if I have 40 gallons on board?"

These are normal multiplication/division type calculations with the only specialty being that they almost always relate to hours, hence the big triangular pointer at the 60-minute mark.

5. Conversion Between Different Units.

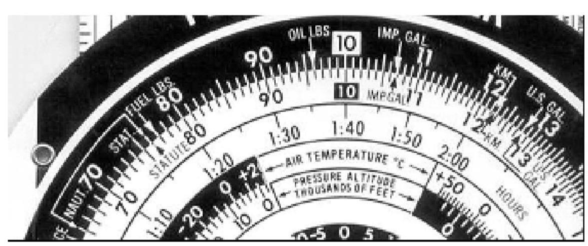


Figure 11. Conversion Gauge Marks on E6B.

Many flight computers have gauge marks to convert statute miles into nautical miles or kilometers, Imperial or US gallons into liters or even pounds of fuel into US Gallons. For this final conversion, a standard gasoline specific gravity of 6 lbs/gal is used, which can give problems with modern light aircraft that run on diesel fuel (s.g. 7.2).

The actual location of the gauge points varies greatly, and the method of conversion can vary even on the same flight computer. Therefore, it is always useful to double-check calculations and/or read the manual to make sure that no error is made.

Most flight computers have conversion scales for converting between Centigrade and Fahrenheit.

6. True Altitude

An aircraft's altitude is determined by measuring the pressure of the outside air using a special type of barometer (static pressure). Altimeters are calibrated according to a standard atmosphere that has a temperature of 15 ° C at sea level and a well-defined pressure and temperature gradient.

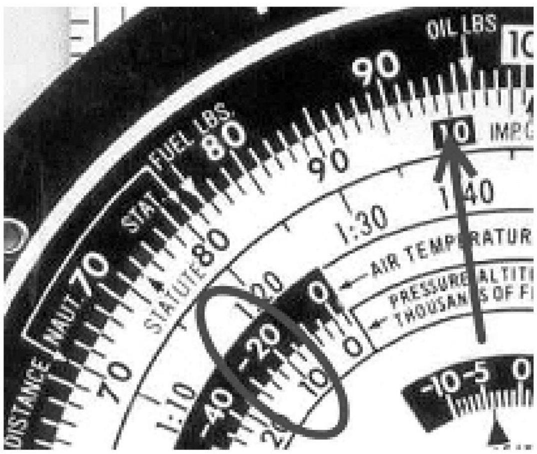


Figure 12. True Altitude Calculation on E6B.

The actual atmosphere is almost always different from this standard and therefore, a compensation has to be made to determine true altitude. Usually, a window is provided for this purpose: set the actual outside temperature over indicated altitude and on the outside scale, the true altitude can be read over the indicated altitude. For example, the "standard" temperature at 10,000 feet would be −5°C, with an outside temperature of −20°C, our actual altitude would be 9,400 feet, which could mean missing or hitting that mountain top. The general rule, both for temperature and pressure gradients, is: "from high to low, look out below".

This is a relatively coarse determination of true altitude, but usually sufficient to stay out of trouble. For more exact calculations of true altitude, for example for precision bombing, during WWII a dedicated altitude computer was developed: the AN5837 with its characteristic fluorescent spiral on a black background, but which is difficult to handle in practice. In the early 1950s this same principle was added to a more or less normal flight computer (designated MB-1) but this had only a short life, so apparently it was not very useful in practice.

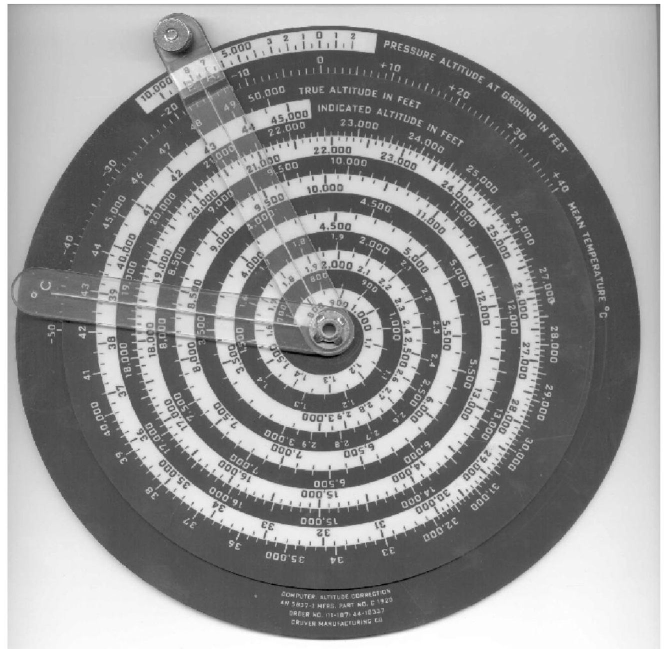


Figure 13. AN5837 True Altitude Computer.

7. True Airspeed

An aircraft's airspeed is measured by "capturing" the air through which the aircraft moves in a pitot tube (dynamic pressure). Since this pressure is not only depending on speed, but also on the characteristics of the air (density, temperature), compensation will have to made to determine the true airspeed from this indicated airspeed.

On standard E6Bs, again a window is used where the outside temperature is set against the indicated altitude and the outside scale is used to read the true airspeed against the indicated airspeed. This can give significant differences: for example, when flying at 10,000 feet at 0 ° C (not uncommon), an indicated airspeed of 120 kts translates into a true airspeed of 141 kts. Considering that the engine uses about as much fuel as it needs to fly at 120 kts at sea level, it is immediately obvious why flying at a high altitude is usually very efficient.

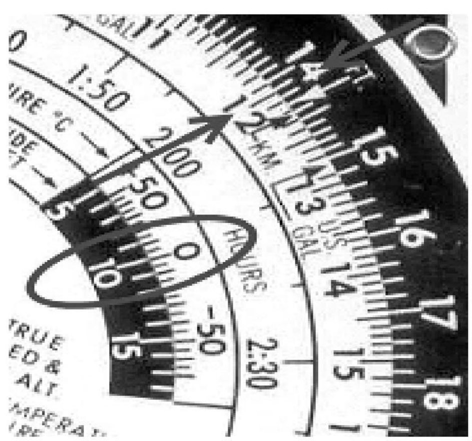


Figure 14. True Airspeed Calculation on E6B.

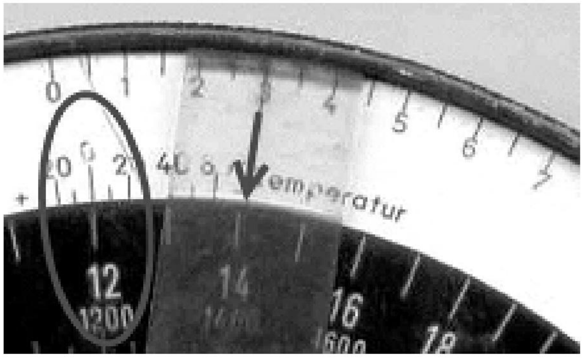


Figure 15. True Airspeed Calculation on DR2.

The German DR2 had a different approach: here an extra scale was added on the outside to calculate the true airspeed: set temperature (0°C) over speed (120 kts), then set cursor at altitude (3000 m = 10,000 feet) and read true airspeed 141 kts under the cursor. The results are exactly the same, but the process is slightly simpler and more intuitive to use.

For high-speed aircraft, compressibility of the air and friction heating have to be taken into account. Civil flight computers of the CR series and military types such as the MB-2, MB-9, and E-11 have special features for this purpose that I will not elaborate upon, since that would be beyond the scope of this overview.

8. Density Altitude

On a hot day, the air is thinner than on a cold day. This means it cannot provide the same lift as on the cold day. In fact, the air behaves as though we were flying at a higher altitude. This is called density altitude. The higher the density altitude, the less lift can be produced and the longer the take-off run will be. This determination of the take-off run is the most important use of the density altitude. On a day with a 30°C air temperature at sea level, the density altitude is 2,000 feet.

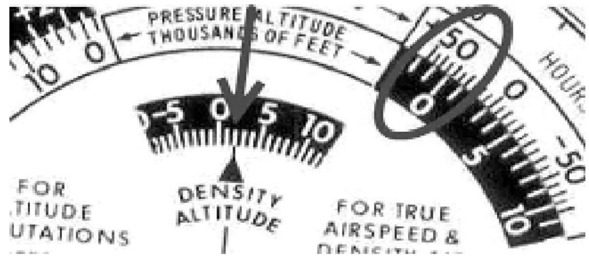


Figure 16. Density Altitude Calculation on E6B.

Flight computers often use yet another window to calculate this, often in combination with the window for true airspeed, as shown in the example.

9. Various functions

Slide rules or other types of mechanical calculators have been developed for many different applications in aviation, such as airfield pattern flying, bomb aiming, star navigation, timing and interpreting of aerial photos, intercepting enemy aircraft or fleets, timing the dropping of paratroopers, and many others.

It would be beyond the scope of this overview to discuss any of these in any detail.

Bibliography

1. Schuitema, IJ, "Luftnavigation", *Sammler Journal*, 11/96 (in German).

2. Sanik, Paul, "U.S. Army Air Corps Aerial Dead Reckoning Computer Type E-6B", *Journal of the Oughtred Society*, 6:1, Fall 1997.

3. Mortimer, Hans, "The Load Adjuster: It Looks Like a Slide Rule, But Is It?", *Journal of the Oughtred Society*, 10:1, Spring 2001.